

**University College London**

**Faculty of Engineering**

**Human Energy Harvesting in the Urban Environment**

**Thesis submitted for the Degree of Doctor of  
Engineering**

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## **Abstract – Human energy harvesting in the urban environment**

The overall aim of the thesis was to provide a holistic view of the potential for electrical energy generation from harvesting of human mechanical work in the urban environment. This required consideration of a broad range of topics including, energy in people, energy conversion technologies and the activity of people and focussed on floor and door integrated devices.

The initial step was to consider the potential offered by an individual through consideration of the flow of energy within people and the potential available for harvesting from single actions on floor and door integrated devices. Secondly the process and technologies available for converting mechanical work into electrical energy were considered with a focus on the efficiency with which this could be achieved. Finally, computer based modelling was carried out to determine the expected energy outputs from a device or system of devices to both determine the maximum achievable values and for various assumption based location scenarios in the urban environment. In addition the economic value and displaced carbon dioxide emissions from the generated energy were considered in terms of replacing grid energy.

It was concluded that although significant potential exists in the form of human activity, utilising this potential is problematic for a variety of reasons. Much of the energy expended by people is required to complete actions necessary for survival and everyday life, leaving only a small fraction available for energy harvesting. The efficiency with which mechanical work can be converted into electrical energy was found to vary greatly between technologies. In addition it was found that the energy potential is spread diffusely throughout the built environment, with even the most suitable locations returning only modest energy generation values. As a direct consequence it was highlighted that the cost and embodied emissions of devices must be low if human energy harvesting is to offer any benefits.



## EngD program overview

The thesis submitted is intended as part of the EngD program in Urban Sustainability and Resilience. The EngD is a 4 year program comprising of three main components and in three phases. The phases that must be completed are the MRes, MPhil/transfer and the EngD and have been addressed below.

### Research:

- MRes: The 1<sup>st</sup> year of the program was based around the completion of the MRes, requiring the completion of at least 4 modules and a thesis submission.
- MPhil/transfer: A second thesis was submitted in order to transfer from the MPhil to EngD programs. This was required 12-18 months after the completion of the MRes.
- EngD: The EngD required the submission of the EngD thesis.

### Industrial sponsorship:

- The project was proposed and sponsored by an industrial sponsor, in this case Battle McCarthy. The project was proposed by Battle McCarthy with the aim of determining whether utilising building integrated human energy harvesting devices offer an appropriate means of energy generation.

### Module completion:

- It was required that 8 modules be completed over the first 3 years of the EngD program, with the completed modules listed below.
  1. Systems lifecycle.
  2. Professional development in Practice.
  3. Investigative research.
  4. Energy systems and Sustainability.

5. Energy systems modelling.
6. The Built environment: The energy context.
7. Resilience.
8. EU Law and Policy on Climate Change.

## Statement of originality

This thesis covers the research work carried out by the author at University College London between September 2009 and March 2014 and is submitted for consideration for the award of an EngD. This research investigates the use of human energy harvesting as a source of electrical energy generation in the urban environment. A holistic approach has been taken to this and has been investigated through computer based models. It is the author's belief that the work carried out in this thesis is original unless otherwise acknowledged in the text by reference. The author claims to have made the following contributions to the subject of electrical energy generation from human energy harvesting in the built environment.

1. An analysis of the flow of energy through the energy harvesting process has been carried out with a particular focus on the efficiency of the process. This starts at the point of ingestion of food through the development of harvestable mechanical work to the generation of useful electrical energy.
2. An analysis of the electrical energy generation potential from floor and door energy harvesting devices is carried out. This considers the efficiency of the process from the conversion of mechanical work into electrical energy to delivery of electrical energy from the energy storage medium. The input energy potential for door devices is determined through computer models and is used to determine the potential for energy generation from the actions of walking and door use.
3. An analysis of the energy outputs from different situations is carried out. This is achieved through modelling based on various assumptions about the activity and utilisation of this activity.
4. Based on the energy potential the economic and displaced emissions are considered to determine thresholds for the viability of human energy harvesting as a means of electrical energy generation.

Signed:

Julius Partridge  
date



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## List of Publications

The following publications were completed as part of the EngD course.

J. Partridge, 2010, The 'Human' Office, Energy Harvesting & Energy Storage Europe 2010, 26-27<sup>th</sup> May, 2010, Munich, Germany

J. Partridge, 2011, The 'Human' Office, Energy Harvesting & Energy Storage Europe 2011, 21-22<sup>nd</sup> June, 2011, Munich, Germany

J. Partridge, 2012, The 'Human' Office, 1<sup>st</sup> International conference on Urban Sustainability and Resilience, 5-7<sup>th</sup> November 2012, UCL, London



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## Nomenclature

$\Delta t$  – Change in time

$\eta$  – Ratio of door opening events to the flow rate.

$\eta_{\text{ascend}}$  – Proportion of users ascending the stairs.

$\eta_H$  – Harvesting efficiency

$\eta_{\text{step}}$  – Utilised potential for footfall

$\theta_0$  – Initial angular position

$\dot{\theta}_0$  – Initial angular velocity

$\theta(t)$  – Angular position at time  $t$

$\dot{\theta}(t)$  – Angular velocity at time  $t$

$\theta_{\text{max}}$  – Maximum door angular position

$\xi$  – Damping ratio

$\tau_0$  – Opening torque

$\tau_G$  – Damping torque of generator

$\Psi$  – Phase angle

$\omega_0$  – Natural frequency

$\omega_d$  – Damping frequency

$A_i$  – Area number  $i$

AE – Additional mechanical energy requirement.

AME – Additional metabolic energy requirement.

C – Capacity factor.

CF – Cost factor.

CI – Cost intensity.

$C_{FR}$  – Capacity factor at a given flow rate.

$C_{\text{theoretical}}$  – Theoretical capacity factor.

$C_1$  – Constant 1

$C_2$  – Constant 2

$C_3$  – Constant 3

$C_4$  – Constant 4

$C_5$  – Constant 5

$h$  – Displacement

$d$  – Damping effect of the generator

$d_c$  – Generator damping coefficient

$d_{critical}$  – Critical damping

$E_{ascent}$  – Total energy generated whilst ascending stairs.

$E_{ascent}$  – Energy generated from a step whilst ascending stairs.

$E_d$  – Energy dissipated in the generator

$E_{descent}$  – Total energy generated whilst descending stairs.

$E_{descent}$  – Energy generated from a step whilst descending stairs.

$E_{D.O.E.}$  – Energy generated from a door opening event.

$E_{step}$  – Energy generated from an individual step.

$E_{tot}$  – Total energy.

$EE_{net}$  – Net energy expenditure

$E_{max}$  – Maximum available energy

$E_{max}$  – Maximum energy output.

$EF$  – Emissions factor

$EI$  – Emissions intensity

$Env_{max}$  – Maximum envelope of operation.

$Env_{min}$  – Minimum envelope of operation.

$EP_{D.O.E.}$  – Energy potential available from a door opening event

$ER$  – Energy ratio.

$E_{useful}$  – Energy delivered by the energy storage system.

$f$  – Force

FEF – Emissions factor from food.

FR – Flow rate

FR<sub>mean</sub> – Mean contribution to flow rate.

F<sub>0</sub> – Opening force.

g - Gravity

I – Moment of inertia

I<sub>L</sub> – Inertia of door leaf

k – Coupling constant

k<sup>2</sup> – Electromechanical coupling constant

k' – Torsional spring constant

k'<sub>1</sub> – Torsional spring constant of spring 1

k'<sub>2</sub> – Torsional spring constant of spring 2

L – Length walked by a person.

L<sub>i</sub> – Leaf number i

m – Mass

m<sub>d</sub> – Mass of the door

m<sub>L</sub> – Mass of door leaf

NE – Net walking efficiency N<sub>D.O.E.</sub> – Number of door opening events.

N<sub>expected</sub> – Expected number of users.

N<sub>f</sub> – Number of full door opening events.

N(FR) – Total number of users for a particular flow rate.

N<sub>h</sub> - Number of half door opening events.

N<sub>max</sub> – Maximum number of door openings

N<sub>people</sub> – Number of users.

N<sub>person</sub> – Number of steps per person.

N<sub>stairs</sub> – Number of stairs.

N<sub>step</sub> – Number of steps.

$N_{\text{step\_ascent}}$  – The total number of steps taken for stair ascent.

$N_{\text{step\_descent}}$  – The total number of steps taken for stair descent.

$N_{\text{total}}$  – Total number of users.

$P_{\text{AVE}}$  – Average power

$p(\text{FR})$  – Probability of a given flow rate occurring.

$P(t)$  – Power dissipated in the generator at time  $t$

$\text{Pot}_{\text{norm}}$  – Normalised potential.

$Q$  – Quality factor

$r_d$  – Width of the door

$r_F$  – Distance from the origin at which the opening force is applied

$r_L$  – Radius of door leaf

$t$  – Time

$t_{\text{D.O.E.}}$  – Time taken for a door opening event to occur

WEE – Walking energy expenditure.

$W_H$  – Harvestable work

## Abbreviations

AC – Alternating current

BMR – Basal Metabolic Rate

BW – Body weight

DC – Direct current

DE – Dielectric elastomer

D.O.D. – Depth of discharge

D.O.E. – Door opening event

EE – Energy expenditure

EM – Electromagnetic

FR – Flow rate

GE – Gross energy

GHG – Greenhouse gas

GRF – Ground reaction force

IEEE – Institute of Electrical and Electronics Engineers

IET – The Institution of Engineering and Technology

IPEG<sup>TM</sup> – Innowattech piezo electric generator

LED – Light emitting diode

Li-ion – Lithium ion

LiNbO<sub>3</sub> – Lithium niobate.

ME – Metabolisable energy

MET – Metabolic equivalent

MIT – Massachusetts Institute of Technology

MOSFET – Metal-oxide-semiconductor field-effect transistor

NHS – National Health Service

Ni-Cd – Nickel Cadmium

OPA – Occupational physical activity

PAL – Physical activity level

PVDF – Polyvinylidene fluoride/difluoride

PZT – Lead Zirconate Titanate

RPM – Revolutions per minute

SDC – Sustainable Dance Club

TEE – Total energy expenditure

TEF – Thermogenic response to food

TOQ – Tecumseh occupational physical activity questionnaire

UK – United Kingdom

USA – United States of America

VM – Voltage multiplier

# 1. Introduction

---

## 1.1. Motivation

In recent decades there has been a realisation that the way in which we generate and use energy must change due to the detrimental affect our current approach has on the global climate. In response to this, international agreements such as the Kyoto Protocol require that developed nations which are signatories are required to reduce greenhouse gas emissions (UNFCCC 1998). This is however, not the only factor in this drive for change. Our current approach to energy generation is heavily dependent on fossil fuels. In the UK in 2008 natural gas and coal contributed 28% and 39% respectively to national electrical energy generation (MacLeay 2010). This presents two additional problems associated with our current approach to energy generation. Firstly there is an appreciation that fossil fuel reserves are finite, in 2013 the ratio of known reserves to production rates of oil, gas and coal where 52.9, 55.7 and 109 years respectively (BP 2013). The second problem lies with the security of fuel supplies, with potential for significant problems if these supplies cannot be secured (Wicks 2009). This relates to the uneven distribution of the remaining reserves, for example Russia and the Middle East account for over 60% of the remaining known natural gas reserves (BP 2013).

The built environment accounts for 20-40% of final energy consumption in the UK and 50% of carbon emissions, with retail and offices accounting for 2% of total energy use (Pérez-Lombard et al. 2008). Despite the UK government's commitment to reducing carbon emissions by 80%, from 1990 levels by 2050 (Britain 2008), there was a 17% increase in the energy consumption in the non-domestic building sector between 1990 and 2003 (Clarke et al. 2008). In addition, the EU has set targets for EU nations through the Renewable Energy Directive, where the UK has a target of 15% of total energy consumption to be produced from renewable sources by 2020 (EU 2009). It is clear that many different sources will be required to meet the nation's energy demands, with much research being carried out into a broad range of technologies in an attempt to meet this demand.

One alternative source of energy generation could be human energy harvesting, where the source of energy generation is energy expended by the human body. Much research has been

carried out in the field of personal energy generators, where a device is attached to an individual and the generated energy used for portable loads. Recently however, there appears to be a trend towards developing devices embedded in the urban environment, and provides the focus of this thesis.

The project was originally proposed by a small Consultancy called Battle McCarthy, with the aim of exploring the potential available from human energy harvesting in the urban environment. It was expected that the research carried out for this project would link in with projects being undertaken by Battle McCarthy. Unfortunately the relationship broke down for a number of reasons, such as lack of funding and available work. This may have been a result of bad timing, in that the project began in 2009, shortly after the start of a recession and thus resulted in a marked downturn in projects available to Battle McCarthy. As such the project was completed without the aid of an industrial sponsor and hence shaped the approach taken towards the research.

Energy harvesting is the concept that energy expended by people through mechanical work in everyday activities such as walking, opening doors or even typing can be harvested by purpose built devices to provide electrical energy. In this situation the human body effectively acts as a battery with the energy stored in the form of chemical energy and is converted into mechanical work (Starner & Paradiso 2004). In most situations the recoverable energy from human activity will be small, with the real benefit of such technologies to be found in the power of the masses. An important point to make about this technology is that it generally requires the user to expend additional energy whilst carrying out an activity for it to be harvested (Starner & Paradiso 2004). As such the installation of such devices throughout the urban environment needs to be carefully considered. Since the generation of electrical energy is inextricably linked to the presence of human activity it follows that areas with high human activity will offer the greatest potential for electrical energy generation. As such it is expected that such devices will only be installed where large numbers of people transit, thus having a negligible effect on an individual whilst still providing considerable potential. Since human activity is spread throughout the urban environment it can be considered as a diffuse source of energy.

The source of energy utilised for human energy harvesting is the energy expended by the human body, ultimately leading back to the energy consumed by people in the form of food. This, combined with the diffuse nature of human activity can make it a uniquely complicated source of energy due to the need to consider the requirements of the human body when assessing the energy source.

In terms of devices embedded in the urban environment, there are a number of commercially available devices offered by companies such as Pavegen, Sustainable Dance Club (SDC), Innowattech and Soundpower. The manufacturers were contacted in an attempt to get more information with regards to the devices and their performance, however they were unwilling to provide further details than were available online and as such this shaped the approach to and focus of the project. They have received considerable online media coverage and have been the recipients of numerous awards. Pavegen, for example has been the recipient of many awards including the IET sustainability prize (2011), Skanska 'Green solution' award (2011) and the UK Trade and Investment 'Exporting for Growth Prize' (2012) as well as media coverage in several newspapers and global news outlets (Pavegen n.d.-a). In addition many claims have been made with regard to the applications and sustainable credentials of the technology. One such claim to be made is,

'A typical installation of tiles with sufficient footfall will generate enough energy to power lighting for over 12 hours' (Pavegen n.d.-b)

However, very little specific information is given with little or no evidence presented to back up such claims. This will be further discussed in Chapter 4 but is an example of the rather elusive statements made with regards to the technology. In addition, the literature revealed a limited amount of research into the technology, particularly with regards to its application. As such, verification of the claimed benefits of the technology appears to have not been properly addressed in the academic literature. The lack of clear information about the potential of human energy harvesting needs to be addressed before the viability of the technology can be properly assessed and was the overall aim of this thesis.

## **1.2. Research questions**

In order to study the potential and feasibility of human energy harvesting, a number of research questions were posed to consider a holistic view of human energy harvesting and determine whether it may offer a feasible source of electrical energy. This requires consideration of a broad range of topics to explore and determine the key parameters involved. The overriding research theme of the thesis was to attempt to understand the potential and limitations to human energy harvesting and was examined through the following questions,

1. How does the human body produce harvestable energy and what are the limitations?
2. What energy potential can be offered by an individual and from which sources?
3. What technologies are available for harvesting energy and the limits to expected energy outputs from human activity?
4. How much energy could be expected to be generated in practical locations?
5. What is the feasibility of the energy generated via human energy harvesting in terms of economic viability?
6. What are the expected environmental impacts and emissions displaced by the generated energy?

The approach taken to answer these questions is laid out in section 1.3. The research questions were developed as a result of the literature review and aimed at providing a holistic view of human energy harvesting in the urban environment.

## **1.3. Research structure**

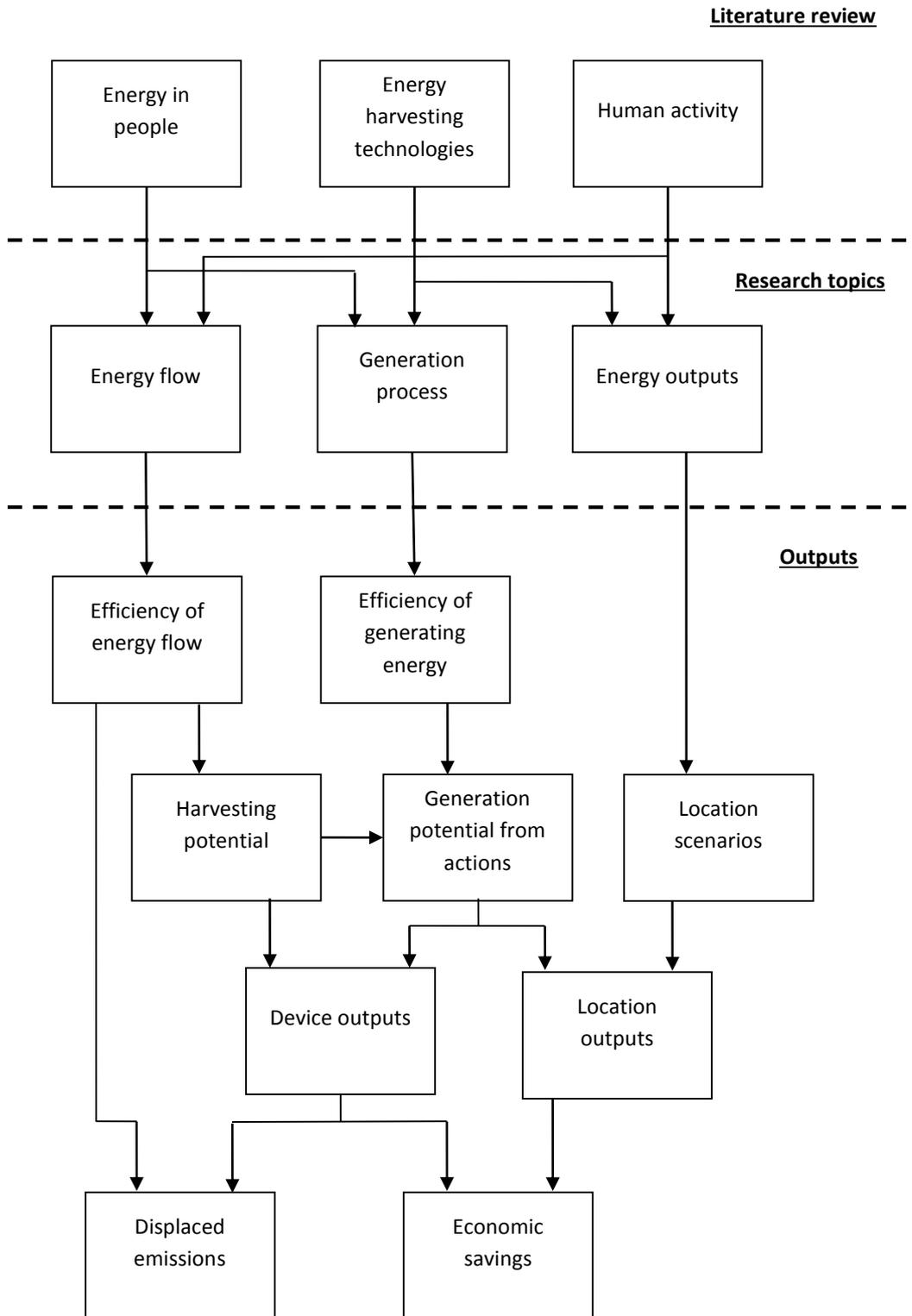
In order to answer the questions posed in section 1.2. the structure laid out in fig. 1-1 was developed. A wide range of topics were assessed ranging from human physiology to electrical energy generation technologies and human activity. A brief overview of the research is given as follows and outlines the work carried out in each chapter of this thesis.

Initially a literature review was carried out and presented in Chapter 2, with the aim of determining the state of research in a number of fields. These were 1) energy in people, 2) energy harvesting and 3) human activity and were all thought to be necessary to properly assess a holistic view of human energy harvesting. A review of the literature is presented in chapter 2 to summarise the current state of the fields and acts as a starting point from which the research was carried out. The literature revealed information in several areas that was deemed to be a useful starting point in answering the research questions posed in section 1.2.

Chapter 3 is concerned with the flow of energy in people and how this relates to the available potential for energy harvesting. Information regarding the intake of energy, the use of energy in the body and the efficiency of developing mechanical work was used to assess the efficiency of developing mechanical work from the input energy contained in food. In addition the energy available for harvesting from walking as well as swing and revolving door use was considered to assess the available energy potential.

Chapter 4 aims to determine the limitations to the efficiency of generating electrical energy from mechanical work. The literature revealed several technologies used to harvest energy from mechanical work and was used to assess the efficiency with which this can be carried out. Much of the literature was aimed at harvesting energy from footsteps, although predominantly for shoe integrated devices. In addition to footsteps, the energy generation potential of swing and revolving door use were considered. This was deemed to be essential for determining the potential of energy harvesting as it gives an indication of the energy that can be generated by a device from a single action.

Chapter 5 continues on from Chapter 4 and considers the potential for energy generation in the urban environment. The potential for energy generation in the urban environment is assessed based on a number of parameters expected to have an effect. Initially the maximum activity a device may experience was considered, followed by the output based on varying levels of activity. The utilisation of the available potential was considered as this was expected to have a significant impact on the generated energy, especially for swing and revolving doors. Finally a number of assumption based models were considered to determine the energy output that could be expected in real locations.



**Fig 1-1: Outline of the structural overview used to assess the research objectives.**

Chapter 6 considers the displaced emissions and economic savings resulting from the energy generated via human energy harvesting. This was based on the expected energy outputs

calculated in Chapter 5 and was related to the efficiency of energy generation explored in Chapters 3 and 4. Due to a lack of information with regards to specific devices a direct assessment of the emissions was not possible, thus the emissions displaced as a result of the energy generated are considered when compared to energy provided via the grid. This provides a threshold value for which the devices must be produced to make a positive contribution.

Finally Chapter 7 outlines the conclusions drawn from the work presented in this thesis along with an outline of further work that was thought to offer some interest. This presents a summary of the research which aimed at providing a holistic view of the potential offered by human energy harvesting in the urban environment, including the flow of energy, energy outputs, the displaced emissions and economic savings. In this process the research questions posed in section 1.2. will be answered.



## 2. Literature review

---

As was outlined in Chapter 1 a literature review was carried out to act as a basis from which this research was carried out. A broad range of topics were considered and have been split into three groups as follows, 1) Energy in the body, 2) Human activity and 3) Energy generation. The aim of the literature review was to gain an understanding of these topics so that a holistic view of the potential offered by human energy harvesting in the urban environment could be considered.

In order to complete the literature review the following approach was taken. The databases searched are listed, along with the search terms used to search these databases in table 2-1. The search has revealed a significant amount of literature that appears relevant to the topics assessed. However much of this is not directly applicable to the field studied within this thesis. For example, when searching for energy harvesting technologies, much of the literature is related to ambient sources of energy, which exhibit much higher frequencies and smaller forces than occur from human motion, resulting in very different considerations for the energy harvesting system. Even when considering human sources, much of the literature focuses on body worn devices. Although this has some relevance to the building integrated devices considered in this thesis, particularly shoe-integrated devices, there are still differing design considerations. In addition since a holistic approach was considered for the limitations to the energy generation potential, it was considered that the efficiency of converting the input mechanical work into electrical energy would be an important parameter. Unfortunately this was not often reported in the literature and limited the available literature.

### **2.1. Energy in the body**

In order to gain an overview of the energy available from energy harvesting it was necessary to consider the energy requirements of the human body and how this relates to the main sources of energy expenditure. Firstly the energy consumption and requirements of the body were considered. This was followed by a review of the development of mechanical work by the human body with a particular focus on the efficiency with which this is carried out for various

activities. Finally the energy potential available for harvesting energy from human physical activity was assessed.

**Table 2-1: List of databases search along with the search terms used for each of the topics.**

|              |                    |                                      |
|--------------|--------------------|--------------------------------------|
| Databases    |                    | Google Scholar                       |
|              |                    | Science direct                       |
|              |                    | IEEE explore                         |
|              |                    | Elsevier                             |
|              |                    | SAGE                                 |
|              |                    | JSTOR                                |
| Search terms | Energy harvesting  | Footfall harvester                   |
|              |                    | Human energy harvester               |
|              |                    | Human energy harvesting              |
|              |                    | Door energy harvester                |
|              |                    | Footfall energy harvester            |
|              |                    | Footfall energy harvesting           |
|              |                    | Energy harvesting from walking       |
|              |                    | Footstep harvester                   |
|              |                    | Swing door energy harvester          |
|              |                    | Revolving door energy harvester      |
|              |                    | Energy scavenging                    |
|              |                    | Human energy scavenging              |
|              |                    | Footfall energy scavenger            |
|              | Mechanical work    | Human Gait                           |
|              |                    | Mechanical work efficiency in humans |
|              |                    | Energy in people                     |
|              |                    | Human energy use                     |
|              |                    | Walking efficiency                   |
|              |                    | Gait efficiency                      |
|              |                    | Developing mechanical work in humans |
|              | Cycling efficiency |                                      |
|              | Physical activity  | Human activity                       |
|              |                    | Occupational physical activity       |
|              |                    | Daily activity                       |
|              |                    | Human physical activity              |
|              |                    | Number of steps per day              |
|              |                    | Population activity                  |

### 2.1.1. Energy requirements

The energy requirements of adults in a population were widely considered in the literature, with the focus of this study on the UK population.

In the work of (Tontisirin et al. 2003) an overview of the process of converting the gross energy contained in food into net energy was outlined. The losses associated with converting the Gross Energy (GE) contained in food into Metabolic Energy (ME) used by the body were outlined. The main losses in this process were identified as urinary energy and surface energy losses. The use of this ME was then considered, with further losses incurred before the available net energy for the basal metabolic rate (BMR) and physical activity were considered. These include losses associated with the thermogenic response of the body to factors such as food, temperature and other stimulants. Conversion factors for determining the ME content of food were introduced based on methods such as the Atwater general factor system, the extensive general factor system and the Atwater specific factor system. The Atwater general method is extensively used due to its simplicity, with the labelling of food products using these conversion factors (Codex Alimentarius Commission 2009) and will thus be considered acceptable for the purposes of this thesis.

The National Diet and Nutrition Survey (2000/1) (Henderson et al. 2003) provides a breakdown of the dietary intake of adults in the UK between the ages of 19-64. Several methods of data collection were employed, including an interview and a weighed dietary record of food and drink consumed over a seven day period. The mean total energy intake for men and women was 9.72 and 6.87 MJ respectively. In addition the percentage breakdown of macronutrients intake in the diet was presented with the values recorded shown in table 2-2.

**Table 2-2: Percentage dietary intake of macronutrients in the UK adult population.**

|       | Carbohydrates | Protein | Fat    | Alcohol |
|-------|---------------|---------|--------|---------|
| Men   | 44.7 %        | 15.4 %  | 33.5 % | 6.5 %   |
| Women | 46.7 %        | 15.9 %  | 33.5 % | 3.9 %   |

(FAO et al. 2004) presented the dietary requirements of humans at different stages of their life. It was claimed that the Doubly Labelled Water or individually calibrated heart rate monitoring gives accurate results for the total energy expenditure (TEE) of free-living individuals. Where appropriate data was not available however, it was stated that a factorial estimate can be made based on assumptions about the BMR and physical activity level (PAL). In adults the main sources of energy expenditure are BMR, metabolic response to food (TEF) and physical activity. Additional energy expenditure is required for growth or during pregnancy, however this was not considered in this thesis. It was claimed that there is significant variation between individuals and can be considered in a population to be represented by a Gaussian distribution around the mean values. The calculation of energy requirements of adults was shown via the factorial method, with equations for the calculation of BMR based on age, gender and mass presented. PAL values were assigned to sedentary, active and vigorous lifestyles. An example of a 55 kg female with an active lifestyle (PAL = 1.85) and aged between 20-30 years of age results in a daily energy requirement of 10.08 MJ/day.

In the work of (SACN 2011) the dietary energy requirements of the UK population were estimated across a range of population groups. A factorial approach was used to estimate the TEE of individuals, it was assumed that this is related to the BMR and the Physical Activity Level (PAL) as  $BMR \times PAL = TEE$ . The TEE of male and female adults was estimated to be 10.9 and 8.7 MJ/day, however significant variability was found between age groups, gender and PAL values.

### **2.1.2. Developing mechanical work**

The development of mechanical work by the human body was expected to add further inefficiency to the process. A review of the literature was carried out to determine the efficiency with which the human body is capable of converting the metabolic energy contained in food into mechanical work. It was expected that this will not be easy to determine and will vary depending on the activity being carried out. Much of the literature was focussed on the efficiency of developing mechanical work for ergometer cycling. This was primarily a result of the simplicity with which mechanical work output could be measured. Even so a considerable amount of literature exists with regards to human gait.

In the work of (Gaesser & Brooks 1975) the effect of speed and work rate were considered when applied to efficiency in ergometer cycling. Gross, net, work and delta efficiencies are calculated from both measured data and theoretical assumptions. It was concluded that delta efficiency was the most appropriate measure of efficiency as it fits with the relationship seen between caloric output and work rate. The gross, net and work efficiencies all appear to show that the efficiency increases with work rate, contradicting the linear trend between caloric output and work rate, whereas the delta efficiency fits this trend. It was considered that much of the increase in efficiency found for gross and net efficiency was a result of the method of calculation.

The work of (Cavagna & Kaneko 1977) presented a method for calculating the mechanical work required for walking and running at different speeds. A cinematographic procedure was used to record and analyse the motion of the participants during walking and running on a level running track. The total work was considered to consist of internal and external work, where external work was considered to be associated with the displacement of the centre of mass and internal work relates to motion not resulting in the displacement of the centre of mass. Plots of the kinetic energy of each of the body segments were presented, with the total positive work determined as the sum of the increases in kinetic energy in these segments. The net efficiency of positive work was calculated as total work/Net energy expenditure. Efficiencies for walking and running were found to be in the range of 0.35-0.4 and 0.45-0.8 respectively, with running efficiency increasing with velocity. These values greatly exceed the efficiency of muscle contraction (0.25) and were a result of negative work being elastically recycled to achieve some component of the positive work.

The work of (Fukunaga et al. 1986) considered the mechanical efficiency of rowing for five university rowers. The determination of mechanical work was determined from the forces applied to the oarlock pin. The energy expenditure was determined from oxygen uptake and heart rate measurements. The Gross, Net, Work and Delta efficiencies were determined as presented in table 2-3. In addition the useful power output was found to be 124-182 W. It was noted that the use of trained rowers in this study may have resulted in higher power outputs and efficiencies than for untrained subjects.

**Table 2-3: Calculated values of the different measures of the mechanical efficiency for rowing.**

| Measure | Gross | Net  | Work | Delta |
|---------|-------|------|------|-------|
| (%)     | 17.5  | 19.8 | 27.5 | 22.8  |

In the work of (Umberger & Martin 2007), the net mechanical efficiency of walking was calculated. Metabolic energy expenditure was determined from the rates of oxygen consumption and carbon dioxide production whilst the participants walked on a treadmill, with the metabolic rate during standing subtracted to determine the net metabolic rate. The mechanical work performed was determined by calculating the moments of inertia and kinetic energy around the hip, knee and ankle from video recordings of the participants walking. These were used to determine the average values of the positive and negative work at each joint over the gait cycle and summed over all the joints to give average positive and negative power over the gait cycle. From these the net mechanical efficiency was determined. It was confirmed that the net efficiency at natural stride frequency is ~35%, as was consistent with the range found in (Cavagna & Kaneko 1977) 35-40%. It was found that the optimum net efficiency was found for a stride rate 8% higher than the natural frequency, whereas the mechanical power was minimised for stride rates lower than the natural frequency.

In the work of (Goosey-Tolfrey & Sindall 2007) the mechanical efficiency of arm cranking was measured for thirteen wheel-chair dependant athletes. The gross, net and work efficiencies were calculated at 60 W and 80 W for synchronous and asynchronous arm ergometry. The net efficiency was measured for 60 W and 80 W output to give  $24.3 \pm 4.0 \%$  and  $23.9 \pm 2.9 \%$  for asynchronous and  $20.9 \pm 3.6 \%$  and  $20.5 \pm 3.5 \%$  for synchronous exercises respectively. Thus the choice of synchronous or asynchronous strategy was found to impact on efficiency with the latter giving higher values.

Furthering the work on the mechanical efficiency of cycling, (Capelli et al. 2008) measured the net efficiency of cycling on flat terrain in seven subjects. Unlike other studies measuring the mechanical efficiency of cycling, the net efficiency was considered to be the most appropriate measure, as is consistent with the requirements of the work in this thesis. The external mechanical power was calculated from measuring the torque and speed of the bike's chain

ring. The net metabolic energy expenditure was determined from measuring the total pulmonary ventilation, heart rate, carbon dioxide output and oxygen uptake, with the baseline subtraction determined whilst standing at rest before the experiments. It was found that the net mechanical efficiency was 25.7% and was consistent with similar studies.

A review of the efficiency in cycling was presented in (Ettema & Lorås 2009), with the aim of clarifying what was meant by efficiency and developing a framework through which different studies can be compared. An important challenge faced in studying physical activity was accurately measuring the work done, although cycling was deemed to be an exception to this. Even so, various definitions were used when defining efficiency, leading to some confusion when comparing the outcomes of different studies. The simplest measure was the gross efficiency. Here the efficiency was calculated as the work divided by the metabolic energy cost. But a problem arises as only part of the metabolic energy cost is directly associated with the development of work. This, results in gross efficiency increasing with work rate due to the diminishing contribution of energy costs not associated with developing work. As such various other measures of efficiency were used including net, work and delta efficiencies. These all use some form of baseline subtraction in order to remove energy expenditure not associated with producing external work, determining a suitable measure for base-line subtraction was however complicated due to the interactions between physiological systems. It was concluded that gross efficiency was the most suitable measure for efficiency as baseline subtractions require assumptions about the increased metabolic energy consumption that are not properly understood.

### **2.1.3. Harvesting potential**

The potential offered for energy harvesting by the human body was explored by a number of sources and considers a range of activities.

In the work of (Antaki et al. 1995) the use of energy expended during normal gait was proposed as a means of generating energy for artificial organs. The energy available from a variety of sources such as the hip, knee, ankle and heel-strike and toe-off were analysed using existing data on the kinematics of human gait. For the purposes of this thesis it was decided that heel-strike and toe-off offer the only relevant source of potential in relation to building

integrated devices as this was the only source capable of interacting with a floor integrated device and was thus the only appropriate source when considering floor integrated devices. It was found that for a 70 kg individual an average of 16.4 W (8.2 W per foot) of power was available for harvesting. This was based on the ground reaction forces during normal gait and for a maximum allowable displacement of 10mm during walking. It is suggested that significantly more power was available during running, with values of 180-240 W found when a displacement of 20 mm was considered. It should be noted that the impact of such a displacement on the user was not considered.

In the work of (Starner 1996) an overview of the potential offered by human energy harvesting was presented. It was determined that significant energy is stored in the human body in the form of fat, where a 68 kg person with 15% body fat has 390 MJ of energy stored as fat. The rate at which this energy was expended varies greatly depending on the activity being performed, ranging from 81 W whilst sleeping to 1.63 kW whilst sprinting. This energy was expended on various actions and results in a number of sources of energy from the human body, with the main sources being body heat and mechanical work. Body heat was ruled out due to the low limit for conversion efficiency, furthermore for application in the urban environment, harvesting this heat would appear impractical. It was calculated that arm motion could provide 60 W of power, whereas walking could provide 67 W. The potential for walking was based on a 68 kg person with a displacement of 5 cm and completing 2 steps/s. The assumption of a 5 cm displacement is based on the vertical movement of the heel during human gait. Although it appears there is significant potential from human gait, it is hard to imagine that all of this 67 W of potential will be available for harvesting without significantly inhibiting the motion of the user due to the assumption of a 5 cm displacement.

In the work of (Stacoff et al. 2005), the ground reaction forces during human gait on level ground and both stair ascent and descent were measured. Two force plates were used to measure the Ground Reaction Forces (GRF) for two successive steps on 20 subjects. The GRF was normalised with the Body Weight (BW) of the subject.

(Gilmore 2008) presented a review of the energy potential of a number of human powered technologies. These were pedal, string, heel strike, vibration generators and biothermal power sources. The daily ME requirement was assumed to be 8370 kJ, where 60% was used for BMR

functions, resulting in 3348 kJ (930 Wh) available for physical activity. The efficiency of developing mechanical work via various activities was then used to determine the overall efficiency from which gross energy (GE) can be converted into mechanical work. Cycling was considered the most efficient means of producing mechanical work (25%), with the values for lifting, walking and running assumed as 14-19%, 21% and 10% respectively. The overall efficiency of developing mechanical work from GE was calculated to be in the range of 2.6-6.5%.

(Louie et al. 2010) produced a simple analysis of the energy available from human powered generation. It was assumed that 2.73 kWh (~9.8 MJ) of digestible energy was consumed daily in the form of food. It was assumed that 60-75% of this energy was used to maintain resting metabolic function and a further 10-20% is used in the digestion of food. It was suggested that the efficiency of the human engine is 18-23%. Based on a value of 20%, it was calculated that 550 Wh of energy is available for electrical energy generation per day from mechanical work.

#### **2.1.4. Summary**

A review of the energy requirements of the human body was carried out to determine the total energy an individual expends during daily life. It was found that this can vary considerably between individuals depending on a wide range of factors including gender, age, mass and activity. Values from the literature vary considerably from 6.87 – 10.9 MJ/day. It was found that there are three main components on which the human body expends the majority of the energy available, these being the Basal Metabolic Rate (BMR), Thermogenic Effect of Food (TEF) and activity. Again it was found that there is considerable variability between individuals as to the proportion of total energy expenditure that was expended on each of these components. In most cases the BMR accounts for the majority of energy expenditure, however the activity of an individual can significantly affect this. Since the source of energy in the energy generation process is mechanical work it is important to understand the energy potential offered in the form of mechanical work.

To consider the energy potential available for energy harvesting, the efficiency with which the ME available for activity is converted into mechanical work must be considered. Considerable literature was concerned with examining this. Four methods of measuring the efficiency of

producing mechanical work were widely used. Of these it was deemed that the net efficiency provided the most appropriate means of measuring the efficiency in the scope of this thesis. Much of the literature has focussed on ergometer cycling due to the ease of measuring the mechanical work produced. Measuring the mechanical work produced during walking was a more complicated process although it has been calculated by the determination of the motion of each segment of the body over the complete gait cycle, with net efficiencies in the range of 35-40% reported for level walking.

A number of studies were carried out to determine the energy potential available for harvesting, either from an individual action or over the course of a day. The overall potential from mechanical work available over the course of a day was estimated based on assumptions of each stage in the process of converting metabolisable energy (ME) into mechanical work. It was estimated in the literature that 1.9-3.35 MJ/day is available in the form of mechanical work. This is however not the complete story when considering human gait, since the process of harvesting of energy is expected to occur externally to the body it was determined that it is the external work performed by the body on the harvesting device that determines the energy potential available for energy harvesting. In terms of walking, the studies of (Antaki et al. 1995) and (Starner 1996) appear in much of the later literature with power outputs of 16.4 W and 67 W respectively. The latter of these is based on the vertical motion of the heel during gait, whereas Antaki (1995) is based on the ground reaction forces of the foot. It was decided that the approach of Antaki (1995) represented a more appropriate approach when considering a device external to the body.

## **2.2. Activity**

It was clear that the potential for energy generation depends on the amount of activity carried out by people in the urban environment. As such a literature review was carried out to determine the activity carried out by people with a particular focus on walking.

(Sequeira et al. 1995) carried out a mechanical pedometer based study to measure physical activity in a large population survey in Switzerland. The pedometer used was the PEDOBOY pedometer. Participants were asked to wear a pedometer for one week. Younger and more active people were found to have a higher participation rate, hence the possibility of over

estimating the activity of the population. This study showed that it is possible to use a pedometer in a large population. It was noted that the pedometer is unable to take into account activity of a static nature. Age was found to be an important factor, where 11,900 to 6,700 steps/day, was found for men in the age categories of 25-34 and 65-74 years respectively and for women 9,300 to 6,700 steps/day for the same age categories. The questionnaire was found to have a weakness in the lack of detail for describing physical activity also it was found that questionnaire results were subjective.

(Swan et al. 1997) carried out a study to determine the accuracy of the Caltrac uni-axial accelerometer in determining energy expenditure (EE) during running, race walking and stepping. The results were compared to heart rate determined energy expenditure. It was found that there was an overestimation to the EE during running and race walking, and an underestimation for stepping. It was however concluded that the Caltrac was a reliable instrument, although for novel movements a tri-axial accelerometer would be more appropriate.

(Steele & Mummery 2003) carried out a study of the occupational physical activity (OPA) of staff at the Central Queensland University. Categorised into professional, white-collar and blue-collar staff, with each participant asked to complete a questionnaire and to wear a pedometer for three consecutive working days. The questionnaire used was the Tecumseh Occupational Physical Activity Questionnaire (TOQ). The pedometer used was the Yamax Digi-walker. In total there were 90 participants. The average number of steps taken in a day was found to vary considerably between occupation types with professional, white-collar and blue-collar staff giving 2,835, 3,616 and 8,757 steps/day respectively. It should be noted that these values were measured over the course of a working day. The results highlight the difference in OPA and pedometer readings of different occupations, with Blue-collar workers being seen to have significantly higher values for both. It was seen that pedometer readings and TOQ scores had a significant correlation and thus pedometers could be considered to give a reasonably accurate measure for OPA (Steele et al. (2003)).

(Schofield et al. 2005) carried out a pedometer based study for measuring occupational physical activity. The aims of the study were 1) measure daily physical activity objectively, both at the worksite and during leisure-time for six different occupational categories; and 2)

ascertain the relationship between various activities collected by self-report and step counts in the same sample of working adults. Of 63 office workers, the average number of steps taken during the day was 9,200, with 5,380 (58,5%) of these coming during the working day.

(Proper & Hildebrandt 2006) carried out a study on the contribution of occupational activity to the overall physical activity across occupational groups in the Netherlands in the years 2000-2002. It was found that on average 30% of physical activity can be attributed to OPA, although this varies significantly between occupational types. Those in policy or higher executive occupations were found to have the lowest work contribution of 19.5%, with agricultural workers the highest at 55.1% of total physical activity. It was concluded that branch specific strategies must be employed to increase OPA.

(Clemes et al. 2007) completed a four-week pedometer based study of 122 normal and overweight individuals in Leicestershire and Cornwall (UK). On average 10,617 steps/day were taken, although this was slightly higher if Sundays were excluded. It was seen that for the normal and over-weight groups the average number of step counts was 11,273 and 10,002 steps per day respectively.

(Engbers et al. 2007) carried out a study with the aim of recording quantitative data for the stair usage of office workers at two office sites. Measurements were taken both objectively through a detection system and self-reported. At worksite 1, the frequency of stair use was 8.3 per week and 5 per week with the number of floors traversed being 30.9 floors/week and 16.8 floors/week for men and women respectively. At worksite 2, the frequency of stair use was 5.4 per week and 4.1 per week with the number of floors covered being 13.1 floors/week and 10.2 floors/week for men and women respectively. These were significantly lower than the values obtained for the self-reported data, although the correlations between results could be considered strong.

(S. a Clemes et al. 2008) carried out a study to test the reactivity to wearing a pedometer, where the participants did not know they were wearing a pedometer for the first week. The pedometer used was a New Lifestyles NL-2000 pedometer. It showed that the number of steps increased from 9,541 to 11,345 steps/day when the participants knew that they were

wearing a pedometer. This was in spite of the pedometer display being taped over so no one could check the step count during the study. This suggests that the knowledge that the participant is wearing a pedometer, increases physical activity.

In the same year (Clemes et al. 2008) carried out a four week pedometer study of participants in the East Midlands (UK) with three groups, normal weight, overweight and obese. A Digi-walker SW-200 was used as the pedometer. It was stated that questionnaire based surveys tend to underestimate the number of steps taken during the day. The normal weight group was found to take an average of 10,247 steps/day, with the overweight group taking 9,095 steps and obese group taking 8,102 steps. It was also noted that across all groups the step count dropped considerably on Sundays.

In the work of (Blake et al. 2008) the use of prompts as a means of increasing stair use were tested in an NHS hospital. Infra-red sensors collected observational data over an 8 week period, with promotional posters located at two stair wells employed as the means of encouraging stair use. Although the results suggest that no significant increase in stair use was found, the results do highlight some interesting points with regards to the direction (climbing/descent) of stair use. It was recorded that 37.4% and 44.0% of users ascended the stairs at the two stairwells examined, showing the tendency of users to descend stairs.

### **2.2.1. Summary**

The literature revealed a number of methods for determining the activity and energy expenditure of a population with the review focussed on walking of free-living adults. These fall under the categories of self-reported, pedometer and accelerometer based studies. It was found that self-reported data generally overestimated the number of steps taken over the course of the day, with pedometer and accelerometer studies both capable of providing an accurate means of determining the number of steps taken by free-living individuals. It was found that significant variability exists between occupation type, age and BMI. Even so it was claimed that 10,000 steps/day are recommended with most of the studies claiming that actual values are generally a little lower than this.

## 2.3. Energy generation

The literature has revealed that a number of technologies can be used to harvest energy from human motion. These can be split into three main categories; piezoelectric materials, electromagnetic generators and dielectric elastomers, although other technologies have been used. Various sources have been utilised with the literature review primarily focussed on harvesting energy from walking.

### 2.3.1. Walking

Much of the literature available for energy harvesting from walking was concerned with shoe integrated devices. Although the source of energy generally remains the same for both shoe and floor integrated devices, developing shoe integrated devices poses a number of problems that are distinct from floor integrated devices. Even so the generation principles are the same and are therefore useful in assessing the generation potential from walking.

(Antaki et al. 1995) continued on from the analysis of the potential from human gait to build and test a 1/17<sup>th</sup> scale model generator, using a lead zirconate titanate (PZT) ceramic slug as the generator. Testing on 4 subjects showed average power outputs of  $5.7 \pm 2.2$  mW/kg for walking and  $23.6 \pm 11.6$  mW/kg for jogging. This was claimed to amount to 6.2 W for a 75 kg subject using a full scale device. This was significantly less than predicted and is thought to stem from uncertainties of piezo constants and the need for improved impedance matching. More advanced power conditioning should reduce the losses.

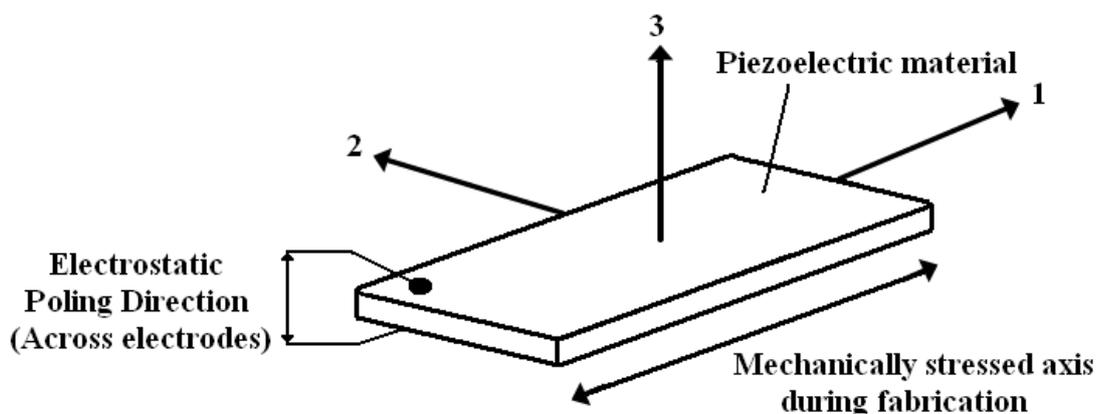


Fig. 2-1: Representation of the axes definition for piezoelectric materials, where the electrodes are placed across the 3 axis.

In the work of (Starner 1996) the potential of the human body was presented, with a particular focus on footfall harvesting. The theory of energy generation using piezoelectric materials was introduced, focussing on Polyvinylidene fluoride/difluoride (PVDF) and PZT piezoelectric materials and examined alongside rotary generators. It was claimed that a 116 cm<sup>2</sup> 40-ply triangular PVDF plate deflected 5 cm by a 68 kg mass 3 times every 5s resulted in a 1.5 W average output. Based on this it was calculated that a 52 kg user walking at 2 step/second would be capable of generating a 5 W average output. It was found that utilising a rotary generator for a 68 kg user would result in 8.4 W of available power, based on a generator efficiency of 50%. These predicted outputs have not been experimentally tested. In addition, a 5 cm deflection seems like a large deflection for the device to deflect during human gait.

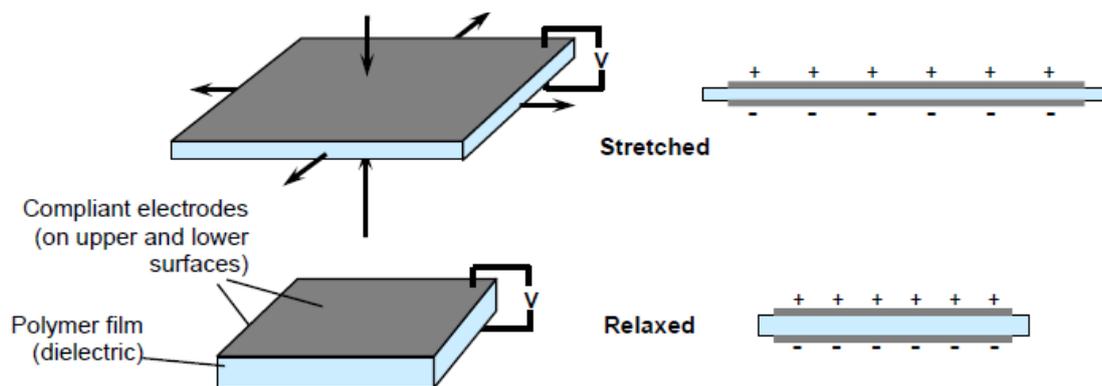
(Kymissis et al. 1998) designed, built and tested three different power generation systems to be fitted into a shoe. The three generation systems used a PVDF insole stave, a PZT unimorph and a rotary magnetic generator. The PZT unimorph generator produced a 1 mW average output and the PVDF stave produced double that, in contrast the rotary generator was able to produce an average 0.23 W output. Despite the increased power output of the rotary generator it was expected that there will be difficulties integrating it into the shoe and may detrimentally affect the users gait.

In the work of (Shenck 1999) a PZT bimorph was created from two THUNDER™ PZT unimorphs with a focus on increasing the conversion efficiency. The design methodology of the generator was presented along with calculation of the conversion efficiency, where a value of 20.1% was found. Even so the power output of 71.8 mW was still very small.

In the work of (Goldfarb & Jones 1999) an analysis of the efficiency of PZT piezoelectric ceramic as an electric power generator was presented. A model was developed to test efficiency as a function of input frequency, resistive load and input force amplitude. It was found that using PZT as an electric energy generator was problematic due to much of the energy being stored and returned as mechanical energy. It was found that the highest efficiency was achieved for very low frequencies that were far below the natural frequency of the material. In addition the efficiency increased with input force, where a maximum efficiency in the region of 40% was found for a 2 Hz 800 N input, reflecting the input

parameters experienced during human gait. It was found however that the displacement is of the order of microns and hence the output energy is very small.

At MIT, Shenk and Paradiso (Shenck & Paradiso 2001) continued on from the work of (Starner 1996) presenting two methods of scavenging energy from heel-strike generators. The generators employed were a PVDF insole stave and a PZT dimorph inserted into the shoe. The resulting outputs are of the order of mW, with efficiencies of 0.5 and 20% for the PVDF and PZT insert respectively, however it was recognised that this could be increased with further work on the electrical system. This includes optimizing the switching transistor for high voltage and low current operation. Other sources of generation are presented with a rotary generator system tested showing vastly increased power outputs. However, each technology was found to present unique problems.



**Fig. 2-2: Diagram representing the operation of a dielectric elastomer generator (Kornbluh et al. 2011).**

It was proposed in the work of (Pelrine & Kornbluh 2001) to use dielectric elastomers as a means of harvesting mechanical work. The theory of dielectric elastomers acting in generation mode was presented, claiming that they offer a high energy density with low cost form of energy generation. A number of sources of energy were proposed, including shoe generators, where it was claimed to offer several advantages over either piezoelectric or electromagnetic generators such as good load matching, simple mechanical design and are lightweight even though they do require more complex electronic circuitry. It was claimed that an acrylic elastomer heel-strike generator produces a 0.28 J output, although it was expected that this could be increased to more than 1 J. Demonstrated energy densities of 0.4 J/g were found

with theoretical values of up to 1.5 J/g predicted. In addition theoretical efficiencies of 80-90 % were predicted.

A different approach to footfall harvesting was introduced by (Niu & Chapman 2006). A linear permanent magnet generator was designed, built and tested to harvest energy from the horizontal motion of the foot during gait. The power was rectified, with average outputs of 70-90mW. It seems, however, that the utilisation of horizontal foot motion would only really be applicable to personal energy generators.

(Takefuji 2008) laid out the principles and development of a piezoelectric power harvesting mat. The first generation was tested in July 2006 and quickly followed by a two month second generation trial in late 2006 at Tokyo train station. A third experiment was carried out in 2008, with 90m<sup>2</sup> of mat. This resulted in a seven fold increase in the performance, giving 1 mWs per step. It was found that with the number of commuters this was sufficient to power the ticket gate system.

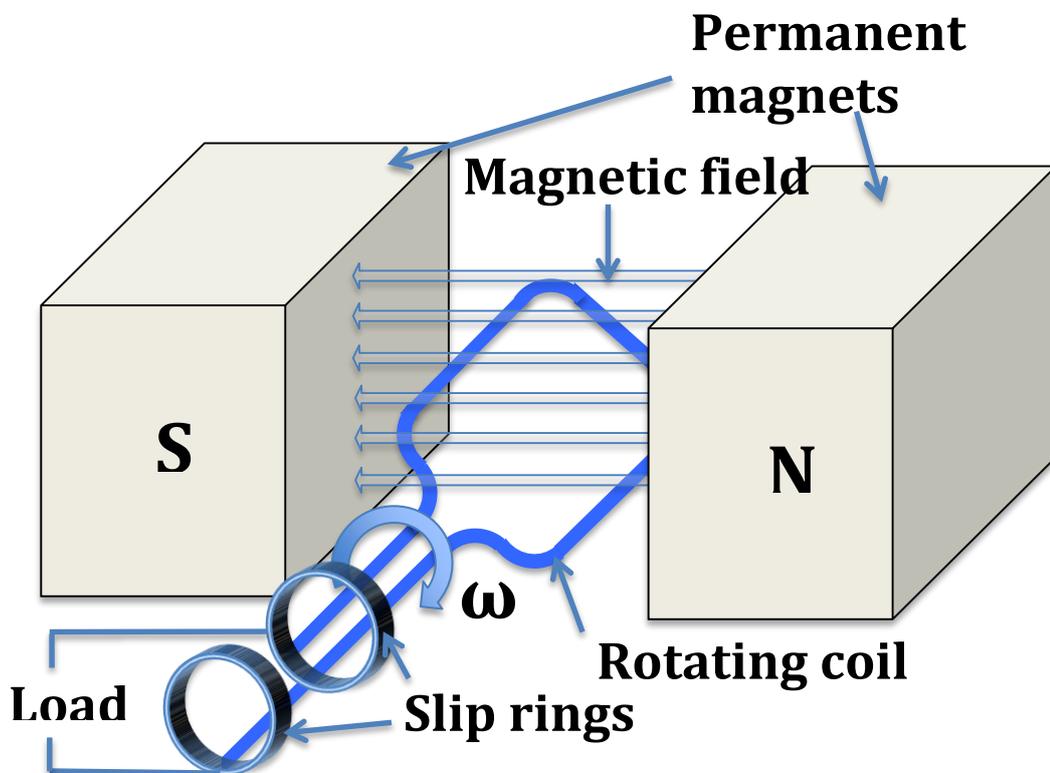


Fig. 2-3: Representation of the operation of a rotary electromagnetic generator.

(Paulides et al. 2009) presented a small scale energy generating floor tile for application in a club. The energy harvesting component consisted of a tile suspended by springs, with the vertical motion converted into rotary motion through a gearing system with the energy harvested through a DC brushed generator. A simple diode rectifier was used to rectify the generated energy, where the average maximum power output was found to be 22.4 W. A single dancer was found to give an average power output of 2-8 W (4.8 W). It was claimed in a follow up paper that the overall efficiency of the system was measured to be 48% (Paulides & Jansen 2011).

(Howells 2009) tested the power generating potential of a heel-strike generator system, utilising a PZT-5A piezoelectric transducer. The average power output after power conditioning was 0.0903 W per step, which was much lower than the target of 0.5 W. It was concluded however, that there was sufficient energy to power some electronic devices in either standby or active mode. A number of improvements were suggested, centred around reducing the stiffness of the blades.

In the work of (Rocha & Goncalves 2010) a fully shoe-integrated generator was developed utilising PVDF as the generator. The power generated was in the range of tens to hundreds of mWs. It was found that the average energy generated peaked at 0.05 J, although this was based on 4 steps/second which is more than would be expected. It was hoped that increasing the thickness of the piezoelectric film by introducing more films will increase the generated energy.

In the work of (Krupenkin & Taylor 2011) the concept of reverse electrowetting was proposed as a means of high-power mechanical energy harvesting, with power densities up to  $10^3 \text{ Wm}^{-2}$ . It was suggested that this technology would be suited to, amongst other applications, heel-strike generators. In this respect there are several advantages, such as easy scaling, very flexible force-displacement relationship and a design with no moving parts. Modelling predicts that in the region of 10 W average power could be generated per footfall, however it was made clear that this was not well understood and no physical system was developed to verify the findings.

In the work of (Kornbluh et al. 2011) it was claimed that a heel-strike generator was capable of generating 0.8 J/step (1 W output whilst walking). It was calculated that this corresponds to a conversion efficiency of 33%. The device used incorporated 20 stacked layers of prestrained VHB 4910 acrylic. Further it was claimed that no additional energy expenditure will be required from the user and a well tuned device may indeed be capable of increasing the efficiency of walking by storing and returning energy during walking. In addition it was claimed that a sea generator operated with 78% efficiency, although the input energy is based on the expected energy available and so the accuracy of this result is not properly known.

In the work of (Xie & Cai, 2013) a floor tile is designed, built and tested to harvest energy from walking. The energy generation technology employed is an electromagnetic generator, using a slider crank mechanism to harvest the mechanical work experienced during a footstep. It was found that a power output of 2W was achieved for a 1Hz footstep frequency.

In the work of (Gilbert & Balouchi, 2014a) the performance of a footfall harvesting device installed in a step of a staircase is proposed. The system was able to produce 60mJ/step and achieved a conversion efficiency of up to 55%. The system consists of a cantilever with permanent magnets attached to it, which is used to convert the input force from the foot into a vibration of the cantilever. As the magnets oscillate between a fixed coil they result in the production of a useable voltage.

In the work of (Gilbert & Balouchi, 2014b) the design of a stair integrated footfall harvesting device is outlined whereby a rotary electromagnetic generator is employed to convert mechanical work into electrical energy. It is highlighted that the input mechanical work from a footstep is not well matched to the efficient operation of such generators. As such a novel approach is proposed using a torsional spring and a flywheel to provide a more appropriate input to the generator. A mathematical model is presented with the parameters of various components in the system chosen to optimise the energy output. A prototype device was installed within a step with an energy output of 0.45 J/step and an efficiency of 11.5%.

In the work of (Li & Strezov, 2014) the energy generation potential available from the implementation of Pavegen tiles in a university library is considered. A study was carried out to

determine the activity experienced in various areas of the library, with this then used to determine the energy generation potential of the system. The energy output per step is assumed to be 7 J/step and is based on the power output of 7W, however as will be discussed in the following thesis this seems to be an optimistic assessment. It was concluded that 1.1 MWh/year could be generated from the deployment of 1820 Pavegen tiles. It was claimed that this could be increased to 9.8 MWh/year if the conversion efficiency of the tiles were to be increased by a factor of 9. It is claimed that this will result in emissions savings of over 10,500 kgCO<sub>2</sub>/year. The expectation that a 9 fold increase to energy outputs may be achievable seems unlikely, since this would result in 63 J/step of energy being generated. As is seen in the thesis this is significantly more than the available potential expected from a footstep.

In the work of (Nasir et al., 2014) a PZT piezoelectric floor tile is design and built for the purpose of providing the energy requirements of an LED light source at bus stops. Tests using a 3.75kg mass dropped from a height of 8cm revealed a peak power output of 16.3W (38.7V and 0.421A), although the energy generation potential from a footstep is not clear. It does however demonstrate that the system is capable of charging a battery for storing the energy.

In the work of (Sharpes, Vučković, & Priya, 2015) an energy harvesting floor tile was designed and built. The purpose was to act as a wireless sensor for determining occupancy in smart buildings and utilized PZT piezoelectric transducers as the energy generation component. The tiles were designed to provide for the energy requirements required to send a wireless signal which was considered to be 100μJ. The tiles were designed to be durable and to minimise the impact on the user. A system has been demonstrated whereby a light is wirelessly controlled through stepping on the floor tile.

### **2.3.2. Body motion**

(Jansen & Stevels 1999) considered the energy expenditure of several activities, such as pushing buttons and turning a handle, which were claimed to offer power outputs of up to 0.64 W and 28 W respectively. These outputs were linked to various end uses through comparing them to the power requirements of various devices. The environmental benefits were outlined, although the need for additional user benefit was noted. It was concluded that

human power can be usefully applied in practice, although many challenges need to be overcome to make the most of human power.

(Pandian 2004) presents the idea of using children's play equipment as a source of energy, with the focus on remote communities. An emphasis was placed on the idea of harvesting energy from play. For this reason the systems were designed to be low-cost, easy to maintain, safe and comfortable as well as environmentally friendly. A compressed air system was deemed to be the best solution, despite the low efficiency. The analysis of the potential power outputs of a see-saw was investigated both theoretically and with a test rig. In the region of 550 J of electrical energy was generated for 3 minutes of play time by a pair of children. The overall system efficiency was 1.6%, with a pneumatic-electrical conversion efficiency of 16.7%. It was found that the efficiency could be improved by using a larger compressed air storage facility. It was concluded that this form of power could be a practically effective means of energy generation.

(Li et al. 2009) developed a knee mounted energy harvester and analysed the physiological principles involved. It was concluded that biomechanical energy harvesting was capable of producing significant amounts of power. This required little additional work from the participant when compared to the non-generating mode, although the additional mass of the device resulted in an increase to the metabolic energy consumption. For a walking speed of 1.5 m/s it was found that  $4.8 \pm 0.8$  W of electrical power was generated with  $5.0 \pm 2.1$  W of additional metabolic energy required.

An energy generating backpack was designed, built and tested, with the results presented in the work of (Rome et al. 2005). The backpack allowed the load to move as a result of the vertical motion experienced during walking, with the relative motion of the load to the frame of the backpack used to drive a DC generator. The frame of the backpack had a mass of 5.6 kg. Testing was carried out for various load masses and it was found that increases in load mass and walking speed generally resulted in greater power outputs. A maximum power output of 7.37 W was recorded. The efficiency of the device was measured to be between 30-40% with a further loss of ~5% in the rectification of energy. It was found that when in generation mode there was an increase in metabolic energy consumption compared to when the load was fixed. This was however less than expected. It was concluded that this form of energy generation

would be beneficial for the situation of replacing the large batteries required for field or disaster-relief workers.

Further to assessing the energy available from mechanical work, (Gilmore 2008) presented an analysis of energy generation from cycling machines. It was considered that a DC generator would have efficiency in the range of 80-90% and an inverter efficiency of 85-95%. The overall efficiency of converting food energy into electrical energy for DC and AC were 5-6% and 4-5% respectively. It was calculated that 7.9% of a fitness facility's energy demands could be met by using cycling machine generators. It was concluded that this is far from economically competitive, although this could change with future technology and electricity costs. It was concluded that human power is a low-density form of renewable energy with the potential for large scale generation due to its widespread abundance.

In the work of (Louie et al. 2010) a hand crank generator was developed as a means of providing electrical power in remote rural communities in the developing world. The goal was to provide power in the 1-10 W range to provide for low power loads. A permanent magnet generator was designed with the added goal of using locally available materials and simple manufacturing processes. A hand crank operated single phase AC generator was theoretically designed and a prototype built and tested with a maximum power output of 4 W obtained. It was reported that a mobile phone battery took 220 minutes to fully recharge. It was stated that significant improvements could be made to the generator, however this would require a more complex manufacturing process.

(Gibson 2011) discusses the attractiveness and potential of harvesting some of the energy expended by people in a gym. A number of examples of where this has been applied in gyms were highlighted with most of these utilising cycling machines. It was a simple idea with commercially available products that were utilised in a number of gyms. It was stated that a healthy person will be able to generate 50-150 W whilst cycling on a cycling machine, with professional cyclists able to generate as much as 400 W. It was claimed that cycling for 30 minutes would be enough to power a laptop for an hour. It was stated that at present the economic payback period of such technology is likely to be several decades, due to the additional cost, up to \$1000 (£597 (Money Converter, 28/05/2014)), of equipment to facilitate energy harvesting. It was expected that this will be reduced in the coming years, particularly if

production volumes of such devices significantly increases. It was calculated that a single cycling machine being used for 5 hours a day with an average of 100 W output would result in 183 kWh/year of generated energy. As a comparison it was calculated that 4600 people would need to cycle for an entire day to provide the energy needs of a home in the USA for one year. It should be noted that gyms are a niche location but they are expected to be well suited to energy harvesting.

The work of (Jorgensen, Ohlert, Pang, & Shapardanis, 2014) considered the design of a pedestrian powered energy generator. A system was designed for harvesting the mechanical work associated with swing door motion with the purpose of charging a battery for use in recharging tablet devices. Each time the door is opened a 6kg mass is raised 20cm via a cable and ratcheted axle. After five door swings the mass falls and drives a rotary generator as a means of charging a battery. At optimal speeds this produced 750mA at 5.5V. It is claimed that 5.54J of energy is produced from each cycle, although it is not clear where this value has been determined. It has been shown that it is possible to utilize an energy harvesting swing door generator as a means of charging a battery.

### **2.3.3. Summary**

A review of the literature revealed a number of technologies used to harvest energy from human mechanical work. Of these four were picked out to be considered further, these were PZT and PVDF piezoelectric generators, electromagnetic generators and dielectric elastomer generators. Much of the literature was focussed on shoe integrated energy harvesting devices which, although utilising the same source of energy as external devices, presents different challenges, mainly stemming from the requirement of small, lightweight devices. Even so, many of the findings of the research were relevant to the aims of this thesis. Two examples of research into floor integrated generation devices were presented utilising a DC and piezoelectric generators. Further to the literature concerned with footfall harvesting, the principles of generating energy from each of the four methods of generation presented were considered with a particular focus on the generation efficiency. In addition to footfall harvesting, a number of sources of human energy harvesting were presented covering a wide range of applications. They cover a wide range of intended applications, from power for remote communities to energy generation in gyms.

## 2.4. Summary of summaries

The literature revealed information on a broad range of topics thought to be relevant to human energy harvesting.

- Significant information was revealed regarding the energy intake and use of this energy by people. It was found that significant energy is ingested by people, however this energy is expended on a range of processes necessary for everyday life.
- The development of mechanical work within the body was extensively considered in the literature with regards to specific actions along with the amount of activity an individual was likely to carry out.
- Harvesting this energy as a means of electrical energy generation was widely researched, however it was noted that the focus of this was primarily on personal generation devices, although this research remains relevant to the energy generation process.

Despite this there remain significant gaps with regards to the potential offered by human energy harvesting, particularly with regard to the urban environment. This has helped shape the focus of the research carried out in this thesis. The first area to be addressed is the flow of energy in the process of developing the mechanical work utilised in human energy harvesting. This has in part been addressed in the work of (Gilmore 2008) and (Louie et al. 2010) although the total mechanical work potential offered by human energy harvesting has not been fully addressed. Consideration of the overall energy flow will be the focus of Chapter 3.

**Table 2-4: Table summarising the assumptions to be used in determining the flow of energy in the process of converting energy within the human body into electrical energy.**

| Energy in the body    |              |         |       | Unit   | Source                          |
|-----------------------|--------------|---------|-------|--------|---------------------------------|
|                       |              | Men     | Women |        |                                 |
| Energy intake         |              | 9.72    | 6.87  | MJ/day | (Henderson et al. 2003)         |
|                       |              | 10.9    | 8.7   | MJ/day | (SACN 2011)                     |
| Mech. Work efficiency | Walking      |         |       |        |                                 |
|                       |              | 35-40   |       | %      | (Cavagna & Kaneko 1977)         |
|                       |              | ~40     |       | %      | (Umberger & Martin 2007)        |
|                       | Running      | 45-80   |       | %      | (Cavagna & Kaneko 1977)         |
|                       | Rowing       | 19.8    |       | %      | (Fukunaga et al. 1986)          |
|                       | Cycling      | 25.7    |       | %      | (Capelli et al. 2008)           |
|                       | Arm cranking |         |       | %      | (Goosey-Tolfrey & Sindall 2007) |
|                       | Overall      | 2.6-6.5 |       | %      | (Gilmore 2008)                  |
| Harvesting potential  | Fat reserves |         | 390   | MJ     | (Starner 1996)                  |
|                       | Walking      |         | 16.4  | W      | (Antaki et al. 1995)            |
|                       |              |         |       | 67     | W                               |
|                       | Mech. Work   |         | 930   | Wh     | (Gilmore 2008)                  |
|                       |              |         |       | 550    | Wh                              |

**Fig. 2-5: Table summarising the activity of people.**

|           |                |                       |        | Unit        | Source                    |                      |
|-----------|----------------|-----------------------|--------|-------------|---------------------------|----------------------|
| Walking   | Age (years)    | Men                   | Women  |             |                           |                      |
|           | 25-34          | 11,900                | 9,300  | Step/day    | (Sequeira et al. 1995)    |                      |
|           | 65-75          | 6,700                 | 7,300  | Step/day    |                           |                      |
|           | Professional   | 2,835 (At work)       |        | Step/day    | (Steele & Mummery 2003)   |                      |
|           | White-collar   | 3,616 (At work)       |        | Step/day    |                           |                      |
|           | Blue-collar    | 8,757 (At work)       |        | Step/day    |                           |                      |
|           | Office workers | 9,200 (5,380 at work) |        | Step/day    | (Schofield et al. 2005)   |                      |
|           | Average        | 10,617                |        | Step/day    | (Clemes et al. 2007)      |                      |
|           | Normal weight  | 11,273                |        | Step/day    |                           |                      |
|           | Over-weight    | 10,002                |        | Step/day    |                           |                      |
|           |                | Not known             | Known  |             | (S. a Clemes et al. 2008) |                      |
|           |                | 9,541                 | 11,345 | Step/day    |                           |                      |
|           |                | Normal                |        | 10,247      | Step/day                  | (Clemes et al. 2008) |
|           |                | Over-weight           |        | 9,095       | Step/day                  |                      |
|           | Obese          |                       | 8,102  | Step/day    |                           |                      |
| Stair use |                | Men                   | Women  |             |                           |                      |
|           | Site 1         | 30.9                  | 16.8   | Floors/week | (Engbers et al. 2007)     |                      |
|           | Site 2         | 13.1                  | 10.2   | Floors/week |                           |                      |
|           |                | Site 1                | Site 2 |             | (Blake et al. 2008)       |                      |
|           | Stair ascent   | 37.4                  | 44.0   | %           |                           |                      |

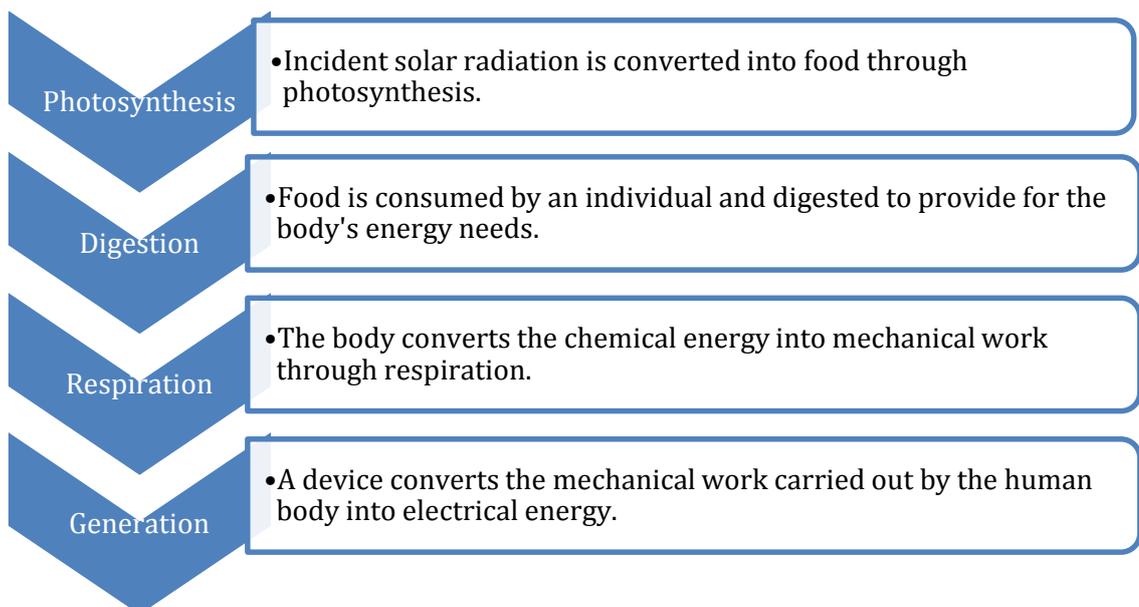
**Fig. 2-6: Table summarising the literature results regarding the generation of electrical energy from human energy harvesting devices.**

| Energy gen. | Technology             | Value               | Unit                   | Source  |
|-------------|------------------------|---------------------|------------------------|---|
| Walking     | PZT                    | 5.7                 | mW/kg                  | (Antaki et al. 1995)                                |
|             | PZT                    | 5                   | W                      | (Starner 1996)                                      |
|             | Rotary                 | 8.4                 | W                      |   |
|             | PZT                    | 1                   | mW                     | (Kymissis et al. 1998)                              |
|             | PVDF                   | 2                   | mW                     |   |
|             | Rotary                 | 0.23                | W                      |   |
|             | PZT                    | 71.8                | mW                     | (Shenck 1999)                                       |
|             |                        | 20.1                | %                      |   |
|             | PZT                    | 40                  | %                      | (Goldfarb & Jones 1999)                             |
|             | PVDF                   | 0.5                 | %                      | (Shenck & Paradiso 2001)                            |
|             | PZT                    | 20                  | %                      |   |
|             | DE                     | 0.28 (1 J expected) | J                      | (Pelrine & Kornbluh 2001)                           |
|             |                        | 80-90               | %                      |   |
|             | Linear generator       | 70-90               | mW                     | (Niu & Chapman 2006)                                |
|             | Piezo mat              | 1                   | mWs/step               | (Takefuji 2008)                                     |
|             | Rotary                 | 2-8 (4.8)           | W                      | (Paulides et al. 2009),<br>(Paulides & Jansen 2011) |
|             |                        | 48                  | %                      |   |
|             | PZT                    | 0.0903              | W                      | (Howells 2009)                                      |
|             | PVDF                   | 0.5                 | J                      | (Rocha & Goncalves 2010)                            |
|             | Reverse electrowetting | 10                  | W                      | (Krupenkin & Taylor 2011)                           |
| DE          | 0.8                    | J/step              | (Kornbluh et al. 2011) |   |
|             | 33                     | %                   |                        |   |
| Body motion | Action                 | Value               | Unit                   | Source  |
|             | Push button            | 0.64                | W                      | (Jansen & Stevels 1999)                             |
|             | Turning handle         | 28                  | W                      |   |
|             | See-saw                | 550 (3 min)         | J                      | (Pandian 2004)                                      |
|             |                        | 1.6                 | %                      |   |
|             | Knee mounted harvester | 4.8 ± 0.8           | W                      | (Li et al. 2009)                                    |
|             | Backpack               | 7.37                | W                      | (Rome et al. 2005)                                  |
|             |                        | 30-40               | %                      |   |
|             | Hand crank             | 4                   | W                      | (Louie et al. 2010)                                 |
|             | Cycling                | 183                 | kWh/year               | (Gibson 2011)                                       |

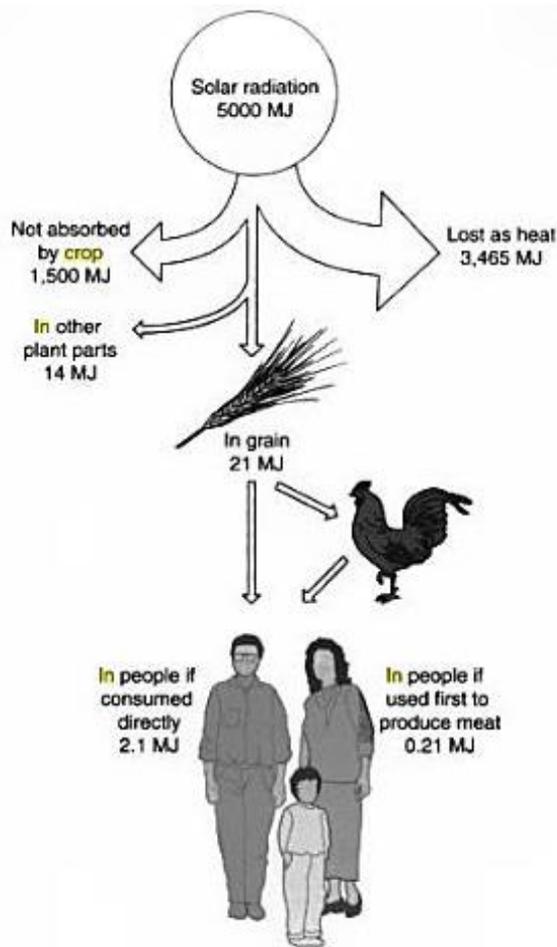
### 3. Energy flow

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It was seen through numerous sources that energy can be harvested from the human body as a means of electrical energy generation. This can come from several sources (as outlined in section 3.1.1.), however for the case of the urban environment it seems that mechanical work is the most appropriate source of energy. In this case, human energy harvesting utilises the mechanical work carried out by people, with the flow of energy to be examined in this chapter. It was felt that the process of converting the chemical energy contained in food into harvestable mechanical work should be examined as a means of considering the limit to the energy potential offered by people and demonstrating that only a small proportion of the total energy use of people is available for energy harvesting. Examining this flow was not simple due to the energy requirements of the human body to carry out the tasks required for survival and for everyday life, with Fig. 3.1. showing a basic representation of this flow. Although it was tempting to consider the human body as the source of energy, it was obvious that the human body requires a source of energy to produce mechanical work that can be harvested. Ultimately the source of energy is solar radiation, with a number of steps being carried out to convert this into harvestable energy. In addition, the sources of harvestable mechanical work in the built environment are considered. Those examined are walking and both swing and revolving door use.



