Supplementary Material – Part I

Towards a sustainable hydrogen economy: optimisation-based framework for hydrogen infrastructure development

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S1. Mathematical formulation

The complete multi-period spatial-explicit MILP formulation of SHIPMod extension is presented in this section. It is based on the work by [1] with multiple novelties. This formulation is composed of the objective function and the constraints for representing (i) the relation of liquid and compressed hydrogen demand, (ii) hydrogen and CO_2 material balances in each region and in the reservoirs, (iii) capacity, evolution and operation of hydrogen production plants, storage facilities and filling stations, (iv) local and regional hydrogen delivery via road transportation and pipelines as well as CO_2 pipelines for carbon sequestration, (v) CO_2 reservoirs, and (vi) international imports. The detailed superstructure of the HSC for each region g and reservoir r in time period t is illustrated in Fig. 3.

The optimisation framework is based on a 'neighbourhood flow' approach [2]. It consists of the definition of a subset of connections $(g, g') \in \mathtt{N} \subseteq \mathtt{G} \times \mathtt{G}$ where each region $g \in \mathtt{G}$ is only linked to divisions $g' \in \mathtt{G}$ characterised by being adjacent, as opposed to a full connectivity matrix $\mathtt{G} \times \mathtt{G}$ where all regions are connected, which would increase the combinatorial part of the problem. In this work, a material can flow from the origin to the destination point by the addition of sequential neighbourhood flows through a sequence of intermediate regions. Additionally, besides the set of connections between adjacent regions $\mathtt{N}$, new links are allowed between two regions g and g' which are not adjacent $\mathtt{G} \times \mathtt{G} \setminus \mathtt{N}$ if their direct distance is shorter than the surrounding route passing by intermediate regions $g'' \in \mathtt{G}$ for a specific transportation mode $l \in \mathtt{L}$. Overall, it is possible to define a subset of connections for transportation modes $\mathtt{LN} \subseteq \mathtt{L} \times \mathtt{G} \times \mathtt{G}$ according to:

$$\begin{aligned} &\text{Let} \quad (l, g, g') \in \mathtt{E}_1 = \mathtt{L} \times \mathtt{N}, \\ &\text{and} \quad (l, g, g') \in \mathtt{E}_2 = \mathtt{L} \times (\mathtt{G} \times \mathtt{G} \setminus \mathtt{N}) \quad | \quad \overline{l}_{lgg'} + l_{margin} \le \min_{\substack{g'' \in \mathtt{G} \,|\, (g, g'') \in \mathtt{N} \\ \wedge\, (g'', g') \in \mathtt{N}}} \left(\overline{l}_{lgg''} + \overline{l}_{lg''g'} \right), \\ &\text{then} \quad (l, g, g') \in \mathtt{LN} = \mathtt{E}_1 \cup \mathtt{E}_2, \end{aligned} \tag{S1}$$

where $\overline{l}_{lgg'}$ is the distance between g and g' for transportation mode l. This definition is especially relevant for transportation modes $l \in \{\text{Trailer}, \text{Tanker}\}$ due to the likely existence of interceptions in road connections.

S1.1. Objective function

The optimisation framework seeks to minimise the total cost (TC), including capital investments related to the installation of new facilities (FCC) and their corresponding operating costs (FOC), capital investments (TCC) and operating costs (TOC) associated to hydrogen and CO_2 transportation –including road transportation and pipelines–, the cost associated to carbon emissions (CEC), and the expenditure on international imports (IIC), as follows:

$$TC = FCC + TCC + FOC + TOC + CEC + IIC. \tag{S2}$$

S1.1.1. Discount factors

In order to compare the costs that occur in different time periods over the planning horizon under study, the mathematical formulation includes a discounted cash flow analysis to calculate the present value of future cash flows. Capital costs are assumed to be deduced at the beginning of the time period of the investment, whereas operating costs are added on an annual basis at the end of each of the Υ years that compose the time period. Then, the discount factor of capital costs (dfc_t) and the summation of discount factors of operating costs (dfo_t) for each time period are:

$$dfc_t = \frac{1}{(1 + dr)^{(o_t - 1)\Upsilon}}, \quad \forall t \in \mathtt{T}, \tag{S3}$$

$$dfo_t = \sum_{y=1}^{\Upsilon} \frac{1}{(1 + dr)^{(o_t - 1)\Upsilon + y}}, \quad \forall t \in \mathtt{T}, \tag{S4}$$

where o_t represents the ordinal of time period t in the ordered set $\mathtt{T}$ and $y \in \{1, ...\Upsilon\}$ represents the years that compose each time period. In some cases, the annuities of capital costs are required for the calculation of fixed operating costs. These are determined by means of the capital recovery factor crf, according to:

$$crf = \frac{dr\ (1 + dr)^n}{(1 + dr)^n - 1}, \tag{S5}$$

where n is the economic life cycle of capital investments.

S1.1.2. Residual values

The residual values of infrastructure assets at the end of the time horizon t^e are deducted in the calculation of capital costs. Such values are determined with a depreciation function that depends on the useful life of each element of the infrastructure and on the time period when it is acquired, namely the sum-of-years-digits function.

S1.1.3. Facilities capital cost

The facilities capital cost (FCC) depends on the number of new hydrogen production plants, storage facilities and filling stations (IP_{ipjgt}, IS_{isjgt} and IF_{ifjgt}) installed in each region g and time period t for processing product i with technology p, s or f, respectively, and size j as follows:

$$\begin{aligned} FCC = & \sum_{t\in\mathtt{T}} \sum_{g\in\mathtt{G}} \sum_{(i,p,j)\in\mathtt{IPJ}} (dfc_t\, pcc_{ipj} - dfc_{t^e}\, rvp_{ipjt})\, IP_{ipjgt} \\ & + \sum_{t\in\mathtt{T}} \sum_{g\in\mathtt{G}} \sum_{(i,s,j)\in\mathtt{ISJ}} (dfc_t\, scc_{isj} - dfc_{t^e}\, rvs_{isjt})\, IS_{isjgt} \\ & + \sum_{t\in\mathtt{T}} \sum_{g\in\mathtt{G}} \sum_{(i,f,j)\in\mathtt{IFJ}} (dfc_t\, fcc_{ifj} - dfc_{t^e}\, rvf_{ifjt})\, IF_{ifjgt}, \end{aligned} \quad \text{(S6)}$$

where parameters pcc_{ipj}, scc_{isj} and fcc_{ifj} stand for the future capital cost of a production, storage or filling station facility and rvp_{ipjt}, rvs_{isjt} and rvf_{ifjt} represent the residual values at the final time of the time horizon for a production, storage or filling station facility constructed during time period t. In this equation, `IPJ` is the subset of production technologies and plant scales available for each hydrogen form. Accordingly, `ISJ` and `IFJ` are the subsets of storage and filling technologies and scales for each hydrogen form. Note that the residual values are discounted at the final time t^e.

