A THOUSAND FLOWERS BLOOM: ENERGY ECONOMIC MODELLING OF MICROGENERATION-DENSE FUTURES FOR THE UK

Francis G. N. Li[a*]
[a] UCL Energy Institute, University College London (UCL), WC1H 0NN, United Kingdom
[*]corresponding author: Francis.Li@ucl.ac.uk

ABSTRACT

Transition pathways to a sustainable energy future depend not only on specific physical and technical factors but are also influenced by social, political and economic considerations. The UK electricity system has evolved under a mixture of government and market led regimes, and is dominated today by large-scale central generators. One possible future transition could see the emergence of a more distributed system with an increased reliance on microgeneration and community-scale energy technologies. Several UK techno-economic studies have explored the potential of distributed generation, but have generally not considered the impacts of a microgeneration-dense future on other economic sectors. ESME is a technology rich partial equilibrium model of the UK energy system. As part of its broad portfolio of energy technologies, ESME includes a range of microgeneration systems, including micro-CHP, micro-wind, building-integrated photovoltaics, and distributed energy storage.

This paper explores the implications of a microgeneration-dense future, in a scenario narrative called *Thousand Flowers*. The provision of electricity and heat in buildings, as well as wider system interactions with the transport and industry sectors are explored using ESME. Model outputs are compared against an alternative scenario, *Central Coordination*, which follows a future technology pathway that is more dependent on centralised low carbon generators such as nuclear power plants. The results show significant total system cost differentials between scenarios, and that microgeneration deployment at scale in a UK context could have important implications for the use of bioenergy and the future role of the gas network. The study illustrates how some microgenerators, such as micro-CHP, could face different resource and marginal cost pressures through time, and demonstrates the benefits of adopting a wider system perspective when analyzing the value of microgeneration to the future energy system.

Keywords: Microgeneration, modelling, policy, economics, energy systems

INTRODUCTION

The deep decarbonization of energy systems

Global efforts to limit the potentially damaging effects of anthropogenic climate change [1] have begun to take the form of national level energy strategies for emissions mitigation, such as those developed for the United States [2], the United Kingdom [3], Japan [4], and others. The decarbonization pathways which are available to different countries are influenced by technical and physical factors, such as national resource availability, the design and condition of their existing energy conversion and distribution systems, the structure of energy demand in their economies, and the availability of energy resources. Empirical observation of past technological transitions suggests that shifts in national energy systems are heavily influenced by social, political and economic factors, as well as the actions of key stakeholders [5–7]. If the past is any guide to the future, then the direction of future energy transitions will be influenced by political ambition, the perceived costs of transition, social attitudes towards new technologies and lifestyles, and the structure of institutional and market frameworks.

Decarbonization in UK energy policy

The political ambition to develop a framework for climate mitigation has been high in the UK, which was the first country to introduce a legally binding requirement to decarbonize its economy. The legislated long-term target, introduced in 2008, is for the country to achieve an 80% reduction on 1990 levels of greenhouse gas (GHG) emissions by 2050 [8]. Since committing to this target, energy research in the UK has focused on how to achieve climate targets while also balancing this goal against other key policy objectives, including energy security and energy affordability [9]. Technological pathway analysis indicates that the least cost approaches for transforming the energy system in the UK all involve the rapid and early decarbonization of electricity supply as a first step, which in turn unlocks mitigation options for buildings and transport through the electrification of these sectors [3,10,11].

Significant attention is therefore being devoted to exploring how the existing electricity system can be transformed and evaluating which options appear to be the most attractive.

The changes implied by the requirement to decarbonize the power system are likely to be profound, but the specific mixture of technologies to be deployed remains uncertain. The leading candidate generation technologies discussed in key UK policy analyses to date include large-scale fossil thermal or bioenergy combustion power stations fitted with carbon capture and storage (CCS), nuclear power, and large-scale wind energy [12–15]. Despite being incentivised through feed-in tarriff type schemes for electricity and heat [16,17], microgeneration and distributed generators have not featured as major contributors in decarbonization pathway analysis to date, and are expected to play only a minor role in the UK Government's Renewable Energy Action Plan [18] for meeting near-term EU wide targets for 2020 [19].

