Multi-model assessment of heat decarbonisation options in the UK using renewable hydrogen

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ABSTRACT

Achieving the UK's long-term climate targets will require a coordinated approach to decarbonising both electricity and heat supply, which will require substituting natural gas with low-carbon energy vectors, such as electricity and hydrogen that could be produced from renewable or other forms of zero-carbon energy. The objective of this paper is to use two established energy system models, RTN and WeSIM, to assess plausible heat decarbonisation pathways for the UK, while utilising their respective strengths – a technology-rich representation of hydrogen production, storage and transport options with high spatial granularity for the former, and high temporal resolution and detailed representation of the power system for the latter. The two models are linked through passing optimised capacities of

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hydrogen production technologies from RTN to WeSIM, and transferring an updated set of electricity prices in the opposite direction. Initial results indicate that model integration can improve the cost-effectiveness of the hydrogen technology mix by reducing the use of inefficient electrolysers during periods of high electricity prices and increasing the capacity and output of more efficient electrolysers, gas reformers and biomass gasification plants.

KEYWORDS

Heat decarbonisation, hydrogen, renewable energy, electrolysis, heat pumps, hydrogen storage, multi-model assessment.

INTRODUCTION

A wide-ranging transformation is expected in energy supply systems around the world over the next three decades to achieve the ambitious targets set for decarbonisation. The UK became the first major economy in the world to adopt a law that requires that its greenhouse gas emissions are brought to net zero by 2050 [1]. The UK's heat sector, predominantly supplied by natural gas at present, accounts for a third of the total carbon emissions. Achieving the UK's long-term climate targets cost-effectively will require a coordinated approach to decarbonise both electricity and heat supply. Likely pathways for heat decarbonisation will involve substituting fossil fuels with low-carbon energy vectors, electricity and hydrogen (H_2), produced from renewable or other forms of zero-carbon energy.

It has been shown that heating and electricity systems can benefit significantly from mutual synergies on their pathways towards decarbonisation [2], by unlocking opportunities for cross-vector flexibility to support the integration of low-carbon generation technologies and to significantly reduce the cost of decarbonisation [3]. Integrated design of electricity and heat supply systems is likely to result in much lower overall cost than if each of those systems is optimised in a decoupled fashion i.e. using a 'silo' approach.

Decarbonisation of energy supply will require a range of technologies to provide flexibility in the context of grid support, balancing, security of supply and integration of variable renewables [4]. These technologies will include various forms of energy storage, demand-side response, expansion of interconnection capacity and more flexible generation technologies, as well as a number of cross-vector flexibility options such as hydrogen production and conversion technologies. A number of studies have shown that flexibility becomes critical for efficient renewable integration as carbon emissions targets for the electricity sector are reduced and therefore the provision of flexibility will become particularly critical in achieving net-zero carbon or net-negative carbon electricity supply [5].

More specifically, the cost-effectiveness of hydrogen as an intermediate energy vector in a highly renewable energy system has been demonstrated in [6], estimating the potential benefits of deploying hydrogen infrastructure at several billions of pounds of savings in annual energy system cost. Such transition would rely on reforming technologies – Steam Methane Reforming (SMR) and Autothermal Reforming (ATR) – coupled with Carbon Capture and Storage (CCS) and negative emission technologies. Currently, hydrogen is mainly produced using reforming technologies. However, biomass gasification and water electrolysis represent viable alternatives for producing green hydrogen in an energy system with a high share of renewable resources, and their costs have been declining [7]. Several recent publications have focused on integrating and utilising hydrogen in the whole energy system. In [8], a hydrogen supply chain including production, storage, and distribution technologies is developed for the UK transport demand. In [9], another hydrogen supply chain is designed by optimising infrastructural and operational costs for the transport sector. A large-scale model is presented in [10] for optimising the interactions between electricity, hydrogen, and transport sectors and identify cost-efficient decarbonisation scenarios for the whole energy system in the UK.

The Resource-Technology Network (RTN) model [11], one of the two models used in this paper, is a spatio-temporal Mixed-Integer Linear Programming (MILP) model that has been used previously to assess the potential of hydrogen in the decarbonisation of the UK's heating sector. For instance, in [12] the authors proposed a model based on wind electricity to supply domestic heating demand either using electric heaters or through the production of hydrogen via water electrolysis. The authors reported that the selection of hydrogen-based technologies was sensitive to the availability of large-scale hydrogen storage. This was also observed by Sunny *et al.*, who concluded that cost-optimal regions present higher heating demand and are located in proximity to hydrogen and CO_2 storage sites [13]. Furthermore, the use of large-scale hydrogen storage and deep geological reservoirs for CO_2 would allow a cost-effective transformation of the incumbent natural gas-based heat supply system to hydrogen.

