# A framework for modelling consumption-based energy demand and emission pathways

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ABSTRACT Energy demand in global climate scenarios is typically derived for sectors – such as buildings, transportation, and industry – rather than from underlying services that could drive energy use in all sectors. This limits the potential to model household consumption and lifestyles as mitigation options through their impact on economy-wide energy demand. We present a framework to estimate the economy-wide energy requirements and carbon emissions associated with future household consumption, by linking Industrial Ecology tools and Integrated Assessment Modelling (IAM). We apply the framework to assess final energy and emission pathways for meeting three essential and energy-intensive dimensions of basic well-being in India: food, housing and mobility. We show, for example, that nutrition-enhancing dietary changes can reduce emissions by a similar amount as meeting future basic mobility in Indian cities with public transportation. The relative impact of energy demand reduction measures compared to decarbonization differs across these services, with housing having the lowest and food the highest. This framework provides complementary insights to those obtained from IAM by considering a

broader set of consumption and well-being related interventions, and illustrating trade-offs between demand and supply-side options in climate stabilization scenarios.

## 1. Introduction

Meeting the goals of the Paris climate agreement will involve greenhouse gas (GHG) emission reductions through a portfolio of mitigation measures, including lowering demand and resource intensity, and decarbonizing the energy supply sector[1,2]. Global scenarios of climate stabilization, such as those developed using Integrated Assessment Models (IAM), place greater emphasis on supply side transformations[3,4], including the energy system and land-use, than they do on demand-side changes, with few exceptions[5,6]. Demand-side measures typically focus on direct energy services in sectors (e.g. buildings, industry and transport) more than they do on consumption and lifestyle changes[4,7] that drive energy demand indirectly through their material use. For example, changes in household demand for mobility and housing can have differing impacts on energy demand depending on their material requirements for manufacturing vehicles and constructing buildings, respectively. These indirect impacts are mostly overlooked by IAM. As a result, global scenarios of climate mitigation are limited in their ability to represent household consumption and lifestyle change through their use of materials and economy-wide energy demand[5,8,9].

Recent research suggests that the linkage of Industrial Ecology (IE) tools to IAMs can strengthen the representation of the supply chains, material cycles and household consumption patterns in climate change stabilization scenarios[10,11]. Previous efforts to integrate IE and energy systems scenarios assess the material implications of energy supply transformations to meet climate targets [11–13]. IE methods, such as Life Cycle Assessment (LCA) and Environmentally Extended

Input-Output (EEIO) analysis, connect production and consumption activities to their associated energy and resource use by mapping supply chains. Integrating IE methods and energy scenarios can enable an assessment of the trade-offs and synergies between production, consumption, material requirements and energy use of different climate change mitigation options.

IE studies that evaluate demand-side emission reduction potential offer a range of flexibility to represent future energy system transformations. Traditional LCA methods were designed to assess specific products and processes. As a result, they tend to be static in time and oriented to a micro-scale[8,14] More recently, several studies assess future environmental changes across a broader scope of economic activity. However, often LCA studies neglect future changes in the energy system[15–17]. Other recent hybrid LCA-IO studies do include impacts of energy system changes, but their main scope of analysis is limited to the electricity sector[18] or specific end-use services, such as transport[19], efficient lighting[20], and energy management systems[21]. On the other hand, EEIO analysis has been widely used to assess historical indirect energy and emissions from sectors based on consumption-based accounting principles[22–27]. Recent studies attempt to project EEIO models into the future based on a given set of technology and climate scenarios and simplified projections of changes in household final demand structure[28,29]. This dependence on specific, and most likely different, scenarios of energy system transformations makes these studies difficult to compare to each other or extend to other demand categories and IAM scenarios of energy system transformation.

Despite these efforts, studies that project economy-wide household service-driven energy and emissions pathways are largely missing. In a previous work[30], we proposed the Service-Driven Energy Accounting model (SEAM) to calculate products' embodied final energy demand, which aggregates relevant direct energy demand in all the traditional sectors involved in the product supply chain. In this paper, we extend the SEAM framework to develop emissions pathways for household services by combining estimates of final embodied energy demand and emissions of products with IAM scenarios of decarbonization. This framework enables a comparison of the mitigation potential of well-being driven interventions to reduce consumption across different product groups and at different points in the supply chain to the more traditional demand reduction and supply-side options in the energy system obtained from IAMs. This approach of integrating consumption with IE and IAM also allows us to differentiate energy and emissions associated with building new infrastructure and that associated with providing services over existing infrastructure. For instance, one could compare the mitigation potential of, such as behavioral change in building space cooling compared to electrification in the mobility sector.