**Fig 3-1: Representation of the flow of energy from incident solar radiation to the production of mechanical work.**



**Fig. 3-2: Energy flow in the production of grain and meat (Ort & Long 2003).**

The process through which the food we consume is produced results in significant losses in converting incident solar radiation into chemical energy (Ort & Long 2003). The losses associated with this process were outlined in fig. 3-2. The production of food is however somewhat superfluous due to the necessity of the process, since, the energy requirements of the human body are met through the consumption of food. As a result the production of this food is necessary to provide for the energy requirements of the population and will hence occur regardless of the inefficiency of the process. It does however demonstrate that most of the incident solar energy is lost by the time the human energy harvesting process even begins.

Once the food has been consumed, the gross energy (GE) contained in food is converted into metabolisable energy (ME) through the process of digestion (Tontisirin et al. 2003). The human body is able to use this ME in completing actions necessary for survival and everyday life. This process results in the loss of some of the gross energy contained in the food. It was calculated that based on the average UK diet, the efficiency of this process is approximately 92%. Appendix 1 shows how this value was calculated, however, it has been omitted here for the following reason. When determining the daily energy consumption of the average person it is based on the stated energy content of foods. These values are given in terms of the energy content of the food once digestion has taken place and hence the inefficiency of the digestion of food is already taken into account (Commission 2009).

Although it is recognised that the flow of energy could be regarded as a somewhat superfluous argument when considering human energy harvesting since the harvesting of a small number

of actions is likely to have a negligible impact upon the daily energy expenditure of an individual. It would therefore be unlikely to affect the amount of food consumed. Even so it was felt that it is important to consider the flow of energy as it allows for the determination of the limit to the energy potential that can be offered from human mechanical work. In doing so it was also highlighted that much of the energy expended by individuals is not available for energy harvesting as this energy is required to complete tasks necessary for everyday life. In a broader context it also demonstrates that if human energy harvesting were to be considered in terms of 'farming' the mechanical work of humans, it would be a very inefficient means of producing electrical energy.

As such a brief consideration of the flow of energy was carried out as outlined below. The boundaries of the system to be considered starts with the available ME in the human body derived from food and ends at the production of harvestable mechanical work. This process was split into three main sections as follows.

- Section 3.1. outlines the main sources upon which the human body expends energy in order to complete the tasks required for everyday life.
- Section 3.2. considers the efficiency with which the human body is capable of developing mechanical work from the energy available for physical activity.
- Section 3.3. furthers this by considering how much of the mechanical work developed by the human body is available for energy harvesting.

### **3.1. Energy usage in adults**

The total energy expenditure and requirements of adults was found to vary considerably, with three main components for which this energy was expended, basal metabolic rate (BMR), metabolic response to food and physical activity (FAO et al. 2004). In addition energy can be expended for growth, during pregnancy and for lactation (FAO et al. 2004), however these are only relevant in special situations and therefore were not considered here.

The BMR is considered as the energy required for vital functions and in most people is the largest component of energy expenditure (Geissler & Powers 2010). Values for this vary

greatly depending on gender, body size, body composition and age, values have been found to vary greatly, 45-70% (FAO et al. 2004) or 60-75% in developed nations (Geissler & Powers 2010) of total energy expenditure. An average proportion of energy expenditure from BMR was in the region of 60-65%, where a value of 65% was used as an average estimate. It was calculated, based on the table in appendix 2, that a 60 kg male in the age range of 18-30 years old was predicted to have an energy expenditure of 6.68 MJ/day to satisfy the demand of the BMR.

Another source of energy expenditure is from thermogenesis, accounting for the bodies reaction to stimuli that might be encountered throughout the day (Geissler & Powers 2010). One component of this is the body's response to food consumption and accounts for a 10% increase to the metabolic rate (FAO et al. 2004). As such 10% of the ME contained in food was assumed to be used in the body's response to it.

**Table 3-1: Table showing the metabolic equivalent energy expenditure and energy consumption rate values for a selection of activities likely to occur in the urban environment. (Ainsworth et al. 2000)**

| Activity                       | METs         | kJ/kg/h |
|--------------------------------|--------------|---------|
| Sleeping                       | 0.9          | 3.8     |
| Standing                       | 2.0          | 8.4     |
| Walking                        | Down stairs  | 3.0     |
|                                | For pleasure | 3.5     |
|                                | Up stairs    | 8.0     |
| Jogging                        | 7.0          | 29.3    |
| Cycling (12-13.9 mph, leisure) | 8.0          | 33.5    |
| Running (10.9 mph)             | 18.0         | 75.3    |

Energy expended during physical activity was thought to be the most relevant for the purpose of energy harvesting in the urban environment. The measurement of physical activity is often expressed in terms of metabolic equivalent (MET) intensity levels. This is given by the ratio of work metabolic rate compared to a standard resting metabolic rate and varies depending on the activity (Ainsworth et al. 2000). The work of Ainsworth et. al. (2000) lists activities and a corresponding MET value, these range from 0.9 METs for sleeping to 18 METs for running at 10.9 mph (Ainsworth et al. 2000), a selection of these are given in Table 3-1. As a result the daily energy requirements will be highly dependant on the lifestyle of the individual. The

proportion of total energy expenditure accounted for by physical activity varies greatly depending on the individual, and in athletes this may account for up to 70% (Geissler & Powers 2010). This is however an exceptional case and for most people it is much lower. It was assumed that the remaining energy after the BMR and thermogenic energy requirements will be available for activity, giving 25% of total available ME.

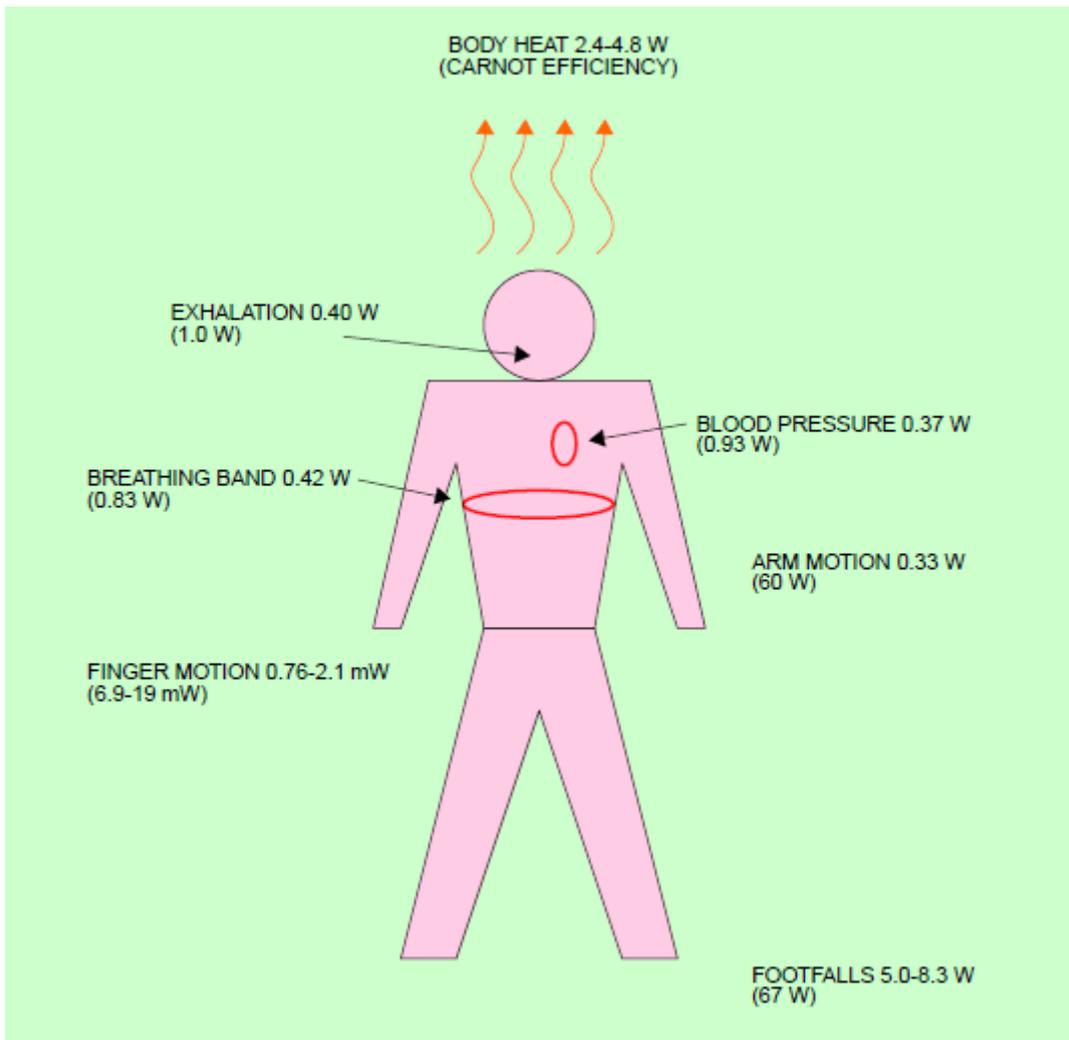
The proportion of ME used for each of the three main components of energy expenditure were assumed to be,

- BMR = 65%
- Thermogenic effect of food (TEF) = 10%
- Available for physical activity = 25%

The total energy requirements of adults in the UK were taken from (SACN 2011). Here the estimated average ME requirements for adults in the UK was 10.9 MJ/day for men and 8.7 MJ/day for women. Assuming that each gender accounts for half the population, this gave an average daily energy requirement of 9.8 MJ/day. Assuming 25% was available for physical activity gives an average of 2.45 MJ/day (0.68 kWh/day) of available energy from an individual. This is similar to values in the literature of 3.35 MJ/day (Gilmore 2008) and 1.98 MJ/day (Louie et al. 2010). In the UK there are approximately 60 million people, which would give a total energy available for physical activity of  $1.47 \times 10^{14}$  J/day (40.8 GWh/day). Although this seems to suggest that there is significant potential, it is somewhat misleading as developing mechanical work results in significant losses. Furthermore it seems fairly obvious that not all of the energy available for physical activity can be harvested due to the need for mechanical work in carrying out everyday activities. Even so, if a small fraction of this potential could be harvested it could contribute a significant amount of energy.

### **3.1.1. Energy sources**

Whilst expending energy, the human body releases energy in several forms which can be harvested for electrical energy generation. Fig. 3-3 illustrates some of these sources, although it was obvious that most of these do not offer significant potential. It seems as if heat and mechanical work offer the best potential and will now be discussed.



**Fig. 3-3: The available sources of energy for harvesting from the human body. (Starner 1996)**

A significant amount of heat energy is released by the human body, however, it was shown in the work of (Starner 1996) that it would be impractical to harvest this energy for electrical energy generation. The maximum theoretical conversion efficiency was considered to be ~5.5%, due to a temperature gradient between the human body and ambient air in the region of only 20°C. Resulting in 2.4-4.8W of available power over the whole body. As a result, it is believed by the author that generation from body heat would only be feasible for very low power devices. In addition harvesting this energy only seems feasible for devices worn on the body. As such the only remaining source of significant potential available for human energy harvesting was mechanical work and will now be discussed.

## **3.2. Mechanical work production**

The human body uses ME stored in the body to produce mechanical work. Much literature was focussed on the efficiency with which the human body is able to achieve this, however the values given vary greatly depending on the study. In part this was due to the different approaches and definitions applied to the term efficiency, leading to some confusion and making comparisons between studies very difficult. Furthermore the determination of work done during physical activity was generally not easy when considering human activity, with cycling being an exception to this (Ettema & Lorås 2009).

The overall efficiency of developing mechanical work in single human muscles has been presented in the work of (He et al. 2000), where it was found that at 20°C the peak efficiency of developing mechanical work was ~40%. Application to real activities was however somewhat more complicated and will be discussed in the following sections. It was also necessary when considering the efficiency of developing mechanical work to understand what it is that is being measured. The literature has revealed a number of definitions. These will now be presented and discussed and the most appropriate measure of efficiency for the purpose of this study will be determined.

### **3.2.1. Measures of efficiency**

The literature revealed four main definitions used to describe the efficiency with which mechanical work is performed by the human body. Namely these are the gross, net, work and delta efficiencies, with the process of calculating these as set out in (Gaesser & Brooks 1975) presented in appendix 3 along with a brief description of each. To explore this ergometer cycling was taken as an example due to the relative ease with which the work performed can be determined (Ettema & Lorås 2009). In such cases the efficiency debate centres on the calorific energy expenditure during the activity and more precisely how the calorific energy requirements of carrying out the work should be calculated. Gross efficiency considers that the total calorific energy expenditure should be used in determining the efficiency, whereas the other methods use some form of baseline subtraction to take account of energy expenditure resulting from sources other than that associated with performing mechanical work. Table 3-2 shows the values calculated for each measure of efficiency in (Gaesser & Brooks 1975) and demonstrates how the choice of measure affects the result.

**Table 3-2: Values for the four measures of mechanical efficiency in ergometer cycling at a work rate of 600 kgm/min and cadence of 80 rpm. Values taken from (Gaesser & Brooks 1975)**

| Efficiency measure | % (at 600kgm/min and 80 rpm) |
|--------------------|------------------------------|
| Gross              | 17.6                         |
| Net                | 21.4                         |
| Work               | 27.4                         |
| Delta              | 20.4                         |

Each of these measures of efficiency can be considered as the most appropriate method, depending on what it is that the study is aiming to measure. For the purpose of this study it was deemed that net efficiency is the most appropriate. It was decided that gross efficiency would not be appropriate due to the inclusion of the BMR in the energy expenditure value. As previously discussed the BMR is a constant value and completely independent of any physical activity carried out. Thus when considering the energy requirements of an individual over the course of a day it was deemed that this should be considered independently of any physical activity and thus some form of baseline subtraction was required. Some care was required when considering the baseline subtraction to use, so as to make sure all energy expenditure was considered. Work efficiency uses a baseline subtraction based on the energy requirements involved in carrying out an activity with no load. When considering cycling this was relatively easy to measure as the work load of the ergometer can be set as 0 and hence the additional energy expenditure involved with moving the limbs for example can be determined. Carrying this out for activities such as walking was more complicated as what would be considered to be no-load walking? Even if this could be carried out it would not be an appropriate measure of efficiency when considering energy harvesting as the energy requirements involved with moving the limbs is directly related to walking and cycling and hence should be included in the measure of efficiency. In a similar way the delta efficiency measures the increase in energy expenditure required to increase the amount of external mechanical work. As such both of these could be deemed appropriate if the efficiency of directly developing mechanical work is required. However when considering energy harvesting it is the total energy requirements of carrying out an activity above resting energy expenditure that is important. This will take into account the energy requirements of internal

work involved with limb movement, balance, temperature regulation and any other factors directly affected by carrying out a physical activity, even if the exact nature of these relationships is not well understood. Net energy efficiency was therefore deemed to be an appropriate measure of efficiency when considering energy harvesting.

### 3.2.2. Net efficiency of developing mechanical work

When considering forms of activity such as walking the calculation of efficiency was further complicated, due to the difficulty in determining a value for the work done. Much literature attempts to deal with the work performed and efficiency associated with various activities, including walking.

**Table 3-3: Net efficiency of developing mechanical work for various activities in converting food energy into mechanical work. (\*Metabolic rate whilst standing is used for baseline subtraction)**

| Activity           | Net Efficiency (%) | Reference                       |
|--------------------|--------------------|---------------------------------|
| Walking            | 35-40              | (Cavagna & Kaneko 1977)         |
|                    | ~35                | (Umberger & Martin 2007)*       |
| Running            | 45-80              | (Cavagna & Kaneko 1977)         |
| Cycling            | 25.7               | (Capelli et al. 2008)           |
| Rowing             | 19.8               | (Fukunaga & Matsuo 1986)        |
| Ergometer arm work | 15.8               | (Poulsen & Asmussen 1962)       |
| Arm crank          | 23.4               | (Goosey-Tolfrey & Sindall 2007) |

In the case of walking, the calculation of work done was carried out by assessing the positive and negative work of each body segment over the course of the gait cycle ((Cavagna & Kaneko 1977) and (Umberger & Martin 2007)). Calculation of the net efficiency of walking and running was presented by (Cavagna & Kaneko 1977) giving net efficiencies of 35-40% and 45-80% respectively. The reported values seem high, in fact higher than the theoretical muscle efficiency in the case of running. This was due to the recycling of negative work in the human body, where energy is stored elastically and then released as positive work (Cavagna & Kaneko

1977). Similarly a net efficiency of ~35% was recorded in (Umberger & Martin 2007) when walking at a natural stride rate. The net efficiencies for several activities thought to offer potential for energy harvesting are presented in Table 3-3.

### 3.2.3. Harvesting efficiency

When considering energy harvesting it is important to consider what is meant by external work. It is obvious that much of the work carried out by the body during walking is required to complete the action. When considering harvesting however, it is the work carried out on the device that is important, with the remainder of the work being assumed to carry out the mechanical work required to complete the action. The mechanical work carried out to complete an action will be termed the useful mechanical work, whereas the energy available for harvesting will be referred to as the harvestable work. As such, when calculating the efficiency of energy harvesting the useful work term in calculating the net efficiency will be substituted as the value of the harvestable work. Hence a new measure of efficiency will be considered here and termed harvesting efficiency,  $\eta_H$ .

$$\eta_H = \frac{\text{Harvestable work}}{\text{Energy expended} - \text{BMR}}$$

Although this can not be deemed to be an appropriate measure of efficiency in a physiological sense it does act as a suitable measure of the efficiency with which the human body converts ME into harvestable mechanical work. It should be noted that the work done on the harvesting device will depend on the device and source from which energy is to be harvested. The handling of this will be addressed in the following section. It is important to consider that the work done, for example, in completing the action of walking, is measured as a loss of efficiency. Evidently this is not true from a physiological perspective as this is energy necessary for completing a given task.

## 3.3. Energy harvesting

In determining the harvesting efficiency it was necessary to consider the various types of energy harvesting. Converting the mechanical work carried out by the human body into useful

electrical energy was considered to be carried out by the harvesting device and electrical system. The process of energy harvesting requires a device to harvest energy expended by the human body. This can be carried out in many ways, with care needed in analysing the various approaches. The definitions of different sources of human energy harvesting and the assessment of the ways in which they should be considered are set out below and are the views of the author.

Harvesting devices were split into three categories based on the way in which they are intended to be used. It is important to consider the work carried out on the device by the user and hence the user/device interface needs to be assessed. The three categories are outlined as follows,

1. **Parasitic:** A device acts to harvest energy from a user's actions, without having a significant impact on the user. The action is one which the user would normally carry out during their everyday life. (e.g. footfall harvesting)
2. **Direct purpose:** The device requires specific action from the user, with the express goal of providing energy to achieve a desired outcome. (e.g. Hand crank)
3. **Recreation:** These aim to utilise a users desire to exercise/play, allowing for energy to be harvested from this. (e.g. Energy generating cycling machine in a gym)

There are a number of general points that can be made about these sources. A general rule that applies to all sources of human power is that they will require the user to expend energy for it to be harvested. In general parasitic devices will only take a small amount of energy from each person per action as harvesting too much energy would be detrimental to the user or the activity in which the user is engaged. In contrast direct purpose and recreation devices are designed with the aim of utilising actions specifically and consciously carried out to generate energy, allowing considerably more of the expended energy to be harvested. To explore this, a floor generating tile and a cycling machine were considered.

Harvesting energy from walking can be carried out using floor tiles and was considered a parasitic form of energy harvesting. Table 3-3 shows that a net efficiency of converting metabolic energy into useful mechanical work can reach 35% for walking at a comfortable

speed (Umberger & Martin 2007). This is however somewhat misleading when considering a parasitic form of energy harvesting. In the case of the floor tile, energy harvesting occurs as a result of the ground reaction forces (GRF) of the foot acting on the generating tile. Fig. 3-4 shows the vertical ground reaction forces during slow and fast gait. Values for the GRF during walking on a level surface were found to be 1.2 times the body weight (BW), whereas for stair ascent and descent they were  $\sim 1.1\text{BW}$  and  $1.6\text{BW}$  respectively (Stacoff et al. 2005). The work done on the device (harvestable work),  $W_H$ , was then calculated as follows,

$$W_H = \text{GRF} \cdot F \cdot h = 1.2\text{BW} \times m \times g \times h$$

Where  $m$  is the mass,  $g$  is acceleration due to gravity and  $h$  is the displacement distance.

A 60 kg person was considered with a tile deflection of 10mm, this gave a value for work carried out on the device of 7.2 J/step. The literature revealed that a number of attempts were made to determine the energy available from a step. In the work of (Antaki et al. 1995) it was calculated that a 70 kg person offers 8.2 J/step (16.4 W) based on the ground reaction forces of heel-strike and toe-push off during the gait cycle. Using the method outlined for this report, the energy available from a 70 kg user is found to be 8.4 J/step. Alternatively (Starner 1996) determined that during walking 67 W of power are available as a result of the vertical motion of the heel during human gait. This was based on the assumption of a 68 kg user walking at a cadence of 2 step/s and a 5 cm vertical motion of the heel during walking. This appears to be a gross exaggeration of the power available for harvesting from walking, stemming from the assumption of a 5 cm heel displacement. It was to be expected that, in general, energy harvesting from footfall will be achieved by harvesting energy from people as they move around the urban environment. The act of harvesting energy from the total motion of the feet during gait would likely greatly inhibit the user as the energy is expended in order to complete the action of walking and harvesting this will require additional work on the part of the user. Furthermore the source of energy must be determined from the user-device interface. In the case of floor integrated devices (and indeed shoe integrated devices as suggested in (Starner 1996)) the interface between the user and the device occurs whilst the foot is in contact with the floor. Hence to harvest all of this 67 W would require the device to deflect by 5 cm with each step. In most situations this would appear completely impractical, although one possible exception could be a cross trainer in a gym. In this situation the feet

remain in contact throughout the gait cycle allowing all of the potential of the heels motion to be harvested, however it was evident that the user remains stationary throughout this process and was hence not analogous to walking around the urban environment. As such it was considered that the most appropriate means of determining the available potential from walking was through the ground reaction forces of the user's feet with the device.

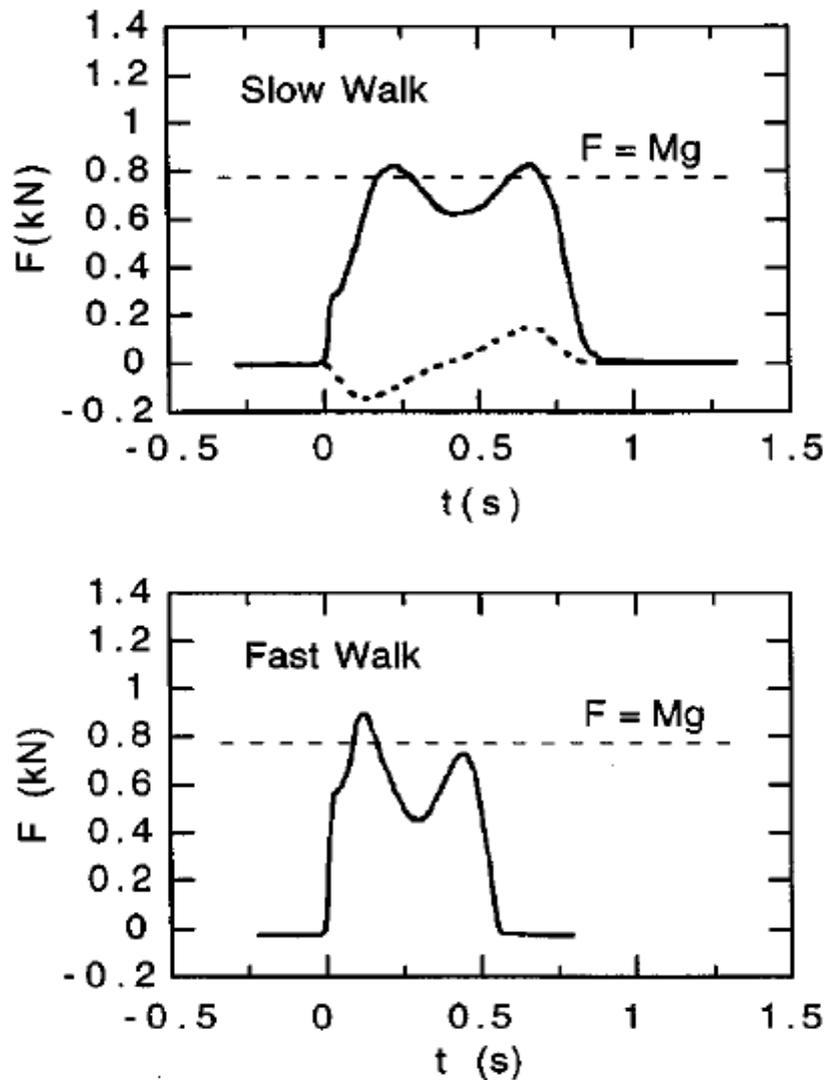


Fig. 3-4: Vertical ground reaction forces during slow and fast gait (Cross 1999).

In order to determine the harvesting efficiency the net energy expenditure,  $EE_{net}$ , of the individual was required. Firstly the BMR was calculated for a 60 kg male in the age range of 18-30 years using the table in appendix 2, giving an energy expenditure from BMR of 6.68 MJ/day (4.64 kJ/min). Walking was measured to expend roughly 3.5 METs (table 3-5), so the rate of energy expenditure was found to be 16.24 kJ/min. It was assumed that the cadence of

the individual results in 90 steps/min, thus the harvestable work was found to be 0.648 kJ/min. This was based on 7.2 J/step being available from walking. This gave,

$$\eta_H = \frac{W_H}{EE_{\text{net}}} = \frac{0.648}{16.24 - 4.64} = \frac{0.648}{11.6} = 0.056 = 5.6\%$$

As such it was estimated that roughly 5.6% of the ME expended as a direct result of walking is available for harvesting. The remainder is either lost as heat in the process of developing mechanical work or as work required to complete the action of walking. Similarly the harvesting efficiency of stair ascent and descent was calculated, giving 1.2% and 6.2% respectively.

An additional factor that may affect the harvesting process of walking is the effect walking on a device will have on energy expenditure when compared to walking on a firm surface. It was reported in (Passmore & Durnin 1955) that the change in energy expenditure will be less than 10% except on extremely rough surfaces. The additional energy cost of walking on different energy harvesting devices is not well understood, due to a lack of information regarding this. It was thus assumed that the energy potential for harvesting will result in an increase to the mechanical work requirements equal to the energy potential.

A cycling machine in a gym was considered to be a recreational device, however a direct purpose device would be considered in the same way. In the instance of direct purpose or recreational devices, all of the useful mechanical work can be considered to act on the generation device. As a result the device was considered to be able to harvest significantly more of the useful mechanical work carried out by the user and as such the harvesting efficiency was considered to be the same as the net efficiency.

When considering some of the potential areas of application for human energy harvesting it becomes clear that there are a number of situations where the consideration of such inefficiencies becomes irrelevant. For example, converting gym equipment to generate energy could offer significant potential and with it considerable energy expenditure. In this case however it could be argued that this energy is expended voluntarily as a means of pleasure or

for personal fitness, meaning that the energy would be expended regardless of whether it is harvested, with no additional energy required above what would ordinarily be expended and hence the argument of whether the process is sufficiently efficient is redundant. For activities such as walking the situation is not quite so clear, in this case additional energy is likely to be required even if this additional energy is relatively small. One of the arguments made for the potential of energy harvesting from walking comes from the sheer number of people that may pass through a location. If, for example, the ticket gates at a busy underground station were to have floor generating tiles installed at them, then each person exiting or leaving the station may only pass over these devices once, however the number of people who entered or exited Waterloo tube station in London was in excess of 88million people in 2013 (TFL 2013). Thus the impact on an individual would be negligible. If however the flooring of a house were replaced with energy generating tiles, then not only would the generated energy be small, with associated impacts on the economic viability, but this may also have a significant impact on those people contributing to the activity. As a result the application of human energy harvesting should be properly considered to avoid the danger of having unintended negative consequences.

### **3.4. Overall efficiency**

Thus far the assumptions used to determine the potential that exists for harvestable energy have been laid out. What follows is an assessment of the total potential that exists for harvestable work done by an individual over the course of a day and an analysis of different sources of harvestable work. The assumptions made with regards to each step in the process of converting the gross energy in food into harvestable mechanical work are laid out in Table 3-4. The parameters used were based on the average energy intake in the UK, with the walking EE, Cycling EE, rate of BMR and harvestable walking work all calculated for a 60 kg male in the range of 18-30 years of age.

#### **3.4.1. Daily Energy flow**

The process of the human body using the gross energy contained in food to perform mechanical work results in significant inefficiencies as outlined earlier. Fig. 3-5 shows a Sankey diagram representing the energy losses over the course of the day. The development of mechanical work in Fig. 3-5 was for that of an individual muscle. It was evident that the type

of activity from which energy is harvested will have a significant impact on the system efficiency.

**Table 3-4: Assumptions used to assess the flow of energy in human energy harvesting.**

|            |                          |       |        |
|------------|--------------------------|-------|--------|
| Inputs     | Gross energy             | 10.9  | MJ/day |
|            | Walking EE               | 16.24 | kJ/min |
|            | Cycling EE               | 37.12 | kJ/min |
| Parameters | GE-ME                    | 90    | %      |
|            | Daily BMR                | 65    | %      |
|            | Rate of BMR              | 4.64  | kJ/min |
|            | TEF                      | 10    | %      |
|            | ME-Mech. work            | 40    | %      |
|            | ME-Walking               | 35    | %      |
|            | ME-cycling               | 25    | %      |
|            | Harvestable walking work | 0.648 | kJ/min |

It was found that the overall efficiency of converting the gross energy content of food into mechanical work is theoretically limited to roughly 9% of daily energy consumption. This amounts to 0.98MJ/day (272 Wh/day) of energy being available for harvesting and represents the upper limit for the amount of mechanical work that can be carried out by an individual over the course of a day. Again assuming a UK population of 60 million people, this gives 16.3 GWh/day of energy available in the form of mechanical work. This is still a very substantial amount of energy, however harvesting this is still a gross overestimation of the harvestable energy potential. In practice the type of activity being carried out will impact upon the overall efficiency. It should be noted that the example given was based on average values, as such there would likely be large variations between individuals. Much of the energy expended was considered to be used to complete tasks that were necessary for the survival of the individual and were not, strictly speaking, losses. The BMR and TEF account for 58.5% and 9% of the

input ME energy respectively. Mechanical work must also be considered in a similar way, it is necessary for an individual to complete useful mechanical work during the course of the day to complete necessary action. As a result much of the mechanical work carried out will not be harvestable as it is required to complete actions, with the proportion that is available being somewhat dependant on the lifestyle of the individual. It also highlights the need to consider the proportion of energy expenditure that is available for harvesting whilst carrying out various activities.

### **3.4.2. Activity harvesting energy flow**

Whilst carrying out an activity the energy expenditure will comprise several components. The breakdown of the flow of energy during walking and cycling was presented in Fig. 3-6 and Fig. 3-7 respectively.

It was seen that during walking roughly 25% (4 kJ/min) of the total energy expenditure is available in the form of mechanical work, although only 4% of the total energy expenditure (0.7 kJ/min) is available for harvesting (5.6% of net energy expenditure). This amounts to an average power of 11.7 W available for harvesting, based on the assumptions laid out earlier. The remaining 3.45 kJ/min is used to carry out the action of walking. The BMR still accounts for a considerable amount of the total energy expenditure, although this is significantly less than the proportion of energy expenditure over the course of the day, due to the significant increase in energy expenditure incurred through walking.

The first point to make was that the total energy expenditure during cycling is significantly higher during cycling than walking, hence the decreased component of the BMR in total energy expenditure. For cycling it contributes roughly 12.5% of total EE, compared to 28.6% for walking. The energy potential for harvesting was significantly higher, 8.12 kJ/min (135 W average), and accounted for 21.9 % of the total energy expenditure. The reasons for this being so much larger than from walking were two fold. Firstly as already mentioned the increase in total energy expenditure and secondly walking is a parasitic form of energy harvesting. As a result only a small proportion of mechanical work can be harvested, whereas ergometer cycling is a recreational source, thus allowing all the energy potential to be available for harvesting.

| Gross energy | Faecal and urinary losses | Metabolisable energy | BMR losses | TEF losses  | ME for activity | Heat losses | Mechanical work |
|--------------|---------------------------|----------------------|------------|-------------|-----------------|-------------|-----------------|
| 10.9 MJ/day  |                           | 9.8 MJ/day           |            |             | 2.45 MJ/day     |             | 0.98 MJ/day     |
|              | 1.1 MJ/day                |                      | 6.4 MJ/day | 0.98 MJ/day |                 | 1.5 MJ/day  |                 |

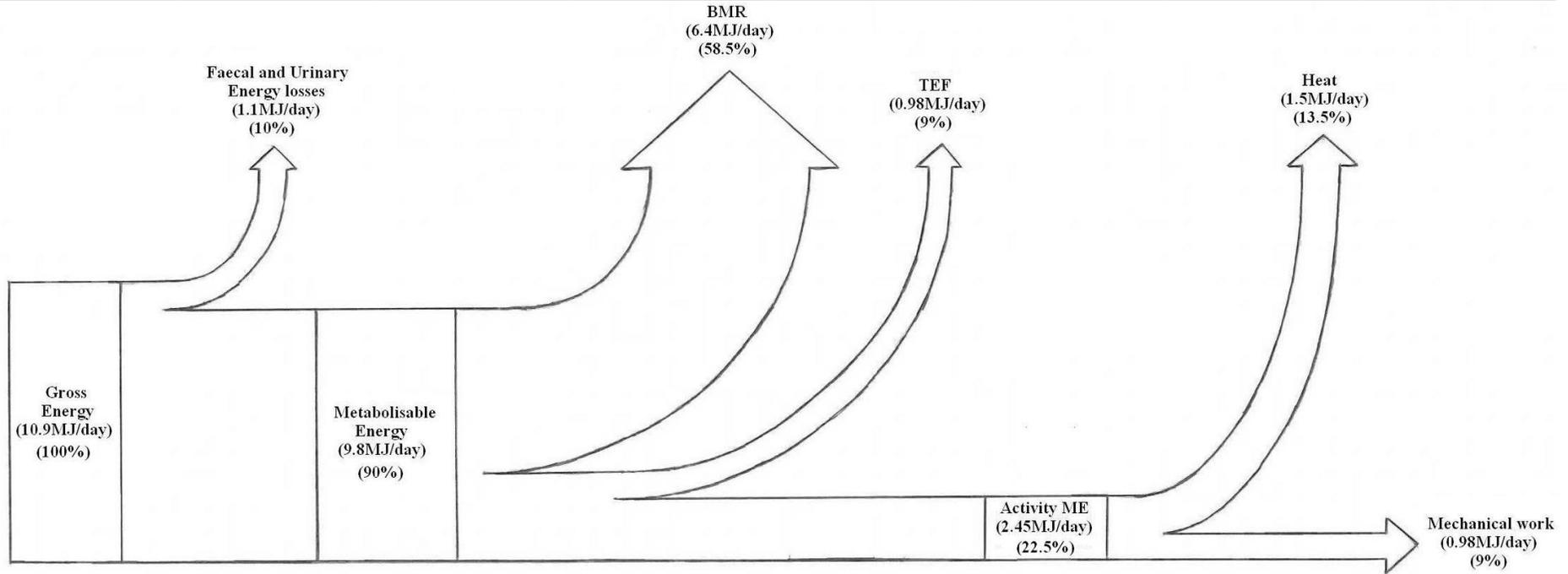


Fig. 3-5: Sankey diagram of the flow of energy through the human body over the course of a day, it should be noted that the value used for the development of mechanical work is the upper limit for developing mechanical work by a muscle.

| Total EE     | BMR losses  | Net EE      | Heat losses | Mechanical work | Walking work losses | Harvestable work |
|--------------|-------------|-------------|-------------|-----------------|---------------------|------------------|
| 16.24 kJ/min |             | 11.6 kJ/min |             | 4.1 kJ/min      |                     | 0.648 kJ/min     |
|              | 4.64 kJ/min |             | 7.5 kJ/min  |                 | 3.45 kJ/min         |                  |

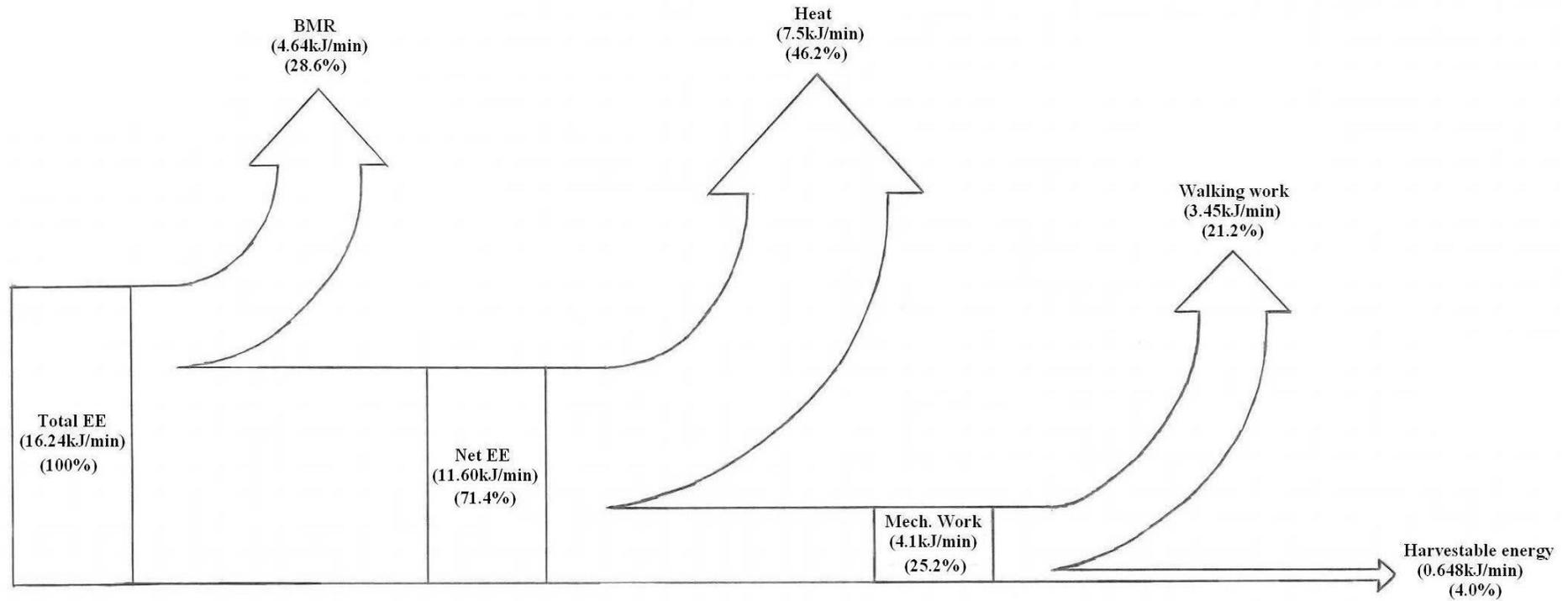


Fig. 3-6: Flow of energy when harvesting energy from walking.

| Total EE     | BMR losses  | Net EE       | Heat losses  | Harvestable energy |
|--------------|-------------|--------------|--------------|--------------------|
| 37.12 kJ/min |             | 32.48 kJ/min |              | 8.12 kJ/min        |
|              | 4.64 kJ/min |              | 24.36 kJ/min |                    |

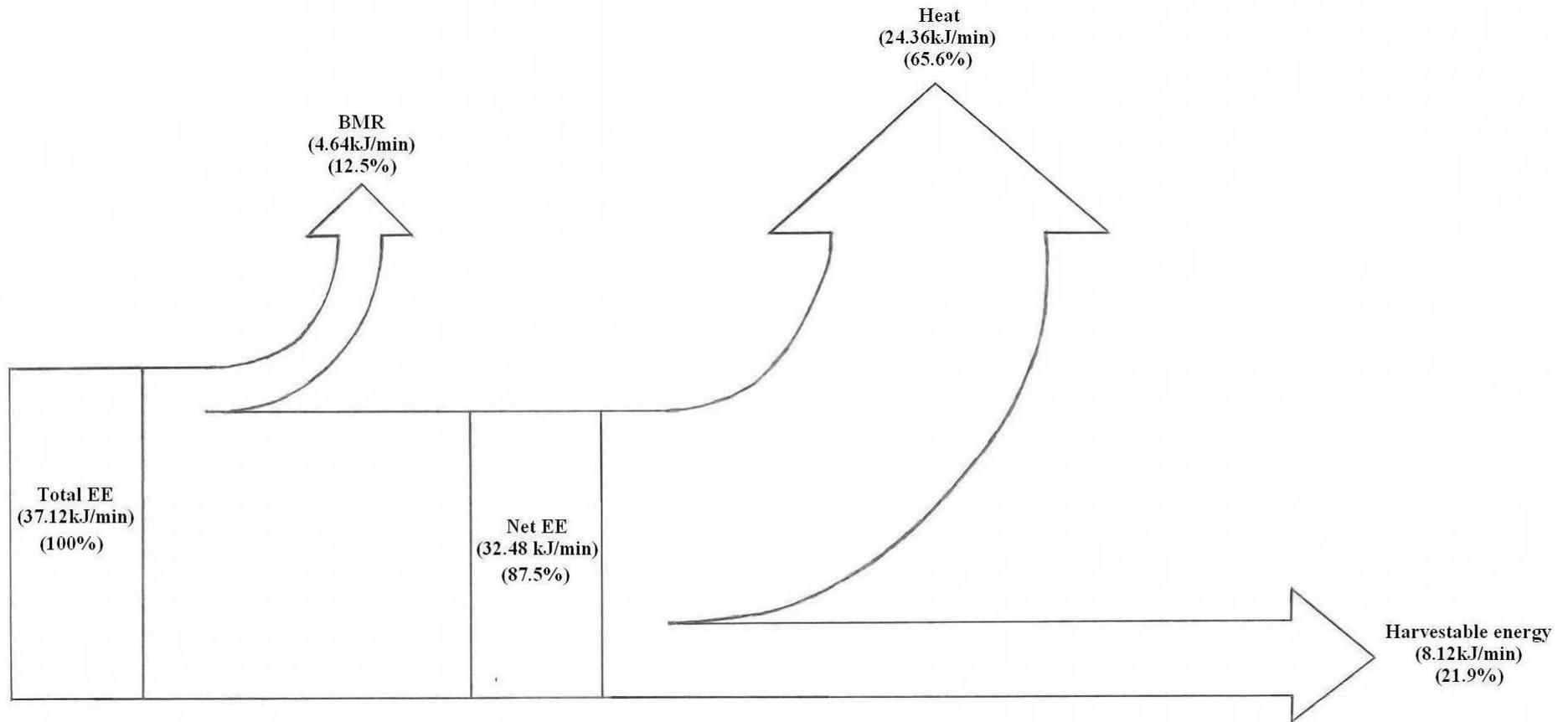


Fig. 3-7: Flow of energy available for energy harvesting during ergometer cycling.

### 3.4.3. Daily energy potential

It was also possible to estimate the potential for energy harvesting from an individual over the course of the day. It was suggested that the number of steps/day is anywhere between 4,000-18,000 steps/day and that 10,000 was a reasonable approximate (Tudor-Locke et al. 2011). Assuming 10,000 steps/day gave an energy potential of 72 kJ/day (20 Wh/day) from an individual. Thus the potential across the UK was calculated to be 1.2 GWh/day from walking.

It was assumed that harvesting energy from walking results in an increase in the mechanical work requirements necessary for walking. As such the 7.2 J of energy available from each step would result in 20.6 J of additional ME being used. If this was considered for 10,000 steps/day then the additional daily energy requirements would be 206 kJ/day. This amounts to an increase of ~2% of the daily energy requirements of an individual. Similarly when cycling for half an hour was considered, then 974.4 kJ of ME would be required, amounting to ~10% of daily energy requirements.

Unfortunately due to the complicated nature of the flow of energy, it was difficult to ascertain whether these additional energy requirements would result in additional food consumption. Evidently the energy would need to come from somewhere. However, particularly in the western world, many people already have a food surplus (Moomaw et al. 2012), thus could provide for this additional energy with no additional food consumption. This overconsumption is reflected in the rates of obesity in the population of England, where it was reported that in 2011, 24% and 26% of men and women respectively were recorded to be obese, with a further 41% of men and 33% of women recorded as overweight (Sutton 2011). It seems likely that harvesting a significant proportion of energy per person would result in an increase in food consumption, however assigning a value to this was beyond the scope of this project. In addition to this the type of activity would make a difference in how it should be considered. Cycling for recreational/fitness reasons is something the individual chooses to do for reasons other than generating energy, hence the energy would be expended regardless of the presence of a harvesting device. In this instance harvesting the mechanical work was really just scavenging energy from an existing source as the primary purpose of the activity is not for harvesting.

## **3.5. Sources of harvestable energy**

Thus far the energy potential for harvestable mechanical work from the human body has been examined to determine the limitations of harvesting mechanical work from people. It is however recognised that to harvest mechanical work will require devices designed for this purpose to be installed in the urban environment. Thus far the harvestable mechanical work offered by walking has been addressed. Two additional sources that were thought to offer some potential were the use of swing door and revolving door devices. Potential for harvesting mechanical work occurs due to the motion of the door, where a single use of the door will be termed as a door opening event (D.O.E.). In order to assess the potential for energy generation from door devices a number of models were developed and used to assess the energy potential. Swing doors are considered in section 3.5.1. and revolving doors in section 3.5.2.. In both cases Matlab Version 7.12.0.635 (R2011a) was employed.

### **3.5.1. Swing door**

#### **3.5.1.1. Design principles**

The layout employed for a swing door is shown in fig. 3-8. The purpose of a door generation device was to harvest some of the energy that was expended in the process of opening a door in order to generate electrical energy. The presence of an energy generating device would have an impact on the motion of the door and hence needs to be modelled to determine the most appropriate method of generating energy. The first step was to model the motion of a door without an energy generation unit. This could then be used as a reference from which the door with an energy generator could be evaluated. Three approaches to energy generation were considered,

1. Motion of the door directly drives a generator during opening and closing.
2. Energy was transferred to two springs during door opening. One of these was used to close the door, whereas the other drives a generator.
3. Replace the damping unit with an energy generation unit to act as the door damper.

The modelling of the motion and generation potential of each of these methods is discussed below.

### **3.5.1.2. Equations of motion**

Firstly a simple door with door closer was modelled, using the following methodology. The door closer consists of a spring which was compressed as the door opens, with the energy then released to close the door. A viscous damper controls the velocity of the door during closing until the door reaches the latching angle. At this point the viscous damper stops acting on the door to allow the door to close properly. As such it was considered that there were four phases to be considered for a door opening event.

1. The door is initially closed and at rest, with a force applied for 1s to open it.
2. The door is then brought to rest as a result of the kinetic energy of the door being converted to potential energy in the spring.
3. The door closes due to the energy stored in the spring acting on the door. The speed is regulated by a viscous damper which offers critical damping.
4. Once the opening angle of the door reaches the latching angle (0.12 rad) the viscous damper no longer acts on the door, with the spring acting to fully close the door.

The motion is described in terms of the equations of motion for a rotating system, with each phase modelled with the appropriate conditions.

1. The door was modelled as a Forced mass-spring system, with a constant force applied.
2. A mass-spring system with initial conditions determined from the conditions at the end of phase 1.
3. A mass-spring-damper system, with the initial conditions set by the end conditions from phase 2.
4. A mass-spring system with initial conditions determined from the end of phase 3.

From this the equations of motion for each phase were determined to be as follows,

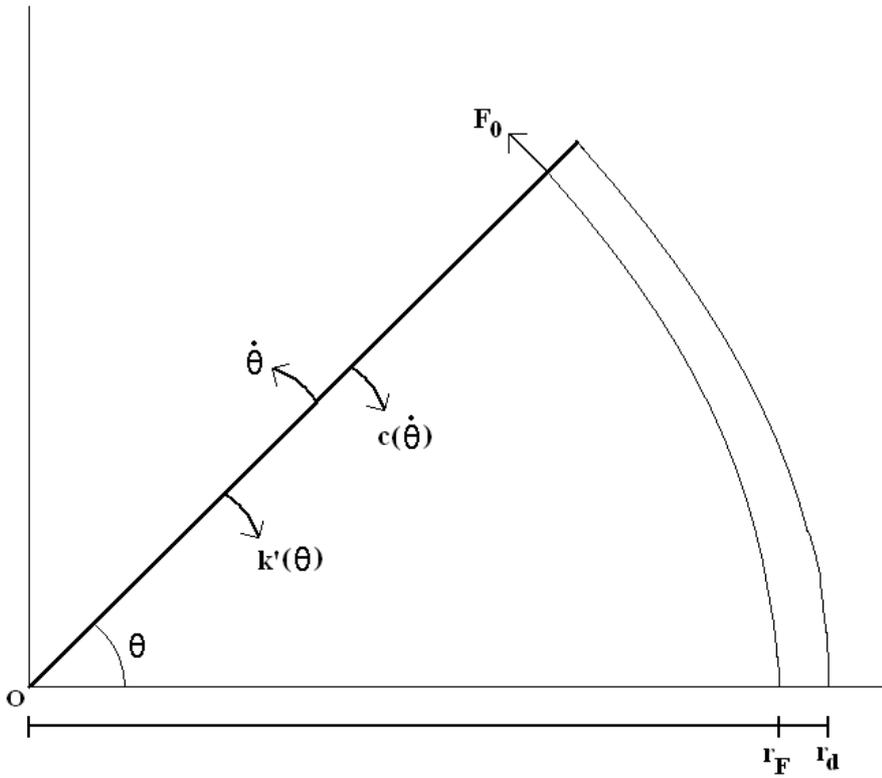


Fig. 3-8: Diagram showing the layout of the door to be modelled.

Phase 1:

$$\theta(t) = \frac{\tau_0}{k'}(1 - \cos(\omega_0 t))$$

$$\dot{\theta}(t) = \frac{\tau_0 \omega_0}{k'} \sin(\omega_0 t)$$

Phase 2:

$$\theta(t) = C_1 \cos(\omega_0 t - \varphi)$$

$$\dot{\theta}(t) = -C_1 \omega_0 \sin(\omega_0 t - \varphi)$$

Where,

$$C_1 = \left( \theta_0^2 + \left( \frac{\dot{\theta}_0}{\omega_0} \right)^2 \right)^{\frac{1}{2}}$$

$$\varphi = \tan^{-1} \left( \frac{\dot{\theta}_0}{\theta_0 \omega_0} \right)$$

**Phase 3:**

$$\theta(t) = (C_2 + C_3 t) \exp(-\omega_0 t)$$

$$\dot{\theta}(t) = (C_3 - C_2 \omega_0 - C_3 \omega_0 t) \exp(-\omega_0 t)$$

Where,

$$C_2 = \theta_0$$

$$C_3 = (\dot{\theta}_0 + \omega_0 \theta_0)$$

**Phase 4:**

The equations of motion for phase 4 were the same as those of phase 2 as the damper is no longer acting on the door and hence the system is a mass-spring system.

**Initial conditions:** The values of  $\theta_0$  and  $\dot{\theta}_0$  were the initial conditions for each phase and were determined from the final values of the previous phase. For phase 1, the values of  $\theta_0$  and  $\dot{\theta}_0$  were assumed to be 0 rad and 0 rad/s respectively.

**Conditions for choosing the phase to use**

It was important to define a set of conditions, which are laid out below, to determine the boundaries for when each phase was used.

|                 |                                       |   |
|-----------------|---------------------------------------|---|
| <b>Phase 1:</b> | $t \leq 1.0 \text{ s}$                |   |
| <b>Phase 2:</b> | $t > 1.0 \text{ s}$                   | $\dot{\theta}(t) > 0 \text{ rad.s}^{-1}$    |
| <b>Phase 3:</b> | $\theta(t) > 0.12 \text{ rad}$        | $\dot{\theta}(t) \leq 0 \text{ rad.s}^{-1}$ |
| <b>Phase 4:</b> | $0 < \theta(t) \leq 0.12 \text{ rad}$ | $\dot{\theta}(t) < 0 \text{ rad.s}^{-1}$    |

**Door parameters**

The equations of motion laid out above require the definition of a number of parameters as laid out below.

The moment of inertia,  $I$ , was given by,

$$I = \sum_i m_i r_i^2 = \frac{1}{3} m_d \cdot r_d^2$$

Where  $r_d$  was the width of the door and  $m_d$  was the mass of the door. The torque,  $\tau_0$ , acting on the door was given by,

$$\tau_0 = F_0 \cdot r_F \cdot \sin(\theta_F) = F_0 \cdot r_F$$

Where  $F_0$  was the magnitude of the force acting on the door,  $r_F$  is the distance from the origin at which the force is applied and  $\theta_F$  is the angle at which the force is applied to the door. It was assumed that the force was applied perpendicular to the door and hence  $\theta_F = 90^\circ$ , thus  $\sin(\theta_F) = 1$ .

For simplicity in calculating the motion of the door a torsional spring with torsional spring constant,  $k'$ , is considered to act in closing the door. Hence the natural frequency,  $\omega_0$ , is given by,

$$\omega_0 = \left( \frac{k'}{I} \right)^{\frac{1}{2}}$$

Using these assumed values allows for the motion of a door with door closer to be modelled.

### 3.5.1.3. Generator modelling

#### Method 1: (M1final.m (appendix 4))

In order to model a generator on the door a number of modifications were required. This was carried out by modelling the generator as a viscous damper on the system. Initially the

generator was assumed to be directly driven by the door's motion, and hence the modelling must be modified to take account of this. As a result the three phases were modelled as follows,

1. The door was modelled as a Forced mass-spring-damper system, with a constant force applied. The damper provides under-damping, with the value determined from the generation system.
2. A mass-spring-damper system with initial conditions determined from the conditions at the end of phase 1. The damping is the same as in phase 1.
3. A mass-spring-damper system, with the initial conditions set by the end conditions from phase 2. The damping is assumed to be critically damped, although this would be a result of a combination of the generation system and the door closer damping system.
4. The door motion was modelled as a mass-spring system.

To model this situation, the equations of motion need to be significantly modified. A number of parameters must first be defined,

$$\omega_d = \sqrt{1 - \xi^2} \omega_0$$

$$\xi = \frac{d}{d_{critical}}$$

$$d_{critical} = 2(I \cdot k')^{0.5}$$

Where  $\omega_d$  is the damped frequency,  $\xi$  is the damping ratio,  $d$  is the damping resulting from the generator and  $d_c$  is the critical damping. The equations of motion are then,

### Phase 1

$$\theta(t) = \frac{\tau_0}{k'} \left( 1 - e^{-\xi \omega_0 t} \cos(\omega_d t) - \left( \frac{-\xi \omega_0}{\omega_d} \right) e^{-\xi \omega_0 t} \sin(\omega_d t) \right)$$

$$\dot{\theta}(t) = \frac{\tau_0}{k'} (e^{-\xi\omega_0 t}) \cdot \left( \omega_d + \frac{-\xi\omega_0^2}{\omega_d} \right) \cdot \sin(\omega_d t)$$

### Phase 2

$$\theta(t) = e^{-\xi\omega_0 t} (C_4 \cos(\omega_d t) + C_5 \sin(\omega_d t))$$

$$\dot{\theta}(t) = e^{-\xi\omega_0 t} ((-\xi\omega_0 C_4 + \omega_d C_5) \cos(\omega_d t) + (-\omega_d C_4 - \xi\omega_0 C_5) \sin(\omega_d t))$$

Where,

$$C_4 = \theta_0 \text{ and } C_5 = \frac{\dot{\theta}_0 + \xi\omega_0\theta_0}{\sqrt{1 - \xi^2}\omega_0}$$

### Phase 3

With regards to the third phase it is possible to model with the same approach as for the non-generation model. This is achieved by assuming that the damper is adjusted such that the combined damping provided by the damper and generator is critical.

### Phase 4

The equations of motion are the same as for phase 4 of the model with no generator present.

### Method 2: (M2final.m (appendix 5))

The second approach considered for generation uses two springs, the first of these,  $k'_1$ , is used to supply the energy required to close the door, whereas the second,  $k'_2$ , is used to drive a generator. For this situation, the first two phases of the modelling are the same as for the non-generation model. There are now however two aspects to the third phase. Firstly the energy stored in  $k'_1$  is used to close the door, with the damping still considered to be critical. The energy stored in  $k'_2$  is used to drive a generator independently to the door motion. A number of changes are needed to the non-generation model in order to model this. The value of  $k'$  used in phase 1 and the natural frequency for phases 1 and 2 are found using,  $k' = k'_1 + k'_2$ . The second change is in phase 3, where the natural frequency is now calculated with  $k' = k'_1$ . This resulted in the need for less damping in the system to provide critical damping. The potential for energy generation is found simply by determining the energy stored in the spring

$k'_2$ . The energy in the spring could easily be determined from the change in angular rotation of the spring and the torsional spring constant.

**Method 3: (M3final.m (appendix 6))**

An alternative method is to replace the viscous damper used to control the speed of the door during closing with a generator unit that provides damping to the doors motion through harvesting energy as a result of the motion of the door during closing. The motion of the door is the same as in the case of a door with no generation unit. As such this method is considered to have an advantage over the two previously discussed, in that the door’s motion is affected by the presence of a generation unit and hence the energy requirements of using the door would not be affected. The energy available for generation was determined by the energy dissipated in the damping unit.

**3.5.1.4. Model parameters**

A number of parameters must be chosen before the calculations can be completed and were set as shown in table 3-5, to give baseline cases. It is worth reiterating that the opening force will be applied for a period of 1 s.

**Table 3-5: Definition of the necessary parameters and the values used for the baseline results of swing door modelling.**

|                           | Notation | Value | Units    |
|---------------------------|----------|-------|----------|
| Mass                      | $m_d$    | 30    | (kg)     |
| Door width                | $r_d$    | 0.8   | (m)      |
| Opening force             | F        | 25    | (N)      |
| Force applied at          | $r_F$    | 0.7   | (m)      |
| Torsional spring constant | $k'$     | 18    | (Nm/rad) |

A useful metric in analysing the energy generation potential of a door harvester was the average power available over the door opening event. This was simply calculated as follows,

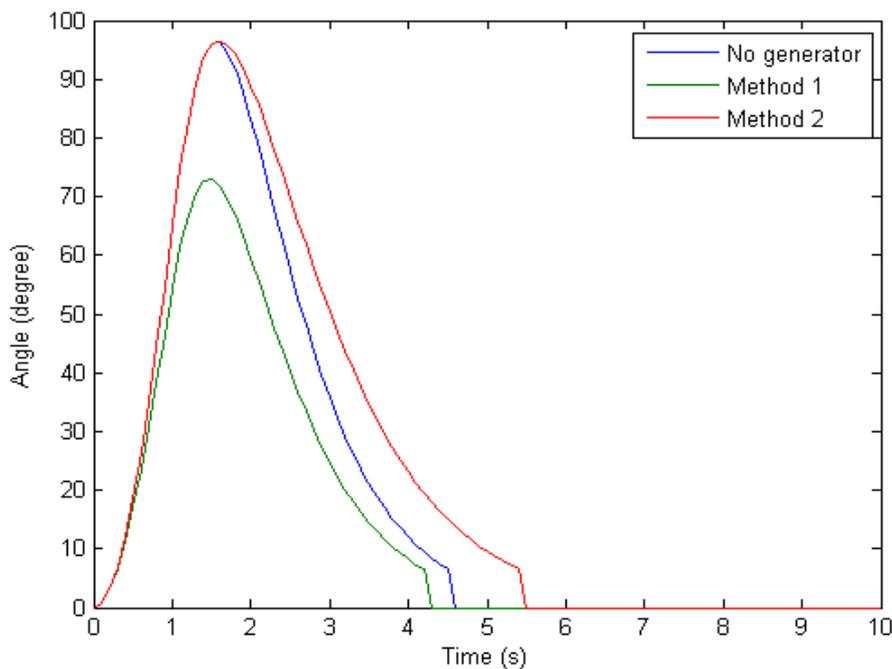
$$P_{Ave} = \frac{E_{D.O.E.}}{t_{D.O.E.}}$$

With the results included in tables 3-9, 3-10 and 3-11. This was a useful measure in determining the relative change in the energy potential and the time for a door opening event to occur and could be used to assess the maximum potential on offer from a door harvesting device.

### 3.5.1.5. Modelled results

#### Comparison of generation methods

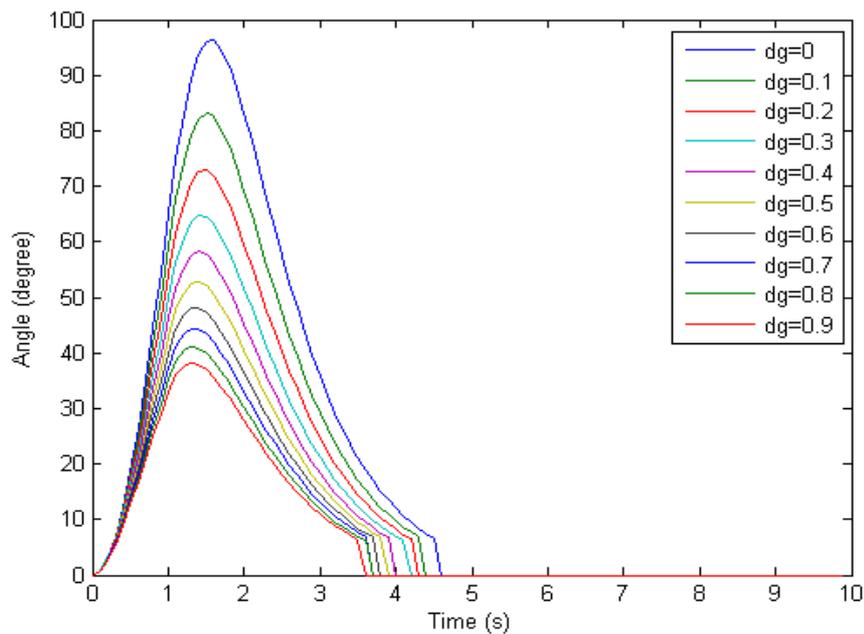
A model (comparison.m (appendix 7)) was developed to test the effect of each generation method on the motion of the door, where the door parameters used are those presented in table 3-5. In addition for method 1 the value of  $\xi$  was taken as 0.2 and for method 2 the value of  $k'_2$  was taken to be 5.6 Nm/rad.



**Fig. 3-9: Comparison of the angular position of the door when no generator is present with the three methods of generation. The opening force was applied for 1s. It should be noted that the no generator plot is identical to that of method 3.**

A comparison was carried out to assess the effect each of the generation methods had on the motion of the door, with the results presented in fig. 3-9. It was clear that the motion of the door was significantly affected by methods 1 and 2, with method 3 having no effect as the generator was acting in place of the viscous damper presented in the non generation case. Utilising method 1 resulted in the maximum opening angle of the door decreasing in comparison to the non generation case, due to the damping effect of the generator during door opening. In addition the time taken for the door to close was slightly decreased from the non generation case due to the smaller maximum opening angle. When method 2 was utilised the motion of the door during opening was unchanged, however the time taken for the door to close was considerably increased when compared to the non generation case. This was due to the lower value of the torsional spring constant available for closing the door.

**Method 1:**

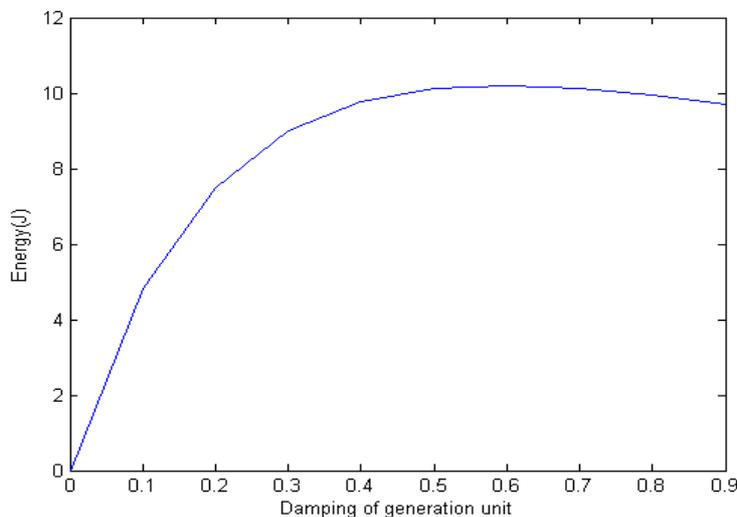


**Fig. 3-10: Angular position of the door during a door opening event for method 1. The damping effect of the generator ( $\xi$ ) on the door is varied.**

In method 1 the generator was modelled to act as a viscous damper with the proportion of damping,  $\xi$ , given as a proportion of critical damping. It was seen from fig. 3-10 that increasing the value of  $\xi$  significantly reduces the maximum opening angle of the door, where for  $\xi = 0$  and 0.9 the value of  $\theta_{\max} = 96.4^\circ$  and  $38.2^\circ$  respectively. In addition increasing  $\xi$  resulted in a

decrease in the value of  $t_{D.O.E.}$ , although the affect was relatively small. For  $\xi = 0$  and 0.9 the values of  $t_{D.O.E.}$  were 4.6s and 3.6s respectively. The reason for this was the retarding action of the generator on the doors motion.

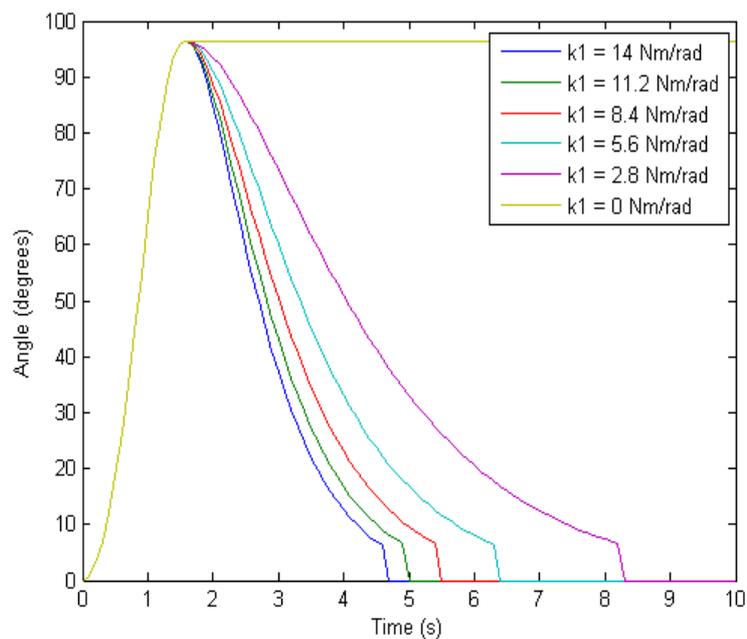
The energy potential available for harvesting was plotted against  $\xi$  in fig. 3-11. The energy potential increased quickly for low values of  $\xi$ , before a plateau in the energy of  $\sim 10$  J for values of  $\xi$  ranging from 0.4-0.9. The maximum value for energy potential was found to occur when  $\xi = 0.6$ , with the values then tailing off slightly. In effect the value of  $\xi$  determines the proportion of kinetic energy being dissipated through the generator, where higher values represent an increase in energy dissipation. As a result it was expected that higher values of  $\xi$  would result in an increase in energy potential, however this increase in energy dissipation resulted in an increased retardation of the doors motion, hence the decrease in the maximum opening angle of the door,  $\theta_{max}$ . For the higher values of  $\xi$  the increase in energy dissipation was offset by the retardation of the doors motion. The maximum energy available for harvesting was found to be 10.2 J with a value of  $t_{D.O.E.}$  of 3.8 s, where  $\xi = 0.6$ . It was however observed that the maximum opening angle to which the door opened in this situation was only  $48.2^\circ$ . It was thought that the angle to which the door opens, represented as  $\theta_{max}$ , must be  $> 60^\circ$ , in this case the maximum energy available when this condition was met occurs for a value of  $\xi = 0.3$ . This results in the available energy being 9 J with a value of  $t_{D.O.E.}$  of 4.2 s and a maximum opening angle of  $64.8^\circ$ .



**Fig. 3-11: Energy potential available for harvesting from method 1 as a function of the damping effect of the generator.**

### Method 2:

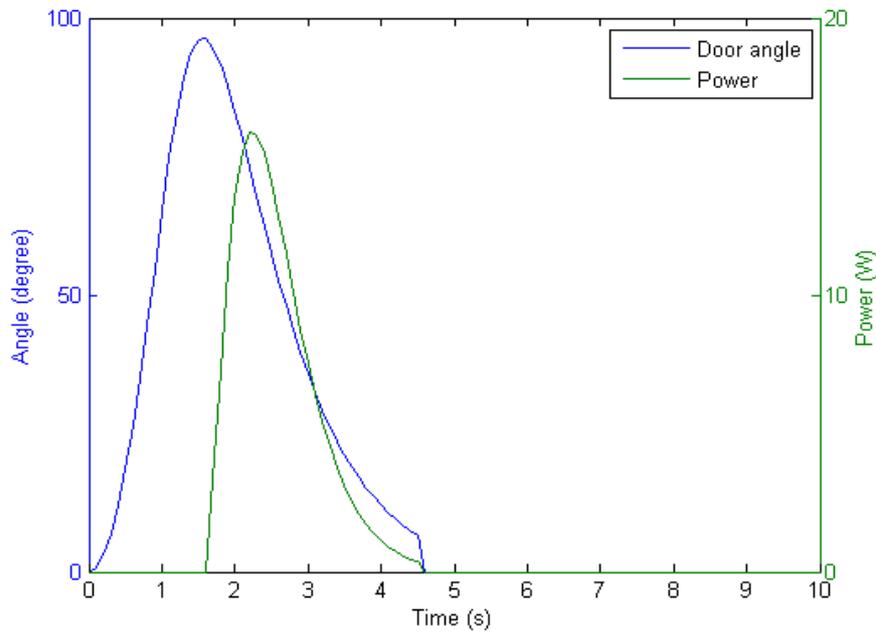
The first point to note about method 2 was that the maximum opening angle of the door was unchanged by variations to  $k'_2$ . This was because the total value  $k'$  during opening remains constant as it was the sum of  $k'_1$  and  $k'_2$ . Variations to  $k'_2$  do have a significant impact on the motion of the door during closing, where an increase in the value of  $k'_2$  resulted in an increase in the time taken for the door to close, as was seen in fig. 3-12. For the case of  $k'_2 = 18 \text{ Nm/rad}$  ( $k'_1 = 0 \text{ Nm/rad}$ ) the value of  $t_{D.O.E.}$  was infinity as no energy was available to close the door and hence the door remained at the fully open position, as was clearly seen in fig. 3-12. This was because as  $k'_2$  increased,  $k'_1$  decreased meaning that the force acting to close the door was reduced. The energy potential available for harvesting increases linearly as the value of  $k'_2$  increases. This was because the maximum opening angle of the door was the same regardless of the proportions of  $k'_1$  and  $k'_2$ , meaning the energy stored in spring  $k'_2$  was proportional to the value of the torsional spring constant. Evidently for  $k'_2 = 0 \text{ Nm/rad}$ , the energy stored was 0 J, whereas for  $k'_2 = 18 \text{ Nm/rad}$ , the energy stored was 19.8 J.



**Fig. 3-12: The angular position of the door using method 2 for varying proportions of the torsional spring constant of springs 1 and 2.**

### Method 3:

The motion of the door when utilising method 3 was unchanged from the non generation situation as the generator was assumed to act as the viscous damper used to control the angular velocity during closing. The maximum energy available for harvesting from this method was 19.7 J with a value of  $t_{D.O.E.}$  of 4.6 s, with the motion and power dissipation shown in fig. 3-13.



**Fig. 3-13: Angular position and power dissipation of the generator for method 3.**

#### 3.5.1.6. Door parameters

To test the energy that may be available three of the door parameters were independently varied, these being the door mass, opening force and torsional spring constant. Each of these were varied independently with the remaining values held as set out in table 3-5. The values used for these variables were shown in table 3-6.

**Table 3-6: Variables to be tested and the values used in the modelling of a swing door.**

|       |                    |
|-------|--------------------|
| $m_d$ | 20, 30, 40, 50, 60 |
| F     | 20, 25, 30         |
| $k'$  | 10, 14, 18, 22     |

### **Varying door mass**

Varying the mass of the door was explored for each of the generation methods, with the results presented in table 3-7. In general it was found that increasing the mass of the door resulted in a decrease to both the maximum door opening angle and the energy potential as well as an increase in the value of  $t_{D.O.E.}$ . As a result it was seen that the value of  $P_{ave}$  decreases with increasing door mass. It was seen that change is large for small values of door mass, with the change tailing off as the mass increases.

