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

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ABSTRACT

This work studies the development of a sustainable hydrogen infrastructure that supports the transition towards a low-carbon transport system in the United Kingdom (UK). The future hydrogen demand is forecasted over time using a logistic diffusion model, which reaches 50% of the market share by 2070. The problem is solved using an extension of SHIPMod, an optimisation-based framework that consists of a multi-period spatially-explicit mixed-integer linear programming (MILP) formulation. The optimisation model combines the infrastructure elements required throughout the different phases of the transition, namely economies of scale, road and pipeline transportation modes and carbon capture and storage (CCS) technologies, in order to minimise the present value of the total infrastructure cost using a discounted cash-flow analysis. The results show that the combination of all these elements in the mathematical formulation renders optimal solutions with the gradual infrastructure investments over time required for the transition towards a sustainable hydrogen economy.

1. Introduction

The energy sector faces a moment of great challenges to move towards sustainable energy futures. Energy systems currently deal with the depletion of natural resources, volatile international oil prices, high pressures on energy security and damaged air quality in congested cities (Floudas et al., 2016). The European Union additionally set the goal of reducing 1990 greenhouse gas (GHG) emission levels below the 80% by 2050. So, decisive measures are needed to bring about low-carbon energy options. In the last decade, hydrogen has been widely discussed as a notable future alternative to replace oil and natural gas delivering high-quality and clean energy in transport and heat sectors (Marbán and Valdés-Solís, 2007). Hydrogen also has important applications in industry, energy storage from intermittent sources like solar and wind power, and stationary fuel cell systems. The relevance of hydrogen as an energy carrier is because it can be generated from a variety of primary energy sources, renewable and non-renewable, and hence it can span the several phases of a transition towards energy futures that meet sustainable goals (Ekins and Hughes, 2009). Even so, a major difficulty is the high investment required for adapting the infrastructure of energy conversion, storage, distribution and end-use technologies, which will determine the position of hydrogen in the coming years. This way, decision-support tools for hydrogen infrastructure design and operation are necessary to evaluate its mid- and long-term economic viability and the associated mitigation of carbon emissions, so that public agencies and shareholders can back the necessary investments and policy-making processes.

In the last decade, extensive literature has emerged addressing the hydrogen supply chain (HSC) infrastructure design at different spatial scales with a diverse level of detail (Agnolucci and McDowall, 2013). In particular, the explicit representation of the hydrogen network across geographical regions is decisive to link the hydrogen production sites to the hydrogen storage and supply locations and to determine accurate hydrogen transportation requirements. Most of the works solve this problem using optimisation-based approaches with spatially-explicit mixed integer linear programming (MILP) models (Agnolucci et al., 2013; Almansoori and Shah, 2009, 2012; De-León Almaraz et al., 2014, 2015; André et al., 2014; Dayhim et al., 2014; Guillén-Gosálbez et al., 2010; Han et al., 2012, 2013; Hugo et al., 2005; Johnson and Ogden, 2012; Kamarudin et al., 2009; Kim et al., 2008; Konda et al., 2011, 2012; Li et al., 2008; Sabio et al., 2010, 2012; Samsatli et al., 2016), similarly to other contributions in bio-energy supply chains (*e.g.* Akgul et al., 2012; Čuček et al., 2014; d'Amore and Bezzo, 2016; Giarola et al., 2011; Marvin et al., 2013; Yue et al., 2014) and general energy systems (Liu et al., 2011). Another key element in the infrastructure

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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
$y \in \{1, \ldots, \Upsilon\}$ 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
$(l, g, g') \in \mathtt{LN} \subseteq \mathtt{L} \times \mathtt{G} \times \mathtt{G}$ connections between regions for 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
$(i, l) \in \mathtt{IL} \subseteq \mathtt{I} \times \mathtt{L}$ combinations of product types and transportation modes
$\check{d} \in \check{D} \subseteq D$ diameter sizes of local hydrogen pipelines
$\bar{d} \in \bar{D} \subseteq D$ diameter sizes of regional hydrogen pipelines
$\underline{d} \in \underline{D} \subseteq D$ diameter sizes of onshore CO_2 pipelines
$\underline{\underline{d}} \in \underline{\underline{D}} \subseteq D$ diameter sizes of offshore CO_2 pipelines
$\bar{g} \in \mathtt{P} \subseteq \mathtt{G}$ 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 {Trailer, Tanker} (y)
$\breve{ay}^0_{\check{d}g}$ initial availability of a local hydrogen pipeline of diameter size $\check{d}$ in region g (0–1)
$\overline{ay}^0_{\bar{d}gg'}$ initial availability of a regional hydrogen pipeline of diameter size $\bar{d}$ 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)
$\breve{ccc}_{\check{d}}$ capital costs of a local hydrogen pipeline of diameter size $\check{d}$ (£ km^{-1})
$\overline{ccc}_{\bar{d}}$ capital costs of a regional hydrogen pipeline of diameter size $\bar{d}$ (£ 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 summation of discount factors for operating costs in time period t
$\breve{dia}_{\check{d}}$ diameter of a local hydrogen pipeline of diameter size $\check{d}$ (cm)
$\overline{dia}_{\bar{d}}$ diameter of a regional hydrogen pipeline of diameter size $\bar{d}$ (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)
$\check{l}_{lg}$ local delivery distance of hydrogen transportation mode l in region g (km)
$\bar{l}_{lgg'}$ regional delivery distance of hydrogen transportation mode l between regions g and g' (km)