We apply this model to illustrate energy and emissions pathways for bridging gaps in three key services of "decent living standards" (DLS) in India [31]: housing, mobility, and food. We generate scenarios to bridge existing service gaps, including building the necessary underlying infrastructure. We explicitly model influences of behavioral and technological changes on energy demand on the one hand, and future changes in energy supply on the emissions pathways, on the other, to illustrate their relative contribution to decarbonization of basic needs.

## 2. Materials and methods

Our generic framework includes three steps (Fig.1). First, we estimate the demand level for residential (square-meters of floor surface per housing type), mobility (p-km per transportation mode) and other services such as food (expenditure level) according to previously identified standards[32–34]. Second, we calculate direct and indirect final energy demand associated with materials and services. For this, we use IE tools, as appropriate, to estimate the indirect energy intensities per service unit: LCA for services with easily definable material requirements, such as buildings and mobility; and EEIO analysis for the remaining services whose material use is more diffused through the economy. We then build scenarios which model current practices as well as low-carbon technologies, consider their future penetration and include material efficiency improvements. We estimate the total final energy requirements by multiplying the demand of the service in each scenario by the respective energy intensities. Third, we calculate emissions pathways under different scenarios of climate policy, including a reference and climate stabilization at 1.5°C, using carbon intensities of fuels from IAM scenarios.

The following sections describe the generic LCA and EEIO methods we developed to estimate the indirect final energy intensities of services, the exemplary application to DLS scenarios, and the three modelled end-use sectors (housing, mobility, and food).

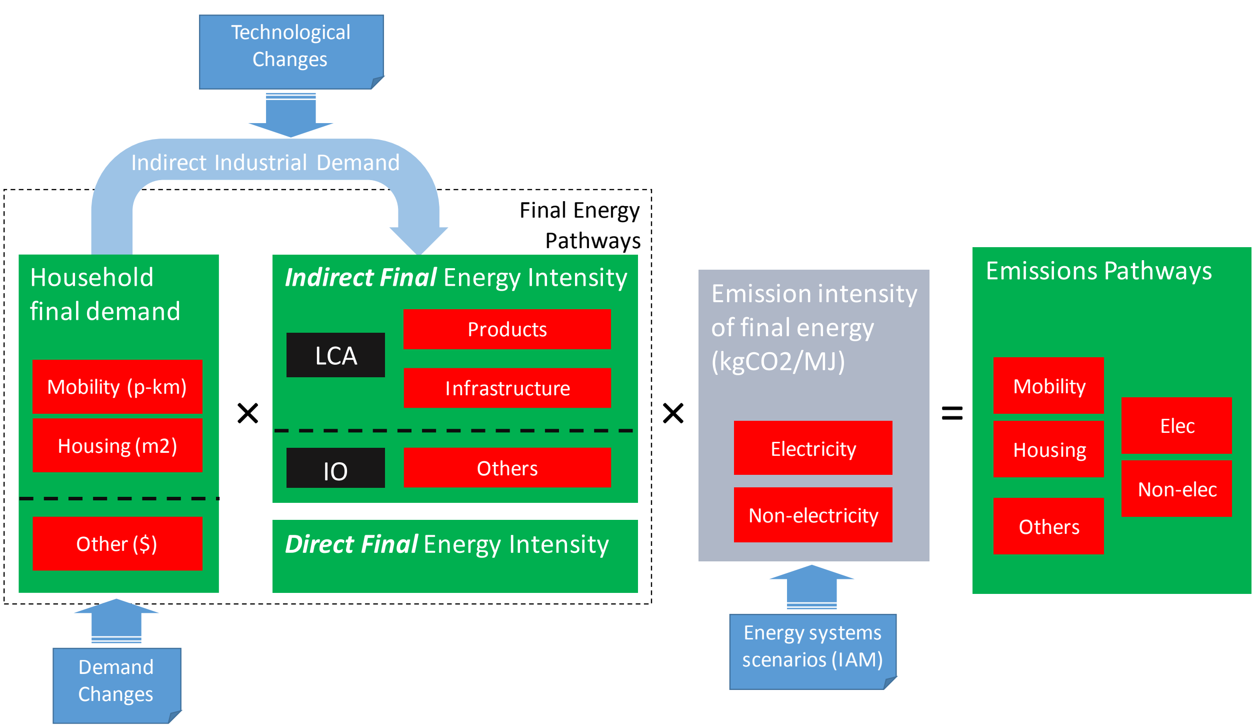


**Figure 1.** Overview of the methods for final energy and emissions pathways.

### *2.1. Energy intensities calculation*

*LCA*

We use process-based LCA to link services to their indirect energy requirements and develop energy demand pathways in final energy terms. This differs from traditional LCA, where final energy is disregarded in favor of primary energy for assessing depletion of energy resources. To our best knowledge, only two studies in literature used a similar approach and estimated energy coefficients from LCA for assessing power sector scenarios[8,35]. Our application differs in that it focuses on end-use services and linkages with induced final energy demand.