Modelling of low- and zero-carbon energy system with high penetrations of variable renewable sources (wind and solar PV) requires both a rich representation of technologies available for producing, transporting storing and delivering low-carbon energy as well as an adequate representation of spatial and temporal variations in the availability of low-carbon supply and in energy demand patterns. The motivation for coupling the two models presented in this paper is to meet these requirements by assessing low-carbon heat supply with technology-rich system representation with sufficiently high spatial and temporal resolution.

The first modelling approach, RTN, allows for developing long-term strategies through multi-period analysis. In the context of decarbonisation, this enables the identification of pathways to transform the existing energy system to one attaining the goal of net zero emissions. Here, different options have been considered to transition from current fossil-based systems, presenting the electrification of the heating and transport sectors as an appealing alternative. In the domestic transport sector, the potential of new onshore wind farms has been explored in electric [14] or hydrogen-based vehicles [15]. On a district level, emission-constraint cost-optimisation models have explored decentralised systems for domestic and commercial heat and electricity demands [16,17].

The other model that is used for assessing the heat decarbonisation options in this paper is the Whole-electricity System Investment Model (WeSIM), presented in [18]. WeSIM has been used extensively to study the challenges of integrating large volumes of low-carbon generation in future electricity systems, including the role and value of a broad range of flexible technologies including smart EV charging [19], Vehicle-to-Grid [20], battery storage [21], pumped-hydro storage [22] and liquid-air and pumped-heat energy storage [23].

The objective of this paper is to take advantage of the two models' strengths to assess heat decarbonisation pathways for the UK, i.e. to utilise the high temporal detail and broad range of technological options in RTN and combine them with a high temporal resolution and detailed representation of the electricity system enabled by WeSIM. To the best of authors' knowledge, there is no multi-model approach in the literature based on interactions between multiple models for heat and electricity sectors with high spatial and temporal resolutions, as presented in this paper, to design a low-carbon energy system with hydrogen-based technologies.

In light of the above, the key proposed contributions of the paper are the following:

1. Develop a robust multi-modelling approach to study pathways for cost-efficient decarbonisation of heat supply;
2. Propose a methodological framework for soft-linking two established energy system models with different geographical scopes, temporal resolutions and technology coverage;
3. Determine cost-effective technology mix for delivering zero-carbon heat through a combination of electrification and hydrogen.

METHOD

Rationale for multi-model assessment

The multi-vector models proposed in literature generally do not simultaneously deal with issues such as technological richness, computational complexity associated with fine temporal scales, coordination of district and national objectives, uncertainty, and multiple agent perspectives including the interactions between national and local energy systems [24,25,26]. In order to overcome the limits of the existing energy system models, the IDLES programme [27], of which this paper is a part of, aims to propose a framework for creating a system-of-systems model that is computationally tractable when dealing with multi-physics models across energy carriers, with high temporal resolution (to capture temporal features of technology and system operation) and with high spatial resolution (for accurate reflection of national and local impact of various types of energy infrastructure). The ambition of this framework is to achieve technology richness sufficient to inform technology development goals, establishing the value that different technologies can provide to the energy system and how this relates to the infrastructure planning, technologies design and operational strategies.

In this context, the key aim of this paper is to combine the high spatial resolution, multi-vector and sector coupling features of RTN with the high temporal resolution of WeSIM, which offers the possibility of local vs. global systems integration and accurate dynamic modelling of selected technologies. This combined multi-model approach allows for an enhanced representation of the complex interactions associated with energy system design and operation at both local and national level, quantifying with higher accuracy the aspects such as the benefits of flexibility, energy storage and ancillary services. Moreover, the integrated approach that combines the capabilities of RTN and WeSIM models could better identify and quantify the system-wide benefits of individual technologies and infrastructures in order to guide the innovation towards the right combinations of features and raise the system value and the prospects for successful deployment of new technologies.