S1.1.4. Facilities operating cost

The facilities operating cost (FOC) depends on the production rate (PR_{ipjgt}) and storage inventory (ST_{isjgt}) of hydrogen form i, production or storage technology p and s, respectively, and size j in region g and time period t, according to:

$$\begin{aligned} FOC = & \sum_{t\in\mathtt{T}} \sum_{g\in\mathtt{G}} \sum_{(i,p,j)\in\mathtt{IPJ}} dfo_t\, \alpha\, upc_{ipj}\, PR_{ipjgt} \\ & + \sum_{t\in\mathtt{T}} \sum_{g\in\mathtt{G}} \sum_{(i,s,j)\in\mathtt{ISJ}} dfo_t\, \alpha\, usc_{isj}\, ST_{isjgt}, \end{aligned} \quad \text{(S7)}$$

where α is the annual network operating period and usc_{isj} represents the unit storage cost of product form i, technology s, and size j. Similarly, upc_{ipj} represents the unit production cost of technology p, in this case including operation and maintenance as well as raw material costs.

S1.1.5. Local and regional transportation capital cost

The transportation capital cost (TCC) is composed of road transportation (RCC) and pipeline (PCC) capital costs according to:

$$TCC = RCC + PCC. \quad \text{(S8)}$$

Road transportation capital cost (RCC) includes the investment for local and regional delivery of compressed and liquid hydrogen, and is calculated with the number of new transportation units ($\widetilde{ITU}_{ilgt}$ and $\overline{ITU}_{ilgg't}$) acquired for carrying product i with transportation modes $l \in \{\text{Trailer}, \text{Tanker}\}$ during time period t in region g or between regions g and g', respectively. Then, RCC is defined as follows:

$$\begin{aligned} RCC = & \sum_{t\in\mathtt{T}} \sum_{\substack{l\in\{\text{Trailer},\\ \text{Tanker}\}}} \sum_{\substack{g:(l,g)\\ \in\mathtt{LG}}} \sum_{\substack{i:(i,l)\\ \in\mathtt{IL}}} (dfc_t\, tcc_{il} - dfc_{t^e}\, rvt_{ilt})\, \widetilde{ITU}_{ilgt} \\ & + \sum_{t\in\mathtt{T}} \sum_{\substack{l\in\{\text{Trailer},\\ \text{Tanker}\}}} \sum_{\substack{(g,g'):\\ (l,g,g')\in\mathtt{LN}}} \sum_{\substack{i:(i,l)\\ \in\mathtt{IL}}} (dfc_t\, tcc_{il} - dfc_{t^e}\, rvt_{ilt})\, \overline{ITU}_{ilgg't}, \end{aligned} \quad \text{(S9)}$$

where parameters tcc_{il} and rvt_{ilt} denote the capital cost and residual value per transportation unit. LN is the subset of connections for transportation modes, LG is the subset of local transportation modes for regions. Similarly, IL is the subset of transportation modes for product forms.

Regarding the pipeline capital cost (PCC), this is composed of the investment for constructing the new pipe sections in each time period, which depends on the pipeline diameter and length. There are four different types of pipelines in the problem under study, namely local and regional pipelines for hydrogen distribution and transmission, and onshore and offshore pipelines for CO_2 transportation to collection points and to reservoirs for its sequestration. Then, binary variables $\breve{Y}_{dgt}$, $\overline{Y}_{dgg't}$, $\underline{Y}_{dgg't}$ and $\underline{\underline{Y}}_{dgrt}$ indicate the selection of pipelines of diameter size d for each type of pipeline in region g, between regions g and g', or between collection points in regions g and reservoirs r in time period t and determine PCC according to:

$$\begin{aligned} PCC = & \sum_{t\in \mathtt{T}} \sum_{l\in\{\text{Pipe}\}} \sum_{\substack{g:\\(l,g)\in\mathtt{LG}}} \sum_{d\in\breve{\mathtt{D}}} \left(dfc_t\, \breve{ccc}_d - dfc_{t^e}\, \breve{rvc}_{dt}\right) \breve{l}_{lg}\, \breve{Y}_{dgt} \\ & + \sum_{t\in \mathtt{T}} \sum_{l\in\{\text{Pipe}\}} \sum_{\substack{(g,g'):\\(l,g,g')\in\mathtt{LN}}} \sum_{d\in\overline{\mathtt{D}}} \left(dfc_t\, \overline{ccc}_d - dfc_{t^e}\, \overline{rvc}_{dt}\right) \overline{l}_{lgg'}\, \overline{Y}_{dgg't} \\ & + \sum_{t\in \mathtt{T}} \sum_{(g,g')\in\mathtt{CN}} \sum_{d\in\underline{\mathtt{D}}} \left(dfc_t\, \underline{ccc}_d - dfc_{t^e}\, \underline{rvc}_{dt}\right) \underline{l}_{gg'}\, \underline{Y}_{dgg't} \\ & + \sum_{t\in \mathtt{T}} \sum_{(g,r)\in\mathtt{GR}} \sum_{d\in\underline{\underline{\mathtt{D}}}} \left(dfc_t\, \underline{\underline{ccc}}_d - dfc_{t^e}\, \underline{\underline{rvc}}_{dt}\right) \underline{\underline{l}}_{gr}\, \underline{\underline{Y}}_{dgrt}, \end{aligned} \tag{S10}$$

where parameters $\breve{ccc}_d$, $\overline{ccc}_d$, $\underline{ccc}_d$ and $\underline{\underline{ccc}}_d$ are the capital costs per length unit for pipelines with diameter size d, for each type of pipeline. Accordingly, $\breve{rvc}_{dt}$, $\overline{rvc}_{dt}$, $\underline{rvc}_{dt}$ and $\underline{\underline{rvc}}_{dt}$ denote the residual values per length unit for pipelines with diameter size d installed in time period t, for each type of pipeline. Finally, $\breve{l}_{lg}$, $\overline{l}_{lgg'}$, $\underline{l}_{gg'}$ and $\underline{\underline{l}}_{gr}$ denote the distance of hydrogen and CO_2 transportation via pipelines, with $l \in \{Pipe\}$. In this equation, CN is the subset of connections between regions for onshore CO_2 pipelines and GR is the subset of connections between regions and reservoirs for offshore CO_2 pipelines. Besides, $\breve{\mathtt{D}}$, $\overline{\mathtt{D}}$, $\underline{\mathtt{D}}$ and $\underline{\underline{\mathtt{D}}}$ are the subset of diameter sizes for each type of pipeline.

S1.1.6. Local and regional transportation operating cost

The transportation operating cost (TOC) is equally composed of road transportation (ROC) and pipelines (POC) operating costs:

$$TOC = ROC + POC. \tag{S11}$$

The road transportation operating cost (ROC) includes local and regional fuel costs ($\breve{FC}$ and $\overline{FC}$), general costs ($\breve{GC}$ and $\overline{GC}$), labour costs ($\breve{LC}$ and $\overline{LC}$), and maintenance costs ($\breve{MC}$ and $\overline{MC}$), as presented in the following equation:

$$ROC = \breve{FC} + \breve{GC} + \breve{LC} + \breve{MC} + \overline{FC} + \overline{GC} + \overline{LC} + \overline{MC}. \tag{S12}$$