We derive final energy demand by calculating ratios of final to primary energy for specific products or processes. As first approximation, we assume that the difference between primary and final energy is the conversion and delivery losses for electricity production and distribution respectively, and that final energy equals primary energy (that is, conversion losses are assumed negligible) for energy carriers other than electricity[36]. Products' and processes' relative final energy intensity differ from their relative primary energy intensity based on the share of electricity – and in turn its efficiency of conversion.

The final electricity embodied in each product of interest is estimated by using the technology matrix[37], which maps inflows and outflows of commodities from processes. The activities supplying electricity for end uses are filtered along the supply chain via the technology matrix and the associated electricity use summed up (see Supplementary Information). We then run the impact assessment and use the indicator Cumulative Energy Demand (CED)[38] to calculate embodied primary energy, which as explained above, for non-electricity products is assumed to be the same as final energy use. The embodied final energy related to other fuels is calculated as the difference between total CED and CED of the electricity supply activities associated with a given product. We finally obtain two coefficients to customize results to the local context for each product: the electricity share of final energy; and the ratio of final to primary energy (see Supplementary Information). We use Brightway2[39] to process data from the database Ecoinvent[40] (v3.3 cut-off).

*EEIO analysis*

We use the standard EEIO equations[41] to calculate the indirect final energy intensities of 200 products of EXIOBASE3—a widely used environmentally extended global multi-regional input-output (EE-GMRIO) database. The key difference with previous studies that use EXIOBASE is that we employ a final energy extension extracted from net energy use (NEU) accounts specifically developed for this analysis. NEU refers to the end use energy of energy products minus exports plus all energy losses (i.e. during extraction, transformation, storage and distribution)[42]. The NEU accounts built for this paper are largely based on the approach used in Stadler et al.[43] and documented in Usubiaga-Liaño et al.[44] (see Supplementary Information). In short, the extended energy balances of the International Energy Agency[45,46] are first transformed from the territory to the residence principle to resolve accounting differences (see Usubiaga et al.[47] for more details). From the resulting dataset we calculate the energy product-specific NEU and only allocate the final energy consumption to EXIOBASE products and final consumers using the same allocation approach as in Stadler et al[43], which results in a final energy use extension. Then, indirect final energy intensities are derived from this extension using the standard demand-pull IO model. The intensities by EXIOBASE product are then mapped to matching COICOP (Classification of Individual Consumption According to Purpose) categories by the approach given in Min and Rao[48]. For the aggregate food energy intensity, we weight-average the final energy intensities by COICOP category with the monetary share of different food items in the diets considered in the DLS scenarios. While the intensities for each of COICOP categories are assumed constant over time (i.e. no changes in production processes), the aggregate intensities change over time due to the changes in diet composition in different scenarios.

### *2.2. Application to DLS scenarios*

Previous work has focused on identifying a set of components defining DLS [31]. Here, we illustrate the merits of the proposed methods by developing final energy and emissions pathways for three key end-use services in DLS scenarios: housing, mobility and food. Energy requirements are divided in two components: the operational energy associated with the provision of goods and services (including direct energy for housing and mobility, and indirect energy for food production); and the construction energy necessary to build the underlying infrastructure (housing construction, public transport infrastructure, and vehicles production). We do not include other food-related energy used directly in households such as cooking or refrigeration. India provides a remarkable case study for the important gaps in access to decent living and opportunities for limiting the energy and GHG emissions required to fill such gaps.

We present two demand scenarios for 2050, where DLS gaps are filled by 2030, in accordance with SDGs targets[49]. These gaps include access to decent housing, motorized transportation and adequate nutrition (see below). In the reference (REF) scenario, requirements are fulfilled with current prevailing development strategies and technologies. The low-carbon technology (LCT) scenario includes exemplary emissions-saving development strategies, such as energy-efficient design for buildings, public transportation and diet changes. A variant of the LCT scenario for mobility (LCT*) evaluates the complete electrification of public transportation by 2030.