The areas of investigation proposed in this application include heat decarbonisation technologies via electric and/or hydrogen systems and the consequent implications in terms of energy system flexibility and storage needs to enable a high penetration of intermittent renewable energy sources for net zero energy scenarios by 2050. However, the proposed multi-model approach is suitable to appreciate the system value of other hybrid heating technologies and inter-seasonal heat storage.

Key features of RTN

In this work, we make use of the RTN model reported in [13], which simultaneously considers a hydrogen and CO_2 value chain to supply domestic and industrial heating demand. To facilitate the integration between RTN and WeSIM, the original formulation has been adapted, omitting the different pressure levels for hydrogen transport in pipelines.

Resources and technologies. In the model, any material or energy stream is a *resource* that is consumed, produced, or stored in a given *technology*. Figure 1 shows the structure of the network, which accounts for five resources, four hydrogen production technologies, three storage technologies, and two heating technologies. Three resources can be imported in the model: electricity, biomass, and natural gas. From these, only electricity can be used directly to provide heat via heat pumps. All three resources can also be used to produce hydrogen via water electrolysis, biomass gasification, and reforming of natural gas coupled with CCS (SMR or ATR). The captured CO_2 is transported and stored at sites allocated for this purpose. The hydrogen produced is transported and can be stored before its consumption in hydrogen boilers. Salt caverns for intra-day and inter-seasonal storage are considered for hydrogen storage purposes. Additional storage in form of pressurised vessel storage is allowed for all cells.

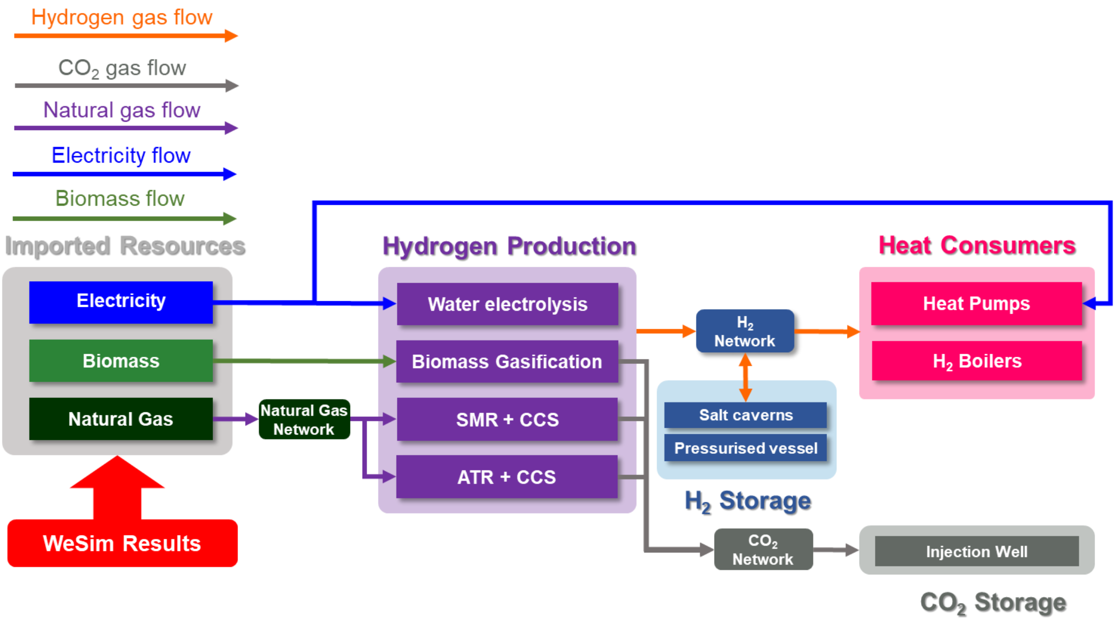

Figure 1. High-level diagram of RTN model

Temporal resolution. The temporal representation of the model includes one major investment periods, four seasons, and four daily periods. The annual heating demand along with electricity profiles for price and carbon intensity are adjusted for each period according to the scenarios described. The biomass and natural gas prices are assumed constant throughout the full time horizon. The annual representation of the model considers 16 time slices, as used in the UK TIMES model [28]. The seasons considered account for summer, autumn/spring, and winter. For the correct sizing of the supply infrastructure, the peak winter demand day is considered explicitly. The daily representation includes four time slices representing the day, evening peak, late evening, and night periods.