Essentially, local and regional operating costs for delivering hydrogen via road transportation depend on the flowrates of each hydrogen type i ($\breve{Q}_{ilgt}$ and $\overline{Q}_{ilgg't}$), and the go and return distances ($2\,\breve{l}_{lg}$ and $2\,\overline{l}_{lgg'}$) in region g and between regions g and g' for road transportation modes $l \in \{\text{Trailer}, \text{Tanker}\}$. This way, local and regional fuel costs are given by:

$$\breve{FC} = \sum_{t\in\mathtt{T}} \sum_{\substack{l\in\{\text{Trailer},\\ \text{Tanker}\}}} \sum_{\substack{g:(l,g)\\ \in\mathtt{LG}}} \sum_{\substack{i:(i,l)\\ \in\mathtt{IL}}} dfo_t\, \alpha\, fp_{il} \frac{2\,\breve{l}_{lg}\, \breve{Q}_{ilgt}}{\breve{fe}_{il}\, tcap_{il}}, \tag{S13}$$

$$\overline{FC} = \sum_{t\in\mathtt{T}} \sum_{\substack{l\in\{\text{Trailer},\\ \text{Tanker}\}}} \sum_{\substack{(g,g'):\\ (l,g,g')\in\mathtt{LN}}} \sum_{\substack{i:(i,l)\\ \in\mathtt{IL}}} dfo_t\, \alpha\, fp_{il} \frac{2\,\overline{l}_{lgg'}\, \overline{Q}_{ilgg't}}{\overline{fe}_{il}\, tcap_{il}}, \tag{S14}$$

where α is the annual network operating period and parameters fp_{il}, $\breve{fe}_{il}$, $\overline{fe}_{il}$ and $tcap_{il}$ represent the fuel price, the local and regional fuel economy and the unit capacity of road transportation mode l delivering product i. Similarly, local and regional general costs are defined by:

$$\breve{GC} = \sum_{t \in \mathrm{T}} \sum_{\substack{l \in \{\text{Trailer}, \\ \text{Tanker}\}}} \sum_{\substack{g:(l,g) \\ \in \mathrm{LG}}} \sum_{\substack{i:(i,l) \\ \in \mathrm{IL}}} dfo_t \, \alpha \, ge_{il} \frac{\breve{Q}_{ilgt}}{\breve{tma}_{il} \, tcap_{il}} \left(\frac{2 \, \breve{l}_{lg}}{\breve{sp}_{il}} + lut_{il} \right), \tag{S15}$$

$$\overline{GC} = \sum_{t \in \mathrm{T}} \sum_{\substack{l \in \{\text{Trailer}, \\ \text{Tanker}\}}} \sum_{\substack{(g,g'): \\ (l,g,g') \in \mathrm{LN}}} \sum_{\substack{i:(i,l) \\ \in \mathrm{IL}}} dfo_t \, \alpha \, ge_{il} \frac{\overline{Q}_{ilgg't}}{\overline{tma}_{il} \, tcap_{il}} \left(\frac{2 \, \overline{l}_{lgg'}}{\overline{sp}_{il}} + lut_{il} \right), \tag{S16}$$

where parameters ge_{il}, $\breve{tma}_{il}$, $\overline{tma}_{il}$, $\breve{sp}_{il}$, $\overline{sp}_{il}$, and lut_{il} designate the general expenses, the local and regional availability, the local and regional average speed, and the load and unload time of road transportation mode l transporting product type i. Next, local and regional labour costs are defined according to:

$$\breve{LC} = \sum_{t \in \mathrm{T}} \sum_{\substack{l \in \{\text{Trailer}, \\ \text{Tanker}\}}} \sum_{\substack{g:(l,g) \\ \in \mathrm{LG}}} \sum_{\substack{i:(i,l) \\ \in \mathrm{IL}}} dfo_t \, \alpha \, dw_{il} \frac{\breve{Q}_{ilgt}}{tcap_{il}} \left(\frac{2 \, \breve{l}_{lg}}{\breve{sp}_{il}} + lut_{il} \right), \tag{S17}$$

$$\overline{LC} = \sum_{t \in \mathrm{T}} \sum_{\substack{l \in \{\text{Trailer}, \\ \text{Tanker}\}}} \sum_{\substack{(g,g'): \\ (l,g,g') \in \mathrm{LN}}} \sum_{\substack{i:(i,l) \\ \in \mathrm{IL}}} dfo_t \, \alpha \, dw_{il} \frac{\overline{Q}_{ilgg't}}{tcap_{il}} \left(\frac{2 \, \overline{l}_{lgg'}}{\overline{sp}_{il}} + lut_{il} \right), \tag{S18}$$

where parameter dw_{il} represents the driver wage of road transportation mode l transporting product type i. Finally, local and regional maintenance costs are defined by:

$$\breve{MC} = \sum_{t \in \mathrm{T}} \sum_{\substack{l \in \{\text{Trailer}, \\ \text{Tanker}\}}} \sum_{\substack{g:(l,g) \\ \in \mathrm{LG}}} \sum_{\substack{i:(i,l) \\ \in \mathrm{IL}}} dfo_t \, \alpha \, me_{il} \frac{2 \, \breve{l}_{lg} \, \breve{Q}_{ilgt}}{tcap_{il}}, \tag{S19}$$

$$\overline{MC} = \sum_{t \in \mathrm{T}} \sum_{\substack{l \in \{\text{Trailer}, \\ \text{Tanker}\}}} \sum_{\substack{(g,g'): \\ (l,g,g') \in \mathrm{LN}}} \sum_{\substack{i:(i,l) \\ \in \mathrm{IL}}} dfo_t \, \alpha \, me_{il} \frac{2 \, \overline{l}_{lgg'} \, \overline{Q}_{ilgg't}}{tcap_{il}}, \tag{S20}$$

where me_{il} stands for the maintenance expenses of road transportation mode l transporting product type i.

Regarding the pipeline operating cost (POC), it is considered proportional to the annuities of pipeline capital cost (PCC) with a ratio δ and is defined by:

$$\begin{aligned} POC = & \sum_{t \in \mathrm{T}} \sum_{l \in \{\text{Pipe}\}} \sum_{\substack{g: \\ (l,g) \in \mathrm{LG}}} \sum_{d \in \breve{\mathrm{D}}} dfo_t \, \delta \, crf \, \breve{ccc}_d \, \breve{l}_{lg} \, \breve{AY}_{dgt} \\ & + \sum_{t \in \mathrm{T}} \sum_{l \in \{\text{Pipe}\}} \sum_{\substack{(g,g'): \\ (l,g,g') \in \mathrm{LN}}} \sum_{d \in \overline{\mathrm{D}}} dfo_t \, \delta \, crf \, \overline{ccc}_d \, \overline{l}_{lgg'} \, \overline{AY}_{dgg't} \\ & + \sum_{t \in \mathrm{T}} \sum_{(g,g') \in \mathrm{CN}} \sum_{d \in \underline{\mathrm{D}}} dfo_t \, \delta \, crf \, \underline{ccc}_d \, \underline{l}_{gg'} \, \underline{AY}_{dgg't} \\ & + \sum_{t \in \mathrm{T}} \sum_{(g,r) \in \mathrm{GR}} \sum_{d \in \underline{\underline{\mathrm{D}}}} dfo_t \, \delta \, crf \, \underline{\underline{ccc}}_d \, \underline{\underline{l}}_{gr} \, \underline{\underline{AY}}_{dgrt}, \end{aligned} \tag{S21}$$

where crf is the capital recovery factor for annualising the pipeline capital costs and $\breve{AY}_{dgt}$, $\overline{AY}_{dgg't}$, $\underline{AY}_{dgg't}$ and $\underline{\underline{AY}}_{dgrt}$ are binary variables that specify the availability of a pipeline of diameter size d in time period t for each type of pipeline.