In the case of method 1, the highest values of  $P_{ave}$  occurred for the highest values of energy output. The values of  $P_{ave}$  ranged from 3.8 – 1.4 W for  $m_d = 20 - 60$  kg. As was outlined earlier, it was decided that the angle to which the door must be opened must be greater than  $60^\circ$ , for which the range in the values of  $P_{ave}$  was 3.6 – 0.5 W. This suggested that the necessity for the door to open to a reasonable angle diminishes the potential for energy generation in method 1, particularly for high values of  $m_d$ . For method 2 the value of  $P_{ave}$  increased as  $k'_2$  increased, although the increase tailed off for high values of  $k'_2$ , where the results for  $k'_2 = 8.4$  and 11.2 Nm/rad are almost the same. This was a result of the values of  $t_{D.O.E.}$  increasing rapidly for high values of  $k'_2$ . The highest value of  $P_{ave}$  occurs for  $k'_2 = 11.2$  Nm/rad where the values range from 3.0 W for  $m_d = 20$  kg to 1.0 W for  $m_d = 50$  kg. No value was recorded for  $m = 60$  kg as  $t_{D.O.E.}$  exceeded 10 s. This suggests that although the highest value for method 1 was greater than for method 2, method 2 was less sensitive to increases in door mass. Method 3 resulted in the largest values over the range of mass of  $P_{ave}$ , with a range from 6.7 – 1.8 W for  $m_d = 20 - 60$  kg. This was because the energy potential for method 3 was high, with the generation method having no effect on the doors motion and hence  $t_{D.O.E.}$  remains low.

**Table 3-7: Results for the motion and energy generation potential of the door opening event using the three defined generation methods for varying door mass.**

| Mass (kg)  |                     | 20    | 30   | 40   | 50   | 60   |
|--|---------------------|-------|------|------|------|------|
| <b>Method 1</b>                                  |                     |       |      |      |      |      |
| $E_{\max}$                                       | $\theta_{\max}$ (°) | 56.5  | 48.2 | 42.7 | 38.7 | 35.7 |
|  | $t_{D.O.E.}$ (s)    | 3.4   | 3.8  | 4.2  | 4.5  | 4.7  |
|  | $EP_{D.O.E.}$ (J)   | 12.8  | 10.2 | 8.5  | 7.3  | 6.4  |
|  | $P_{ave}$ (W)       | 3.8   | 2.7  | 2.0  | 1.6  | 1.4  |
| $E_{\max}$ for<br>( $\theta_{\max} > 60^\circ$ ) | $\xi$               | 0.5   | 0.3  | 0.2  | 0.1  | 0.1  |
|  | $\theta_{\max}$ (°) | 61.6  | 64.8 | 64.7 | 67.0 | 61.7 |
|  | $t_{D.O.E.}$ (s)    | 3.5   | 4.2  | 4.7  | 5.3  | 5.7  |
|  | $EP_{D.O.E.}$ (J)   | 12.7  | 9.0  | 6.2  | 3.3  | 2.9  |
|  | $P_{ave}$ (W)       | 3.6   | 2.1  | 1.3  | 0.6  | 0.5  |
| <b>Method 2</b>                                  |                     |       |      |      |      |      |
|  | $\theta_{\max}$ (°) | 112.5 | 96.4 | 85.2 | 77.6 | 71.2 |
| $k'_2 = 2.8$                                     | $t_{D.O.E.}$ (s)    | 4.3   | 5.0  | 5.6  | 6.0  | 6.5  |
|  | $EP_{D.O.E.}$ (J)   | 5.4   | 4.0  | 3.1  | 2.6  | 2.2  |
|  | $P_{ave}$ (W)       | 1.3   | 0.8  | 0.6  | 0.4  | 0.3  |
| $k'_2 = 5.6$                                     | $t_{D.O.E.}$ (s)    | 4.8   | 5.5  | 6.1  | 6.6  | 7.1  |
|  | $EP_{D.O.E.}$ (J)   | 10.8  | 7.9  | 6.2  | 5.1  | 4.3  |
|  | $P_{ave}$ (W)       | 2.3   | 1.4  | 1.0  | 0.8  | 0.6  |
| $k'_2 = 8.4$                                     | $t_{D.O.E.}$ (s)    | 5.5   | 6.4  | 7.1  | 7.6  | 8.2  |
|  | $EP_{D.O.E.}$ (J)   | 16.2  | 11.9 | 9.3  | 7.7  | 6.5  |
|  | $P_{ave}$ (W)       | 2.9   | 1.9  | 1.3  | 1.0  | 0.8  |
| $k'_2 = 11.2$                                    | $t_{D.O.E.}$ (s)    | 7.1   | 8.3  | 9.2  | 9.9  | -    |
|  | $EP_{D.O.E.}$ (J)   | 21.6  | 15.8 | 12.4 | 10.3 | 8.6  |
|  | $P_{ave}$ (W)       | 3.0   | 1.9  | 1.3  | 1.0  | -    |
| <b>Method 3</b>                                  |                     |       |      |      |      |      |
|  | $\theta_{\max}$ (°) | 112.5 | 96.4 | 85.5 | 77.6 | 71.5 |
|  | $t_{D.O.E.}$ (s)    | 4.0   | 4.6  | 5.1  | 5.5  | 5.9  |
|  | $EP_{D.O.E.}$ (J)   | 26.9  | 19.7 | 15.4 | 12.7 | 10.7 |
|  | $P_{ave}$ (W)       | 6.7   | 4.3  | 3.0  | 2.3  | 1.8  |

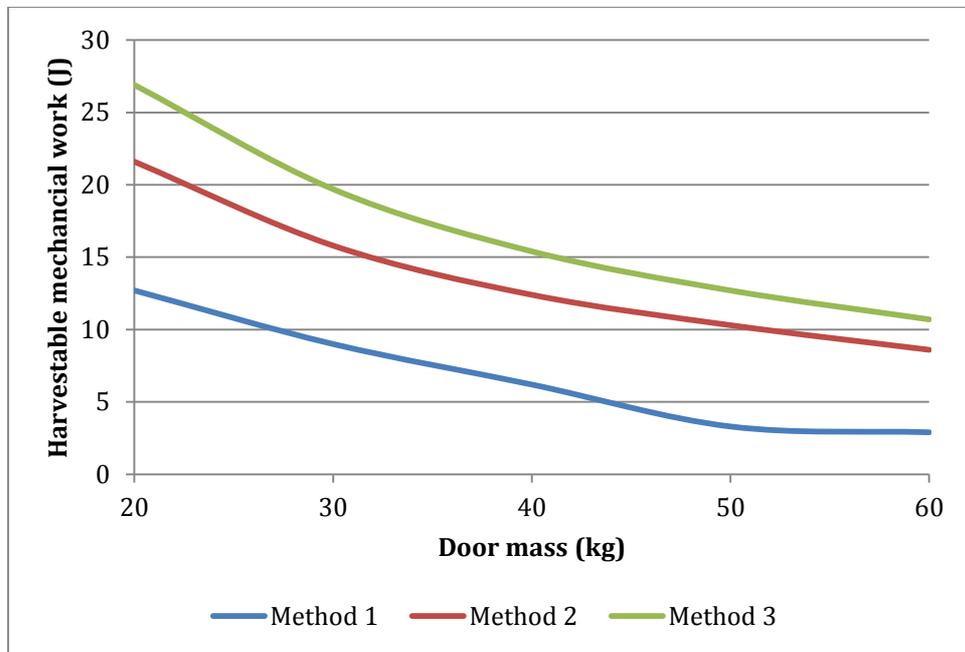


Fig. 3-14: Harvestable mechanical work available from each generation method for a swing door of varying door mass.

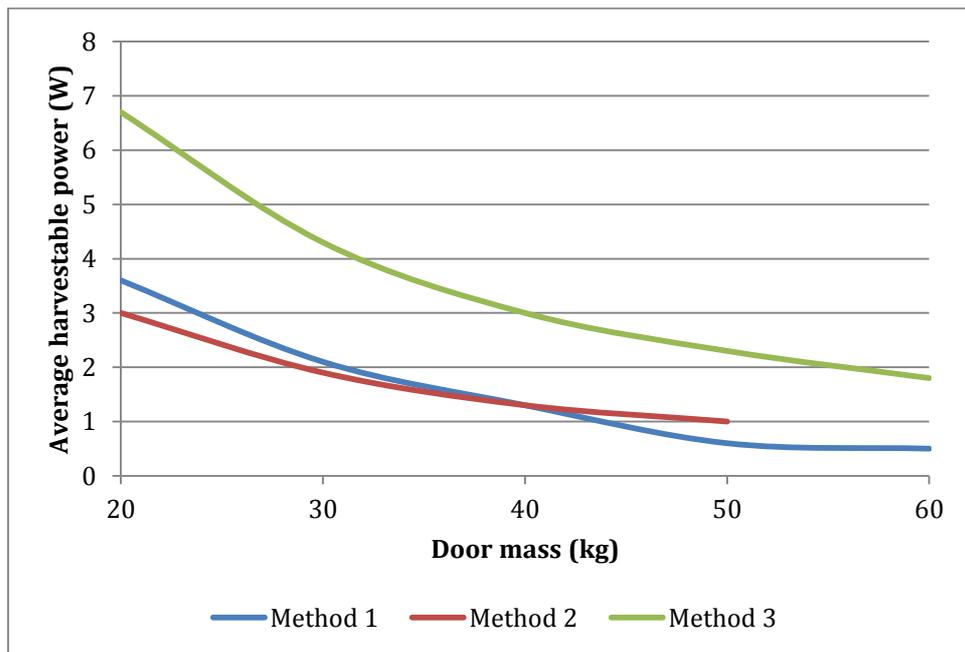


Fig. 3-15: Average harvestable power available from each generation method for a swing door of varying door mass.

### Varying opening force

The results for variable opening force were presented in table 3-8, where an increase in the opening force resulted in an increase to the maximum opening angle of the door, the energy potential and the value of  $t_{D,O.E.}$ . The value of  $P_{ave}$  increased in all cases with increasing values of  $F_0$ . Since both the values of  $EP_{D,O.E.}$  and  $t_{D,O.E.}$  increase with increased  $F_0$  it signifies that the increase in energy potential increases more quickly than the value of  $t_{D,O.E.}$ .

In the case of method 1 a similar effect was seen as for the case of variable mass. Again the highest values of  $P_{ave}$  occur for maximum energy output, where the values range from 1.8 – 3.7 W for  $F_0 = 20 - 30$  N. When the condition of  $\theta_{max} > 60^\circ$  was considered,  $P_{ave} = 0.7 - 3.6$  W, again showing that harvesting energy using method 1 had a detrimental affect on the door's motion. This was particularly true for low values of  $F_0$ . For method 2 the results for  $P_{ave}$  again increased with increased values of  $k'_2$ , with the values tailing off for high values of  $k'_2$ . The largest values were seen for  $k'_2 = 11.2$  Nm/rad, where  $P_{ave} = 1.3 - 2.7$  W for  $F = 20 - 30$  N. The values obtained for method 3 were again the highest of the three methods, with a range of 2.9 – 5.6 W for  $F_0 = 20 - 30$  N. Again this was due to method 3 not having an affect on the doors motion.

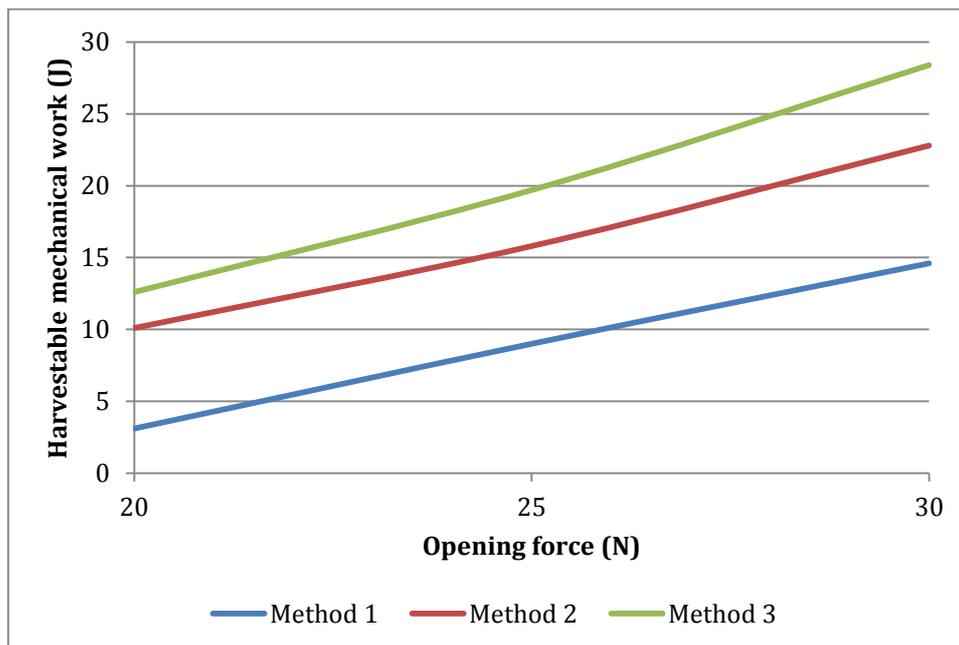
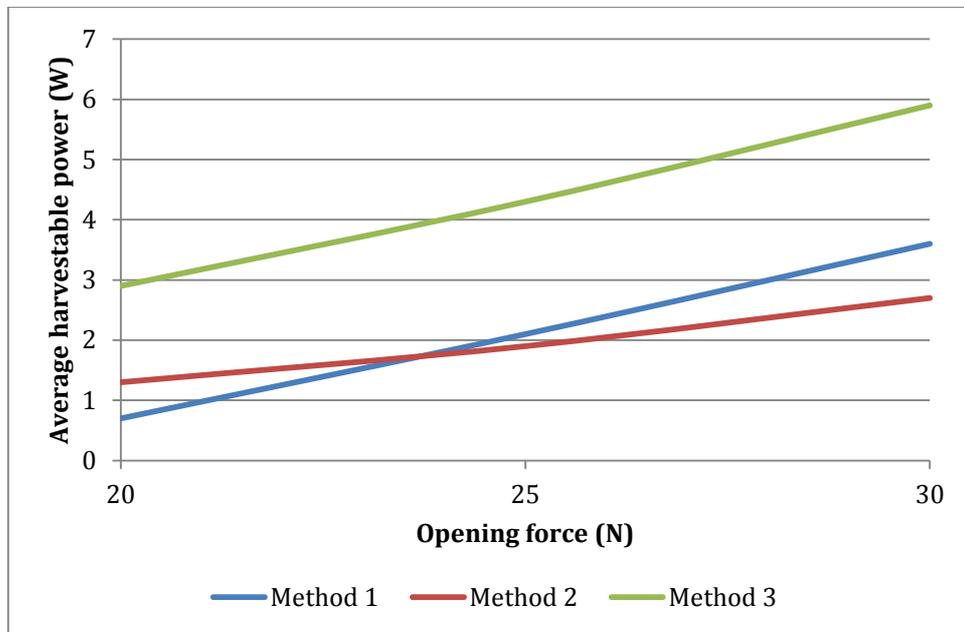


Fig. 3-16: Harvestable mechanical work available from each generation method for a swing door with varying opening force.

**Table 3-8: Results for the motion and energy generation potential of the door device using the three defined generation methods for varying opening force.**

|   | Force (N)          | 20   | 25   | 30    |
|---|--------------------|------|------|-------|
| <b>Method 1</b>                             |                    |      |      |       |
| $E_{max}$                                   | $\theta_{max}$ (°) | 38.5 | 48.2 | 57.8  |
|   | $t_{D.O.E.}$ (s)   | 3.6  | 3.8  | 4.0   |
|   | $EP_{D.O.E.}$ (J)  | 6.5  | 10.2 | 14.7  |
|   | $P_{ave}$ (W)      | 1.8  | 2.7  | 3.7   |
| $E_{max}$ for ( $\theta_{max} > 60^\circ$ ) | $\xi$              | 0.1  | 0.3  | 0.5   |
|   | $\theta_{max}$ (°) | 66.6 | 64.8 | 63.4  |
|   | $t_{D.O.E.}$ (s)   | 4.3  | 4.2  | 4.1   |
|   | $EP_{D.O.E.}$ (J)  | 3.1  | 9.0  | 14.6  |
|   | $P_{ave}$ (W)      | 0.7  | 2.1  | 3.6   |
| <b>Method 2</b>                             |                    |      |      |       |
|   | $\theta_{max}$ (°) | 77.1 | 96.4 | 115.7 |
| $k'_2 = 2.8$                                | $t_{D.O.E.}$ (s)   | 4.8  | 5.0  | 5.2   |
|   | $EP_{D.O.E.}$ (J)  | 2.5  | 4.0  | 5.7   |
|   | $P_{ave}$ (W)      | 0.5  | 0.8  | 1.1   |
| $k'_2 = 5.6$                                | $t_{D.O.E.}$ (s)   | 5.3  | 5.5  | 5.7   |
|   | $EP_{D.O.E.}$ (J)  | 5.1  | 7.9  | 11.4  |
|   | $P_{ave}$ (W)      | 1.0  | 1.4  | 2.0   |
| $k'_2 = 8.4$                                | $t_{D.O.E.}$ (s)   | 6.1  | 6.4  | 6.6   |
|   | $EP_{D.O.E.}$ (J)  | 7.6  | 11.9 | 17.1  |
|   | $P_{ave}$ (W)      | 1.2  | 1.9  | 2.6   |
| $k'_2 = 11.2$                               | $t_{D.O.E.}$ (s)   | 7.8  | 8.3  | 8.6   |
|   | $EP_{D.O.E.}$ (J)  | 10.1 | 15.8 | 22.8  |
|   | $P_{ave}$ (W)      | 1.3  | 1.9  | 2.7   |
| <b>Method 3</b>                             |                    |      |      |       |
|   | $\theta_{max}$ (°) | 77.1 | 96.4 | 115.7 |
|   | $t_{D.O.E.}$ (s)   | 4.4  | 4.6  | 4.8   |
|   | $EP_{D.O.E.}$ (J)  | 12.6 | 19.7 | 28.4  |
|   | $P_{ave}$ (W)      | 2.9  | 4.3  | 5.9   |



**Fig. 3-17: Average harvestable power available from each generation method for a swing door with varying opening force.**

### Varying the torsional spring constant

The results for varying  $k'$  were presented in table 3-9, where an increase in the torsional spring constant resulted in a decrease to the maximum opening angle, the energy potential and the value of  $t_{D,O,E}$ . The value of  $P_{ave}$  appeared to increase with increased  $k'$ , however the change was less pronounced than for variations in mass or opening force. This was a result of the  $E$  and  $t_{D,O,E}$  values both decreasing at a similar rate as  $k'$  was increased.

For method 1 the maximum values were again found for the maximum values of energy potential, with a range of  $P_{ave} = 2.5 - 2.7$  W for  $k' = 10 - 22$  Nm/rad. However if the condition of the opening angle was again considered then the range for  $P_{ave} = 2.4 - 1.1$  W. For method 2 the results for  $P_{ave}$  again increase with increased values of  $k'_2$ , with the values tailing off for high values of  $k'_2$ . The largest values were seen for  $k'_2 = 11.2$  Nm/rad, where  $P_{ave} = 1.9 - 2.2$  W for  $k' = 14 - 22$  Nm/rad, with no value recorded for  $k' = 10$  Nm/rad due to the length of time taken for the door to close. Method 3 produced the results with the highest values of  $P_{ave}$  with a range from  $3.8 - 4.9$  W for  $k' = 10 - 22$  Nm/rad.

**Table 3-9: Results for the motion and energy generation potential of the door using the three generation methods and varying the torsional spring constant.**

|   | $k'$ (Nm/rad)                  | 10    | 14   | 18   | 22   |
|---|--------------------------------|-------|------|------|------|
| <b>Method 1</b>                                 |                                |       |      |      |      |
| $E_{\max}$                                      | $\theta_{\max}$ ( $^{\circ}$ ) | 58.6  | 48.2 | 41.5 | 36.6 |
|   | $t_{D.O.E.}$ (s)               | 4.6   | 3.8  | 3.4  | 3.0  |
|   | $EP_{D.O.E.}$ (J)              | 11.6  | 10.2 | 9.1  | 8.2  |
|   | $P_{ave}$ (W)                  | 2.5   | 2.7  | 2.7  | 2.7  |
| $E_{\max}$ for ( $\theta_{\max} > 60^{\circ}$ ) | $\xi$                          | 0.5   | 0.3  | 0.2  | 0.1  |
|   | $\theta_{\max}$ ( $^{\circ}$ ) | 64.1  | 64.8 | 62.6 | 62.9 |
|   | $t_{D.O.E.}$ (s)               | 4.7   | 4.2  | 3.8  | 3.5  |
|   | $EP_{D.O.E.}$ (J)              | 11.4  | 9.0  | 6.8  | 4.0  |
|   | $P_{ave}$ (W)                  | 2.4   | 2.1  | 1.8  | 1.1  |
| <b>Method 2</b>                                 |                                |       |      |      |      |
|   | $\theta_{\max}$ ( $^{\circ}$ ) | 117.2 | 96.4 | 82.4 | 72.6 |
| $k'_2 = 2.8$                                    | $t_{D.O.E.}$ (s)               | 6.0   | 5.0  | 4.4  | 3.9  |
|   | $EP_{D.O.E.}$ (J)              | 4.2   | 4.0  | 3.7  | 3.5  |
|   | $P_{ave}$ (W)                  | 0.7   | 0.8  | 0.8  | 0.9  |
| $k'_2 = 5.6$                                    | $t_{D.O.E.}$ (s)               | 6.6   | 5.5  | 4.8  | 4.3  |
|   | $EP_{D.O.E.}$ (J)              | 8.4   | 7.9  | 7.4  | 7.1  |
|   | $P_{ave}$ (W)                  | 1.3   | 1.4  | 1.5  | 1.7  |
| $k'_2 = 8.4$                                    | $t_{D.O.E.}$ (s)               | 7.7   | 6.4  | 5.5  | 4.9  |
|   | $EP_{D.O.E.}$ (J)              | 12.5  | 11.9 | 11.2 | 10.6 |
|   | $P_{ave}$ (W)                  | 1.6   | 1.9  | 2.0  | 2.2  |
| $k'_2 = 11.2$                                   | $t_{D.O.E.}$ (s)               | -     | 8.3  | 7.1  | 6.3  |
|   | $EP_{D.O.E.}$ (J)              | 16.7  | 15.8 | 14.9 | 14.1 |
|   | $P_{ave}$ (W)                  | -     | 1.9  | 2.1  | 2.2  |
| <b>Method 3</b>                                 |                                |       |      |      |      |
|   | $\theta_{\max}$ ( $^{\circ}$ ) | 117.2 | 96.4 | 82.7 | 72.6 |
|   | $t_{D.O.E.}$ (s)               | 5.5   | 4.6  | 4.0  | 3.6  |
|   | $EP_{D.O.E.}$ (J)              | 20.8  | 19.7 | 18.5 | 17.5 |
|   | $P_{ave}$ (W)                  | 3.8   | 4.3  | 4.6  | 4.9  |

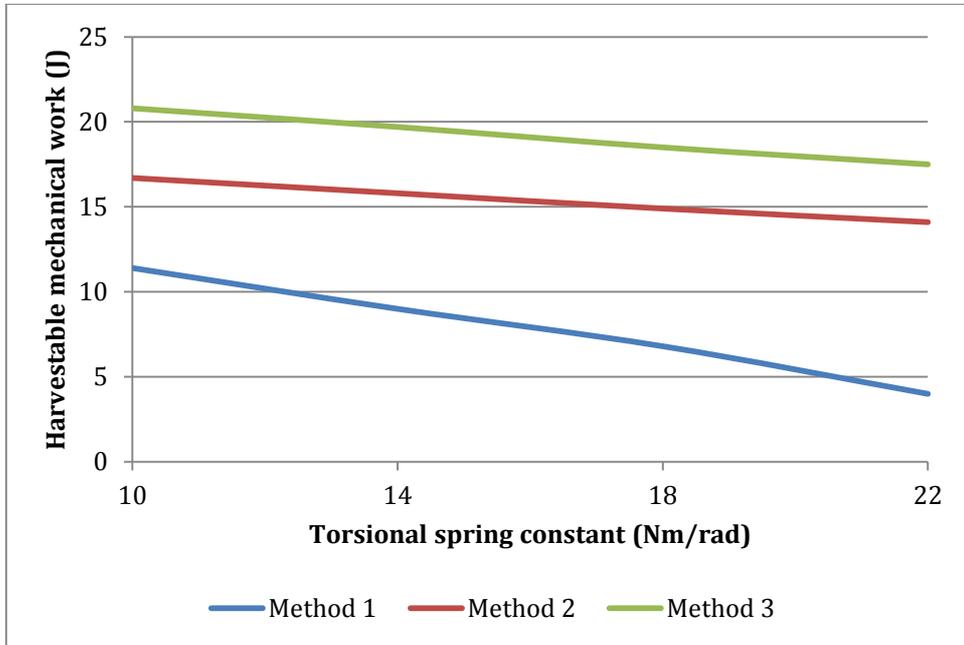


Fig. 3-18: Harvestable mechanical work available from each generation method for a swing door with varying torsional spring constant.

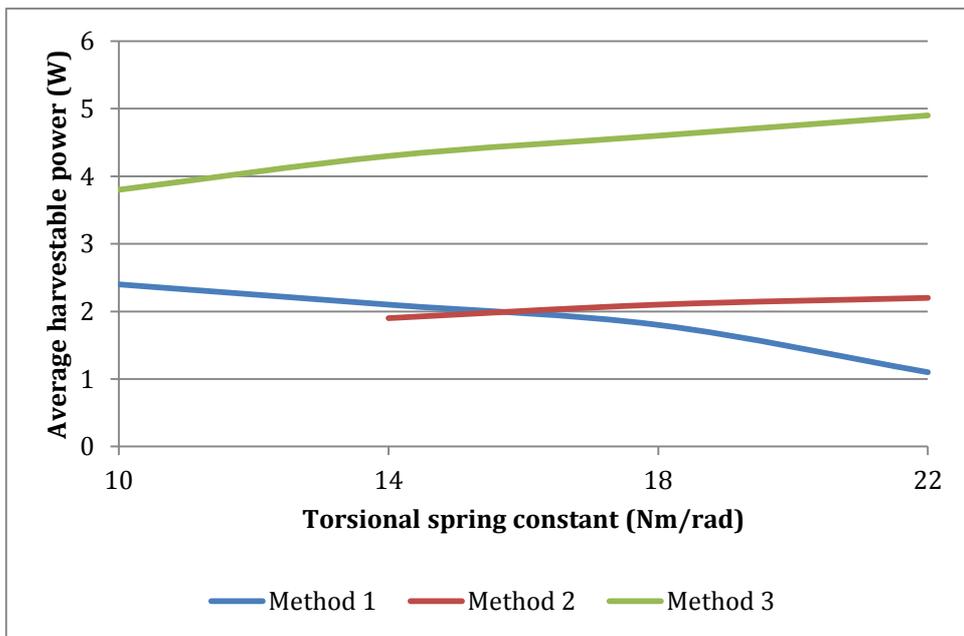


Fig. 3-19: Average harvestable power available from each generation method for a swing door with varying torsional spring constant.

### 3.5.2. Revolving door

It was expected that a revolving door will offer a greater energy potential than a swing door, since the revolving door is not required to have a returning force to shut the door. Fig 3-20 shows the layout and labelling of the door to be modelled with the model presented in appendix 8.

A number of assumptions were made with regards to the door.

- Four-leaf revolving door, where the angles between each leaf was set at 90° and each leaf is assumed to be identical.
- The door is manually operated.
- Each of the four areas,  $A_i$ , were assumed to allow only one user at a time.
- Opening force ( $F_o$ ) applied perpendicular to the face of the door, at a distance  $r_F$  from the axis of rotation.
- Generator acts as a damper on the doors rotation.
- It was deemed that a single user is required to make the door rotate through 180° to pass through the door.

#### Revolving door parameters

Door leaf mass,  $m_L = m_1 = m_2 = m_3 = m_4$

Leaf radius =  $r_L = r_1 = r_2 = r_3 = r_4$

Leaf inertia =  $I_L = \frac{m_L \cdot r_L^2}{3}$

Door inertia =  $I = 4I_L$

Force applied by the user =  $F_o$

Force applied at distance from the axis of rotation =  $r_F$

Opening torque =  $\tau_o = F_o \cdot r_F$

Damping coefficient =  $d_c$

Damping torque of generator =  $\tau_G(t) = d_c \cdot \dot{\theta}(t)$

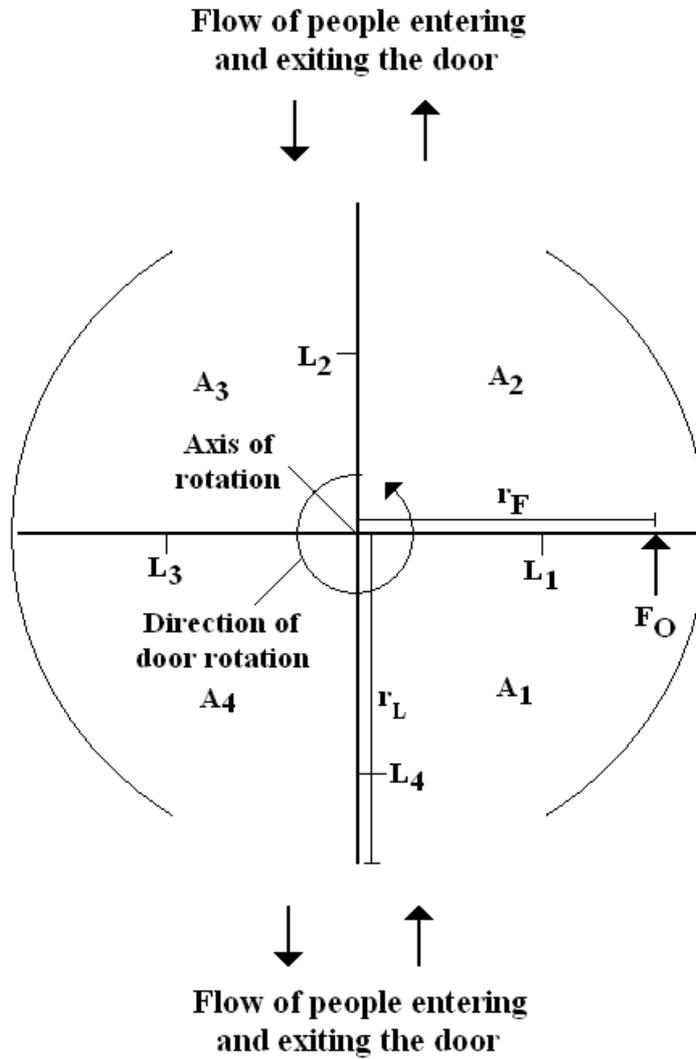


Fig. 3-20: Diagram showing the layout of the revolving door to be modelled.

Initial conditions

$$\theta(0) = 0 \text{ rad}$$

$$\dot{\theta}(0) = 0 \text{ rad/s}$$

$$\ddot{\theta}(0) = \frac{\tau_o - \tau_G(0)}{I} = \frac{\tau_o - 0}{I} = \frac{\tau_o}{I} \text{ rad/s}^2$$

Modelling door motion

The motion of the door was considered to consist of two phases. Initially the door is at rest. An opening force ( $F_o$ ) is applied by the user on one of the door's leaves and acts to rotate the door. The presence of a generator acts to dampen the motion of the door with the retarding

torque being dependent on the angular velocity of the door. The calculation of the door's motion is calculated using the following equations. It is worth noting that  $\Delta t = 0.1s$ .

$$\theta(t) = \theta(t - 1) + (\dot{\theta}(t - 1) \cdot \Delta t)$$

$$\dot{\theta}(t) = \dot{\theta}(t - 1) + (\ddot{\theta}(t - 1) \cdot \Delta t)$$

$$\ddot{\theta}(t) = \frac{\tau_o - \tau_G(t)}{I}$$

The opening force is applied until the angle through which the door has rotated is  $\geq 180^\circ$ . At this point the opening force is no longer applied, resulting in,  $\tau_o = 0$ . At this point the acceleration of the door is determined by,

$$\ddot{\theta}(t) = -\frac{\tau_G(t)}{I}$$

This results in the door decelerating and coming to rest as the kinetic energy of the door is dissipated through the generator.

#### Energy generation of a single user

The energy potential available for harvesting from the operation of a single user was calculated based on the motion of the door and the energy dissipated by the generator. The power dissipated in the generator is assumed to be that available for energy generation and is determined as,

$$P(t) = \tau_G \cdot \dot{\theta}(t)$$

The energy dissipated during time  $\Delta t$  is then given by,

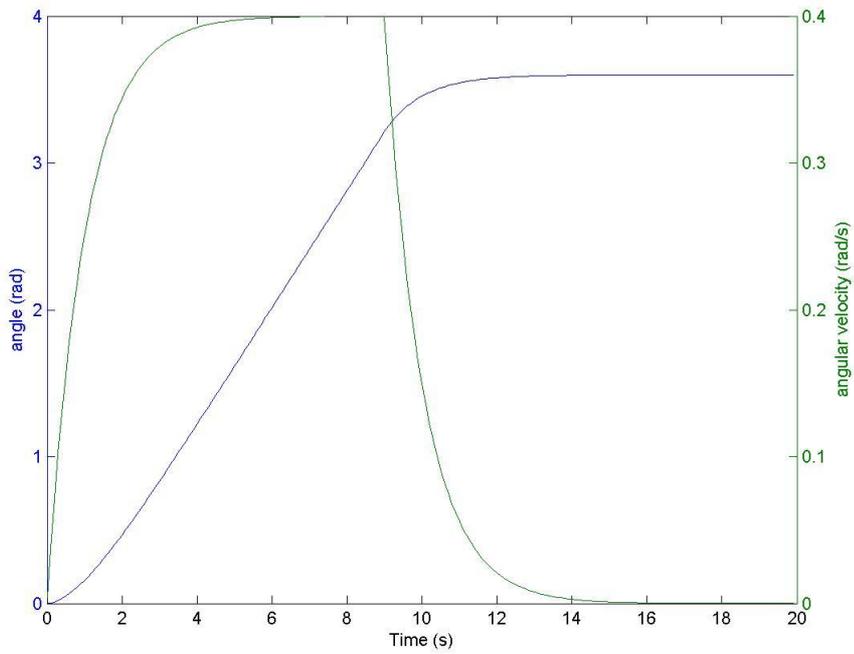
$$E_d(t) = P(t) \cdot \Delta t$$

So the total energy dissipated is given by,

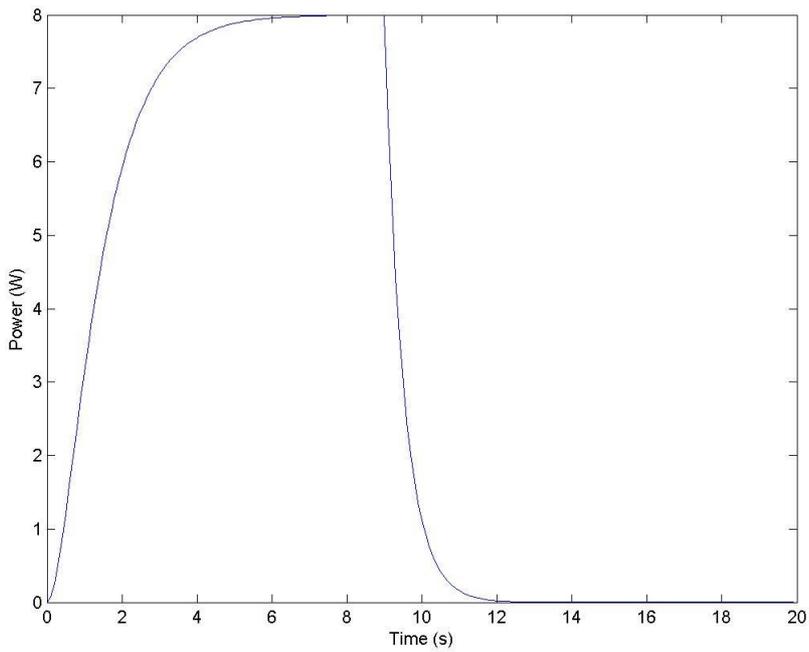
$$E_{D.O.E.} = \sum E_d(t)$$

#### Baseline case

An initial baseline example was considered where,  $m_L = 40kg$ ,  $F_o = 25N$ ,  $r_F = 0.8$  and  $d_c = 50$  N.m.s with the results shown in fig.s 3-21 and 3-22.



**Fig. 3-21: Graph showing the angle of rotation and angular velocity of the revolving door with baseline values as a single user passes through.**



**Fig. 3-22: Graph showing the power dissipated through the generator as a single user passes through the revolving door for the baseline values.**

It was found that the energy potential of a D.O.E.,  $EP_{D.O.E.} = 63.89 \text{ J}$  and  $t_{D.O.E.} = 8.9 \text{ s}$ . It should be noted that the value of  $t_{D.O.E.}$  was considered as the time taken for the door to rotate  $180^\circ$ , although the door continues to rotate after this point.

#### Affect of variables

As with the swing door a number of variables were varied in order to test their affect on the energy potential and value of  $t_{D.O.E.}$ . The variables to be varied are outlined in table 3-10. The values to be taken for the variables not being varied are shown in table 3-11.

**Table 3-10: Parameters to be varied for the modelling of the revolving door.**

|               |    |    |    |     |
|---------------|----|----|----|-----|
| $m_L$ (kg)    | 20 | 30 | 40 | 50  |
| $F_O$ (N)     | 20 | 25 | 30 | -   |
| $d_c$ (N.m.s) | 25 | 50 | 75 | 100 |

**Table 3-11: Values to be held constant for the modelling of the revolving door.**

|            |           |               |
|------------|-----------|---------------|
| $m_L$ (kg) | $F_O$ (N) | $d_c$ (N.m.s) |
| 40         | 25        | 50            |

#### Variation to leaf mass

**Table 3-12: Modelling results for variations to the leaf mass of the revolving door.**

|                          |       |       |       |       |
|--------------------------|-------|-------|-------|-------|
| $m_L$ (kg)               | 20    | 30    | 40    | 50    |
| $EP_{D.O.E.}$ (J)        | 63.37 | 63.62 | 63.89 | 63.36 |
| Final angle ( $^\circ$ ) | 192.5 | 199.4 | 206.3 | 210.8 |
| $t_{D.O.E.}$ (s)         | 8.4   | 8.7   | 9     | 9.2   |
| $P_{ave}$ (W)            | 7.54  | 7.31  | 7.10  | 6.89  |

The first point to note from table 3-12 is that the energy potential offered from a user passing through a revolving door is not significantly affected by the mass of the door leafs. It is however seen that the value of  $t_{D.O.E.}$  increases with door mass. As a result the average power

dissipated through the generator as a user passes through decreases from 7.54 W for a 20kg door leaf mass to 6.89 W for a 50kg door leaf mass. In addition the final angle at which the door comes to rest increases, as a result of the increase of the inertia of the door.

Variation to opening force

**Table 3-13: Modelling results for variations to the opening force acting on the revolving door.**

|                   |       |       |       |
|-------------------|-------|-------|-------|
| $F_o$ (N)         | 20    | 25    | 30    |
| $EP_{D.O.E.}$ (J) | 50.62 | 63.89 | 77.03 |
| Final angle (°)   | 200.0 | 206.3 | 212.0 |
| $t_{D.O.E.}$ (s)  | 10.9  | 9     | 7.7   |
| $P_{ave}$ (W)     | 4.64  | 7.10  | 10.00 |

It is clear from table 3-13 that the energy potential increases significantly as the applied opening force increases. In addition the value of  $t_{D.O.E.}$  decreases significantly as the opening force increases. As a result the average power increases from 4.64 W to 10.00 W for a 20N and 30N opening force respectively. In addition the final angle of the door increases with increasing  $F_o$  as the angular velocity of the door is greater at the point where the force stops being applied.

Variation to damping effect of generator

**Table 3-14: Modelling results for variations to the damping coefficient of the revolving door.**

|                   |       |       |       |       |
|-------------------|-------|-------|-------|-------|
| $d_c$ (N.m.s)     | 25    | 50    | 75    | 100   |
| $EP_{D.O.E.}$ (J) | 64.55 | 63.89 | 63.16 | 63.29 |
| Final angle (°)   | 275.0 | 206.3 | 190.8 | 186.8 |
| $t_{D.O.E.}$ (s)  | 6.0   | 9     | 12.5  | 16.3  |
| $P_{ave}$ (W)     | 10.76 | 7.10  | 5.05  | 3.88  |

It is apparent from table 3-14 that the energy potential from a user is not significantly affected by the value of  $d_c$ . It is however apparent that the value of  $t_{D.O.E.}$  increases significantly. As a result the average power dissipated through the generator decreases from 10.76W for  $d_c = 25$ , to 3.88W for  $d_c = 100$ . The final resting angle of the door decreases as the value of  $d_c$  increases. This is a result of the generator applying less torque in damping the motion of the door.

### 3.6. Summary

In this chapter the source of the energy from which energy can be harvested was considered. It was seen that this is a complicated process and one that is intrinsically linked to the fundamental needs of an individual. As such many of what were considered to be losses in this process are indeed fundamental requirements of the human body. The total metabolic energy input was found to be  $\sim 10$  MJ/day for the average person in the UK, although this varies significantly between individuals.

It was found the human body is efficient in converting the gross energy contained within food into metabolic energy which can be used to provide for the functions of the human body. The human body uses this energy on three main components, namely the basal metabolic rate (BMR), thermogenic response to food (TEF) and on carrying out physical activity. The BMR accounts for the majority of energy usage in most people and was assumed to account for roughly 65% of total energy expenditure, although this can vary significantly. The BMR is constant for an individual, although the rate of energy expenditure varies between individuals based on age, gender and weight. The proportion of energy used to carry out physical activity was assumed to be 25% of metabolic energy expenditure of an individual (2.45 MJ/day), but this varies greatly depending on the lifestyle of the individual. As such the metabolic energy expenditure and proportion used in developing mechanical work varies greatly between individuals.

It was identified that mechanical work is the most appropriate source of energy for energy harvesting, and as such the process of developing mechanical work is an important step in assessing the available potential. A maximum net efficiency of  $\sim 40\%$  was found for developing mechanical work in single human muscles and would amount to 0.98 MJ/day of mechanical

work being carried out by the average person in the UK. This was considered an upper limit for the mechanical work available for harvesting due to both changes in efficiency of different activities and the need to use mechanical work to carry out other activities necessary in everyday life. An example of this was seen when harvesting from walking was considered, much of the work is used to complete the action of walking with  $\sim 5.6\%$  of the net energy expenditure available for harvesting. This amounts to an average power of 11.7 W and a daily energy potential of 20 Wh for a 60 kg individual. In contrast 25% of the net energy expenditure was found to be available for harvesting for ergometer cycling, with the increase being due to ergometer cycling being a recreational form of energy harvesting as opposed to parasitic in the case of walking.

It was assumed in the case of walking that for energy to be harvested requires additional energy to be expended to complete the action of walking. It was found that to provide for the 7.2 J of additional energy required for each step, an additional 20.6 J of metabolic energy would be required. It was recognised that the relationship between energy harvesting and additional energy expenditure is not well understood and needs clarification.

It was found that the flow of energy involved with human energy harvesting is complicated due to the needs of the human body and the variations between individuals. The approach taken was to consider the process from the perspective of an average person throughout the process. Regardless it was found that significant energy potential exists from which mechanical work can be harvested for electrical energy generation.

The energy potential available for harvesting from a single action use of a door was considered for swing and revolving doors. For swing doors, three methods of generation were considered, whereas it considered that the doors motion would directly drive a generator for the revolving door. It was found that the revolving door offers significantly more energy harvesting potential than the swing door.

In the case of the swing door, it was found that method 3 offered the highest energy potential in all cases, where a maximum energy harvesting potential of 28.4 J/D.O.E. was found. In addition it was found that increasing the door leaf mass or the torsional spring constant

resulted in a decrease to the available energy potential. Increasing the opening force applied to the door resulted in an increase to the available energy potential, as may be expected.

It was found that a revolving door offers significantly more energy potential than a swing door, where a maximum energy potential of 77 J was found, although this was a result of an increase to the opening force applied. Varying the mass of the door and the damping coefficient was found to have very little impact upon the energy harvesting potential, however they did have a significant effect on the value of  $t_{D.O.E.}$ . As a result the average power available was found to vary considerably with values in excess of 10 W found.

Within this chapter the process of developing harvestable mechanical work was addressed both in terms of the efficiency of the process and the potential available for energy harvesting. This is however only the first step in generating electrical energy, where the conversion of the available harvestable mechanical energy into electrical energy needs to be considered before the potential for electrical energy generation can be determined and is the focus of Chapter 4.

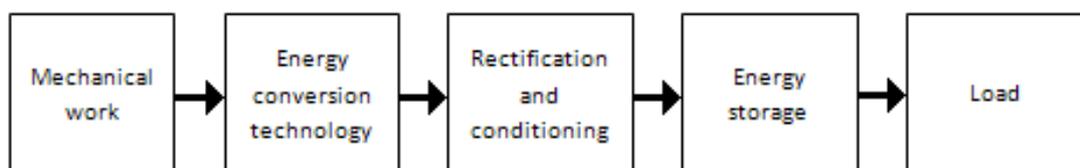


## 4. Energy Conversion

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The previous chapter considered the flow of energy in the human body as the energy source for human energy harvesting and the energy potential offered through a single step or door opening event for a swing and a revolving door. Although it was seen that the overall harvesting potential energy efficiency of the system was low, it was still found that considerable potential exists. This, however, is only part of the story, as this potential must still be converted from mechanical work into useful electrical energy with a schematic of the expected steps shown in fig. 4-1. This is considered in this chapter, through each of the steps required to achieve the conversion. Firstly the mechanical work was converted into electrical energy, this was then rectified and conditioned and then potentially stored before it could be usefully applied to the required load.

It was highlighted in 3.3. that there are three main groups of energy harvesters when considering human energy harvesting. Much of the research encountered was focussed on personal energy generators, with the aim of providing energy for use by the individual upon whom the device was attached. Within this report, the main focus was on devices that are part of the urban environment. In terms of fixture devices, there were three main sources that were thought to offer some potential, these being floor generating devices and swing and revolving door integrated devices. Furniture devices such as gym equipment can also be used in the urban environment and indeed offer significantly more potential than from, for example, walking, as was outlined in the previous chapter. It was evident that although this form of generation would normally be a niche application, it may however offer significant potential in the locations to which it is available.



**Fig. 4-1: Schematic of the steps required in converting mechanical work into electrical energy.**

## **4.1. Energy conversion technologies**

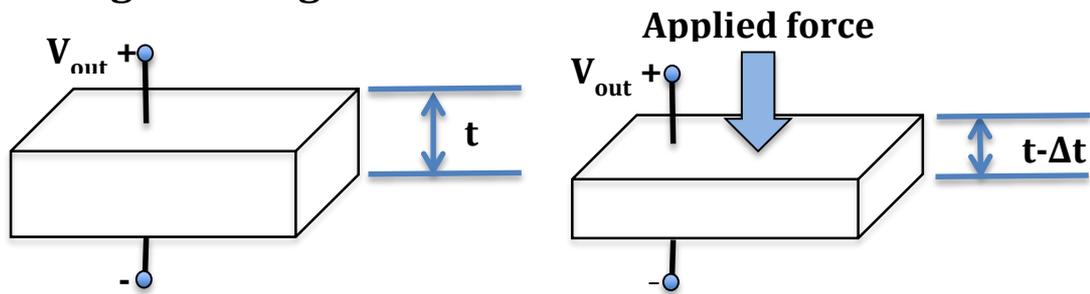
A number of technologies were considered to harvest energy from human work. The main types that were thought to be applicable were piezoelectric, electromagnetic and dielectric elastomer generators. A brief overview of the technologies along with their application and relevant literature, particularly for human energy harvesting, is presented as follows.

### **4.1.1. Piezoelectric**

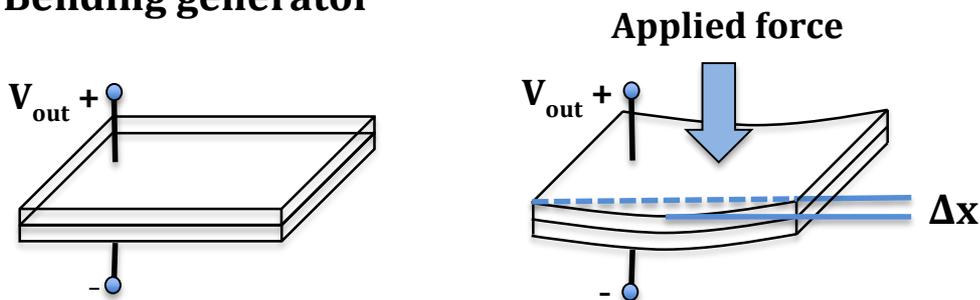
The theory of piezoelectricity was comprehensively covered in much of the literature, with piezoelectric materials exhibiting a property that allows the conversion of mechanical into electrical energy. For the purpose of energy generation, a mechanical strain applied to the material results in the production of an electric charge (Starner & Paradiso 2004). In the actuator mode the converse is true, where the presence of an electric field will result in mechanical strain. A detailed description will not be presented here, but can be found in the IEEE Standard on Piezoelectricity (Meitzler et al. 1988). Although much of the literature was concerned with piezoelectric materials as energy generators, much of it was in respect to high frequency inputs. In the case of the human gait, the input frequency would be in the region of 2Hz and it is likely that for a single device the input force would be an individual event. A brief description of the piezoelectric effect will be presented, specifically for low frequency inputs and footfall harvesting devices. The literature regarding generation from human gait was focussed mainly on Lead Zirconate Titanate (PZT) and Polyvinylidene fluoride/difluoride (PVDF) generators, although more suitable properties may be exhibited by different piezoelectric materials.

The mode of operation is defined by two numbers and was represented as subscript numbers for the values of the coupling constant,  $k$ . The first number refers to the axis on which electrical charge was produced and the second refers to the strain axis. Thus mode 31 in generation mode refers to a strain applied to axis 1 and an electric charge produced on axis 3, whereas 33 refers to an applied strain on axis 3 and an electric charge produced along axis 3.

## Longitudinal generator



## Bending generator



**Fig. 4-2:** Diagram representing the operation of a piezoelectric ceramic such as Lead Zirconate Titanate (PZT) as a generator. Two modes of operation are shown, these being i) Longitudinal generator and ii) Bending generator. In both cases a force applied to the material results in a mechanical strain being applied on the material. As a result, a voltage is produced in an attempt to return the material to its original position.

First the operation of piezoelectric ceramics was explored. In the work of (Goldfarb & Jones 1999) a model was developed and experimentally tested, using a commercially available PZT stack, to determine the efficiency of PZT ceramics in generating electrical energy. It was found that higher efficiencies occurred at relatively low frequencies, in the region of 5 Hz, despite this being several orders of magnitude below the structural resonance of the stack. In addition it was observed that the amplitude of the input force significantly affects the efficiency, where larger inputs result in higher efficiencies. It was seen that for a 50 N force an efficiency of ~10% was observed, whereas for an 800 N force the efficiency of electrical energy generation approached 40% (Goldfarb & Jones 1999). Given that the force applied during footfall of a 60 kg person is roughly 720 N and the frequency will be ~2 Hz, this indicates that the efficiency of energy generation using PZT ceramic stacks could be reasonably high. It should however be noted that the displacements observed were of the order of microns (Goldfarb & Jones 1999). Similarly Platt et al. (2005) carried out work to determine the characteristics of electrical

energy generation for low frequency inputs (<20 Hz) and high force (~1 kN) for PZT ceramics in the  $d_{33}$  mode. For a frequency of 1 Hz the peak efficiency approached 20%. It should however be noted that raw power outputs of only 4 mW were recorded (Platt et al. 2005), due to the small displacement.

In the work of (Richards et al. 2004) it was proposed that the efficiency of converting mechanical to electrical energy can be determined by two factors. Firstly the electromechanical coupling factor,  $k^2$ , and secondly the quality factor,  $Q$ . It was proposed that when applied to the work presented in (Goldfarb & Jones 1999) the mechanical to electrical efficiency would be in the region of 53%. The literature presented was concerned with generation through utilising the  $d_{33}$  mode of operation. It was clear that for the forces involved with human gait the output power would be on the order of mW. It was stated that this was due to the high elastic modulus of PZT, meaning that very high forces are required to compress the material (Starner & Paradiso 2004). As such only low levels of energy generation were recorded, despite the high efficiency. It may be possible to increase the displacement through utilising the  $d_{31}$  mode of operation. It was shown in (Starner & Paradiso 2004) that a beam of PZT 20 cm in length will tolerate a 1 cm deflection. It seems likely, however that this will result in a loss of efficiency due to the decrease in electromagnetic coupling factor from  $k_{33} = 0.69$  to  $k_{31} = 0.35$  (Starner & Paradiso 2004).

It was highlighted that it may be possible to improve the electromechanical conversion efficiency by using different materials. (Funasaka et al. 1998) compared  $\text{LiNbO}_3$  with PZT under the impact of a hammer, where it was found that the efficiency of the generator for these materials was 78% and 65% respectively. The test was carried out at a much higher frequency than is present in walking and thus may not be strictly relevant for human walking. However, it does show that alternative materials may offer better characteristics.

A number of PZT generation devices were designed to act as shoe inserts. (Antaki et al. 1995) used a PZT stack integrated to a hydraulic system. It was calculated that for PZT ceramics the efficiency of electrical energy conversion in the  $d_{31}$  and  $d_{33}$  modes could be 25-29% and 47-56% respectively. A 1/17<sup>th</sup> size prototype was developed and inserted into a shoe. Experimental data suggests that  $5.7 \pm 2.2$  mW/kg of body weight could be generated. It was claimed that for a 75 kg person and full size devices this will amount to 6.2 W. Considerable

work was carried out at MIT, using a PZT bimorph, consisting of two THUNDER™ PZT unimorphs. 14.4 mW average power output was achieved with an electromechanical efficiency of the transducer of 20.1% (Shenck 1999). (Howells 2009) developed a shoe insert PZT generator, where 0.09 W average power output was recorded. This was well below the target of 0.5 W, however this could be partially explained by difficulties with integration into the shoe. While integration of the above devices into a shoe proved to be problematic, it was expected that for a floor integrated device this would not be as much of a problem. An alternative solution for a floor generating device was presented in the work of (Takefuji 2008) where a floor mat was developed with the aim of generating 1 mJ/step. It was not clear what material was used for energy generation but in earlier tests the piezoelectric material was taken from a speaker and hence it was expected that they were ceramics. The technology was commercially developed by Soundpower, and is discussed in section 4.5..

Another piezoelectric material that shows some promise was PVDF which is a piezoelectric polymer material. This offers several advantages over PZT when referring to human energy harvesting, these being much greater flexibility than PZT as well as being a tougher and lighter material (Antaki et al. 1995). This, however comes as a trade-off, due to a decreased value in the electromechanical coupling factor,  $k = 0.11$ . It was shown in the work of (Mateu & Moll 2005) that unlike with PZT, where the d33 mode is the most appropriate for energy harvesting, a higher energy output will be obtained when operated in the d31 mode. (Antaki et al. 1995) predicted that the conversion efficiency for PVDF would be 1-2% and 2.5-5% for the d31 and d33 modes respectively. A PVDF generator was utilised in the work of (Kymissis et al. 1998), where an electromechanical conversion efficiency of 1% was recorded. It was thought by utilising the d31 mode of operation, efficiencies may approach 25%, however it was thought that this would require a complicated mechanical mount (Kymissis et al. 1998). It was expected that with a floor integrated device, this would not be as significant a problem and hence better conversion efficiencies could be expected.

(Fourie 2009) developed a shoe insert utilising a PVDF stave and average power outputs of 0.06 mW were recorded with a conversion efficiency of 1-2%. A PVDF foil was used to act as the shock absorber insert in a shoe, where a power output of the order of 100s of mW was recorded. The design configuration allowed for the utilisation of both the d31 and d33 modes of operation allowing for greater conversion efficiency, although this was not increased when

compared to other literature values. It was also noted that by using two PVDF layers, the output voltage was doubled. Therefore, increasing the number of layers can result in significant increases to the power generated (Rocha & Goncalves 2010), although it was not clear whether this relationship remains linear for further increases to the number of layers.

#### 4.1.2. Electromagnetic generation

If a rotary machine were to be used it is likely that a gearing system would be required to drive the generator at reasonable RPMs that most generators need. For a floor system the vertical motion of the floor would require a rack and pinion system to convert this into rotational motion. The efficiency of gearing systems can be very high, with values of 98-99 % (Ewart 1997). If a system of 4 gears were considered then a gearing efficiency of ~94% is assumed to be achievable. This value is used going forward, although it was evident that a poorly designed system will result in significantly lower efficiencies.

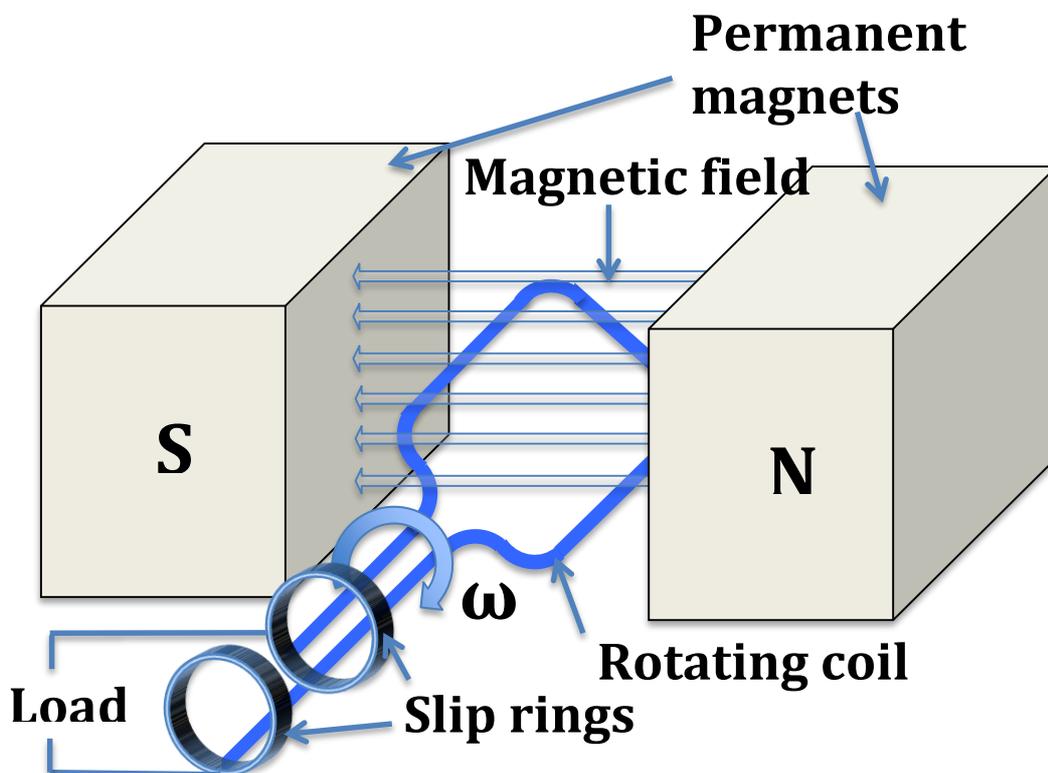


Fig. 4-3: Diagram showing the operation of a basic rotating electromagnetic generator.

Electromagnetic generators are a technology that is both proven and offers the possibility of high conversion efficiencies (Kymissis et al. 1998). A rotary generator was designed as a means

of a shoe integrated generator. An average power output of 0.25 W was recorded, far exceeding the power outputs recorded for the piezoelectric devices presented (Kymissis et al. 1998). It was thought, however that the 3cm displacement would significantly compromise the users actions. The use of electromechanical devices in heel-strike generators is hindered by difficulties in integrating such a device into a shoe heel (Kymissis et al. 1998). For floor integrated devices it was thought that this will be less of a concern certainly in terms of device weight, although practicably the size (or depth) of the device would still be of concern. A review of microscale magnetic power generation was presented in (Arnold 2007), where it was reported that efficiencies in the region of 10-70% are achievable in the range of mWs to tens of watts. It is worth noting that, particularly with smaller scale devices, the efficiency may not be the critical factor to consider in the design process. As such efficiency value are often not reported in the literature (Arnold 2007). In the work of (Li et al. 2009) a knee mounted biomechanical energy harvester was developed using a brushless DC generator. Although the application was not deemed relevant to fixture devices, the sizing and performance of the system is relevant. For the generator chosen the efficiency of electrical generation was the product of the transmission and generator efficiencies. A generation efficiency of 64.7% was measured (70% was predicted), although size restrictions to the gearing system appear to have inhibited the generation efficiency. In fixture devices this is not likely to be a concern, hence higher conversion efficiency values may be achieved. In addition a DC generator was used as the means of generation in a backpack energy harvester. A rack and pinion system with a gearing ratio of 25:1 was used to convert the linear motion of the load into rotational motion for the generator. The efficiency of conversion was however low, with values in the range 30-40% (Rome et al. 2005). As such it was assumed that the efficiency of electromagnetic generators was in the range of 30-70 %.

As a result of electromechanical generator technology maturity and high efficiency it came as no surprise that a floor integrated device was developed in the work of (Paulides et al. 2009). The design of the floor generating tile was presented with the aim of generating energy from people on a dance floor. The system utilises motion of the floor panel to drive a brushed DC generator, via a gearing system. In addition to the energy generating dance floor a sustainable floor panel was also created, it was claimed that this will generate between 2-10 J of energy per step (SDC 2013).

### 4.1.3. Dielectric elastomer

Dielectric elastomers (also referred to as electroactive polymers (EAPs)) are a form of electrostatic generator. They can act in both actuator and generator modes to convert mechanical energy to and from electrical energy. The operation in the generator mode is as follows. A dielectric film, such as silicone rubber, is placed between two electrodes. An electric charge is applied to the film when in the stretched state, when the film contracts the electrical energy increases and raises the voltage of the charge, allowing energy to be removed. This results from the decrease in thickness of the film and hence the distance between the electrodes (Pelrine & Kornbluh 2001). An advantage of dielectric elastomers is they can withstand large strain, much more than piezoelectric materials including PVDF (Kornbluh & Pelrine 2002). It is expected that this will make them suitable for the large displacement required for application to human walking.

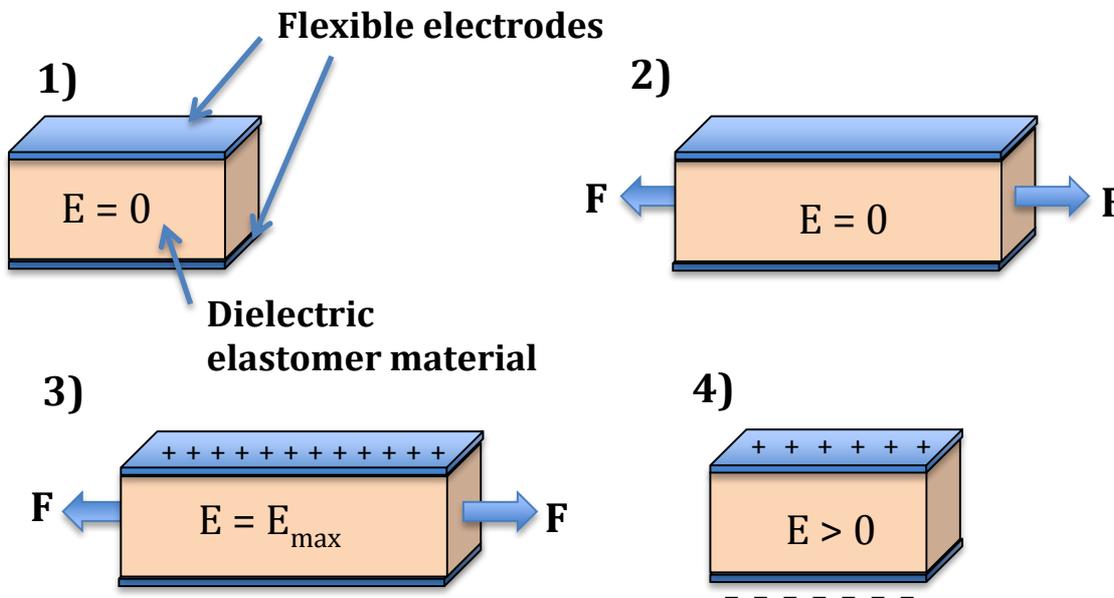


Fig. 4-4: 1) Initially there is no charge and no force applied to the dielectric elastomer. 2) A force is applied to the elastomer, causing it to stretch and resulting in a decrease in the thickness of the material. This reduces the distance between the electrodes and hence increases the capacitance whilst storing spring energy in the material. 3) An electric charge is applied to the electrodes in the fully stretched position resulting in the development of an electric field. 4) The force applied to the material is removed, allowing the elastomer to return to its initial unstretched state. In doing so the capacitance drops and energy stored as mechanical strain in the elastomer is converted into electric field energy. This energy can then be harvested as the dielectric elastomer discharges.

The use of dielectric elastomers as generators was not covered extensively within the literature. In the generating state, dielectric elastomers act as variable capacitors, with the theory of energy generation presented in (Pelrine & Kornbluh 2001). High energy densities were seen, with 1.5 J/g predicted (Pelrine & Kornbluh 2001) and 0.4 J/g demonstrated (Pelrine 2002). In addition it was also predicted that theoretical energy efficiencies could reach 80-90%, although practical limitations would be expected to reduce this. It was claimed in (Kornbluh et al. 2011) that a heel-strike generator integrated into a boot was capable of generating 0.8 J/step, with a conversion efficiency of 33%.

#### 4.1.4. Summary

An overview of the expected mechanical to electrical conversion efficiencies were presented in table 4-1.

**Table 4-1: Theoretical and practical values of the efficiency of converting mechanical work into electrical energy for the generation technologies presented.**

| Technology           | Mechanical to electrical conversion efficiency (%) |                           |                        |                        |
|----------------------|--|---------------------------|------------------------|------------------------|
|                      | Theoretical  |                           | Achieved in literature |                        |
| PZT                  | 56   | (Antaki et al. 1995)      | 20                     | (Shenck 1999)          |
| PVDF                 | 25   | (Kymissis et al. 1998)    | 2                      | (Fourie 2009)          |
| Electromagnetic      | 70   | (Arnold 2007)             | 64.7                   | (Li et al. 2009)       |
| Dielectric elastomer | 80-90  | (Pelrine & Kornbluh 2001) | 33                     | (Kornbluh et al. 2011) |

It was claimed in (Shenck & Paradiso 2001) that rotary generators offer the potential for significantly higher energy outputs than from piezoelectric generation devices. Such systems, however, add significant complication to integration into a shoe. It was felt that for a floor mounted device these complications were not likely to be a major issue. The range of conversion efficiencies would suggest that electromagnetic devices will offer greater energy potential. Dielectric generators are predicted to offer the highest potential efficiencies, however practical devices fall well short of the theoretical predicted values. Even so dielectric elastomers appear to offer a number of advantages when compared to other generation technologies for human energy harvesting. The advantages include better load matching,

lower cost, lighter weight, higher energy density, higher efficiency and reduced the mechanical complexity, particularly when compared to electromechanical devices. In contrast the electronics required may prove to be a disadvantage (Pelrine & Kornbluh 2001).

## **4.2. Energy system**

Thus far the efficiency of converting mechanical work into electrical energy has been considered for various technologies. The next stage is to consider the rectification, conditioning and storage of this energy. It was necessary to consider the rectification and conditioning of the generated energy so that it can be used by the desired load or stored in a suitable energy storage medium. It was noted that energy storage would not be needed if the energy were to be used to directly power the load. However, it was thought that storage will generally be required.

### **4.2.1. Power rectification and conditioning**

The energy generated must first be rectified to DC, with the DC power being conditioned to meet the load or output requirements. This can be achieved in one step through AC-DC conversion with integrated voltage regulation or in two steps with AC-DC rectification followed by a separate DC-DC converter to control the output DC voltage (Szarka et al. 2012). The rectification and conditioning of energy was considered to be carried out using power electronic devices. Many topologies can be used to achieve this. It was noted that each technology has different requirements and should therefore be considered separately. Electromechanical devices can be rectified and conditioned with relative ease and high efficiency. Conversely piezoelectric and dielectric polymer generators exhibit poor generation characteristics, requiring more complicated approaches to convert the generated energy into useable energy (Pelrine & Kornbluh 2001).

#### **4.2.1.1. Piezoelectric**

It was documented in (Platt et al. 2005) that the rectification and conditioning of energy generated using a piezoelectric generator is not simple due to the high voltage - low current characteristics of piezoelectric generators. In addition, at low frequencies, such as those associated with human gait, the impedance is highly capacitive.

AC-DC conversion can be achieved using passive or active rectifiers. Passive rectifiers were the simplest such circuits, with full-bridge rectifiers being the most common type. These utilise four diodes arranged in a bridge formation with the main losses stemming from the forward voltage drop of the diodes and reverse leakage currents. It is possible to improve the efficiency of passive rectifiers by utilising MOSFETs, Schottky diodes or transistors instead of conventional diodes and although active rectifiers can reduce conduction losses they require additional energy consumption for the control circuitry. Efficiencies in the range of 80-90% are achievable even at low powers and are thus considered more efficient than passive designs (Szarka et al. 2012). (Lee & Han 2011) developed an energy conversion topology for a piezoelectric device using an active diode rectifier. Despite the low power levels ( $\mu\text{W}$  range), it was indicated that the AC-DC conversion efficiency reached 92.6%. Once the rectification is carried out the DC power must then be conditioned to produce the required voltage for either energy storage or supplying the load. DC-DC switch mode converters including buck, boost and buck-boost topologies can be employed. Efficiencies of 85% were reported for an integrated buck converter, designed to operate with a switched-inductor resonant rectifier. Switch-mode converters were able to reduce the switching losses, with the losses scaling with size. It was reported that theoretical efficiencies of 85-95% could be achieved in the microwatt range (Szarka et al. 2012). A Low-drop regulator was employed in the work of (Lee & Han 2011) to regulate the voltage output with an efficiency of 90%. The overall efficiency of the rectifier and voltage regulator was 83.3%.

Alternatively AC-DC conversion with voltage regulation can be carried out in one step using switched-capacitor converters. Passive designs are known as voltage multipliers (VM) and active ones as charge pumps. Passive VM devices can have efficiencies in the region of 40%, although values in the range of 65% have been recorded. Active devices were seen with efficiencies up to 94% (Szarka et al. 2012).

#### **4.2.1.2. Electromagnetic**

Rectification of electromagnetic devices was considered first due to the relative simplicity involved. For the device presented in (Paulides et al. 2009) a simple diode bridge was used to rectify the output energy. It was claimed before rectification the average peak outputs before and after rectification were 24.1 W and 22.4 W respectively. This indicates a rectification efficiency of 93% is achievable even with simple rectification. It was noted that the average

power output before rectification is not presented and so peak values were used. It was expected that operation at lower power levels will result in a decrease in rectification efficiency for the following reason. It was noted in (Szarka et al. 2012) that for passive rectification (eg. Diode bridge) the main losses stem from the forward voltage drop of the diodes and leakage current. It was expected that the losses associated with the forward voltage drop of the diode would have a greater effect for lower power levels. As was the case with piezoelectric generation, the rectification efficiency could be improved by using MOSFETs, Schottky diodes or transistors instead of diodes (Szarka et al. 2012). It was claimed in (Rome et al. 2005) that rectification was carried out with an efficiency of ~95%, although the method used was not detailed. A conversion efficiency of 95% was therefore assumed to be achievable in the power ranges experienced.

#### **4.2.1.3. Dielectric elastomer**

Dielectric elastomers require similar energy harvesting circuits to piezoelectric harvesting systems, however dielectric elastomers typically operate at higher voltages typically in the kV range (Kornbluh et al. 2011). As such it was expected that the rectification of energy can be completed with an efficiency of 93%. (Pelrine 2002) showed 70-80% efficiency in step down of high voltage. It was highlighted that the availability of low-power, high-voltage transistors was a problem, although this was due to a lack in current markets and not a fundamental problem associated with transistors.

#### **4.2.2. Energy storage**

Thus far the main sources and technologies for electrical energy generation have been considered, however this energy needs to be used with the likely need for some means of energy storage. What follows is a summary of various energy storage methods thought to be appropriate for human energy harvesting. It was assumed that once rectification and conditioning were completed the storage of energy can be carried out using any of the methods that follow.

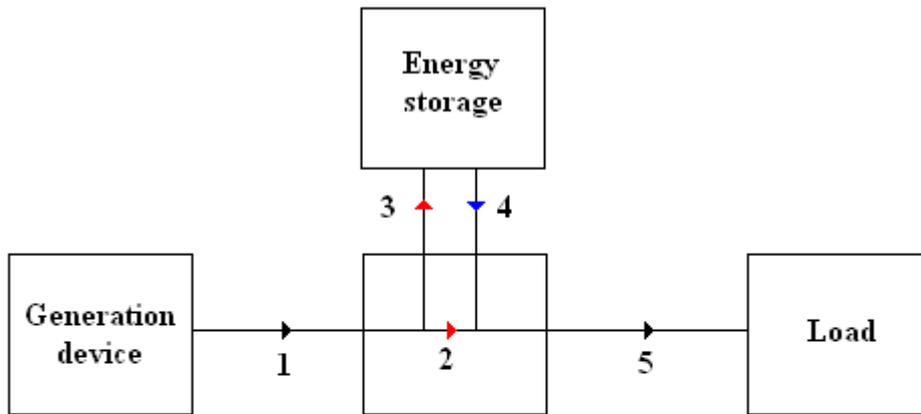
In terms of energy harvesting for stationary systems, it was deemed that the charge-discharge efficiency would be critical due to the relatively low expected energy outputs of the generation system. Hence only relatively high efficiency storage methods were considered, although this

was not the only factor to be considered. The cycle durability and capital costs of the system were considered to be somewhat interlinked and were an important consideration, especially when assessing the lifetime of the system. Arguably the specific energy and energy density should also be considered, however these were likely to be less important than for portable applications where size and mass are critical factors. It seems likely that for most applications the energy would not be required to be stored for long periods and hence the self discharge rate was only likely to be an important characteristic for technologies that have a very high rate of self discharge or if energy was required to be stored for long periods of time.

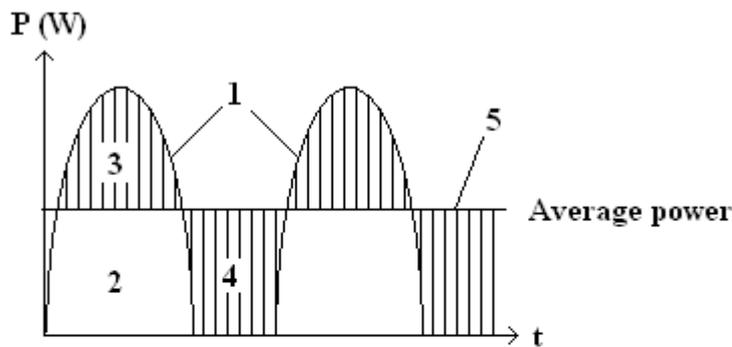
Although many forms of energy storage could be applicable to human energy harvesting, certain approaches can be ruled out solely on efficiency considerations. One such system would be a pneumatic system, where energy is stored as a compressed gas as was proposed by (Pandian 2004) to harvest energy from children's play. Although this offers a simple solution, the system efficiency is likely to be very low. In the case presented, the pneumatic to electrical conversion was 16.7 % and the overall system efficiency was 1.6% (Pandian 2004). Large MW scale systems can provide efficiencies in the range of 70-89 % (Chen et al. 2009), although it was expected that this would not be possible for human energy harvesting systems because the power output from an individual was of the order of Ws. Flywheels are a high efficiency method of energy storage, 90-95%, although they were ruled out for a number of reasons. Firstly the energy is produced electrically and hence a conversion via a motor would be required to produce the rotational kinetic energy required for storage, followed by a generator to produce the electricity when required. This adds a certain degree of complexity and inefficiency into the system. As a result the energy storage methods to be considered will consist of rechargeable chemical battery and capacitor technologies.