Microgeneration in the UK energy system

Microgeneration and the community ownership of local energy supply systems have been explored in a UK context through a number of major research consortia. Notable projects include Supergen Highly Distributed Power Systems (HDPS), Supergen Highly Distributed Energy Futures (HiDEF) and Realising Transition Pathways (RTP) [20,21]. Past work has explored the technical implications of deploying high volumes of microgeneration on local distribution networks [22–28], the potential contribution of distributed generation to system stability and energy security [29,30], and performed microeconomic analyses of microgrid operation [31–33]. Other areas of investigation have included exploring barriers to the adoption of distributed energy technologies [34–36], developing planning and evaluation frameworks for microgeneration [37–40], and scoping of regulatory reforms that might be used for moving to a "smarter" grid which could incorporate additional distributed generation [41,42]. Finally, the deployment of microgeneration technologies has played a significant role in studies focusing on the residential building stock [43–52] and studies focusing on heat demand more generally [53,54].

Wider system impacts of microgeneration

A review of the literature suggests that the UK energy research community has to date tended to focus on exploring the deployment of microgeneration and distributed energy systems in two specific areas: residential buildings and electricity networks. This relatively narrow scope has allowed for highly detailed studies of distributed energy systems but limited the conclusions that can be drawn regarding their contribution to national policy targets. For example, a number of UK residential sector decarbonization studies identify that increasing the supply of low carbon energy is key to meeting emissions targets, and recommend that this is achieved through microgeneration deployment, but simulatenously ignore the potential of large-scale generation to also decarbonize [45,51]. Kannan and Strachan's review of UK housing stock models notes that this lack of interaction with the dynamics of the power sector is a common limitation [55].

Past electricity system studies have tended to prioritise providing deep insights, but arguably at the expense of breadth. The UK Government's 2006 microgeneration strategy [56] suggested that microgeneration could provide 30-40% of the UK's electricity demand but based this on a logistic curve technology diffusion model that only contained microgeneration technologies. Their analysis did not explicitly represent how the marginal costs and performance of alternatives, such as large-scale low carbon energy supply, might change in future [57], which prohibited any exploration of the future trade-offs between distributed and centralised system typologies. The UK Government has also in the past relied on models which assess only the electrical component of combined heat and power (CHP) plant but not the heat produced [58]. The core scenarios used for the Supergen HDPS project have been amongst the most detailed produced to date [59], and explore futures with up to 40-50% of energy supply from decentralised technologies. However, the scenarios do not consider the wider impacts of such a highly distributed power system on other sectors, such as industrial energy use or transportation.

In summary, policy analyses of distributed energy futures in the UK energy system have not yet addressed the economy-wide aspects of such transitions. This conclusion is corroborated in a recent review by Allan [60]. The wider question of the value of microgeneration to an energy system in transition remains open. Past studies have employed assessment methods that include only incomplete or highly abstracted depictions of the wider energy system, leading to highly conditional conclusions regarding the feasibility of microgeneration-dense futures, their relative costs and their national impacts. There appear to have been no long-term economic analyses to date of the relative costs of an energy system with a high penetration of microgeneration technologies, whether it would achieve the UK's 2050 environmental targets, and what this choice of power generation technology would mean for other economic sectors such as industry, transport, and primary resources.

Aims and objectives

The Realising Transition Pathways project is an interdisciplinary study of the UK's transition towards a decarbonized energy system, which employs three core scenario narratives, entitled *Market Rules*, *Central Coordination*, and *Thousand Flowers*. In all three cases, the UK energy system undergoes a low carbon transition, but the technical detail of the future energy system and the market and governance arrangements that bring about the transformation are different. In *Market Rules* the UK's future low carbon transition is delivered by an oligopoly of powerful energy companies operating under the influence of a high carbon tax. In *Central Coordination* the UK government establishes a Strategic Energy Authority which takes on the role of the electricity system architect, issuing central contracts for generation capacity and taking overall responsibility for delivering the transition. In *Thousand Flowers*, a profound shift in social attitudes leads to an upsurge in the community and municipal ownership of energy generation assets, leading to a highly distributed energy future. The rationale and process for developing the pathways, as well as a fuller description of the core narratives themselves can be found in related publications by Foxon et al. [20,61].