Spatial resolution. The geographical area of the UK is aggregated into 51 equally sized cells using the open-source Geographic Information System QGIS [29]. Each cell is characterised by the aggregated total annual demand of the domestic and industrial sector, the distance to its bordering cells, the aggregated hydrogen and CO_2 storage capacity and existing natural gas transmission lines.

Overall, the model seeks to minimise the total annualised cost over the full-time horizon, which consists of annualised investment cost of the technologies selected for installation and the operating costs that are calculated based on the cost of imported resources and operating parameters of the technologies. The formulation of the objective function allows for applying different weighting factors to investment costs and operating costs depending on the emphasis of the analysis. The full RTN formulation is presented in [13].

Key features of WeSIM

Capturing the interactions across different time scales and across different asset types is essential for the analysis of future low-carbon electricity systems that include flexible technologies such as energy storage and Demand Side Response (DSR). Clearly, the application of those technologies may improve not only the economics of real-time system operation, but also reduce the investment into generation and network capacity in the long run.

In order to characterise these effects, and in particular trade-offs between different flexible technologies, it is critical that they are all included in a single integrated modelling framework. Accordingly, a comprehensive system analysis model WeSIM has been developed that is capable of simultaneously optimising long-term investment decisions against short-term operation decisions, across generation, transmission, and distribution systems, in an integrated fashion. A detailed formulation of the model is provided in [18], and the model has been implemented in FICO Xpress Optimization framework [30].

WeSIM determines optimal decisions for investing into generation, network and/or storage capacity (both in terms of volume and location), aiming to supply the projected electricity demand in an economically optimal way, while at the same time ensuring appropriate security and adequacy levels for electricity supply. An advantage of WeSIM over most traditional models is that it is capable of simultaneously including system operation decisions and capacity additions to the system, with the ability to quantify trade-offs of using alternative mitigation measures, such as DSR and storage, for real-time balancing and transmission and distribution network and/or generation reinforcement management. Additionally, a key feature of the WeSIM model is the ability to optimally determine the necessary investments in distribution networks in order to meet demand growth and/or distributed generation uptake, based on the concept of statistically representative distribution networks.

Analysing future electricity systems at sufficient temporal and spatial granularity is essential for assessing the cost-effectiveness of alternative decarbonisation pathways. In this context, WeSIM-based modelling has clearly demonstrated that in order to more accurately quantify system operation and investment costs and determine CO_2 emissions of different technologies, it is necessary to simulate second-by-second power balancing problems at the same time as multi-year investment decisions (e.g., low inertia in electrical networks with massive integration of renewable energy resources may trigger significant investment in flexible technologies). Additionally, and more importantly, electricity system decarbonisation will also require capturing synergies and conflicts related to infrastructure requirements in local/district and national/trans-national levels, which is another essential capability of the WeSIM model.

The WeSIM model solves a unified optimisation problem to find the optimal investment/operation decisions and includes two different planning horizons: (1) short-term operation periods with a typical resolution of one hour or half an hour (while also taking into account frequency regulation and short-term reserve requirements), which is coupled with (2) long-term investment, i.e., planning decisions with the time horizon of typically one year (the time horizons can be adjusted if needed). All annual investment decisions and 8,760 hourly operation decisions are determined simultaneously in order to achieve an overall optimality of the solution. In summary, the key features and constraints of the WeSIM model include: a) supply-demand balance, b) reserve and response requirements, c) generator operating limits, d) DSR capability; e) transmission and distribution network investment/reinforcement, f) carbon emission constraints, g) constraints on electricity imports/exports, and h) adequacy and security constraints.

For the purpose of this paper and to enable the integration with RTN outputs, the original formulation of WeSIM has been extended to also explicitly consider technologies for hydrogen production (electrolysis, ATR and SMR), storage and transport. A high-level diagram of WeSIM model (as used in this paper) is presented in Figure 2.