Given that the energy outputs from a harvesting device are expected to be small, the efficiency of the energy storage medium is of paramount importance and will now be discussed. The energy efficiency of a secondary battery was found to be a result of two factors, the coulombic efficiency and voltaic (voltage) efficiency. The coulombic efficiency takes account of the electric current wasted in non-productive side reactions with values commonly above 90% (Dell & Rand 2001). The voltage efficiency is given as the ratio between the discharge and charge voltages, with the average values over the period being considered used to determine this (Wenzl 2009). The voltage during charging always exceeds that during discharging and is a

result of the internal resistance of the battery and polarisation losses at the electrodes (Dell & Rand 2001). It should be noted that the higher the charge and discharge currents, the larger the voltage losses (Dell & Rand 2001). It is known that this depends on many factors such as the internal resistance, temperature, age of battery, charge characteristics and application (Wenzl 2009).



- ↑ Energy is provided to the load from the generation device, with the excess sent to the energy storage medium.
- ↓ Energy is provided to the load from the energy storage medium when there is no power from the generation device.



1. Generated energy
2. Energy flows directly to the load.
3. Surplus energy is sent to the energy storage medium.
4. Energy is provided to the load from the energy storage medium when there is a shortfall in generated energy.
5. Power provided to the load.

Fig. 4-5: Schematic showing the approach to smoothing the generated energy for use by the load through utilisation an energy storage system.

In addition the economics of different battery technologies is likely to be a critical factor in determining which technology is most appropriate. Although the capital cost of a system is the obvious way of measuring this, it was decided that for a stationary system intended as a permanent system a more useful metric would be the per cycle costs. The per cycle cost incorporates the efficiency and lifetime of the technology into the cost, making it a more appropriate measure for evaluating the lifetime costs of a technology (Chen et al. 2009).

An additional concern occurs in the instance where the generated energy is expected to be used immediately after generation occurred. It was expected that the energy generated would be distributed as peaks reflecting the distribution of actions on the energy generation devices. This presents a problem in that the energy delivered to the load must be conditioned to provide the required power output. It was expected that this could be achieved as set out in fig. 4-5. When energy was generated from a harvesting device it would provide the required power to the load, with any additional energy sent to the energy storage system. When no energy was available from the harvesting device energy was provided to the load via the energy storage system, hence maintaining the supply to the load.

#### **4.2.2.1. Chemical batteries**

Chemical batteries store energy via chemical reactions in the electrolytic solution, with the reaction depending on the chemistry of the battery technology (Dell & Rand 2001). Secondary or rechargeable batteries are a commonly used source of energy storage with a wide range of technologies available, the choice of battery being dependant on the use. Cells are the term used for individual units from which batteries are created, where tables 4-2 and 4-3 shows the characteristics of the cells for various technologies.

Batteries consist of a number of cells connected in either series or parallel to provide the storage capacity and voltage potential required by the load (Singamsetti & Tosunoglu 2012). Lead acid batteries are the oldest and most commonly used secondary (rechargeable) battery technology (Chen et al. 2009). Their popularity is due to low cost, easy manufacturability, large available capacity and good high rate performance. However the relatively low specific energy and energy densities, combined with the limited number of charge-discharge cycles, make them unsuitable for certain applications (Singamsetti & Tosunoglu 2012). By contrast

lithium ion batteries make up more than 50% of the portable market primarily due to their high energy and power densities, even though their relatively high cost is a drawback (Chen et al. 2009). As such it was clear that the requirements of the application will determine which technology is most appropriate.

**Table 4-2: The properties of the chemical battery storage technologies considered.**

| Technology     | Specific energy<br>(Wh/kg) | Specific power<br>(W/kg) | Self-discharge<br>(%/month) | Cycle durability     |                     | Per cycle cost<br>(£/kWh-per cycle) <sup>+</sup> |
|----------------|----------------------------|--------------------------|-----------------------------|----------------------|---------------------|--|
|                |                            |                          |                             | (cycles @100 d.o.d.) | (cycles @10 d.o.d.) |  |
| Lead acid      | 30-40                      | 180                      | 3-20                        | 300-1500*            | 1000-3000*          | 0.12-0.61**                                      |
| Nickel cadmium | 40-60                      | 150                      | 10                          | 1500*                | 2000*               | 0.12-0.61**                                      |
| Lithium ion    | 100-250                    | 250-350                  | 8                           | 1000-2000*           | 5000-8000*          | 0.09-0.61**                                      |

(Singamsetti & Tosunoglu 2012), \*(Perrin & Lemaire-Potteau 2009), \*\*(Chen et al. 2009), <sup>+</sup> converted on 07/01/14 using (<http://themoneyconverter.com/>)

**Table 4-3: Energy efficiency of each of the battery chemistries presented.**

|                | Energy efficiency (%) | Reference                       |
|----------------|-----------------------|---------------------------------|
| Lead acid      | 50-92                 | (Singamsetti & Tosunoglu 2012)  |
|                | 70-90                 | (Chen et al. 2009)              |
|                | 85-93                 | (Perrin & Lemaire-Potteau 2009) |
| Nickel cadmium | 70-90                 | (Singamsetti & Tosunoglu 2012)  |
|                | 60-70                 | (Chen et al. 2009)              |
|                | 75-86                 | (Perrin & Lemaire-Potteau 2009) |
| Lithium ion    | 80-90                 | (Singamsetti & Tosunoglu 2012)  |
|                | ~100                  | (Chen et al. 2009)              |
|                | 80-98                 | (Perrin & Lemaire-Potteau 2009) |

It appears that lithium ion batteries provide the highest values for energy efficiency, where it was claimed that efficiencies of ~100% are achievable (Chen et al. 2009) and they are not expected to be below 80%, as well as high energy and power densities. The cycle durability appears favourable when compared to other chemical battery chemistries, although this is dependent on the extent to which the battery is discharged. Discharging to 10% D.O.D was expected to result in cycle durability of 5-8,000 cycles, although it was claimed in (Chen et al. 2009) that a cycle durability of 10,000 cycles could be achieved, with expected lifetimes of 5-15 years. The main drawback appears to be relatively high cost, although capacity loss and safety concerns when over-charged are still of concern. Despite the high initial cost, the durability and energy efficiency of Li-ion batteries gives a per cycle cost of 0.09-0.61 £/kWh-per cycle (Chen et al. 2009).

The performance characteristics of lead acid batteries are unfavourable when compared to lithium ion batteries, although high efficiencies (~90%) were found to be achievable. Cycle durability was expected to be a problem as the lifetime was not expected to exceed 3,000 cycles, although it was claimed that lifetimes of 5-15 years are expected (Chen et al. 2009). The low cost does make them a good candidate when considering the economics of energy harvesting, although the low cycle durability was expected to result in the need for more regular replacement (Singamsetti & Tosunoglu 2012). As a result the per cycle cost was expected to be in the region of 0.12-0.61 £/kWh-per cycle for lead acid (Chen et al. 2009).

It was claimed that Nickel cadmium batteries were also capable of high charge-discharge efficiencies, table 4-3 suggests that the energy efficiency would be in the range of 60-90%. The durability of Ni-Cd batteries was comparable to lead-acid batteries with 2,000 cycles expected, however it was claimed in (Chen et al. 2009) that they have a lifetime of 10-20 years. They were however expensive and contain cadmium, which is a toxic heavy metal, making disposal difficult (Chen et al. 2009). The per cycle costs are comparable with lead acid batteries, with a range of 0.12-0.61 £/kWh-per cycle (Chen et al. 2009).

Depending on the application the storage duration could be important, where each of the technologies presented was considered suitable for storing energy for minutes to days due to the relatively low self-discharge rates.

#### 4.2.2.2. Capacitors

Capacitors were found to be a simple form of energy storage and store charge on two electric plates separated by a dielectric material, or in the case of supercapacitors, an electrolyte solution (Chen et al. 2009). It was noted that supercapacitors do not require a chemical reaction to take place and are very different from chemical batteries. As a result much faster charging and discharging can be achieved (Mallika & Kumar 2011). It should be noted that supercapacitors were sometimes referred to as ultracapacitors (Sharma & Bhatti 2010).

**Table 4-4: Performance characteristics of capacitors and super-capacitors.**

|                 |         |           | Self discharge | Energy Efficiency | Cycle durability | Cost      | Per cycle cost    |
|-----------------|---------|-----------|----------------|-------------------|------------------|-----------|-------------------|
|                 | (Wh/kg) | (W/kg)    | (%/day)        | (%)               | (Cycles)         | (£/kWh)   | (£/kWh-per cycle) |
| Capacitor       | 0.05-5  | 100,000   | 40             | 60-90             | 50,000+          | 300-2,000 | -                 |
| Super-capacitor | 2.5-15  | 500-5,000 | 20-40          | 90+               | 100,000-         | 500-1,000 | 0.01-0.12         |
|                 |         |           |                | 84-99*            | 500,000*         |           |                   |

(Chen et al. 2009), \*(Perrin & Lemaire-Potteau 2009)

They both exhibit high coulombic efficiencies, with supercapacitors capable of 99% (Mallika & Kumar 2011). The energy efficiency of super-capacitors was found to be dependant on the same parameters as for electrochemical batteries presented in the previous section (Wenzl 2009). The energy efficiency depends on the charge and discharge rate and was a measure of the ratio of the energy required from the charging source to that being delivered to the load. The energy efficiency of capacitors extends up to 90%, whereas supercapacitors fall within the range of 84-99%. As such it appeared that supercapacitors are comparable with lithium-ion batteries in terms of the energy efficiency.

They were shown to possess very good cycle durability, with >100,000 cycles seen for super-capacitors with expected lifetimes of ~5 years for capacitors and 20+ years for super-capacitors. The cost per unit of energy storage was comparable to battery systems and due to the increased cycle durability the per cycle cost characteristics were found to be significantly improved, 0.01-0.12 £/kWh-per cycle (Chen et al. 2009).

It was shown that ultracapacitors were suitable for very high charging current profiles, whereas batteries require limits to charging current to avoid damage to the battery (Mallika & Kumar 2011). Capacitors and super-capacitors were considered to be ideally suited to providing short bursts of high power, with discharge times in the order of ms to 60 minutes (Chen et al. 2009). Capacitors offer very high power densities, supercapacitors were not considered to be capable of such high power densities although they still exceed those of secondary batteries.

There were two major drawbacks to consider, these being the energy storage density and the self-discharge rate. The main drawback was the energy storage density, which was very low (Sharma & Bhatti 2010) meaning that the system was likely to be large and heavy. Although this was not expected to be a critical feature it may become important if space were at a premium. In addition the self discharge rates were found to be very large, in the range of 20-40% per day, as such they were only considered suitable for storage durations of seconds to hours (Chen et al. 2009).

#### **4.2.2.3. Summary**

In terms of energy storage the technologies considered were chemical battery and capacitor technologies. A number of parameters were deemed to be important when considering which technology was most appropriate. These were the energy efficiency, cycle durability, cost and, to a lesser extent, the energy storage density and self-discharge.

In terms of energy efficiency, it was possible to achieve high energy efficiencies in particular lithium-ion and super-capacitors, where energy efficiencies of 98% and 99% respectively are achievable. The values of energy efficiency to be taken forward were listed in table 4-5. The cycle durability of chemical batteries was expected to be in the order of thousands of cycles, whereas super-capacitors were expected to greatly exceed that with values in the hundreds of thousands of cycles. As was stated the costs of each technology were presented in terms of the per cycle costs as this measure includes the energy efficiency and durability of the technologies. Each of the battery technologies performed at similar levels, with super-capacitors offering the cheapest lifetime solution. This was considered further in chapter 6.

The energy storage density of chemical batteries greatly exceeds those recorded for capacitor technologies. As was previously mentioned this was only likely to be critical if space were at a premium. Finally the self-discharge rate was a measure of the energy lost when stored for extended periods of time. It was considered likely that the energy would be used relatively shortly after generation and hence the self-discharge would not be of critical importance. Even so, the self-discharge of batteries was significantly lower than for super-capacitor technologies.

In summary it would appear that super-capacitors were likely to offer the most appropriate characteristics unless system size was important or there was requirement for the energy to be stored for extended periods of time.

**Table 4-5: Table listing the range of energy efficiency values to be assumed for each energy storage technology.**

| Technology        | Lead-acid | Ni-Cd  | Li-ion | Super-capacitor |
|-------------------|-----------|--------|--------|-----------------|
| Energy efficiency | 50-93%    | 60-90% | 80-98% | 84-99%          |

### 4.3. System efficiency

When considering the energy system, it was useful to determine the efficiency with which mechanical work could be converted into useful electrical energy. This comprised of three main components, 1) The energy harvester, 2) Power rectification and conditioning and 3) Energy storage. Each of these stages was addressed in this chapter, with the performance of the overall system as a means of energy harvesting considered here. The combination of stages 1 and 2 were considered as the harvesting system. The efficiency of the first stage was considered in section 4.1., with the inclusion of stages 2 and 3 in section 4.2.. The expectation is that each of the energy storage technologies would be compatible with all of the generation technologies.

### 4.3.1. Energy generation and rectification

In total four technologies for energy harvesting were presented, with large variations in the generation efficiencies. The highest efficiency range was for a dielectric elastomer (DE) generator where 90% was considered to be theoretically achievable, although 33% was the highest demonstrated value when applied to human walking. Electromagnetic (EM) generators were found to be a more mature technology, although for such small generators it was expected that the efficiency would be limited to 70%. The piezoelectric ceramic investigated was PZT, which was found to be capable of theoretical conversion efficiencies of up to 56%, however the physical characteristics may limit the achievable energy output. PVDF was a more flexible material, thus matching the mechanical energy input from walking better than PZT. This however came with an efficiency penalty, where a range of 2-25% was expected.

**Table 4-6: Efficiency of each stage in converting mechanical work into useful electrical energy for each of the generation technologies.**

| Technology      | Gearing efficiency (%) | Mechanical-electrical conversion (%) | Rectification (%) | Conditioning (%) | Overall (%) |
|-----------------|------------------------|--------------------------------------|-------------------|------------------|-------------|
| PZT             | -                      | 20-56                                | 93                | 90               | 17-47       |
| PVDF            | -                      | 2-25                                 | 93                | 90               | 2-21        |
| Electromagnetic | 94                     | 30-70                                | 95                | 90               | 24-56       |
| DE              | -                      | 33-90                                | 93                | 75               | 23-63       |

As was seen in table 4-6 the efficiency of converting mechanical into electrical energy was highly dependant on the technology utilised. It appears that electromagnetic and dielectric polymers offer the best conversion efficiencies, with values ranging from 24-56% and 23-63% respectively. It was clear, in theory, that the system efficiency for dielectric elastomers was higher than for electromagnetic generators. This was despite the high output voltages associated with piezoelectric and dielectric elastomer generators, which resulted in a higher conversion penalty when rectifying and conditioning the raw electrical power. Piezoelectric

generation efficiencies were considerably lower due to both low mechanical to electrical conversion efficiencies as well as having poor output power characteristics, resulting in a conversion penalty. This was especially true for PVDF, where the mechanical to electrical conversion efficiency was not expected to exceed 25%. It should be noted that the mechanical to electrical conversion efficiency for piezoelectric materials could potentially be increased by using different materials.

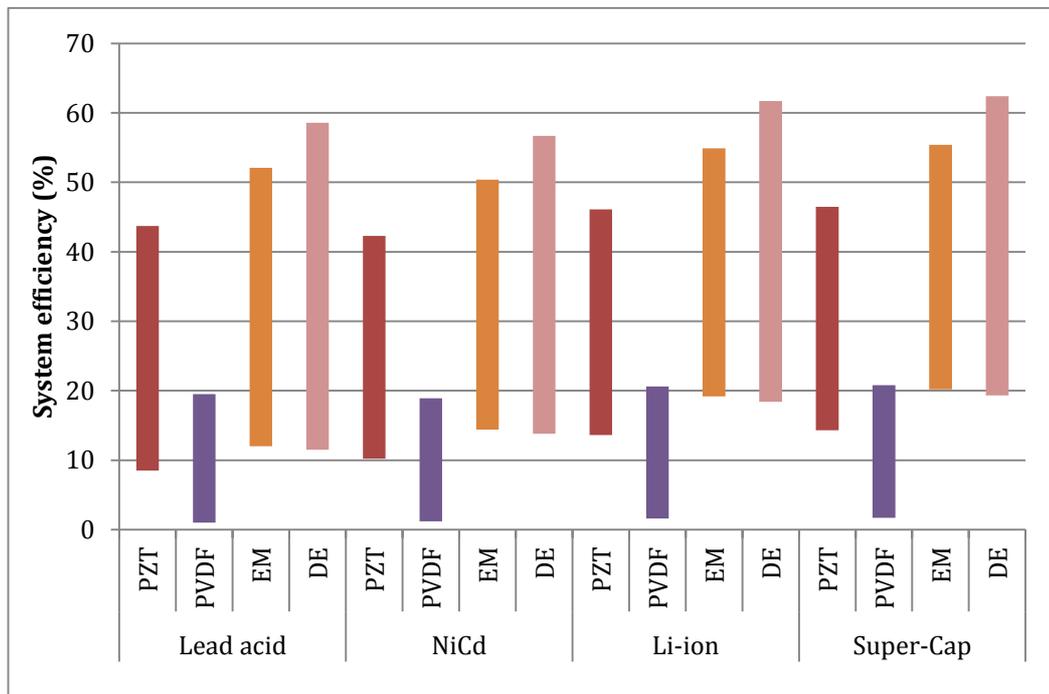
#### **4.3.2. Including storage**

Inclusion of energy storage focused on four technologies, these were lead-acid, nickel-cadmium and lithium-ion batteries as well as super-capacitors. The range of values taken for each of the energy storage technologies were taken from table 4-5.

It was noted that the values given in table 4-6 do not include the energy storage required to produce useful electrical energy. The use of an energy storage system resulted in a further efficiency penalty. The options for energy storage seem to be primarily in the form of electrochemical batteries and super-capacitors, although long term storage would be problematic for the latter owing to the relatively high rate of self-discharge. It was considered that the three most important factors were the charge-discharge efficiency, cycle durability and cost. It was clear that trade-offs would need to be made between these factors, although other factors such as energy storage densities and self-discharge may prove important, depending on the location and application. The range of efficiencies was large and depends on both the generation efficiency and the storage option. It appeared from fig 4-6 that the overall system efficiency was most heavily dependent on the generation efficiency and in turn the technology implemented. Even so the storage system could still have a significant impact on the overall system efficiency.

In terms of efficiency Lithium-ion batteries and super-capacitors appeared to offer the most appropriate solutions, with values as high as 98% and 99% respectively. However the efficiency of all of the technologies presented can potentially reach 90%. These represent the best case, where in contrast the lowest energy efficiency was for lead acid batteries where values as low as 50% were reported. The range of overall system efficiency based on the generation and storage technologies was given in fig. 4-6. It was seen that values in excess of

60% may be possible for a DE generator when using Li-ion and super-capacitor energy storage technologies. Even if the lower end of storage energy efficiency for these technologies was considered, values greater than 50% could be achieved. Similarly for an EM generator efficiencies of ~55% were found when utilising Li-ion and super-capacitor technologies. The lowest energy efficiency of energy storage was for lead-acid batteries where it was found to be as low as 50%. This resulted in the system efficiency nearly halving when compared to the best performing storage systems.



**Fig. 4-6: Overall system efficiency in converting mechanical work into useful electrical energy for each of the generation technologies and storage methods.**

Another important characteristic of the storage technology was cycle durability, where super-capacitors offer significantly better performance than chemical batteries. Of more importance for system consideration is the expected lifetime. For super-capacitors this was in excess of 20 years, whereas for lead-acid and lithium ion batteries this was found to be as low as 5 years, although they can reach 15 years. In permanent systems this is likely to be an important parameter. This variability in expected lifetimes was likely to have a significant effect on the lifecycle costs of the system and will be discussed further in chapter 6.

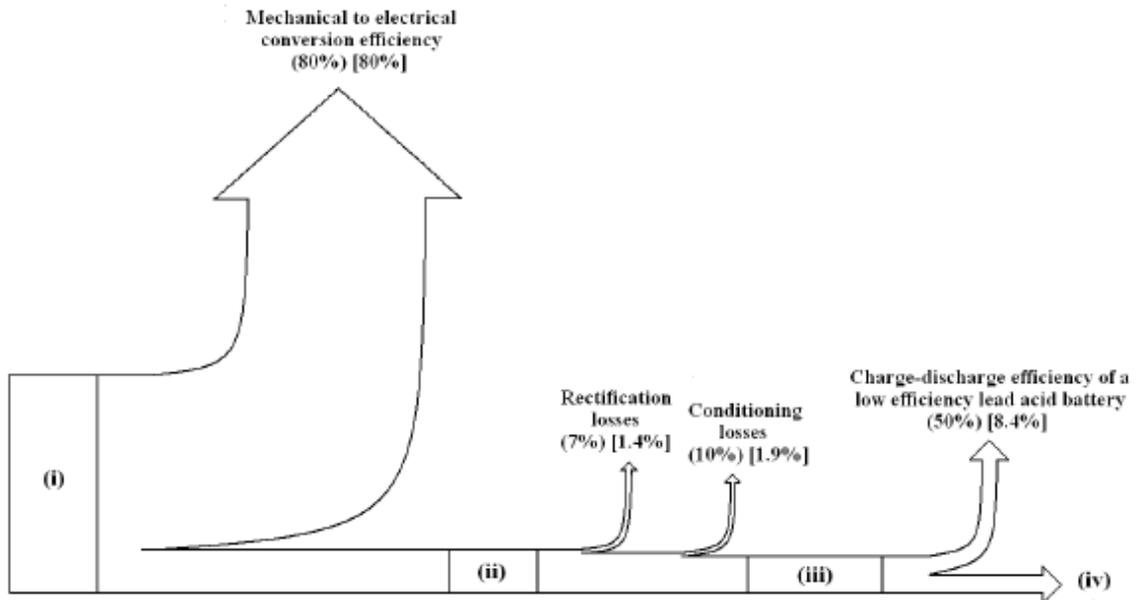
Thus far it appears that super-capacitors offer the most appropriate form of energy storage due to their high efficiency and long lifetime. There were however, a number of characteristics for which they perform poorly. Their energy storage densities were much lower than chemical batteries, and hence were likely to require significant space if considerable energy storage capacity was required. In addition self-discharge rates were very high, with rates as high as 40%/day. As a result they were only considered suitable for relatively short term storage of the order of seconds to hours. This would be important if the energy was to be stored for any reasonable length of time. In contrast chemical batteries exhibit much greater energy densities and in comparison low self-discharge rates.

To illustrate the energy that was lost throughout the generation process a number of Sankey diagrams have been drawn, as shown in fig.'s 4-7 – 4-9. To do this the minimum and maximum potential offered by the piezoelectric ceramic PZT, electromagnetic generators and dielectric materials was shown.

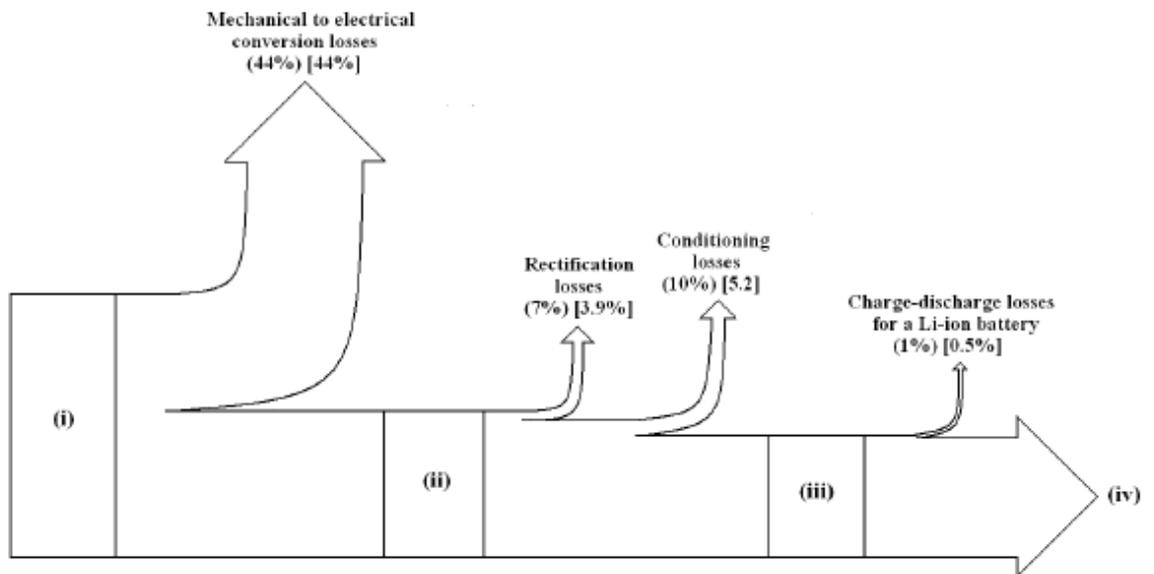
Once the raw energy was generated, the rectification and conditioning of the energy could be achieved with relatively high efficiency for all of the technologies. As such it appeared that the mechanical to raw electrical energy conversion was the stage with the largest impact on the efficiency of the harvesting system. From fig. 4-7 – 4-9 it was clear that for high generator efficiencies the rectification and conditioning of the raw electrical energy starts to contribute significantly more to the total system losses. In the case of electromagnetic generators the losses associated with these stages are 9.9% and 4.1% of the input mechanical energy, for maximum and minimum generator efficiencies respectively, as shown in fig. 4-8 (a) and (b).

### 4.3.3. Sankey diagrams

(a) PZT minimum efficiency



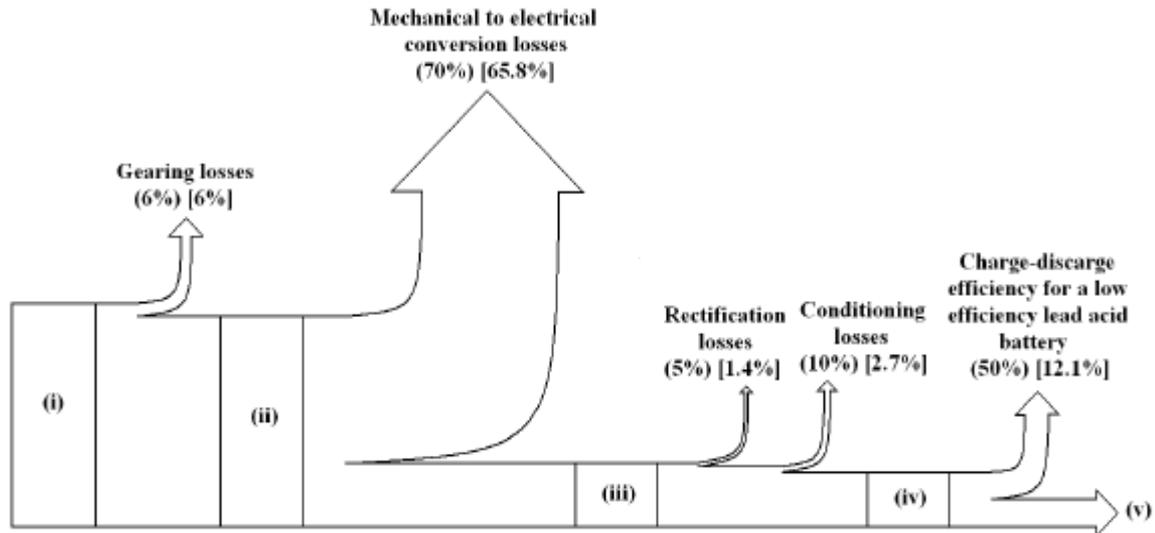
(b) PZT maximum efficiency



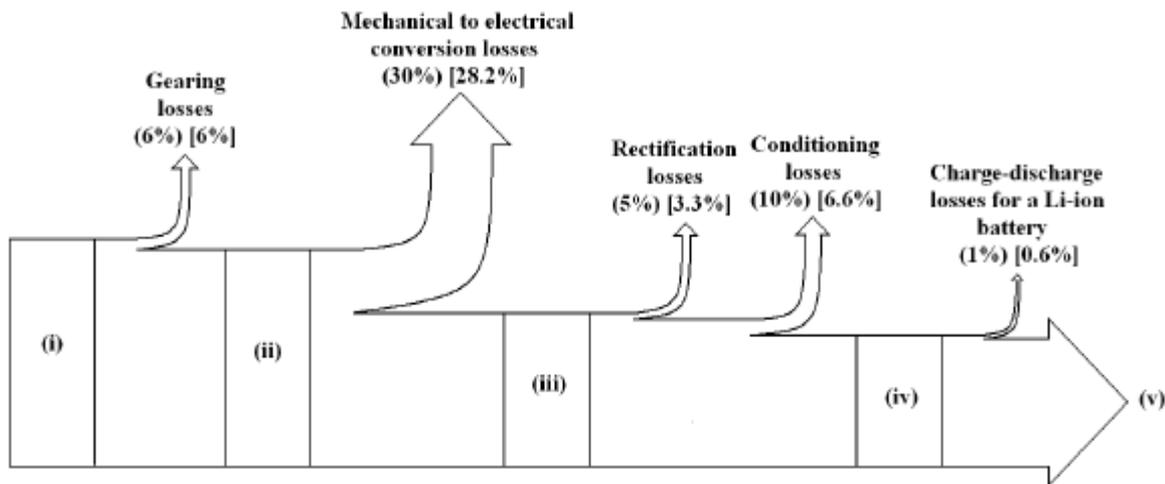
|     | (i)               | (ii)                  | (iii)             | (iv)                     |
|-----|-------------------|-----------------------|-------------------|--------------------------|
|     | Mechanical energy | Raw electrical energy | Electrical energy | Output electrical energy |
| (a) | 100%              | 20%                   | 16.7%             | 8.4%                     |
| (b) | 100%              | 56%                   | 46.9%             | 46.4%                    |

Fig. 4-7: Sankey diagram showing the loss of energy in converting mechanical input energy into useful electrical energy for a lead zirconate titanate generator. (a) minimum efficiency (b) maximum efficiency. (i) indicates the percentage losses incurred, [ ] indicates the losses as a percentage of input energy.

(a) EM minimum efficiency



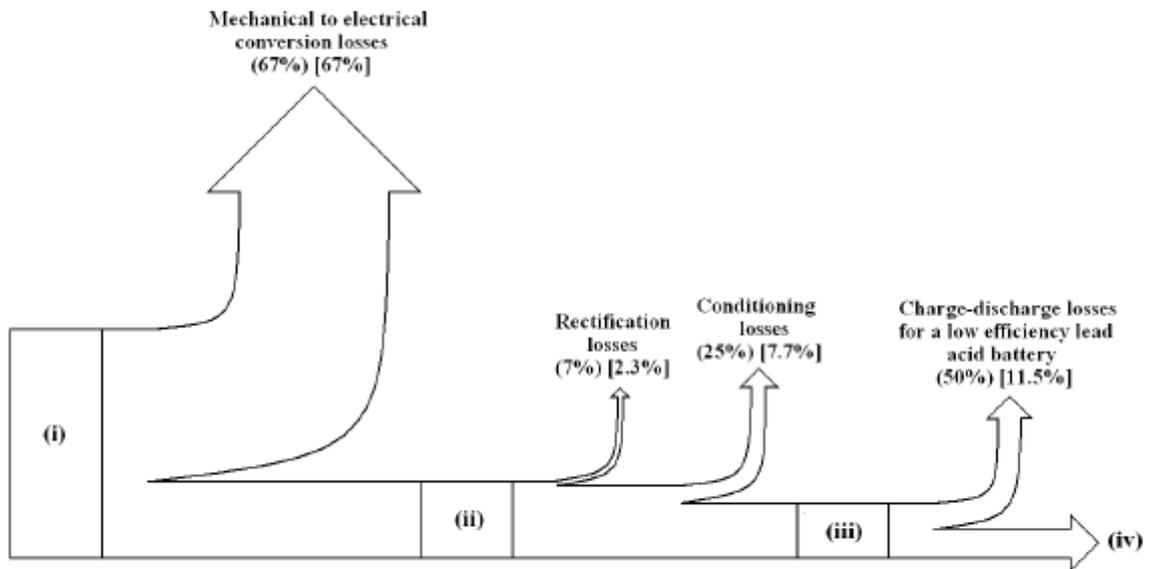
(b) EM maximum efficiency



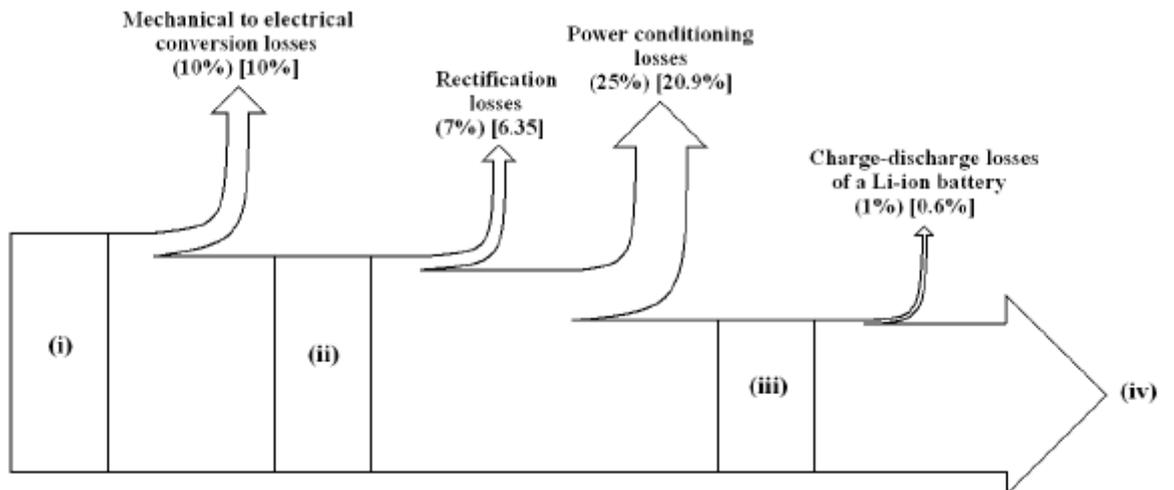
|     | (i)               | (ii)                    | (iii)                 | (iv)              | (v)                      |
|-----|-------------------|-------------------------|-----------------------|-------------------|--------------------------|
|     | Mechanical energy | Rotational mech. energy | Raw electrical energy | Electrical energy | Output electrical energy |
| (a) | 100%              | 94%                     | 28.2%                 | 24.1%             | 12.1%                    |
| (b) | 100%              | 94%                     | 65.8%                 | 56.3%             | 55.7%                    |

Fig. 4-8: Sankey diagram showing the loss of energy in converting mechanical input energy into useful electrical energy for an electromagnetic generator. (a) minimum efficiency (b) maximum efficiency. ( ) indicates the percentage losses incurred, [ ] indicates the losses as a percentage of input energy.

(a) DE minimum efficiency



(b) DE maximum efficiency



|     | (i)               | (ii)                  | (iii)             | (iv)                     |
|-----|-------------------|-----------------------|-------------------|--------------------------|
|     | Mechanical energy | Raw electrical energy | Electrical energy | Output electrical energy |
| (a) | 100%              | 33%                   | 23%               | 11.5%                    |
| (b) | 100%              | 90%                   | 62.8%             | 62.2%                    |

Fig. 4-9: Sankey diagram showing the loss of energy in converting mechanical input energy into useful electrical energy for a dielectric elastomer generator. (a) minimum efficiency (b) maximum efficiency. (i) indicates the percentage losses incurred, [] indicates the losses as a percentage of input energy.

## **4.4. Energy outputs**

Using the system efficiencies outlined in the previous section the expected electrical energy outputs were determined for each of the technologies presented.

### **4.4.1. Floor devices**

The expected energy generation outputs from each generation technology were calculated based on the mass of an individual ranging from 40-140 kg, corresponding to a range of energy potential from 4.8-16.8 J/step as shown in table 4-7.

The range of expected energy outputs from level walking and stair use for users of varying mass were presented in table 4-7. This encompasses the results for users of varying mass carrying out level walking, stair use in both directions and for each of the technologies presented. The results were based on a 10mm deflection of the generation device and the ground reaction forces set out in Section 3.3..

Using the expected values for the efficiency of the system, the expected energy outputs could be determined for level walking and stair use of floor devices. The useful energy output delivered from the storage device was also considered for each of the storage technologies presented.

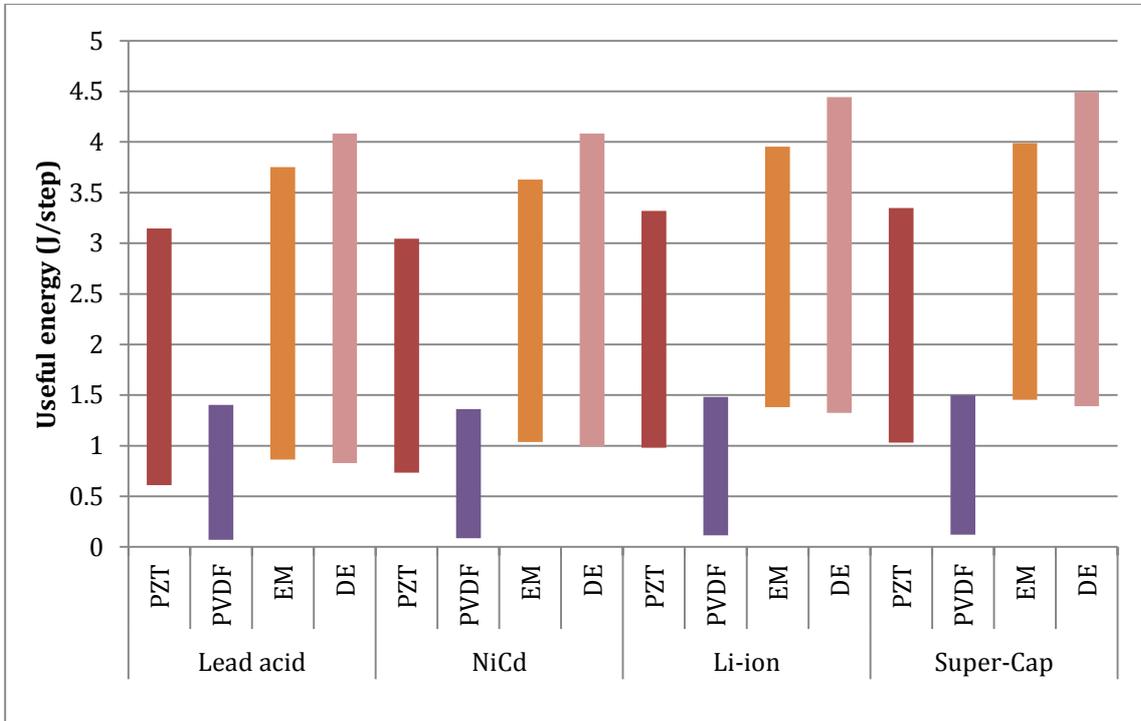
The energy potential for harvesting increased with increased user mass and follows a linear relationship ranging from 4.8-16.8 J/step for user masses ranging from 40-140 kg whilst level walking. This decreased to 4.4-15.4 J/step for stair ascent and increased to 6.4-22.4 J/step for stair descent. These changes were a result of the differing ground reaction forces associated with stair walking.

The expected energy output varied greatly depending on the generation technology, as seen in table 4-7. The lowest values were for PVDF, where the range for minimum and maximum values of useful energy output was found to be 0.1-0.3 J/step and 1.0-3.5 J/step respectively over the range of 40-140kg users. The highest values were for Dielectric elastomers, where the minimum and maximum ranges were 1.1-3.9 J/step and 3.0-10.6 J/step respectively over

the same mass range. In the case of stair walking, these decrease for stair ascent and increase for stair descent, where a maximum range of 5.2-14.4 J/step recorded for a DE generator during stair descent. It was expected that the energy output from each technology would lie within the maximum and minimum range of values.

**Table 4-7: Expected energy output per step for each generation technology for users of varying mass.**

| Mass (kg) |         | Potential (J/step) | PZT (J/step) | PVDF (J/step) | EM (J/step) | DE (J/step) |
|-----------|---------|--------------------|--------------|---------------|-------------|-------------|
| 40        | Level   | 4.8                | 0.8-2.3      | 0.1-1.0       | 1.2-2.7     | 1.1-3.0     |
|           | Ascent  | 4.4                | 0.7-2.1      | 0.1-0.9       | 1.1-2.5     | 1.0-2.8     |
|           | Descent | 6.4                | 1.1-3.0      | 0.1-1.3       | 1.5-3.6     | 1.5-4.0     |
| 80        | Level   | 9.6                | 1.6-4.5      | 0.2-2.0       | 2.3-5.4     | 2.2-6.0     |
|           | Ascent  | 8.8                | 1.5-4.1      | 0.2-1.8       | 2.1-4.9     | 2.0-5.5     |
|           | Descent | 12.8               | 2.2-6.0      | 0.3-2.7       | 3.1-7.2     | 2.9-8.1     |
| 100       | Level   | 12                 | 2.0-5.6      | 0.2-2.5       | 2.9-6.7     | 2.8-7.6     |
|           | Ascent  | 11                 | 1.9-5.2      | 0.2-2.3       | 2.6-6.2     | 2.5-6.9     |
|           | Descent | 16                 | 2.7-7.5      | 0.3-3.4       | 3.8-9.0     | 3.7-10.1    |
| 120       | Level   | 14.4               | 2.5-6.8      | 0.3-3.0       | 3.5-8.1     | 3.3-9.1     |
|           | Ascent  | 13.2               | 2.2-6.2      | 0.3-2.8       | 3.2-7.4     | 3.0-8.3     |
|           | Descent | 19.2               | 3.3-9.0      | 0.4-4.0       | 4.6-10.8    | 4.4-12.1    |
| 140       | Level   | 16.8               | 2.9-7.9      | 0.3-3.5       | 4.0-9.4     | 3.9-10.6    |
|           | Ascent  | 15.4               | 2.6-7.2      | 0.3-3.2       | 3.7-8.6     | 3.5-9.7     |
|           | Descent | 22.4               | 3.8-10.5     | 0.4-4.7       | 5.4-12.5    | 5.2-14.1    |



**Fig. 4-10: Expected outputs for each generator and storage technology for a 60 kg user.**

The choice of energy storage technology can impact on the useful energy output from each step. The range of energy outputs for the generation and storage technologies presented is shown in fig 4-10. The maximum outputs were for a DE generator where 4.1-4.5 J/step was available, assuming maximum generation efficiency and storage efficiency of the storage technology. If, however, the energy efficiency of the storage technology is taken as 50%, the useful energy output is only 2.3 J/step. As was the case with system efficiency, the useful energy delivered to the storage device was most heavily dependent on the generation technology implemented, as can be clearly seen in fig. 4-10. In chapter 3 it was estimated that 1.2 GWh/day of energy potential was available from human walking in the UK. Following this approach and assuming the maximum generation and storage efficiency a maximum value for energy generation could be determined. Thus for 4.5 J/step, where there were considered to be 60 million people taking 10,000 steps/day, gave 750 MWh/day. It should be noted that this represented the maximum available energy, however, it is not clear how much of this could be practically recovered.

#### 4.4.2. Swing door devices

In order to determine the potential for energy generation from swing doors, it was assumed that a DC generator would offer a simple solution. As such the efficiency of the process was considered to be in the range of 26-56% when converting the mechanical energy into useful electrical energy with a further loss from the storage method chosen. The expected energy generation potential from a swing door device was presented in fig. 4-11 – 4-13 and the average power generated over the course of the door opening event was presented in fig. 4-14 – 4-16. The expected energy outputs were determined for each of the three generation methods proposed and discussed in section 3.5.1..

Using the baseline values given in table 3-6, the expected energy outputs for methods 1, 2 and 3 were 2.2-5 J, 3.8-8.8 and 4.7-11 J respectively. It should be noted that these were for the maximum potential of each of the generation methods, with the condition that the door must open to  $>60^\circ$ . The results for method 2 represent the upper limit for the expected generation potential as it was for  $k'_2 = 11.2 \text{ Nm/rad}$ . As was explained, the time taken for the door to close increases as the value of  $k'_2$  increases, although more energy was available in the case of  $k'_2 = 14 \text{ Nm/rad}$ , there was no energy available to close the door and hence was not considered as an option. The expected energy outputs vary in the same pattern as the energy potential, with a maximum value of 16.1 J for the case of a 20 kg door and utilising method 3.

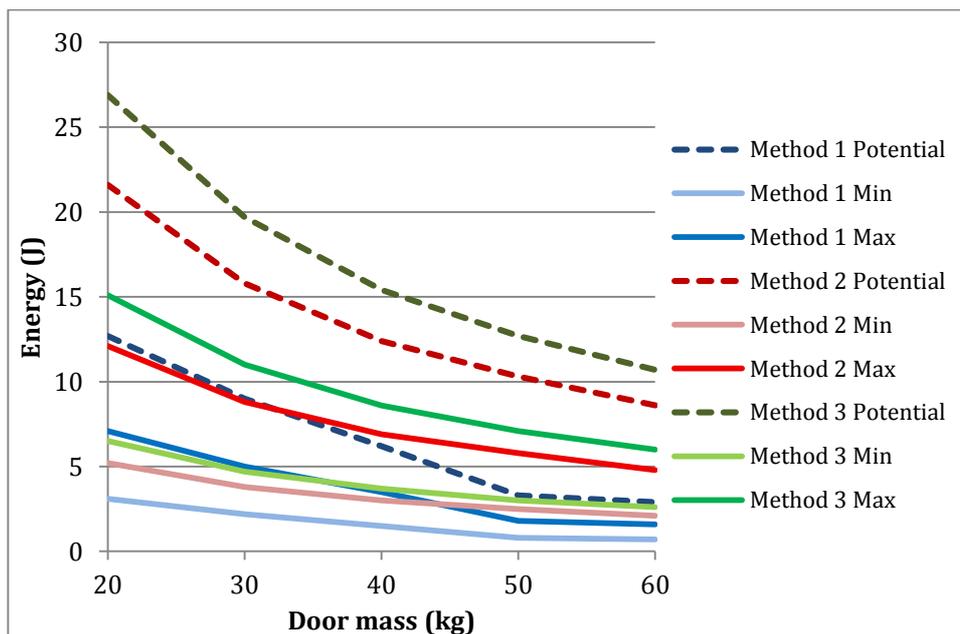


Fig. 4-11: Expected energy output from a swing door generator utilising an electromagnetic generator for each method and varying door mass.

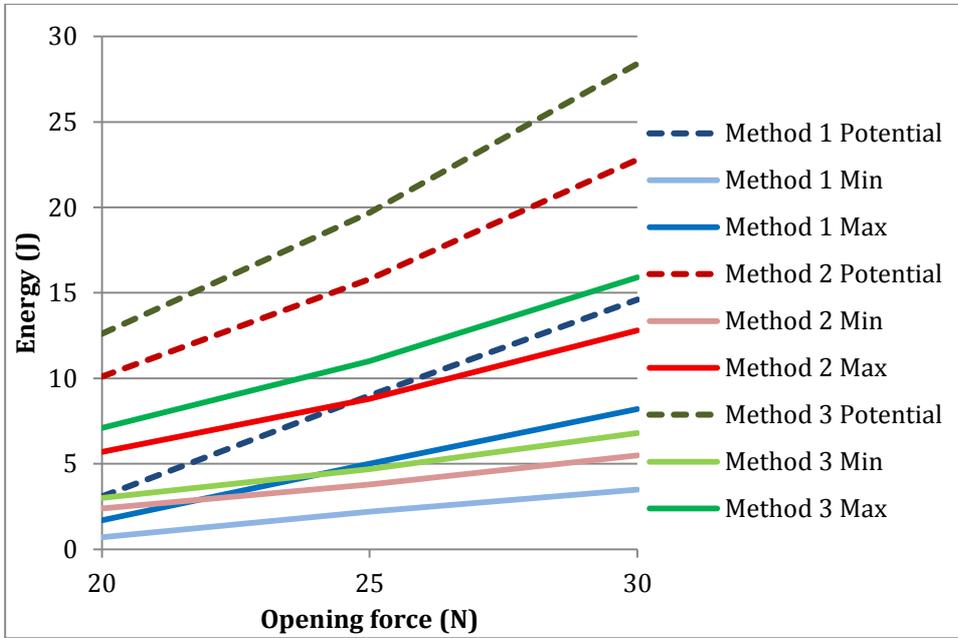


Fig. 4-12: Expected energy output from a swing door generator utilising an electromagnetic generator for each method and varying opening force.

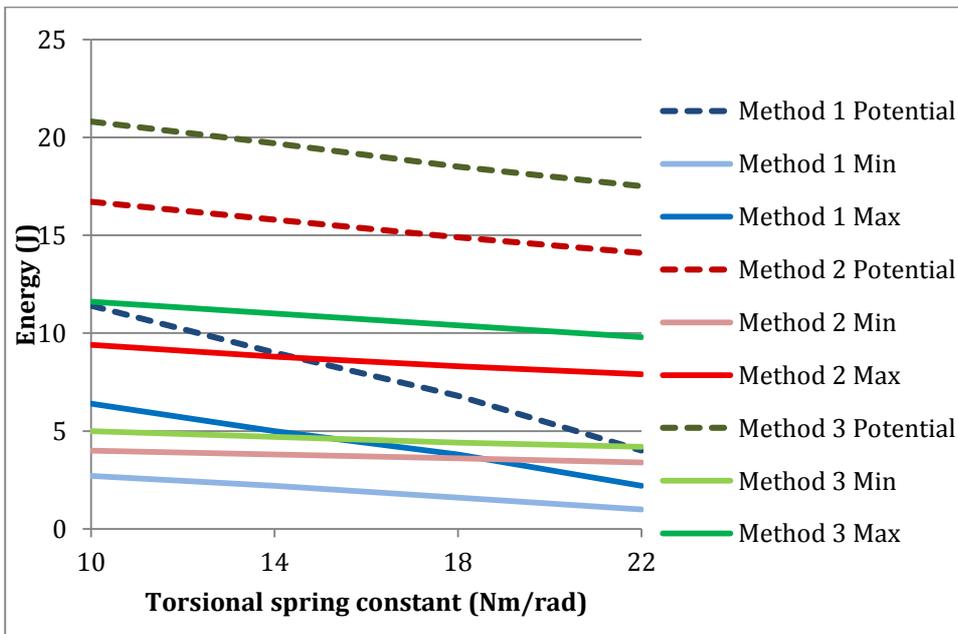


Fig. 4-13: Expected energy output from a swing door generator utilising an electromagnetic generator for each method and varying torsional spring constant.

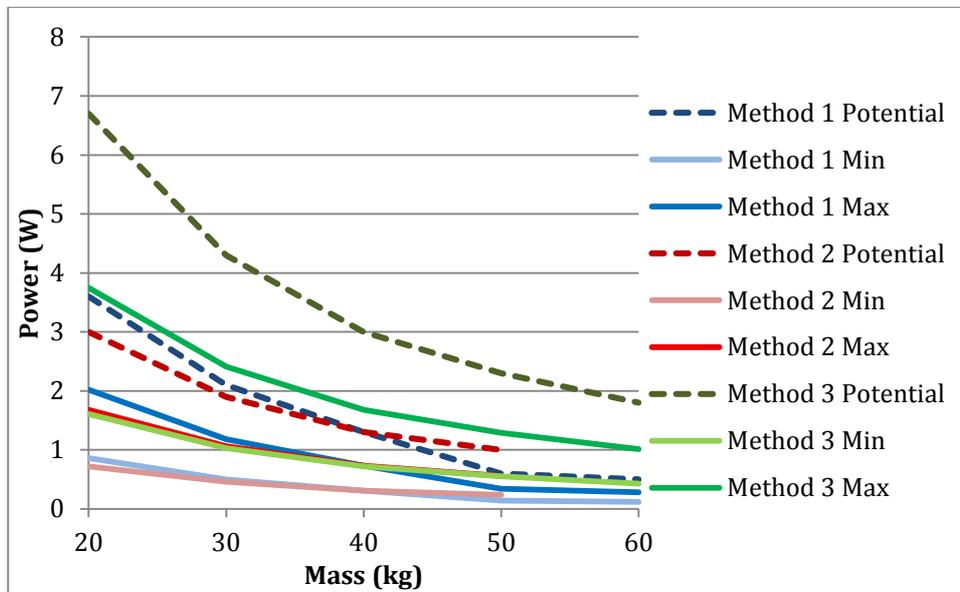


Fig. 4-14: Expected average power output from each generation method for varying swing door mass.

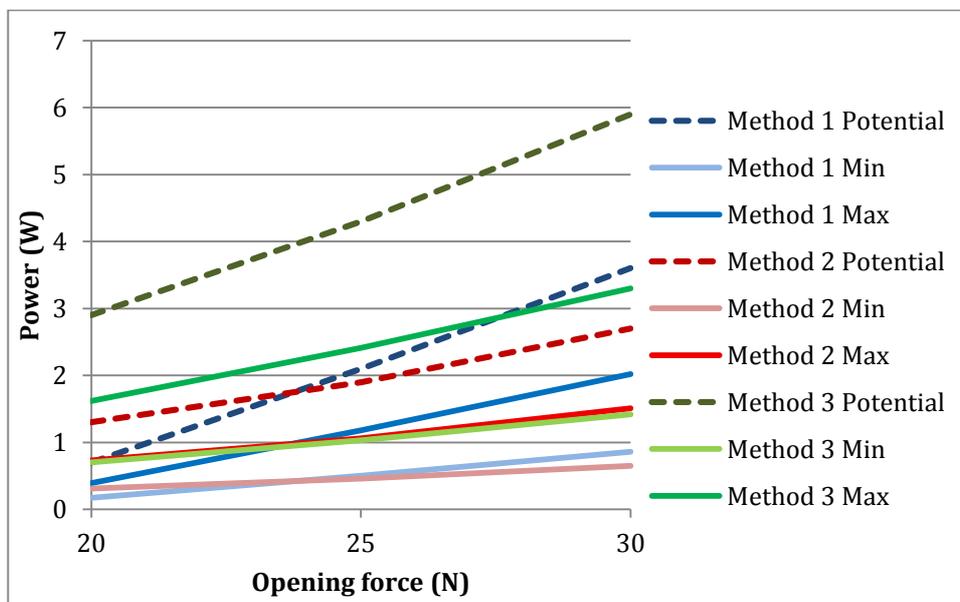
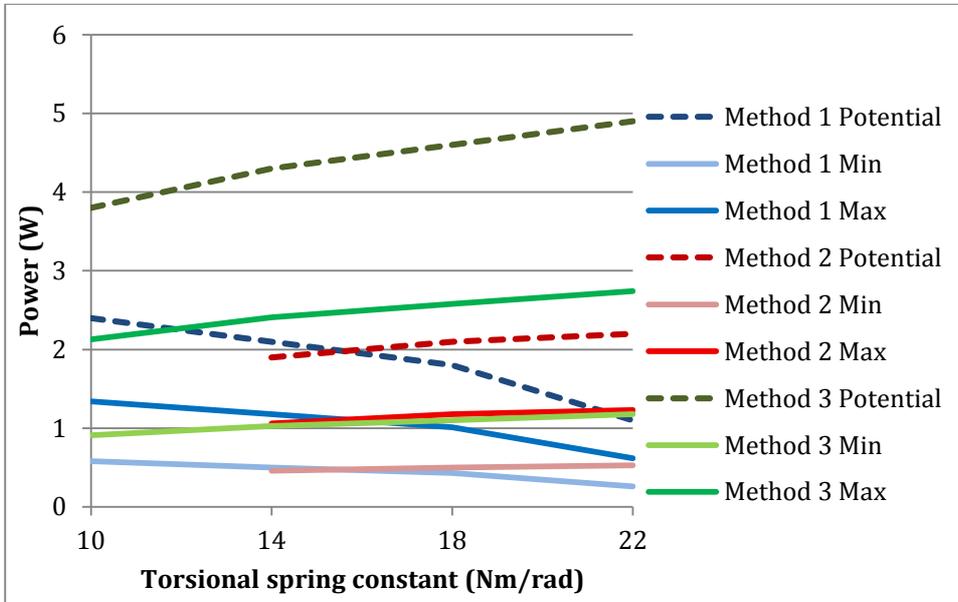


Fig. 4-15: Expected average power output from each generation method for varying opening force.

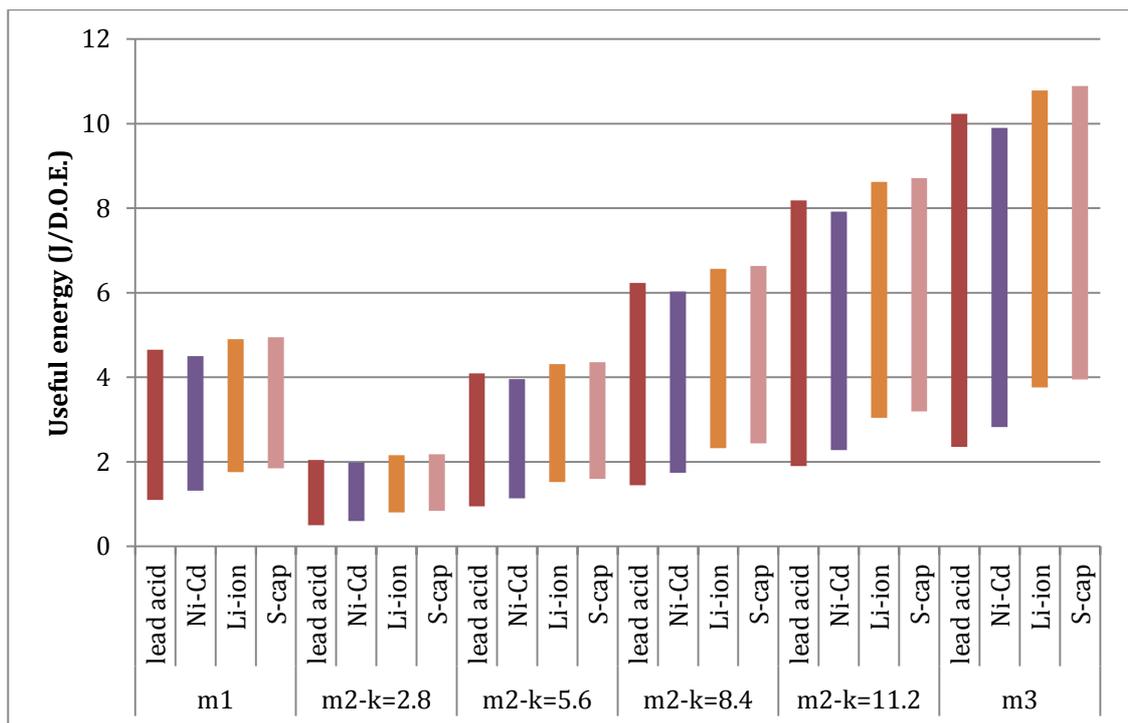


**Fig. 4-16: Expected average power output from each generation method for varying torsional spring constant.**

It was clear that for a given value of  $t_{D,O.E.}$  there would be a maximum number of times that a door opening event can occur in a given time, placing an upper limit on the potential for total energy generation. Since harvesting energy using methods 1 and 2 has an affect on  $t_{D,O.E.}$  it was interesting to consider the average power output over the course of the door opening. For the baseline case, power outputs of 0.5-2-1 W, 0.5-1.1 W and 1.0-2.4 W for methods 1, 2 and 3 respectively. Although method 2 generated more energy the additional time taken for the door to close resulted in the average power output from methods 1 and 2 being the same. Method 3, resulted in the highest average power outputs as a result of the presence of the generation unit not affecting the value of  $t_{D,O.E.}$ . The values of  $P_{ave}$  were affected by changing the doors variables, where  $P_{ave}$  increases for increasing opening force and decreasing mass and torsional spring constant. In general this increase was most pronounced for method 1 where the range of maximum power outputs for varying the mass, opening force and torsional spring constant were 2.02-0.28 W, 0.39-2.02 W, 1.34-0.62 W respectively. The highest values for  $P_{ave}$  occurred for method 3, where the range of maximum power outputs for varying the mass, opening force and torsional spring constant were 3.75-1.01 W, 1.62-3.3 W and 2.13-2.74 W respectively.

When the storage of this energy was taken into consideration the total energy available from a D.O.E. was reduced further. The results shown in fig. 4-17 were for a 30 kg door with a 18 Nm/rad torsional spring constant and an applied opening force of 25N. These values were chosen as they were the values to be taken forward for the following chapters. It was evident that changing the parameters of the door or opening force will change the energy output values.

It was clear that while the useful energy output was dependant on the per cycle efficiency of the storage technology, the main factor in determining the output was determined by the choice of generation method chosen. The maximum outputs were found when utilising method 3 and assuming the maximum energy efficiency of the generation technologies resulted in a range of 9.9-10.9 J/D.O.E depending on the storage technology used. Although this indicates that the choice of energy storage technology had only limited impact on useful energy output, it was seen that if the minimum energy efficiency of 50% was applied, then the useful energy output amounts to only 5.5 J/D.O.E., highlighting the importance of choosing an appropriate energy storage system.



**Fig. 4-17: Useful energy delivered by the energy storage medium for each generation method for a swing door generator.**

#### 4.4.3. Revolving door devices

It was again assumed that an electromagnetic generator could easily be used to harvest the energy potential available from a revolving door, where the system efficiency was in the range of 24-56%.

The results for the revolving door suggest that the energy generation potential significantly exceeds that of the swing doors, where the baseline case gave a range of 15.3-35.8 J/D.O.E.. It was found that neither the leaf (door) mass, nor the damping coefficient had a significant impact on the value of  $E_{D.O.E.}$ . The opening force had a considerable affect on the energy generation potential, where for  $F_o = 20$  N and 30 N, gave  $E_{D.O.E.} = 12.1 - 28.3$  J and  $18.5 - 43.1$  J respectively. Each of the variables was found to impact upon the value of  $t_{D.O.E.}$ . Increases to leaf mass and the damping coefficient resulted in increased values of  $t_{D.O.E.}$ , whereas increasing the opening force resulted in a decrease in  $t_{D.O.E.}$ . Changes to the leaf mass resulted in a small change in the value of  $t_{D.O.E.}$ , whereas the opening force and damping coefficient had a significant impact.

**Table 4-8: Generated energy outputs from a revolving door for variations to the leaf mass.**

| $m_L$ (kg)       | 20          | 30          | 40          | 50          |
|------------------|-------------|-------------|-------------|-------------|
| E (J)            | 15.2 – 35.5 | 15.3 – 35.6 | 15.3 – 35.8 | 15.2 – 35.5 |
| $t_{D.O.E.}$ (s) | 8.4         | 8.7         | 9           | 9.2         |
| $P_{ave}$ (W)    | 1.8 – 4.2   | 1.8 – 4.1   | 1.7 – 4.0   | 1.7 – 3.9   |

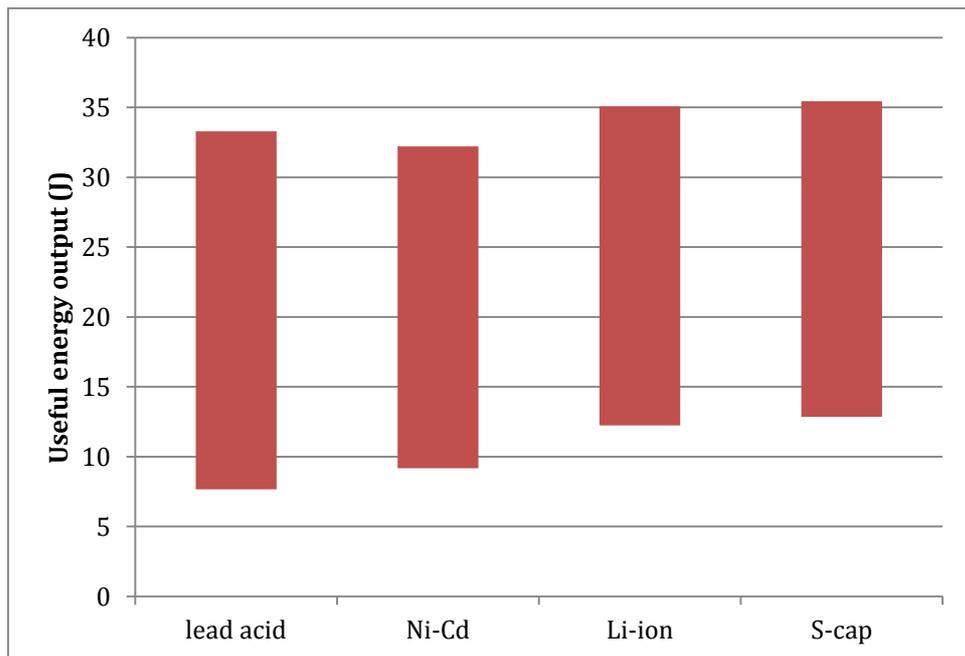
**Table 4-9: Generated energy outputs from a revolving door for variations to the applied opening force.**

| $F_o$ (N)        | 20          | 25          | 30          |
|------------------|-------------|-------------|-------------|
| E (J)            | 12.1 – 28.3 | 15.3 – 35.8 | 18.5 – 43.1 |
| $t_{D.O.E.}$ (s) | 10.9        | 9           | 7.7         |
| $P_{ave}$ (W)    | 1.1 – 2.6   | 1.7 – 4.0   | 2.4 – 5.6   |

**Table 4-10: Generated energy outputs from a revolving door for variations to the damping coefficient.**

| $d_c$ (N.m.s)    | 25          | 50          | 75          | 100         |
|------------------|-------------|-------------|-------------|-------------|
| E (J)            | 15.5 – 36.1 | 15.3 – 35.8 | 15.2 – 35.4 | 15.2 – 35.4 |
| $t_{D.O.E.}$ (s) | 6.0         | 9           | 12.5        | 16.3        |
| $P_{ave}$ (W)    | 2.6 – 6.0   | 1.7 – 4.0   | 1.2 – 2.8   | 0.9 – 2.2   |

In terms of the average power generated, it was found that as the leaf mass increased there was a small decrease in the average generated power and is a result of the slight increase to the value of  $t_{D.O.E.}$  with increasing leaf mass. It was seen from table 4-9 that an increase to the applied opening force resulted in a significant increase to the energy potential and a decrease in the value of  $t_{D.O.E.}$ , resulting in a significant increase in the average power output. In the case of the damping coefficient the generated energy decreased slightly as the value of  $d_c$  increased. However, the value of  $t_{D.O.E.}$  increased significantly from 6s to 16.3s for  $d_c = 25$  N.m.s and 100 N.m.s respectively. As a result the average generated power significantly decreases as  $d_c$  increases, where the highest value was found for  $d_c = 25$  N.m.s with  $P_{ave} = 2.6 - 6$  W.



**Fig. 4-18: Useful energy output from a single user of a revolving door for the baseline case.**

Consideration of the energy storage system reduces the useful energy available. Fig. 4-18 shows the results for each of the storage technologies when applied to the baseline case. Evidently the per cycle efficiency of the storage technology will impact upon the energy available from a D.O.E.. The highest values were found for the Li-ion and super capacitor technologies where 12.2-35.1 J and 12.9-35.4 J were found respectively. In the case of a lead-acid battery it was found that the range of useful energy outputs was 7.7-33.3 J/D.O.E., again highlighting the importance of a well designed system.

#### **4.5. System without energy storage**

Thus far it has been considered that the use of the electrical energy generated from human energy harvesting devices will require some means of energy storage. It may however be possible to avoid the use of energy storage by implementing a hybrid system, whereby the energy generated from human energy harvesting is used to provide some of the energy requirements of a load. Additionally it may be possible to match the profile of the energy generation source to a specific load. As an example LED lighting will be explored as a load, firstly where the energy harvesting devices provide all of the energy requirements without the use of a storage medium, and secondly as part of a hybrid system.

In the instance where the energy for the load is provided directly from the energy harvesting devices, it is apparent that the total energy requirements of the LED lighting load will need to be provided for. To consider this, flooring devices will be considered in terms of the area of lighting that could potentially be provided as an individual walks along a corridor.

A simple approach has been taken to determine a value for the power required to illuminate 1m<sup>2</sup> of flooring in a corridor using LED lighting and follows the procedure set out below. It is first necessary to define a number of values used in this calculation. It is recommended that a corridor inside a building requires an illuminance of 100 LUX (European committee for standardization, 2011). The coefficient of utilisation is the ratio of useful light that reaches a workplane when compared to the total light emitted by the light source, typically this is in the range of 0.5-0.8 (Schiler, 1997) , where a value of 0.6 will be assumed here.

$$\text{Number of lamps} = \frac{\text{Illuminance} \times \text{Area}}{\text{Lumens per lamp} \times \text{Coefficient of utilisation} \times \text{maintenance factor}}$$

This has been rearranged to determine a value of the number of lumens required from the LED lighting source to provide the required illuminance for 1m<sup>2</sup> of flooring (area = 1m<sup>2</sup>). For simplicity the maintenance factor, which is a measure of how the output in lumens of the lighting source degrades over time, is assumed to be 1. Hence it is assumed that the output of the lighting source does not drop over time. Since the example here is considering the upper limit of the area that may be possible to illuminate it is deemed that this is a reasonable assumption, although it should be recognised that in practice the output will deteriorate. This gives,

$$\text{Number of lamps} \times \text{Lumens per lamp} = \frac{\text{Illuminance}}{\text{Coefficient of utilisation}} = \text{Lumens}$$

As such it is expected that 167 Lumens per m<sup>2</sup> of flooring will be required from the LED lighting source. The energy efficacy of LED lighting is considered to be in the range of 50-100 Lumen/W, although this figure is constantly improving (LIA, n.d.). The power requirements of lighting a corridor are therefore found to be in the range of 1.67-3.33 W/m<sup>2</sup>. As was determined in section 4.4, the maximum achievable energy output from a footstep during level walking was found to be 6J for an 80 kg user. If a cadence of 90 steps/min is assumed, then the average power output is 9W. As such it appears that an 80kg individual walking at a cadence of 90 steps/min would be capable of providing the power requirements to light an area of 2.7-5.4 m<sup>2</sup> using LED lighting. On the face of it, it appears that this may be a feasible use of the generated energy, however there are a number of points that must be considered.

The first consideration centres around the differences that would be expected within a population. The calculations presented represent an example for an 80kg individual walking along a corridor at a cadence of 90 steps/minute. Since the average power output from a user will depend on the mass and cadence of the user, it is evident that the area of lighting that could be provided for will be dependant on these factors, where a reduction in either user mass or cadence will result in a decrease to the area that could be illuminated. Without a

means of energy storage it would not be possible to even out such variations and would result in different conditions for each user.

As an extension of the consideration of the cadence of a user, an altogether more problematic concern becomes apparent. Since there is no means of energy storage the power requirements of the load can only be met when energy is being generated by at least one energy harvesting device. As a result if the user were to stop walking, then no energy would be generated and so the load would not be provided with the required energy. Evidently this would result in the LED lights going dark and negating their use. Evidently this impacts upon the locations where such a system could provide some practical benefit. It seems immediately obvious that in a location such as an office, where people are generally stationary whilst at their desk, this approach would not be of benefit since the system would require users to walk in order to provide the power requirements of the load. As such it can only be considered in locations such as a corridor, entrance or other through fare, where users are passing through and hence in most instances continually moving. Even in through-fare locations such as those listed above it does seem that this limitation would rule out a system without an energy storage medium. This is because although users may predominantly be in motion, there will still be instances where users are not in motion, such as having a conversation or waiting outside a room.

Even so it may be possible to find a load that matches both the low power output and necessity of human action associated with utilising human energy harvesting devices without the use of energy storage. One example could be the ticket gates at a train station, as was highlighted in the work of (Takefuji, 2008). In this instance, the user would be required to be in motion to pass through the gate and would hence necessitate motion when the load requires power. However it is expected that such applications would be fairly niche.

If a hybrid system were to be considered, then the shortfall in energy requirements of the load could be met via the grid when the energy generated from human energy harvesting devices is unable to meet the overall load requirements. This has the advantage of being able to meet the energy requirements of the load at all times, however it comes at the cost of significant complexity to the overall system. Whereby two separate systems would be required in order to provide the requirements of the load. As a result the cost of the harvesting system would

be additional to grid connection and as such the cost of the human energy harvesting system would be additional to the usual cost of grid connection. This would mean that the cost of a hybrid system would always be greater than for simply connecting to the grid and as such the economic viability would be dependant only on the savings from the generated energy. As such it appears that it may be possible to install a system without the inclusion of an energy storage system if a hybrid system is considered, however, the additional cost of such a system would likely make it unfavourable.

In this section the operation of a human energy harvesting system without the use of energy storage has been explored. In a stand-alone system with no alternative source of energy it has been highlighted that there would be problems associated with the operation of LED lighting, although there may be a few loads that match up exactly with the power generation profile of the energy harvesting system. This shortfall in the performance of the system could be overcome if the system were to be a hybrid. However the benefit of this immediately seem limited as it necessitates a ore expensive system. As a result it appears that the inclusion of an energy storage system will be required if the human energy harvesting system is to provide any benefits.

#### **4.6. Commercial floor devices**

A number of flooring devices were found in a commercial context, these were proposed by Pavegen, Powerleap™, Piezopower, innowattech, Waydip, Soundpower and Sustainable dance club (SDC). Technical data regarding these products was generally scarce, making analysis of the products difficult, although given the commercial nature of the products and the relative immaturity of the technologies this was not unexpected. Information regarding Piezopower was available however this was for a business plan based on dubious values, as was discussed below and was ruled out. A brief overview of each device was presented below along with any available information regarding performance, cost, lifetime, technology and applications with the values summarised in table 4-11.

Innowattech developed the innowattech Piezo Electric Generator (IPEG™), with the suggested applications covering railroads, roads, runways and pedestrian locations (Innowattech 2014-a). It was claimed that a 100m length of passage way with 3,000 people passing through would be

capable of generating 1 kWh/hour of electrical energy (Innowattech 2014-b). If it were assumed that on average each person will take between 100-150 steps (0.67-1 m stride length) when passing through the passage, then the average electrical energy output from the IPEG™ would be ~8-12 J/step. Unfortunately no information was presented to back up the company's claims or stated energy outputs.

A number of devices were developed by Pavegen with the purpose of converting the kinetic motion of people walking into electrical energy, where it was claimed that 4-8 J/step could be generated (Pavegen n.d.-b). The technology implemented to achieve this was not stated on the company website, however it appears to be a hybrid piezoelectric technology (Wattnow 2012). Indeed a patent was granted to the company outlining energy harvesting mechanisms, with both electromagnetic and piezoelectric generation systems outlined (Kemball-Cook & Tucker 2011).



**Fig. 4-19: Pavegen floor tiles installed in the urban environment (Pavegen 2014-a).**

The technology was deployed at a number of locations as both permanent and temporary systems with a number of such systems highlighted on the website and through press releases available on the company website. The generated energy could either be stored in a battery or used to power low-voltage loads such as LED lighting or advertising displays (Pavegen 2014-b). An example of this was seen at West Ham tube station, where 12 Pavegen tiles were

installed on a walkway. It was expected that energy would be harvested from 12 millions footsteps during the 2012 London Olympics Games, generating 72 MJ (20 kWh) of energy, based on the assumption that 6 J/step of energy would be generated by the devices (Pavegen 2012-a). Another application was carried out in collaboration with the clothing firm Uniqlo, where 6 systems were installed at various Uniqlo locations around London. The press release provides claims with regards to the energy generated, where over the first 4 days it was reported that 114,323 steps were recorded, generating 4.7 MJ of electrical energy (Pavegen 2012-b). This equates to 1.3 kWh of electrical energy (1 MJ = 0.278 kWh), although the press release states that 4.7MJ was equivalent to 13 kWh (Pavegen 2012b). Furthermore, 4.7 MJ from 114,000 steps, equates to ~41 J/step, which was significantly higher than would be expected for harvesting energy from a footstep and an order of magnitude higher than their own reported outputs of 4-8 J/step. As such the reported generation results lead to considerable confusion with regards to the energy generated. If indeed ~114,000 steps were recorded and each step was considered to generate 4-8 J of electrical energy as claimed, then 0.126-0.253 kWh would be generated. As such it appears that the 13 kWh value stated was significantly overestimated.

