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Whole-Systems Modelling of Alternatives for Future Domestic Transport

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Abstract

Two alternatives for future domestic transport, powered by renewable wind energy, were compared from a whole-systems point of view using a mixed-integer linear programming model that accounts for the pathways from the primary energy source to the end use. The model simultaneously determines the number, size and location of conversion and storage technologies and the structure of the transmission network, as well as their hourly operation over an entire year. The integrated wind-electricity-hydrogen network presented in Samsatli et al., 2015 (for hydrogen fuel cell vehicles only) was extended to include grid-scale batteries and electricity demands from electric cars, accounting for the aggregate charge state of the vehicles' batteries. Two cases were considered: one where the electric vehicle batteries could only be charged overnight and one where some of the vehicles could also be charged in the afternoon (e.g. while the owners are at work). The former case results in a more expensive network due to the grid-scale battery storage required; both cases are cheaper than satisfying transport demand using fuel cell vehicles mainly because of the much higher cost of the hydrogen distribution network.

Keywords: MILP; electric and hydrogen vehicles; energy storage; transmission and distribution; renewable energy networks; power to gas

1. Introduction

The transport sector, which still relies almost exclusively on oil, is a major contributor to GHG emissions and the most challenging sector to decarbonise. Twenty percent of the emissions in Great Britain (GB) are due to domestic transport and decarbonising this sector is the main driver behind the development of electric and fuel cell vehicles. Although this reduces the local emission levels, the electricity or hydrogen must be generated from low-carbon and renewable sources in order to make a significant contribution to meeting energy and emissions targets. Opportunely, GB has vast and diverse sources of renewable energy, especially wind, which is considered to be the best in Europe (Department of Energy and Climate Change, 2011). Converting the wind energy to either electricity or hydrogen that can power electric or fuel cell vehicles results in very low emissions.

In this paper, the two alternatives for future domestic transport were compared from a whole-systems point of view, based on their economic performance, using a mathematical model that accounts for the pathways from primary energy sources to the end use. The network comprises technologies that convert one energy resource to another, such as wind turbines and electrolyzers and fuel cells to interconvert electricity and hydrogen; electricity and hydrogen storage; electricity transmission networks and hydrogen pipelines; and the electric cars and fuel cell vehicles themselves. Storage and transport technologies are the key-enabling elements of the system because of the intermittent and distributed nature of wind availability and demands.

2. Problem statement and model description

The design and operation of the integrated wind-hydrogen-electricity networks were determined using the spatio-temporal mixed integer linear programming (MILP) model, STeMES, the full mathematical formulation of which was presented in Samsatli and Samsatli (2015). STeMES can represent whole-energy systems with spatially-distributed resources and technologies and a temporal resolution that is sufficiently fine to account for the intermittency of wind and the dynamics of energy storage. The problems solved here are briefly summarised as follows:

Given:

- The hourly domestic transport demand at different locations
- The hourly availability of wind power at different locations
- Efficiency, capital and operating costs etc. of each technology

Determine:

- The optimal number, size and location of each technology
- The structure and hourly operation of the H₂ and electricity networks
- The hourly operation of each technology

Subject to:

- The available land area for the wind turbines
- Satisfying the transport demand in all locations at all times

Objective:

- Minimise total network costs

The model is based on the Resource-Technology Network (RTN) representation, where resources represent energy or material states (e.g. electricity and hydrogen) and technologies represent facilities that are able to convert one set of states to another (conversion technologies), move a resource from one location to another (transport technologies) or store a resource (storage technologies). Space is represented by dividing the region of interest into a number of zones and allowing infrastructure connections between them. It is a dynamic model, in order to model storage, with a non-uniform hierarchical time decomposition: h for hourly intervals, d for day types and t for seasons. The key constraint is the resource balance:

$$U_{rzht} + M_{rzht} + P_{rzht} + Q_{rzht} + S_{rzht} \geq D_{rzht} + X_{rzht} \quad (1)$$

which states that the sum of the amount of available resource r utilised in zone z at time (h, d, t) , U_{rzht} , the amount imported, M_{rzht} , the net amount produced by conversion technologies, P_{rzht} , the net inflow from other zones, Q_{rzht} , and the utilisation from storage facilities, S_{rzht} , must balance the demands, D_{rzht} , and the amount exported, X_{rzht} . The inequality aids feasibility of the problem. The full mathematical formulation, adapted for integrated wind-hydrogen-electricity networks, is given in our earlier work (Samsatli et al., 2015).