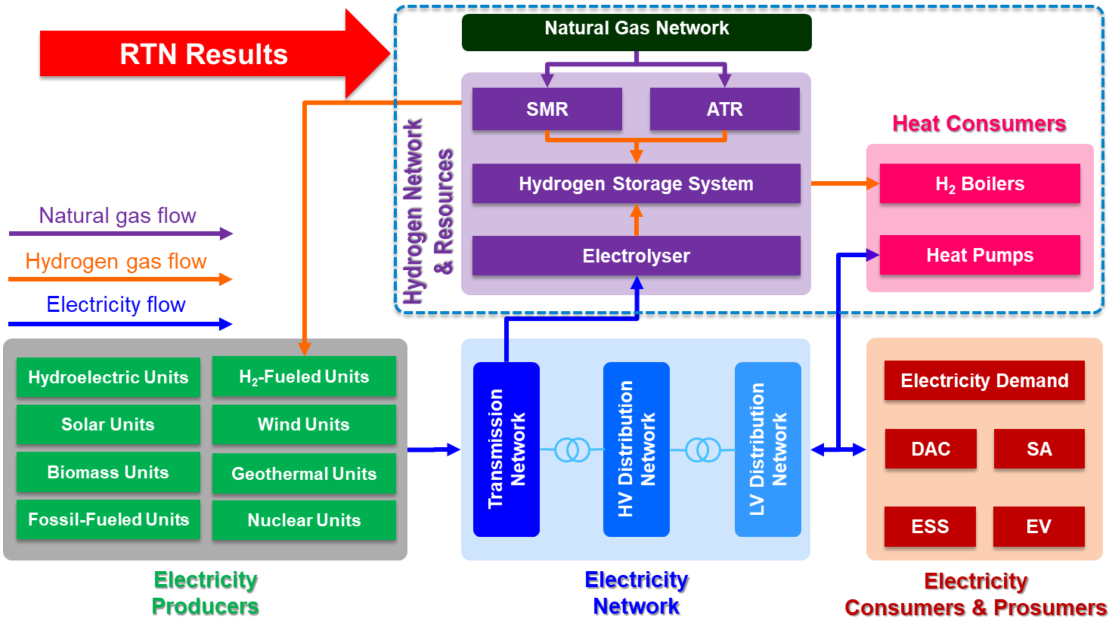

Figure 2. High-level diagram of WeSIM model

Linking the two models

Figure 3 presents the interactions between the models used in this paper. RTN is used to find the cost-optimal investment plan to decarbonise the heat sector through a MILP problem, while WeSIM finds the optimal investment plan to decarbonise the electricity sector through a Linear Programming (LP) formulation.

In the RTN model, only zero-emission investment candidates (i.e., heat pumps and hydrogen boilers) are considered to supply heat consumers. WeSIM on the other hand considers various types of zero-emission (e.g., hydrogen-fuelled generation), positive-emission (e.g., gas-fired CCGT and CCS generation), and negative-emission (e.g., direct air capture) technologies to supply electricity consumers. The electricity sector supplies the electrolyser and heat pump demand characterised in RTN (Figure 1), while the hydrogen production technologies (electrolysers, ATR and SMR) all supply hydrogen for both end-user hydrogen boilers as well as for the hydrogen-fuelled units considered in WeSIM (Figure 2). Therefore, the RTN and WeSIM models are highly co-dependent given that for each run RTN requires inputs from WeSIM and vice versa.

As illustrated in Figure 3, in the first iteration RTN assumes a constant electricity price for all 16 time slices in the planning horizon and uses this to determine the cost-optimal decarbonisation plan for the heat sector. This optimal investment plan is passed onto WeSIM, including capacities and locations of electrolysers, heat pumps, ATRs, SMRs, hydrogen transport and hydrogen storage systems. Based on this information, WeSIM finds the optimal decarbonisation plan for the electricity sector and returns hourly electricity prices for the entire year to the RTN model. This iterative procedure continues until there are little or no changes between solutions for two successive iterations. For the sake of simplicity, only the results of the first iteration are presented in this paper.