S1.1.7. Carbon emissions cost

The carbon emissions cost (CEC) is determined by the production rates PR_{ipjgt} and emission factors γ^e_{ipjt} of each product type i, technology p and scale j recorded in all regions g and time periods t, as follows:

$$CEC = \sum_{t\in\mathtt{T}} \sum_{g\in\mathtt{G}} \sum_{(i,p,j)\in\mathtt{IPJ}} dfo_t\, \alpha\, ct_t\, \gamma^e_{ipjt}\, PR_{ipjgt}, \tag{S22}$$

where ct_t is the carbon price per unit of CO_2 emitted in time period t. Such value is defined by UK and European directives such that low-carbon solutions with GHG emission bellow the GHG emission targets can be guaranteed.

S1.1.8. International import cost

In addition to national hydrogen production, liquid hydrogen can be also imported from overseas via maritime transportation. The cost of imported hydrogen is calculated as follows:

$$IIC = \sum_{t\in\mathtt{T}} \sum_{g\in\mathtt{P}} \sum_{i\in\{\mathrm{LH_2}\}} dfo_t\, \alpha\, ip\, IMP_{igt}, \tag{S23}$$

where ip is the price of imported liquid hydrogen and IMP_{igt} is the import flow rate of $i \in \{\mathrm{LH_2}\}$ in time period t in region $g \in \mathtt{P}$, where $\mathtt{P}$ is the subset of regions with major liquid freight ports.

S1.2. Demand Constraints

The objective of this problem is to fully satisfy a given hydrogen demand (dem_{gt}) per region g and time period t. Such demand can be supplied from liquid-gas and gas-gas filling stations, which accept hydrogen in either liquid or compressed form $i \in \{\mathrm{LH_2}, \mathrm{GH_2}\}$. The division of the total hydrogen demand into the two forms i is represented by positive variable DEM_{igt} according to:

$$dem_{gt} = \sum_{i\in\mathtt{I}} DEM_{igt}, \qquad \forall g \in \mathtt{G}, t \in \mathtt{T}. \tag{S24}$$

Moreover, hydrogen can be distributed locally via road transportation or via pipelines with local hydrogen flowrates ($\check{Q}_{ilgt}$), according to:

$$DEM_{igt} = \sum_{\substack{l:(i,l)\in\mathtt{IL}\\ \wedge(l,g)\in\mathtt{LG}}} \check{Q}_{ilgt}, \qquad \forall i \in \mathtt{I}, g \in \mathtt{G}, t \in \mathtt{T}. \tag{S25}$$

S1.3. Mass Balance Constraints

The mass balance is defined for each hydrogen type i, in every region g and time period t, such that the hydrogen production (PR_{ipjgt}) and input from other regions g' ($\overline{Q}_{ilg'gt}$) meets the hydrogen output to other regions g' ($\overline{Q}_{ilgg't}$) and supply (DEM_{igt}) for fulfilling the demand, as follows:

$$\sum_{\substack{(p,j):\\(i,p,j)\in\mathtt{IPJ}}} PR_{ipjgt} + \sum_{\substack{l:(i,l)\\ \in\mathtt{IL}}} \sum_{\substack{g':(l,g',g)\\ \in\mathtt{LN}}} \overline{Q}_{ilg'gt} + IMP_{igt} = \sum_{\substack{l:(i,l)\\ \in\mathtt{IL}}} \sum_{\substack{g':(l,g,g')\\ \in\mathtt{LN}}} \overline{Q}_{ilgg't} + DEM_{igt}, \qquad \forall i \in \mathtt{I}, g \in \mathtt{G}, t \in \mathtt{T}. \tag{S26}$$

The CO_2 mass balance should be likewise satisfied in every region g and time period t in order to quantify the infrastructure needs for CO_2 sequestration. In this case, the CO_2 captured in hydrogen production plants ($\gamma^c_{ipjt}\, PR_{ipjgt}$) and the CO_2 input via onshore pipelines from other regions g' ($\underline{Q}_{g'gt}$) must be equal to the CO_2 output via onshore pipelines to other regions g' ($\underline{Q}_{gg't}$) and via offshore pipelines to reservoirs r ($\underline{\underline{Q}}_{grt}$), as follows:

$$\sum_{\substack{(i,p,j)\\ \in\mathtt{IPJ}}} \gamma^c_{ipjt}\, PR_{ipjgt} + \sum_{\substack{g':(g',g)\\ \in\mathtt{CN}}} \underline{Q}_{g'gt} = \sum_{\substack{g':(g,g')\\ \in\mathtt{CN}}} \underline{Q}_{gg't} + \sum_{\substack{r:(g,r)\\ \in\mathtt{GR}}} \underline{\underline{Q}}_{grt}, \qquad g \in \mathtt{G}, t \in \mathtt{T}, \tag{S27}$$

where parameter γ^c_{ipjt} denotes the coefficient of CO_2 capture for producing product i by plant type p and size j in time period t.

S1.4. Production Constraints

The total production rate of hydrogen form i produced with technology p and size j in region g and time period t is limited by the number of available plants (NP_{ipjgt}) and their minimum and maximum production capacities ($pcap_{ipj}^{min}$ and $pcap_{ipj}^{max}$) as follows:

$$pcap_{ijp}^{min} NP_{ipjgt} \leq PR_{ipjgt} \leq pcap_{ipj}^{max} NP_{ipjgt}, \qquad \forall (i,p,j) \in \mathtt{IPJ}, g \in \mathtt{G}, t \in \mathtt{T}. \tag{S28}$$

For the specific case of distributed and small scales, hydrogen production can be only consumed locally. This way, the sum of distributed and small production rates PR_{ipjgt} in each region g and time period t cannot exceed the corresponding demand, as established by:

$$\sum_{\substack{j \in \{\text{Small}, \\ \text{Distributed}\}}} \sum_{\substack{p:(i,p,j) \\ \in \mathtt{IPJ}}} PR_{ipjgt} \leq DEM_{igt}, \qquad \forall i \in \mathtt{I}, g \in \mathtt{G}, t \in \mathtt{T}. \tag{S29}$$

The number of available production plants of each type in region g during period t is determined by the number of available production plants in the preceding period $t-1$, the number of newly installed plants in current period t and the number of plants installed in $t - t^p$ whose useful life Υ^p has finished, as given by:

$$NP_{ipjgt} = NP_{ipjg,t-1} + IP_{ipjgt} - IP_{ipjg,t-t_{ipj}^p}, \qquad \forall (i,p,j) \in \mathtt{IPJ}, g \in \mathtt{G}, t \in \mathtt{T}, \tag{S30}$$

where t_{ipj}^p is equal to Υ^p/Υ. In the first period, the available plants in $t-1$ correspond to the zero condition, namely the plants that have been installed previously to the planning horizon under study.