In a second step, the scenarios above are further developed by incorporating potential changes in energy supply system that lead to a decrease of emission intensities for supplying electricity and other non-electric fuels (separately for industry and transportation) from two representative climate policy scenarios. One is no energy policy scenario (PS1), where we assume no policy changes from status quo, and thus the average emission intensities of India in 2015 are kept constant until 2050 (0.235 $kgCO_2/MJ$ for electricity, 0.055 $kgCO_2/MJ$ for non-electric fuels in industry, 0.072 $kgCO_2/MJ$ for non-electric fuels in transportation). The other (PS2) is an ambitious policy scenario, which represents the efforts needed to have 66% chance of limiting the global temperature increase to under 1.5°C in 2100 [50] (emission intensities in 2050 are -0.002 $kgCO_2/MJ$ for electricity, 0.007 $kgCO_2/MJ$ for non-electric fuels in industry, 0.044 $kgCO_2/MJ$ for non-electric fuels in transportation). We include non-energy emissions for cement in housing construction and methane in food production (see Supplementary Information for more details on emissions intensities). From this, we can separately investigate the relative contribution of demand- and supply-side policies in reducing emissions growth.

*Housing*

The DLS for housing include minimum floor surface (10 $m^2$ per person, minimum 30 $m^2$ up to 3 persons), permanent construction materials and a suitable level of thermal comfort[31,33]. We represent rural and urban housing by a single-story and a multi-story archetype respectively, reflecting prevailing construction practices[51–55], and focus on construction and space cooling-heating only (appliances and other end uses are not considered). We rely on previous studies for the estimation of energy requirements for space cooling and heating under the five different climatic zones in India (see Supplementary Information). In the REF scenario, we keep the characteristics of new housing unaltered over time. In the LCT scenario, we incorporate energy-efficient building design that reduce both construction and operational energy requirements[51] and material efficiency improvements for steel and other construction materials.

The extension of the housing stock is estimated for every time step based on the housing demand, driven by population growth and the housing gap. Currently, India has a housing gap of 50 million units[56], due to poor construction quality, overcrowding and homeless population. We assume universal access to decent homes by 2030 according to SDG11 (Sustainable cities and communities). The yearly building turnover rate is fixed at 2% of the total stock, considering a service life of 50 years[55,57,58].

*Mobility*

Normative requirements for mobility include access to motorized public and private transportation. In previous work, we adopt a minimum mobility requirement of 10,000 p-km, triangulated from a number of data points on minimum travel distance in dense industrialized countries[32,59]. In the REF scenario, we keep transportation mode shares constant at present levels. In the LCT scenario, all future incremental mobility demand in cities is met by public transport, which has lower energy intensity per p-km and congestion reduction benefits [60], while the mode shares are maintained constant in rural areas. The fuel mix of the fleet is considered as constant over time in both scenarios. The construction energy for public transportation infrastructure is estimated based on previous studies[61], construction of roads is not included. We use a stock model for LDVs production activities over time (see Supplementary Information).

*Food*

For food, in the REF scenario, nutritional requirements (represented by dietary reference intakes (DRI)) are met in 2030 based on present diets[62]. The LCT scenario represents emissions-minimizing diets that also meet the DRIs, but only by 2050, to allow for the time associated with the implied dietary shifts. Note that the calorie requirement is constant over time, but its composition varies with the scenarios. In particular, the calorie share of methane-intensive rice reduces from 31% in REF to 5.6% in LCT due to its substitution by other grains such as wheat, potato, corn, bajra, etc.

## 3. Results and Discussion

This analysis enables a comparison of the embodied energy intensities of basic *services* enjoyed by households in an economy, independent of their economic value and energy supply. We discuss the features and benefits of these types of results in three steps: we first compare these energy intensities to conventional approaches that present primary energy intensities; we then compare the construction and operational energy requirements of these services; lastly, we discuss the relative mitigation potential across services and across the energy supply chain (i.e. demand reduction vs decarbonization). We discuss the empirical findings as well, but primarily as a vehicle to illustrate the methodological contribution.

### *3.1. Final vs primary energy intensities*

Figure 2 compares the final and primary energy intensities for different housing types (new construction) and transport modes (panel A) and the averages for all the services in both REF and LCT scenarios in 2050 with no changes in the current energy system (panel B). We separate the energy associated with electricity and the rest, in order to illustrate their difference in decarbonization potential.