Powerleap™ developed an energy generating floor tile utilising a piezoelectric generator, with a solid piezoelectric harvester and a PVDF hybrid material harvesting generator suggested (Redmond 2011). Very few details were provided including the expected energy outputs, however the system appears to differ from other systems primarily in the use of the generated energy. The Powerleap system was intended to act as a sensor with the main advantage coming from energy savings using energy management (Redmond 2011).

Piezopower have proposed a piezoelectric sub floor system, electroturf, to generate electrical energy through a piezoelectric generator, with polarised rochelle salts used as the piezoelectric material (Walsh 2011). It was claimed that a 17 W average power output could be achieved by harvesting 25% of the 70 W that were claimed to be available (Walsh 2011). The value of 70 W was a very optimistic claim for the available energy, as was shown in the previous chapter. It was also claimed that 1 million footsteps would generate 720 kWh of electrical energy (Walsh 2011), although it was not clear how this has been calculated. Even assuming the optimistic assumption of a cadence of 1 step/s were assumed then 17 J is available per step. From 1 million footsteps ~4.7 kWh (17 MJ) of electrical energy would be

generated. It was also claimed that electro turf will help to reduce carbon emissions, however the plan to import much of the material from China to the USA seems to be at odds with this claim. It was evident that although information regarding, performance, unit size and cost are presented, it was only a business plan based on primarily dubious assumptions and as such no further attention was paid.



**Fig. 4-20: Presentation of the SDC floor tile (SDC 2014) Last accessed 26/02/14).**

The sustainable dance club (SDC) developed a number of devices with the aim of harvesting energy from the kinetic energy produced during motion. Originally the device was designed with the purpose of harvesting energy from dancing through the dance floor module. This was developed in collaboration with Eindhoven University of Technology, with the design presented in (Paulides et al. 2009). The design utilised the vertical motion of a platform which was used to drive a DC brushless generator through a gearing system. It was claimed that 2-8 W could be continuously generated whilst being danced on (Paulides et al. 2009). The average energy output of the device presented in (Paulides & Jansen 2011) was stated to be 5.3 W when the dance floor was being danced on. The motion of dancing is however different from walking in that whilst dancing the device would be in constant use, whereas with walking the device will experience a more sporadic input. An energy generating flooring system was also developed as a means of generating energy from walking (SDC 2014). It was claimed that 2-20 J/step could be generated from the sustainable energy floor, depending on the mass and

movement of the individual as well as the deflection of the floor, where the deflection was between 10-20 mm (SDC 2013). The conversion efficiency of the system was claimed to be 50% (SDC n.d.). The technical specifications claim that the energy generated was in the range of 2-10 J/step (SDC 2013), no indication was given as to why this differs from the earlier claim although this could be a result of allowing only a 10 mm deflection. For the sake of consistency a range of 2-10 J/step was assumed for a 10mm deflection from here on in.

Soundpower developed an energy generating floor mat, as laid out in the work of (Takefuji 2008). A number of demonstrations were carried out, in particular at a Tokyo rail station. The aim was to power the ticket gate system with a target of 1 mJ per person and a daily total of 500 kJ. This was surpassed in the tests, where 766 kJ was generated on one day, with all days providing sufficient energy to power the required systems. It was advertised that the commercially available device was capable of power levels of 0.1-0.3 W whilst in operation for a 60 kg person. The rental cost was ¥30,000 (£177) for one piece for one week, although discounts were available for more pieces or longer time scales (Soundpower n.d.). Although the energy generated using this device was less than from other devices, it did provide enough energy to power the required load.

Waydip developed the Waynergy energy harvesting devices, with a pedestrian and a vehicle device available (Duarte & Casimiro n.d.). It was claimed that the energy was harvested through electromagnetic technology, although further information was not available. It was claimed that it would not require any additional effort from the user, however this could not be verified. Similarly it was claimed that 10 W/step could be generated, although no data was presented to back up this claim.

**Table 4-11: Table showing a summary of some of the main characteristics of commercially available energy harvesting floor devices.**

| Company                | Technology    | Energy                    | Dimensions                                | Lifetime                          | Cost                          |
|------------------------|---------------|---------------------------|---|-----------------------------------|-------------------------------|
| Innowattech            | Piezoelectric | 8-12 J/step*              | -   | -                                 | -                             |
| Pavegen                | Piezoelectric | 4-8 J/step                | 0.6 x 0.45 x 0.08 (m)<br>(Pavegen n.d.-b) | >3 million step<br>(Pavegen 2013) | £2,227**                      |
| Powerleap              | Piezoelectric | -                         | -   | -                                 | -                             |
| Soundpower             | Piezoelectric | 0.1-0.3 W                 | 0.5 x 0.5 x 0.3 (m)                       | -                                 | £177.13***<br>(weekly rental) |
| Sustainable Dance Club | Dynamo        | 2-10 J/step<br>(SDC 2013) | 0.5 x 0.5 x 0.1 (m) (SDC 2013)            | 15 years<br>(SDC 2013)            | -                             |
| Waydip                 | EM            | 10 W/step                 | 0.4 x 0.4 (m)                             | -                                 | £337**                        |

\*Based on the assumption that the average number of steps for a person to travel 100m is between 100-150 steps. \*\* See Section 6.6.2.1.. \*\*\*Conversion of ¥30,000 using (Money converter, 30/01/14)

#### 4.6.1. Comparison to commercial devices

A comparison of the stated energy outputs of commercially available floor devices with the range of expected energy outputs predicted using the assigned values was considered.

In terms of the piezoelectric device, Innowattech does not give specific outputs so it was calculated from information presented by the company that 8-12 J/step was required to generate the stated output. The upper values for efficiency of energy generation using PZT were assumed as 56% for the raw energy output and 47% for the system (without storage). The required mass of the user to generate the stated outputs are 119-178 kg for the Innowattech product for the raw energy output and 142-213 kg for the system outputs. The

range for the user mass required to produce the energy outputs for the Innovattech system are considerably higher than could reasonably be expected. As was previously stated, the exact generation technology was not stated, and so it is possible that a different piezoelectric material was used. If the range of the mass of the user was considered to be 50-100 kg, then the efficiency of converting the mechanical work into raw electrical energy would need to be  $\geq 100\%$ . It is apparent that an efficiency of  $>100\%$  is not feasible and hence it is unlikely that a range of 8-12 J/step would be practically achievable.

It is not clear from the information available which technology/technologies were implemented in the Pavegen device, although it appears that both piezoelectric and electromagnetic generation systems have been patented by the company. It was stated that 4-8 J/step would be generated per step. It was unclear whether these values take into account the whole energy system or represent the raw energy output from the device. It is assumed that the range in values was primarily a result of the varying mass of the users however no indication was given as to the conditions that will produce these values, making it impossible to accurately assess the efficiency of the device. A range of required masses was determined for piezoelectric and electromagnetic generators, where for the raw energy output values, 60-119 kg and 48-95 kg were found respectively. For the system output these increased to 70-140 kg and 60-120 kg. The ranges of masses for the raw energy output certainly seem feasible, particularly for the electromagnetic generation technology.

The energy output from the SDC device was claimed to be in the range of 2-10 J/step (SDC 2013). It was also claimed that the system efficiency of the sustainable energy floor was 50% (SDC n.d.) and that the dance floor proposed by (Paulides & Jansen 2011) had an efficiency of 48%, where a DC motor was used as the energy generation unit.. These values for the efficiency fall within the range of 24-56 % given in table 4-6. No breakdown of the efficiency of different components of the system was given, however it was noted that the rectification of energy for the device presented in (Paulides & Jansen 2011) was carried out using a simple diode bridge. It was expected that the losses stemming from this could be reduced by implementing an active rectifier. It was not clear whether this was the reason for the increase in efficiency of the sustainable energy floor over the dance floor device. Using an efficiency of 50% the required mass of the user was in the range of 33-167 kg to give an energy output

range of 2-10 J/step. This encompassed a wide range of values although they appear to be within a reasonable range.

The Waydip device claims to provide an output of 10 W/step, if a cadence of 2 steps/s was assumed then the energy output is 5 J/step. Maximum and minimum harvesting efficiency of an electromagnetic system requires a user mass of 74 kg and 174 kg respectively. A mass of 74 kg appeared to be a reasonable value for the mass of a user and hence it seemed likely that the efficiency of the harvesting system was at the upper end of the expected system efficiency for electromagnetic generation systems.

## **4.7. Summary**

The preceding chapter outlined the potential for energy generation from human energy harvesting for footfall, swing and revolving door devices. A range of technologies were considered as well as the process of electrical power rectification and conditioning before storage options were considered. There was a focus on the efficiency of each unit of the system, with an attempt made to determine a range of expected output energy values that may be expected for each of the proposed technologies.

The generation technologies examined were piezoelectric, electromagnetic and dielectric elastomer generators. It was found that the efficiency with which mechanical energy could be converted into raw electrical energy varies greatly depending on the technology. It was expected that dielectric elastomer and electromagnetic technologies would offer better efficiencies. For dielectric elastomers a maximum theoretical value of 90 % was predicted but despite this 33 % was the highest reported practical efficiency, probably owing to the relative immaturity of the technology. Electromagnetic generation, a more mature technology, offered a maximum reported efficiency of 64.7 %. Although higher efficiencies can be obtained, the efficiency was not expected to exceed 70% for generators of this size. In addition a gearing system would be required to operate the generator at the high speeds required. This adds a level of complexity and associated energy losses. It is expected that a well designed system would be capable of an efficiency of ~94 % although a poorly designed system could significantly increase the losses. It appeared that the most important factor in determining the overall system efficiency was the mechanical to electrical conversion

efficiency, due to the relatively high efficiency with which raw electrical energy could be converted into useful electrical energy. This should be achieved easily for electromagnetic generators, but will be more complicated for piezoelectric and dielectric generators due to the poor power generation characteristics.

The potential for energy generation from footfall was expected to vary significantly between users of different masses and on the location of installation. It was expected that the potential offered from stair use would differ to level walking, with stair ascent offering slightly lower potential, whereas stair descent resulted in significantly increased potential, due to differences in the GRFs.

Energy storage was expected to be possible with very high efficiency for Li-ion and super-capacitor technologies (98-99%), although efficiencies of 90% were considered possible for all the energy storage technologies examined. The best choice of technology was likely to depend on the exact system requirements.

The system efficiency varies greatly depending on the choice of technology, ranging from ~1% for a PVDF generator and utilising a lead acid battery to 62.4% and 55.4 % for dielectric elastomer and electromagnetic generators utilising Li-ion or super-capacitor storage technology. These resulted in maximum expected energy outputs of a floor device for a 60 kg person of 3.3, 1.5, 4.0 and 4.5 J/step for PZT, PVDF, electromagnetic and dielectric elastomer technologies respectively.

For swing door devices it was assumed an electromagnetic generator could be easily used to harvest the energy with a maximum expected generated energy output of 16.1 J/D.O.E. for method 3. The presence of a generator could have an effect on the time taken for the door to complete a D.O.E., particularly for method 2. As such the average power output was more useful in determining the maximum energy that could be generated over a period of time, with a maximum value of 3.75 W. This was again for method 3 and resulted from both the high generated energy values and the low value of  $t_{D.O.E.}$ .

For revolving door devices it was found that the expected generated energy was in the range of 15.3-35.8 J/D.O.E for the baseline case and was considerably higher than would be expected

for a swing door. In part this is thought to stem from the requirement of a swing door to return energy to the door in order to close the door.

Comparison of the efficiency and expected outputs of the technologies presented and commercially available devices was not simple. For electromagnetic generators it appeared that the SDC and Waydip devices operate at the higher end of the predicted performance. For piezoelectric devices however it was not so easy, it appears that the Pavegen device operates at a slightly higher efficiency than was predicted. The innowattech device outputs were calculated based on the company's claims to give an output of 8-12 J/step. This was larger than the energy potential for people of a reasonable mass and thus this range seems unachievable.

In conclusion a range of technologies were presented to carry out energy harvesting along with different energy storage technologies. It appeared that the method and more precisely efficiency of energy conversion was the most important factor in determining the useful energy that could be generated from walking, as well as the method of generation for swing door devices. It was determined that a revolving door offers significantly more potential than a swing door. It was important to consider the energy storage system as although high efficiencies could be achieved for each of the technologies it was also possible to waste considerable amounts of the generated energy for a poorly chosen storage system.

In this chapter the process of converting the harvestable mechanical work produced by the human body into useful electrical energy was considered. It was outlined in Chapter 1 that one of the main aims of this thesis was to determine the potential for energy harvesting in the urban environment with the focus being on devices embedded in the urban environment. As such it was necessary to consider the potential offered in the urban environment and was the focus of Chapter 5.

# 5. Energy system modelling

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In chapter 4 the efficiency and expected energy outputs available from floor and door devices were presented and in chapter 3 it was shown that human energy harvesting offers significant potential for energy generation. Even so it remains to be seen how much energy may be available from a device or system of devices in a practical environment and is the focus of this chapter.

Very little literature was available which attempts to answer this question, although some is available. In the work of Takefuji (2008) an aim of >500 kJ/day of generated energy was set for a system installed at a Tokyo train station. This was exceeded and a peak of 766 kJ/day recorded. In addition a number of claims were made by commercial human energy harvesting device manufacturers regarding the expected energy outputs and were laid out in the commercial devices section in the previous chapter (4.5.). It was found that the claims of Innovattech of 1 kWh/hour for 3,000 users passing along a 100m (Innovattech, 2014-b) were slightly higher than would be expected, as indeed were the claims of Pavegen (Pavegen, 2012-b) and Piezopower (Walsh, 2011). In terms of modelling potential outputs, a number of student projects were carried out at the University of British Columbia to determine the potential benefits of installing Pavegen devices as part of a redevelopment project, the results of which vary considerably and will be considered in the discussion of this chapter.

It is obvious that the energy output of a device over a given period of time will depend on two factors. These are the expected energy output of the devices for a single action and the number of actions experienced by them. In the case of floor devices the potential was considered as the number of steps that occur on the device and for the door device it was the number of times the door was operated. The expected energy outputs from individual actions were discussed in the previous chapter, with the values used for the modelling laid out in tables 5-1, 5-2 and 5-3. The methodology followed was set out in this chapter and aimed at providing a framework through which the expected energy outputs of a system of devices could be determined for practical situations.

## 5.1. Energy system outputs

In order to determine the potential for energy generation from a system it was first necessary to assign values for the useful electrical energy output generation from a device. The values to be assigned for floor and door generators are detailed below.

### 5.1.1. Floor devices

For floor devices, PZT, PVDF, electromechanical and dielectric elastomer generators were considered. The energy potential was determined from the average mass of adults, where 70 kg was taken to be the European average (Walpole et al., 2012). For level walking this gave an energy potential of 8.4 J/step of mechanical work on the device and for stair ascent and descent gave 7.7 J/step and 11.2 J/step respectively. Using these values, the energy outputs for a person of average mass were determined based on the range of system efficiencies detailed in chapter 4 as shown in table 5-1. These values were used when considering the total outputs over a given time period.

**Table 5-1: System efficiency and energy outputs from walking for each technology for a 70 kg user.**

| Technology           | Efficiency (%) | Level walking<br>(J/step) | Stair walking (J/step) |         |
|----------------------|----------------|---------------------------|------------------------|---------|
|                      |                |                           | Ascent                 | Descent |
| PZT                  | 17-47          | 1.4-3.9                   | 1.3-3.6                | 1.9-5.3 |
| PVDF                 | 2-21           | 0.2-1.8                   | 0.2-1.6                | 0.2-2.4 |
| Electromagnetic      | 24-56          | 2.0-4.7                   | 1.8-4.3                | 2.7-6.3 |
| Dielectric elastomer | 23-63          | 1.9-5.3                   | 1.8-4.9                | 2.6-7.1 |

### 5.1.2. Swing door devices

It was found in chapters 3 and 4 that the potential offered from swing door generation depends on the method chosen. The values taken forward were for the baseline case with the results shown in table 5-2, however it should be noted that these could be increased by

altering the door parameters or increasing the opening force. These values were used in assessing the total energy outputs over a period of time.

**Table 5-2: Energy generation potential and average power output of a swing door device from each of the generation methods to be used.**

| Method |                      | $E_{D.O.E.}$ (J) | Time (s) | $P_{ave}$ (W) |
|--------|----------------------|------------------|----------|---------------|
| 1      |                      | 2.2-5            | 4.2      | 0.5-1.2       |
| 2      | $k'_2 = 2.8$ Nm/rad  | 1.0-2.2          | 5.0      | 0.2-0.5       |
|        | $k'_2 = 5.6$ Nm/rad  | 1.9-4.4          | 5.5      | 0.3-0.8       |
|        | $k'_2 = 8.4$ Nm/rad  | 2.9-6.7          | 6.4      | 0.5-1.1       |
|        | $k'_2 = 11.2$ Nm/rad | 3.8-8.8          | 8.3      | 0.5-1.1       |
| 3      |                      | 4.7-11           | 4.6      | 1.0-2.4       |

### 5.1.3. Revolving door devices

**Table 5-3: Parameters and energy generation values to be used in assessing the revolving door.**

|                  | Case 1    | Case 2    | Case 3    |
|------------------|-----------|-----------|-----------|
| $m_L$ (kg)       | 40        | 40        | 40        |
| $F_0$ (N)        | 25        | 25        | 25        |
| $d_c$ (N.m.s)    | 100       | 50        | 25        |
| $E_{D.O.E.}$ (J) | 15.2-35.4 | 15.3-35.8 | 15.5-36.1 |
| $t_{D.O.E.}$ (s) | 16.3      | 9         | 6         |
| $P_{ave}$ (W)    | 0.9-2.2   | 1.7-4.0   | 2.6-6.0   |

With regards to the revolving door, three cases were taken forward from the previous chapter, with the door parameters and relevant results shown in table 5-3. It was decided that the

results obtained from varying the damping coefficient would be most appropriate as they provide the greatest variation in the values of  $t_{D.O.E.}$  and  $P_{ave}$ .

#### **5.1.4. Energy storage**

Energy storage was considered in the chapter 4, with each of the technologies presented being deemed to be applicable to energy harvesting systems. The storage of the generated energy had efficiency losses associated with it and was dependant on the technology chosen. It was seen that the charge-discharge efficiency of each of these technologies could be high for a well designed system and should thus not be a major source of energy loss. A simple approach to energy storage will be taken in this chapter, where the range of energy efficiencies was taken for the technologies presented in section 4.2.2.. As such a range of 50-99% was considered as the range of efficiency with which the energy storage medium was capable of storing and delivering the generated energy to the end load.

## **5.2. Utilisation of potential**

In order to determine the likely energy outputs from a system it was necessary to determine the potential that will be experienced by a generation device. In its most simple sense this could be determined by either the number of steps in a given location or the number of people passing through a door. In the case of swing door generators, and to a lesser extent revolving doors, this appears to be a gross simplification as it seemed unlikely that every person passing through the door would be required to open it. In order to determine how this was likely to affect the potential experienced by the device a study was carried out to test the utilisation of the total potential. Similarly with a floor device, the total number of steps experienced by a system of devices would decrease if the devices were not installed to cover the total floor area of the location.

### **5.2.1. Footfall utilisation**

The utilisation of the total potential offered through footfall depends on the number and distribution of devices in a given location. In the situation where the total area considered was covered by tiles then all of the potential would be utilised. In a location such as an entrance this may be the case, as all of the potential was funnelled through a relatively small area. It

may however not be feasible to cover the whole area but instead distribute them throughout the location. The simplest way of considering this was to assume that the footfall potential was evenly distributed throughout the location. In this case the utilised potential,  $\eta_{step}$ , could be estimated using,

$$\eta_{step} = \frac{\text{Area of devices}}{\text{Area of location}}$$

This would affect the total expected energy generation in a proportional manner, however it would not impact upon the energy generated by an individual device.

## **5.2.2. Utilisation of swing door potential**

### **5.2.2.1. Data collection**

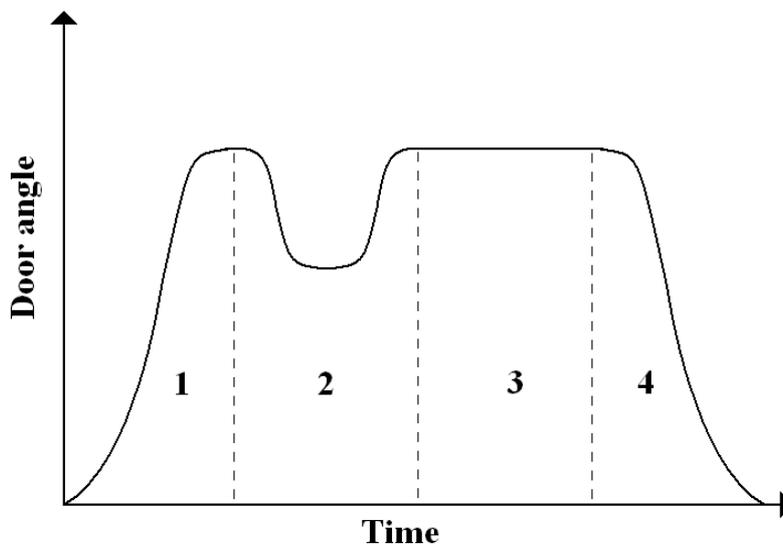
It seemed immediately obvious that the potential offered by a swing door would be less than 1 Door Opening Event (D.O.E.) per person. This was because, particularly in instances of high flow rate, more than one person would be likely to pass through the door when a D.O.E. occurs due to either the door not shutting completely or being held open for other users to pass through. This is represented in fig. 5-1. In order to gain an understanding of this a further study was carried out. This comprised of collecting data for a door at a shopping centre and lecture theatre. Measurements of the flow rate of people through the door (FR), and number of Door Opening Events ( $N_{D.O.E.}$ ), were taken. The number of D.O.E.s was measured as both full D.O.E ( $N_f$ ) and half D.O.E. ( $N_h$ ). The half D.O.E.s were used to account for times when the door was partially closed but not fully closed before another person passes through, it was assumed a linear response would be considered, so the potential offered would be half that of a full D.O.E. event.

Four sites were chosen, where sites 1, 2 and 3 were entrances to buildings and site 4 was the entrance to a lecture theatre as shown in table 5-4. For sites 1, 2 and 3, three sets of data were recorded with 20 measurements taken for each set and each measurement being collected over a 1 minute period. These were taken at times deemed to have low, average and high levels of activity. The lecture theatre was treated in a different way where measurements

were taken over the course of a lecture. The lecture chosen was a 2 hour lecture with a break in the middle during which people were able to enter and leave the theatre at will. In both cases the first person passing through the door in a given minute was considered to require a D.O.E. to occur.

**Table 5-4: Locations of each of the doors at which results were collected for the assessment of the utilisation of available potential for a swing door.**

|        |  |
|--------|--|
| Site 1 | Entrance to Westfield shopping centre in White City                  |
| Site 2 | Entrance to the University of London Union                           |
| Site 3 | Entrance to the print room café at Universtiy College London         |
| Site 4 | Entrance to the lecture theatre B.05 in the Chadwick Building at UCL |



**Fig. 5-1: Representation of the swing door angle where multiple users pass through the door in a short period of time. 1) The door is opened by the first user. 2) The door partially shuts before another user re-opens the door to pass through. 3) The door is held open to allow multiple users to pass through. 4) The door shuts after the last user passes through.**

The time taken for a D.O.E. event to occur was measured for each of the doors and was shown in table 5-5. The values have been rounded, as the exact time of a D.O.E. was dependent on the angle to which the door was opened, how quickly the door was opened and the angle at which the door was considered closed. It is likely that the time required for a D.O.E. to occur

will have an impact on the ratio of D.O.E./flow rate, with the expectation that the larger this time the lower the ratio.

It was stated that the data was collected at times deemed to be of low, average and high activity. To clarify this, for site 1, the high activity data set was completed in the build up to Christmas 2010, the low activity was carried out on a Tuesday afternoon (2 PM) in February 2011, with a time of average activity taken as a Thursday in the early evening (6pm).

**Table 5-5: Time taken for a complete door opening event to occur for the swing door present at each of the sites where data was collected.**

| Door 1 (s) | Door 2 (s) | Door 3 (s) | Door 4 (s) |
|------------|------------|------------|------------|
| ~6         | ~8         | ~10        | ~3         |

It was expected that the activity would play a vitally important role to the utilisation of the available potential. In the case of the data collected, it was deemed necessary to collect data in times of low, average and high activity in order to obtain results from a broad spread of flow rates. The analysis of these results removes the consideration of how likely a given flow rate is to occur, but instead focuses on the affect the flow rate has on the utilization of the available potential. It was expected that this would remove the consideration of the total activity experienced in an area and allow for a general relationship between the flow rate and the utilisation of the potential to be considered. In addition this allows for a comparison between the different locations, despite the differing distributions of the activity. In doing so it is possible to assess the impact of the value of  $t_{D.O.E.}$  on this relationship. These relationships can then be applied to specific levels of activity and distributions of flow rates to give an expected value for the utilization of potential at the desired location of study.

It is recognized that the results collected are limited in the number of data points taken, whereby only 60 data points were collected for sites 1, 2 and 3 and only 20 points where  $FR \neq 0$  at site 4. Evidently this has a detrimental impact on the statistical significance of the data. It is recognised that if more data were to be collected it would improve on the statistical significance of the results and would hence improve the confidence in the model. Even so,

since the results are from case-studied locations they still present an insight into the affect of the flow rate and time of door opening events on the utilization of the available potential.

### 5.2.2.2. Methodology

In order to determine the effect on swing door potential the flow rate, FR, of people through the door for a given test was plotted against the total utilised potential,  $N_{D.O.E.}$ , as seen in fig. 5-2. This was done for sites 1, 2 and 3. It was decided that not enough data was available for site 4 as only 20 of the 136 minutes over which data was collected had a flow rate greater than 0. The concentration of the total potential at site 4 was seen in fig. 5-3.

The total utilised potential was calculated using,

$$N_{D.O.E.} = N_f + 0.5N_h$$

With the ratio of D.O.E. to flow rate ( $\eta$ ) given by,

$$\eta = \frac{N_{D.O.E.}}{FR}$$

An envelope of operation was set for each of the doors whereby a minimum and maximum value was determined for given flow rates. For a minimum it was assumed that the first person passing through the door for any given minute would be required to open the door and that no other door openings would occur over that minute. Hence the minimum envelope of operation was given by,

$$Env_{\min} = \frac{1}{FR}$$

This would be the same regardless of the time taken for a D.O.E. to occur. Likewise a maximum envelope was defined, however this would vary depending on the time taken for a D.O.E. to occur. Here a maximum value for utilised potential,  $N_{\max}$ , was determined,

$$N_{\max} = \frac{60}{t_{D.O.E.}}$$

With the maximum envelope of operation then defined as,

$$Env_{\max} = \frac{N_{\max}}{FR}$$

### **Total effect on potential**

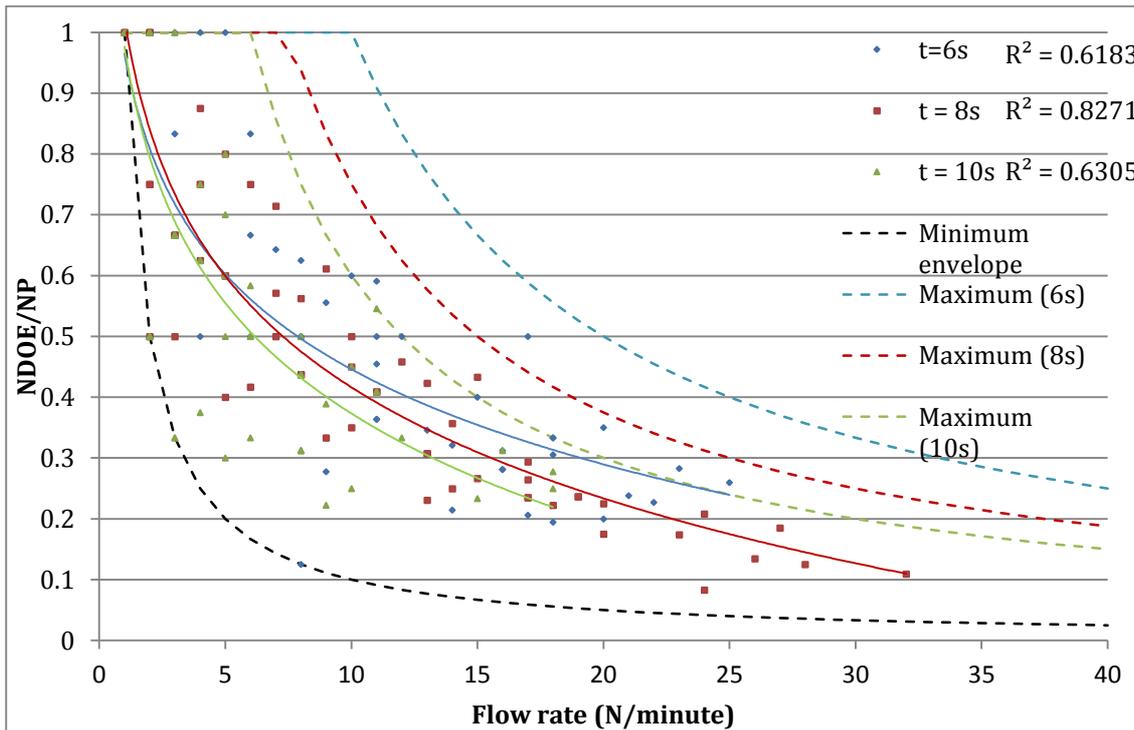
When considering the overall impact on the utilisation of potential over a significant period of time it was easier to consider the capacity factor,  $C$ , as given below,

$$C = \frac{N_{D.O.E.}}{N_{people}}$$

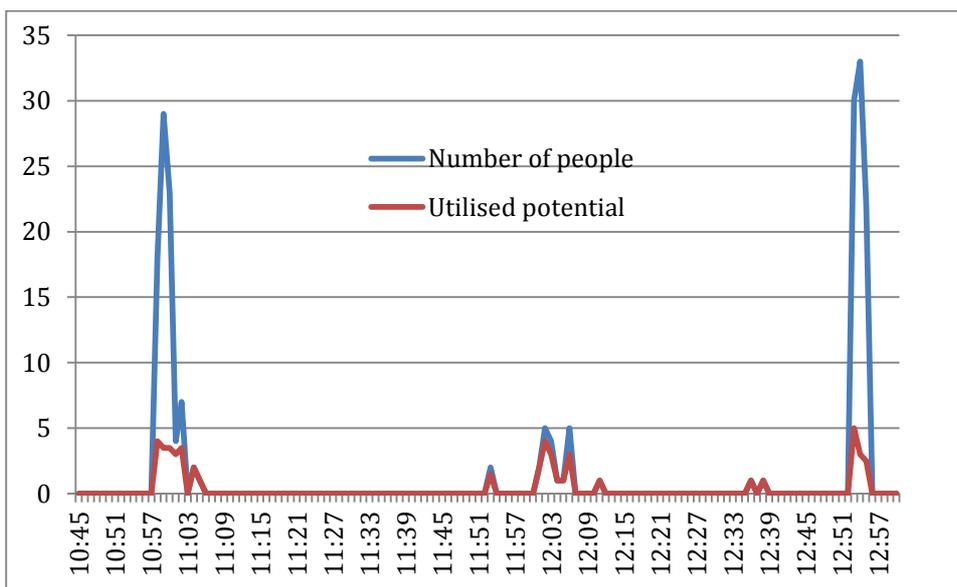
This was only useful if data was specifically collected for the site, so an attempt was made to predict the capacity factor using the results from fig. 5-2.

The data collected for door usage was used to plot a scatter plot of the utilisation factor,  $\eta_{FR}$ , against flow rate,  $FR$ , as shown in fig. 5-2 allowing two main conclusions to be drawn. Firstly the utilized potential for all the doors decreases with flow rate. Secondly the decrease in utilized potential as a function of flow rate was affected by the time taken for a D.O.E. to occur. From fig. 5-2 it was possible to see that all of the data points fit within the envelopes of operation. When assessing the envelope of operation it was seen that a value of  $\eta = 1$  was only possible up to a certain value of  $FR$ , with this value being dependant on the value of  $t_{D.O.E.}$ . It was seen that the value of  $\eta$  for a given flow rate could vary quite considerably, however

there appears to be a trend of decreasing  $\eta$  with increased FR. Trendlines were fitted to the data in an attempt to model the change in expected  $\eta$  as a function of FR to be used in predicting the value of  $C_{\text{theoretical}}$  for a given door location. Using these trendlines and the real distribution of flow rates for each of the doors, the values of  $C_{\text{theoretical}}$  were estimated.



**Fig. 5-2: The utilization of potential for energy generation experienced by a swing door as a function of the flow rate for each of the sites where data was collected.**



**Fig. 5-3: Representation of the total potential and the utilization of this potential for the swing door at the entrance to a lecture theatre (site 4).**

Another interesting point was seen for door 4, where the capacity factor was found to be 0.26 even with an average flow rate of 1.4 people per minute. Here the location appears to play an important role in determining the utilized potential. The door was an entrance to a lecture theatre, with the distribution of activity over the course of a lecture shown in fig. 5-3. Nearly all of the activity occurred during very short bursts, with more than 80% of the activity occurring in just 6 minutes. The high activity during these times resulted in low utilization of the potential, as would be expected. This showed how the concentration of activity into short bursts could have a hugely detrimental impact on the capacity factor and that the mean flow rate could not be used to estimate the capacity factor.

### **Theoretical prediction of capacity factor**

An attempt was made to predict a theoretical value for the capacity factor,  $C_{\text{theoretical}}$ , for different situations and locations. In order to complete this, a number of parameters were defined.

The first step was to determine theoretical values for the capacity factor at different flow rates,  $C_{FR}$ . This was carried out by fitting lines of best fit to each of the data series as shown in fig. 5-2, with the results presented below.

$$\text{Door 1: } C_{FR} = -0.225 \cdot \ln(FR) + 0.9649$$

$$\text{Door 2: } C_{FR} = -0.264 \cdot \ln(FR) + 1.0232$$

$$\text{Door 3: } C_{FR} = -0.262 \cdot \ln(FR) + 0.9764$$

$$\text{Door 4: } C_{FR} = -0.27 \cdot \ln(FR) + 1.0479$$

Using these equations, the capacity factor for a given flow rate were assigned for the values of  $t_{D.O.E.}$  measured for the doors.

### Distribution of flow rates

The second parameter was the determination of the probability distribution of flow rates through the door and how this would impact upon the capacity factor over a period of time. An initial study was carried out based on the data recorded for the doors.

Firstly the probability of a given FR occurring,  $p(FR)$ , was determined using,

$$p(FR) = \frac{N(FR)}{N_{Total}}$$

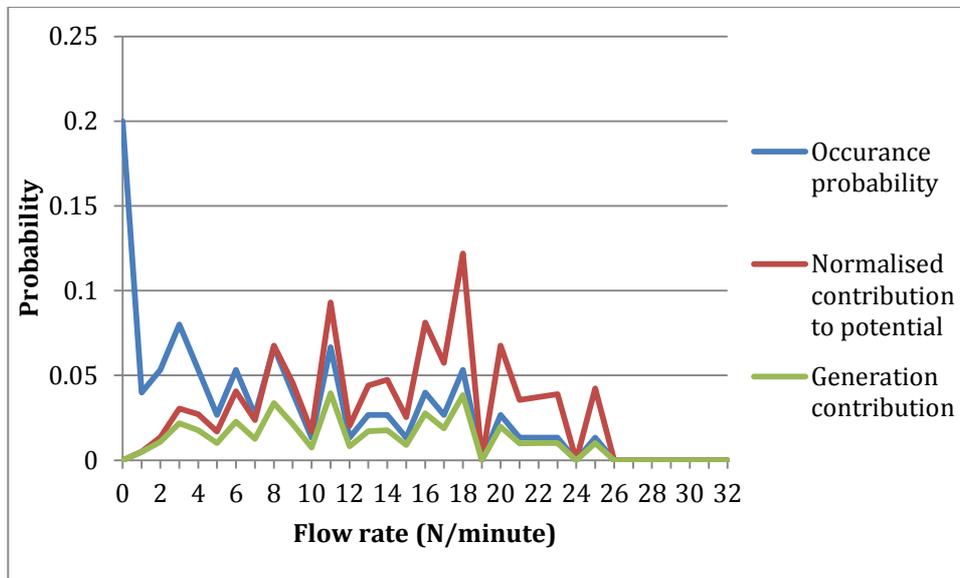
The next parameter to determine was the normalized contribution to the total potential,  $Pot_{norm}$ , and was given by,

$$Pot_{Norm} = \frac{p(FR).FR}{\sum p(FR).FR}$$

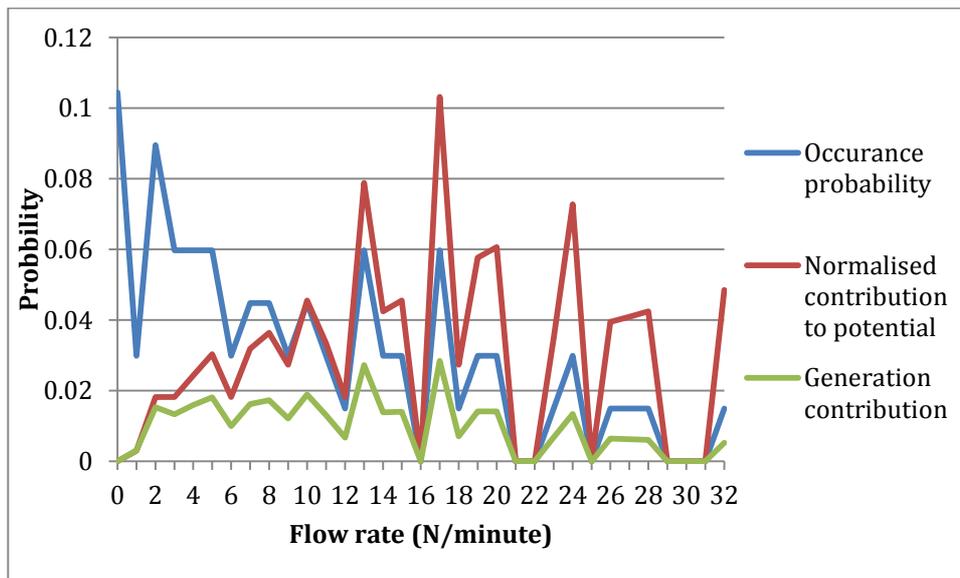
It was evident that in the situation when  $FR = 0$ , these would not contribute to the total potential. Determining the  $Pot_{Norm}$  values as a function of flow rate was necessary to allow for the weighting of increases in the flow rate to the total potential. A theoretical prediction of the capacity factor was then determined using,

$$C_{theoretical} = \sum Pot_{Norm}(FR).C_{FR}(FR)$$

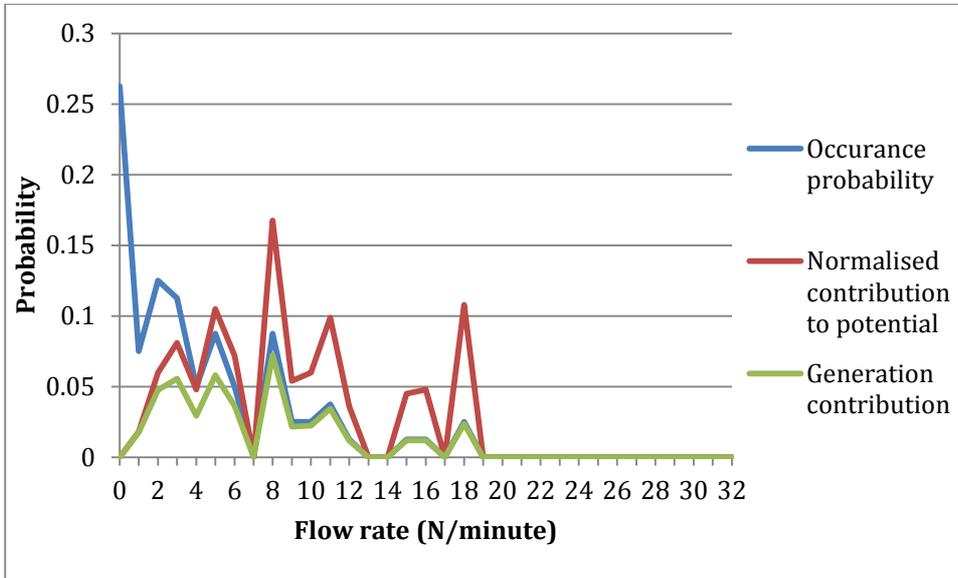
This process was applied to each of the data collected for each of the doors, with the results shown in figs 5-4 – 5-7.



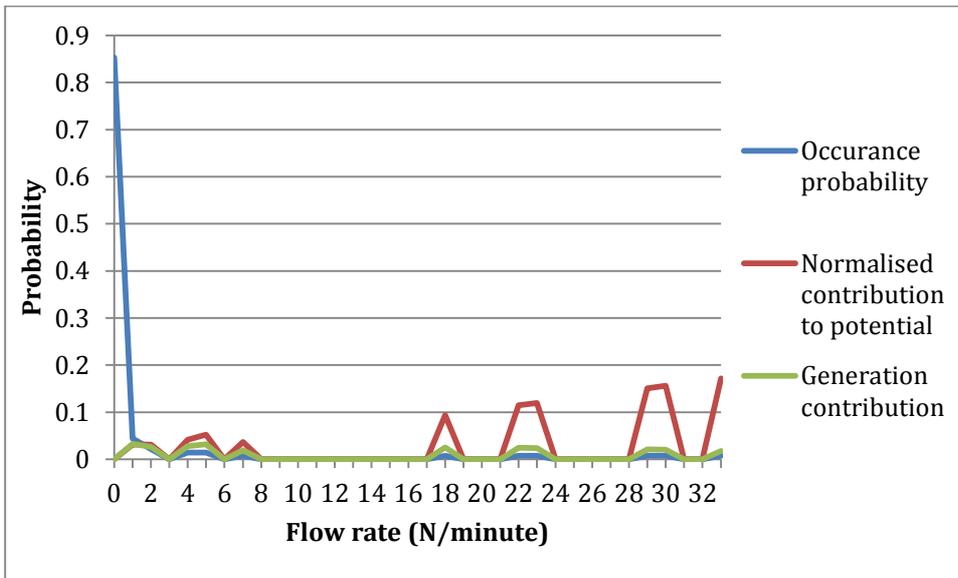
**Fig. 5-4: Plot showing the occurrence probability, normalized contribution and generation potential contribution to total potential as a function of flow rate from the data collected for door 1.**



**Fig. 5-5: Plot showing the occurrence probability, normalized contribution and generation potential contribution to total potential as a function of flow rate from the data collected for door 2.**



**Fig. 5-6: Plot showing the occurrence probability, normalized contribution and generation potential contribution to total potential as a function of flow rate from the data collected for door 3.**



**Fig. 5-7: Plot showing the occurrence probability, normalized contribution and generation potential contribution to total potential as a function of flow rate from the data collected for door 4**

It was seen from table 5-6 that the values of  $C_{\text{theoretical}}$  closely match, with values for doors 1, 2 and 3 and all within 1.3% of the measured value. The value for door 4 was just over 5% larger

than was measured, this increased discrepancy was likely a result of the small number of data points collected for this site.

**Table 5-6: Comparison of the recorded and theoretically calculated values of the capacity factor for the data collected.**

| Door                     | 1     | 2     | 3     | 4     |
|--------------------------|-------|-------|-------|-------|
| C                        | 0.395 | 0.320 | 0.461 | 0.258 |
| C <sub>theoretical</sub> | 0.400 | 0.323 | 0.455 | 0.271 |

In order to assess the potential impact of the activity experienced by a door on the capacity factor, probability distributions for  $Pot_{Norm}$  were assigned. It was assumed that a normal distribution would be capable of assessing how the mean contribution of flow rate affect the value of  $C_{theoretical}$ . The reasons for assigning a distribution of contribution to total potential as opposed to probability distribution are two-fold. Firstly when  $FR = 0$ , there is zero net contribution to potential, also determining  $C_{theoretical}$  was found to not be dependent on average FR, but instead on the contribution of value of FR to total potential. Secondly by considering the contribution to flow rate, the weighting associated with increasing FR was taken into account, resulting in simpler calculation of  $C_{theoretical}$ .

As such normal distributions were created using the parameters set out below and over the range of  $FR = 1 - 40$  people per minute, fig. 5-8. The flow rate must be  $\geq 0$  and in the case of  $FR = 0$ , there will be no contribution to the total flow rate. These distributions were normalised so as to produce a total potential of 1 for all distributions and explains the increased magnitude of the distributions with low mean values. Varying the mean of the distribution was carried out to try and assess the impact to  $C_{theoretical}$  at different locations. For high mean values, the contribution to total potential primarily comes from high values of FR, representing locations where there was either constant high activity or when there were large peaks in activity, such as the lecture theatre or the entrance to a large office building. Decreasing the mean represents situations where there was either low activity or when the activity was spread fairly evenly with no peaks in activity. This was represented by locations such as door 3, which was an entrance to a café, where the activity did not experience any large peaks. It was noted that these distributions were independent of the total activity.

**Varying mean:** The values taken were 5, 10, 15 and 20, with the standard deviation held constant at 5.

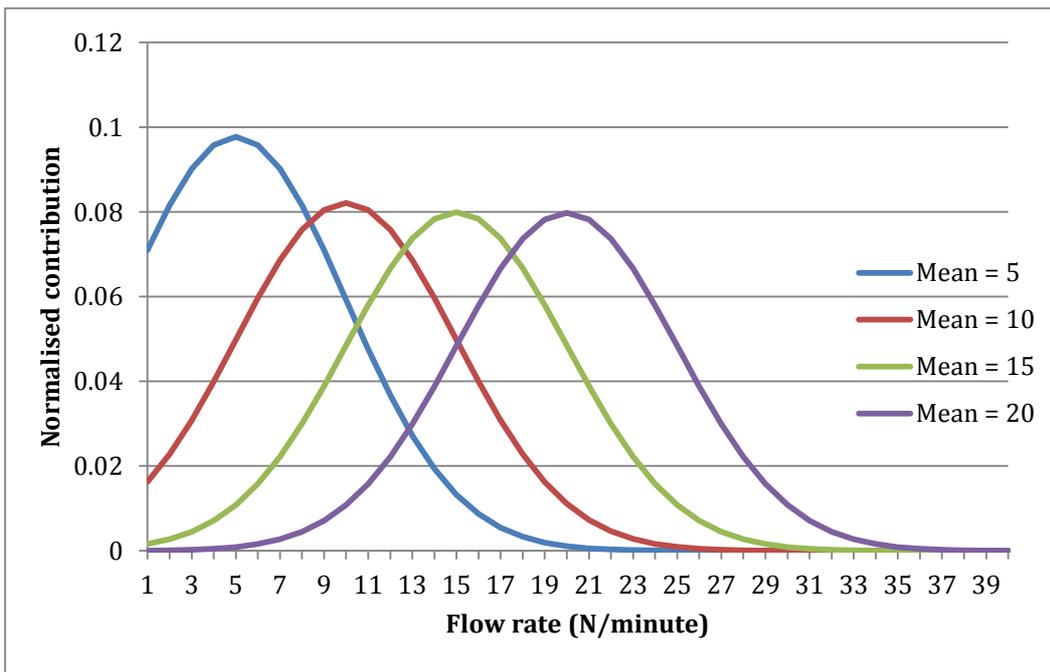
The values for  $C_{\text{theoretical}}$  were calculated in the same way as presented for the real data, with the results presented in fig. 5-10. In addition, the probability distribution of FR for each scenario was presented in fig. 5-9, and calculated using,

$$p(FR) = \frac{\left(\frac{Pot_{Norm}}{FR}\right)}{\left(\sum \frac{Pot_{Norm}}{FR}\right)}$$

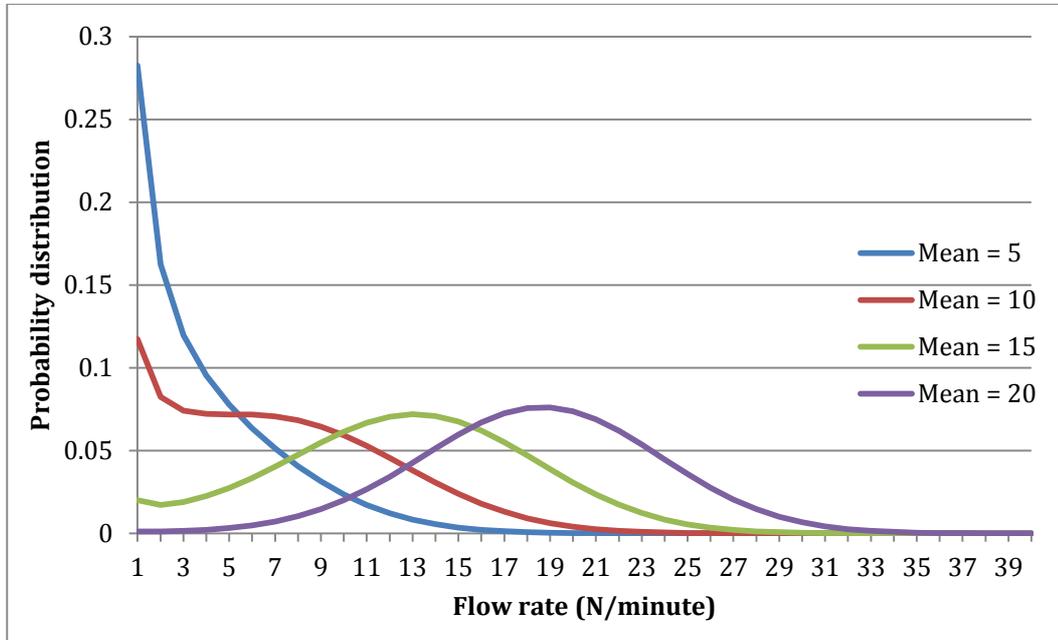
In addition the contribution to C for each of the scenarios as a function of FR were shown in fig. 5-11.

### 5.2.2.3. Results

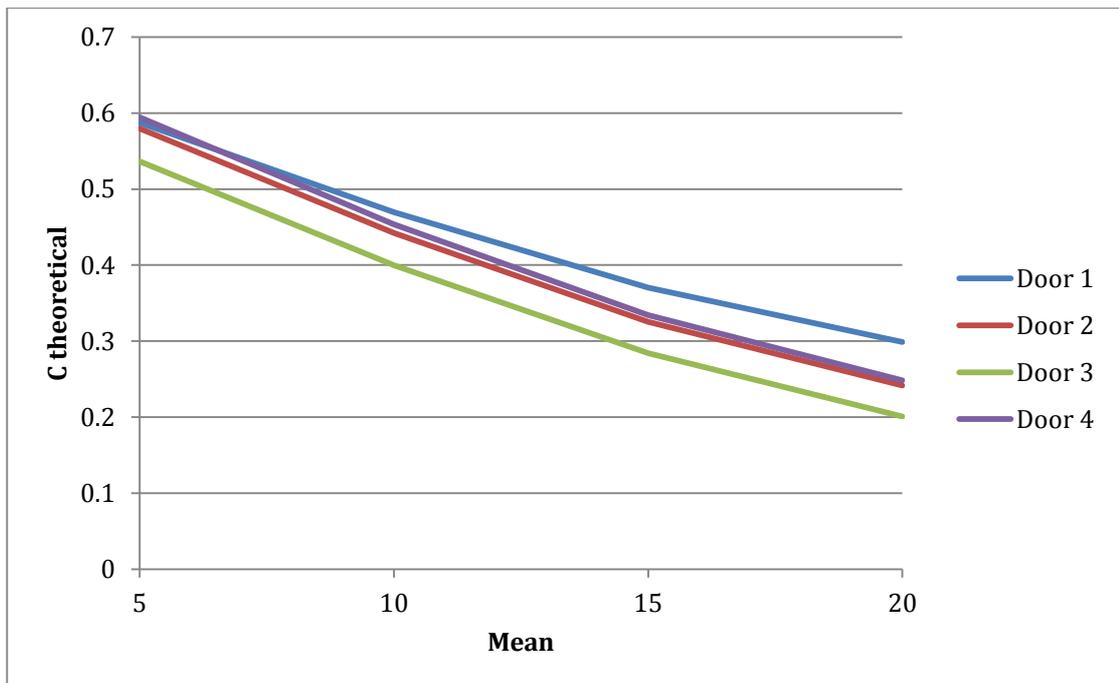
The results for the utilisation of door potential are presented in fig.'s 5-8 – 5-11,



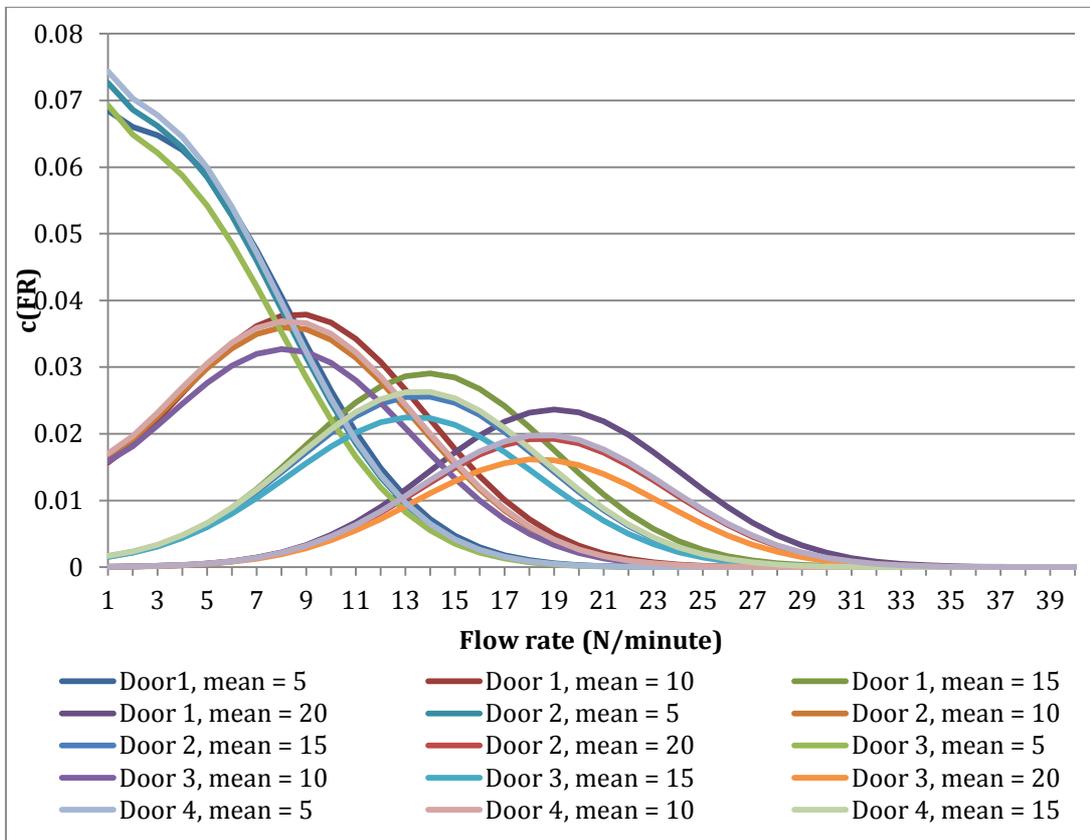
**Fig. 5-8: Normalised contribution to the total potential for varying mean values of the normal distribution.**



**Fig. 5-9: Probability distribution of flow rate for varying mean value of the normal distribution.**



**Fig. 5-10: Change in  $C_{\text{theoretical}}$  using trendlines from each of the doors and varying mean contribution to flow rate.**



**Fig. 5-11: Contribution towards the utilized potential as a function of flow rate for varying values of the mean contribution to flow rate.**

In order to determine a value of  $C_{theoretical}$  for a given value of  $t_{D.O.E.}$ , the results of  $C_{theoretical}$  were plotted as a function of  $t_{D.O.E.}$  with linear trendlines fitted to give the relationship where,

$$C_{theoretical} = x \cdot t_{D.O.E.} + y$$

Where the values of  $x$  and  $y$  were presented in table 5-7.

It was concluded that to determine the values of  $C_{theoretical}$  for a given location, it was necessary to consider the contribution to total potential as a function of FR. Evidently when FR = 0, there would be no contribution to the total potential. As such probability distributions of the normalized potential as a function of FR were assigned to represent different locations. The mean values of the generated distributions were varied to determine the effect on  $C_{theoretical}$ . It was found that the values of  $C_{theoretical}$  decreased rapidly with increased mean of  $Pot_{Norm}$ . The

change in  $C_{\text{theoretical}}$  was roughly 0.3 over the range of mean values used. This was due to the decrease in contribution of total potential from times of low FR.

**Table 5-7: Values used to determine the theoretical value of the capacity factor for different values of the mean flow rate.**

| Mean | 5       | 10      | 15      | 20      |
|------|---------|---------|---------|---------|
| X    | -0.0125 | -0.0175 | -0.0215 | -0.0245 |
| Y    | 0.668   | 0.5773  | 0.4983  | 0.4433  |

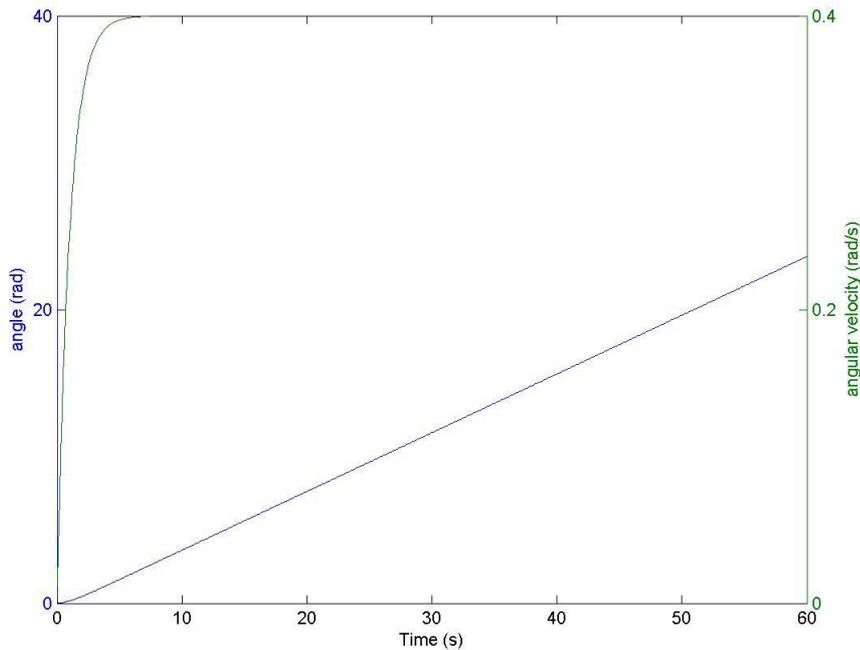
In addition to the distribution of activity, the value of  $t_{D.O.E.}$  had an impact on the likely value of  $C_{\text{theoretical}}$ . It was expected that as  $t_{D.O.E.}$  increased, the value of  $C_{\text{theoretical}}$  would decrease. This was seen for doors 1, 2 and 3, where it appeared that a linear relationship existed, although this only covers three values of  $t_{D.O.E.}$ . The results for door 4 do not fit this trend, with most of the values of  $C_{\text{theoretical}}$  being lower than for door 1, despite the decrease in  $t_{D.O.E.}$ . This was particularly true for distributions with a high contribution from high flow rates. This may be a result of recording only 20 datum and was excluded when determining the affect of  $t_{D.O.E.}$ .

### 5.2.3. Utilisation of revolving door potential

It was expected that the utilisation of the available potential for a revolving door would again diminish as the flow rate (FR) increased. It was however expected that the requirement of the revolving door to at least partially rotate for each user would mean this effect is diminished when compared to a swing door. In addition it was expected that a revolving door will have a very definite limit to possible values of FR.

For multiple users, the situation is somewhat more complicated. If the situation where two users were to pass through the door is considered, there are a number of scenarios. It is assumed that the opening force is 25 N, with the instance where multiple users are using the door resulting in the combined opening force applied being 25 N. The relative proportion of force applied by each user is not important, only that the combined force is equal to 25 N.

In order to assess this, the model was run where the door starts at rest. A user immediately passes through the door with the door remaining in use for 1 minute, the motion of the door for the baseline case is shown in fig. 5-12.



**Fig. 5-12: Motion of the revolving door over the course of 1 minute when in continual operation for case 2.**

It can be seen in fig. 5-12 that the angular velocity of the door quickly increases from 0 rad/s up to 0.4 rad/s at which point it remains constant. The total angle through which the door rotates and the corresponding value of  $N_{D.O.E.}$  in a 1 minute period are shown in table 5-8. It was considered that this provides the maximum number of D.O.E.s over 1 minute. Evidently for flow rates lower than 7.5, the maximum value of  $N_{D.O.E.} = FR$ . The same approach was then carried out for cases 1, 2 and 3.

**Table 5-8: Values for the total angular rotation and number of door opening events for each case of the revolving door over a 1 minute period.**

|                        | Case 1 | Case 2 | Case 3 |
|------------------------|--------|--------|--------|
| Angular rotation (rad) | 11.91  | 23.60  | 46.37  |
| $N_{D.O.E.}$           | 3.80   | 7.52   | 14.76  |

Consideration of the minimum value of  $N_{D.O.E}$  for a given flow rate was carried out as follows. It has already been stated that a single D.O.E requires the door to rotate through  $180^\circ$ , however the situation of multiple users is somewhat more complicated and will be assessed for both uni-directional (all users travel in the same direction) and bi-directional flow (users travelling in both directions). In order to do this fig. 3-20 (pg. 68) will be considered.

#### Uni-directional flow

If the first user enters in area  $A_1$  and the second user enters in area  $A_2$  then the total angle through which the door is required to rotate to allow both users to pass through the door is  $270^\circ$  since the door will have rotated  $90^\circ$  by the time the second user enters and will be required to rotate a further  $180^\circ$  for the second user to pass through. Therefore,

$$N_{D.O.E} = 1.5$$

If users continue to enter each successive area, then each user will require the door to rotate a further  $90^\circ$ , giving a general solution for the minimum number of D.O.E.s as,

$$N_{D.O.E} = (0.5 \cdot N_{people}) + 0.5$$

#### Bi-directional flow

Two users enter at the same time, one in area  $A_1$ , and the other in area  $A_3$ . This will require the door to rotate through  $180^\circ$  for both users to pass through and will hence give.

$$N_{D.O.E} = 1$$

If a third user is to enter, then it is necessary for the door to rotate a further  $90^\circ$ .

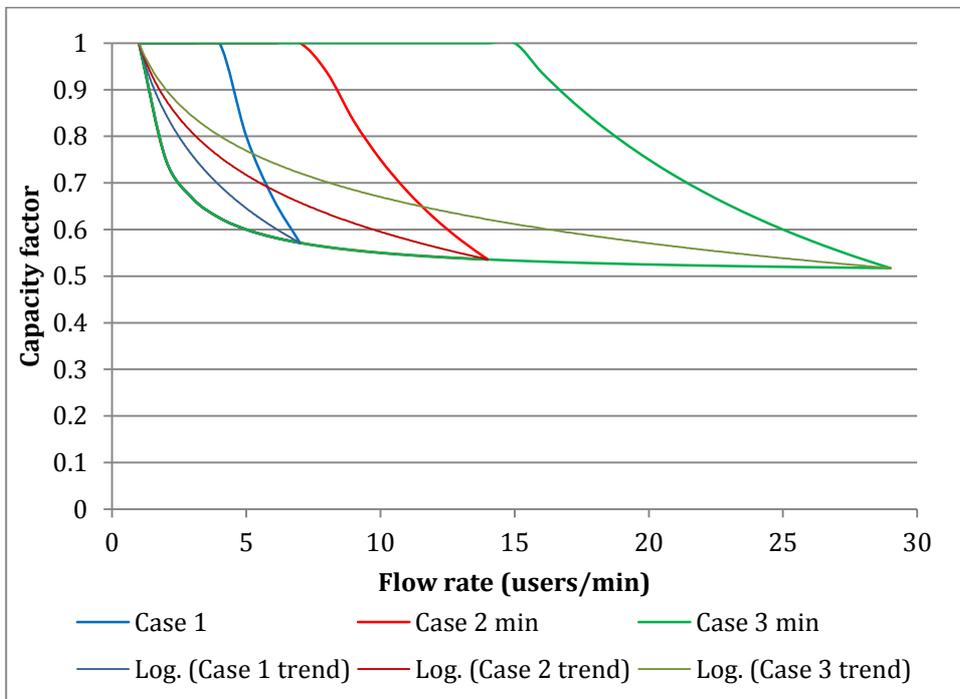
$$N_{D.O.E} = 1.5$$

It is noted that if four users were to enter, with two travelling in each direction, then the minimum value of  $N_{D.O.E.}$  would still be 1.5. This trend continues where for every 2 additional users, the minimum possible value of  $N_{D.O.E.}$  will increase by 0.5.

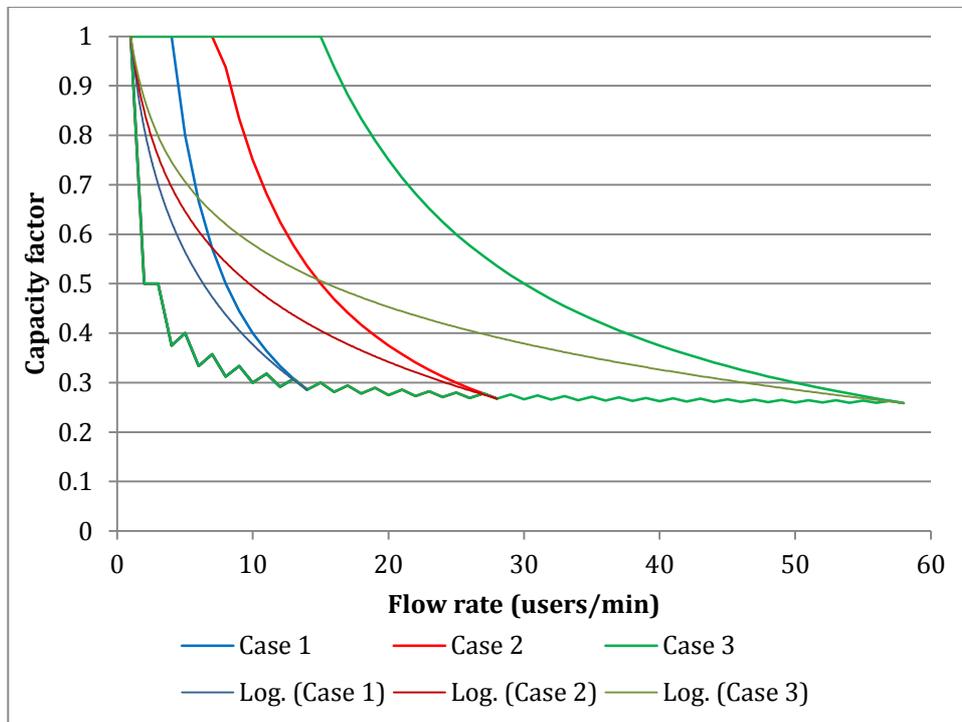
Envelope of operation

The envelope of operation for both uni and bi-directinal flow was considered, where the capacity factor was determined using,

$$c = \frac{N_{D.O.E.}}{FR}$$



**Fig. 5-13: Envelope of operation for limits to the capacity factor as a function of flow rate for uni-directional flow of a revolving door.**



**Fig. 5-14: Envelope of operation for limits to the capacity factor as a function of flow rate for bi-directional flow of a revolving door.**

with the results shown in fig.s 5-13 and 5-14. From these a number of conclusions can be drawn. It is seen that the maximum achievable capacity factor is dependant on the value of  $t_{D,O.E.}$ . Where uni and bi-directional flow have the same values for a given flow rate, however it is noted that the maximum flow rate is twice as high for bi-directional flow. It is also seen that there are very definite limitations to the maximum possible flow rate due to the requirement of each user to rotate the door to pass through, resulting in a maximum flow rate limited by the value of  $t_{D,O.E.}$ . In addition the requirement of the door to rotate to allow each user to pass through places limitations on the minimum achievable capacity factor. For uni and bi-directional flow the capacity factor tends to 0.5 and 0.25 respectively as the flow rate increases. This is significantly higher than for swing doors and suggests that revolving doors will offer significantly better values for the capacity factor.

#### Predicted values

In order to determine a value of the capacity factor for a given flow rate it was assumed that the trend would follow a logarithmic fit. It was considered that at  $FR = 1, c = 1$ , would act as the lower limit.

For the ending point, the value of c was taken from those calculated for the maximum achievable flow rate in fig.s 5-13 and 5-14, with the values shown in table 5-9.

**Table 5-9: Values of the capacity factor for the upper limit to flow rate for each case of the revolving door case.**

|                 | Case 1 |       | Case 2 |       | Case 3 |       |
|-----------------|--------|-------|--------|-------|--------|-------|
|                 | FR     | C     | FR     | C     | FR     | C     |
| Uni-directional | 7      | 0.571 | 14     | 0.536 | 29     | 0.517 |
| Bi-directional  | 14     | 0.286 | 28     | 0.268 | 58     | 0.259 |

These two points were used for each door case to determine a trend line from which the capacity factor could be determined for a given flow rate for cases 1, 2 and 3, where the equations determined for each case are shown in table 5-10.

**Table 5-10: Equations determined to calculate the capacity factor for a given flow rate for each case of the revolving door case.**

|                 | Case 1                                | Case 2                                | Case 3                                |
|-----------------|---------------------------------------|---------------------------------------|---------------------------------------|
| Uni-directional | $C = -0.22 \cdot \ln(\text{FR}) + 1$  | $C = -0.176 \cdot \ln(\text{FR}) + 1$ | $C = -0.143 \cdot \ln(\text{FR}) + 1$ |
| Bi-directional  | $C = -0.271 \cdot \ln(\text{FR}) + 1$ | $C = -0.22 \ln(\text{FR}) + 1$        | $C = -0.183 \ln(\text{FR}) + 1$       |

### Theoretical prediction

An attempt was made to determine the theoretical value for the capacity factor based on the probability distribution of flow rates. The same methodology was used as for the swing door, where the mean value of the contribution to flow rate was varied. The results are shown in table 5-11.

As would be expected, it was found that in all cases the value of C decreased as the mean contribution to potential value increased. For Bi-directional flow it was found that as  $t_{D.O.E}$  decreased, the value of C increased. For uni-directional flow it was not so simple. The highest

values for each mean were found for case 3 due to the low value of  $t_{D.O.E.}$ . It was however found that as the value of mean value of  $Pot_{norm}$  increased the values for the capacity factor for case 1 exceeded those of case 2, despite the higher value of  $t_{D.O.E.}$ . It was thought that this was a result of the low value of maximum flow rate for case 1. For uni-directional flow, the maximum flow rate was less than 7 people per minute, and hence the distribution of flow rates was significantly skewed when high flow rates were expected.

**Table 5-11: Calculated values of the capacity factor for varying values of the mean contribution to flow rate for uni and bi-directional flow.**

|                                    | Mean contribution to potential |     | 2.5  | 5    | 7.5  | 10   |
|------------------------------------|--------------------------------|-----|------|------|------|------|
| Case 1<br>( $t_{D.O.E.} = 16.3$ s) | C                              | Uni | 0.74 | 0.72 | 0.70 | 0.67 |
|                                    |                                | Bi  | 0.62 | 0.56 | 0.50 | 0.44 |
| Case 2<br>( $t_{D.O.E.} = 9.0$ s)  | C                              | Uni | 0.75 | 0.71 | 0.67 | 0.64 |
|                                    |                                | Bi  | 0.68 | 0.63 | 0.57 | 0.52 |
| Case 3<br>( $t_{D.O.E.} = 6.0$ s)  | C                              | Uni | 0.79 | 0.76 | 0.72 | 0.69 |
|                                    |                                | Bi  | 0.74 | 0.69 | 0.64 | 0.60 |

### 5.3. Energy models

Although it was seen that the expected energy outputs from a single use of a device were small it was thought that in a well chosen location the number of uses would be high, thus greatly increasing the energy harvested. This section aims to determine the energy outputs that are achievable from practically installed devices.

#### 5.3.1. Floor devices

Determining the expected energy generation output from a floor device was calculated as follows,

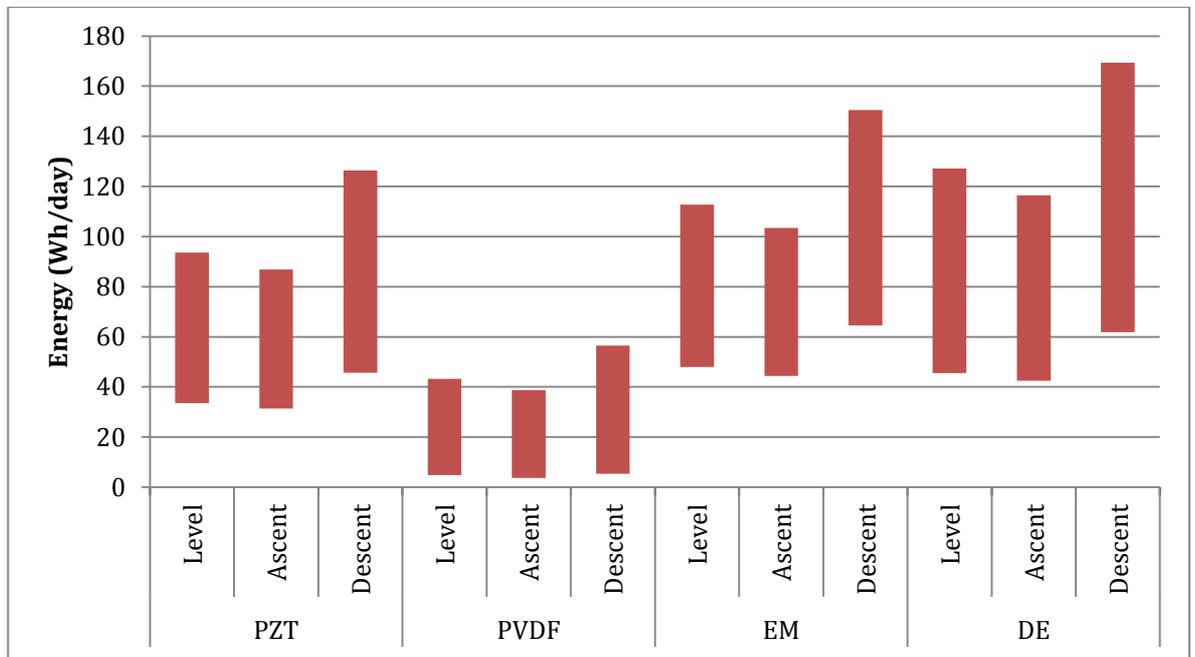
$$E_{tot} = N_{step} \cdot E_{step}$$

Where  $N_{\text{step}}$  was the number of steps taken on the device and  $E_{\text{step}}$  was the expected energy output from the floor device.