This paper assesses the impact of a microgeneration-dense future for the UK electricity system on the wider energy economy. The power sector elements of the Thousand Flowers narrative, which uses a significant level of microgeneration and distributed renewable resources, are implemented in a national decarbonization pathway model that represents the whole energy system. The influence of the highly distributed power generation portfolio on the wider energy economy is assessed in the context of national carbon emission targets. The results are compared and contrasted against a counterfactual model scenario using the power sector from the Central Coordination narrative, which relies mostly on large-scale centralized generation, particularly nuclear power.

METHOD

Energy System Modelling Environment

ESME (the Energy System Modelling Environment) is a national energy pathway optimization model developed by the UK Energy Technologies Institute (ETI) which has been used for several deep decarbonization studies by the ETI themselves [15], UK academia [62], the UK Government's Department of Energy and Climate Change (DECC) [63], and the UK's statutory climate regulatory body, the Committee on Climate Change (CCC) [64]. ESME explicitly represents the buildings, industry, power and transport sectors with a technology and cost database of over 200 technologies. As well as a broad portfolio of large-scale generators, the model includes a range of distributed microgeneration technologies, including micro-CHP, micro-wind, building integrated photovoltaics, as well as different forms of energy storage.

The energy system in ESME is not limited to representing electricity supply and demand. As well as conversion, storage, transmission, distribution, and end-use technologies for electricity, the model also includes a parallel level of infrastructure detail for energy vectors such as liquid fuels, hydrogen, heat, natural gas, bioenergy, waste-to-energy and CO_2 captured from industrial processes and power generation plants. This enables the model to represent complex supply chains such as the conversion of biomass into biogas, liquid biofuels or hydrogen. Energy efficiency measures in the buildings sector are also captured through the use of multiple dwelling types with different levels of thermal performance and suitability for energy retrofitting. In terms of spatial detail, the model is split into 24 regions, with 12 land-based nodes, 9 sea-based nodes and 3 carbon storage nodes. The default temporal resolution for the analysis involves demand and supply matching in 5 diurnal time slices and 2 seasons, as well as additional peak day constraint.

ESME employs a linear programming algorithm to select a portfolio of technologies which will minimize the total system costs incurred from 2010-2050 while also meeting all carbon emissions constraints, not exceeding resources, and ensuring that energy demand and supply are met in all time periods. The total system costs employed in the objective function are discounted using a social discount rate of 3.5%, which is in line with UK Treasury guidelines for environmental assessment [65].

Conceptual approach

The socio-technical narratives for the Thousand Flowers and Central Coordination pathways represent detailed storyline scenarios for the future evolution of the energy system. At the time of writing, the power sector elements for each narrative are the most developed, having been quantified in significant detail in previous publications [66,67].

A detailed interrogation of the Central Coordination narrative has however revealed the "fragile nature of the storyline" when subjected to quantitative cross-examination using multiple models and proposed that an iterative process be used to further explore the development of the pathways [68]. Future publications from the consortium are therefore likely to elaborate further on issues such as energy efficiency and demand side response as the pathway narratives continue to be developed.

The analysis presented here seeks to contribute to this process by undertaking a normative assessment of how the wider UK energy economy might react to the generation capacity portfolios from the Thousand Flowers and Central Coordination pathways when employing neoclassical economic assumptions about resource allocation and presented with the requirement to meet the UK's 2050 emissions targets. The use of a whole economy energy system optimization model (ESOM) for assessing pathway compliance with UK 2050 targets as well as the implications for primary resources such as natural gas and bioenergy has yet to be explored to date by the consortium.

Model inputs

The generation capacity portfolios from the Thousand Flowers and Central Coordination storylines were deterministically replicated in ESME v3.4 for the 2030 and 2050 system states through the use of different build rate constraints. Figure 1 illustrates the 2050 power generation portfolios for each narrative, which are radically different. Thousand Flowers employs mass deployment of renewable CHP and solar photovoltaics, whereas Central Coordination is more geared towards nuclear energy and fossil thermal power stations with carbon capture and storage (CCS). Solar energy in the Central Coordination case is represented in ESME using large-scale ground mounted photovoltaics (PV), while in the Thousand Flowers case the solar capacity is met using micro-scale PV. In the Central Coordination case, onshore wind is provided completely by large-scale turbines, while in the Thousand Flowers case, both micro-scale wind and large turbines are used.