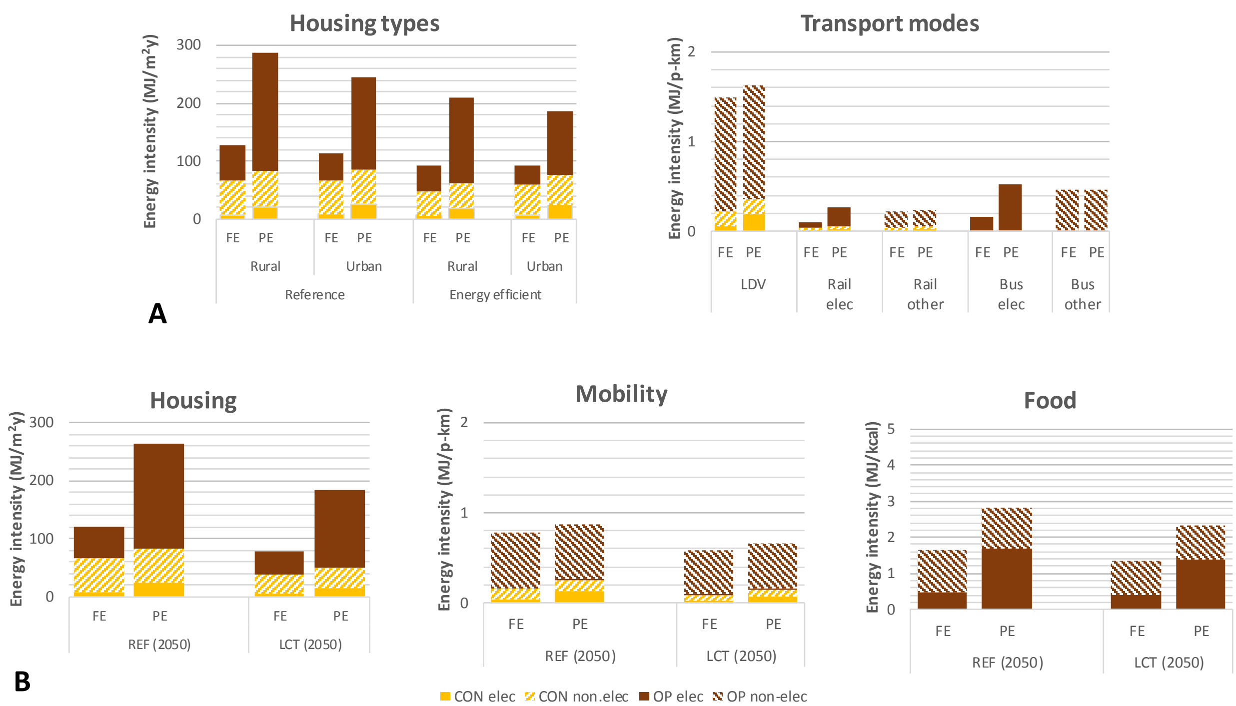


**Figure 2.** Panel A - Final energy (FE) and primary energy (PE) intensities of housing types (new construction) and transport modes. Panel B - Average FE and PE for housing, mobility and food in India in the reference (REF) and low-carbon technologies (LCT) scenarios in 2050 with no changes in the current energy system (panel B). Breakdown of FE and PE shown into construction (CON) and operation (OP) energy, and attributable to electricity use (elec) and other fuels (non.elec). See Supplementary Information for more details.

Due to the high conversion losses in electricity production, the energy demand when portrayed in terms of primary energy shows a misleading dominance of use. Electricity use for cooling, for instance, comprises less than half of the life-cycle energy demand for buildings, but in primary energy terms its contribution is around two-thirds. This share is even less in urban areas, because multi-storey buildings are more efficient per unit of floorspace. Viewing energy demand in final energy terms better informs the leverage efficiency improvements in operation can have on overall energy use relative to upstream changes in building construction (e.g. cement production) or electricity production. Furthermore, with this information one can assess the impact on energy demand from just the structure of growth (e.g. urbanization), in this case, through its effect on building stock. For mobility, electricity comprises a greater share of construction energy demand (25 percent) than in buildings (9-12 percent) because of the electricity intensity of steel, which in turn comprises a higher share of materials in vehicles than in buildings. For food, a relatively small share of electricity in overall final energy shows that efficiency improvements in typical electricity consumption along the supply chain of food (e.g. storage, refrigeration, packaging) will have a limited role under the current practice. The relative proportion between reductions in final energy terms and in primary energy terms, for a specific service, is therefore influenced considerably by the share of electricity versus other fuels for the adopted measures.

Having service-driven energy intensities also enables complementary scenario analysis, in that the relative effects of interventions at different points in the supply chain can be compared (Figure 2-B). For instance, a comparison of the average energy intensities of services in the REF and LCT scenarios in 2050 reveals that the relative extent of energy demand reduction from different interventions in the three services: 35 percent for housing from improved design and low-embodied energy materials; 24 percent for mobility from deeper penetration of public transit, and 17 percent for food from diet shifts.