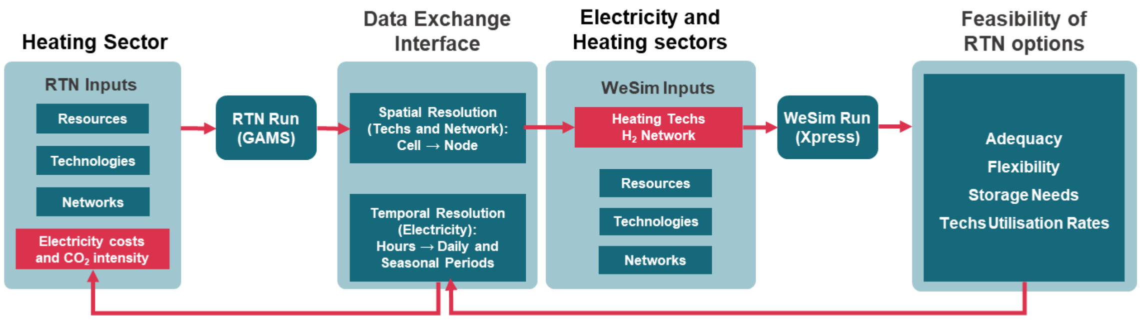

Figure 3. High-level diagram of interactions between RTN and WeSIM

The solution of the RTN model provides the infrastructure and resources required to satisfy the residential and commercial heating demand of the UK. The information exchanged with WeSIM includes the annual demand for hydrogen and electricity, technologies deployed for heat supply, and H_2 transportation network and storage. To this end, we aggregate the information from 51 different cells in the RTN model according to the 5 GB regions used in WeSIM. The aggregated information is then sent to WeSIM, which optimises the capacity mix and operation of the electricity system and the hourly provision of heating based on capacities determined by RTN. The solution of the model provides an updated assessment of the heat supply options deployed by RTN and their feasibility from the electricity system perspective, while updating hourly electricity prices and carbon intensities resulting from the model. In the next step the electricity price data is aggregated from the hourly resolution used in WeSIM into 16 representative daily and seasonal periods (i.e., time slices) used by RTN.

System scenarios and main assumptions

System-level assumptions were broadly based on the System Transformation scenario from National Grid's Future Energy Scenarios (FES) [31]. Both models were only run for the 2050 time horizon, when it was assumed that heat supply needs to be fully decarbonised; therefore the only two options to deliver zero-carbon heat in RTN were end-use heat pumps and hydrogen boilers. The electricity system was assumed to incorporate a high share of electrified road transport (i.e., electric vehicles).

Costs of electricity supply technologies used in WeSIM were assumed in line with [5], while those associated with hydrogen production, storage and transportation in RTN were taken from [13]. Total heat demand for residential and commercial sectors that was considered in the model was just under 600 TWh annually. Interconnection between GB and continental Europe was also modelled in WeSIM, assuming energy neutrality for the GB electricity system (i.e., although at any hour interconnections can be exporting or importing, electricity exports match imports over the course of a year). Security of the GB system was ensured by enforcing a Loss of Load Expectation (LOLE) criterion of up to 3 hours per year.

RESULTS AND DISCUSSION

This section outlines the key results obtained from running the two models, focusing on how their interaction affects the heat supply solution proposed by the model. The results of this analysis are highly dependent on the input assumptions considered, which are subject to a large degree of uncertainty. Therefore, the main focus of this contribution is how the two models could effectively exchange information and in the process gradually improve the quality of the solution.

Initial RTN run

For the initial RTN run, a constant electricity price of £47.97/MWh was assumed across all time slices. This price was based on earlier preliminary runs of WeSIM. Note that this price represents a proxy for the wholesale price of electricity. With this electricity price and the assumptions on the cost of end-use heating technologies (where H_2 boilers were assumed to be 3 times cheaper per unit of heat output than heat pumps), the model suggested that the entire residential and commercial heat in 2050 should be cost-efficiently delivered through hydrogen.

The portfolio of hydrogen production technologies is presented in the left-hand side of Figure 4. It consists of a mix of biomass gasification, ATR, SMR and electrolyser capacity. The low-efficiency electrolysers (around 115 GW overall) were used during periods of high demand, in the evening peak times during winter and autumn/spring (this is elaborated in more detail in the section discussing the second RTN run).

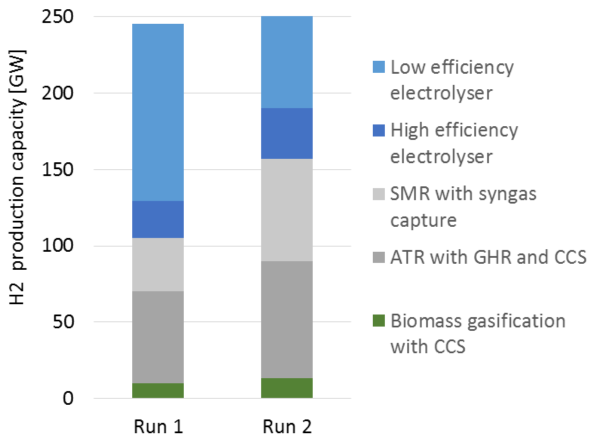

Figure 4. Hydrogen production capacity mix determined by RTN in Run 1 (constant electricity price) and Run 2 (electricity price profile)