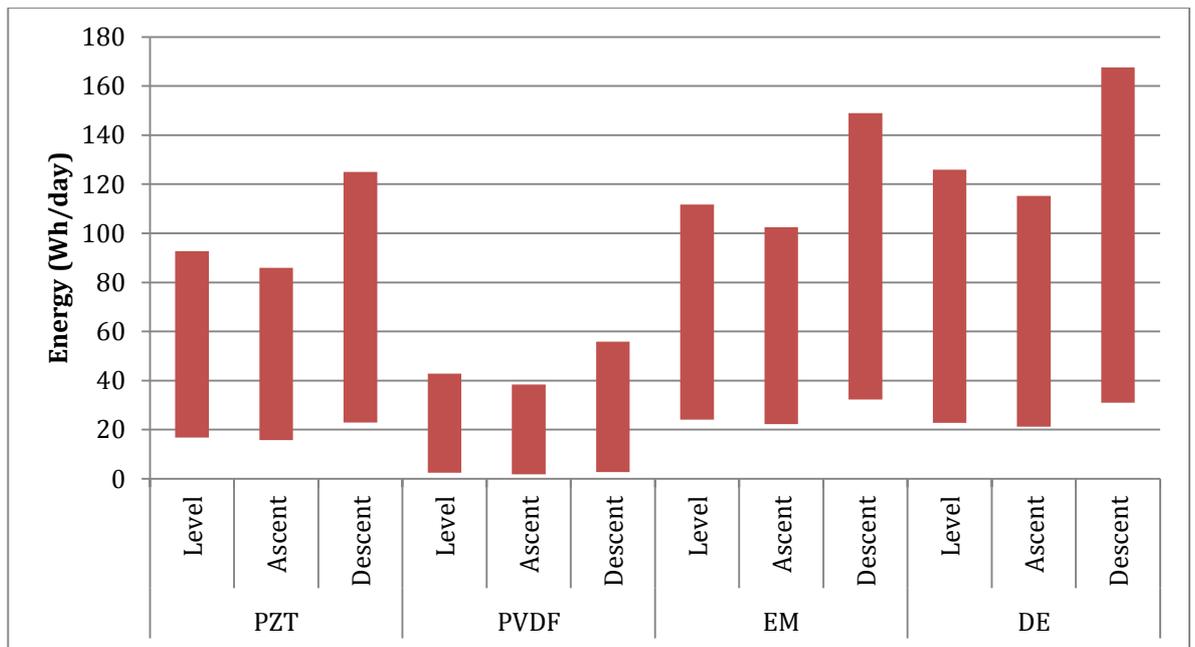
#### **5.3.1.1. Maximum energy outputs**

Determining the maximum energy generated by an individual device was easily determined by making an assumption about the maximum frequency of steps on the device. It was assumed that 1 step/s was the maximum frequency at which steps could occur on a device. As a result the maximum number of steps that could occur on an individual device over the course of a day was 86400 step/day. This was used to determine the maximum potential and in turn energy outputs from each of the technologies considered for floor devices over the course of a day, with the results presented in fig. 5-15. This was carried out for level walking, stair ascent and descent.

For level walking it was found that up to 112.8 and 127.2 Wh/day could be generated from a single device using an EM or DE generator respectively and assuming the upper limit for generation efficiency. As would be expected from the change in the Ground Reaction Force (GRF) for stair ascent and descent the expected generated energy outputs vary slightly. For stair ascent the energy outputs are slightly lower, giving a maximum of 116.4 Wh/day for DE technology. In contrast stair descent sees a substantial increase, with a maximum of 169.3 Wh/day for DE technology. This was to be expected due to the changes in energy potential of stair walking. The values represent the maximum energy generation potential from a single device, however practical values were expected to be significantly lower, owing to a decrease in expected activity. It was noted that these values were for a 70kg user as this was roughly the average for a person in the UK. In certain situations the average mass of the users may vary, for example in a school where a lower average mass would be expected. This would result in a decrease to the maximum energy generation.



**Fig. 5-15: Maximum energy output over the course of a day from a floor device for level walking, stair ascent and stair descent for each technology.**



**Fig. 5-16: Maximum energy output over the course of a day from a floor device for level walking, stair ascent and stair descent for each technology with energy storage.**

The useful energy delivered by the energy storage system was highly dependent on the energy efficiency of the storage system, with the generated and useful energy outputs presented in

fig. 5-16. It was expected that a high energy efficiency was achievable, in which case the useful energy delivered by the storage system to the load would nearly match that generated. It was evident however that a poorly chosen system with low energy efficiency would result in a significant proportion of the generated energy being wasted before it was delivered to the load.

**Table 5-12: Maximum available energy generation output range from a single flooring device as a function of device lifetime for each generation technology.**

| Lifetime |               | PZT         | PVDF       | EM            | DE            |
|----------|---------------|-------------|------------|---------------|---------------|
| (years)  |               | (kWh)       | (kWh)      | (kWh)         | (kWh)         |
| 1        | Level walking | 12.3-34.2   | 1.8-15.8   | 17.5-41.2     | 16.6-46.4     |
|          | Stair ascent  | 11.4-31.5   | 1.8-14.0   | 15.8-37.7     | 15.8-42.9     |
|          | Stair descent | 16.6-46.4   | 1.8-21.0   | 23.7-55.2     | 22.8-62.2     |
| 5        | Level walking | 61.3-170.8  | 8.8-78.8   | 87.6-205.9    | 83.2-232.1    |
|          | Stair ascent  | 56.9-157.7  | 8.8-70.1   | 78.8-188.3    | 78.8-214.6    |
|          | Stair descent | 83.2-232.1  | 8.8-105.1  | 118.3-275.9   | 113.9-311.0   |
| 10       | Level walking | 122.6-341.6 | 17.5-157.7 | 175.2-411.7   | 166.4-464.3   |
|          | Stair ascent  | 113.9-315.4 | 17.5-140.2 | 157.7-376.7   | 157.7-429.2   |
|          | Stair descent | 166.4-464.3 | 17.5-210.2 | 236.5-551.9   | 227.8-622.0   |
| 20       | Level walking | 245.3-683.3 | 35.0-315.4 | 350.4-823.4   | 332.9-928.6   |
|          | Stair ascent  | 227.8-630.8 | 35.0-280.3 | 315.4-753.4   | 315.4-858.5   |
|          | Stair descent | 332.9-928.6 | 35.0-420.5 | 473.0-1,103.8 | 455.5-1,243.9 |

The maximum achievable useful energy output over the lifetime of the device was then dependant on the expected lifetime of the device. Table 5-12 shows the maximum lifetime outputs for each of the generation technologies for varying device lifetimes. This was carried out for level walking, stair ascent and stair descent.

The expected lifetime of a device would evidently impact on the maximum achievable lifetime generation, as was shown in table 5-12. For level walking, the total lifetime generation was in the range 1.8 - 46.4 kWh and 35.0 - 929.6 kWh for device lifetimes of 1 and 20 years respectively. As would be expected, installation on stairs would impact these values. For stair ascent the 20 year maximum decreased to 858.5 kWh and for stair ascent it increased to 1.24 MWh. Although replacement of a floor device could in theory be simple, the economic and environmental viability was considered to be highly dependant on the overall energy generated by a device over it's lifetime and hence the device lifetime.

### 5.3.1.2. System outputs

Assessing the likely energy generation outputs from a system of devices was carried out as follows. This was most simply carried out by first assuming that the total area of interest was covered in floor generating tiles.

#### Level walking

The length and area of the location was assigned allowing the locations area to be calculated, it was assumed that the length,  $L$ , of the area was the distance over which each person must travel. It was assumed that the average stride length of a user was 0.78 m (Rowe, Barreira, & Kang, 2010), meaning the average number of steps taken by an individual,  $N_{person}$ , was given by,

$$N_{person} = \frac{L}{0.78}$$

The total number of steps,  $N_{Steps}$ , in a location was then dependent on the number of people,  $N_{people}$ , passing through and was given by,

$$N_{Step} = N_{person} \cdot N_{people}$$

This represents the total activity in a given location. The generated electrical energy was then determined by,

$$E_{Total} = N_{Steps} \cdot E_{Step}$$

This was used to assess the likely range of system energy outputs in a given location for the technologies presented. Since the range of energy outputs for a given technology was constant, the system energy output was dependant on the number of people passing through the location.

In practice it may not be feasible to install devices across the whole location area, but instead strategically distribute a number of devices within the area. The expected energy outputs were simply assessed by assuming that the distribution of steps was evenly spread throughout the area. In this case the proportion of the total number of steps utilised by the system was given by  $\eta_{step}$ , as set out in section 5.2.1., with the expected system energy output given as,

$$E_{Total} = \eta_{step} \cdot N_{step} \cdot E_{Step}$$

It should be noted that if the whole floor area was covered by devices, then  $\eta_{step} = 1$ .

To determine the expected energy outputs, three parameters were independently tested. These were the number of people, the proportion of utilised potential and the length each user was required to walk along, where table 5-13 showed the range explored for these parameters. The width of the area covered by devices was considered to be 3 m. When testing one of the parameters the other two are held constant, where  $N_{people} = 10,000$ ,  $\eta_{step} = 1$  and  $L = 10$  m. In terms of the number of people passing through a location, it was expected that this can range from very low values where only a few people pass through a location, up to very high values where hundreds of thousands of people pass through a location. As an example, King's cross tube station in London was reported to have in excess of 240,000 people passing through the ticket gates on an average weekday in 2013 (TFL, 2013). Ultimately the total energy generated depends on the number of steps taken on the installed devices, with the number of steps dependant on each of the variables assessed.

**Table 5-13: Parameter values used to assess the expected energy outputs of a system of energy harvesting devices.**

|                      |    |     |       |       |        |        |         |         |
|----------------------|----|-----|-------|-------|--------|--------|---------|---------|
| $N_{\text{people}}$  | 50 | 100 | 1,000 | 5,000 | 10,000 | 50,000 | 100,000 | 200,000 |
| $\eta_{\text{step}}$ | 0  | 0.1 | 0.2   | 0.4   | 0.5    | 0.6    | 0.8     | 1       |
| L (m)                | 1  | 5   | 10    | 25    | 50     | 75     | 100     | 150     |

The number of people was likely to be highly dependant on the location at which the system is installed. It was expected that this would vary greatly between locations. The range of values for the number of users was varied between 50 and 200,000 people to represent areas from very low to very high activity with the results shown in fig 5-17. In the case of 50 people the generated energy was less than 1 Wh for all of the technologies. For locations with very high activity the expected energy generated was found to be in excess of 1 kWh/day, with a peak range of 1.35-3.77 kWh/day for DE technology. Similarly for the length walked by the users, the generated energy increased linearly with distance walked. This was a direct result of the total number of steps each user would be required to walk to pass through a location. The length walked by the users was varied from 1m to 150m, with generated energy values for DE technology of 6.77-18.87 Wh/day and 1.01-2.83 kWh/day respectively. It was seen that of the generation technologies presented, the expected outputs from PVDF were less than half of those obtained from the other generation technologies.

In many of the case studies presented for the commercially available devices it was seen that the devices were dispersed over an area and thus not all of the footsteps occurring in the location would be harvested. When assuming that the potential was evenly distributed across the location's area, the generated energy decreased linearly with a decreased proportion of area covered by devices as shown in fig. 5-18. Similarly the length over which each user was expected to walk would affect the energy generated due to the change in number of steps of each user with the results shown in fig. 5-19.

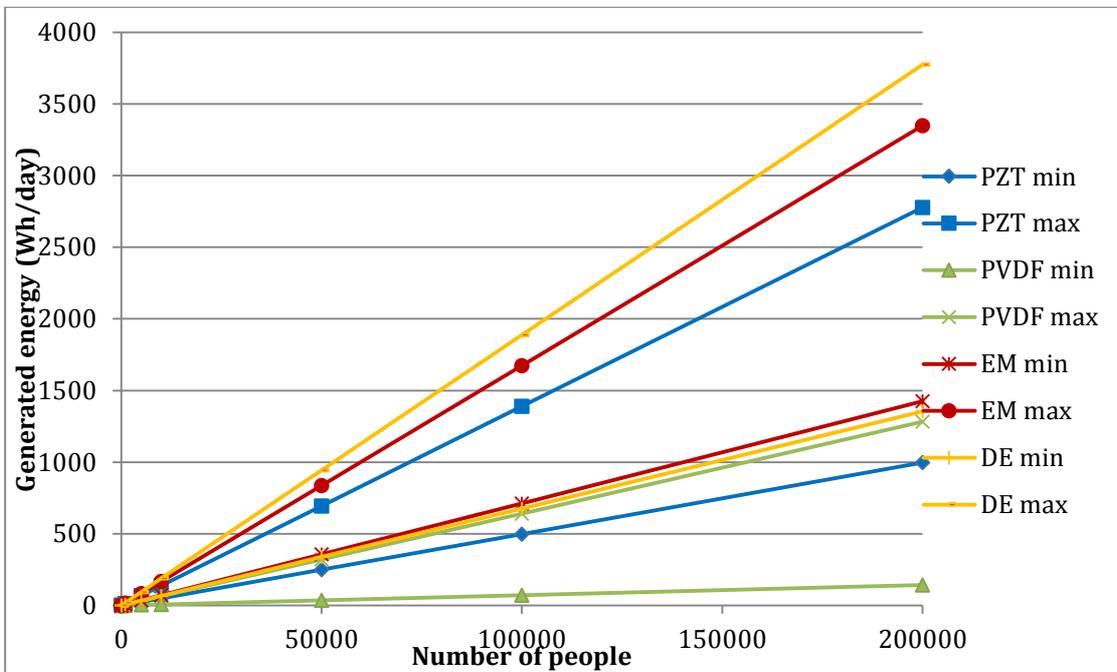


Fig. 5-17: Daily generated energy outputs for a system of energy harvesting floor devices as a function of the number of people using the location.

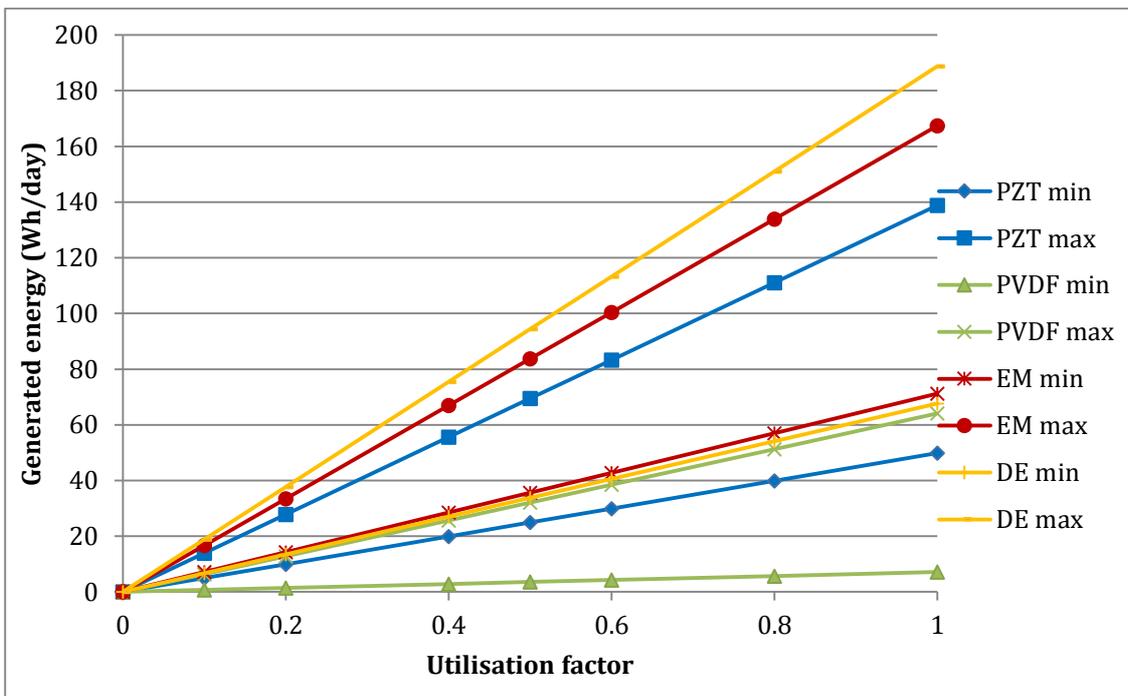


Fig. 5-18: Daily generated energy outputs for a system of energy harvesting floor devices as a function of the utilisation factor.

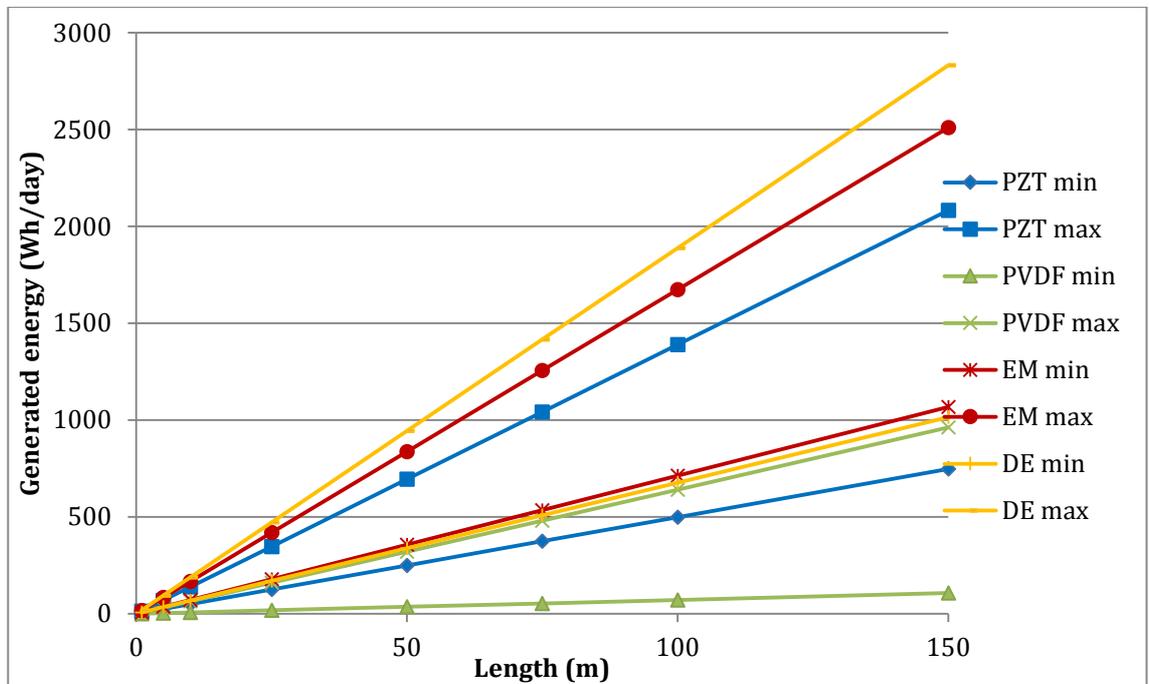


Fig. 5-19: Daily generated energy outputs for a system of energy harvesting floor devices as a function of length travelled by each user.

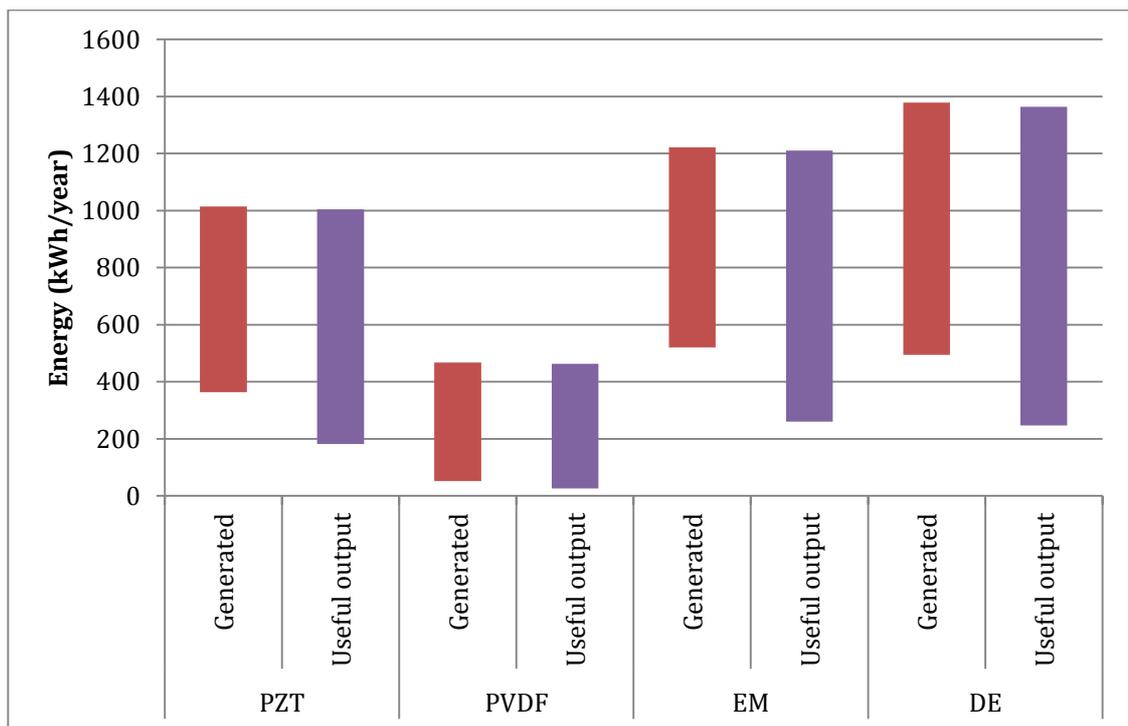


Fig. 5-20: Annual energy output from 10m x 3m area with 200,000 users per day, with the generated energy and energy available after storage for each of the energy generation technologies.

The energy output from a 10m (length) x 3m (width) area with 200,000 users/day was presented in fig. 5-20 with both generated energy and useful energy delivered by the energy storage system. It was seen that maximum values of >1 MWh/year were expected for PZT, EM and DE generators where high energy efficiency of the storage system was assumed. This contrasts dramatically with the lower end of expected values where values <260 kWh/year were found for all technologies due to both lower generation and storage energy efficiency. The lowest value used for energy storage efficiency was 50%, meaning that half of the generated energy was wasted in the process of delivery of useful energy to the load.

### Stairs walking

A similar approach to level walking was used to assess the energy generation from a system of floor generators installed on stairs. A number of differences were however apparent and were considered to model the likely outputs. The first change was the number of steps taken by an individual being determined by the number of steps in the flight of stairs, based on the assumption that only one step was taken at a time by an individual. The second difference concerns the number of people assumed to use the location. Unlike with level walking, where each user was considered in the same way, the energy generated by a user on a stair was dependant on whether they were ascending or descending the stairs. As such the total activity was considered in terms of the stair ascent and descent activity with the total number of steps taken for each calculated. As such the total energy generated was calculated using,

$$E_{tot} = E_{ascent} + E_{Descent}$$

The values obtained would still be dependant on the number of steps taken on the stairs. The number of steps taken in each direction was calculated using the following equations.

$$N_{step\_ascent} = N_{people} \cdot N_{stairs} \cdot \eta_{ascent}$$

$$N_{step\_descent} = N_{people} \cdot N_{stairs} \cdot (1 - \eta_{ascent})$$

Where  $N_{people}$  was the number of people using the staircase,  $N_{stairs}$  was the number of stairs in the staircase and  $\eta_{ascent}$  was the proportion of the total users who ascend the staircase, where

the value ranges from 0-1. From this the energy generated by stair ascent and descent was found using,

$$E_{ascent} = N_{step\_ascent} \cdot E_{step\_ascent}$$

$$E_{descent} = N_{step\_descent} \cdot E_{step\_descent}$$

Where  $E_{ascent}$  and  $E_{descent}$  were the values for the energy generated per step for ascending and descending the stairs respectively.

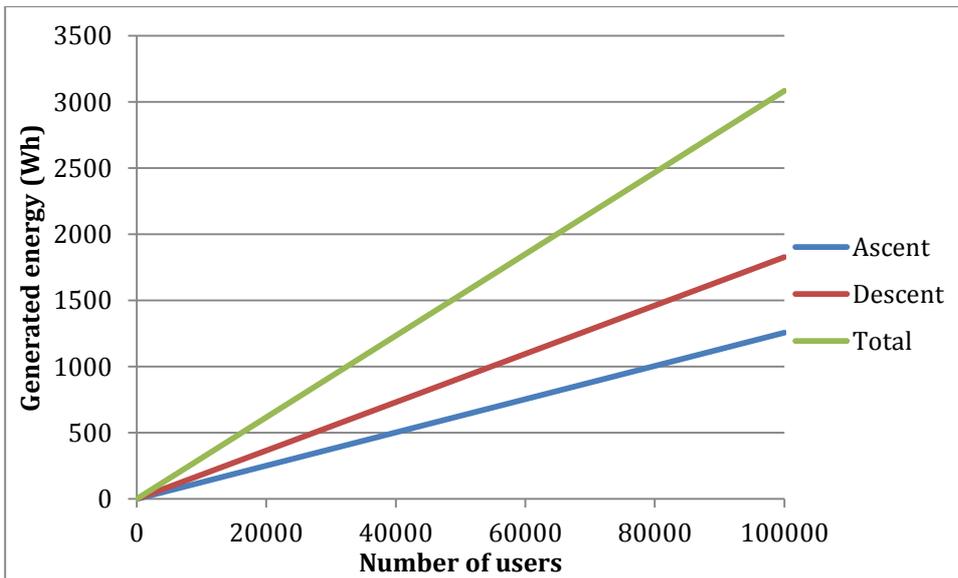
This methodology was used to assess the expected generated energy outputs of a system of devices installed on a staircase. To test this, three variables were independently varied  $N_{people}$ ,  $N_{stairs}$  and  $\eta_{ascent}$  with the values shown in table 5-14. Baseline values were assigned for each of these parameters and used when the parameter was not a variable and were as follows,  $N_{people} = 1,000$ ,  $N_{stairs} = 25$  and  $\eta_{ascent} = 0.5$ .

**Table 5-14: Values used to assess the affect of the number of people, number of steps and the proportion of users ascending the stairs on the generated energy outputs from stair use.**

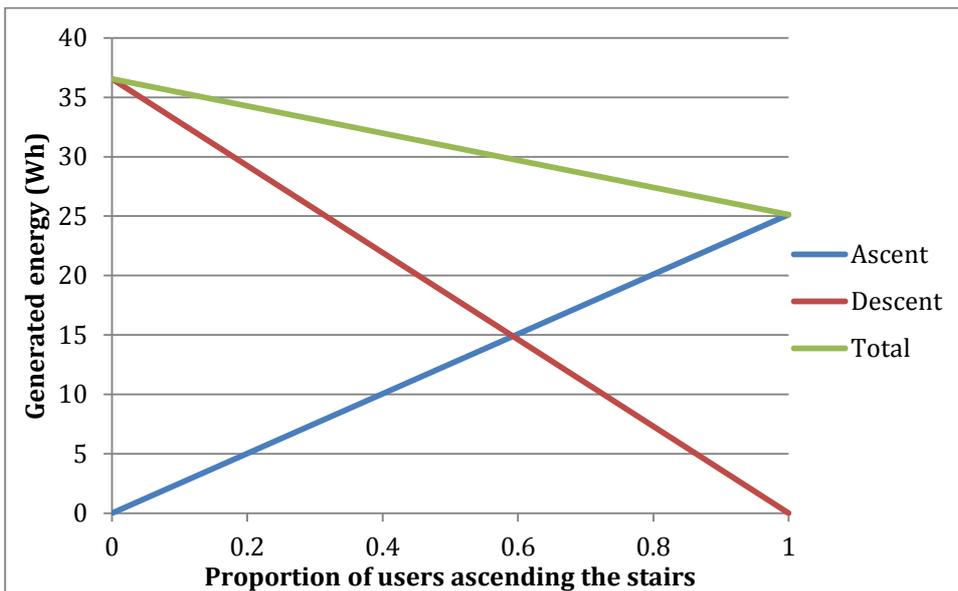
|               |    |     |      |       |        |    |
|---------------|----|-----|------|-------|--------|----|
| $N_{people}$  | 10 | 100 | 1000 | 10000 | 100000 | -  |
| $N_{steps}$   | 5  | 10  | 15   | 20    | 25     | 50 |
| $\eta_{step}$ | 0  | 0.2 | 0.4  | 0.6   | 0.8    | 1  |

In the case of stair walking the direction of the user affects the energy generated per step, where stair descent gave higher outputs than ascent. As such the total energy generated depended on both the number of steps and the direction of flow of the user. In the case of  $\eta_{ascent} = 0.5$ , the contribution from users ascending the stairs was ~40% of the total generated energy. Varying the value of  $\eta_{ascent}$  from 0-1 resulted in a decrease in the energy generated, for a DE generator the expected ranges were 17.9-49 and 12.3-33.7 Wh/day for  $\eta_{ascent} = 0$  and 1 respectively as seen in fig. 5-22. In the work of (Blake, Lee, Stanton, & Gorely, 2008) stair use was observed in two stair wells in a hospital, these revealed that the proportion of people ascending the stairs was 37.4 % and 44.0 % for the two stairwells. This implies that users were

more likely to descend stairs than ascend when there was an alternative method of travelling between floors, where a value of  $\eta_{\text{ascent}} = 0.4$  seems reasonable. There will not always be an alternative mode of travelling between floors and in this instance it seemed likely that a value of  $\eta_{\text{ascent}} = 0.5$  would be expected. Although this appears to imply that such locations would result in a lower value of generated energy, it was considered that the total activity would be larger as there was no alternative means of travelling between floors and hence users who may choose to use alternative means would be forced to use the stairs.

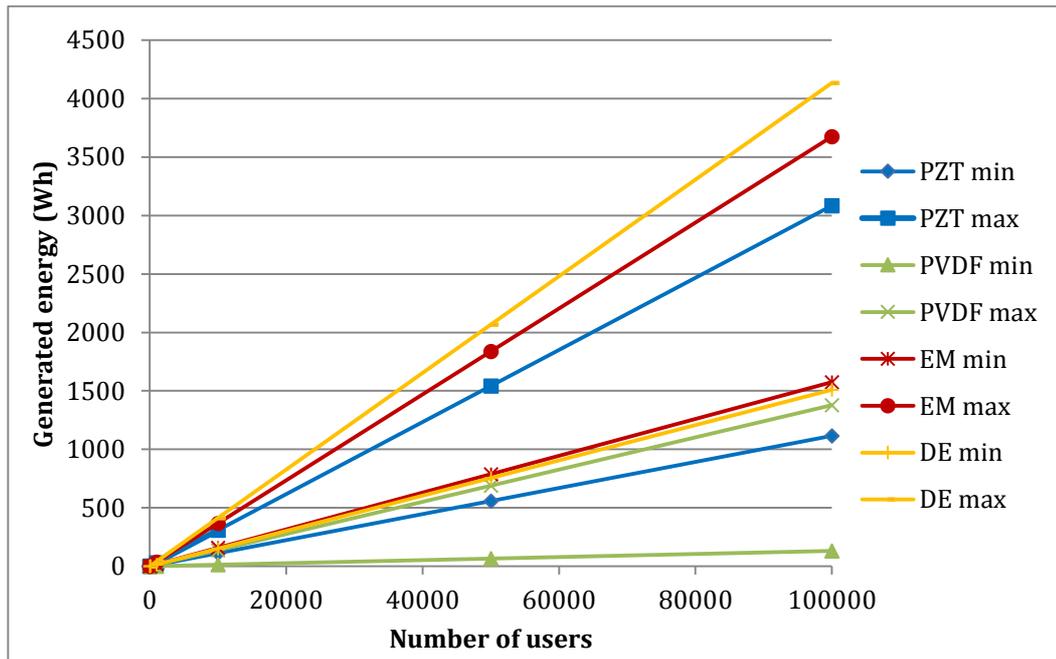


**Fig. 5-21: Daily total generated energy and contribution of stair ascent and descent where the number of user ascending and descending the stairs is equal.**

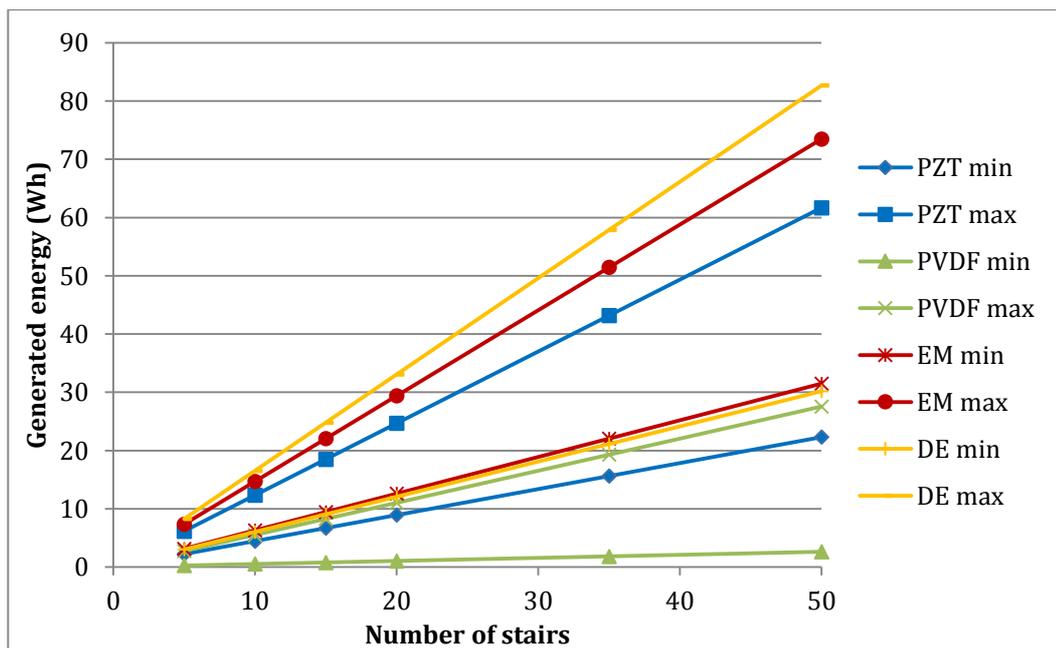


**Fig. 5-22: Influence of varying proportion of users ascending the stairs on the daily total energy generated and the contribution to this total from stair ascent and descent.**

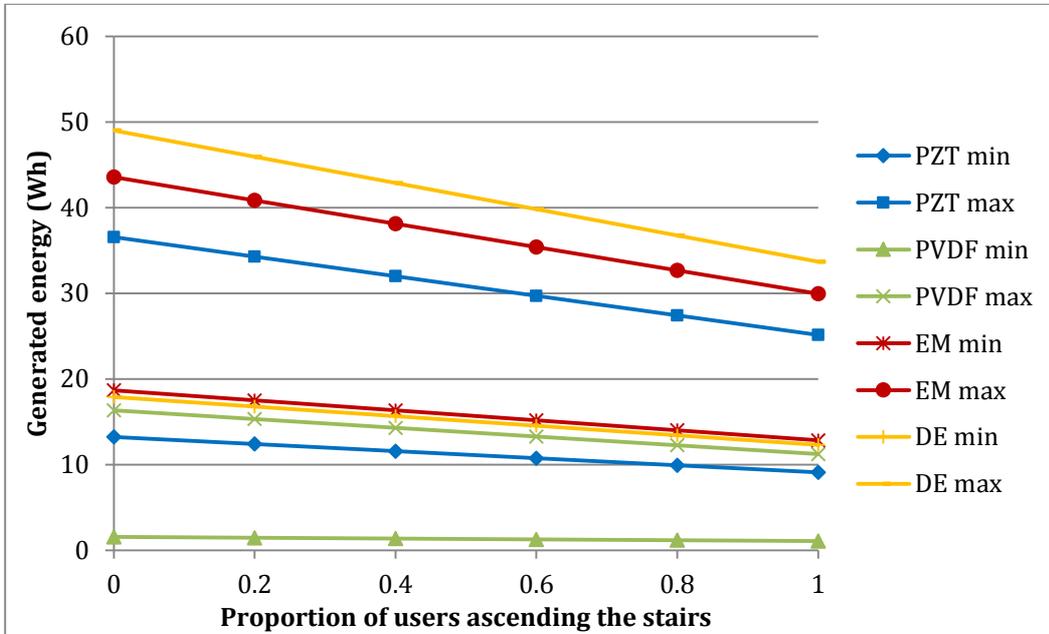
The number of steps taken was dependant on the number of users and the number of stairs with installed devices. The number of steps taken varies linearly with both of these variables, with an associated linear change in the total generated energy as was shown in fig.s 5-23 and 5-24.



**Fig. 5-23: Daily Energy outputs from a system of energy harvesting devices installed on stairs as a function of the number of users for each of the energy generation technologies.**



**Fig. 5-24: Daily energy outputs from a system of energy harvesting devices installed on stairs for varying number of stairs for each of the energy generation technologies.**



**Fig. 5-25: Daily energy outputs of a system of energy harvesting devices installed on stairs for varying proportions of users descending the stairs for each of the energy generation technologies.**

There is very little research available considering the overall potential offered by human energy harvesting in the urban environment. Four student led studies were carried out at the University of British Columbia to assess the potential offered from the installation of 8 Pavegen tiles (Cramm, El-Sherif, Lee, & Loughlin, 2011), (Epp, Bal, & Bhogal, 2011), (Crockett, Fleming, & Kim, 2011) and (Seow, Chen, & Khairudin, 2011). The discrepancy between the calculated energy outputs from these studies was very large, ranging from 56 kWh/day (Cramm et al., 2011) to 8,400 J/day (Epp et al., 2011). The assumptions for the activity experienced by the devices were fairly similar for each, where several thousand steps/day were assumed. The consideration of the energy available from a footstep varies however by several orders of magnitude. In the work of (Epp et al., 2011) a value of 2.1 J/step was considered and in (Crockett et al., 2011) 3 J/step, both were compatible with the values determined in chapter 4 of this thesis although less than half the maximum value advertised by Pavegen. It was calculated in (Crockett et al., 2011) that just over 1kWh/year would be expected from the 8 installed tiles. In contrast a value of 0.293 Wh/step (~1 kJ/step) was used in (Seow et al., 2011) and the calculations used to determine energy output in (Cramm et al., 2011) were not clear. As such only the values presented in (Epp et al., 2011) and (Crockett et al., 2011) seem to produce reasonable outputs.

### 5.3.2. Swing door devices

Thus far the utilisation of potential and the energy generation potential of swing door opening events was discussed. What follows was a consideration of the energy generation from swing doors in a practical location.

#### 5.3.2.1. Maximum energy output

Using the outputs from section 4.4.2., the potential for energy generation from a swing door device was assessed. First an upper limit for energy generation was determined as laid out below.

Over the course of a day the maximum number of possible door opening events was determined using,

$$N_{D.O.E.} = \frac{86400}{t_{D.O.E.}}$$

Where the time was expressed in the units of seconds and 86400 was the number of seconds in a day. The maximum potential for energy generation was then given by,

$$E_{Max} = E_{D.O.E.} \times N_{D.O.E.}$$

The results from this were presented in table 5-15. Theoretically it appears there was significant potential from swing door energy harvesting, it was expected that these maximum values represent a gross overestimation of the likely outputs. The maximum energy output that was generated from a door device was found to be dependant on two factors, the maximum number of door openings and the value of generated energy per door opening event ( $E_{D.O.E.}$ ). It was found that there was a wide range in these values depending on the method of generation, where the highest range was found for method 3 with 24.5-57.4 Wh/day as shown in table 5-15. This represents the maximum achievable output, however this requires people to continuously pass through the door and for the capacity factor to be 1.

As such the expected energy outputs for the activity scenarios described earlier and for a range of activity levels were explored.

**Table 5-15: Table showing the results for the daily maximum energy generation potential for each method of generation of a swing door.**

| Generation method |                         | $t_{D.O.E.}$ | $N_{D.O.E.}$ | $E_{D.O.E.}$ | $E_{max}$  |           | Useful $E_{max}$ |
|-------------------|-------------------------|--------------|--------------|--------------|------------|-----------|------------------|
|                   |                         | (s)          |              | (J/D.O.E.)   | (kJ/day)   | (Wh/day)  | (Wh/day)         |
| 1                 |                         | 4.2          | 20,571       | 2.2-5        | 45.3-102.9 | 12.6-28.6 | 6.3-28.3         |
| 2                 | $k_2=2.8\text{Nm/rad}$  | 5.0          | 17,280       | 1-2.2        | 17.3-38.0  | 4.8-10.6  | 2.4-10.5         |
|                   | $k_2=5.6\text{Nm/rad}$  | 5.5          | 15,709       | 1.9-4.4      | 29.8-69.1  | 8.3-19.2  | 4.2-19.0         |
|                   | $k_2=8.4\text{Nm/rad}$  | 6.4          | 13,500       | 2.9-6.7      | 39.2-90.5  | 10.9-25.1 | 5.5-24.8         |
|                   | $k_2=11.2\text{Nm/rad}$ | 8.3          | 10,410       | 3.8-8.8      | 39.6-91.6  | 11.0-25.4 | 5.5-25.1         |
| 3                 |                         | 4.6          | 18,783       | 4.7-11       | 88.3-206.6 | 24.5-57.4 | 12.3-56.8        |

### 5.3.2.2. Expected energy outputs

The total energy generated,  $E_{tot}$ , from a door device in a practical location was given by,

$$E_{Tot} = E_{D.O.E.} \cdot N_{Expected} \cdot C_{theoretical}$$

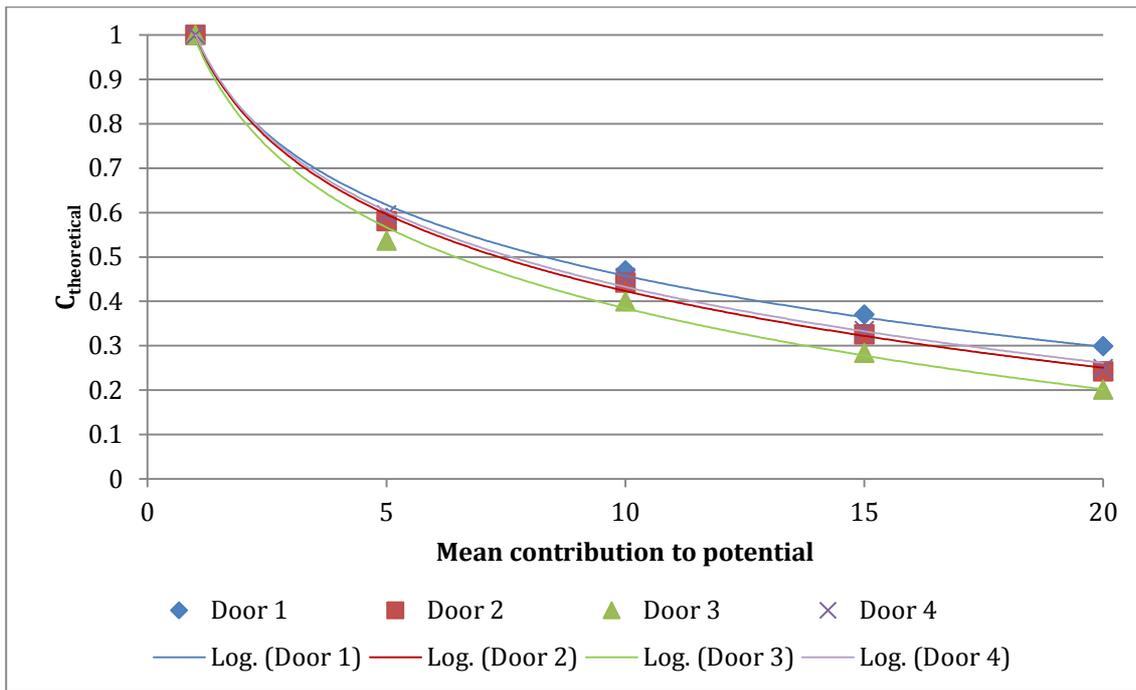
Where  $N_{expected}$  was the number of people that were expected to pass through the door during the course of the day and was varied to consider the impact of the total activity at a location.  $C_{theoretical}$  was to be determined based on the distribution of activity throughout the day and the expected value of  $t_{D.O.E.}$ . The values of  $E_{D.O.E.}$  presented in table 5-2 were used, where the associated values of  $t_{D.O.E.}$  were used to determine values of  $C_{theoretical}$ .

As was seen in section 5.2.2., the value of  $C_{theoretical}$  was dependent on a several factors with a wide range of potential values. Thus determination of these values was based on a number of assumptions, as laid out below. In table 5-16 the number of users over the course of the day was varied between 50 and 10,000 users/day. It was likely that if a door experiences a high number of users over the course of the day then the value of  $C_{theoretical}$  would be lower than for

a door which experienced a low number of users since it was likely that the contribution to total potential would be more dependent on higher values of FR. It was noted that the number of users did not exactly relate to the mean contribution to flow rate, but it did place limitations on the values. In order to consider the total expected energy outputs it was necessary to make a few assumptions.

- It was assumed that the distribution of potential was a normal distribution with s.d. = 5. As such it was the value of mean contribution to potential that was important.
- A value for FR = 0 was assigned to represent the percentage of time for which the door experiences an FR of 0 people/min. This was assigned in a fairly arbitrary manner, where an increase to the number of users was expected to result in a lower probability of FR = 0. In order to complete this a number of assumptions were made. Firstly it was assumed that over the course of a day the time over which the door was used occurs over a 10 hour period with the distribution of users spread relatively evenly over this time.
- This was used to determine the mean flow in the minutes where FR  $\neq$  0. This value was assumed to be the mean value of the normal distribution.
- Equations for determining  $C_{\text{theoretical}}$  were determined for varying mean values and extrapolated back to 1, where 1 gives  $C_{\text{theoretical}} = 1$ . This was carried out with the results shown in fig. 5-26, for each of the door values.. This allowed a  $C_{\text{theoretical}}$  value to be determined for each of the numbers of users, where  $t_{\text{D.O.E.}} = 6$  s. The results of which for the assigned number of users are shown in table 5-16.
- Define envelope of operation assumptions. This was calculated based on the assumption that the users pass through the door at evenly distributed intervals throughout the minute intervals of a day. The mean flow rate was then used to determine a value of  $C_{\text{theoretical}}$ . If the mean flow rate was  $< 1$ , then it is assumed that  $C_{\text{theoretical}} = 1$ . It should be noted that for  $FR_{\text{mean}} > 1$ , the distribution within a given minute was not considered to be distributed evenly but instead the value of  $C_{\text{theoretical}}$  was determined from the equations determined in 5.2.2.2.. If it were assumed that the distribution of users was spread evenly throughout each minute then the maximum number of users for which  $C_{\text{theoretical}} = 1$  would depend on the value of  $t_{\text{D.O.E.}}$ .

It was noted that changes to the assumptions set out above could significantly impact upon the results.

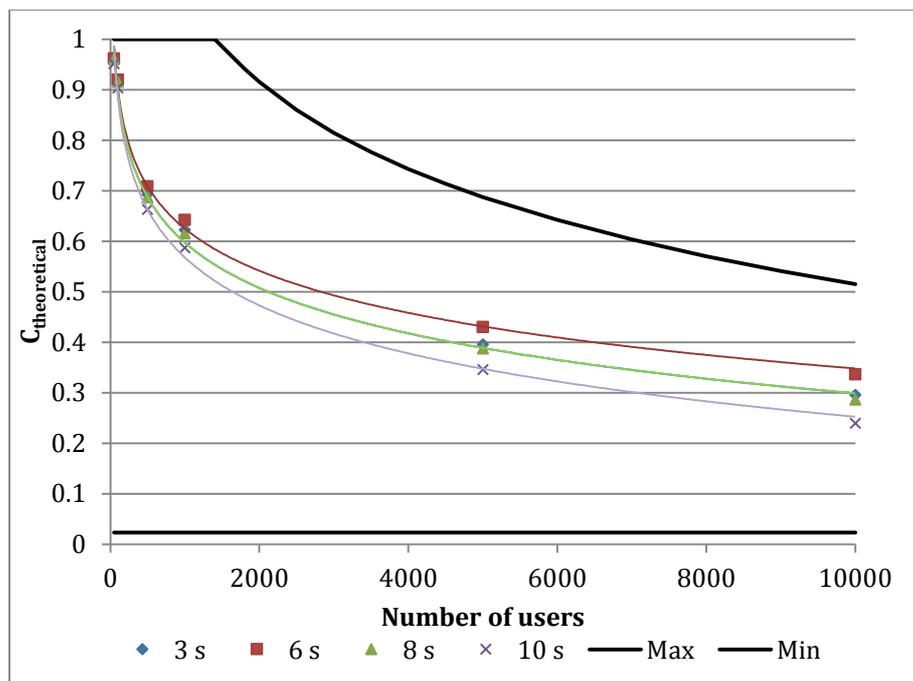


**Fig. 5-26: Variations to the theoretical capacity factor of a swing door as a function of the mean contribution to flow rate.**

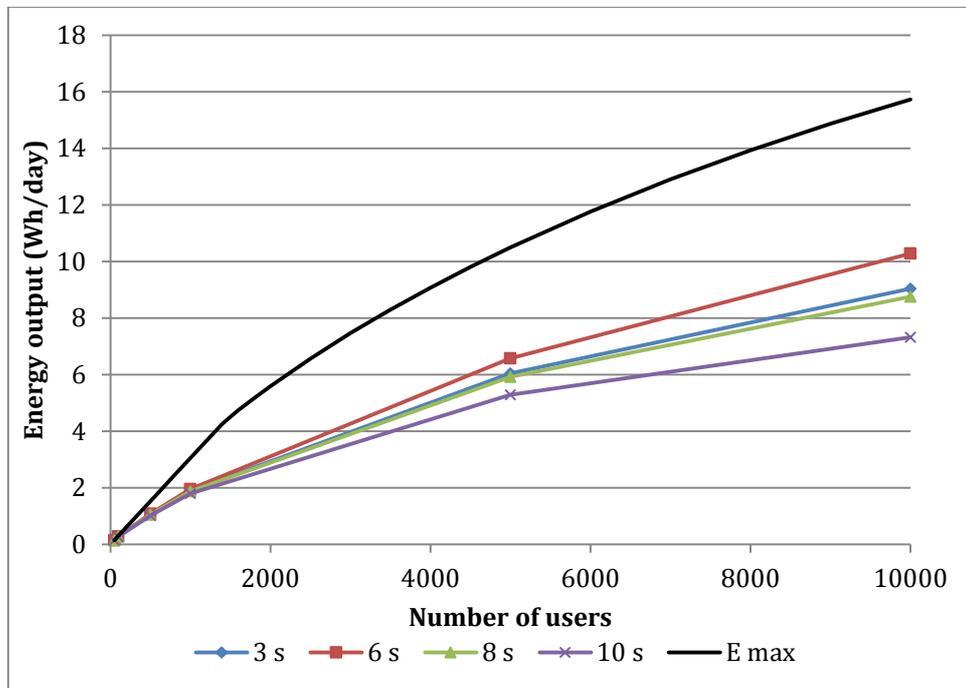
Based on these assumptions it was determined that for 50 users and  $t_{D,O.E.} = 10s$  the value of  $C_{theoretical}$  was 0.95. This fell quickly with an increase in the number of users, where for 10,000 users a value of 0.24 was calculated. The value of  $t_{D,O.E.}$  was expected to have very little affect for a small number of users, but to increase with user numbers, where a difference of 0.10 was found in the value of  $C_{theoretical}$  for 10,000 users, as was seen in table 5-16. It was found that a logarithmic function fitted this drop for each value of  $t_{D,O.E.}$ . In addition it was noted that an envelope of operation was shown on fig. 5-27, this indicates that the value of  $C_{theoretical}$  could vary considerably for a given number of users and depends on the distribution with respect to time of users through the door. Hence the values calculated represent the likely energy outputs based on the assumptions made. It was noted that the envelope of operation does not actually represent the absolute maximum as the maximum number of users for a door with  $t_{D,O.E.} = 10 s$  and  $C = 1$ , was 8640 users. This was for the case where users continually use the door and are distributed at 10 s intervals. The envelope of operation shown assumes that for more than 1 user in a given minute and a large number of tests would result in  $C < 1$ .

**Table 5-16: Assumptions used to determine the theoretical value of the capacity factor for varying numbers of users over the course of a day for a swing door.**

| Number of users | FR = 0 (%) | Mean flow rate contribution | $C_{\text{theoretical}}$ |        |        |         |
|-----------------|------------|-----------------------------|--------------------------|--------|--------|---------|
|                 |            |                             | t = 3s                   | t = 6s | t = 8s | t = 10s |
| 50              | 0.97       | 1.16                        | 0.96                     | 0.96   | 0.96   | 0.95    |
| 100             | 0.95       | 1.39                        | 0.92                     | 0.92   | 0.92   | 0.90    |
| 500             | 0.90       | 3.47                        | 0.69                     | 0.71   | 0.69   | 0.66    |
| 1000            | 0.85       | 4.63                        | 0.62                     | 0.64   | 0.62   | 0.59    |
| 5000            | 0.7        | 11.57                       | 0.40                     | 0.43   | 0.39   | 0.35    |
| 10000           | 0.6        | 17.36                       | 0.30                     | 0.34   | 0.29   | 0.24    |



**Fig. 5-27: Plot showing the theoretical capacity factors of a swing door used as a function of the number of users over the course of a day.**



**Fig. 5-28: Expected daily energy outputs for different door opening times of a swing door and varying number of users over a day. A maximum value is shown, where the energy generated per door opening event is 11 J/D.O.E..**

As a result of the expected decrease in  $C_{\text{theoretical}}$  with the increased number of users the expected values for generated energy did not increase linearly, as was seen in fig. 5-28. The expected energy outputs increased with increasing number of users, however the decreasing value of  $C_{\text{theoretical}}$  with increased number of users resulted in the expected energy outputs tailing off. The maximum outputs were in the range of 7.32-10.29 Wh/day for 10,000 users. The maximum expected outputs were also shown for the upper limit of  $C_{\text{theoretical}}$  where a peak of 15.73 Wh/day was calculated for 10,000 users. As was expected from the calculated values of  $C_{\text{theoretical}}$  the value of  $t_{\text{D.O.E.}}$  plays a role in determining the expected energy outputs. This was minimal for a low number of users and increased as the number of users increased.

Fig. 5-29 shows that for high energy efficiency of energy storage the useful energy output was not significantly lower than the generated energy.

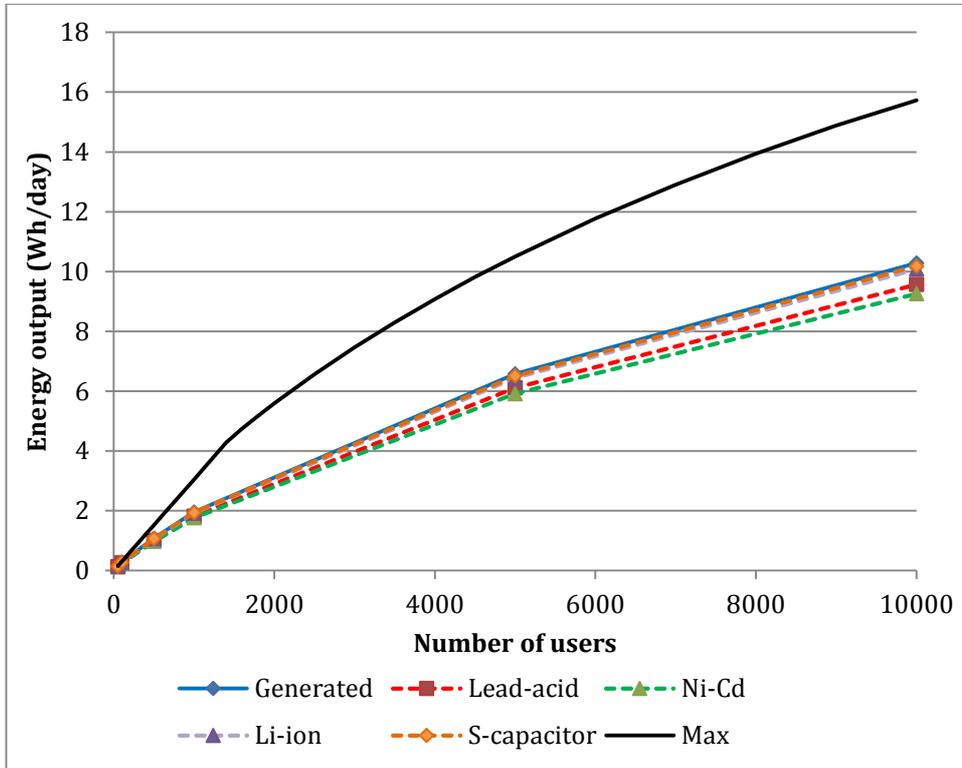


Fig. 5-29: Daily energy output from a swing door device for varying user numbers and each of the energy storage technologies.

### 5.3.3. Revolving door devices

#### 5.3.3.1. Maximum output

The maximum achievable output from a revolving door was considered in a slightly different way to the swing door. This was a result of the revolving door not being required to close, but instead a maximum output was considered for the situation where the door is in continual use. As such it was decided that a more appropriate method would be to consider the power dissipated through the revolving door. Thus the maximum achievable outputs were calculated using.

$$E_{max} = P \times 86400$$

Since the maximum output is for the case where the door is in continual use, it does not make a difference if the flow of people is uni or bi-directional.

**Table 5-17: Potential power output and range of maximum generated energy values for the revolving door over the course of a day for each of the cases considered.**

|                           | Case 1      | Case 2       | Case 3       |
|---------------------------|-------------|--------------|--------------|
| $P_{ave}$ (W)             | 0.96 – 2.24 | 1.92 – 4.48  | 3.84 – 8.96  |
| Generation $E_{max}$ (Wh) | 23.0 – 53.8 | 46.1 – 107.5 | 92.2 – 215.0 |

The maximum energy output from a revolving door is depends on the maximum value of  $P_{ave}$ . The maximum range of values was found for case 3, where  $E_{max} = 92.2 – 215$  Wh/day. This far exceeds the performance of the swing door devices. Even for case 1, where the lowest outputs were found, the results are comparable with the best performing swing door device.

### 5.3.3.2. Expected outputs

In order to determine the expected energy outputs for a range of activity levels the same methodology set out for the swing door (section 5.3.2.2.) was followed, with the results shown in table 5-18 and Fig.s 5-30, 5-31 and 5-32 for case 1,2 and 3 respectively.

Since the flow rate of users through the revolving door is limited by the value of  $t_{D.O.E.}$ , it was found that for case 1 that the required flow rate was higher than the maximum achievable flow rate for the highest number of users. This was more pronounced for uni-directional flow since the maximum flow rate is half that for bi-directional flow. As such a number of additional values for the number of users per day were included to give a better estimate for the range of expected values. These values were for 2,500, 7,250 user per day. These correspond to the limitation of the uni-directional flow for case 1 and case 2 respectively.

In addition since the limits to the range of values for the capacity factor are limited by the value of  $t_{D.O.E.}$  it is possible to determine an envelope of operation for each case. The maximum value represents the maximum achievable generated energy if the potential offered by the users is spread evenly over 10 hours and assumes both the maximum energy output per D.O.E. and the maximum achievable capacity factor. The minimum value represents both the minimum energy output per D.O.E. and the minimum achievable capacity factor. The minimum achievable capacity factor is taken assuming bi-directional flow. The area enclosed

by these lines is the possible range of values for the displaced emissions, where for a given number of users over a day, the displaced emissions must fall within this range. Alternatively an expected maximum value is considered where the mean flow rate contribution of users is taken from table 5-18, with the assumption of the maximum achievable capacity factor and maximum  $E_{D,O.E.}$ .

**Table 5-18: Assumptions used to determine the theoretical value of the capacity factor for varying numbers of users over the course of a day for a revolving door.**

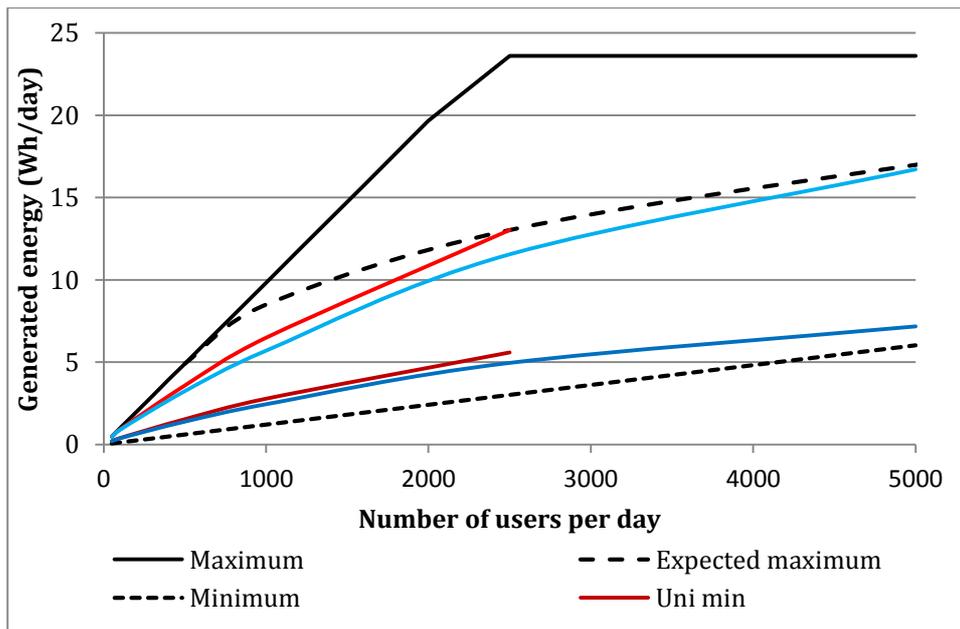
| Number of users | FR = 0 (%) | Mean flow rate contribution | $C_{theoretical}$ |      |        |      |        |      |
|-----------------|------------|-----------------------------|-------------------|------|--------|------|--------|------|
|                 |            |                             | Case 1            |      | Case 2 |      | Case 3 |      |
|                 |            |                             | Uni               | Bi   | Uni    | Bi   | Uni    | Bi   |
| 50              | 0.97       | 1.16                        | 0.97              | 0.96 | 0.97   | 0.97 | 0.98   | 0.97 |
| 100             | 0.95       | 1.39                        | 0.93              | 0.91 | 0.94   | 0.93 | 0.95   | 0.94 |
| 500             | 0.90       | 3.47                        | 0.73              | 0.66 | 0.78   | 0.73 | 0.82   | 0.77 |
| 1000            | 0.85       | 4.63                        | 0.66              | 0.58 | 0.73   | 0.66 | 0.78   | 0.72 |
| 2500            | 0.77       | 7.55                        | 0.53              | 0.47 | -      | -    | -      | -    |
| 5000            | 0.7        | 11.57                       | -                 | 0.35 | 0.57   | 0.46 | 0.65   | 0.55 |
| 7250            | 0.65       | 14.38                       | -                 | -    | 0.52   | 0.42 | -      | -    |
| 10000           | 0.6        | 17.36                       | -                 | -    | -      | 0.37 | 0.59   | 0.48 |

As was the case with the swing door, the capacity factor decreased as the number of users increased as reflects the findings of section 5.2.3., with the values used shown in table 5-18. It was however found that this rate of decrease was lower in the case of revolving doors.

For each of the cases, the decrease in the capacity factor was greater for bi-directional flow than uni-directional flow. This suggests that uni-directional flow is preferable to bi-directional flow, however it does place a far greater constraint on the number of users able to use the door. To clarify, in general it is not expected that the direction of travel would be constrained

to one direction, but instead will be a result of the location in which the door is installed. In the case of an office building it is expected that the flow will be effectively uni-directional in the morning when people arrive and the evening when they depart. Whereas for a shop it would be expected that the flow would be bi-directional as people enter and leave in a less constrained manner.

As a result of the decrease in capacity factor for higher numbers of users the expected generated energy outputs do not follow a linear trend, but instead tail off as the number of users increases. This is true in all three cases, however the effect is lessened as the value of  $t_{D.O.E.}$  decreases, as can be seen from comparing fig.'s 5-30 – 5-32. As such it is clear that the value of  $t_{D.O.E.}$  has a significant affect on the expected generated energy outputs. The maximum expected output for bi-directional flow of 5,000 users for cases 1 and 3 were 16.72 Wh/day and 27.58 Wh/day respectively. Comparing the revolving door and swing door (fig. 5-28) it can be seen that in general this tailing off has less of an effect for the revolving door than for the swing door. This is a direct result of the diminished decrease in the capacity factor for a revolving door as was discussed in section 5.2.3..



**Fig. 5-30: Values for the generated energy outputs as a function of the number of users over the course of a day for case 1 of the revolving door for both uni and bi-directional flow.**

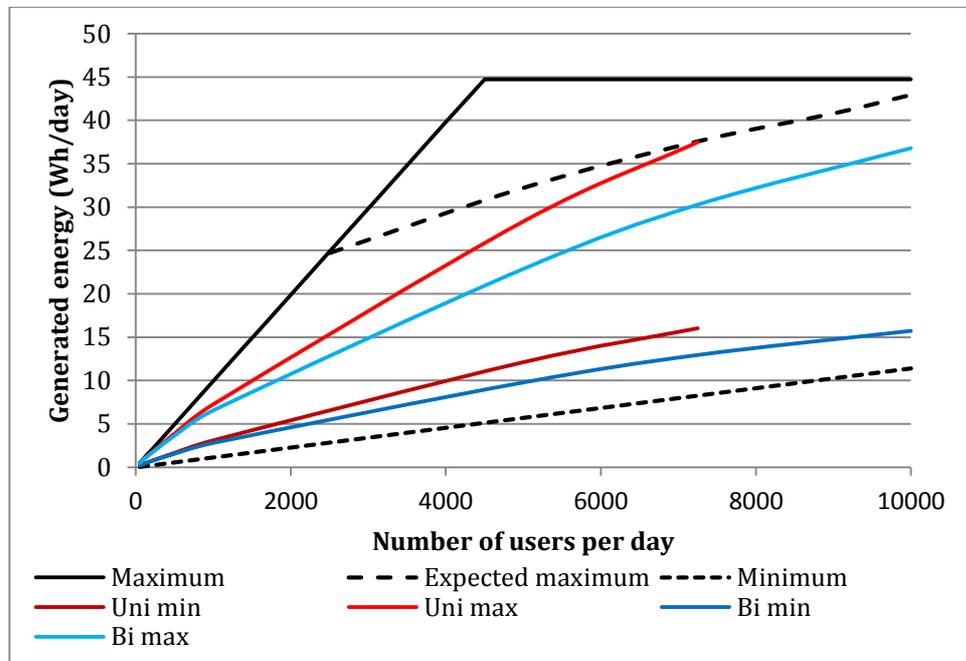


Fig. 5-31: Values for the generated energy outputs as a function of the number of users over the course of a day for case 2 of the revolving door for both uni and bi-directional flow.

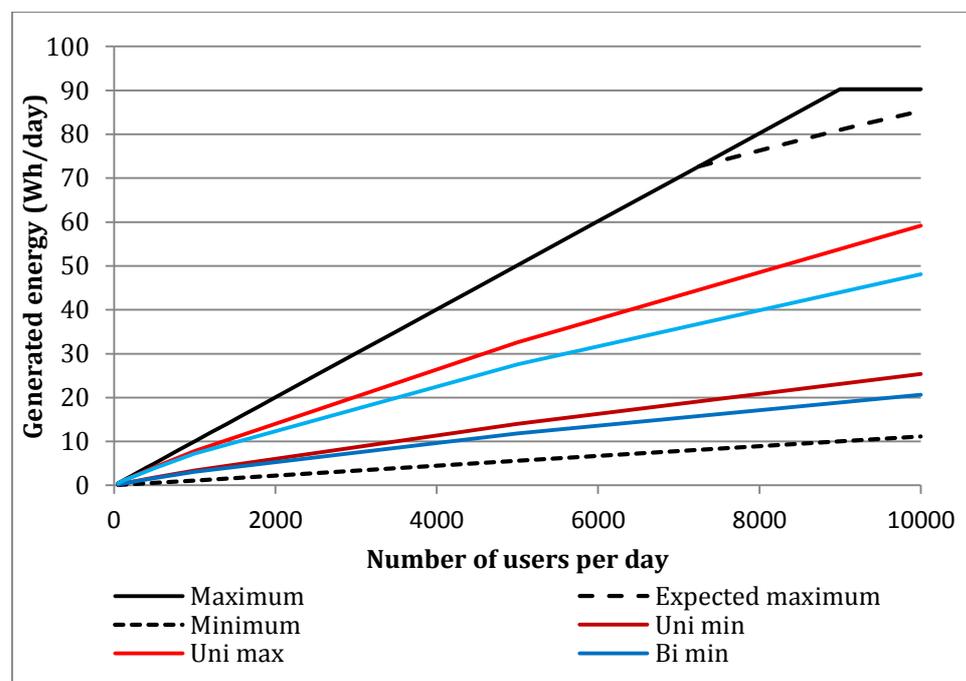


Fig. 5-32: Values for the generated energy outputs as a function of the number of users over the course of a day for case 3 of the revolving door for both uni and bi-directional flow.

In all cases it was found that uni-directional flow was found to offer higher energy generation values than bi-directional flow, where for 10,000 users in case 3, the maximum expected

outputs for uni and bi-directional flow were 59.16 Wh and 48.13 Wh respectively. This owes to the higher expected values of the capacity factor for uni-directional flow as was discussed in section 5.2.3.. It was seen that the effect is most pronounced for situations with high numbers of users.

Since the door is required to rotate for each user, there is a definite limit to the flow rate passing through a revolving door and is limited by the value of  $t_{D,O.E.}$ . It was found that the maximum number of users is greater for bi-directional flow as the maximum achievable flow rate is double that of uni-directional flow. Based on the parameters set out in table 5-18 it was found that for case 1 the required average flow rate exceeded the maximum achievable flow rate for a high number of daily users. As would be expected this was more pronounced for uni-directional flow than for bi-directional flow. In addition it can be seen in fig. 5-30 and 5-31 that as the number of users reaches the maximum achievable value, the maximum expected energy output tends towards the maximum achievable value. This is a result of the constraints on the capacity factor, as was discussed in section 5.2.3.. Since the minimum assumes bi-directional, the results for uni-directional flow do not converge on the minimum, however bi-directional flow will converge on both the minimum and maximum.

The envelope of operation for each case has been determined and is shown on fig.'s 5-30 – 5-32. The envelope of operation enclosed by the minimum and maximum lines represents the range of possible outputs for a given number of users. The minimum values do not vary considerably due to there being only a small change in the minimum values of the capacity factor and  $E_{D,O.E.}$  for each case. The maximum value represents the maximum output for a given number of users. This increases linearly until the maximum achievable output is reached. This is the situation where the door is in constant use by at least one user for the whole 10 hour period. It is clear from fig.'s 5-30 – 5-32 that the maximum achievable output increases as the value of  $t_{D,O.E.}$  decreases due to the increase in the maximum value of  $N_{D,O.E.}$ . The expected maximum diverges from the maximum value as the mean flow rate is higher due to the assumptions laid out in table 5-18. This is more prevalent for higher values of  $t_{D,O.E.}$ .

## 5.4. Assumption based location models

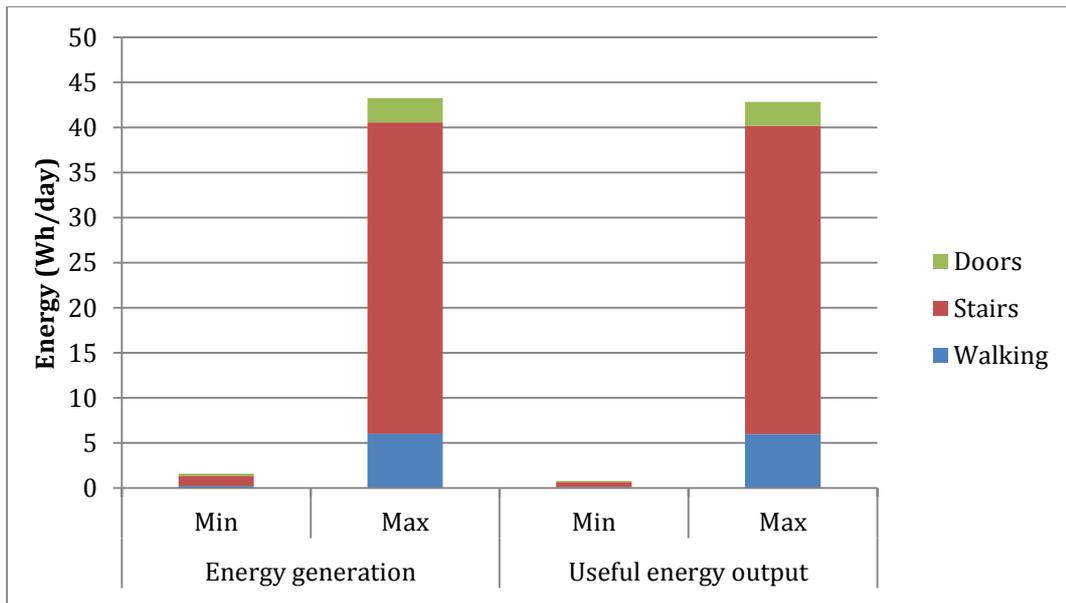
In order to assess the potential for energy generation in the urban environment the activity in such locations was considered. Initially this was carried out via a questionnaire based approach at two small office sites in London. It was however decided that assumption based models would be a more appropriate means of considering locations in the urban environment.

A number of assumption based models were developed to determine the potential for energy generation offered in various locations. The seven locations chosen were a corridor, stairwell, shopping centre, entrance (3 scenarios) and a ticket gate at a busy station with the parameters assumed for each of these sites set out in table 5-19. The devices employed to harvest energy from people were stated along with the relevant parameters to describe the expected activity experienced. The expected generated energy outputs at each of these sites were calculated based on these parameters. The useful energy output was considered to be the energy available once the charge-discharge cycle associated with energy storage was considered. The calculation of expected energy outputs followed the methodology set out previously in this chapter.

It was assumed that  $E_{\text{step}}$  for level walking, stair ascent and descent were 0.2-5.3, 0.2-4.9 and 0.2-7.1 J/step respectively and  $E_{\text{D.O.E.}} = 1-11$  J/D.O.E. Additionally for the entrance, two scenarios involving revolving doors were considered, where both uni-directional and bi-directional flows were considered. For the revolving door, it was considered that  $E_{\text{D.O.E.}} = 15.3-35.8$  J/D.O.E.. Uni-directional flow is considered to be for a location such as an office where the flow of users is generally in a single direction, whereas bi-directional flow is considered to be for a location such as a shop where users are assumed to travel in both directions over the course of the day. As such the values for the capacity factor are greater for entrance 2 (uni-directional) than for entrance 3 (bi-directional). In the situation where energy storage was required, a range of 50-99% was assumed for charge-discharge efficiency. Applying this to the values of generated energy, gave the range of expected useful energy outputs. The results from the assumption based models were presented below and show the variability in potential of different locations. It was expected that a high efficiency would be needed due to the small energy outputs of most systems.