### ***3.2. Final energy demand of services***

Combining energy intensities with service levels associated with basic needs, we can compare the relative contribution of these services to aggregate energy demand. We see from Figure 3 that, by far, the operational energy for road vehicles (which is primarily diesel) dominates energy demand for basic needs. This demand is about a factor of 2.5 greater than the next largest category, the non-electric fuel demand in the supply chain to construct the vehicles. In the building sector, the immediate demand is for bridging the existing housing deficit, but with time the share of new homes to meet population growth in urban areas and building turnover remains relatively constant. With this kind of decomposition, we are able to estimate the change in energy demand for rural and urban homes from social policies that affect population growth, such as those associated with women's education and associated changes in fertility, in addition to energy policies. Introducing more energy-efficient buildings (LCT scenario) has an immediate effect on reducing the construction energy for filling the housing gap. However, the reduction in operative energy at stock level is slower due to relatively long building turnover cycles for replacing the current stock.

We also see that a shift in mode shares towards public transit in cities (LCT scenario) without any other changes can reduce mobility-related energy demand by over 25 percent. This shift also reduces the construction energy for the fewer needed vehicles. Full electrification of public transport (LCT* scenario) further reduces final energy by an additional 20 percent – an all-electric bus fleet demands a third of the final energy demand of a conventional fleet. In contrast, shifting construction practices to adopt more efficient building materials produces a higher percentage reduction in building construction energy, but the aggregate impact is insignificant compared to the shift in transport modes, also due to the slower uptake of new buildings. This kind of comparison of impacts across services and at different points in the energy supply chain is made possible by this service-driven model for indirect energy demand.

In comparison to buildings and mobility, energy use for food is relatively invariant across the two scenarios. This is because food emissions in India are dominated by methane from rice, while energy use is dominated by fertilizers[63], which vary comparatively less across grains. As a result, emissions-reducing diets reduce rice use and methane, but only marginally reduce fertilizer and energy use.

