



# A multi-objective MILP model for the design and operation of future integrated multi-vector energy networks capturing detailed spatio-temporal dependencies

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## HIGHLIGHTS

- MILP model for strategic design & tactical operation of multi-vector energy networks.
- Evolution of integrated natural gas, electricity, hydrogen and syngas networks to 2050.
- Multi-objective: min cost, max profit, min emission, max renewable energy production.
- Optimal combination of conversion & storage technologies & transport infrastructures.
- When & where to invest in facilities; what resources to use, how to transport & store.

## ARTICLE INFO

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## ABSTRACT

A multi-objective optimisation model, based on mixed integer linear programming, is presented that can simultaneously determine the design and operation of any integrated multi-vector energy networks. It can answer variants of the following questions:

What is the most effective way, in terms of cost, value/profit and/or emissions, of designing and operating the integrated multi-vector energy networks that utilise a variety of primary energy sources to deliver different energy services, such as heat, electricity and mobility, given the availability of primary resources and the levels of demands and their distribution across space and time? When to invest in technologies, where to locate them; what resources should be used, where, when and how to convert them to the energy services required; how to transport the resources and manage inventory?

Scenarios for Great Britain were examined involving different primary energy sources, such as natural gas, biomass and wind power, in order to satisfy demands for heat, electricity and mobility via various energy vectors such as electricity, natural gas, hydrogen and syngas. Different objectives were considered, such as minimising cost, maximising profit, minimising emissions and maximising renewable energy production, subject to the availability of suitable land for biomass and wind turbines as well as the maximum local production and import rates for natural gas.

Results suggest that if significant mobility demands are met by hydrogen-powered fuel cell vehicles, then hydrogen is the preferred energy vector, over natural gas, for satisfying heat demands. If natural gas is not used and energy can only be generated from wind power and biomass, electricity and syngas are the preferred energy carriers for satisfying electricity and heat demands.

## 1. Introduction

Traditionally, energy networks evolved independently, with fossil fuels as the dominant primary resource and electricity and natural gas

as the energy vectors. As we strive to move towards a more sustainable and low-carbon future energy system, a much greater variety of primary sources of energy (such as wind, solar and biomass) and more technologies with different types and scales for generating,

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transmitting, distributing and storing energy will be utilised. A change in the energy mix can be expected and other energy vectors, such as hydrogen, syngas, methanol etc., may also play important roles. Each of these energy vectors is capable of delivering multiple energy service demands, such as heat, electricity and mobility. Similarly, an energy service demand can be satisfied through different energy vectors. For example, hydrogen, electricity, natural gas and biofuels are all potential alternatives to petroleum for meeting mobility demands. Furthermore, with the higher penetration of renewables, all of the networks need to be aware of the intermittent supply from renewables, covering for shortfalls and allowing full utilisation when supply exceeds demand. Integrating the networks for different energy vectors can improve the efficiency of the whole energy system and also increase the penetration of renewables.

There are many complex issues associated with the integration of energy networks and mathematical modelling is a valuable tool to help understand them. Mathematical models (hereafter called “models”) can provide an accurate representation of the potential technologies, infrastructures and resources that may become part of the network. Through computational experiments, the behaviour of the system can be explored at the national level over a long future planning horizon. Using optimisation techniques, the best design among the many possible alternatives can be determined – this involves selecting the appropriate combinations of technologies for resource conversion, storage, transmission and distribution, when to invest in them, where to locate them and what their capacities should be. Models can aid in determining the most effective way of operating the system and formulating control strategies to ensure that the operation is robust in the presence of disturbances and uncertainties. They can also provide a holistic understanding of the system, which could help inform policy on the future shape of the energy sector as a whole.

Motivated by the desire to develop efficient and sustainable systems that can deliver the energy needs of today’s and future societies, the aim is to develop a mathematical model that can simultaneously determine the best design and operation of the integrated multi-vector energy networks to obtain the most value from limited available resources. One of the main challenges is that primary energy resources are available at different quantities, at different times and at different locations. The demands for energy services are also distributed in space and time but often not matched to the availability of primary resources. Therefore, the model needs to be sufficiently detailed to account for the distribution of resources across space and time, the interactions between different networks and energy vectors and the operational issues at different time scales (e.g. accounting for hourly variation, differences between days of the week, seasonality and long-term planning and investment).