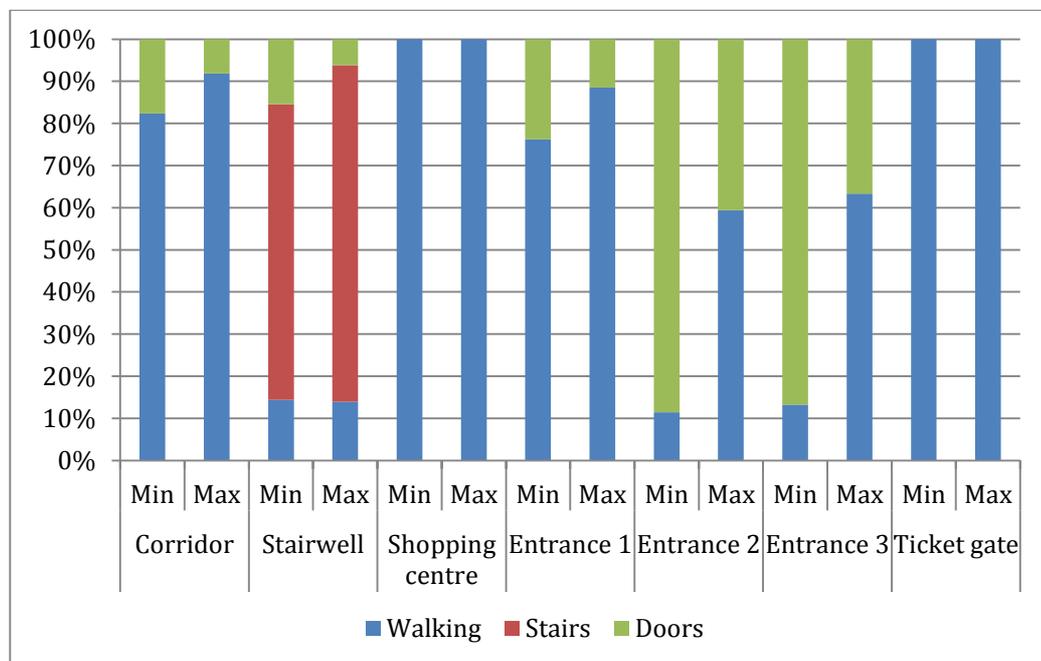
**Table 5-19: The assumption used to model the energy generation potential of a variety of location based scenarios.**

|                 | Location |       | $N_{\text{people}}$ | Flooring             | Stairs |                        | Doors |                          |                          |
|-----------------|----------|-------|---------------------|----------------------|--------|------------------------|-------|--------------------------|--------------------------|
|                 | L (m)    | W (m) |                     | $\eta_{\text{step}}$ | No.    | $\eta_{\text{ascent}}$ | No.   | $N_{\text{D.O.E./user}}$ | $C_{\text{theoretical}}$ |
| Corridor        | 20       | 3     | 1,000               | 1                    | 0      | N/A                    | 2     | 2                        | 0.55                     |
| Stairwell       | 4        | 3     | 800                 | 1                    | 25     | 0.4                    | 2     | 2                        | 0.55                     |
| Shopping centre | 100      | 8     | 65,000              | 0.2                  | 0      | N/A                    | 0     | N/A                      | N/A                      |
| Entrance 1      | 5        | 2     | 5,000               | 1                    | 0      | N/A                    | 2     | 1                        | 0.4                      |
| Entrance 2      | 5        | 2     | 5,000               | 1                    | 0      | N/A                    | 2     | 1                        | 0.65                     |
| Entrance 3      | 5        | 2     | 5,000               | 1                    | 0      | N/A                    | 2     | 1                        | 0.55                     |
| Ticket gate     | 1        | 15    | 240,000             | 1                    | 0      | N/A                    | 0     | N/A                      | N/A                      |



**Fig. 5-33: Range of generated energy and useful energy outputs for a system of energy harvesting devices in the stairwell. This shows the contribution from swing door, floor and stair harvesting devices.**

The cumulative contribution of different generation devices to the expected energy outputs in each of the scenarios were shown in fig. 5-34. It was seen that the largest contribution to energy generation comes from level walking in most cases, with exceptions being for the stairwell where stairs resulted in the largest contribution to generation and for the minimum outputs for entrances 2 and 3 where doors contributed the overwhelming majority of the generated energy. In the case of the stairwell, stair walking contributed 70-80 % of the total generated energy, with the remainder coming in similar proportions from level walking and doors. This was due to the greater number of steps taken by each user on the stairs than for level walking in this location. From fig. 5-34 it was seen that swing door generation did not generally contribute significantly to the total energy outputs, with the range of contributions of 6.2-23.8 %. For entrances 2 and 3 the use of revolving doors resulted in a significantly higher proportion of the generated energy coming from door generation, compared to entrance 1. For both case roughly 90% and 40% of the generated energy came from the doors for the minimum and maximum outputs respectively.



**Fig. 5-34: Cumulative contributions of each source of energy generation to the total generated energy outputs.**

The expected useful energy outputs vary greatly between locations as detailed in table 5-20. The largest potential was found at the shopping centre, where a range of 46-2,400 Wh/day was recorded. This was due to the large number of users and the length over which each user passed, despite a  $\eta_{\text{step}}$  value of 0.2. The ticket gate also gave a reasonable range of 9-450

Wh/day for useful energy outputs even though each user was only required to pass over 1m of installed devices. Despite this the large number of people passing through the gates resulted in a high concentration of activity. The results from the corridor, stairwell and entrance 1 were much more modest, with peak outputs of 40-50 Wh/day. For entrances 2 and 3, the useful energy outputs are slightly increased to 78.7 and 73.8 Wh/day respectively. This shows that in locations where revolving doors can be deployed, the energy outputs are likely to be greater. The reason for this increase is two fold, firstly the values of the capacity factor are slightly higher and secondly the energy output per D.O.E. is significantly increased.

**Table 5-20: Summary of the useful energy outputs from the system of energy harvesting devices for each of the assumption based location scenarios.**

|                 |     | Useful energy output |            |
|-----------------|-----|----------------------|------------|
|                 |     | (Wh/day)             | (kWh/year) |
| Corridor        | Min | 0.87                 | 0.31       |
|                 | Max | 40.70                | 14.65      |
| Stairwell       | Min | 0.79                 | 0.29       |
|                 | Max | 42.85                | 15.43      |
| Shopping centre | Min | 46.3                 | 16.67      |
|                 | Max | 2,429.17             | 874.5      |
| Entrance 1      | Min | 1.17                 | 0.42       |
|                 | Max | 52.76                | 19.00      |
| Entrance 2      | Min | 7.80                 | 2.81       |
|                 | Max | 78.71                | 28.34      |
| Entrance 3      | Min | 6.73                 | 2.42       |
|                 | Max | 73.79                | 26.56      |
| Ticket gate     | Min | 8.55                 | 3.08       |
|                 | Max | 448.46               | 161.45     |

## 5.5. Summary

Within this chapter the potential for energy generation from a device or system of devices was considered with a number of conclusions made.

Firstly the utilisation of the available potential was considered. For walking devices it was considered that a device would be able to harvest energy from each step taken on it. In the case where not all of the area of a location was covered with floor harvesting devices, it was assumed that the distribution of steps within the area was even, to help simplify the analysis.

Swing door harvesting devices were found to be more difficult to assess. An initial study was carried out in a number of locations to try and determine the main parameters at play. It was found the proportion of potential that was utilised was dependant on FR and  $t_{D.O.E.}$  and was generally less than 1 for  $FR > 1$ . It was found that the value of FR played a far more significant role than the value of  $t_{D.O.E.}$ . It was determined that the mean FR was not a good indicator as to the value of C, instead the mean FR for contribution to the total potential offers a much more useful measure as it removes periods of no activity. A methodology was then outlined to try and determine a  $C_{theoretical}$  value for different locations.

The utilisation of potential for revolving doors was considered using the same methodology as for a swing door with the utilisation of the available potential following a similar pattern. It was found that the flow rate has less of an impact upon the capacity factor than for a swing door. Additionally differences were found depending on whether the flow was considered to be uni or bi-directional, where the capacity factor was found to be higher for uni-directional flow. Unlike with swing doors, it was determined that the maximum flow rate through a revolving door was a limiting factor, particularly for uni-directional flow, and was a direct result of the value of  $t_{D.O.E.}$ . Indeed this limit to the flow rate resulted in a well defined envelope of operation for revolving door devices.

The maximum achievable outputs for a single device were considered. For walking devices it was assumed that a maximum of 1 step/s was achievable, amounting to 86,400 steps/day (equivalent to walking 67.4 km). The maximum output was calculated to be 127.2 Wh/day for a single device, however there were large variations both between and within the range of

technologies, where the overall range was from 4.8-127.2 Wh/day. As was expected it was found that for stair use the maximum achievable outputs varied due to the expected energy outputs from a device. In the case of stair ascent the total energy output decreased and for stair descent they increased. Finally the lifetime of the device determined the maximum energy that could be generated from a single device, where for a 20 year lifetime a maximum of 928.6 kWh was calculated.

In more practical situations the energy outputs were expected to be considerably lower. Based on the assumptions laid out in section 5.3.1.2.. It was found that a number of factors play a critical role in determining the output from a system of devices. As was expected the number of users was critical to the generated energy outputs and highlights the importance of the location. In addition the size of the system and more specifically the length (and number of steps) each user was required to pass over and the proportion of the location covered by harvesting devices played a critical role. Similarly with stairs, the number of users and steps play a key role, in addition the direction of flow of the users also affected the outputs, where, increasing the proportion of users descending the stairs increased the output of the system where the total number of actions was constant.

In the case of swing doors, the maximum output was considered to be in the case where the door, once opened was allowed to fully shut and was then immediately opened. As such the maximum number of users was dependant on the value of  $t_{D.O.E.}$ . The maximum output was calculated to be 57.4 Wh/day, however it was expected that in practice the outputs would be considerably lower. Using the methodology laid out in section 5.3.2.2., it was determined that as the number of users increases, the value of  $C_{theoretical}$  decreases. As a result, although the expected value for the generated energy increased with the number of users it was not a linear relationship. Instead the expected outputs tailed off for a high number of users due to the decrease in the capacity factor. As such for 50 users the calculated values for  $C_{theoretical}$  and generated energy were in the range of 0.95-0.96 and 0.01-0.15 Wh/day respectively. In the case of 10,000 users, these were 0.24-0.34 and 6.7-10.29 Wh/day.

For revolving doors, the maximum achievable outputs were found to be higher than for swing doors, where a maximum output of 215 Wh/day was found. This was a result of the higher average power output from revolving doors, stemming from the higher values of  $E_{D.O.E.}$ . In

terms of the expected outputs, it was again found that the capacity factor decreased as the number of users increased. The rate at which the capacity factor decreased was significantly affected by both the value of  $t_{D,O.E.}$  and whether the flow of users was uni or bi-directional. The expected energy outputs were found to be higher for revolving doors than for swing doors. It was however noted that revolving doors will be constrained with regards to the range of possible flow rates, meaning that there will be a more definite limit to the number of users. In turn this places definite limits on the possible range of generated energy outputs for any given revolving door and is a function of the values of  $t_{D,O.E.}$  and  $E_{D,O.E.}$ .

The assumption based location models were considered to try and determine the potential arising from vastly different scenarios. For the corridor, stairwell and entrances the maximum expected energy outputs were of the order of a few 10s of Wh/day, whereas the values for the ticket gate and shopping centre were considerably higher, at 448 and 2,429 Wh/day respectively. This was primarily a result of the number of users, however the large area covered by the shopping centre led to a greater potential input from each individual user. In addition it was found that the contribution to total potential in most of the locations was dominated by floor generators. It was found that the contribution from swing door devices was normally less than 20% and stems from the fact that a user will take considerably more steps than they will open doors. In the scenarios entrance 2 and 3, the utilisation of revolving doors resulted in increased energy outputs over entrance 1, due to both the increase values of  $E_{D,O.E.}$  and  $C$  for a revolving door over a swing door. As a direct result the contribution to the total potential from door generation is considerably larger for revolving doors than swing doors.

In conclusion it was found that many parameters are at play in determining the total energy outputs of a device or system of devices. It was found that the energy outputs would in most situations be very small and even in well chosen locations the outputs were still found to be modest.

Within this chapter the parameters affecting the total energy outputs of a device or system of devices were considered. These included the generation and energy storage technologies implemented, the level of activity experienced and size of the system. It was however not clear whether this energy could provide any benefits. As such there is need to consider the

displaced emissions and economic savings resulting from the useful energy outputs of human energy harvesting. This is the focus of Chapter 6, where thresholds were determined for the emissions and cost of the devices beyond which some benefits would be found.

## 6. Energy benefits

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Thus far the focus of the project has been on the potential for energy generation offered by human energy harvesting. Two more aspects that need to be considered are environmental impacts and economic viability resulting from utilisation of the technology and are the focus of this chapter. It was alluded to, by a number of device manufacturers, that energy was generated in an environmentally friendly way ((SDC n.d.) and (Pavegen 2014-b)), however no evidence was presented to confirm this.

It was seen in chapter 5 that the energy outputs from human energy harvesting are small and diffuse. The result of this was that the output from a single device was very small with the requirement that GHG emissions must be small if any benefit in terms of Greenhouse gas (GHG) emissions was to be found. Firstly an assessment of the emissions associated with the fuel source, which in this case was the food we consume, was carried out. Secondly the emissions displaced as a result of the generated energy were determined so as to provide a threshold value for the emissions associated with a system. It was noted that the assessment carried out was not intended to consider all aspects of the system, nor the practical implementation of the technology but instead to assess whether the technology was capable of providing low carbon energy. Similarly, the economic viability was considered in terms of the savings resulting from the generated energy.

Little literature was concerned with these aspects, however in Chapter 5 it was highlighted that a number of student group projects were carried out at the University of British Columbia with the aim of assessing the impacts of installing Pavegen tiles at the university (Seow et al. 2011), (Crockett et al. 2011), (Epp et al. 2011) and (Cramm et al. 2011). These were aimed at the environmental, economic and social impacts of installing Pavegen tiles, with greatly varying outcomes in relation to these impacts.

In the analysis presented in this chapter it has been considered that the generated energy will act as a replacement for energy otherwise provided by the mains power network. There are

however a number of additional factors that should be taken into consideration when assessing the viability of utilising human energy harvesting.

It is necessary to clarify the boundaries for the cost and emissions associated with the energy harvesting system. In the case of a door device it is expected that the door will be present regardless of whether there is an energy harvesting unit. As such it is only the cost and emissions associated with the energy harvesting system that should be considered. Additionally it could be argued that since the device is expected to act in place of a door closer/damper device, that it is the difference between the cost and emissions associated with the harvesting system and the device which it is replacing.

Just as the location is crucial to the energy that can be generated, it may also play an important role in determining the viability of the technology. For example in locations that are remote from the electricity grid, the cost and associated emissions of connecting the desired load to the grid should be taken into account when assessing the feasibility of utilising a human energy harvesting system. This would need to be carried out on a location specific basis, but it is recognised that it could have a considerable impact to the viability of the technology.

## **6.1. Approach of assessment**

The assessment of both the environmental impacts and the economics of human energy harvesting were closely linked to the energy generated via the technology. As such expected energy outputs were determined based on a variety of criteria and used as the basis from which these assessments were considered.

It is recognized that the assessment of the environmental and economic aspects of human energy harvesting in the built environment are based on basic assumptions and hence the analysis and conclusions drawn from them are limited. These limitations are primarily due to the complicated nature of the human energy harvesting process as well as the relative immaturity of the technology, which results in a significant number of unknown variables. A

detailed analysis would need to take these into account, however at present there would be little confidence in assumptions made with regards to these.

In terms of the emissions savings, a base value has been considered, based on the energy intensity of energy provided by the electrical energy grid. Evidently this parameter will change with time, however it is not easy to consider how this will vary. In addition there are a number of considerations that need to be taken into account in terms of the energy harvesting devices before an in depth analysis can be performed. One such problem is the lack of specific information regarding particular devices. Without such information any direct analysis is very difficult to carry out, as discussed in section 6.1.1.. As well as this there is little information with regards to how the technology will respond over time, both in terms of the construction of devices as well as there degradation over time and lifetime.

As such it is necessitated that the following analysis is basic, whereby more detailed analysis needs to be carried out as the technology matures. Even so the analysis presented does give an insight into the likely requirements of human energy harvesting technology if it is to provide any benefits.

### **6.1.1. Carbon impact**

An assessment was made to try and determine how favourably the GHG emissions associated with human energy harvesting compare with other conventional forms of energy generation. There were three main components that contribute to the viability of a technology in terms of GHG emissions. These were the fuel source, embodied energy of the system and the generated energy. The generated energy was assessed both with and without an energy storage system. Assessing the GHG emissions from human energy harvesting requires a reference unit from which comparisons with conventional sources could be made, this was  $\text{kgCO}_{2\text{eq}}/\text{kWh}_{\text{useful}}$ .

The approach taken to assess the environmental viability of human energy harvesting was carried out as follows.

- The emissions associated with the fuel source were considered. This extends on from Chapter 3, where the efficiency of the flow of energy in the human body was considered and from Chapter 4, where the energy generation process was considered.
- To properly assess a specific device, it was necessary to determine the emissions associated with the materials used in manufacturing the device. As was seen previously, information with regards to particular devices was hard to come by. Section 6.4.2. details a number of student led projects carried out to estimate the embodied emissions of a Pavegen tile. The outcomes varied considerably depending on which assumptions were used, with the conclusion that such an analysis resulted in relatively arbitrary outcomes. As such the most appropriate approach was to estimate the displaced emissions resulting from the energy generated via human energy harvesting, with threshold values determined to mark a limit for the emissions associated with the manufacture of a device. In the case of floor devices the values were considered in terms of displaced emissions per m<sup>2</sup> and for door devices in terms of displaced emissions per door.

### **6.1.2. Economic viability**

Consideration of the economic viability was carried out to determine limitations for the cost. It was possible to consider individual devices in terms of their energy generation potential and the savings achievable from this. It was assumed that the energy produced was to act as grid replacement energy and hence the economic viability was assessed in comparison to the savings made from the energy replaced. The units used to assess this were £/kWh. It has been shown that the energy generated by a device is dependant on the activity experienced. When considering a system of devices, the number of steps taken by each user added to this, however an array of devices was required to harvest this energy. As such it was necessary to first consider the economic viability of an individual device, followed by the implementation of a system of devices. Again floor devices were considered per m<sup>2</sup> and door devices per door.

## **6.2. Conventional energy**

In order to assess the displaced emissions and economic impact of utilising human energy harvesting as a means of electrical energy generation, it was necessary to use a benchmark from which an assessment could be made. In the context of this thesis, human energy harvesting was considered as a means of energy generation and was thus compared to energy provided via the UK electricity grid. It was found that the emissions associated with energy delivered via the national grid, in the UK Electricity emissions = 0.497 kgCO<sub>2</sub>/kWh (DEFRA 2012), with a cost of 0.17 £/kWh.

## **6.3. Energy System**

The assumptions upon which human energy harvesting is being assessed are now laid out. Initially this considers the energy within the users, as detailed in section 6.3.1.. This is followed by an assessment of the benefits of the generated energy. To do this it is evident that the generated energy from a device must be determined, with the assumptions laid out in section 6.3.2.. Finally the role of energy storage is laid out in section 6.3.3..

### **6.3.1. Fuel source**

It was outlined in chapter 3 that the fuel source for human energy harvesting was ultimately the food consumed by the user. As such an assessment of the environmental impacts of producing electrical energy through this method was considered. The food consumed had emissions associated with it. Determining a value was a complicated task as it was dependent on many factors, although a number of studies were carried out to try and quantify this. As was expected the emissions associated with the food we consume varies depending on the food product, where for example beef and milling wheat resulted in 12.12 and 0.52 kgCO<sub>2</sub>e/kg of product respectively, in the UK (Audsley et al. 2009). The values used for the analysis of food chain emissions were based on the diet of the average adult in the UK, however it was noted that there was significant scope to reduce these emissions, not least through changes in diet (Macdiarmid et al. 2011).

**Table 6-1: Values for the carbon emissions associated with the food consumed by people from the literature.**

|  |       | Requirements  | Emissions                           | Reference                |
|--|-------|---------------|-------------------------------------|--------------------------|
| UK diet (per person)                                   | Men   | 10.6 (MJ/day) | 8.51 (kgCO <sub>2eq</sub> /day)     | (Macdiarmid et al. 2011) |
|  | Women | 8.1 (MJ/day)  | 6.50 (kgCO <sub>2e</sub> /day)      |                          |
| UK food emissions (UK total excluding land use change) |       |               | 152,183 (ktCO <sub>2eq</sub> /year) | (Audsley et al. 2009)    |
| Dutch food emissions (per household)                   |       |               | 2,800 (kgCO <sub>2eq</sub> /year)   | (Kramer et al. 1999)     |

The values given in (Macdiarmid et al. 2011) were used for the following analysis. From these values a conversion factor was determined for the emissions per unit of ME of food consumed by adults in the UK.

$$FEF = \frac{Emissions}{Intake}$$

Using this, the conversion factors for men and women were found to be 0.8028 and 0.8024 kgCO<sub>2e</sub>/MJ respectively. An average value of 0.8026 kgCO<sub>2e</sub>/MJ<sub>ME</sub> (2.89 kgCO<sub>2e</sub>/kWh<sub>ME</sub>) was thus assumed. The values used in assessing the emissions from the fuel source were discussed in the preceding chapters and were presented in table 6-2. The range of values for energy generation for each technology were taken from those determined in Chapter 4, with the net efficiency and walking energy expenditure values taken from Chapter 3.

It was first necessary to consider the additional work that was required to complete each step. It was not clear how the presence of a floor generator would impact upon energy expenditure of regular gait. It was the change compared to normal walking that constitutes the energy attributable to generation from walking. This was because the energy expended during walking was primarily expended to complete the action of walking which was deemed

necessary in everyday life and would occur regardless of the presence of a harvesting device. To investigate the potential impact of a walking device a range of 0-10% was considered in terms of the increase to the required work. A 10% limit was considered as in the work of (Passmore & Durnin 1955) it was claimed that an increase in energy of <10% was likely for light terrain.

$$AE = WEE \times NE$$

Once the additional work required for each step was calculated, the metabolic energy (AME) requirements to provide this could be determined by assuming that the net efficiency of walking was 37.5%. As shown in chapter 3, the literature reveals values in the range of 35-40%. Thus for 1J of additional mechanical work carried out, required 2.67 J of additional ME expenditure.

$$AME = \frac{AE}{\left(\frac{NE}{100}\right)}$$

**Table 6-2: Values used to assess the emissions associated with the flow of energy in the process of converting mechanical work into electrical energy in human energy harvesting.**

|                                    |      |         |                                      |
|------------------------------------|------|---------|--------------------------------------|
| Food emissions per kWh of ME (FEF) |      | 2.89    | kgCO <sub>2</sub> /kWh <sub>ME</sub> |
| Walking energy expenditure (WEE)   |      | 140.9   | (J/step)                             |
| Net walking efficiency (NE)        |      | 37.5    | (%)                                  |
| Additional energy (AE)             |      | 0-10    | (%)                                  |
| Energy generation                  | PZT  | 1.4-3.9 | (J/step)                             |
|                                    | PVDF | 0.2-1.8 | (J/step)                             |
|                                    | EM   | 2.0-4.7 | (J/step)                             |
|                                    | DE   | 1.9-5.3 | (J/step)                             |

In order to make a useful comparison, the additional ME requirements per kWh<sub>e</sub> were determined. Due to the variations in technology efficiency this was technology dependent. As such the number of steps required by each technology to generate 1 kWh<sub>e</sub> were determined and multiplied by the per step values to give kWh<sub>ME</sub>/kWh<sub>e</sub>. Finally these were used to determine the emissions associated with energy flow for each technology.

### **6.3.2. Energy generation**

It was seen in chapter 5 that the useful energy output over the lifetime of a system was dependent on several factors. These were the choice of technology, both for energy generation and energy storage, the location and associated activity levels, system lifetime and the size of the system. When assessing the environmental impacts, four parameters were varied, as laid out below. The energy generation values follow the methodology laid out in chapter 5. Energy generation outputs were considered for each of the energy generation and energy storage technologies. The results for the energy outputs were then determined depending on the activity levels, device lifetimes, location scenarios and for differing energy storage capacities.

Varying the activity was shown in Chapter 5 to greatly affect the expected energy outputs. The activity was considered in a slightly simpler manner here, where it was measured in units of steps/m<sup>2</sup>/day and resulting in the energy output being expressed as kWh/m<sup>2</sup>/year for flooring devices. The higher limit was chosen to coincide with the maximum achievable activity values. A slightly different approach was employed in assessing swing and revolving door devices. Initially the maximum achievable activity was considered, with a further assessment based on varying activity levels (users/door). This measure took into account the decrease in the capacity factor and was based on the methodology set out in Chapter 5.3.2.2.. Finally the seven location models set out in Chapter 5.4. were considered using the energy outputs values calculated.

The values assumed to determine the energy outputs were laid out in Tables 6-3, 6-4 and 6-5 below. It is worth noting that the activity values in table 6-3 correspond to the step density used to determine the energy outputs assessed in chapter 5.3.1.2., where an area of 30m<sup>2</sup> was considered. The values taken for tables 6-4 and 6-5 use the values set out in chapter 5.3.2 and

5.3.3. respectively. In addition the energy outputs in table 6-5 are taken for case 3 of the revolving door.

**Table 6-3: Parameters assumed to model the energy outputs of energy harvesting floor devices.**

|                       |      |         |       |        |        |        |                             |
|-----------------------|------|---------|-------|--------|--------|--------|-----------------------------|
| Generation technology | PZT  | 1.4-3.9 |       |        |        |        | (J/step)                    |
|                       | PVDF | 0.2-1.8 |       |        |        |        | (J/step)                    |
|                       | EM   | 2.0-4.7 |       |        |        |        | (J/step)                    |
|                       | DE   | 1.9-5.3 |       |        |        |        | (J/step)                    |
| Activity              | 22   | 427     | 4,273 | 21,368 | 42,735 | 85,500 | (steps/m <sup>2</sup> /day) |

**Table 6-4: Parameters assumed to determine the expected energy outputs for energy harvesting swing door devices.**

|                 |          |      |     |       |       |        |             |
|-----------------|----------|------|-----|-------|-------|--------|-------------|
| Energy per use  | 1.0-11.0 |      |     |       |       |        | (J/D.O.E.)  |
| Activity        | 50       | 100  | 500 | 1,000 | 5,000 | 10,000 | (Users/day) |
| Capacity factor | 0.97     | 0.95 | 0.9 | 0.85  | 0.7   | 0.6    |             |

**Table 6-5: Parameters assumed to determine the expected energy outputs for energy harvesting revolving door devices.**

|                 |           |      |      |       |       |        |             |            |
|-----------------|-----------|------|------|-------|-------|--------|-------------|------------|
| Energy per use  | 15.5-36.1 |      |      |       |       |        |             | (J/D.O.E.) |
| Activity        | 50        | 100  | 500  | 1,000 | 5,000 | 10,000 | (Users/day) |            |
| Capacity factor | Uni       | 0.98 | 0.95 | 0.82  | 0.78  | 0.65   | 0.59        |            |
|                 | Bi        | 0.97 | 0.94 | 0.77  | 0.72  | 0.55   | 0.48        |            |

### 6.3.3. Storage technology

An assessment was made based on the different storage technologies considered previously in this thesis. The performance of these technologies depends on many factors, however an

attempt was made to determine the emissions intensity ( $\text{kgCO}_{2\text{eq}}/\text{kWh}_{\text{useful}}$ ) and cost ( $\text{£}/\text{kWh}_{\text{useful}}$ ). The methodology for this was set out below.

Firstly an attempt was made to determine the total useful energy that could be delivered over the lifetime of the energy storage device.

$$E_{\text{useful}} = 0.1 \times \text{capacity} \times \text{energy efficiency} \times \text{Lifetime}$$

It was noted that the lifetimes considered here were for the number of cycles expected for each technology for 10% D.O.D.. In addition the energy efficiency of the technology was taken into consideration.  $E_{\text{useful}}$  was the useful energy delivered by the energy storage system over the lifetime of the energy storage device. The storage capacity required was expected to change depending on the generation potential of a location with the capacity required likely to depend on a number of factors. These were the generation technology, location activity and the storage technology implemented. It was decided that it was the ratio of the useful energy delivered over the lifetime of the energy storage system to the capacity of the storage system, ER, that was important, as this removed considerations of the capacity of the energy storage system and was given by,

$$ER = \frac{E_{\text{useful}}}{\text{Capacity}} = 0.1 \times \text{lifetime} \times \text{energy efficiency}$$

This was used to determine the emissions intensity, EI, and cost intensity, CI, of each of the energy storage technologies. For the emissions intensity,  $EF = \text{emissions factor}$  ( $\text{kgCO}_2/\text{kWh}_{\text{capacity}}$ ) and for the cost intensity,  $CF = \text{cost factor}$  ( $\text{£}/\text{kWh}_{\text{capacity}}$ ).

$$EI = \frac{EF}{ER}$$

$$CI = \frac{CF}{ER}$$

These measures were used to assess the impact of each of the energy storage systems when considering human energy harvesting.

**Table 6-6: Characteristics of the energy storage options considered.**

|                 | Efficiency | Lifetime            | Cost  |                                 | Emissions  |                                     |
|-----------------|------------|---------------------|---|---------------------------------|--|-------------------------------------|
|                 | (%)        | (Cycles @90% D.O.D) | (£/kWh <sub>useful</sub> ) <sup>+</sup><br>++ | (£/kWh-per cycle) <sup>++</sup> | (kgCO <sub>2</sub> /MJ <sub>capacity</sub> )                             | (kgCO <sub>2eq</sub> /kWh capacity) |
| Lead-acid       | 50-93      | 1,000-3,000         | 122-243                                       | 0.12-0.61                       | 5-7*   | 1.4-1.9                             |
| Ni-Cd           | 60-90      | 2,000               | 487-913                                       | 0.12-0.61                       | 10-15*   | 2.8-4.2                             |
| Li-ion          | 80-98      | 5,000-8,000         | 365-1,522                                     | 0.09-0.61                       | 17-27*   | 4.7-7.5                             |
| Super capacitor | 84-99      | 100,000-500,000     | 183-1,217                                     | 0.01-0.12                       | 6.91x10 <sup>-4</sup><br>(tonnes CO <sub>2</sub> /MWh <sub>cap</sub> )** | 691                                 |

\*(McManus 2012), \*\*(Hou et al. 2011), +(Chen et. al. (2009), \*\*GBP/USD = 0.60872 (<http://themoneyconverter.com/>) (20/01/14).

## 6.4. Emissions results

### 6.4.1. Fuel flow

An assessment of the fuel flow was carried out to assess the potential impact of utilising human mechanical work. The increase to energy expenditure was varied from 0-10%, with the results presented for a 70 kg individual.

It was seen that a 10% increase in mechanical work resulted in 14.1 J/step of additional work to be carried out. This required 37.6 J/step of metabolic energy to account for the increase in mechanical work. Although this was relatively small, the electrical energy output from a single step was not expected to exceed 5.3 J/step. As a result, to generate 1 J<sub>e</sub> requires a range of 7.1-188.0 J<sub>ME</sub> depending on the efficiency with which the harvesting device converts

mechanical work into electrical energy. The overall efficiency of generating energy from the metabolic energy used by the human body was in the range of 0.1-14.1 %. Much of this inefficiency depended on the efficiency of the electrical energy generation process. The process of electrical energy generation was expected to be the main source of this variation, as the losses associated with the conversion of ME into harvestable mechanical work were assumed to be fixed. It is noted that footfall devices may affect the net efficiency of gait, however no information is available to assess this. The values of efficiency presented here refer to the input energy as the increase in metabolic energy expenditure resulting from the presence of a harvesting device. As was discussed in chapter 3, many of the sources of energy expenditure were not considered in this process as they were not strictly related to the harvesting of mechanical work.

**Table 6-7: Results for the emissions associated with the additional energy required to produce 1 kWh of electrical energy from each of the energy generation technologies and for an increase in required mechanical work of 0-10%.**

| Additional work |          | Additional ME | PZT                                    | PVDF                                   | EM                                     | DE                                     |
|-----------------|----------|---------------|--|--|--|--|
| (%)             | (J/step) | (J/step)      | (kgCO <sub>2</sub> /kWh <sub>e</sub> ) |
| 0               | 0        | 0             | 0                                      | 0                                      | 0                                      | 0                                      |
| 2               | 2.8      | 7.5           | 15.5-5.6                               | 108.6-12.1                             | 10.9-4.6                               | 11.4-4.1                               |
| 4               | 5.6      | 15.0          | 31.0-11.1                              | 217.2-24.1                             | 21.7-9.2                               | 22.9-8.2                               |
| 6               | 8.5      | 22.5          | 46.5-16.7                              | 325.8-36.2                             | 32.6-13.9                              | 34.3-12.3                              |
| 8               | 11.3     | 30.1          | 62.0-22.3                              | 434.3-48.3                             | 43.4-18.5                              | 45.7-16.4                              |
| 10              | 14.1     | 37.6          | 77.6-27.8                              | 542.9-60.3                             | 54.3-23.1                              | 57.2-20.5                              |

Further to this inefficiency, the carbon emissions associated with food production were very high at 2.89 kgCO<sub>2</sub>/kWh<sub>ME</sub>. Table 6-6 shows the contribution of additional energy to carbon emissions for generating electrical energy. The values indicate that the emissions associated with producing electrical energy far exceed those of conventional fuels from the fuel alone. Even a small increase in energy expenditure of just 2% resulted in emissions of more than 4

kgCO<sub>2</sub>/kWh<sub>e</sub> from the additional metabolic energy expenditure. This far outstrips the emissions associated with even the most polluting forms of conventional energy.

### **Case study**

The assignment of additional energy was carried out in a simple way, it was however not that simple. It was assumed that all additional work necessitates additional energy to be consumed by the user. If it was assumed that walking on a device requires an increase of 10% to the mechanical work requirements and that 10,000 steps a day were taken by a user then the additional energy consumed above the average only accounts for an increase to daily energy expenditure of 3.8% (0.376 MJ/day). This was a relatively modest increase and would be significantly lower if either the increase in required energy was less than 10% or not all of a person's daily steps were taken on a harvesting device. In addition it was reported that there was a trend towards overconsumption of food in the developed and developing world (Moomaw et al. 2012). As a result it seemed that a small increase to energy consumption could be absorbed by the existing energy surplus. As such it appears that the increase in energy expenditure would be unlikely to increase food consumption for such modest changes and so the fuel source should not necessarily be included in the assessment of emissions.

As a means of comparison, the energy expenditure of a 70 kg male was considered during cycling using tables 3-4. For 30 minutes of cycling it was found that 1.2 MJ of energy would be expended and amounts to a 10.8% increase in daily energy expenditure. This was a considerable increase to the daily EE, although assigning this as additional EE was not quite that simple. If the definitions for different sources of energy harvesting as laid out in section 3.3. were considered then assigning this energy expenditure depends on what source it was considered. If the cycling machine is used as a means of recreation within a gym then the energy generated can be thought of as being harvested from a source of otherwise wasted energy. If on the other hand the cycling machine was considered as a direct purpose device then the energy expended by the individual was being expended directly to generate energy and can no longer be considered as waste energy.

As such considering the implications of the fuel source was not simple to assess. Although the emissions associated with the food consumed by people were high, assigning this energy to

activities was not easy due to the difficulty in determining whether additional food was consumed as a result of the harvesting process. For parasitic devices where the increase in total energy expenditure was small, if it exists at all, then it seemed likely that this would result in no measurable additional food consumption. For recreational and direct purpose devices the increase to total EE was significant, however since recreational devices were harvesting otherwise wasted energy the emissions from food should not be assigned, whereas for direct purpose devices where the energy was specifically expended for the purpose of powering a device then the emissions from additional food should be considered. In the case of direct purpose devices, it appears that attempting to harvest too much energy could result in significant negative environmental impacts.

### 6.4.2. Floor devices

As would be expected, the emissions displaced by a device were dependant on the technology and the efficiency with which mechanical work was converted into electrical energy. In addition the level of activity had a large impact on the emissions displaced, both of which were shown in fig. 6-1.

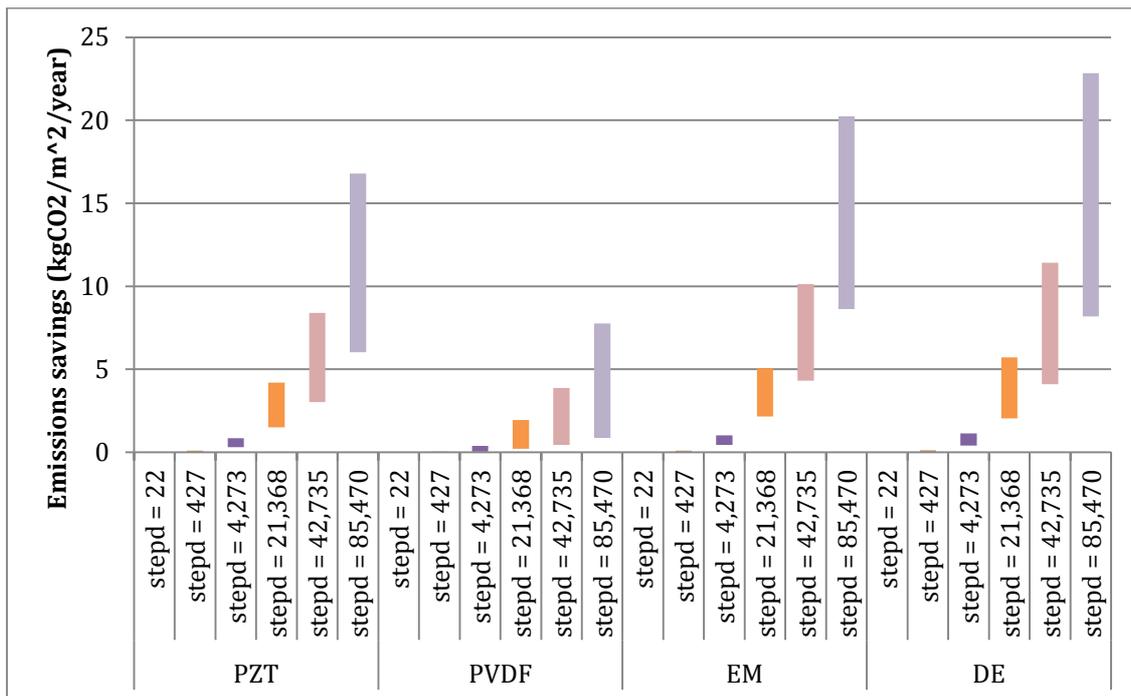


Fig. 6-1: Emissions displaced annually as a result of the energy generated from energy harvesting floor devices for each technology and for varying activity. (stepd = step<sub>density</sub> (steps/m<sup>2</sup>/day)).

The emissions displaced presented were considered in a  $\text{m}^{-2}\text{year}^{-1}$  basis to assess the general case of the threshold emissions for which  $1 \text{ m}^2$  of flooring would need to be produced to provide energy with a lower carbon footprint than conventional sources of grid energy. The results were considered in units of  $\text{m}^{-2}\text{year}^{-1}$  so as to normalise the results and allow a direct comparison between situations. The highest range of values for displaced emissions was found for a DE generator with an activity level of  $85,470 \text{ steps/m}^2/\text{day}$ , where values of  $8.18\text{-}22.83 \text{ kgCO}_2/\text{m}^2/\text{year}$  were recorded. This drops significantly with either a change in the generated energy per step or the activity experienced by the device. For locations with very low activity, it was found that only a few  $\text{gCO}_2$  would be saved as a result of the energy generated. Similarly reductions to the energy generated per step resulted in a reduction to the energy generated and therefore the displaced emissions, as seen in fig. 6-1, where the peak for a PVDF generator was found to be  $0.86\text{-}7.75 \text{ kgCO}_2/\text{m}^2/\text{year}$ . It was seen that both the activity and generation technology had a large impact on the total emissions displaced, as was expected due to the huge difference between the minimum and maximum activity and generation efficiency. As such it appeared that the choice of location was critical when considering the viability of floor generator devices.

**Table 6-8: Emissions displaced over a 5 year lifetime as a result of the energy generated from energy harvesting floor devices for each of the energy harvesting technologies and varying levels of activity.**

| Activity                          | Technology                                |   |   |   |
|-----------------------------------|---|---|---|---|
|                                   | PZT                                       | PVDF                                      | EM  | DE  |
| (steps/ $\text{m}^2/\text{day}$ ) | ( $\text{kgCO}_{2\text{eq}}/\text{m}^2$ ) | ( $\text{kgCO}_{2\text{eq}}/\text{m}^2$ ) | ( $\text{kgCO}_{2\text{eq}}/\text{m}^2$ ) | ( $\text{kgCO}_{2\text{eq}}/\text{m}^2$ ) |
| 22                                | 0.008-0.021                               | 0.001-0.010                               | 0.01-0.03                                 | 0.01-0.03                                 |
| 427                               | 0.15-0.42                                 | 0.02-0.19                                 | 0.22-0.51                                 | 0.20-0.57                                 |
| 4,274                             | 1.51-4.20                                 | 0.22-1.94                                 | 2.15-5.06                                 | 2.05-5.71                                 |
| 85,470                            | 30.15-83.98                               | 4.31-38.76                                | 43.07-101.21                              | 40.92-114.13                              |

Thus far the annual values for displaced emissions were considered, however the emissions displaced scale with the lifetime of the devices. Tables 6-8 and 6-9 show the lifetime values for 5 and 20 year lifetimes. In the case of a 5 year lifetime, the displaced emissions peak at  $114.13$

kgCO<sub>2</sub>/m<sup>2</sup> and for 20 years at 456.53 kgCO<sub>2</sub>/m<sup>2</sup>. It was fairly evident that the expected lifetime of the device was vital in determining the displaced emissions over the lifetime of a device, as was the activity and energy generated per step. Each of these parameters were found to detrimentally impact on the total displaced emissions if non-peak values were used. The maximum value was for a DE generator of lifetime 20 years and 85,470 steps/m<sup>2</sup>/day. This represented a location with the maximum possible activity and a long lifetime with no degradation to the device. It seemed likely that a generation device would suffer from degradation over time, although this was not detailed in the literature regarding commercial devices.

**Table 6-9: Emissions displaced over a 20 year lifetime as a result of the energy generated from energy harvesting floor devices for each of the energy harvesting technologies and varying levels of activity.**

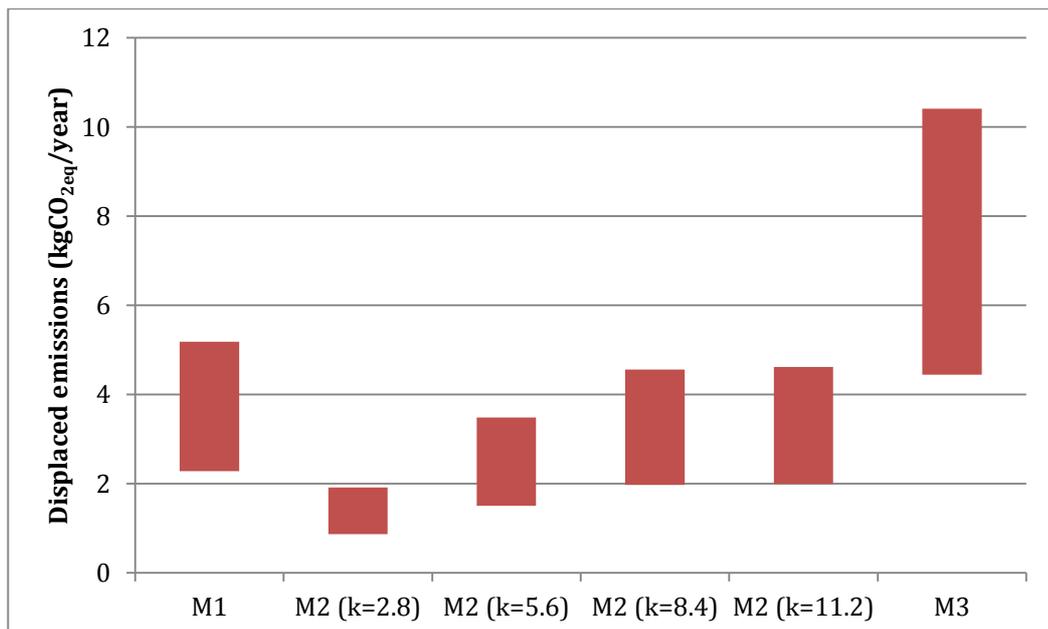
| Activity                    | Technology                             |  |  |  |
|-----------------------------|--|--|--|--|
|                             | PZT                                    | PVDF                                   | EM                                     | DE                                     |
| (steps/m <sup>2</sup> /day) | (kgCO <sub>2eq</sub> /m <sup>2</sup> ) |
| 22                          | 0.03-0.08                              | 0.004-0.04                             | 0.04-0.10                              | 0.04-0.11                              |
| 427                         | 0.60-1.68                              | 0.09-0.78                              | 0.86-2.02                              | 0.82-2.28                              |
| 4,274                       | 6.03-16.80                             | 0.86-7.75                              | 8.61-20.24                             | 8.18-22.83                             |
| 85,470                      | 120.59-335.94                          | 17.23-155.05                           | 172.27-404.85                          | 163.66-456.53                          |

The energy resulting from the production of a device was dependant on the types and amounts of materials used in producing the device or system. This was not available for the commercially available devices making a straightforward assessment very hard. The work carried out at the University of British Columbia made some attempt at estimating the emissions associated with the manufacture of the Pavegen tile devices. In the work of (Seow et al. 2011) it was estimated that each Pavegen tile requires 1.59 kgCO<sub>2</sub> in the manufacture process, based on the use of recycled rubber and stainless steel in the device. The work of (Crockett et al. 2011) additionally considered the use of recycled aluminium and toughened glass in the tiles, where a total mass of materials was estimated at 6.5 kg and a total of 6.034 kgCO<sub>2</sub> was used in the manufacture of the materials used. This goes to show that without

knowledge of the materials used in the devices, any attempt at measuring the carbon emissions associated with the materials used was somewhat arbitrary. Even so, if these values are an indication as to the emissions associated with the manufacture of a floor device then it appears that harvesting energy from floor devices may offer some benefit in terms of emissions savings if a durable and well located device is considered. As an example it was found that for an EM generator with a 5 year lifetime and in a location receiving 21,268 steps/day, the maximum displaced emissions from the device are 25.3 kgCO<sub>2</sub>. In order to ascertain whether any emissions savings could be made would require an assessment of the materials used in a specific device, the location in which it is expected to be installed and the lifetime of the device. In addition the use of an energy storage system would need to be considered.

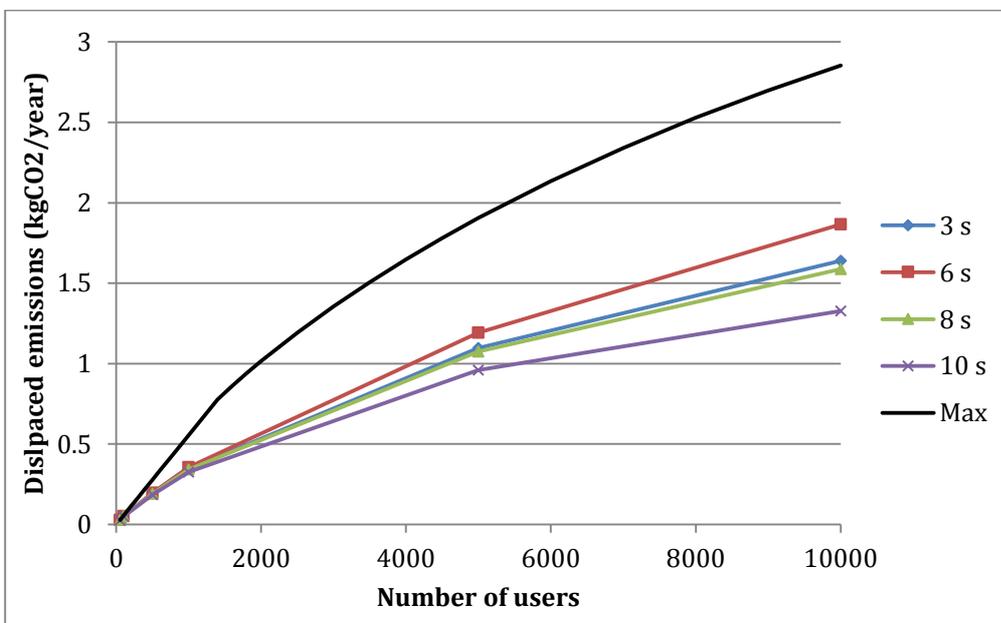
### 6.4.3. Swing Door devices

The results for the displaced emissions of a swing door generator were considered initially in terms of the maximum achievable displaced emissions and then as a function of increasing activity, as set out in table 6-4.



**Fig. 6-2: Maximum annually displaced emissions from an energy harvesting swing door device for each of the generation methods proposed.**

The maximum achievable displaced emissions were calculated for each of the generation methods, with the results shown in fig. 6-2. For method 2, the displaced emissions increase as the value of  $k'_2$  increase due to the increase in generated energy. As discussed in chapter 5.3.2., the generated energy per D.O.E. increases as  $k'_2$  increases, although for high values of  $k'_2$  this is somewhat mitigated by an increase in the value of  $t_{D.O.E.}$ . As a result the maximum value for the displaced emissions begin to level off for high values of  $k'_2$  with a maximum found for  $k'_2 = 11.2 \text{ Nm/rad}$  at  $4.6 \text{ kgCO}_{2\text{eq}}/\text{year}$ . The results for method 1 show a slight increase when compared to method 2 with a maximum of  $5.2 \text{ kgCO}_{2\text{eq}}/\text{year}$ . As would be expected, method 3 results in the highest displaced emissions values, where a range of  $4.4\text{-}10.4 \text{ kgCO}_{2\text{eq}}/\text{year}$  was found. These results represent the maximum achievable values, with the expectation that in practice the values would be significantly lower as will now be discussed.



**Fig 6-3: Values for the expected daily displaced emissions from swing door devices as a function of the number of users per day.**

For swing door devices, the results for the displaced emissions from the generated energy were shown in fig. 6-3, where the maximum output for given flow rates was calculated. For low flow rates the displaced emissions were small, where for 50 users the maximum displaced emissions were calculated to be  $0.03 \text{ kgCO}_2/\text{year}$ . It was found that changes to the value of  $t_{D.O.E.}$  did not make a significant difference for a small number of users due to the low expected

flow rates and hence similar  $c$  values. The displaced emissions increase with the number of users, as did the effect of  $t_{D.O.E.}$ . For 10,000 users per day the maximum annual displaced emissions were calculated to be in the range of 1.33-1.87 kgCO<sub>2</sub>/year. The maximum envelope of operation was found to give a maximum value of 2.85 kgCO<sub>2</sub>/year. As such the displaced emissions associated with door devices were low, especially for a low number of users.

#### 6.4.4. Revolving door devices

The displaced emissions resulting from the energy generated for a revolving door device are now presented.

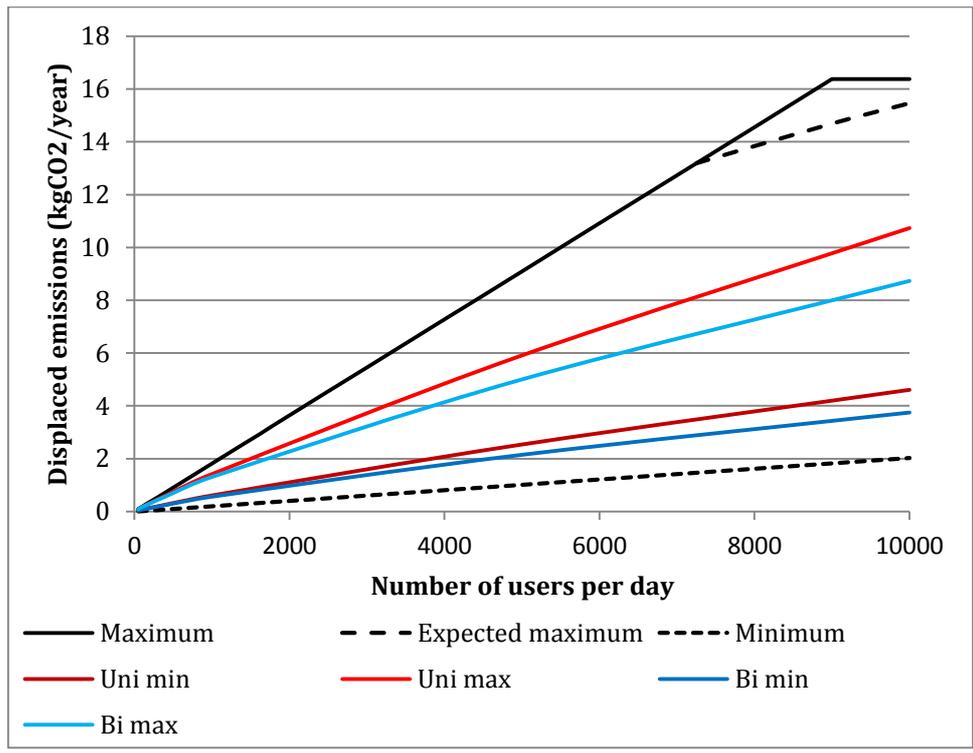
**Table 6-10: Results for the maximum achievable annually displaced emissions of an energy harvesting revolving door device for various device lifetimes.**

| Lifetime (years) | Displaced emissions |                           |
|------------------|---------------------|---------------------------|
| 1                | 16.7-39.0           | (kgCO <sub>2</sub> /year) |
| 5                | 83.5-180            | (kgCO <sub>2</sub> )      |
| 20               | 334-780             | (kgCO <sub>2</sub> )      |

The displaced emissions associated with the energy generated by a revolving door are significantly higher than for a swing door as a result of the increased potential for energy generation (power output), as was seen in chapter 5.3.3.. A range 16.7-39 kgCO<sub>2</sub>/year was calculated depending on the efficiency of the energy generation system. Evidently the lifetime of the device has a considerable impact on the displaced emissions, where for a 20 year lifetime, the maximum achievable displaced emissions are in the range of 334-780 kgCO<sub>2</sub>.

As was the case with the swing door, the expected savings are considerably lower than would be expected from the total number of users, owing to the drop in the value of the capacity factor when the door experiences a high number of users, as can be seen in fig. 6-4. It was noted in Chapter 5 that changes to the assumptions will impact upon the expected generated energy outputs and hence the displaced emissions. As such it was decided that the range of possible displaced emissions values would provide a useful means of considering revolving

door use. Unlike with swing doors, there is a minimum value for the expected outputs for a given flow rate, due the definite envelope of operation for a revolving door.



**Fig. 6-4: Expected annually displaced emissions for a revolving door as a function of the number of users, based on the energy outputs calculated in section 5.3.3..**

The values calculated using the energy outputs determined in Chapter 5.3.3. fall within the range of expected values, with a maximum of 10.7 kgCO<sub>2</sub>/year was recorded. The option of uni or bi-directional flow impacts upon the likely values for the displaced emissions. Uni-directional flow is likely to result in greater values of displaced emissions for a given number of users due to the improved values of the capacity factor. However the maximum number of users is expected to be a limiting factor due to the limitations on the maximum value of N<sub>D.O.E.</sub>.

#### 6.4.5. Storage system

The emissions associated with the energy storage device impacted upon the environmental viability of human energy harvesting. Table 6-11 shows the emissions intensity calculated for each of the energy storage technologies considered. These were calculated based on the useful energy that was expected to be delivered over the lifetime of the energy storage device

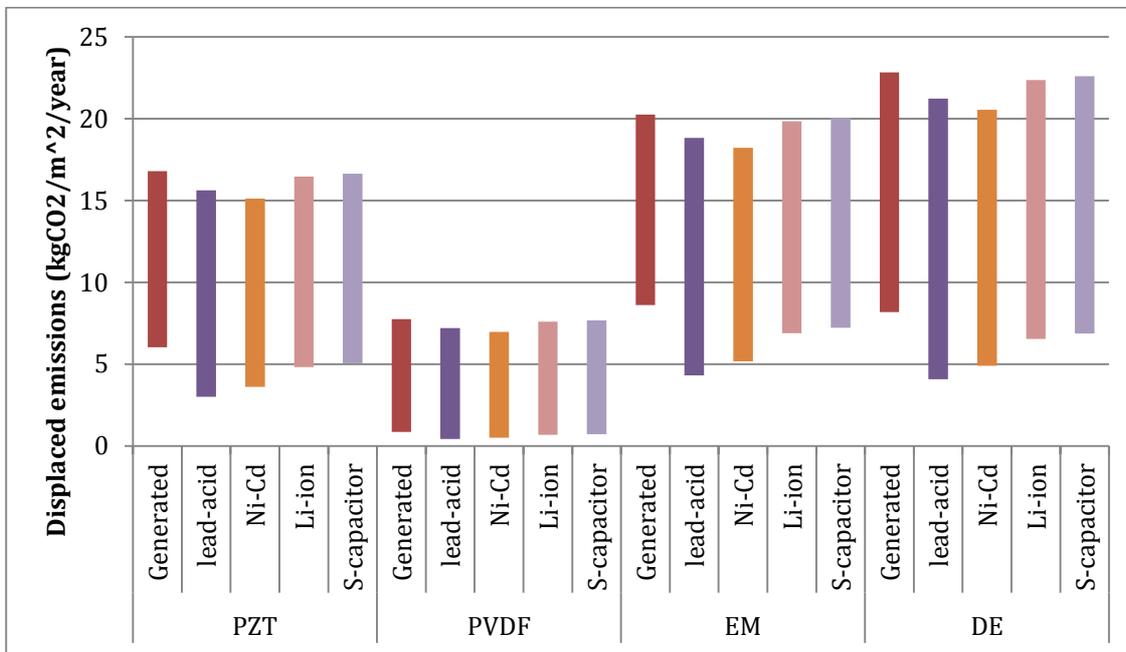
and followed the methodology set out in section 6.3.3.. However, it was noted that the results would be susceptible to the way in which the storage system was used.

**Table 6-11: Range of values for the carbon emissions intensity of each of the energy storage options.**

|   | Lead-acid                  | Ni-Cd         | Li-ion                     | S-cap          |
|---|----------------------------|---------------|----------------------------|----------------|
| ER<br>(kWh <sub>useful</sub> /kWh <sub>capacity</sub> ) | 50 – 279                   | 120 – 180     | 400 – 784                  | 8,400 – 49,500 |
| EF<br>(kgCO <sub>2</sub> /kWh <sub>capacity</sub> )     | 1.4 – 1.9                  | 2.8 – 4.2     | 4.7 – 7.5                  | 691            |
| EI (kgCO <sub>2</sub> /kWh <sub>useful</sub> )          | 5x10 <sup>-3</sup> – 0.038 | 0.016 – 0.035 | 6x10 <sup>-3</sup> – 0.019 | 0.014 – 0.08   |

The results presented in table 6-11 it appears that the EI from each of the energy storage options is significantly lower than from the grid. It appeared that the battery energy storage options offer the best potential in terms of the emissions where the emissions range from 5-38 gCO<sub>2eq</sub>/kWh<sub>useful</sub>. Lithium ion batteries appeared to offer the best potential, where a maximum of 19 gCO<sub>2eq</sub>/kWh<sub>useful</sub> was calculated. Super-capacitor technology was found to have slightly higher range EI than the chemical battery technologies although a maximum of 80 gCO<sub>2</sub>/kWh<sub>useful</sub> was still far less than the value for grid energy. It was found that the emissions factor is more than 100 times greater for super-capacitors than for the chemical battery options. This was somewhat mitigated by the long cycle lifetime of super-capacitor technologies and indeed the maximum stated lifetimes of >500,000 cycles meant that this could be further mitigated if the lifetime were to be considerably increased beyond 500,000 cycles. When comparing these values to the emissions associated with grid energy, 0.497 kgCO<sub>2eq</sub>/kWh<sub>useful</sub>, it was clear that for all of the energy storage technologies the emissions intensity was significantly lower than for grid energy. It was noted that this only considers the energy storage component of the system and so still requires the emissions associated with the energy harvesting device. If the difference between the storage system emissions and the baseline grid value were considered for the battery and super-capacitor technologies then >0.4 kgCO<sub>2eq</sub>/kWh<sub>generated</sub> was the limit for which energy harvesting would have a positive impact in terms of GHG emissions.

In addition the use of an energy storage system would impact upon the displaced emissions due to the efficiency penalty associated with the energy efficiency of the storage system where fig. 6-5 showed the impact of each of the energy storage technologies on floor generators. In terms of the affect on displaced emissions, Li-ion and super-capacitor technologies were found to have the smallest impact, where in the best case the affect was fairly negligible. As would be expected Ni-Cd and Lead-acid have the greatest impact, where for the minimum energy efficiency the displaced emissions were almost halved. This again shows the importance of choosing an appropriate energy storage system as the wasted energy impacts upon the potential benefits of human energy harvesting. It was expected however that the main impact would result from the emissions associated with the production of the energy storage technologies.



**Fig. 6-5: Annually displaced emissions resulting from the generated energy and after energy storage for each of the energy generation and energy storage technologies per m<sup>2</sup> of floor. The step density is 85,470 steps/m<sup>2</sup>/year.**

#### 6.4.6. Locations models

The energy generation results for the location models presented in chapter 5 were used to assess the potential displaced emissions resulting from the energy outputs of the system. These were presented as the whole system displaced emissions over the course of a year in

table 6-12. Table 6-13 presented the results in a per m<sup>2</sup>, per step and per device form for level walking, stair walking and door use respectively.

As was expected the total emissions displaced vary considerably between locations, as reflects the variations in total energy generated. The largest displacement occurred for the shopping centre and ticket gate, where a range of 16.57-439.02 kgCO<sub>2</sub>/year and 3.06-81.05 kgCO<sub>2</sub>/year were found respectively. The corridor, stairwell and entrance 1 all resulted in similar values of <10 kgCO<sub>2</sub>/year. Entrances 2 and 3 showed slightly increased values of 2.79-14.23 and 2.41-13.33 kgCO<sub>2</sub>/year, owing to the use of revolving doors. The contributions from different sources to the total displaced emissions were also presented in table 6-12. Flooring devices contributed the majority of the energy and hence displaced emissions in most of the scenarios, however it was expected that the number of flooring devices would significantly exceed the number of door devices. The stairwell was the exception to this, where stair walking contributed the majority of the displaced emissions. It was found that in locations where swing doors were employed, they contributed only a small proportion to the total displaced emissions. The revolving doors considered for entrances 2 and 3 significantly increased the contribution from door devices.

**Table 6-12: Results for the annual total displaced emissions resulting from the whole system of energy harvesting devices for the assumption based models.**

|                 | Walking      | Stairs    | Doors     | Total        |                           |
|-----------------|--------------|-----------|-----------|--------------|---------------------------|
| Corridor        | 0.25-6.75    | -         | 0.05-0.60 | 0.31-7.36    | (kgCO <sub>2</sub> /year) |
| Stairwell       | 0.04-1.08    | 0.20-6.18 | 0.04-0.48 | 0.28-7.74    | (kgCO <sub>2</sub> /year) |
| Shopping centre | 16.57-439.02 | -         | -         | 16.57-439.02 | (kgCO <sub>2</sub> /year) |
| Entrance 1      | 0.32-8.44    | -         | 0.10-1.09 | 0.42-9.54    | (kgCO <sub>2</sub> /year) |
| Entrance 2      | 0.32-8.44    | -         | 2.47-5.78 | 2.79-14.23   | (kgCO <sub>2</sub> /year) |
| Entrance 3      | 0.32-8.44    | -         | 2.09-4.89 | 2.41-13.33   | (kgCO <sub>2</sub> /year) |
| Ticket gate     | 3.06-81.05   | -         | -         | 3.06-81.05   | (kgCO <sub>2</sub> /year) |

Thus far the total emissions displaced from a location have been discussed, however the area and number of devices varied considerably between locations. For floor devices the highest values were still found for the shopping centre and ticket gate where the ranges of values are 0.104-2.744 and 0.20-5.40 kgCO<sub>2</sub>/m<sup>2</sup>/year respectively. The total emissions displaced for the shopping centre was larger than for the ticket gate, however the area of flooring devices in the shopping centre was also much larger than for the ticket gate, with values of 160 m<sup>2</sup> and 15 m<sup>2</sup> respectively. The corridor, stairwell and entrance 1 all had similar system outputs, however the per m<sup>2</sup> values for entrance 1 (0.032-0.844 kgCO<sub>2</sub>/m<sup>2</sup>/year) were significantly higher than for either the corridor (0.004-0.113 kgCO<sub>2</sub>/m<sup>2</sup>/year) or stairwell (0.003-0.090 kgCO<sub>2</sub>/m<sup>2</sup>/year). This was a result of both an increased number of users and the users being funnelled through a small area.

**Table 6-13: Results for the displaced emissions per m<sup>2</sup>, per stair and per door resulting from the energy outputs determined for the assumption based location models.**

|                 | Walking                                   | Stairs                         | Doors                          |
|-----------------|---|--------------------------------|--------------------------------|
|                 | (kgCO <sub>2</sub> /m <sup>2</sup> /year) | (kgCO <sub>2</sub> /step/year) | (kgCO <sub>2</sub> /door/year) |
| Corridor        | 0.004-0.113                               | -                              | 0.027-0.301                    |
| Stairwell       | 0.003-0.090                               | 0.008-0.247                    | 0.022-0.241                    |
| Shopping centre | 0.104-2.744                               | -                              | -                              |
| Entrance 1      | 0.032-0.844                               | -                              | 0.050-0.547                    |
| Entrance 2      | 0.032-0.844                               | -                              | 1.24-2.89                      |
| Entrance 3      | 0.032-0.844                               | -                              | 1.05-2.45                      |
| Ticket gate     | 0.20-5.40                                 | -                              | -                              |

When the displaced emissions are considered on a per device basis, the door devices fared far better than for the system due to the limited number of devices in a location. For swing doors the per device values were however still low, with a maximum for entrance 1 of 0.547 kgCO<sub>2</sub>/door/year. The values for the revolving door are significantly higher with a maximum for uni-directional flow of 2.89 kgCO<sub>2</sub>/door/year.

Stair use was only seen for the stairwell, when compared to level walking in the same location, it was seen that stair walking increased the emissions displaced by 0.008-0.247 kgCO<sub>2</sub>/stair/year compared to 0.003-0.090 kgCO<sub>2</sub>/m<sup>2</sup>/year. It was noted that the values are still considerably less than for level walking in either the shopping centre, ticket gate or entrance locations. This was primarily due to the small number of users expected for a stairwell and may be increased in some situations.

## 6.5. Economic assessment

### 6.5.1. Floor devices

To be economically viable the device must be able to be produced for less than the potential lifetime economic savings. As with the displaced emissions, the economic savings are considered in a per m<sup>2</sup> basis, with the likely savings calculated to determine a threshold cost per m<sup>2</sup> of flooring for different levels of activity. The results are presented in fig. 6-6. It should be noted that the economic assessment does not take into consideration any discounting to account for the future value of money.

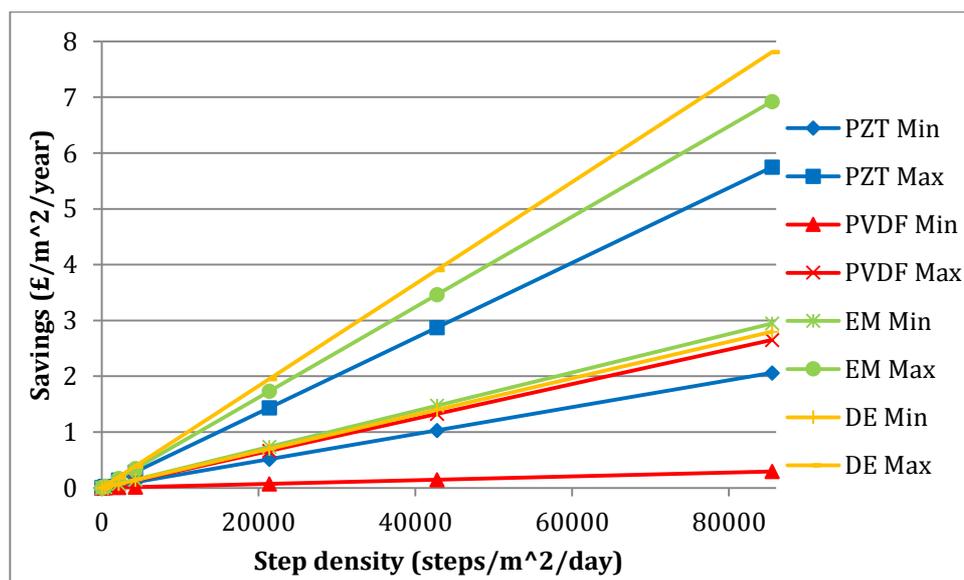


Fig. 6-6: Economic savings per m<sup>2</sup> per year from energy harvesting floor devices as a function of step density.

Consideration of the economic viability was carried out in order to determine thresholds upon which an assessment of the viability of a device should be based. It was evident that the savings from a device must exceed the device costs. The savings were based on the cost per unit of energy and the total lifetime generation potential of a device. This generation potential was based on many factors such as the generation efficiency, location parameters and the expected lifetime of a device.

It was determined that the savings from a device were small even when considering the maximum achievable energy outputs, where savings of  $<8 \text{ £/m}^2/\text{year}$  were recorded for level walking. As such the importance of a durable device was clear to see, with savings of nearly £160 for a 20 year device lifetime. Even so this was small when compared to the cost of commercial devices, with the lowest device cost being £337 (0.4m x 0.4m) so the savings were less than half the cost even for a 20 year lifetime. Even worse was the fact this represents the maximum savings, with the savings in most locations expected to be considerably lower than this. Thus far the numbers discussed were for situations with exceptionally high activity. It was seen previously that the generated energy was linearly dependant on the activity, hence the savings decrease linearly with step density. As an example the savings in a location with 50 step/m<sup>2</sup>/day were less than 1 p/m<sup>2</sup>/year. This shows the importance of choosing a location with high activity.

The savings could be increased slightly in the case of a stair device for user descent, here  $>10 \text{ £/year}$  in savings could be achieved although it seems unlikely that the activity level would be achievable in practice. The values given above are somewhat misleading as they said nothing about the size of the device, however they did give an idea of the limits to device cost.

In terms of comparing the potential savings to the cost of commercial devices it was seen that they are currently not able to provide an economically viable solution. It was suggested in the work of (Crockett et al. 2011), (Cramm et al. 2011), (Seow et al. 2011) and (Epp et al. 2011) that 8 Pavegen tiles would cost £17,815 (CD\$30,800) (Money converter, 13/12/13), amounting to £2,227 each. It was clear that even in locations with very high activity the payback period will be several hundred years. It was however hoped that this cost will reduce with time, with a goal of £50 per tile (Bloomberg 2013). If this goal were reached it may prove possible to provide economically viable energy, however only in locations with very high activity and if the

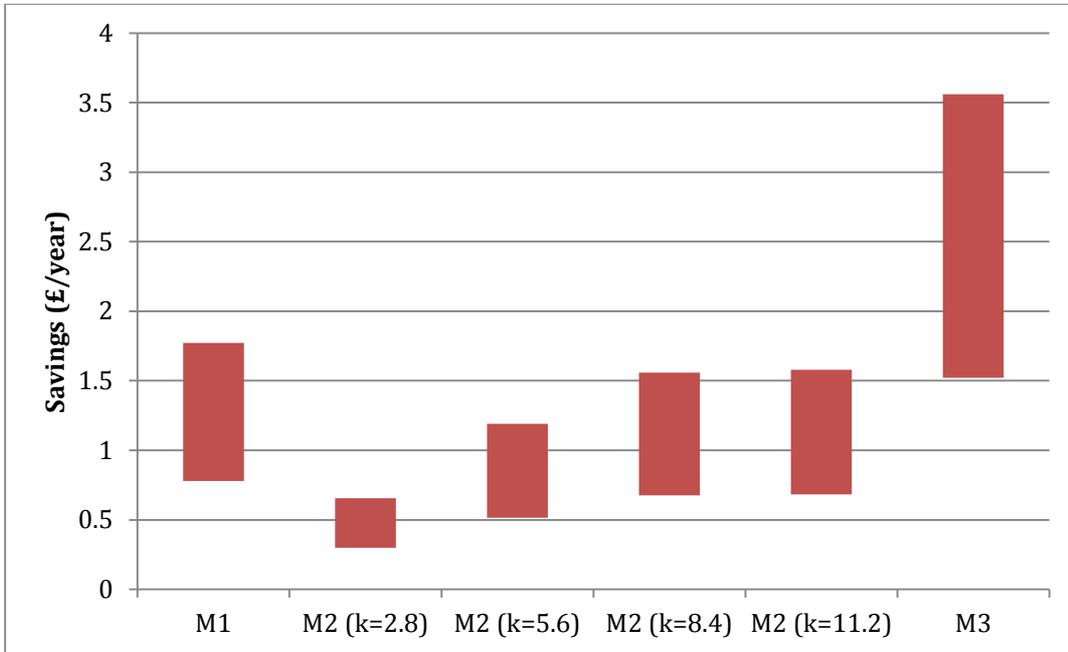
device has a long lifetime. On the Pavegen website it was claimed that the tiles have been tested to over 3 million footsteps (Pavegen 2013), although other values have been claimed, where 5 years or 20 million steps was suggested by a company spokesman (Gizmag 2011). Based on 3 million steps and taking a value of 8 J/step it was calculated that the total lifetime energy generated would be 6.7 kWh, and for 20 million steps, 44.4 kWh. Even based on the higher value this only amounted to a total lifetime savings of £7.55. As such even if the target of £50 per tile were reached, the durability of the devices would need to be in excess of 132 million steps. In addition it was not indicated whether the battery used for energy storage was included in this price. To some extent the economics of the technology depend on the required use and location with an example to power traffic bollards, where it was claimed that connection of these to the grid would cost £10,000 (Lee 2011). This would evidently impact positively upon the economic viability of the technology.

It was claimed that the Waydip device will cost £337 (€400, converted using (Money converter, 14/12/13). This indicated a payback period in excess of 40 years, even in the most suitable locations. Although no information was provided as to the lifetime of the device, a 40 year lifetime seems ambitious.

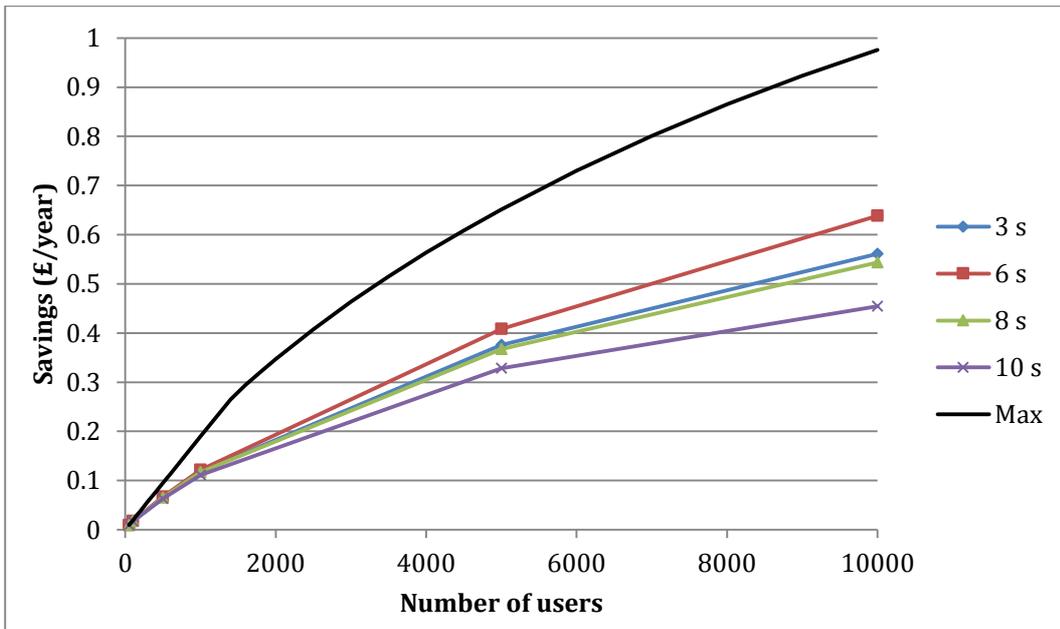
### **6.5.2. Swing door devices**

As with flooring devices the savings from the generated energy were calculated, with the upper limit for various device lifetimes examined first.

Similarly for swing door devices, threshold values were obtained, starting with the maximum achievable energy generation outputs. The results suggested that the savings possible over the course of a year would amount to a few £ per device as was seen in fig. 6-8. A maximum value of 3.5 £/door/year was found for a device utilising generation method 3. As would be expected the savings scale with lifetime, meaning that for a 20 year lifetime up to £70 could be saved per device.



**Fig. 6-7: Annual economic savings from a swing door device for maximum energy outputs for each generation method proposed.**



**Fig 6-8: Annual economic savings resulting from a swing door generator as a function of the number of users expected over the course of a day.**

For more practical situations the economic savings were expected to be significantly lower. Firstly it was expected that the number of people passing through the door would be

significantly lower than for the maximum possible output. Secondly the utilisation of this potential would further reduce the expected energy outputs. The expected maximum savings were presented in fig. 6-9, where savings of <1 £/door/year were found even in for very high levels of activity. Development of a swing door device therefore seemed to offer very little in terms of economic potential.