S1.5. Storage Constraints

The total average inventory of hydrogen form i stored in region g and period t is defined such that the hydrogen supply is guaranteed during a given storage period β, as given by:

$$\sum_{\substack{(s,j): \\ (i,s,j) \in \mathtt{ISJ}}} ST_{isjgt} = \beta \, DEM_{igt}, \qquad \forall i \in \mathtt{I}, g \in \mathtt{G}, t \in \mathtt{T}. \tag{S31}$$

Like in the case of the production rate, the total inventory of hydrogen form i that can be stored with technology s and size j in region g and time period t is limited by the number of available storage facilities (NS_{isjgt}) and their minimum and maximum storage capacity ($scap_{isj}^{min}$ and $scap_{isj}^{max}$) as follows:

$$scap_{isj}^{min} NS_{isjgt} \leq ST_{isjgt} \leq scap_{isj}^{max} NS_{isjgt}, \qquad \forall (i,s,j) \in \mathtt{ISJ}, g \in \mathtt{G}, t \in \mathtt{T}. \tag{S32}$$

The number of available storage facilities of each type in region g during period t is determined by the number of available storage facilities in the preceding period $t-1$, the number of newly installed facilities in current period t and the number of facilities installed in $t - t^s$ whose useful life Υ^s has finished, as given by:

$$NS_{isjgt} = NS_{isjg,t-1} + IS_{isjgt} - IS_{isjg,t-t^s}, \qquad \forall (i,s,j) \in \mathtt{ISJ}, g \in \mathtt{G}, t \in \mathtt{T}. \tag{S33}$$

where t^s is equal to Υ^s/Υ. In the first period, the available storage facilities in $t-1$ correspond to the facilities that have been installed previously to the planning horizon under study.

S1.6. Filling Station Constraints

Similarly, the total filling capacity of hydrogen form i with technology f and size j in region g and time period t is determined by the number of available filling stations (NF_{ifjgt}) and their maximum capacity ($fcap_{ipj}^{max}$) as follows:

$$DEM_{igt} \leq \sum_{\substack{(f,j): \\ (i,f,j) \in \mathtt{IFJ}}} fcap_{ifj}^{max} \, NF_{ifjgt}, \qquad \forall i \in \mathtt{I}, g \in \mathtt{G}, t \in \mathtt{T}. \tag{S34}$$

In the specific case of hydrogen production in a distributed scale, the hydrogen can be only supplied by distributed gas-gas filling stations. This way, the total distributed production rate of product i is limited by the total distributed gas-gas filling capacity, according to:

$$\sum_{\substack{p:(i,p,j)\\ \in \mathtt{IPJ}}} PR_{ipjgt} \leq \sum_{\substack{j:(i,f,j)\\ \in \mathtt{IFJ}}} fcap_{ifj}^{max}\, NF_{ijfgt}, \qquad \forall i \in \mathtt{I}, j \in \{\text{Distributed}\}, f \in \{\text{distributed gas-gas}\}, g \in \mathtt{G}, t \in \mathtt{T}. \tag{S35}$$

The number of available filling stations of each type in region g during period t is determined by the number of available stations in the preceding period $t-1$, the number of newly installed stations in current time period t and the number of facilities installed in $t-t^f$ whose useful life Υ^f has finished, as given by:

$$NF_{ifjgt} = NF_{ifjg,t-1} + IF_{ifjgt} - IF_{ifjg,t-t^f}, \qquad \forall (i,f,j) \in \mathtt{IFJ}, g \in \mathtt{G}, t \in \mathtt{T}, \tag{S36}$$

where t^f is equal to Υ^f/Υ. In the first period, the available filling stations in $t-1$ correspond to the zero condition, namely the stations that have been installed previously to the planning horizon under study.

S1.7. Road Transportation Constraints

Hydrogen road transportation takes place through a discrete number of transportation units, namely trailers and tankers for carrying compressed and liquid hydrogen, respectively. The available number of local and regional transportation units ($\overset{\smile}{NTU}_{ilgt}$ and $\overline{NTU}_{ilgg't}$) required for moving hydrogen type i via road transportation mode $l \in \{\text{Trailer}, \text{Tanker}\}$ in region g and between regions g and g' in time period t depends on the hydrogen flowrates ($\check{Q}_{ilgt}$ and $\overline{Q}_{ilgg't}$), the go and return distances ($2\,\check{l}_{lg}$ and $2\,\overline{l}_{lgg'}$), the unit capacity ($tcap_{il}$), the transportation mode availability ($\overset{\smile}{tma}_{il}$ and $\overline{tma}_{il}$), the average speed ($\check{sp}_{il}$ and $\overline{sp}_{il}$) and the load and unload time (lut_{il}). Overall, the local and regional transportation units are determined by:

$$\overset{\smile}{NTU}_{ilgt} \geq \frac{\check{Q}_{ilgt}}{\overset{\smile}{tma}_{il}\, tcap_{il}} \left(\frac{2\check{l}_{lg}}{\check{sp}_{il}} + lut_{il} \right), \quad \forall l \in \{\text{Trailer}, \text{Tanker}\}, i : (i,l) \in \mathtt{IL}, g : (l,g) \in \mathtt{LG}, t \in \mathtt{T}, \tag{S37}$$

$$\overline{NTU}_{ilgg't} \geq \frac{\overline{Q}_{ilgg't}}{\overline{tma}_{il}\, tcap_{il}} \left(\frac{2\overline{l}_{lgg'}}{\overline{sp}_{il}} + lut_{il} \right), \quad \forall l \in \{\text{Trailer}, \text{Tanker}\}, i : (i,l) \in \mathtt{IL}, (g,g') : (l,g,g') \in \mathtt{LN}, t \in \mathtt{T}. \tag{S38}$$

The number of available transportation units of each type in region g or between regions g and g' during period t is determined by the number of available transportation units in the preceding period $t-1$, the number of newly acquired units in current period t and the number of units acquired in $t-t^t$ whose useful life Υ^t has finished, as given by:

$$\overset{\smile}{NTU}_{ilgt} = \overset{\smile}{NTU}_{ilg,t-1} + \overset{\smile}{ITU}_{ilgt} - \overset{\smile}{ITU}_{ilg,t-t^t}, \forall l \in \{\text{Trailer}, \text{Tanker}\}, i : (i,l) \in \mathtt{IL}, g : (l,g) \in \mathtt{LG}, t \in \mathtt{T}, \tag{S39}$$

$$\overline{NTU}_{ilgg't} = \overline{NTU}_{ilgg',t-1} + \overline{ITU}_{ilgg't} - \overline{ITU}_{ilgg',t-t^t}, \forall l \in \{\text{Trailer}, \text{Tanker}\}, i : (i,l) \in \mathtt{IL}, (g,g') : (l,g,g') \in \mathtt{LN}, t \in \mathtt{T}. \tag{S40}$$

where t^t is equal to Υ^t/Υ. In the first period, the available transportation units in $t-1$ correspond to the zero condition, namely the units that have been acquired previously to the planning horizon under study.

S1.8. Pipeline Constraints

Compressed hydrogen can be also transferred at local and regional levels via distribution and transmission pipelines, respectively. Additionally, onshore and offshore CO_2 pipelines are required for transporting the CO_2 captured in hydrogen production plants to CO_2 collection points first and, later, to the offshore reservoirs for its long-term storage. The availability of pipelines of diameter size $d \in \check{\mathtt{D}}$, $\overline{\mathtt{D}}$, $\underline{\mathtt{D}}$ or $\underline{\underline{\mathtt{D}}}$ in region g, between regions g and g' or between region g and reservoir r, in time period t for each type of pipeline is represented by binary variables $\overset{\smile}{AY}_{dgt}$, $\overline{AY}_{dgg't}$, $\underline{AY}_{dgg't}$ and $\underline{\underline{AY}}_{dgrt}$, respectively. The corresponding flowrates ($\breve{Q}_{ilgt}$, $\overline{Q}_{ilgg't}$, $\underline{Q}_{gg't}$ and $\underline{\underline{Q}}_{grt}$) of hydrogen gas and CO_2 via pipelines, with $l \in \{\text{Pipe}\}$, are limited by the maximum flowrate ($\breve{q}_d^{max}$, $\overline{q}_d^{max}$, $\underline{q}_d^{max}$ and $\underline{\underline{q}}_d^{max}$) of the selected diameter size d, according to:

