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The implications of a decentralised energy system in the United Kingdom

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ABSTRACT

As the United Kingdom continues to discuss a transition towards a more energy efficient and renewable energy system, decentralised energy is becoming an increasingly mentioned concept. However, decentralised energy remains ill-defined and loosely applied, making it difficult to understand its potential and consequences from a system point of view. This research aims to understand what the implications are of a decentralised energy system for the UK, looking to 2050. First, the notion of decentralised energy is discussed both in social and technical terms, then placed within a Smart Energy Systems context in order to conceptualise a decentralised energy system. This is modelled alongside a centralised energy system scenario and a business as usual scenario, to compare the impacts in terms of structure and performance. This is then used to discuss the further impacts of a decentralised energy system with regards to how the energy system is viewed and organised, what contribution smart energy could bring, and what kind of planning processes would be necessary in a decentralised energy system.

The modelling shows that a decentralised energy system presents a highly cost-effective strategy to decarbonise the energy system. In addition to reducing CO_2 emissions by 11% more than the centralised scenario, the decentralised energy system integrates a fundamentally higher level of intermittent renewables and costs 15 billion euro less per year than the centralised energy system. This is due to the increased connectivity and flexiblity in the decentralised energy system. A trust and coordination game is used as an analogy to show the technical interconnectivity and interdependance of a decentralised energy system has concequences for the way energy is viewed, and the levels of trust, coordination, and regulation necessary in order to sustain such a system. The focus moves from towards investing in infrastructure, redistributing the benefits of a decentralised energy system and planning practices that enable the interconnected nature of the decentralised energy system. The conclusion is a decentralised energy system could provide great benefits in terms of carbon emmisions reduction and cost, but would imply a shift in the way energy is invested in, planned, and regulated. This provides an impetus for further research to discuss in which ways a decentralised energy system could be impemented, and how an energy transition could be achieved.

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1. INTRODUCTION

As Europe and the United Kingdom continue to try and improve their energy systems, decentralised energy is receiving increasing attention. Recent moves such as the Combined Heat and Power Association renaming itself the Association for Decentralised Energy and the Greater London Area's focus and targets for decentralised energy have shown that it is, at least for some, a guiding concept for policy development (ADE, 2015; GLA, 2011). Simultaneously, the Department for Energy and Climate has started discussing community energy, decentralised energy, distributed energy, and a variety of technologies that appear to be related to these concepts (DECC, 2013; DECC, 2014). This is especially interesting in the UK, which traditionally has a centralised system and endemic resistance to local renewables and energy installations 'in my back yard'.

In addition, this has also meant that different interpretations and definitions of what decentralised energy is, and what constitutes a decentralised energy system have become current. This discourse has taken place primarily between NGOs, stakeholders, and in policy documents, but not extensively in academic literature (Greenpeace, 2005; E.ON, 2015; CLG, 2007). Where it has, interpretations differ and delimitations of what decentralised energy is and is not have been difficult (Wolfe, 2008; Woodman and Baker, 2008; Devine-Wright and Wiersma, 2013). A deeper understanding of what decentralised energy is, and what it would mean for the UK if it were to be implemented, is necessary. Both the concept, and the direction of decentralised energy have become relevant to discuss, and understand the merits of.

This comes at the same time that an increasing body of research is investigating the benefits of decentralised heating systems, in the form of energy efficiency and district heating. After the two pre-studies of Heat Roadmap Europe, the optimum level of decentralised heating has been mapped, modelled and discussed for five EU countries, including the UK, in the STRATEGO project (Connolly et al., 2015). The advantage of the approach taken in the Heat Roadmap Europe projects is that it works within a Smart Energy Systems framework, and uses both high resolution localised mapping and a system-based approach to look at the potential that decentralising the heating system has on the energy system at large. The system-based approach allows for a much deeper understanding of the effect the heating system has on the energy system at large and the synergies that occur because of decentralisation, as opposed to focussing on one or several technologies only.

By looking at the UK specifically, the STRATEGO project found that there is a huge potential in decentralising the heating sector in the UK. Reducing heating demands by 40% is likely to be cost optimal, and district heating can optimally be extended to 70% of the buildings. By 2050, heat pumps in more rural, non-district heating areas mean that a decentralised heating and cooling approach could cut carbon dioxide (CO_2) emissions in the heating sector almost in half, reduce primary energy supply (PES) by almost 35%, and cut costs for heating and cooling by almost 15% in comparison to business as usual (BAU) predictions (Connolly et al., 2015). Clearly, decentralisation has huge potential in the heating sector.

The rise of interest in decentralised energy at large, and the specific studies into decentralised heating provide a clear context to see decentralised energy from a system perspective. The combination of these two developments means that it becomes interesting to look at a decentralised energy system as a whole, including both heating and cooling and electricity. In other words;

What are the implications of a decentralised energy system in the United Kingdom, looking towards 2050?

Solving this problem is in effect two-fold: first, it is necessary to create a decentralised energy system, and determine how a decentralised energy system would perform. Secondly, to understand the full implications of a decentralised energy system it is appropriate to analyse what a decentralised energy system would mean for the way the energy system is viewed.

In order to do so, a broad research design will be followed. The first step in answering the question is to discover and explain what centralised and decentralised energy systems are and what makes them so. Chapter 2 (Theories) provides this analysis. This is done by reviewing current understandings, and further developing what decentralised energy means based on the Smart Energy System concept. These technical understandings are combined with the decision making processes and social aspects that add to the socio-technical structures of energy systems and technologies within energy systems. In doing so, a workable understanding is developed of what characteristics a centralised and decentralised system are likely to have.