Renewable CHP capacity in the Thousand Flowers case is represented using micro-CHP in buildings and distributed biomass CHP supplying community heat networks. Micro-CHP forms an important part of the storyline narrative for Thousand Flowers, but ESME will rarely deploy this technology if left with its standard settings because the default price projections for micro-CHP technology (which are consistent with those found in a detailed review by Staffel and Green [69]), do not render it competitive with conventional gas boilers, even by 2050. To achieve micro-CHP deployment in the model and include this important part of the Thousand Flowers storyline in the model assessment, competition was artificially removed by introducing constraints on gas boiler replacement from 2020 onwards. As will be seen in later in discussion of model results however, micro-CHP deployment does still come under marginal cost pressures from other technologies.

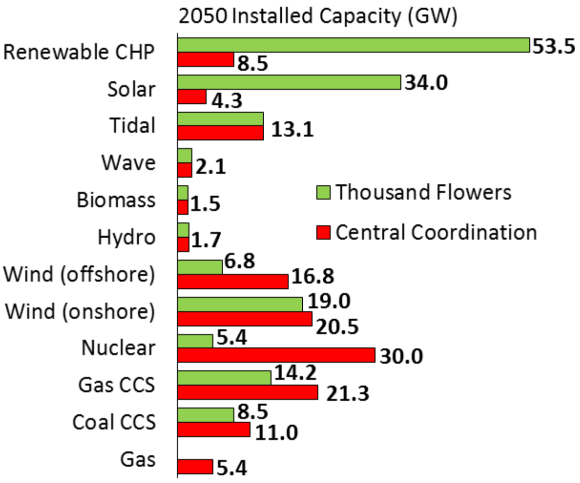

Figure 1: 2050 Generation Portfolios

Having matched these capacity portfolios, the model was left to endogenously determine the choice of other technologies in the buildings, industry, and transport sectors according to its cost minimization formulation. A number of changes to end-use demand were also implemented in order to reflect key elements of the narrative storylines. In the period to 2050, electricity demand from appliances was set to fall by 30% in Thousand Flowers and by 10% in Central Coordination. Industrial output also reduces by 40% in both cases, with reductions occuring mostly in high emitting sectors such as steel manufacturing or chemical processing. Carbon constraints for both scenarios were set to be consistent with an 80% reduction in UK GHG emissions by 2050, implemented as a linear decarbonization trajectory.

Biomass is a resource that is likely to be limited in availability in future, and one which past analyses of decarbonized UK energy systems shows to be in particularly high demand. To reflect the relative scarcity of bioenergy, ESME was run iteratively for each scenario to find solutions that would meet all model constraints using the minimum amount of imported biomass.

RESULTS AND DISCUSSION

Buildings

Figure 2 compares the transitions in technologies used for building space and water heating between scenarios. ESME includes a variety of building heating technologies, including gas, biomass and oil boilers, micro-CHP devices, district heating, electric resistive heating, ground and air source heat pumps, and solar thermal systems. When run with the Central Coordination generation portfolio, ESME endogenously undertakes a large shift away from gas boilers to electric forms of heating (mostly air-to-air heat pumps) in the period 2010-2050, with more than half of heat demand supplied by electricity in 2050.

When run with the Thousand Flowers generation portfolio, ESME demonstrates two distinctive transitions in the same time period. First, gas boilers start to become largely replaced by micro-CHP systems from 2020 onwards (although this is a product of the input settings rather than a truly endogenous shift, as highlighted earlier). Second, district heating and electric heating begin to gain market share and replace micro-CHP from 2040 onwards. By 2050, more than half of residential heat demand is met by district heating, which is ultimately supplied from distributed biomass CHP. This is a direct result of the large proportion of distributed bioenergy CHP mandated by the generation capacity portfolio for Thousand Flowers (see Figure 1).