$$\breve{Q}_{ilgt} \leq \sum_{d \in \breve{D}} \breve{q}_d^{max} \, \breve{AY}_{dgt}, \qquad \forall\, l \in \{\text{Pipe}\}, i \in \{\text{GH}_2\}, g : (l,g) \in \texttt{LG}, t \in \texttt{T}, \tag{S41}$$

$$\overline{Q}_{ilgg't} \leq \sum_{d \in \overline{D}} \overline{q}_d^{max} \, \overline{AY}_{dgg't}, \qquad \forall\, l \in \{\text{Pipe}\}, i \in \{\text{GH}_2\}, (g,g') : (l,g,g') \in \texttt{LN}, t \in \texttt{T}, \tag{S42}$$

$$\underline{Q}_{gg't} \leq \sum_{d \in \underline{D}} \underline{q}_d^{max} \, \underline{AY}_{dgg't}, \qquad \forall\, (g,g') \in \texttt{CN}, t \in \texttt{T}, \tag{S43}$$

$$\underline{\underline{Q}}_{grt} \leq \sum_{d \in \underline{\underline{D}}} \underline{\underline{q}}_d^{max} \, \underline{\underline{AY}}_{dgrt}, \qquad \forall\, (g,r) \in \texttt{GR}, t \in \texttt{T}. \tag{S44}$$

The availability of pipelines is determined by the availability of each pipeline in the preceding period $t-1$, the new installation of pipelines in current time period t and the pipelines installed in $t-t^c$ whose useful life Υ^c has finished, as following represented for each type of pipelines:

$$\breve{AY}_{dgt} = \breve{AY}_{dg,t-1} + \breve{Y}_{dgt} - \breve{Y}_{dg,t-t^c}, \qquad \forall d \in \breve{D}, g : (\text{Pipe}, g) \in \texttt{LG}, t \in \texttt{T}, \tag{S45}$$

$$\overline{AY}_{dgg't} = \overline{AY}_{dgg',t-1} + \overline{Y}_{dgg't} - \overline{Y}_{dgg',t-t^c}, \qquad \forall d \in \overline{D}, (g,g') : (\text{Pipe}, g, g') \in \texttt{LN}, t \in \texttt{T}, \tag{S46}$$

$$\underline{AY}_{dgg't} = \underline{AY}_{dgg',t-1} + \underline{Y}_{dgg't} - \underline{Y}_{dgg',t-t^c}, \qquad \forall d \in \underline{D}, (g,g') \in \texttt{CN}, t \in \texttt{T}, \tag{S47}$$

$$\underline{\underline{AY}}_{dgrt} = \underline{\underline{AY}}_{dgr,t-1} + \underline{\underline{Y}}_{dgrt} - \underline{\underline{Y}}_{dgr,t-t^c}, \qquad \forall d \in \underline{\underline{D}}, (g,r) \in \texttt{GR}, t \in \texttt{T}. \tag{S48}$$

The installation of more than one diameter size d is not allowed for any type of pipelines over the whole timeframe, this is:

$$\sum_{d \in \breve{D}} \breve{AY}_{dgt} \leq 1, \qquad \forall g : (\text{Pipe}, g) \in \texttt{LG}, t \in \texttt{T}, \tag{S49}$$

$$\sum_{d \in \overline{D}} \overline{AY}_{dgg't} \leq 1, \qquad \forall (g,g') : (\text{Pipe}, g, g') \in \texttt{LN}, t \in \texttt{T}, \tag{S50}$$

$$\sum_{d \in \underline{D}} \underline{AY}_{dgg't} \leq 1, \qquad \forall (g,g') \in \texttt{CN}, t \in \texttt{T}, \tag{S51}$$

$$\sum_{d \in \underline{\underline{D}}} \underline{\underline{AY}}_{dgrt} \leq 1, \qquad \forall (g,r) \in \texttt{GR}, t \in \texttt{T}. \tag{S52}$$

S1.9. Reservoirs

The inventory of CO_2 is computed through the CO_2 material balance in reservoirs, as the CO_2 inventory level (RI_{rt}) in reservoir r and time period t hast to be equal to the CO_2 amount in the previous period t plus the accumulated CO_2 input in each time period t, and reads as:

$$RI_{rt} = RI_{r,t-1} + \Upsilon\, \alpha \sum_{(g,r) \in \texttt{GR}} \underline{\underline{Q}}_{grt}, \qquad \forall r \in \texttt{R}, t \in \texttt{T}, \tag{S53}$$

where $\underline{\underline{Q}}_{grt}$ is the CO_2 flowrate between region g and reservoir r and $\Upsilon\, \alpha$ represents the duration of each time period in days. Additionally, reservoir r is only active if it is connected to a offshore CO_2 pipeline that is available, determined by $\underline{\underline{AY}}_{dgrt}$, and the inventory level can never exceed the maximum reservoir capacity ($rcap_r^{max}$):

$$RI_{rt} \leq \sum_{d \in \underline{\underline{D}}} \sum_{g:(g,r) \in \texttt{GR}} \underline{\underline{AY}}_{dgrt}\, rcap_r^{max}, \qquad \forall r \in \texttt{R}, t \in \texttt{T}. \tag{S54}$$

S1.10. Hydrogen import

The total amount of hydrogen import can be constrained according to the following equation:

$$\sum_{g \in \texttt{P}} \sum_{i \in \{\text{LH}_2\}} IMP_{igt} \leq \iota \sum_{g \in \texttt{G}} dem_{gt}, \qquad \forall t \in \texttt{T}, \tag{S55}$$

where ι is the maximum percentage of international hydrogen imports over the total demand in each period t.

Notation

Acronyms and abbreviations

BG	biomass gasification
CCS	carbon capture and storage
CG	coal gasification
GH_2	gas hydrogen
GHG	greenhouse gas
HSC	hydrogen supply chain
LH_2	liquid hydrogen
MILP	mixed-integer linear programming
SHIPMod	Spatial hydrogen infrastructure planning Model
SMR	steam methane reforming
WE	water electrolysis

Sets

$d \in \mathtt{D}$	diameter sizes of pipelines
$f \in \mathtt{F}$	filling station types
$g, g' \in \mathtt{G}$	regions
$i, i' \in \mathtt{I}$	product types
$j \in \mathtt{J}$	sizes of production, storage or filling facilities
$l \in \mathtt{L}$	transportation modes
$p \in \mathtt{P}$	production technologies
$r \in \mathtt{R}$	reservoirs
$s \in \mathtt{S}$	storage technologies
$t \in \mathtt{T}$	ordered time periods
$y \in \{1, ...\Upsilon\}$	years in each time period

Subsets

$(g, g') \in \mathtt{N} \subseteq \mathtt{G} \times \mathtt{G}$ neighbouring regions

$(g, g') \in \mathtt{CN} \subseteq \mathtt{G} \times \mathtt{G}$ connections between regions for onshore CO_2 pipelines

$(g, r) \in \mathtt{GR} \subseteq \mathtt{G} \times \mathtt{R}$ connections between regions and reservoirs for offshore CO_2 pipelines

$(i, f, j) \in \mathtt{IFJ} \subseteq \mathtt{I} \times \mathtt{F} \times \mathtt{J}$ combinations of product types, filling technologies and filling station sizes