3. Network structure

The RTN presented in Samsatli et al. (2015) was extended to include electrochemical storage devices and the demand for electricity from electric cars. The main characteristics of the electrochemical storage devices are given in Table 1, all of which are assumed to have a lifespan of 10000 cycles (Carnegie et al., 2013), which is longer than the planning horizon considered in this paper. As shown in Figure 1, wind turbines may be sited in each zone, in which case they generate electricity (up to the available wind capacity, at any given time). The electricity can then be used directly to power electric vehicles (via substations to convert to the appropriate voltage) or can be stored in electrochemical

batteries. Excess production of electricity in one zone may also be transported to a neighbouring zone via a number of transmission lines. The alternative method for satisfying transport demand is by hydrogen-powered fuel cell vehicles. Electricity is converted to hydrogen using electrolyzers and the resulting high-pressure H₂ can either be stored (in underground caverns or pressurised containers) or expanded to the lower pressure required for transmission and distribution to fuelling stations (also generating some electricity). Hydrogen can also be converted back to electricity via stationary fuel cells.

Table 1. Battery storage technologies considered in the case studies, estimated from Carnegie et al. (2013).

Battery type	Max. capacity (MWh)	Charging rate (MW)	Discharge rate (MW)	Round trip efficiency (%)	Unit capital cost (£M)	Unit O&M costs (£k/yr)
Lead-Acid	400	100	100	88	162	3.24
Li-ion	25	25	25	90	79.05	1.58
Na-S	300	50	50	75	96.3	1.93
Vanadium redox	250	50	50	70	102	2.04
Zn/Br redox	250	50	50	60	48	0.96

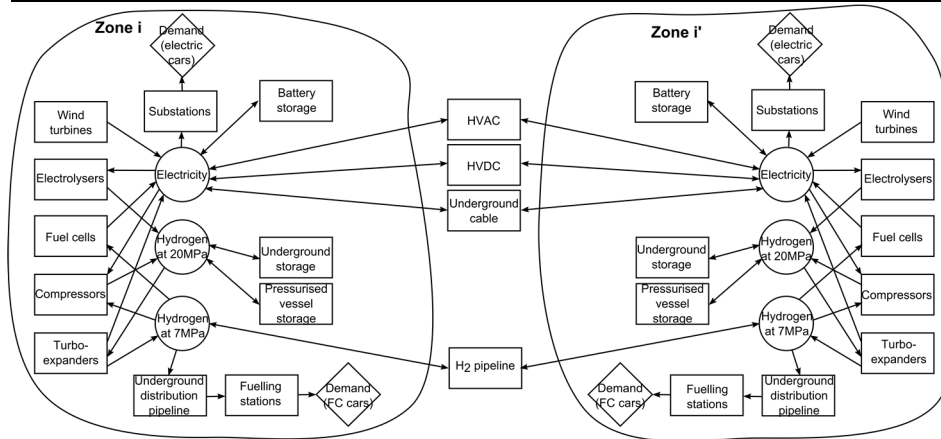


Figure 1. Superstructure of the network of conversion, storage and transmission technologies connecting 2 zones.

Since all of the demands in each zone have to be satisfied, the design and operation of the distribution technologies is the same for any configuration of the rest of network. For this reason, and also to reduce the computational burden of the model, the distribution network was assumed to be independent of the decisions made at the transmission level, i.e. its cost is just a constant in the objective function. A detailed calculation of the cost for distribution of hydrogen was presented in Samsatli et al. (2015), in which the number of fuelling stations and the total distribution distance from the centre of demand (where the zone-to-zone transmission of hydrogen was assumed to take place) to all points in the zone were calculated from the demand density at the 1 km level. Assuming that additional capacity in the electricity distribution network will need to be installed to support the wide-scale use of electric vehicles, the same approach can be used to obtain the cost of electricity distribution, which was estimated to be £793M/yr, assuming that 240 MVA primary substations are located at the centre of demand to convert electricity from 400 kV down to 132 kV, with a unit cost of £2.5M; depending on the demands, a number of 30 MVA secondary substations to convert electricity from 132 kV to 11 kV, with a unit cost of £0.31M; and the 11 kV electricity cable costs £73k/km. These values were

estimated from Parsons Brinckerhoff (2013) and IEA ETSAP (2014). A further 10% was added to the cost to account for the pole transformers that convert electricity from 11 kV to the voltage required by the cars.

If both electric cars and fuel cell vehicles are present in any of the zones, then both networks for electricity and hydrogen distribution may be required in all zones. This ensures that the vehicles can be refuelled or recharged if they are driven between different zones. Therefore, the full cost (whole of GB) of the electricity distribution network is incurred if at least one electric vehicle is in use; and for the hydrogen distribution network. As shown in Figure 3, all of the transport demand is satisfied through electric cars. The electricity generated by the wind turbines is used directly to satisfy the demand, i.e. there are no conversion technologies selected. The transmission network is larger than in the hydrogen case (Samsatli et al., 2015) and electricity storage, in the form of Zn/Br batteries, is required. Most of GB is connected by overhead transmission lines; wind turbines are located throughout GB apart from the Midlands, South Wales and Northern Scotland; storage technologies are installed in zones that do not contain wind turbines. The annualised¹ cost of the optimised network is £4,855M/yr plus distribution costs of £793M/yr, resulting in a total cost of £5,648M/yr (cf. £21,820M/yr for fuel cell cars).