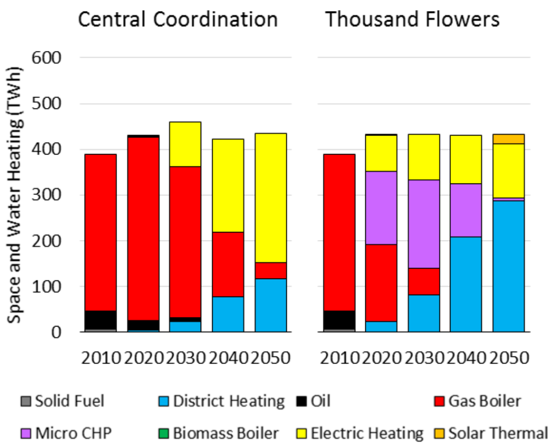

Figure 2: Building heating transitions

Figure 3 compares the thermal performance of the building stock in each model run. ESME defines multiple classes of building, segmented by thermal performance (poor, moderate, good, excellent), urban density (low, medium, high) and whether or not they have been retrofitted with energy efficiency measures (with two levels of improvement possible). Thermal performance also varies by spatial region, reflecting differences in climate between different parts of the country.

Figure 3 illustrates aggregate totals for dwellings from different urban densities and spatial regions. It can be seen that in the Thousand Flowers case, ESME retrofits a lower total number of thermally poor buildings, but also that the retrofits that it does undertake are to a higher standard than those in Central Coordination. ESME also starts to meet demand for new housing in Thousand Flowers during the 2040s using a small fraction of thermally *excellent* buildings, while in the Central Coordination case, the model continues to construct dwellings in this time period to a merely a *good* thermal standard.

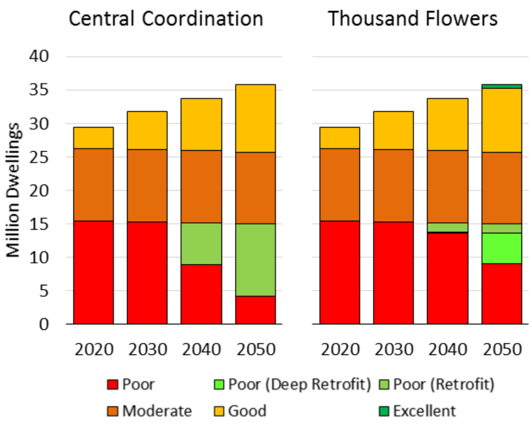

Figure 3: Building stock transitions

The large-scale direct electrification of building heating in the Central Coordination model run is reflected in the total electricity consumption values shown in Figure 4. In the Central Coordination case a significant electrical load associated with biokerosine production is also observed in 2050. This is used for reducing emissions from aviation (discussed below).

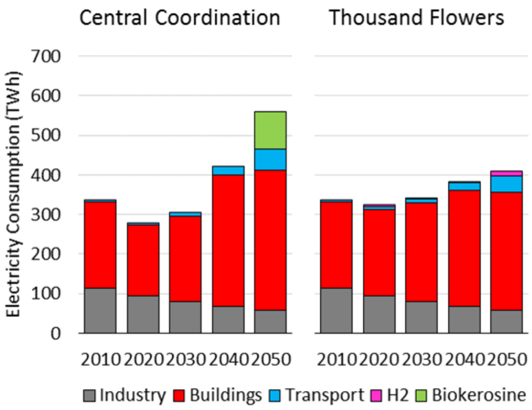

Figure 4: Electricity consumption

Industry

ESME's treatment of industrial energy demand is similar between model runs. Figure 5 shows that in both cases the model reduces its dependence on electricity, coal, and liquid fuels over time. The main distinction between model runs can be found in 2050, where the Central Coordination case meets around 17% of demand from biomass and the Thousand Flowers case uses almost none. The Thousand Flowers case in turn, uses slightly more electricity, liquid fuels, gas, and hydrogen in preference to biomass.