$(i, l) \in \mathtt{IL} \subseteq \mathtt{I} \times \mathtt{L}$ combinations of product types and transportation modes

$(i, p, j) \in \mathtt{IPJ} \subseteq \mathtt{I} \times \mathtt{P} \times \mathtt{J}$ combinations of product types, production technologies and plant sizes

$(i, s, j) \in \mathtt{ISJ} \subseteq \mathtt{I} \times \mathtt{S} \times \mathtt{J}$ combinations of product types, storage technologies and storage sizes

$(l, g) \in \mathtt{LG} \subseteq \mathtt{L} \times \mathtt{G}$ transportation modes in regions

$(l, g, g') \in \mathtt{LN} \subseteq \mathtt{L} \times \mathtt{G} \times \mathtt{G}$ connections between regions for transportation modes

$\check{d} \in \check{\mathtt{D}} \subseteq \mathtt{D}$	diameter sizes of local hydrogen pipelines
$\bar{d} \in \bar{\mathtt{D}} \subseteq \mathtt{D}$	diameter sizes of regional hydrogen pipelines
$\underline{d} \in \underline{\mathtt{D}} \subseteq \mathtt{D}$	diameter sizes of onshore CO_2 pipelines
$\underline{\underline{d}} \in \underline{\underline{\mathtt{D}}} \subseteq \mathtt{D}$	diameter sizes of offshore CO_2 pipelines
$\bar{g} \in \bar{\mathtt{P}} \subseteq \mathtt{G}$	regions with major liquid freight ports

Parameters

α	annual network operating period (d y^{-1})
β	storage time interval (d)

γ^c_{ipjt}	coefficient of CO_2 capture for producing product i by plant type p and size j in time period t (kg CO_2 kg^{-1} H_2)
γ^e_{ipjt}	coefficient of CO_2 emission for producing product i by plant type p and size j in time period t (kg CO_2 kg^{-1} H_2)
δ	ratio of pipeline operating costs to capital costs
ι	maximum percentage of international hydrogen imports over the total demand (%)
Υ	duration of time periods (y)
Υ^c	useful life of hydrogen and CO_2 pipelines (y)
Υ^f	useful life of hydrogen filling stations (y)
Υ^p	useful life of hydrogen production plants (y)
Υ^s	useful life of hydrogen storage facilities (y)
Υ^t	useful life of hydrogen road transportation modes $\{\text{Trailer}, \text{Tanker}\}$ (y)
$\breve{ay}^0_{\breve{d}g}$	initial availability of a local hydrogen pipeline of diameter size $\breve{d}$ in region g (0-1)
$\overline{ay}^0_{\overline{d}gg'}$	initial availability of a regional hydrogen pipeline of diameter size $\overline{d}$ between regions g and g' (0-1)
$\underline{ay}^0_{\underline{d}gg'}$	initial availability of a onshore CO_2 pipeline of diameter size $\underline{d}$ between regions g and g' (0-1)
$\underline{\underline{ay}}^0_{\underline{\underline{d}}gr}$	initial availability of a offshore CO_2 pipeline of diameter size $\underline{\underline{d}}$ between collection point in regions g and reservoir r (0-1)
$\breve{ccc}_{\breve{d}}$	capital costs of a local hydrogen pipeline of diameter size $\breve{d}$ (£ km^{-1})
$\overline{ccc}_{\overline{d}}$	capital costs of a regional hydrogen pipeline of diameter size $\overline{d}$ (£ km^{-1})
$\underline{ccc}_{\underline{d}}$	capital costs of an onshore CO_2 pipeline of diameter size $\underline{d}$ (£ km^{-1})
$\underline{\underline{ccc}}_{\underline{\underline{d}}}$	capital costs of an offshore CO_2 pipeline of diameter size $\underline{\underline{d}}$ (£ km^{-1})
crf	capital recovery factor
ct_t	carbon tax in time period t (£ kg^{-1} CO_2)
dem_{gt}	total hydrogen demand in region g in time period t (kg H_2 d^{-1})
dfc_t	discount factor for capital costs in time period t
dfo_t	discount factor for operating costs in time period t
$\breve{dia}_{\breve{d}}$	diameter of a local hydrogen pipeline of diameter size $\breve{d}$ (cm)
$\overline{dia}_{\overline{d}}$	diameter of a regional hydrogen pipeline of diameter size $\overline{d}$ (cm)
$\underline{dia}_{\underline{d}}$	diameter of a onshore CO_2 pipeline of diameter size $\underline{d}$ (cm)
$\underline{\underline{dia}}_{\underline{\underline{d}}}$	diameter of a offshore CO_2 pipeline of diameter size $\underline{\underline{d}}$ (cm)
dr	discount rate (%)
dw_{il}	driver wage of road transportation mode l transporting product type i (£ h^{-1})
$fcap^{max}_{ifj}$	maximum capacity of a filling station of type f and size j supplying product type i (kg H_2 d^{-1})
fcc_{ifj}	capital cost of filling station type f and size j for product type i (£)
$\breve{fe}_{il}$	local fuel economy of road transportation mode l transporting product type i within a region (km l^{-1})
$\overline{fe}_{il}$	regional fuel economy of road transportation mode l transporting product type i between two regions (km l^{-1})
fp_{il}	fuel price of road transportation mode l transporting product i (£ l^{-1})
ge_{il}	general expenses of road transportation mode l transporting product type i (£ d^{-1})
ip	price of imported liquid hydrogen (£ kg^{-1} H_2)
$\breve{l}_{lg}$	local delivery distance of hydrogen transportation mode l in region g (km)
$\overline{l}_{lgg'}$	regional delivery distance of hydrogen transportation mode l between regions g and g' (km)
$\underline{l}_{gg'}$	delivery distance of a onshore CO_2 pipeline between regions g and g' (km)

$\underline{\underline{l}}_{gr}$ delivery distance of a offshore CO_2 pipeline between a collection point in region g and a reservoir r (km)

l_{margin} distance margin for establishing a direct route between two non-adjacent regions (km)

lut_{il} load and unload time of road transportation mode l transporting product type i (h)

me_{il} maintenance expenses of road transportation mode l transporting product type i (£ km^{-1})

n economic life cycle of capital investments (y)

nf^0_{ifjg} initial number of hydrogen filling stations of type f and size j for product type i in region g

np^0_{ipjg} initial number of hydrogen production plants of technology p and size j producing product type i in region g

ns^0_{isjg} initial number of hydrogen storage facilities of type s and size j storing product type i in region g

o_t order of time period t in the ordered set T

$pcap^{max}_{ipj}$ maximum capacity of a hydrogen production plant of type p and size j producing product type i (kg H_2 d^{-1})

$pcap^{min}_{ipj}$ minimum capacity of a hydrogen production plant of type p and size j producing product type i (kg H_2 d^{-1})

pcc_{ipj} capital cost of a production plant of type p and size j producing product type i (£)

$\breve{q}^{max}_{\breve{d}}$ maximum flowrate in a local hydrogen pipeline of diameter size $\breve{d}$ (kg H_2 d^{-1})

$\overline{q}^{max}_{\overline{d}}$ maximum flowrate in a regional hydrogen pipeline of diameter size $\overline{d}$ (kg H_2 d^{-1})

$\underline{q}^{max}_{\underline{d}}$ maximum flowrate in a onshore CO_2 pipeline of diameter size $\underline{d}$ (kg CO_2 d^{-1})