WeSIM run

Once the hydrogen production capacities (as well as hydrogen storage and transport capacities) have been determined by RTN, these values were used as inputs for WeSIM, providing a limit on the hourly production of hydrogen. WeSIM was then run to cost-optimise the composition of the electricity generation mix under system-wide zero-carbon constraint. As shown in Figure 5, the model decides to invest in a portfolio of low-carbon generation technologies, including onshore and offshore wind, solar PV, nuclear and biomass generation. In addition to low-carbon generation the model also invests into a very large volume of battery storage capacity (around 200 GW).

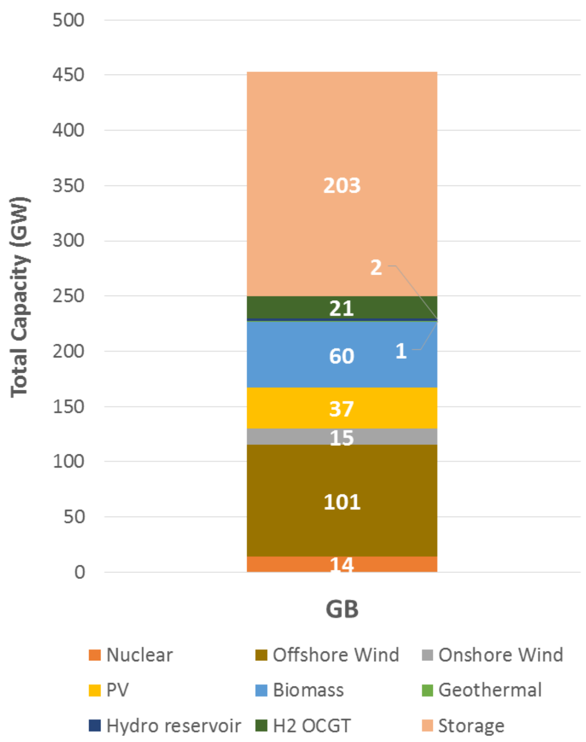

Figure 5. Total capacity of electricity generation technologies

One of the results of the WeSIM run is also an updated set of hourly electricity prices, varying in line with variations in supply and demand balance in the system. Figure 6 shows how the resulting updated power price variations across RTN time slices in Run 2 compare to the constant power price used in Run 1. In some time slices (mainly those characterised by lower demand such as night hours) the price falls below the average price of Run 1. On the other hand, during 'peak' time slices the prices rise significantly above the average price level, getting to levels around £90/MWh. Nevertheless, as these prices are averaged across all hours that fall into a given time slice, the actual hourly variations in power prices are generally much higher.

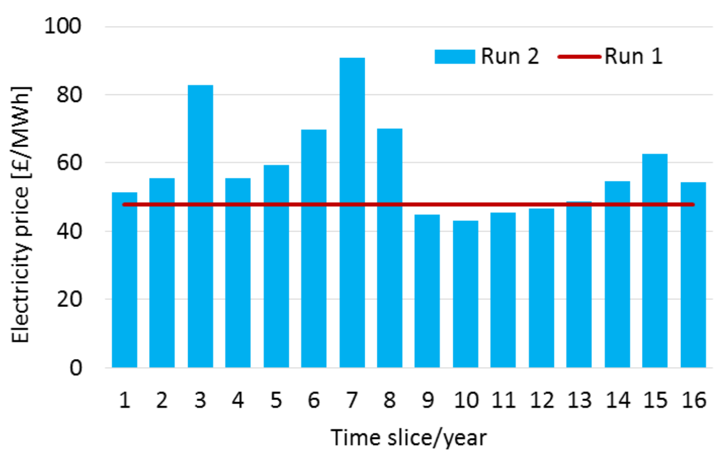

Figure 6. Electricity price profiles for RTN Runs 1 and 2

Second RTN run

The optimised hydrogen production capacity mix determined in the second RTN run using the updated power prices from Figure 6 the optimised hydrogen production capacity mix determined in the second run of RTN is shown in the right-hand side of Figure 4. The greatest impact of the change in electricity prices is the reduction of capacity and output of low-efficient electrolyser and a consequent increase in capacities of all other hydrogen sources (biomass gasification, ATR, SMR and more efficient electrolysers). For instance, the SMR capacity doubles from 35 GW to 70 GW. This obviously occurs as a consequence of higher electricity prices in those time slices when low-efficient electrolysers are used as peak sources of hydrogen. To illustrate this more clearly, Figure 7 compares hydrogen output levels across different technologies and across time slices for Runs 1 and 2.