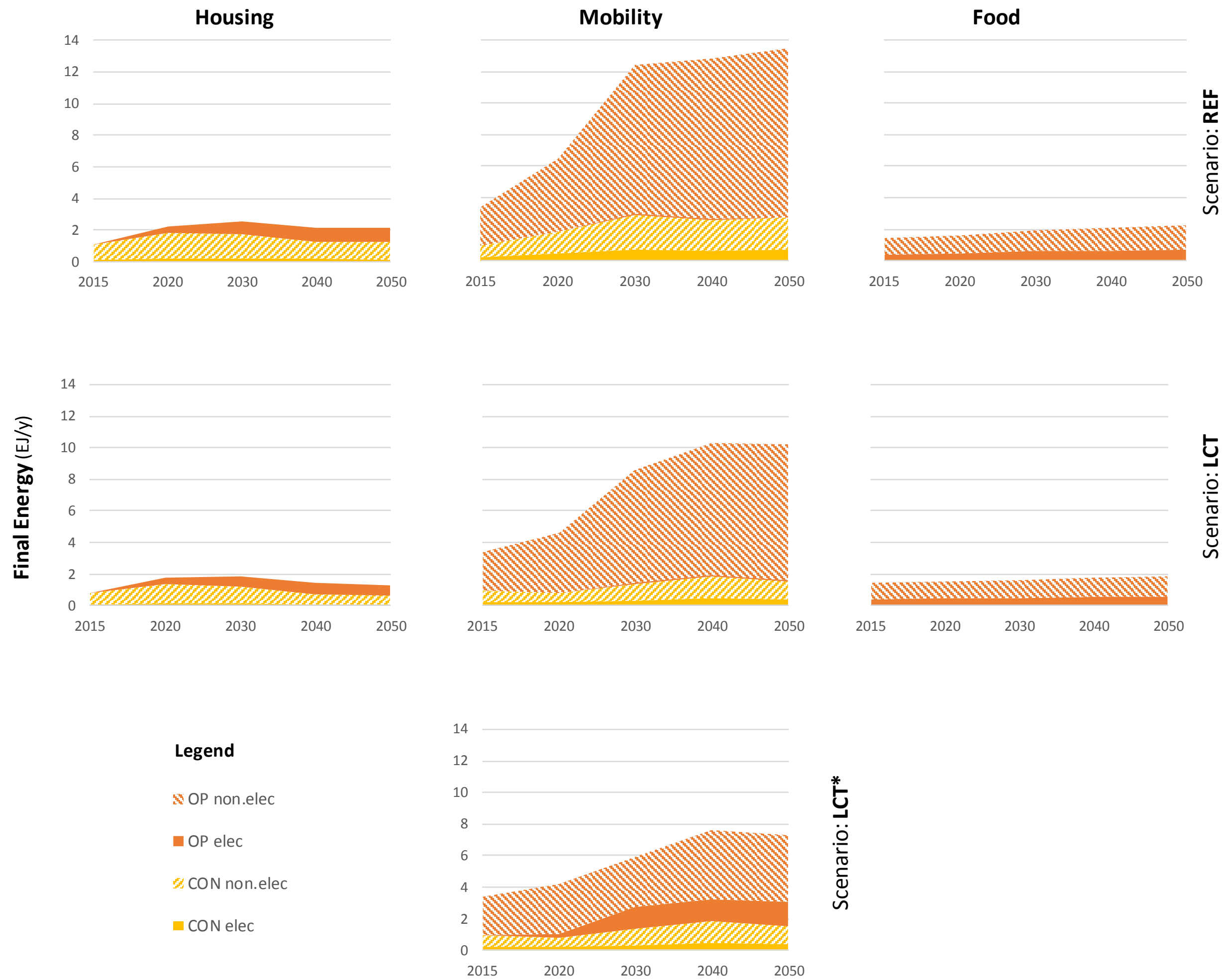


**Figure 3.** Final energy pathways for DLS scenarios for housing, mobility, and food in India. Demand side scenarios: reference (REF), low-carbon technologies (LCT), and low-carbon technology with full public transport electrification (LCT*). Breakdown by construction (CON) and operation (OP) energy and by electricity (elec) and other fuels (non.elec).

### *3.3. Identifying mitigation priorities*

We apply carbon intensities of fuels to meet the above energy demand projections from two decarbonization futures at two extremes of ambition, one with current climate policy frozen (PS1), and the other achieving the 1.5°C target (PS2). In doing so, we illustrate the comparative mitigation potential from different mitigation measures from the supply and demand side, and include changes in how basic needs are met without reducing wellbeing.

First, note that the absolute emissions levels of the three demand categories are comparable (Figure 4), even though their final energy demand differs widely (Figure 3), with mobility dominating the other services by over a factor of five. In the case of food, this is largely because of the dominance of non-energy emissions from rice cultivation in food-related emissions. For buildings, this is in part because of non-energy emissions from cement production and the relatively high share of electricity in final energy, which has a high carbon intensity due to coal.

The relative impact of decarbonization and energy demand reduction differs for each service. As discussed earlier, demand-side measures have a greater potential to reduce energy demand with mobility compared to housing, which propagate to their respective emissions reductions potential (straight orange lines in Figure 4). For the case of food, although energy demand doesn't reduce from demand-side diet shifts, significant emissions can be reduced due to the avoidance of methane emissions from shifts away from rice. This reduction exceeds the potential for emissions reductions from the energy demand reduction in the other two services.

Assuming, hypothetically, that India decarbonizes the energy sector in accordance with a 1.5°C, in absence of demand changes (dotted blue lines in Figure 4), the potential emissions reductions by 2050 are on the order of 55 and 80 percent for housing and mobility respectively, but far less for food, as expected, due to high non-energy emissions. Notably, for food, diet changes produce comparable emissions reductions as does this ambitious shift to decarbonized fuel.

In housing, because of the dominance of electricity in energy demand, emissions reduction from decarbonizing electricity production dominates overall mitigation potential, which is comparable in both 1.5°C scenarios, with and without demand reduction. What emissions remain in both cases come from cement used in construction. In contrast, with mobility demand reduction through mode shifting has a substantial mitigation potential and enables quicker near-term emission reductions than for housing. With full electrification of public transport (LCT*), just from the combination of higher occupancy and efficiency with electric public transit, emissions can be almost halved by 2050 without any decarbonization, while providing the same level of mobility to all.

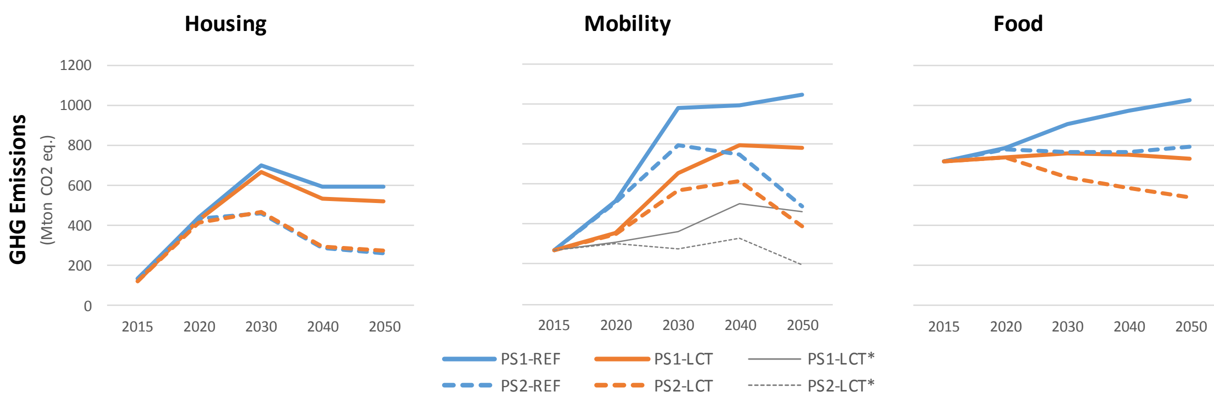


**Figure 4.** Emissions pathways for DLS scenarios for housing, mobility, and food in India. Demand side scenarios: reference (REF), low-carbon technologies (LCT), and low-carbon technology with public transport (bus) electrification (LCT*) by 2030. Supply-side scenarios: current energy system (PS1) and 1.5°C (PS2).