$\underline{\underline{q}}^{max}_{\underline{\underline{d}}}$ maximum flowrate in a offshore CO_2 pipeline of diameter size $\underline{\underline{d}}$ (kg CO_2 d^{-1})

$rcap^{max}_r$ total capacity of reservoir r (kg CO_2-eq)

ri^0 initial CO_2 inventory in reservoir r (kg CO_2)

$\breve{rvc}_{\breve{d}t}$ residual value of a local hydrogen pipeline of diameter size $\breve{d}$ built in time period t, calculated at the final time (£ km^{-1})

$\overline{rvc}_{\overline{d}t}$ residual value of a regional hydrogen pipeline of diameter size $\overline{d}$ built in time period t, calculated at the final time (£ km^{-1})

$\underline{rvc}_{\underline{d}t}$ residual value of an onshore CO_2 pipeline of diameter size $\underline{d}$ built in time period t, calculated at the final time (£ km^{-1})

$\underline{\underline{rvc}}_{\underline{\underline{d}}t}$ residual value of an offshore CO_2 pipeline of diameter size $\underline{\underline{d}}$ built in time period t, calculated at the final time (£ km^{-1})

rvf_{ifjt} residual value of a filling station of type f and size j for product type i built in time period t, calculated at the final time (£)

rvp_{ipjt} residual value of a hydrogen production plant of type p and size j producing product type i built in time period t, calculated at the final time (£)

rvs_{isjt} residual value of a storage facility of type s and size j storing product type i built in time period t, calculated at the final time (£)

rvt_{ilt} residual value of road transportation mode l of product type i acquired in time period t, calculated at the final time (£ $unit^{-1}$)

$scap^{max}_{isj}$ maximum capacity of a storage facility of type s and size j storing product type i (kg H_2)

$scap^{min}_{isj}$ minimum capacity of a storage facility of type s and size j storing product type i (kg H_2)

scc_{isj} capital cost of a storage facility of type s and size j storing product type i (£)

$\breve{sp}_{il}$ local average speed of road transportation mode l transporting product type i within a region (km h^{-1})

$\overline{sp}_{il}$ regional average speed of road transportation mode l transporting product type i between two regions (km h^{-1})

$tcap_{il}$ capacity of road transportation mode l transporting product type i (kg H_2 $unit^{-1}$)

tcc_{il}	capital cost of establishing a road transportation unit of transportation mode l delivering product type i (£ unit^{-1})
$\widetilde{tma}_{il}$	local availability of road transportation mode l transporting product i within a region (h d^{-1})
$\overline{tma}_{il}$	regional availability of road transportation mode l transporting product i between two regions (h d^{-1})
upc_{ipj}	unit production cost for producing product type i in a production plant of type p and size j (£ kg^{-1} H_2)
usc_{isj}	unit storage cost for storing product type i in a storage facility of type s and size j (£ kg^{-1} H_2 d^{-1})

Integer variables

IF_{ifjgt}	investment of new filling stations of type f and size j for product type i in region g in time period t
IP_{ipjgt}	investment of new plants of type p and size j producing product type i in region g in time period t
IS_{isjgt}	investment of new storage facilities of type s and size j storing product type i in region g in time period t
$\widetilde{ITU}_{ilgt}$	number of new transportation units of type l and product type i for local transportation by road in region $g$acquired in time period t
$\overline{ITU}_{ilgg't}$	number of new transportation units of type l and product type i for regional transportation by road from regions g to g' acquired in time period t
NF_{ifjgt}	number of filling stations of type f and size j for product type i in region g in time period t
NP_{ipjgt}	number of plants of type p and size j producing product type i in region g in time period t
NS_{isjgt}	number of storage facilities of type s and size j storing product type i in region g in time period t
$\widetilde{NTU}_{ilgt}$	number of transportation units of type l and product type i for local transportation by road in region g in time period t
$\overline{NTU}_{ilgg't}$	number of transportation units of type l and product type i for regional transportation by road from regions g to g' in time period t

Binary variables

$\widetilde{AY}_{\check{d}gt}$	availability of hydrogen pipelines of diameter size $\check{d}$ for local distribution in region g in time period t
$\overline{AY}_{\bar{d}gg't}$	availability of a hydrogen pipeline of diameter size $\bar{d}$ between regions g and g' in time period t
$\underline{AY}_{\underline{d}gg't}$	availability of a onshore CO_2 pipeline of diameter size $\underline{d}$ between regions g and g' in time period t
$\underline{\underline{AY}}_{\underline{\underline{d}}grt}$	availability of a offshore CO_2 pipeline of diameter size $\underline{\underline{d}}$ between collection point in region g and reservoir r in time period t
$\check{Y}_{\check{d}gt}$	establishment of hydrogen pipelines of diameter size $\check{d}$ for local distribution in region g in time period t
$\overline{Y}_{\bar{d}gg't}$	establishment of a hydrogen pipeline of diameter size $\bar{d}$ between regions g and g' in time period t
$\underline{Y}_{\underline{d}gg't}$	establishment of a onshore CO_2 pipeline of diameter size $\underline{d}$ between regions g and g' in time period t
$\underline{\underline{Y}}_{\underline{\underline{d}}grt}$	establishment of a offshore CO_2 pipeline of diameter size $\underline{\underline{d}}$ between collection point in region g and reservoir r in time period t

Continuous variables

CEC	carbon emissions cost (£)

DEM_{igt}	total demand for product type i in region g in time period t (kg H_2 d^{-1})
$\breve{FC}$	fuel cost for local transport (£)
$\overline{FC}$	fuel cost for regional transport (£)
FCC	facilities capital cost (£)
FOC	facility operating cost (£)
$\breve{GC}$	general cost for local transport (£)
$\overline{GC}$	general cost for regional transport (£)
IIC	international import cost (£)
IMP_{igt}	flow rate of international import of product type $i \in \{LH_2\}$ in region g in time period t (kg H_2 d^{-1})
$\breve{LC}$	labour cost for local transport (£)
$\overline{LC}$	labour cost for regional transport (£)
$\breve{MC}$	maintenance cost for local transport (£)
$\overline{MC}$	maintenance cost for regional transport (£)
PCC	pipeline capital cost (£)
POC	pipeline operating cost (£)
PR_{ipjgt}	production rate of product type i produced by a plant of type j and size p in region g in time period t (kg H_2 d^{-1})
$\check{Q}_{ilgt}$	local flowrate of product type i via transportation mode l in region g in time period t (kg H_2 d^{-1})
$\overline{Q}_{ilgg't}$	regional flowrate of product type i via transportation mode l between regions g and g' in time period t (kg H_2 d^{-1})
$\underline{Q}_{gg't}$	regional flowrate of CO_2 via onshore pipelines between regions g and g' in time period t (kg CO_2 d^{-1})
$\underline{\underline{Q}}_{grt}$	flowrate of CO_2 via offshore pipelines from a collection point in region g to a reservoir r in time period t (kg CO_2 d^{-1})
RCC	road transportation capital cost (£)
RI_{rt}	inventory of CO_2 in reservoir r in time period t (kg CO_2-eq)
ROC	road transportation operating cost (£)
ST_{isjgt}	average inventory of product type i stored in a storage facility of type s and size j in region g in time period t (kg H_2)
TC	total supply chain cost (£)
TCC	transportation capital cost (£)
TOC	Transportation operating cost (£)

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