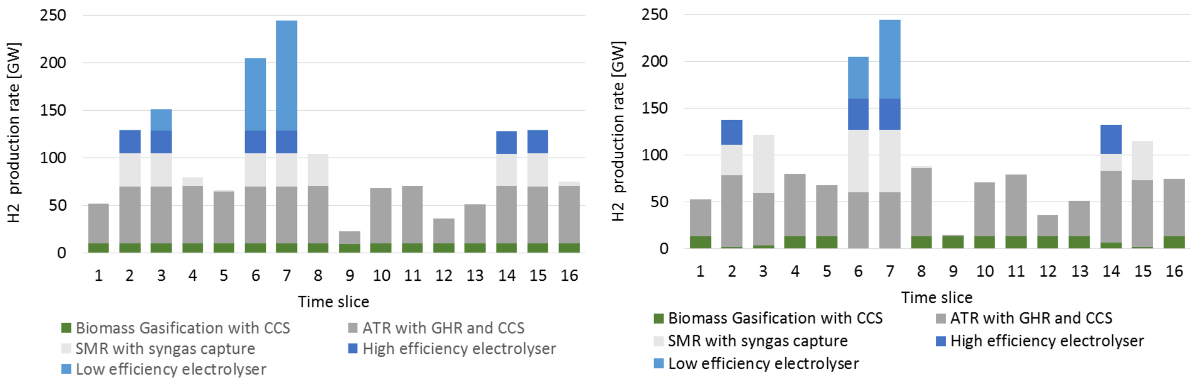

Figure 7. Comparison of hydrogen output levels across technologies between RTN Run 1 (left) and Run 2 (right)

In Run 2 the output of less efficient electrolysers in time slices 6 and 7 is significantly reduced, which is compensated by higher output of SMR and more efficient electrolysers. High efficiency electrolysers are still operated throughout the day but not during evening peaks. Biomass gasification output also drops or even becomes zero during those time slices when electricity prices are the highest, which follows from the fact that this technology is assumed to use some electricity alongside biomass to produce hydrogen. Its higher capacity is therefore used more intensely during time slices with moderate power price levels. Larger amounts of hydrogen are stored in the intraday cavern during the night and day periods to be retrieved for the evening peak, thus avoiding high electricity costs. Nevertheless, the total annualised cost of designing and operating the energy system only changes by less than 0.1% between Runs 1 and 2.

CONCLUSION

This paper has proposed an approach for soft-linking two energy system models, RTN and WeSIM, both with their specified strengths in order to study the decarbonisation of heat supply in the UK by 2050. This multi-model approach allowed for a technology-rich representation of hydrogen production, storage and transport options with high spatial granularity, while at the same time validating the proposed solution using an electricity system model with high temporal resolution and high level of technical detail.

Initial results of iterating between the two models indicate that their integration can improve the cost-effectiveness of the solution by providing RTN with a more refined estimate of electricity prices from WeSIM, which is able to capture specific features of low-carbon electricity systems and how these translate into prices that are input into RTN. With time-differentiated electricity prices obtained based on hourly marginal power prices from WeSIM the solution proposed by RTN relies less on the output of inefficient electrolysers during periods of high hydrogen demand (which also coincide with periods of high electricity prices) than in the case with constant electricity prices. Lower electrolyser output is compensated by higher capacity and output of more efficient (but more capital-intensive) electrolysers, ATR, SMR and biomass gasification plants.

Note that the emphasis of this paper was not so much on offering quantitative evidence on the most cost-efficient pathway for heat decarbonisation in the UK, but rather on establishing a method for soft-linking and exchanging data between the two models. The quantitative outputs presented here are affected by the input assumptions made, in particular those regarding the cost of end-use low-carbon heating technologies. A significant volume of sensitivity analysis and further testing will be required in order to provide robust answers on cost-efficient pathways for heat decarbonisation.

Further research in this area will focus on automating the iteration process between the two models, expanding the model scope to include a refined set of technologies for heating and hydrogen, considering the evolution of low-carbon heating between today and 2050 rather than just the endpoint.

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