### 6.5.3. Revolving door devices

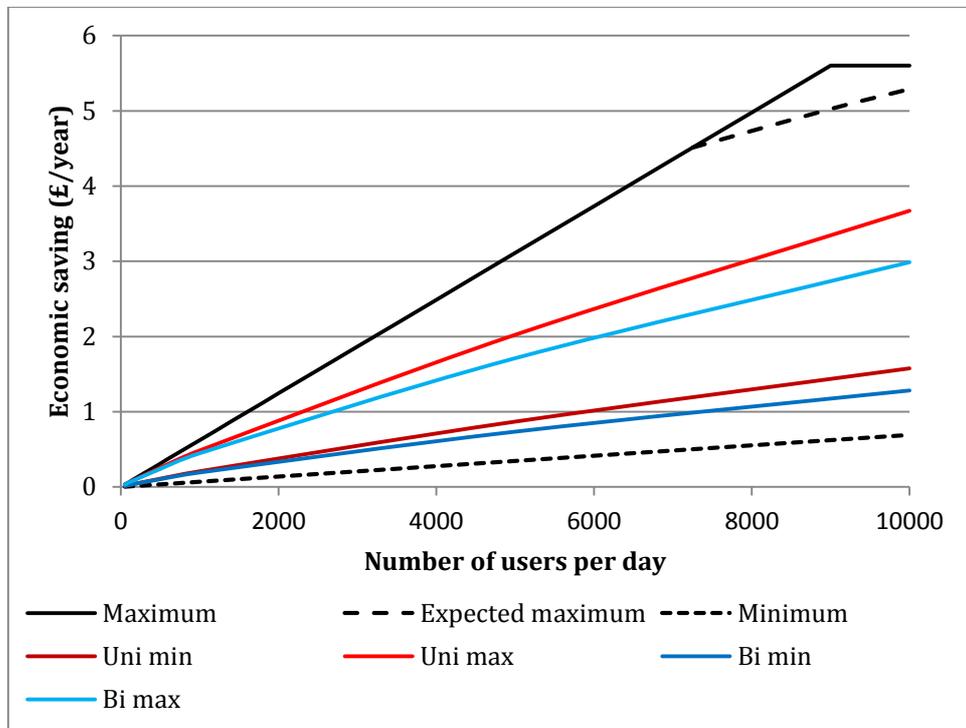
The economic savings resulting from the energy outputs of a revolving door are now presented. Firstly in terms of the maximum achievable values and secondly based on expected results for varying activity.

**Table 6-14: Results for the maximum achievable annual economic savings from each of the cases for case 3 of an energy harvesting revolving door device.**

| Lifetime | Economic savings |          |
|----------|------------------|----------|
| 1        | 5.72-13.34       | (£/year) |
| 5        | 28.6-66.7        | (£)      |
| 20       | 114.4-266.8      | (£)      |

The maximum achievable economic savings are fairly modest, with a maximum of 13.34 £/year, although they far exceed those of swing doors. It is again expected that the practical savings will be significantly lower than this, with the results presented in fig. 6-9.

The results from the revolving door are presented for varying numbers of users, with the expected generated energy outputs considered as those determined in section 5.3.3.. As was expected the economic savings were significantly reduced when compared to the maximum achievable savings. Whilst the maximum achievable savings were 13.34 £/year, the expected outputs shown in fig. 6-9 were expected to be <4 £/year. This was due to both the affect of the capacity factor and the limitation to the number of possible users. Indeed if the door were in use for 10 hours/day, then the maximum achievable savings would be limited to 5.6 £/year. Alternatively a minimum savings of <1 £/year were recorded, even for a large number of users.



**Fig. 6-9: Expected annual economic savings for case 3 of an energy harvesting revolving door as a function of the number of users, based on the energy outputs calculated in section 5.3.3..**

#### 6.5.4. Energy storage

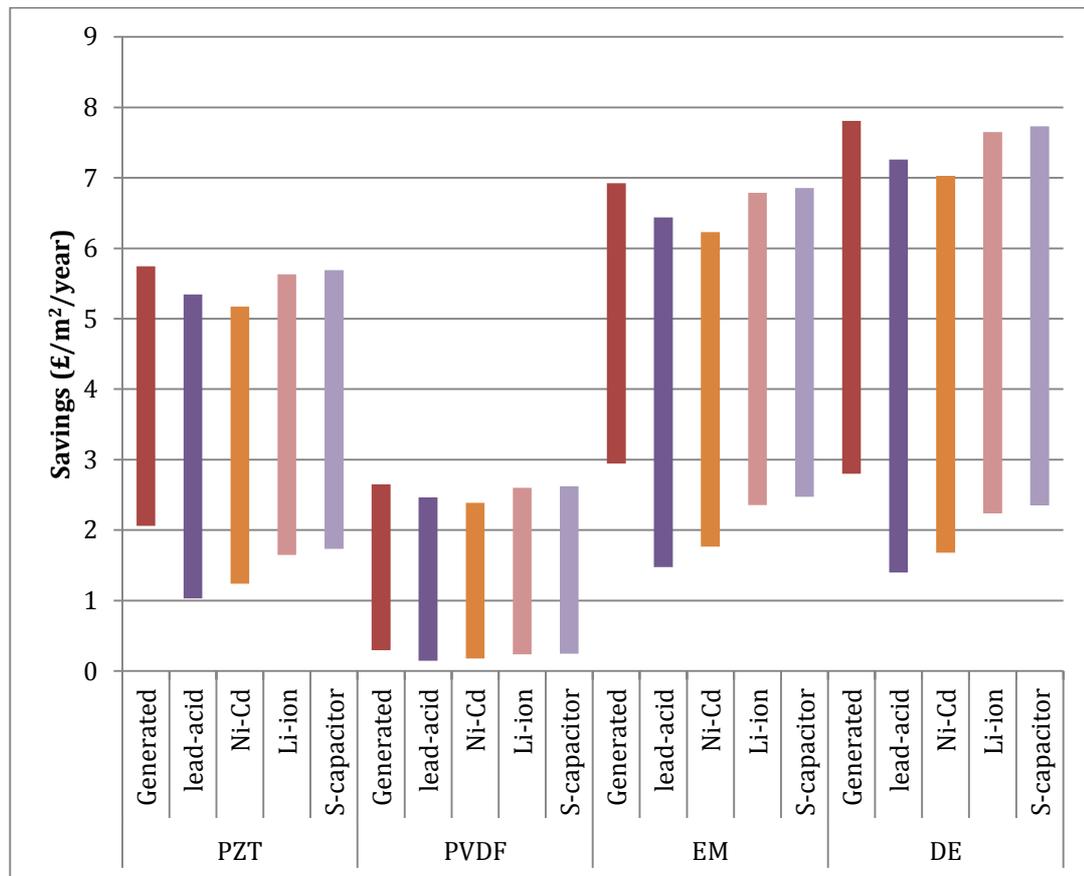
The economic impact of utilising an energy storage system is now considered. The cost intensity of the energy storage system was considered with the results shown in table 6-15.

**Table 6-15: Range of values for the cost intensity of each of the energy storage options.**

|   | Lead-acid   | Ni-Cd       | Li-ion      | S-cap                     |
|---|-------------|-------------|-------------|---------------------------|
| ER<br>(kWh <sub>useful</sub> /kWh <sub>capacity</sub> ) | 50 – 279    | 120 – 180   | 400 – 784   | 8,400 – 49,500            |
| CF (£/kWh <sub>capacity</sub> )                         | 122 – 243   | 487 – 913   | 365 – 1,522 | 183 – 1,217               |
| CI (£/kWh <sub>useful</sub> )                           | 0.44 – 4.86 | 2.71 – 7.61 | 0.47 – 3.81 | 4x10 <sup>-3</sup> – 0.15 |

In a similar way as for the displaced emissions, the inclusion of an energy storage system detrimentally impacted on the economic viability of human energy harvesting. In this instance

the consideration of the chemical battery technologies presented results in a higher cost intensity than the cost of grid energy, 17 p/kWh. It hence appears that utilising chemical battery storage technology would not offer an economically viable solution. Conversely super-capacitors offered significantly better performance with the lower end of the range being <1 p/kWh, although the range extends up to 15 p/kWh. These values only took into account the energy storage system and hence the cost of producing the energy harvesting device would still need to be taken into account. As was previously mentioned, additional cost associated with connecting a specific load to the grid would need to be taken into account on a location specific basis.



**Fig. 6-10: Economic savings after energy storage per m<sup>2</sup> of energy harvesting floor devices. The step density is 85,470 steps/m<sup>2</sup>/year.**

To add to this, the inclusion of an energy storage system further decreased the savings that could be made due to the efficiency penalty of the storage system, as was shown in fig. 6-10 for floor devices.

### 6.5.5. Location scenarios

The total energy generated over the lifetime of the system was dependant on the location and technologies implemented.

An economic analysis was also carried out based on the locations scenarios outlined in Chapter 5. It was calculated that for the corridor, stairwell and entrance the savings were small and in the range of 0.10-3.26 £/year. This was thought to primarily result from the small number of users at these locations. The case for the ticket gate resulted in savings of 1.05-27.72 £/year and for the shopping centre 5.67-150.17 £/year, these were significantly higher than for the other scenarios. In the case of the ticket gate this was due to the sheer number of users, this was also true for the shopping centre, with the additional factor of increased number of steps per user, due to the comparably large area encompassed by the location. In terms of the breakdown by technology the savings from swing door devices were small with a maximum saving of 0.37 £/year. For entrances 2 and 3 the savings from revolving doors was much higher, although still less than 2 £/year. In all cases bar the stairwell, the main savings come from floor devices as was expected from the contributions to the generated energy discussed in Chapter 5.

**Table 6-16: Results for the total economic savings resulting from the whole system of energy harvesting devices for the assumption based location models.**

|                 | Walking     | Stairs    | Doors     | Total       |          |
|-----------------|-------------|-----------|-----------|-------------|----------|
| Corridor        | 0.09-2.31   | -         | 0.02-0.21 | 0.11-2.52   | (£/year) |
| Stairwell       | 0.01-0.37   | 0.07-2.11 | 0.01-0.16 | 0.10-2.65   | (£/year) |
| Shopping centre | 5.67-150.17 | -         | -         | 5.67-150.17 | (£/year) |
| Entrance 1      | 0.11-2.89   | -         | 0.03-0.37 | 0.14-3.26   | (£/year) |
| Entrance 2      | 0.11-2.89   | -         | 0.85-1.98 | 0.95-4.87   | (£/year) |
| Entrance 3      | 0.11-2.89   | -         | 0.72-1.67 | 0.82-4.56   | (£/year) |
| Ticket gate     | 1.05-27.72  | -         | -         | 1.05-27.72  | (£/year) |

It was interesting to consider the savings that result from each device or in the case of flooring per m<sup>2</sup> of floor covered. Since the cost of the system was likely to depend heavily on the number of devices required, this approach revealed more about the appropriateness of a location. For floor devices, the savings vary greatly and depend on the number of users or more precisely the footfall density (steps/m<sup>2</sup>/year). For the corridor and stairwell the savings were calculated to be negligible, in the range of 0.001-0.04 £/m<sup>2</sup>/year. The increased number of users at the other locations results in larger savings, with a maximum value found for the ticket gate, where 0.07-1.85 £/m<sup>2</sup>/year. The stairwell resulted in similarly disappointing results, again due to the low number of users. The swing door devices present in the corridor, stairwell and entrance scenarios were calculated to offer savings of 0.01-0.19 £/door/year. As such swing door devices appear to perform better on a per device level than comparing to the whole system. Even so the savings were still very small with the necessary requirement that they be very cheap if they were to offer any advantage. The revolving doors offered better savings, with values up to 0.99 £/door/year found at entrance 2, although the costs would still be required to be very low.

**Table 6-17: Results for the economic savings per m<sup>2</sup>, per stair and per door resulting from the assumption based location models.**

|                 | Walking                  | Stairs        | Doors         |
|-----------------|--------------------------|---------------|---------------|
|                 | (£/m <sup>2</sup> /year) | (£/step/year) | (£/door/year) |
| Corridor        | 0.001-0.04               | -             | 0.01-0.10     |
| Stairwell       | 0.001-0.03               | 0.003-0.08    | 0.01-0.08     |
| Shopping centre | 0.04-0.94                | -             | -             |
| Entrance 1      | 0.01-0.29                | -             | 0.02-0.19     |
| Entrance 2      | 0.01-0.29                | -             | 0.42-0.99     |
| Entrance 3      | 0.01-0.29                | -             | 0.36-0.84     |
| Ticket gate     | 0.07-1.85                | -             | -             |

## 6.6. Summary

In this Chapter the potential benefits offered by human energy harvesting were considered through assessing the displaced emissions and economic savings resulting from the generated energy.

The emissions resulting from the fuel flow represented a complicated problem. It was seen that the emissions associated with the fuel source were very high if the harvesting of energy results in even a small increase to ME expenditure. These compare unfavourably to conventional sources of energy, however the argument may be superfluous. This was because the inclusion of this flow of fuel was only relevant if the process of harvesting this energy resulted in an increase to the food consumed. This was not easily measured, particularly as even if a 10% increase in ME expenditure was required for footfall energy harvesting and an individual was considered to take 10,000 steps per day it only mounted to a small increase of a few percent in daily ME expenditure. It was not clear whether this increase would result in additional food consumption since many people already exist on an energy surplus.

It was suggested that the emissions associated with manufacturing harvesting devices could not be reasonably determined without specific information regarding the materials used. As such the emissions displaced as a result of the energy generated were assumed to act as a threshold value for the emissions resulting from the manufacture of the device. The displaced emissions were dependent on the total energy generated and hence depend on the same parameters. For low activity locations the displaced emissions only amount to a few  $\text{gCO}_2/\text{m}^2/\text{year}$ , where even if the device were to have a long lifetime the displaced emissions were negligible. For high activity the emissions displaced reach a maximum of  $28.5 \text{ kgCO}_2/\text{m}^2/\text{year}$ , where for even a 5 year lifetime the savings could be  $>100 \text{ kgCO}_2/\text{year}$ . Energy harvesting swing or revolving door devices exhibit similar values for low activity, where the displaced emissions amount to a few  $\text{gCO}_2/\text{year}$ . The maximum values amount to only a few  $\text{kgCO}_2/\text{year}$  for swing doors, although this was significantly increased for revolving doors, where  $39 \text{ kgCO}_2/\text{year}$  was found to be the maximum. It was evident that the location plays a critical role in determining the benefits derived from harvesting energy via such technologies. However, even in the best locations, the displaced emissions are significantly lower than the maximum values.

The location scenarios presented in chapter 5 gave a clearer indication as to the displaced emissions resulting from the implementation of energy harvesting technology. The corridor, stair well and entrance 1 resulted in savings of <10 kgCO<sub>2</sub>/year. It was found that replacing the swing door with a revolving door would increase the displaced emissions. Significantly larger savings were made for the shopping centre and ticket gate, where a maximum of 439 kgCO<sub>2</sub>/year was recorded for the shopping centre due primarily to the high number of users. When the displaced emissions resulting from a floor device were considered (kgCO<sub>2</sub>/m<sup>2</sup>/year), the ticket gate offered the best potential with a maximum of 5.40 kgCO<sub>2</sub>/m<sup>2</sup>/year. This was because of the high number of users passing through a relatively small area. Stairs were seen to outperform walking although the displaced emissions were still very low. Entrance 1 resulted in slightly higher values than the corridor or stair well due to the relatively small area covered by devices. It seemed that unless very durable devices could be produced with little associated emissions then they would offer no benefit in terms of displaced emissions. The per device values for door devices exceeded those of floor devices, especially for revolving doors.

In terms of the economic savings, the results were again heavily dependent on the activity experienced by a device. For flooring device the maximum savings were found to be <8 £/m<sup>2</sup>/year and decrease linearly with activity. As such even for durable devices savings were not expected to exceed £160. For lower activity level the savings were found to be nominal. Slight increases were recorded for stair use, however they were not substantially increased. Comparing the savings to the device prices suggests that the technology was not economically competitive at present although it was claimed that prices will drop considerably. If these price decreases were realised then the economics of the technology would improve considerably, although durable devices lasting several decades would still be required. Swing door harvesting devices offer similarly small savings, with a maximum of a few £/door/year. More practical values suggest that even for high activity savings of just over 1 £/door/year would be achieved. As such swing door harvesting devices would need to be very cheap to be economically competitive. As with the displaced emissions, revolving door devices performed better than swing door devices, with maximum savings of 13.34 £/year, although in practical locations these were expected to be <4 £/year.

As may be expected the savings resulting from the corridor, stairwell and entrances amount to a few £/year, with a maximum found for the shopping centre, where savings of 150 £/year were recorded. When the savings per m<sup>2</sup> were considered it became clear that they were very low even in the best location. A maximum was found for the ticket gate where a saving of 1.85 £/m<sup>2</sup>/year were calculated. The contribution from a swing door device was very low, with a maximum of 0.19 £/door/year. Revolving doors fared slightly better, although savings of <1 £/door/year were still expected. The results seemed to suggest that even if durable and low cost devices could be developed, the savings would not be significant even in the most suitable locations.

In conclusion it appeared that human energy harvesting is unlikely to offer either environmental or economic benefits in most situations for the foreseeable future. It could be possible to provide an environmental benefit, although this depends on the specific device and indeed the expected energy output over the device's lifetime.

## 7. Conclusions

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The aims of this thesis laid out in Chapter 1 were assessed through a holistic consideration of the main components involved with human energy harvesting in the urban environment. The questions to be answered were reiterated within this chapter with the conclusions drawn regarding them presented. In answering these questions a number of conclusions were drawn with regards to the feasibility of implementing human energy harvesting as a means of electrical energy generation and were as follows.

1. How does the human body produce harvestable energy and what were the limitations to this?

The first stage of the research was aimed at considering the flow of energy in the human body, from the point of ingestion of food to the development of mechanical work by the human body. It was found that the average adult in the UK consumes about 10 MJ/day in the form of metabolic energy from food, although there was significant variability between individuals. In addition it was shown in the literature that large amounts of energy was stored in the human body in the form of body fat and was used to suggest that the human body could offer significant potential for energy harvesting (Starner 1996). This was however a somewhat simple and misleading interpretation due to the unavoidable need for the human body to use much of the energy for processes necessary for survival, such as the BMR. As a result in most people only 25% of the energy expended over the course of a day was used to carry out activities, giving an energy potential of 2.45 MJ/day (Chapter 3.1.). As with the energy intake, there was significant variability between individuals where very active individuals would expend a higher percentage of total energy expenditure on carrying out mechanical work. Values for energy expended on mechanical work in the literature were consistent with those calculated in Chapter 3, although vary slightly due to differing assumptions with regards to energy intake and the use of this energy.

The development of mechanical work from the energy expended on physical activity resulted in an efficiency penalty and further reduces the energy potential available for energy

harvesting. Several definitions of efficiency were identified from the literature, with the net efficiency deemed to be the most appropriate when considering human energy harvesting. Further to this, in many situations most of the mechanical work developed was found to be used to complete an action. As such the potential for energy harvesting was dependant on the external mechanical work performed on the harvesting device. In the case of walking it was found in Chapter 3.3. that only 5.6 % of the net energy expended during walking was available for energy harvesting (4% of total energy expenditure). As such it was concluded that although significant energy was consumed and used by the human body, the vast majority of this was unavailable for energy harvesting. In Chapter 3.4.3. It was estimated that 20 Wh of energy potential was available for energy harvesting from an individual during walking over the course of a day. Although this was fairly modest, the potential from a population scales with the number of people, meaning the potential for energy generation in the UK was 1.2 GWh/day. This represented significant potential, where harvesting even a fraction of this appeared worthwhile.

## 2. What energy potential can be offered by an individual and from which sources?

It was revealed in the literature that the human body offers two main sources of energy, body heat and mechanical work. Although significant energy was released in the form of heat, harvesting this energy for electrical energy generation was impractical. As such only mechanical work was considered further. In the urban environment three main sources of mechanical work were considered, these being walking, swing door and revolving door use. It was found in Chapter 3.3. that the potential offered by a single step was dependant on the mass of the user, where for a 70 kg individual completing level walking, roughly 8.4 J/step was available. Stair walking was found to impact on the energy potential, where a slight increase was found for stair descent and a decrease found for stair ascent. The motion of swing and revolving doors were considered in Chapter 3.5. through computer modelling to assess the potential available from energy harvesting. For swing doors, up to 20 J/D.O.E. was found to be available. Revolving doors offered significantly more energy potential, with up to 64.6 J/D.O.E. available for harvesting.

## 3. What technologies were available for harvesting energy and the limits to expected energy outputs from human activity?

In chapter 4 the generation potential from a single footstep and single use of a swing door and revolving door were explored. It was found that several technologies were utilised to harvest the energy potential available from walking, with PZT, PVDF, Dielectric elastomer and electromagnetic generators considered. The efficiency with which each of these technologies was able to convert the mechanical work potential into electrical energy was considered, with a range of values representing the currently practically achievable and theoretically achievable values determined. It was determined in Chapter 4.3. that the range of efficiencies varied greatly between technologies, with PVDF 2-21% and DE 23-63% providing the lowest and highest conversion efficiencies respectively. These conversion efficiencies were used to determine the range of energy generation outputs per step for level walking and stair use. It was found in Chapter 4.4.1. that for an individual step of an 80 kg individual for level walking the energy output was in the range of 0.2-6.0 J/step. It was found that stair ascent resulted in slightly lower outputs, whereas for stair descent the expected energy outputs were higher, owing to the greater ground reaction forces of a footstep. It was deemed that an electromagnetic generator would be the most suitable method for harvesting energy from door motion, with the range of generated energy outputs determined using the range of conversion efficiencies. The expected range of generated energy outputs are shown in Chapter 4.4.2., where for the baseline case it was found to be 1-11 J/D.O.E. for swing doors. This was found to depend on both the generation efficiency and generation method utilised. For revolving doors (Chapter 4.4.3.) the expected range of outputs increased considerably with a range of 15.3-35.8 J/D.O.E. found for the baseline case. It was concluded that the energy available from either a single step or door opening was very limited (in the range of a few J), however this would again scale with the number of users and will hence be very dependant on the location in which a device was installed.

Throughout most of the thesis it was considered that the energy harvesting system would require some form of energy storage. Section 4.5 considered whether it may be possible to avoid the use of an energy storage system and instead provide the power directly to the load. LED lighting in a corridor was taken as an example with the conclusion that several m<sup>2</sup> of flooring could potentially be illuminated whilst the user is in motion. Even so, it is still expected that such a system would not work in practice as it requires the user to be in continual motion to provide for the requirements of the load. As such a back up source of power would be required in practice. In theory this could come from the electrical grid via a hybrid system, however this necessitates significant additional complexity and was hence

thought to be impractical. It is recognised that there may be some scope to utilise the generated energy directly to provide for low power loads such as a ticket gate, however it is thought that these will be niche applications.

#### 4. How much energy could be expected to be generated in practical locations?

In chapter 5 the energy outputs from each of the energy generation sources was used to determine the expected energy outputs that were achievable in practical situations. Floor and door devices were considered in a general sense in an attempt to determine the role of several parameters on the expected energy outputs.

When considering swing (Chapter 5.2.2.) and revolving door (Chapter 5.2.3.) devices it was shown that the total available potential would be less than the number of users. This was due to the fact that not every user would be required to open the door, with a study carried out to determine the practical affect of this. Two factors were found to affect the capacity factor, these being the flow rate of users through the door and the time taken for a door opening event to occur. For swing doors, it was found that even for relatively modest flow rates the proportion of users required to open the door falls very quickly with average values in the range of 0.258-0.461 found over the course of the studies conducted. It was noted that the number of samples collected in this study was small and hence the statistical significance of the data is fairly limited, however since the results are from a case study it was felt that they offer a useful insight into the utilisation of the energy potential offered by swing doors. This study was used as the basis from which theoretical values could be determined to estimate the proportion of users opening the door in different scenarios. Similarly revolving doors were found to suffer from the same effect, although to a lesser extent due to the requirement for the door to be at least partially rotated by each user. This did however result in limitations to the maximum achievable flow rate of users through a revolving door.

For a floor device it was found that the number of users, device lifetime and area covered by devices all impacted upon the total energy generated. The maximum achievable output was determined in Chapter 5.3.1.1. and was found to be 127 Wh/day (~46 kWh/year). It was however found that the generated energy output was small in most practical situations.

Evidently the output scales linearly with the number of users, size of the system and expected device lifetime. It was found that well chosen locations could offer some potential.

The generated energy outputs for a swing door are shown in Chapter 5.3.2., where a maximum achievable output of 57.4 Wh/day was calculated. The activity and hence expected energy outputs were however expected to be considerably lower. In addition the utilisation of potential for a swing door device was expected to fall considerably with increasing flow rate. As such the energy outputs were not expected to increase linearly with increased activity, but instead tail off for high activity, with the generated energy outputs not expected to exceed 10 Wh/day.

Revolving door devices were found to offer significantly more potential than swing door devices as shown in Chapter 5.3.3., with a maximum of 215 Wh/day. Again the expected outputs were considerably lower, due to both lower activity and a decrease in the capacity factor for high activity levels. Additionally, the direction of flow was found to impact upon the capacity factor, where uni-directional flow was expected to offer better values than bi-directional flow. The capacity factor was found to have a definite envelope of operation for both maximum and minimum values. In addition, the maximum flow rate was found to have a definite limit due to the requirement of the door to rotate to allow a user to pass through and was governed by the value of  $t_{D.O.E.}$ . As such the limits to energy generation are more clearly defined for a revolving door than for a swing door.

A number of assumption based location models were considered in Chapter 5.4. to determine the expected energy outputs and assess the importance of location when considering energy harvesting. Seven locations were modelled, a corridor, stairwell, shopping centre, three entrances and a ticket gate at a railway station. A number of conclusions were made from these. It was found that for most of the scenarios, walking contributed the vast majority of the expected generated energy to the total. This was a result of a combination of fewer door generation devices than floor generation devices as well as the diminishing values of the capacity factor expected for door use, particularly in locations with high activity. The exceptions to this occurred for the entrances utilising revolving door devices due to both the increased generated energy output from a D.O.E. and improved values of the capacity factor. It was found that the expected energy outputs calculated resulted in modest values. In the

case of the corridor, stairwell and entrance these were very low with the maximum values expected only on the order of a few tens of Wh/day. Higher outputs were expected for the shopping centre and ticket gate, with outputs of 2.43 and 0.45 kWh/day respectively. Although these were significantly higher they were still modest outputs. The causes of the increased outputs from these two sites were the high number of users, in the case of the shopping centre this was complimented by the number of steps taken by each user. As such it was concluded that the location is critical to the expected energy outputs.

5. What was the feasibility of the energy generated via human energy harvesting in terms of economic viability?

The economic assessment presented in Chapter 6.5 aimed to determine thresholds for the cost of devices at which they would become economically feasible. Since the economic savings were dependent on the energy outputs, it seemed clear that they will depend on a number of factors, such as the device energy output and activity experienced by the device. It was found that the potential savings were modest even in the most suitable locations, where it was expected that they would not exceed a few £/year for a floor, swing door or revolving door device. For more practical scenarios the situation was even worse, where for areas with low activity the savings were expected to be significantly less than 1 £/m<sup>2</sup>/year for floor devices. Further to this, the inclusion of an energy storage system negatively impacts upon the viability of the technology in an economic sense. Considering the economic impacts of energy storage, super-capacitors appeared to offer the most cost effective solution, with all of the battery technologies resulting in a considerable economic disadvantage. When compared to the cost of commercially available devices it was apparent that the technology was far from economically viable, where the cheapest was in excess of £300. Thus it was concluded that for human energy harvesting to offer any economic benefits in terms of the generated energy the devices used must be cheap, durable and in a location with high activity. It was noted that remote locations may result in significant financial cost to connect to the electricity grid, this could affect the economic viability in a given location and would need to be considered on a location specific basis.

6. What were the expected environmental impacts and emissions displaced by the generated energy?

The environmental assessment presented in chapter 6.4 considered the potential displaced emissions resulting from the electrical energy generated by human energy harvesting. It is recognised that the assessment carried out is based on simplified assumptions, in part due to the complex nature of the energy source and the lack of specific information available regarding particular devices. Even so it is felt that the assessment does provide an insight into the thresholds for which the technology could provide some benefit in terms of emissions savings.

An assessment of the emissions associated with the fuel source was considered. In order to do this the additional metabolic energy required to generate electrical energy was considered, where it was found that the efficiency of converting ME into useful electrical energy was in the range of 0.1-14.1%. When compared to the emissions resulting from the production of food it was found that the fuel source results in dramatically higher emissions than from any conventional source of energy generation, although it was noted that this was not necessarily important as the increase in energy expenditure was very small and may not result in an increase in food consumption for the individual. Even so it does demonstrate that attempting to farm energy from people could have a significant negative environmental impact.

Further to this the emissions displaced resulting from the expected generated energy were assessed. It was evident that these would depend on the expected energy outputs and would thus depend on the same parameters as those examined in chapter 5. As was the case with the expected energy outputs, the displaced emissions were fairly modest. Even in the best situations these were expected to be on the order of a few  $\text{kgCO}_2/\text{m}^2/\text{year}$ . When the inclusion of an energy storage system was considered two impacts were found. Firstly the displaced emissions decreased due to the energy efficiency of the storage systems. Secondly the emissions associated with the energy storage system significantly diminish any potential benefits. It was found that chemical batteries offered the best potential in terms of the emissions impacts, although each of the technologies was thought to be a viable means of providing energy storage. Comparison to commercially available devices was difficult due to a lack of available information regarding the materials used in the devices, however a well chosen location may offer some benefits in terms of displaced emissions.

## **Final thoughts**

The research presented in this thesis was aimed at assessing the potential offered by human energy harvesting in the urban environment. The process of developing mechanical work was evaluated and it was determined that the vast majority of the energy consumed as food was required to account for the needs of everyday life, leaving only a small proportion available in the form of harvestable mechanical work. Even so it appeared that significant potential exists in the form of mechanical work due to the scaling with population size.

Conversion of the available mechanical work into electrical energy was considered with four generation technologies presented, these being PZT and PVDF piezoelectric generators, electromagnetic generators and dielectric elastomer generators. The efficiency with which these technologies convert mechanical work into electrical energy varied greatly, with EM and DE generators offering the best values.

Although it was found that significant potential exists, it was seen that this was spread diffusely through the urban environment. The expected energy outputs vary greatly between locations depending on the activity. In most situations the outputs were very small and even in the best locations the outputs were still modest.

As a result the economic savings and displaced emissions resulting from the expected generated energy were also small. As such, if human energy harvesting technologies were to offer any benefits the technology would need to be both very cheap and have low emissions associated with their manufacture, installation and maintenance. As such it appeared that human energy harvesting would in most locations not offer a viable form of energy generation.

## **Further considerations**

The conclusions drawn from the research presented in this thesis have claimed that human energy harvesting does not appear to offer a beneficial means of generating energy in the urban environment. However there are a number of areas of research that could be considered to further this understanding.

It has been seen that the economic and emissions savings from the energy generated via human energy harvesting are small. As such it appears that the cost and embodied emissions of a device or system of devices will determine whether human energy harvesting could provide a beneficial means of generating energy in the urban environment. Although the cost of the commercially available devices is far in excess of the value of the generated energy, if a very low cost device can be developed with low embodied energy, then it may be possible for human energy harvesting to provide some benefit in well chosen locations. As yet it remains to be seen if this can be practically achieved. A better understanding of the materials used in specific devices would allow for an assessment of the viability of a particular device. It was however noted in this thesis that details of the specific components of commercially available devices were not readily available. An alternative approach would be to consider the components required in the energy harvesting system for each of the technologies presented. Although this would necessitate an assumption based approach it would give an indication as to the viability of each technology both in terms of cost and embodied emissions.

In this thesis the generation of electrical energy has been considered, however the use of this energy has been considered in terms of replacing grid energy. The load for which the energy is used has not been considered although will be critical in determining the use of a system. As such consideration of prospective end loads needs to be addressed in order to determine whether human energy harvesting could provide sufficient energy to fulfil the requirements of specific loads. It has been stated that the Pavegen (Pavegen n.d.-b) and SDC (SDC 2014) devices available are capable of providing lighting, however it is not clear if the energy generated is sufficient to power all of the lighting needs in the location of installation and needs to be addressed. If not all the needs can be met it may be possible to produce a hybrid system where any shortfall in the energy derived from human energy harvesting is met via grid energy. It is expected that this would require a degree of additional complexity and would need to be considered in terms of economic and environmental impacts to determine if it would be an appropriate solution. As such determination of the viability of specific locations needs to be addressed to determine where human energy harvesting can offer a viable solution. It seems likely that this would be particularly relevant to applications remote from the grid, where it may be expensive to connect to the grid to provide the energy needs.

A further potential application may be to use the energy generated to act as a sensor network with the aim of improving energy efficiency in the urban environment. For loads such as lighting, where the load is only required in the presence of a person, this may prove beneficial. Since the input energy for human energy harvesting is inextricably linked to the presence of a person it may prove a useful means of controlling the use of such loads. Further work would be necessary to determine the energy requirements of such a system and the potential for energy savings that such a system may offer. This may shift the focus of energy harvesting devices to some extent, where maximising the energy output may not be necessary, but instead providing only for the energy requirements of the control system. In addition the activity experienced in a location may prove to be less important, as the overall energy output needs only to cover the requirements of the control system. It may even turn out that areas with low activity will see the greatest benefit as energy wastage will be minimised.

In addition the practical and social impact on users of utilising human energy harvesting devices in the urban environment is not well known with a few areas that need consideration. Firstly the deflection of the floor during walking may pose a trip risk, particularly if a large deflection occurs. Secondly it is not clear how people will react to the presence of a harvesting device. It may be that people will actively try and engage with them, however it is also possible that people would chose to avoid using them, particularly if they considerably affect the comfort of the user. Finally, the use of harvesting devices could play role in educating people with regards to their understanding of energy. If people can be educated with regards to their energy use through interaction with the generation process then energy harvesting could potentially play a role in influencing people's energy consumption.

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## Appendix 1: Digestion energy losses

The gross energy contained in food is converted into metabolisable energy, which the human body uses to provide for necessary functions. The main losses occurring from this process are outlined as follows,

1. At the point of ingestion the amount of energy contained within the food is known as Gross Energy (GE). This is measured as the total combustible energy content of food and is measured using bomb calorimetry.
2. Incomplete digestion of food in the small intestine results in faecal energy and gaseous energy losses. Accounting for these losses gives the digestible energy.
3. Further energy is lost as urinary energy and from the body surface as surface energy. Once these losses have been taken into account the result is metabolizable energy (ME). (Tontisirin et al. 2003)

Accounting for these losses and hence converting the GE content of food into an ME value can be carried out using food energy conversion factors. Several approaches exist, with the Atwater general factor system used here due to its simplicity (Tontisirin et al. 2003) and the use of these conversion factors in food labelling (Commission 2009). The system is based on the heat of combustion of protein, fat, carbohydrate and alcohol with corrections made for digestion, absorption and urinary losses (Tontisirin et al. 2003). Table A1 shows the energy values used for different sources of food energy.

**Table A1: Energy values of energy sources in food. A conversion factor of 4.184 kJ = 1 kcal is used<sup>+</sup>. (<sup>+</sup>(Merrill & Watt 1973), <sup>\*\*</sup>(Tontisirin et al. 2003))**

|               | Gross energy      |                   | Digestibility<br>(%) | Atwater factors   |                  | Efficiency |
|---------------|-------------------|-------------------|----------------------|-------------------|------------------|------------|
|               | (kcal/g)          | (kJ/g)            |                      | (kcal/g)          | (kJ/g)           |            |
| Protein       | 5.65 <sup>*</sup> | 23.6 <sup>+</sup> | 92 <sup>*</sup>      | 4.0 <sup>**</sup> | 17 <sup>**</sup> | 0.71       |
| Fat           | 9.40 <sup>*</sup> | 39.3 <sup>+</sup> | 95 <sup>*</sup>      | 9.0 <sup>**</sup> | 37 <sup>**</sup> | 0.96       |
| Carbohydrates | 4.15 <sup>*</sup> | 17.3 <sup>+</sup> | 97 <sup>*</sup>      | 4.0 <sup>**</sup> | 17 <sup>**</sup> | 0.96       |
| Alcohol       | 7.07 <sup>*</sup> | 29.6 <sup>+</sup> | -                    | 7.0 <sup>**</sup> | 29 <sup>**</sup> | 0.99       |

As is apparent from table 1, the losses associated with digestion will depend on the relative mix of protein, fat, carbohydrates and alcohol in the diet. The body has a high digestibility of

most foodstuffs, as shown in table 1. In order to use the energy that has been digested, oxidation must occur. In the case of carbohydrate and fat this is complete, however for protein the oxidation is incomplete and leads to urinary energy losses. A value of 5.3 kJ/g of protein is considered to be lost in this way. This value must be subtracted from the post digestion value to give the metabolisable energy content derived from protein (Geissler & Powers 2010). This amounts to an additional loss of 22.5% when converting the GE contained in protein into ME. The values given in table 3-1 show some discrepancy between the digestibility and the overall efficiency of converting GE into ME. The reason for this is the use of the Atwater factors when considering the ME value of food. These values are slightly different from those given in (Merrill & Watt 1973), however the Atwater values were used here as they are used in the determination of the energy content in food labelling (Commission 2009).

## Diet

It was evident that the efficiency with which the human body can convert the GE of food into ME will be dependant on the diet of the individual. Table A2 shows the average energy needs for men and women between the ages of 19-65 in the UK. These values have been obtained from the National Diet and Nutrition Survey (2000/1) (Henderson et al. 2003). In addition a breakdown of the various macronutrient sources was given. It should be noted that the energy was calculated from the food consumed (Henderson et al. 2003), with the Atwater values used to calculate the energy content of foods (Guidelines of nutrition and food labelling). Hence the values given represent the ME.

**Table A2: The average energy requirements of adults in the UK, with a breakdown of the contributions of the major macronutrients. \* (Henderson et al. 2003)**

|       | ME     | Carbohydrates | Protein       | Fat           | Alcohol      |
|-------|--------|---------------|---------------|---------------|--------------|
|       | MJ/day | MJ/day (%)    | MJ/day (%)    | MJ/day (%)    | MJ/day (%)   |
| Men   | 9.72*  | 4.34 (44.7%*) | 1.50 (15.4%*) | 3.26 (33.5%*) | 0.63 (6.5%*) |
| Women | 6.87*  | 3.21 (46.7%*) | 1.09 (15.9%*) | 2.30 (33.5%*) | 0.27 (3.9%*) |

The values given in table A2 were used to calculate the GE content of each component of the diet and overall conversion efficiency for the average male and female in the UK. The

conversion efficiencies used for each of the macronutrients were assumed as those presented in table A1.

**Table A3: The input of GE that is required to provide for the energy requirements of the average person in the UK and the conversion efficiency based on the mix of macronutrients in the diet.**

|         | Carbohydrate<br>(MJ/day) | Protein<br>(MJ/day) | Fat<br>(MJ/day) | Alcohol<br>(MJ/day) | Total |      |
|---------|--------------------------|---------------------|-----------------|---------------------|-------|------|
|         |                          |                     |                 |                     | GE    | %    |
| Men     | 4.47                     | 2.08                | 3.43            | 0.64                | 10.62 | 91.5 |
| Women   | 3.21                     | 1.51                | 2.37            | 0.27                | 7.36  | 93.3 |
| Average | 3.84                     | 1.76                | 2.90            | 0.46                | 8.99  | 92.3 |

Table A3 shows that the efficiency of converting gross energy into metabolisable energy is fairly high in humans, with an average efficiency of 92.3%. Even though the relative mix of each of the energy containing nutrients will have an affect on the efficiency, it was surmised that this will be relatively small and will not change significantly between individuals.



## Appendix 2: Energy expenditure from the BMR.

The energy expended over the course of a day as a result of the BMR can be estimated for an individual based on age and mass using the equations shown in table A4. As an example a 60 kg male in the age range of 18-30 years old was predicted to have an energy expenditure of 6.68 MJ/day to satisfy the demand of the BMR.

**Table A4: BMR estimation based on age, gender and mass (FAO et al. 2004).**

| Age<br>(years) | BMR                             |                                  |
|----------------|---------------------------------|----------------------------------|
|                | (MJ/day)                        | (kcal/day)                       |
| Male           |                                 |                                  |
| 18-30          | $0.063 \cdot \text{kg} + 2.896$ | $15.057 \cdot \text{kg} + 692.2$ |
| 30-60          | $0.048 \cdot \text{kg} + 3.653$ | $11.472 \cdot \text{kg} + 873.1$ |
| Female         |                                 |                                  |
| 18-30          | $0.062 \cdot \text{kg} + 2.036$ | $14.818 \cdot \text{kg} + 486.6$ |
| 30-60          | $0.034 \cdot \text{kg} + 3.538$ | $8.126 \cdot \text{kg} + 845.6$  |



### Appendix 3: Measures of physiological efficiency

$$\text{gross efficiency} = \frac{\text{work accomplished}}{\text{energy expended}}$$

$$\text{net efficiency} = \frac{\text{work accomplished}}{\text{energy expended} - \text{energy expended at rest}}$$

$$\text{work efficiency} = \frac{\text{work accomplished}}{\text{energy expended} - \text{energy expended for zero load work}}$$

$$\text{delta efficiency} = \frac{\text{change in work accomplished}}{\text{change in energy expended}}$$

In the case of gross energy the total calorific energy expenditure during the activity is used to determine efficiency. Although the simplicity of this method may make it seem attractive, the total calorific energy expenditure includes some component of the BMR, which, as previously discussed, is necessary to perform the functions the body requires to survive and will thus occur regardless of physical activity. The gross efficiency of cycling increases as the work rate increases, although this is in part a result of the diminishing proportion of the BMR to total calorific energy expenditure. Even so, in the work of (Ettema & Lorås 2009) the gross efficiency was considered to be the most appropriate approach to measuring efficiency, as the baseline values used in determining other types of efficiency used assumptions that did not properly account for the complexities of the interactions associated with physiological systems.

The net efficiency considers the calorific energy expenditure as the total minus the energy expended by an individual at rest and results by definition in the net efficiency being greater than the gross efficiency. The net efficiency considers all energy expended above the BMR to be a result of developing mechanical work and was considered as the mechanical efficiency in the work of (Capelli et al. 2008).

Work efficiency was deemed to be the most appropriate measure of efficiency in (Whipp & Wasserman 1969). The baseline subtraction used was for carrying out ergometer cycling with no load. This assumed that work carried out in limb motion is not directly associated with the development of mechanical work and instead was only concerned with the additional energy required to complete physical work.

In a similar way, delta efficiency is a measure of the increase in calorific energy expenditure associated with an increase in external work, and was considered in the work of (Gaesser & Brooks 1975) as the most appropriate measure of efficiency. In terms of the physiological efficiency of directly developing mechanical work, the work and delta efficiencies are arguably the most appropriate, however they do not take into account other factors associated with carrying out an activity.

## Appendix 4: Generation method 1 (m1final.m)

```

clear

%Door characteristics
m = 30;           % (kg) door mass
rd = 0.8;        % (m) Door width
F0 = 25;         % (N) opening force
rF = 0.70;       % (m) opening force applied at
kr = 14;         % (Nm/rad) torsional return constant

%Characteristic calculations
I = (m*(rd^2)/3); % (kgm^2) Door moment of inertia
T0 = F0*rF;       % (Nm) Opening torque
wn = (kr/I)^0.5;  % (s^-1) Natural frequency

%Generator effect
cc = 2*(I*kr)^0.5; %Value for critical damping

%initial conditions
ang = 0;         %Initial value for the angle
angv = 0;        %Initial value for the angular
velocity

%Calculation of results
for j=1:1:10
    dg(j)=(j-1)*0.1; %Damping coefficient
    c(j)=dg(j)*cc; %Damping
    wd(j)=((1-(dg(j))^2)^0.5)*wn; %Damped frequency
    t(1) = 0; %Inital value for time
    for i=1:1:100
        t(i) = (i-1)*0.1; %Calculates time value
    %Phase 1
        if t(i) <= 1.0; %Condition for
using phase 1
            phil(j) = atan(dg(j)/(1-(dg(j)^2))^0.5);
            ang(j,i) = (T0/kr)*(1-((1/(1-(dg(j)^2))^0.5)*(exp(-
dg(j)*wn*t(i)))*cos((wd(j)*t(i))-phil(j)))); %Calculates
angle for phase 1
            angv(j,i) = (T0/kr)*(((dg(j)*wn)/(1-(dg(j)^2))^0.5)*(exp(-
dg(j)*wn*t(i)))*cos((wd(j)*t(i))-phil(j)))+((wd(j))/(1-
(dg(j)^2))^0.5)*(exp(-dg(j)*wn*t(i)))*sin((wd(j)*t(i))-phil(j)));
            %Calculates angular velocity for phase 1
            x1f = ang(j,i); %Stores values of
angle for phase 1
            v1f = angv(j,i); %Stores values of
angular velocity for phase 1
            t1f = t; %Stores time
values for phase 1
    %Phase 2
        elseif (t(i-1) >= 1.0 & angv(j,i-1) > 0); %Condition for
using phase 2
            t2i = max(t1f); %Determines time
at which phase 2 begins
            t2(i) = t(i) - t2i; %Calculates time
from when phase 2 started
            x2i(j) = x1f; %Initial angle
condition for phase 2

```

```

        v2i(j) = v1f; %Initial
angular velocity condition for phase 2
        C21(j) = x2i(j);
%Determines constant 1
        C22(j) = ((v2i(j)+(dg(j)*wn*x2i(j)))/(wd(j)));
%Determines constant 2
        ang(j,i) = (exp(-
dg(j)*wn*t2(i))* (C21(j)*cos(wd(j)*t2(i))+C22(j)*sin(wd(j)*t2(i)));
%Calculates angle for phase 2
        angv(j,i) = (exp(-dg(j)*wn*t2(i))* (((-
dg(j)*wn*C21(j)+C22(j)*wd(j))*cos(wd(j)*t2(i)))+((-C21(j)*wd(j)-
dg(j)*wn*C22(j))*sin(wd(j)*t2(i))))); %Calculates angular velocity
for phase 2
        v2f = angv(j,i); %Stores angular
velocity for phase 2
        t2f = t; %Stores time for
phase 2
        x2f = ang(j,i); %Stores angle for
phase 2
%Phase 3
        elseif (ang(j,i-1) > 0.12 & angv(j,i-1) <= 0); %Condition for
using phase 3
        t3i = max(t2f); %Determines time
at which phase 3 begins
        t3(i) = t(i) - t3i; %Calculates time
from when phase 3 started
        v3i = v2f; %Initial
angular velocity condition for phase 3
        x3i = x2f; %Initial angle
condition for phase 3
        B = v3i + (wn*x3i); %Determines
constant B
        A = x3i; %Determines
constant A
        Bt(i) = B*t3(i);
        ang(j,i) = (A + Bt(i))*exp(-wn * t3(i));
%Calculates angle for phase 3
        angv(j,i) = (B - (A*wn) - (B*wn*(t3(i)))) * exp(-wn*t3(i));
%Calculates angle for phase 3
        x3f = ang(j,i); %Stores angle for
phase 3
        v3f = angv(j,i); %Stores velocity
for phase 3
        t3f = t(i); %Stores time
values for phase 3
%Phase 4
        elseif (ang(j,i-1) <= 0.12 & angv(j,i-1) < 0 & ang(j,i-1) > 0);
%Conditions for using phase 4
        t4i = max(t3f); %Determines
time at which phase 4 begins
        t4(i) = t(i)-t4i; %Determines
time from when phase 4 started
        x4i = x3f; %Initial
angle condition for phase 4
        v4i = v3f; %Initial
angular velocity condition for phase 4
        C4 = ((x4i^2)+((v4i/wn)^2))^0.5; %Determines
value of amplitude for phase 4
        phi4 = atan(v4i/(x4i*wn)); %Determines
phase angle for phase 4

```

```

        ang(j,i) = - C4 * cos((wn*t4(i)) - phi4);           %Calculates
angle for phase 4
        angv(j,i) = ((C4 * wn)* sin((wn)*t4(i)) - phi4);   %Calculates
angular velocity for pase 4
        if ang(j,i) < 0                                     %These
conditions stop the door reopening
            ang(j,i) = 0;                                   %If
the angle is less than 0 then the angle is set to 0
        end
        if angv(j,i) > 0                                    %If
the angular velocity is more than 0 it is set to 0
            angv(j,i) = 0;
        end
    else
        ang(j,i) = 0;                                       %Sets
angle as 0 after the DOE
        angv(j,i) = 0;                                       %Sets
angular velocity as 0 after the DOE
    end
    %Calculation of energy potential
    angd(j,i)=ang(j,i)*(180/pi);                             %Converts angle
values into degrees
    Tg(j,i) = (c(j)*angv(j,i));                             %Torque applied by
the generator on the door
    Pg(j,i) = Tg(j,i)* angv(j,i);                          %Power available
for generation
    E = sum(Pg,2)*0.1;                                       %Energy potencial
as a function of dg (sums over each row)
end
plot(t,angd)                                               %Plots time vs
angle
xlabel('Time (s)')                                         %x-axis label
ylabel('Angle (degree)')                                   %y-axis label
hleg =
legend('dg=0','dg=0.1','dg=0.2','dg=0.3','dg=0.4','dg=0.5','dg=0.6','d
g=0.7','dg=0.8','dg=0.9','dg=1.0');
%Legend labels
print -dbitmap Methodlangle.bmp;                          %Outputs graph of
time vs angle
clear t;                                                  %Clears time t
end

for i=1:1:100                                             %recalculates time
to use in the following graphs
    t(i)=(i-1)*0.1;
end
plot(t,Pg)                                               %Plots t vs Power
over dg
xlabel('Time (s)')                                         %x-axis label
ylabel('Power (W)')                                       %y-axis label
hleg =
legend('dg=0','dg=0.1','dg=0.2','dg=0.3','dg=0.4','dg=0.5','dg=0.6','d
g=0.7','dg=0.8','dg=0.9','dg=1.0');
Legend labels
print -dbitmap Methodlpower.bmp                          %Outputs graph of
power vs time

```

```
plot(dg,E)                                %Plots energy vs
damping value                             %x-axis label
xlabel('Damping of generation unit')      %y-axis label
ylabel('Energy(J)')                       %Outputs grap
print -dbitmap Method1E.bmp              %Clears time
clear t;
```

## Appendix 5: Generation method 2 (m2final.m)

```

clear

%Door characteristics
m = 30;           % (kg) door mass
rd = 0.8;        % (m) Door width
F0 = 25;         % (N) opening force
rF = 0.70;       % (m) opening force applied at distance from origin
kt = 14;         % (Nm/rad) combined spring constant of both springs

I = (m*(rd^2)/3); % (kgm^2) Door moment of inertia
T0 = F0*rF;      % (Nm) Opening torque

for j = 1:1:6
    t(1) = 0;           %set initial time
    k1(j) = kt*(1-((j-1)/5)); %Value of k1
    k2(j) = kt*((j-1)/5); %Value of k2
    kro(j) = (k1(j)+k2(j)); %Value of k for door
    opening
        krc(j) = k1(j); %Value of k for door
    closing
        wg(j) = (kro(j)/I)^0.5; %Natural frequency for
    door opening
        wc(j) = (krc(j)/I)^0.5; %Natural frequency for
    door closing
        ang(j,1) = 0; %Initial angle
        angv(j,1) = 0; %Initial angular velocity
    for i = 1:1:101
        t(i) = (i-1)*0.1; %Calculation of time
    %Phase 1
        if t(i) <= 1.0;
    %Condition for using phase 1
            ang(j,i) = (T0/kro(j))*(1 - cos(wg(j)*t(i)));
    %Calculation of angle
            angv(j,i) = ((wg(j)*T0)/kro(j))*(sin(wg(j)*t(i)));
    %Calculation of angular velocity
            x1f(j) = ang(j,i);
    %Stores values of angle for phase 1
            v1f(j) = angv(j,i);
    %Stores values of angular velocity for phase 1
            t1f(i) = t(i);
    %Stores values of time for phase 1
    %Phase 2
            elseif (t(i) >= 1.0 & angv(j,i-1) > 0);
    %Condition for using phase 2
                t2i = max(t1f);
    %Determines time at which phase 2 begins
                t2(i) = t(i) - t2i; %Time
    from when phase 2 started
                x2i(j) = max(x1f(j));
    %Initial angle condition for phase 2
                v2i(j) = max(v1f(j));
    %Initial angular velocity condition for phase 2
                C2 = ((x2i(j)^2)+((v2i(j)/wg(j))^2))^0.5;
    %Determines amplitude constant for phase 2

```

```

        phi2 = atan(v2i(j)/(x2i(j)*wg(j)));
%Determines phase for phase 2
        ang(j,i) = C2 * cos((wg(j)*t2(i)) - phi2);
%Calculation of angle
        angv(j,i) = - (C2 * wg(j))* sin((wg(j)*t2(i)) - phi2);
%Calculation of angular velocity
        t2f = t(i);
%Stores time for phase 2
        x2f(j) = ang(j,i);
%Stores values for angle of phase 2
%Phase 3
        elseif (ang(j,i-1) > 0.12 & angv(j,i-1) <= 0)
%Condition for using phase 3
            t3i = max(t2f);
%Determines time at which phase 3 begins
            t3(i) = t(i) - t3i; %Time
from when phase 3 started
            v3i(j) = 0;
%Initial angular velocity condition for phase 3
            x3i(j) = max(x2f);
%Initial angle condition for phase 3
            B(j) = v3i(j) + wc(j)*x3i(j);
%Constant calculation
            A(j) = x3i(j);
%Constant calculation
            Bt(j,i) = B(j)* t3(i);
            ang(j,i) = (A(j) + Bt(j,i))* exp(-wc(j) * t3(i));
%Calculation of angle
            angv(j,i) = (B(j) - (A(j)*wc(j)) - (B(j)*wc(j)*(t3(i)))) *
exp(-wc(j)*t3(i)); %Calculation of angular velocity
            x3f(j)= ang(j,i); %Stores
values of angle for phase 3
            v3f(j)= angv(j,i); %Stores
values of angular velocity for phase 3
            t3f(i) = t(i);
%Stores time values for phase 3
%Phase 4
            elseif (ang <= 0.12 & angv < 0 & ang > 0)
%Condition for using phase 4
                t4i = max(t3f);
%Determines time at which phase 4 begins
                t4(i) = t(i)-t4i; %Time
from when phase 4 begins
                x4i(j) = min(x3f(j)); %Initial
angle condition for phase 4
                v4i(j) = max(v3f(j)); %Initial
angular velocity condition for phase 4
                C4 = ((x4i(j)^2)+((v4i(j)/wc(j))^2))^0.5;
%Determines amplitude constant for phase 4
                phi4 = atan(v4i(j)/(x4i(j)*wc(j)));
%Determines phase for phase 4
                ang(j,i) = - C4 * cos((wc(j)*t4(i)) - phi4);
%Calculates angle for phase 4
                angv(j,i) = (C4 * wc(j))* sin((wc(j)*t4(i)) - phi4);
%Calculates angular velocity for phase 4
            else
                ang(j,i) = 0; %Sets
angle at 0 once the DOE has finished
                angv(j,i) = 0; %Sets
angular velocity at 0 once DOE has finished
            end

```

```

angd(j,i)=ang(j,i)*(180/pi);
%Converts angle values into degrees
angmax = max(ang(j,i));
%Determines the maximum opening angle value
end

for j = 1:1:6
    k2(j) = kt*((j-1)/5);
%Calculates torsional spring constant of spring 2
E(j) = 0.5*(k2(j) * (angmax^2)) ;
%Calculates maximum energy stored in spring 2
end
clear t;
clear t1f;
clear t2f;
clear t3f;
clear t2;
clear t3;
clear t4;
end

for i = 1:1:101
    t(i) = (i-1)*0.1;
end
plot(t,angd) %Plots
time vs angle
xlabel('Time (s)') %x-
axis label
ylabel('Angle (degrees)') %y-
axis label
hleg = legend('k1 = 14 Nm/rad','k1 = 11.2 Nm/rad','k1 = 8.4
Nm/rad','k1 = 5.6 Nm/rad','k1 = 2.8 Nm/rad','k1 = 0 Nm/rad');
%Legend labels
print -dbitmap Method2angle.bmp
%Outputs graph to filename (Method2angle.bmp)

plot(k2,E) %Plots
energy potential vs value of k2
xlabel('k1 (Nm/rad)') %x-
axis label
ylabel('Maximum energy stored (J)') %y-
axis label
print -dbitmap Method2energy.bmp
%Outputs graph to filename (Method2energy.bmp)

clear t;

```



## Appendix 6: Generation method 3 (m3final.m)

```

clear

%Door parameters
m = 30;           % (kg) door mass
rd = 0.8         % (m) door width
cm = 0.4;       % (m) door's centre of mass
rk = 0.2;       % (m) force from spring applied at
F0 = 25;        % (N) opening force
rF = 0.70;      % (m) opening force applied at
kr = 14;        % (Nm/rad) torsional return constant

I = (m*(rd^2)/3); % (kgm^2) Door moment of inertia
wn = (kr/I)^0.5; % (s^-1) Natural frequency
dc = 2*(I*kr)^0.5; % Defines the damping coefficient
T0 = F0*rF;      % (Nm) Opening torque

%initial conditions
ang = 0;
angv = 0;

for i = 1:1:100
    t(i) = (i-1)*0.1;
    %Phase 1
    if t(i) <= 1.0 %Condition for
        using phase 1
            ang(i) = (T0/kr)*(1 - cos(wn*t(i))); %Calculates angle
            angv(i) = ((wn*T0)/kr)*(sin(wn*t(i))); %Calculates
            angular velocity
            x1f = ang; %Stores the angle
            values for phase 1
            v1f = angv; %Stores the
            angular velocity values for phase 1
            t1f = t; %Stores time value
            for phase 1
                P(i) = 0; %Sets the power
            value as 0 for this phase
        %Phase 2
        elseif (t(i) >= 1.0 & angv(i-1) > 0); %Conditions for
            using phase 2
                t2i = max(t1f); %Determines time
            at which phase 2 begins
                t2(i) = t(i) - t2i; %Determines time
            from when phase 2 started
                x2i = x1f(end); %Initial angle
            condition for phase 2
                v2i = v1f(end); %Initial velocity
            condition for phase 2
                C2 = ((x2i^2)+((v2i/wn)^2))^0.5; %Determines
            amplitude constant for phase 2
                phi2 = atan(v2i/(x2i*wn)); %Determines phase
            for phase 2
                ang(i) = C2 * cos((wn*t2(i)) - phi2); %Calculates angle
                angv(i) = - (C2 * wn) * sin((wn*t2(i)) - phi2); %Calculates
            angular velocity

```

```

        v2f = angv(i); %Stores angular
velocity values for phase 2
        t2f = t; %Stores time
values for phase 2
        x2f = ang(i); %Stores angle
values for phase 2
        P(i) = 0; %Sets power as 0
for phase 2
%Phase 3
        elseif (ang(i-1) > 0.12 & angv(i-1) < 0) %Conditions for
using phase 3
        t3i = max(t2f); %Determines time
at which phase 3 begins
        t3(i) = t(i) - t3i; %Determines time
from when phase 3 started
        v3i = min(v2f); %Initial angular
velocity condition for phase 3
        x3i = max(x2f); %Initial angle for
phase 3
        B = v3i + wn*x3i; %Determines
constant B
        A = x3i; %Determines
constant A
        Bt(i) = B*t3(i); %Determines value
of Bt
        ang(i) = (A + Bt(i))*exp(-wn * t3(i)); %Calculates angle
        angv(i) = (B - (A*wn) - (B*wn*(t3(i)))) * exp(-wn*t3(i));
%Calculates angular velocity
        Tdc(i) = dc*angv(i); %Calculates the
torque acting on the door as a result of the generator
        P(i) = Tdc(i)*angv(i); %Calculates the
available power to the generator
        t3f = t(i); %Stores time value
for phase 3
        x3f = ang(i); %Stores angle
value for phase 3
        v3f = angv(i); %Stores angular
velocity value for phase 3
%Phase 4
        elseif (ang(i-1) < 0.12 & angv(i-1) < 0 & ang(i-1) > 0)
%Conditions for when to use phase 4
        t4i = max(t3f);
%Determines starting time of phase 4
        t4(i) = t(i)-t4i;
%Determines time from when phase 4 started
        x4i = x3f;
%Initial angle condition for phase 4
        v4i = v3f;
%Initial angular velocity for phase 4
        C4 = ((x4i^2)+((v4i/wn)^2))^0.5;
%Amplitude constant for phase 4
        phi4 = atan(v4i/(x4i*wn)); %Phase
for phase 4
        ang(i) = - C4 * cos((wn*t4(i)) - phi4);
%Calculates angle
        angv(i) = ((C4 * wn) * sin((wn)*t4(i)) - phi4);
%Calculates angular velocity
        P(i) = 0; %Sets
power value as 0 for phase 4
        if ang(i) < 0

```

```

        ang(i) = 0; %Condition to set
angle to 0 once DOE is complete
    end
    if angv(i) > 0; %Condition to set
        angv(i) = 0;
angular velocity to 0 when DOE is complete
    end
else
    ang(i) = 0; %Sets angle as 0
    angv(i) = 0; %Sets angular velocity
as 0
    P(i) = 0; %Sets power as 0
end
    angd(i) = ang(i)*(180/pi); %Converts angle values
into degrees
    E = sum(P)*0.1; %Sums over the power
array to return energy
end

E

%Graph drawing
[AX,H1,H2] = plotyy(t,angd,t,P,'plot'); %Plots graph of
angle and power against time
set(get(AX(1),'Ylabel'),'string','Angle (degree)') %Defines angle
y-axis label
set(get(AX(2),'Ylabel'),'string','Power (W)') %Defines power y-
axis label
xlabel('Time (s)') %Defines x-axis
label
hleg = legend('Door angle','Power'); %Defines legend
print -dbitmap Method3angle&power.bmp %Outputs graph

```



## Appendix 7: Comparison of generation methods (comparison.m)

```

clear

%Door parameters
m = 30;           %(kg) door mass
rd = 0.8;        %(m) Door width
kr = 14;         %(Nm/rad) spring constant
F0 = 25;        %(N) opening force
rF = 0.70;       %(m) opening force applied at

I = (m*(rd^2)/3);   %(kgm^2) Door impulse
T0 = F0*rF;        %(Nm) Opening torque
wn = (kr/I)^0.5;   %(s^-1) Natural frequency

%Door motion when no generator is present
ang0 = 0;
angv0 = 0;
t0 = 0;

for i = 1:1:100
    t0(i) = (i-1)*0.1;
%Phase 1
    if t0(i) <= 1.0 %Condition for
using phase 1 %Calculates
        ang0(i) = (T0/kr)*(1 - cos(wn*t0(i)));
angle %Calculates
        angv0(i) = ((wn*T0)/kr)*(sin(wn*t0(i)));
angular velocity %Stores the angle
        x1f = ang0;
values for phase 1 %Stores the
        v1f = angv0;
angular velocity values for phase 1 %Stores time
        t1f = t0(i);
value for phase 1
%Phase 2
        elseif (t0(i) >= 1.0 & angv0(i-1) > 0); %Conditions for
using phase 2 %Determines time
        t2i = max(t1f);
at which phase 2 begins %Determines time
        t2(i) = t0(i) - t2i;
from when phase 2 started %Initial angle
        x2i = x1f(end);
condition for phase 2 %Initial velocity
        v2i = v1f(end);
condition for phase 2 %Determines
        C2 = ((x2i^2)+((v2i/wn)^2))^0.5;
amplitude constant for phase 2 %Determines phase
        phi2 = atan(v2i/(x2i*wn));
for phase 2
        ang0(i) = C2 * cos((wn*t2(i)) - phi2); %Calculates angle
        angv0(i) = - (C2 * wn)* sin((wn*t2(i)) - phi2); %Calculates
angular velocity %Stores angular
        v2f = angv0(i);
velocity values for phase 2 %Stores time
        t2f = t0;
values for phase 2 %Stores angle
        x2f = ang0(i);
values for phase 2

```

```

%Phase 3
elseif (ang0(i-1) > 0.12 & angv0(i-1) < 0)           %Conditions for
using phase 3
    t3i = max(t2f);                                   %Determines time
at which phase 3 begins
    t3(i) = t0(i) - t3i;                             %Determines time
from when phase 3 started
    v3i = min(v2f);                                   %Initial angular
velocity condition for phase 3
    x3i = max(x2f);                                   %Initial angle for
phase 3
    B = v3i + wn*x3i;                                 %Determines
constant B
    A = x3i;                                           %Determines
constant A
    Bt(i) = B*t3(i);                                  %Determines value
of Bt
    ang0(i) = (A + Bt(i))*exp(-wn * t3(i));          %Calculates angle
    angv0(i) = (B - (A*wn) - (B*wn*(t3(i)))) * exp(-wn*t3(i));
%Calculates angular velocity
    t3f = t0(i);                                       %Stores time
value for phase 3
    x3f = ang0(i);                                     %Stores angle
value for phase 3
    v3f = angv0(i);                                   %Stores angular
velocity value for phase 3
%Phase 4
elseif (ang0(i-1) < 0.12 & angv0(i-1) < 0 & ang0(i-1) > 0)
%Conditions for when to use phase 4
    t4i = max(t3f);
%Determines starting time of phase 4
    t4(i) = t0(i)-t4i;
%Determines time from when phase 4 started
    x4i = x3f;
%Initial angle condition for phase 4
    v4i = v3f;
%Initial angular velocity for phase 4
    C4 = ((x4i^2)+(v4i/wn)^2)^0.5;
%Amplitude constant for phase 4
    phi4 = atan(v4i/(x4i*wn));                         %Phase
for phase 4
    ang0(i) = - C4 * cos((wn*t4(i)) - phi4);
%Calculates angle
    angv0(i) = ((C4 * wn)* sin((wn)*t4(i)) - phi4);
%Calculates angular velocity
    if ang0(i) < 0
        ang0(i) = 0;                                   %Condition to set
angle to 0 once DOE is complete
    end
    if angv0(i) > 0;
        angv0(i) = 0;                                   %Condition to set
angular velocity to 0 when DOE is complete
    end
else
    ang0(i) = 0;                                       %Sets angle as 0
    angv0(i) = 0;                                       %Sets angular
velocity as 0
end
    angd0(i) = ang0(i)*(180/pi);                       %Converts angle
values into degrees
end

```

```

A = [t0;ang0;angv0];

%Method 1
%Generator effect
cc = 2*(I*kr)^0.5;
dg = 0.2;
wd = ((1-(dg)^2)^0.5)*wn;

%initial conditions
ang = 0;
angv = 0;
t = 0;

for i=1:1:100
    t1(i) = (i-1)*0.1; %Calculates time value
%Phase 1
    if t1(i) <= 1.0; %Condition for
using phase 1
        phi1 = atan(dg/(1-(dg^2))^0.5);
        angl(i) = (T0/kr)*(1-((1/(1-(dg^2)))^0.5)*(exp(-
dg*wn*t1(i)))*cos((wd*t1(i))-phi1))); %Calculates angle
for phase 1
        angv1(i) = (T0/kr)*(((dg*wn)/(1-(dg^2))^0.5)*(exp(-
dg*wn*t1(i)))*cos((wd*t1(i))-phi1))+((wd)/(1-(dg^2))^0.5)*(exp(-
dg*wn*t1(i)))*sin((wd*t1(i))-phi1)));
        %Calculates angular velocity for phase 1
        x1f = angl(i); %Stores values of
angle for phase 1
        v1f = angv1(i); %Stores values of
angular velocity for phase 1
        t1f = t1; %Stores time
values for phase 1
%Phase 2
        elseif (t1(i-1) >= 1.0 & angv1(i-1) > 0); %Condition for
using phase 2
        t2i = max(t1f); %Determines time
at which phase 2 begins
        t2(i) = t1(i) - t2i; %Calculates time
from when phase 2 started
        x2i = x1f; %Initial angle
condition for phase 2
        v2i = v1f; %Initial angular
velocity condition for phase 2
        C21 = x2i;
%Determines constant 1
        C22 = ((v2i+(dg*wn*x2i))/(wd));
%Determines constant 2
        angl(i) = (exp(-
dg*wn*t2(i)))*(C21*cos(wd*t2(i))+C22*sin(wd*t2(i)));
%Calculates angle for phase 2
        angv1(i) = (exp(-dg*wn*t2(i)))*((-
dg*wn*C21+C22*wd)*cos(wd*t2(i))+((-C21*wd-dg*wn*C22)*sin(wd*t2(i))));
%Calculates angular velocity for phase 2
        v2f = angv1(i); %Stores angular
velocity for phase 2
        t2f = t1; %Stores time for
phase 2

```

```

        x2f = angl(i); %Stores angle for
phase 2
%Phase 3
        elseif (angl(i-1) > 0.12 & angv1(i-1) <= 0); %Condition for
using phase 3
        t3i = max(t2f); %Determines time
at which phase 3 begins
        t3(i) = t1(i) - t3i; %Calculates time
from when phase 3 started
        v3i = v2f; %Initial
angular velocity condition for phase 3
        x3i = x2f; %Initial angle
condition for phase 3
        B = v3i + (wn*x3i); %Determines
constant B
        A = x3i; %Determines
constant A
        Bt(i) = B*t3(i);
        angl(i) = (A + Bt(i))*exp(-wn * t3(i));
%Calculates angle for phase 3
        angv1(i) = (B - (A*wn) - (B*wn*(t3(i))) * exp(-wn*t3(i));
%Calculates angle for phase 3
        x3f = angl(i); %Stores angle for
phase 3
        v3f = angv1(i); %Stores velocity
for phase 3
        t3f = t1(i); %Stores time
values for phase 3
%Phase 4
        elseif (angl(i-1) <= 0.12 & angv1(i-1) < 0 & angl(i-1) > 0);
%Conditions for using phase 4
        t4i = max(t3f); %Determines
time at which phase 4 begins
        t4(i) = t1(i)-t4i;
%Determines time from when phase 4 started
        x4i = x3f; %Initial
angle condition for phase 4
        v4i = v3f; %Initial
angular velocity condition for phase 4
        C4 = ((x4i^2)+(v4i/wn)^2)^0.5; %Determines
value of amplitude for phase 4
        phi4 = atan(v4i/(x4i*wn)); %Determines
phase angle for phase 4
        angl(i) = - C4 * cos((wn*t4(i)) - phi4); %Calculates
angle for phase 4
        angv1(i) = ((C4 * wn)* sin((wn)*t4(i)) - phi4); %Calculates
angular velocity for phase 4
        if angl(i) < 0 %These
conditions stop the door reopening
                angl(i) = 0; %If the
angle is less than 0 then the angle is set to 0
        end
        if angv1(i) > 0 %If the
angular velocity is more than 0 it is set to 0
        end
    else
        angl(i) = 0; %Sets
angle as 0 after the DOE
        angv1(i) = 0; %Sets
angular velocity as 0 after the DOE

```

```

    end
    angd1(i)=ang1(i)*(180/pi);           %Converts angle
    values into degrees
end

%Method 2

k1prop = 0.4;

k1 = k1prop * kr
k2 = (1-k1prop)*kr;
kro = kr;
krc = k2;

wg = (kro/I)^0.5;
wc = (krc/I)^0.5;

for i = 1:1:101
    tg2(i) = (i-1)*0.1;                 %Calculation of time
%Phase 1
    if tg2(i) <= 1.0;
%Condition for using phase 1
        ang2(i) = (T0/kro)*(1 - cos(wg*tg2(i)));
%Calculation of angle
        angv2(i) = ((wg*T0)/kro)*(sin(wg*tg2(i)));   %Calculation
of angular velocity
        x1f = ang2(i);                         %Stores
values of angle for phase 1
        v1f = angv2(i);                       %Stores
values of angular velocity for phase 1
        t1f(i) = tg2(i);
%Stores values of time for phase 1
%Phase 2
        elseif (tg2(i) >= 1.0 & angv2(i-1) > 0);
%Condition for using phase 2
            t2i = max(t1f);
%Determines time at which phase 2 begins
            t2(i) = tg2(i) - t2i;
%Time from when phase 2 started
            x2i = max(x1f);                     %Initial
angle condition for phase 2
            v2i = max(v1f);                     %Initial
angular velocity condition for phase 2
            C2 = ((x2i^2)+((v2i/wg)^2))^0.5;    %Determines
amplitude constant for phase 2
            phi2 = atan(v2i/(x2i*wg));         %Determines
phase for phase 2
            ang2(i) = C2 * cos((wg*t2(i)) - phi2);
%Calculation of angle
            angv2(i) = - (C2 * wg)* sin((wg*t2(i)) - phi2);
%Calculation of angular velocity
            t2f = tg2(i);
%Stores time for phase 2
            x2f = ang2(i);                       %Stores
values for angle of phase 2
%Phase 3

```

```

elseif (ang2(i-1) > 0.12 & angv2(i-1) <= 0)
%Condition for using phase 3
    t3i = max(t2f);
%Determines time at which phase 3 begins
    t3(i) = tg2(i) - t3i;
%Time from when phase 3 started
    v3i = 0; %Initial
angular velocity condition for phase 3
    x3i = max(x2f);
%Initial angle condition for phase 3
    B = v3i + wc*x3i; %Constant
calculation
    A = x3i; %Constant
calculation
    Bt(i) = B* t3(i);
angle
    ang2(i) = (A + Bt(i))* exp(-wc * t3(i)); %Calculation of
angle
    angv2(i) = (B - (A*wc) - (B*wc*(t3(i)))) * exp(-wc*t3(i));
%Calculation of angular velocity
    x3f = ang2(i); %Stores
values of angle for phase 3
    v3f = angv2(i); %Stores
values of angular velocity for phase 3
    t3f(i) = tg2(i);
%Stores time values for phase 3
%Phase 4
elseif (ang2(i-1) <= 0.12 & angv2(i-1) < 0 & ang2(i-1) > 0)
%Condition for using phase 4
    t4i = max(t3f);
%Determines time at which phase 4 begins
    t4(i) = tg2(i)-t4i; %Time
from when phase 4 begins
    x4i = min(x3f); %Initial angle
condition for phase 4
    v4i = max(v3f); %Initial
angular velocity condition for phase 4
    C4 = ((x4i^2)+((v4i/wc)^2))^0.5; %Determines
amplitude constant for phase 4
    phi4 = atan(v4i/(x4i*wc)); %Determines phase
for phase 4
    ang2(i) = - C4 * cos((wc*t4(i)) - phi4); %Calculates
angle for phase 4
    angv2(i) = (C4 * wc)* sin((wc*t4(i)) - phi4); %Calculates
angular velocity for phase 4
    if ang2(i) < 0
        ang2(i) = 0;
    end
    if angv2(i) > 0
        angv2(i) = 0;
    end
else
    ang2(i) = 0; %Sets
angle at 0 once the DOE has finished
    angv2(i) = 0; %Sets
angular velocity at 0 once DOE has finished
end
angd2(i)=ang2(i)*(180/pi);
%Converts angle values into degrees
end

%C = [t0;ang0;angv0;t;ang;angv;tg2;angg2;angvg2;angag2];

```

```
%xlswrite('C:calculationresults1.xls', C)

plot(t0, angd0, t1, angd1, tg2, angd2)
xlabel('Time (s)')
ylabel('Angle (rad)')
hleg = legend('No generator', 'Method 1', 'Method 2');
print -dbitmap Comparison.bmp;
```



## Appendix 8: Revolving door model

```
clear

%Door parameters
nl = 4;
lm = 40;    %kg
lr = 1;     %m
F0 = 25;    %N
rF = 0.8;   %m

%Door properties
T0 = F0 * rF;
I = 4 * (lm*(lr^2)/3);

%Generator
dc = 25;    %Nms

t(1) = 0;
angl1(1) = 0;
angv(1) = 0;
TG(1) = dc * angv(1);
anga(1) = (T0 - TG(1)) / I;

for i = 2:1:601
    t(i) = 0.1*(i-1);
    if t(i) <= 60
        angv(i) = angv(i-1) + (anga(i-1)* 0.1);
        angl1(i) = angl1(i-1) + (angv(i)* 0.1);
        TG(i) = (dc * angv(i));
        anga(i) = (T0 - TG(i)) / I;
    else
        angv(i) = angv(i-1) + (anga(i-1)* 0.1);
        angl1(i) = angl1(i-1) + (angv(i)* 0.1);
        TG(i) = (dc * angv(i));
        anga(i) = (0 - TG(i)) / I;
    end
    P(i) = TG(i) * angv(i);
    E(i) = P(i)*0.1;
end

Et = sum(E)

h = figure;
[AX,H1,H2] = plotyy(t,angl1,t,angv,'plot');
set(get(AX(1),'ylabel'),'string','angle (rad)')
set(get(AX(2),'ylabel'),'string','angular velocity (rad/s)')
xlabel('Time (s)')
saveas(h,'revolving door','jpg')

g = figure;
plot(t,angl1)
xlabel('Time (s)')
ylabel('Power (W)')
saveas(g,'rotation angle','jpg')
```