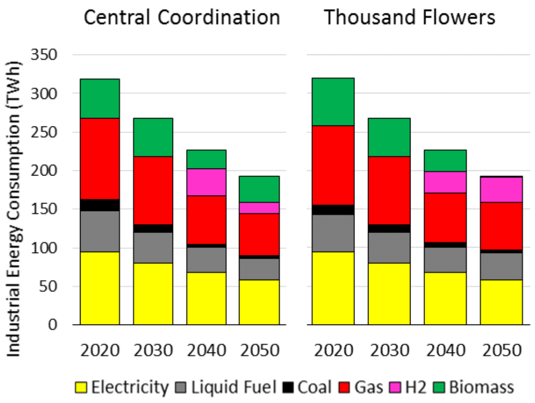

Figure 5: Industrial energy transitions

Transport

Aviation, rail, and maritime transport have limited options for fuel switching in ESME. Endogenous transitions observed in the model runs involve some rail electrification in both scenarios and a large uptake of biokerosine to replace fossil-based aviation jet fuel in the Central Coordination case. Endogenous changes in the road vehicle fleet were significantly different between the Central Coordination and Thousand Flowers cases, as shown below. Figure 6 illustrates different road vehicle technologies by their primary fuel. For clarity, the large number of vehicle types in ESME (passenger cars, freight vehicles, buses etc. including hybrids and dual fuel vehicles) have been aggregated together.

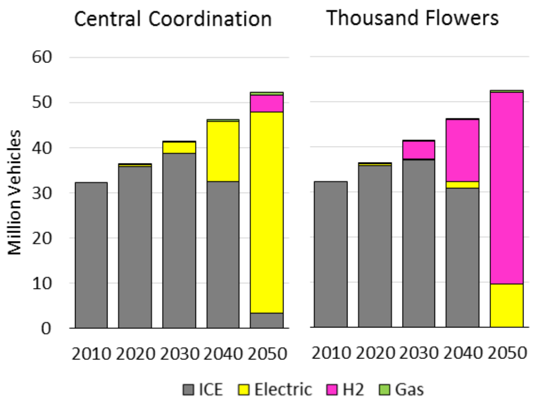

Figure 6: Road vehicle transitions

Using the Central Coordination generation capacity portfolio results in ESME developing a 2050 road vehicle fleet that is largely using alternative fuels, with 85% of vehicles using electric drivetrains. 67% of road vehicles (around 33 million) are plug in hybrid vehicles (PHEVs). Using the Thousand Flowers power system however, results in a 2050 road vehicle fleet that is nearly completely hydrogen based, with almost 90% of vehicles being fuel cell vehicles (FCVs), and most of the remainder using electricity.

The variation in outcomes for the transport sector can be traced to the differences between model runs in terms of their power sector decarbonization trajectory and their use of bioenergy resources. Figure 7 shows that using the electricity generation portfolio for Thousand Flowers in ESME results in the power sector decarbonizing at a slower pace and having a higher residual level of emissions in 2050 when compared to Central Coordination. ESME, unlike some other models, has default settings which explicitly acknowledge that a fraction of future bioenergy production may not be grown and transported with zero emissions i.e. some greenhouse gas (GHG) emissions are still assumed to be released from agricultural processes, transportation of the biomass to its destination etc. The carbon accounting and future sustainability of bioenergy resources have been widely debated in other work [70–72].

As a result of the higher residual emissions from the power sector in the Thousand Flowers case, the model is forced to make carbon savings in other areas to meet the UK's 2050 emissions target. This is achieved through carbon emissions sequestration using bioenergy with carbon capture and storage (CCS) to produce hydrogen. This enables negative emissions accounting and results in the switch from fossil fuel vehicles to hydrogen vehicles in transport.