### *3.4. Recast of industrial energy demand*

The linkage of consumption to indirect *final* energy demand enables a broader picture of the economy-wide energy and emissions reduction potential from changes in consumption, and thereby a means to relate resource use directly to socioeconomic trends and material well-being. This in turn enables a more comprehensive analysis of sustainable development pathways considering wellbeing and environmental impacts. Integrating IE methods and energy scenarios allows recasting the industrial energy by the underlying driving services − rather than by sectors − and further assess the impact of consumption changes and demand-side measures on energy and environment. Our results for India show that providing basic services would require a considerable amount of final embodied energy in 2015: 1.0 EJ for housing, 0.9 EJ for mobility, and 1.4 EJ for food. One can compare these results with the current energy consumption for India[64] and estimate the share of total industrial final energy that would be needed to satisfy basic needs, i.e. 11% for housing, 10% for mobility and 14% for food in 2015. Such analyses can be extended to other types of consumption, to characterize their economy-wide energy use. The linkage between service demand and IAMs could also enable—through IE methods' other environmental impact indicators—broader sustainability assessments that examine alongside climate mitigation goals other objectives among the Sustainable Development Goals (SDG), such as sustainable consumption and production, or even health and wellbeing-related goals, since consumption can be linked to basic human needs. Furthermore, representing energy embodied in products and services in final − rather than primary − terms, makes it possible to decouple material energy requirements and future changes in the energy supply sector. With this flexibility, it is possible to explicitly assess consumption-side, energy demand and supply-side measures in climate stabilization pathways.

### ***3.5. Limitations and further research***

Some limitations apply regarding the data we used in LCA, representation of changes in the manufacturing structure, and accounting of different types of fuel.

For the LCA methods, we relied on data from internationally recognized databases to estimate the ratio primary-to-final energy and the share of electricity. This might not completely reflect the supply chains in the analyzed country, India, due to potentially different production processes. However, country-specific life-cycle inventory data are mostly not available for developing countries. Process-based LCA involves truncation errors as it depends on pre-defined system boundaries[65]. The magnitude of such errors depends on the cut-off criteria and sector groups. Thus, the comparability of LCA and EEIO results might be limited due to such issues as different system boundaries and different treatment of capital inputs. To further ensure the direct comparability of the results across demand categories, future research could examine the use of hybrid IO-LCA and also compare with the results given in this work.

In our scenarios, we represent key technological and demand changes for housing, mobility and food driven by targeted policies. Regarding future changes in manufacturing processes, our analysis is limited to material efficiency improvements for building construction. A broader representation of future changes in the manufacturing structure along different scenarios is currently missing. With improved data availability and accounting of such changes in LCA-IO methods [66,67], structural and technological changes could be explicitly represented in the model.

In our methods we focused exclusively on the energy losses in the electric sector losses to approximate the difference between primary and final energy. Future studies should further characterize the efficiency losses in other fuel supply chains. Recasting of service-driven demands for key industries, such as cement, steel, aluminum, pulp and paper, and petrochemical is also suggested. This study presented a first step towards linking Industrial Ecology tools and IAMs through a simplified methodology for decarbonization pathways. Future work should focus on further integration with IAMs to improve the comparability of results across end-use services and upscaling for more comprehensive and economy-wide accounting of services, as well as broader geographical coverage. This will enable the development of more robust and comprehensive climate stabilization scenarios, including the evaluation of trade-offs between material and technology use, energy demand and decarbonization options.

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Life Cycle Assessment methods: Alessio Mastrucci. Input-Output methods: Jihoon Min and Arkaitz Usubiaga-Liaño. Scenarios development, results interpretation and paper writing: Alessio Mastrucci, Jihoon Min, Narasimha D. Rao.

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## Associated Content

**Supporting Information**. The following files are available free of charge.

Final energy accounts for Life Cycle Assessment and Input-Output, carbon emission intensities, and description of the Decent Living Scenarios, including narratives, assumptions, detailed input data, calculations and results. (PDF)

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