4. Electric vehicles as temporary storage devices

In the previous section, demand for electricity from electric vehicles was satisfied directly from the electricity generated by the wind farms. However, the demand profiles are based on the data from the Department for Transport (2014), who provide the level of road activity as a function of time of day, day of week and month: i.e., this is directly related to the demand for road transport. The actual demand for electricity cannot be the same as these profiles because the electric vehicles usually cannot be charged while they are being driven. The formulation must therefore be extended to model the aggregate charge state of all electric vehicles in each zone, which can only be recharged when the vehicles are not being driven. Note that the earlier approach was acceptable for hydrogen fuel cell vehicles because demand for fuel at the pumps is more closely linked to the number of vehicles on the road. Ideally, the actual demands at the fuelling stations would

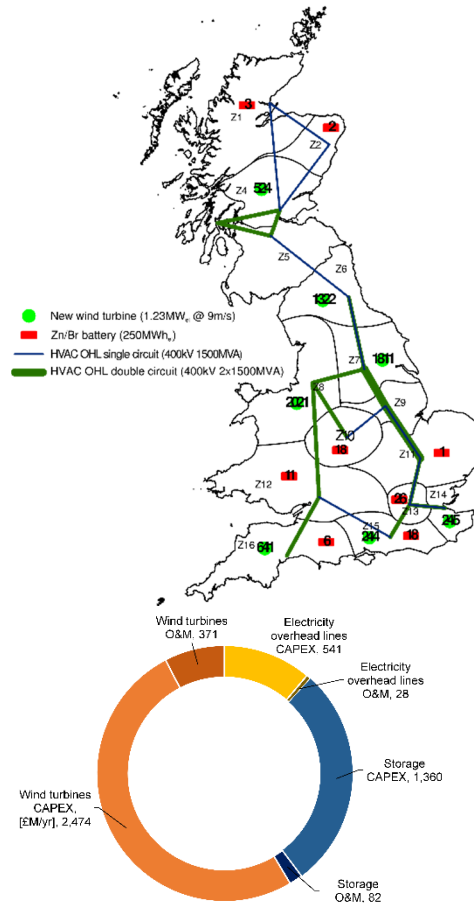


Figure 3. Optimal network structure and breakdown of cost.

¹ A capital charge factor (of 3 in this study) is used to annualise the capital cost.

have been used but these data were not available.

The electric vehicles are modelled as a special type of storage device so that the demand for electricity from the electric vehicles *can only be satisfied directly from its inventory*. (Therefore the demands from electric vehicles must not be included in the general electricity demands applied in the resource balance.) The storage constraints (Eqs. 23–25 in Samsatli et al., 2015) for electric vehicle batteries are therefore modified to be:

$$I_{szhdt} = n_h^{\text{hd}} \left[\sum_r (\mathcal{S}_{szhdt}^{\text{put}} \sigma_{sr,\text{dst}}^{\text{put}} + \mathcal{S}_{szhdt}^{\text{hold}} \sigma_{sr,\text{src}}^{\text{hold}} + \mathcal{S}_{szhdt}^{\text{get}} \sigma_{sr,\text{src}}^{\text{get}}) - D_{zhdt}^{\text{EV}} \right],$$

$s = \text{"Bat-EV"}$ (2)

$$\mathcal{S}_{szhdt}^{\text{put}} \leq N_z^{\text{EV}} s_s^{\text{put,max}} f_{zhdt}, \quad s = \text{"Bat-EV"} \quad (3)$$

$$\mathcal{S}_{szhdt}^{\text{get}} \leq N_z^{\text{EV}} s_s^{\text{get,max}} g_{zhdt}, \quad s = \text{"Bat-EV"} \quad (4)$$