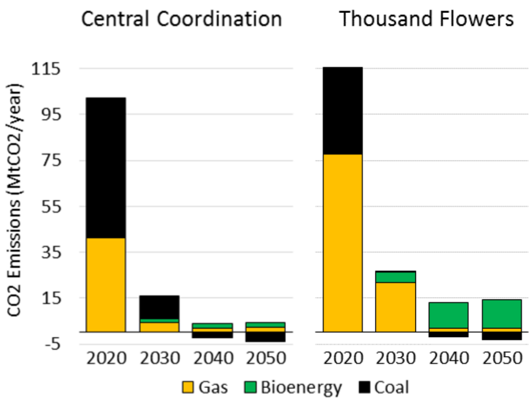

Figure 7: Power sector emissions

Figure 8 shows that nearly all of the bioenergy in the Thousand Flowers case is consumed in distributed CHP plant, with most of the remainder used for manufacturing hydrogen. This hydrogen is mostly used to supply road transport. In the Central Coordination case, heavy bioenergy consumption begins later and is mostly devoted to producing biokerosine for decarbonising air travel. Another interesting difference is that more than half of the hydrogen produced from bioenergy in the Central Coordination case goes to supply industry rather than transport.

The levels of biomass utilised in both model runs are beyond the range of estimates for UK domestic production [73] and imply significant importing. Future UK bioenergy availability is a complex issue and is dependent on assumptions about domestic land use change, global trade patterns for bioenergy, and whether bioenergy will be used in future or not for decarbonization by other countries [74]. The sensitivity of these transition pathways to bioenergy availability is clearly an important area for future investigation.

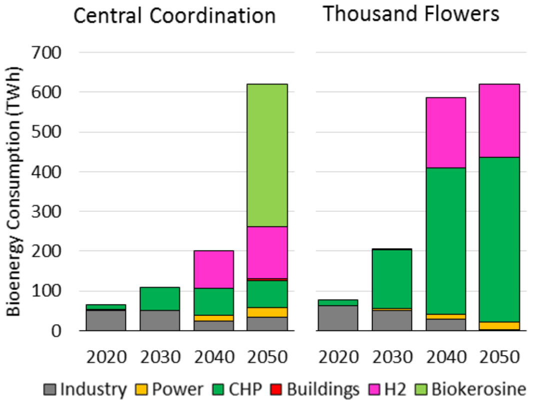

Figure 8: Bioenergy consumption

Gas consumption

Figure 9 shows that the Thousand Flowers case maintains a higher level of gas consumption in 2050 than Central Coordination, and that this difference is due to the use of gas for hydrogen production. The future of the gas network remains an area of major uncertainty in UK energy policy [75], so it is interesting to note that the microgeneration-dense future illustrated here shows a longer-term future for sustained gas use.

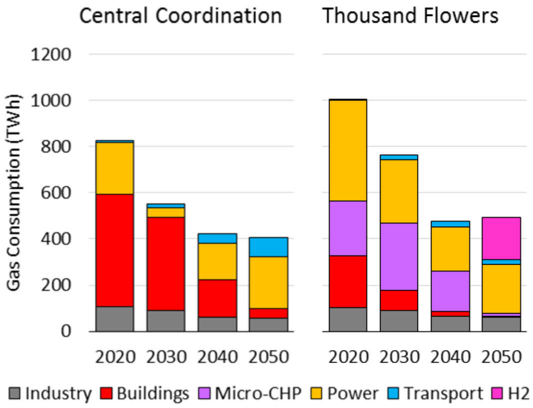

Figure 9: Gas consumption

Total system costs

The total discounted energy system costs over the period 2010-2050 for these model runs are around 20% higher in the Thousand Flowers case than in the Central Coordination case.

CONCLUSIONS

The work presented demonstrates an initial long-term economic analysis of a microgeneration-dense future for the UK energy system which meets UK 2050 climate mitigation targets. Comparison with a counterfactual case based on centralised low carbon generators illustrates that the highly distributed energy future may incur higher transition costs when assessed from a total system perspective and has a different balance of resources; less nuclear fuel, more renewable electricity, and a significantly increased reliance on bioenergy and natural gas.

The results illustrate how different future generation capacity portfolios may result in varing rates of power sector decarbonization, which can have knock-on effects for transitions in other sectors. The results also demonstrate how different microgeneration technologies (such as micro-CHP) may come under different pressures through time, relating to resource availability and the dynamics of marginal cost competition.

In the case of the UK, bioenergy is shown to be a critical resource for hitting ambitious climate targets for 2050, and its influence should be further explored in future publications using these scenario narratives. This work demonstrates the importance of taking a whole systems perspective when exploring the value of microgeneration technologies and their role in national decarbonization pathways.

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