There are a number of different modelling approaches to planning energy systems at national scale that employ mathematical programming but most of them are not suitable for optimising the design and operation of integrated multi-vector energy networks. These models typically fall into two very broad categories: equilibrium models, such as MARKAL/TIMES [1,2] and all of its variants, and energy supply chain models (also known as network models) based on a multi-echelon supply chain representation. An extensive review of these models appears in our previous publications [3–5] and is summarised in the following paragraphs.

Equilibrium models are typically steady state, multi-period models that consider how economics, supply and demand change over a number of planning periods, e.g. years. Although they can represent a large number of conversion technologies, their major weakness is that they are not spatially-resolved, have little or no temporal detail below the planning periods and do not contain a detailed (or typically any) representation of the energy transmission/distribution networks or of energy storage. Various temporal MARKAL type models [6] feature “time slicing”, reflecting different time periods with different demand and renewable supply patterns. However, dynamics cannot be

considered because these periods are not linked and therefore operational issues such as storage and ramp-up/ramp-down rates of technologies cannot be modelled; storage is only considered by shifting some demands to a *user-selected* time interval and assuming sufficient storage capacity to support this. Therefore this family of models is not suited to solving the complex problem of designing integrated multi-vector energy networks, in which one must consider in detail: the transmission and distribution of energy (hence a high spatial resolution is required); the detailed operation of the network, which requires a fine temporal resolution to account for operational issues; and new interactions between the networks when they become more distributed and include a higher penetration of intermittent supply technologies, as can be expected to occur. Storage may also be expected to play a key role in supporting these highly integrated networks with intermittent supply of energy; this also requires a fine temporal resolution and a model that can predict the dynamics of the system and track the inventory of stored energy over time so that the storage facilities can be sized correctly.

Energy supply chain models, on the other hand, typically include nodes and edges to represent the spatial dependence of the system. Nodes represent locations of entities in the chain (e.g. production sites, conversion technologies, storage facilities) and edges represent transport connections between the nodes. Although there are many energy supply chain models in the literature, almost all of these models are based on manufacturing supply chains so they have a multi-echelon structure that breaks down the supply chain into a number of stages or echelons (e.g. for hydrogen networks, typical echelons include primary resources/raw materials, production plants, storage facilities and distribution centres, which are very similar to the echelons of manufacturing supply chains). In this representation, the direction of the flow of resources across the echelons is specified or fixed before the optimisation (e.g. from primary resources to production plants to storage facilities to distribution), which means that the resources can only flow in the specified direction. For example, in the model presented by Almansoori and Shah [7–9] for hydrogen supply chains, on which many energy supply chain models are based (e.g. [10–22]), the resources from the production plants will always have to go to the storage facilities and cannot be transported to other regions or distributed directly to the customers. Also, the reverse pathways cannot be handled by the multi-echelon formulation and adding a technology (e.g. fuel cell, which will define the reverse pathway of converting hydrogen back to electricity), will require a significant change to the *core mathematical structure* of the model. This inflexibility makes the multi-echelon formulation unsuitable for modelling integrated multi-vector energy networks. A suitable model will need to be able to decide at any given time what to do with a particular resource in order to optimise the whole system: converting it to another resource vs. holding it in a storage facility vs. transmitting it to another location vs. distributing it to customers to satisfy demands. At the same time, the model needs to determine what form of energy is most suitable for transportation and storage. A further limitation of existing supply chain models is their representation of time: while many of these models can consider a long-term horizon, they are multi-period (e.g. each period represents the average over a five-year period); all of them lack the shorter time scale to capture the seasonality of energy service demands and availability of renewable sources and even finer time scale to account for the intermittency of renewable sources and dynamics of energy storage, which requires at least an hour-by-hour account of the operation of the network and an inventory balance for storage.

There are also other recent studies that considered multi-vector energy networks, but with only gas and electricity as energy carriers; other carriers such as hydrogen and syngas are not part of the system. For example, Chaudry and co-workers developed an NLP model to optimise the operation of integrated gas and electricity networks of a fixed design [23], which was later extended to include capacity expansion [24]. Devlin et al. [25] presented an MILP model for unit

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