In Eq. (2) the demand for electricity due to electric vehicles, D_{zhdt}^{EV} , is taken directly from the inventory, I_{szhdt} , of the electric vehicle batteries ($s = \text{"Bat-EV"}$) – this is the on-the-road demand. The $\mathcal{S}_{szhdt}^{\text{put}}$ variables represent the rate at which the batteries are charged, which is restricted (Eq. (3)) by the maximum charging rate, $s_s^{\text{put,max}}$, of a single battery (in this study, assumed to be a quick-charging battery, which fully charges in half an hour) multiplied by the number of vehicles in each zone, N_z^{EV} , and the fraction of vehicles plugged in to be charged, f_{zhdt} . When the electric vehicles are stationary and plugged in, the batteries may also be used as temporary storage to balance other electrical loads (policy permitting) but the batteries must always be sufficiently charged to satisfy the demands for road transport. The rate of withdrawal of electricity from the batteries is similarly restricted (Eq. (4)) by the maximum discharge rate, $s_s^{\text{get,max}}$, and the parameter g_{zhdt} , which is the fraction of vehicles plugged in and available for load balancing. g_{zhdt} must always be less than or equal to f_{zhdt} but will typically be strictly less than f_{zhdt} . In particular, if $g_{zhdt} = 0$ then no electric vehicle batteries may be used for balancing of other electrical loads. $\sigma_{sr,\text{dst}}^{\text{put}}$, $\sigma_{sr,\text{src}}^{\text{hold}}$ and $\sigma_{sr,\text{src}}^{\text{get}}$ are related to the efficiencies of charging, holding charge and discharging the batteries. n_h^{hd} is the length of hourly time interval h . These are explained in full detail in Samsatli et al., 2015.

Two cases were considered: one where the electric vehicles can only be charged overnight and another where a moderate fraction (one quarter) of the electric vehicles may also be plugged in while their owners are at work. These scenarios are defined by setting specific profiles for the f_{zhdt} and g_{zhdt} parameters, both of which are functions of hour, day type and season. In both cases, the charge state of the vehicles must not fall below 25% of their capacity. Figure 4 shows the network structure for both cases. In the first case, where the vehicles can only be charged overnight, grid-scale battery storage is required to supplement the wind-generated electricity when the electric vehicles must be charged (Figure 4a). When more flexible charging patterns are allowed in case 2 (Figure 4b) the grid-scale batteries are no longer required due to the charging of some batteries being shifted from the night to the afternoon. The total cost of each network is £15,749M/yr and £6,965M/yr for case 1 and 2, respectively; the cost of the batteries required in case 1 is £6,207M/yr.

5. Conclusion

The integrated networks for wind, electricity and hydrogen, presented in Samsatli et al. (2015), that satisfy all of the demands of the GB domestic transport sector were extended to include electric vehicles and grid-scale electricity storage in the form of electrochemical batteries in order to compare the overall efficiency of converting wind to electricity-powered transport with that of hydrogen fuel cell vehicles.

The results indicate that it is much cheaper to satisfy the UK domestic transport demand by supplying electric vehicles with wind-generated electricity than by converting this electricity to hydrogen for use in fuel cell vehicles. This is mainly because the hydrogen distribution network is much more expensive. The network depends strongly on when the electric vehicles may be charged: if charging takes place only overnight, then the transmission network is smaller but a large number of grid-scale Zn/Br batteries are required, making the cost of the network much greater than when some of the vehicles can be charged while their owners are at work, which results in a larger distribution network but requires no grid-scale storage. Providing facilities for more vehicles to charge at any time of the day allows the wind power to be utilised whenever it is available and avoids the need to invest in expensive grid-scale batteries.

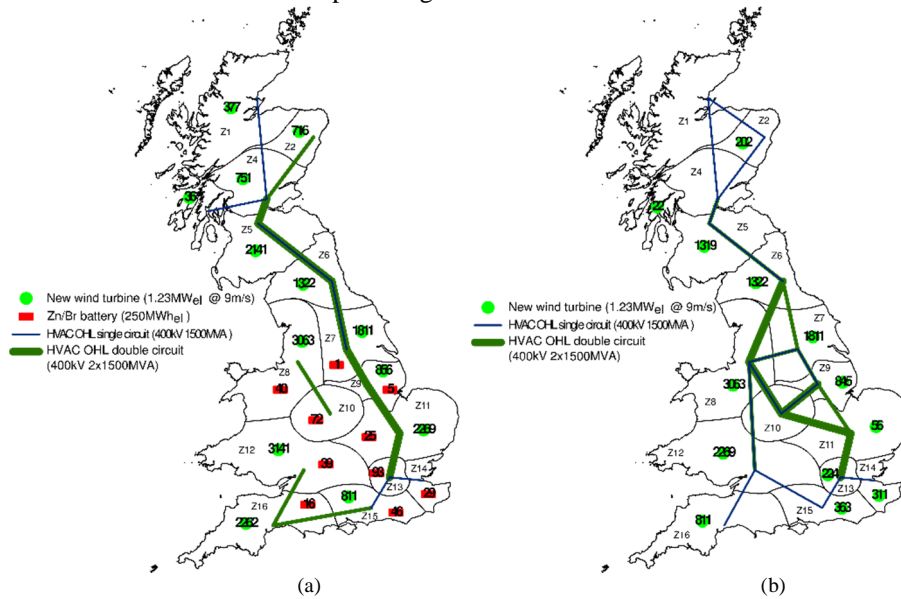


Figure 4. Network structure (a) electric vehicles can only be charged overnight and (b) when some of the electric vehicles can also be charged in the afternoon.

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