Then, it is possible to create centralised and decentralised scenarios for the UK to model next to a BAU scenario, and understand what these systems would actually look like, how robust they are, and assess their relative benefits and drawbacks. This allows for an assessment of the initial implication of a decentralised energy system; that it is desirable. Secondly, modelling the centralised and decentralised energy systems allows for a better understanding of how they work, and what aspects of it are likely to underpin its advantages and disadvantages. The way in which the decentralised energy system was built is described in Chapter 3 (Methodology) and the results presented in Chapter 4 (Results). Based on those results, the theoretical understanding will be applied to discuss the technical and conceptual implications, and what they tell us about a decentralised energy system in the UK. This analysis, presented in Chapter 5 (Discussion and conclusion), ventures further into the implications for the way energy systems are understood, organised, and influenced were a decentralised energy system to be implemented by 2050.

Delimiting the research is key in order to ensure that depth is reached in the areas that are focussed on. Firstly, the theoretical understanding, the modelling, and the analysis are very much from a system point of view; this means that while individual technologies are discussed where appropriate, the primary aim is to understand how the system works as a whole. This also means that it is difficult to discuss, in detail, the synergies that arise from a decentralised or centralised system. They can be induced based on the understanding of how the different technologies work, which will be done. However, in the actual results it is only clear that there are synergies which total to a certain amount of costs saved, fuel saved, or renewables integrated. The aim is not to identify which technologies specifically contribute to which synergies and by how much, but rather to understand how the system at large works and how synergetic the system is. This also feeds into the analysis; the implications discussed refer more to the way the system behaves and is seen in society at large, rather than a step by step technology guide of implementing reform.

Secondly, the aim of this report is not to provide a roadmap towards a decentralised energy system by 2050. This research shows that a decentralised energy system, with all its implications, is desirable, and what conditions must likely be met in order for it to exist; but it does not lie out a strategy for change. Policy and planning implications are discussed, because the existence of a decentralised energy system would have a profound impact on the way the energy system is planned. However, implementation, catalysing change, and system transition could not be done justice if discussed in combination with the basic understanding of what a decentralised energy system would look like, as this research aims to do. This is where more research is needed; to understand what would be necessary to move forward and be able to reap the benefits of a decentralised energy system.

2. THEORIES

Understandings of decentralised energy

The concept of decentralised energy is increasingly used, both in academic literature, in policy papers, and by stakeholders, but its understanding and definition remains very fluid and vague (Walker & Devine-Wright, 2008; Walker et al., 2010). Most definitions refer to a specific set of technologies that are seen as representative of an idea; but the concept they represent remains vague. On the one hand, a surprising amount is written about decentralised energy without any or a serious attempt at defining or delimiting, indicating there is a perception of clarity surrounding the issue (e.g. Williams, 2010; Molitor et al., 2011). At the same time, the idea of decentralised energy is used synonymously, blurred with or tied up to distributed energy, community energy, micro grids, micro-generation, energy efficiency, renewability and a variety of other related concepts (Basak et al., 2012; Woodman and Baker, 2008; Devine-Wright and Wiersma, 2013). A more explicit discussion of what the concept or idea of decentralised energy really means to people is necessary in order to be able to clearly define it and construct a decentralised system.

When it comes specifically to decentralised energy in the UK, there are two specific aspects that are invariably mentioned; firstly, decentralised energy seems to include the use of CHP and district heating. Secondly, there is the use of on-site (within the building or property) or near-site generation: photovoltaics (PVs), solar thermal, heat pumps, biomass boilers, micro-CHP, etc.. These two concepts recur almost repetitively. In essence, this means the literature largely describes a decentralised energy system as the implementation of CHP and district heating cooling, and focusses on building-scale (on-site generation) for the remainder. For example; in their outlining of ten key steps toward decentralised energy by Greenpeace UK, 4 key steps concern CHP or waste heat and 3 key steps concern the encouragement of individual-scale technologies (including the mention of micro-turbines) (2005). In essence, decentralised energy means producing one's own energy, and supplementing with district heating where possible.

Government understandings seem to support this general characterisation of decentralised energy. The Department for Communities and Local Government uses the following definition, which is nearly identical to that of distributed energy in the Renewable Energy Strategy:

> *"Energy supply from local renewable and local low-carbon sources (i.e. on-site and near-site, but not remote off-site) usually on a relatively small scale. Decentralised energy is a broad term used to denote a diverse range of technologies, including micro-renewables, which can locally serve an individual building, development or wider community and includes heating and cooling energy." (CLG, 2007)*

This explicitly includes the word community and an example of community-owned wind mills, but other than in the district heating still primarily focusses on individual building technologies. The idea of broadening electricity generation to a non-building scale has (to an extent) made it into the Community Energy Strategy, but the use of the term decentralised energy is notably scarce in this document (DECC, 2014). This would imply that in policy, the concept of decentralised energy is fairly narrow, consisting effectively of building-scale renewables or energy efficient solutions, and

CHP/district heating. Community energy is seen as a form of simultaneous concept; more concerned with the social, ownership, and finance aspects of the technology than understanding it within the wider system. The descriptions of decentralised energy in the policy documents are all very peculiar in that they seem to use the term decentralised as a justification for encouraging certain technologies, rather than the other way around.

The academic literature sometimes follows in this vein, but is sometimes more broadly encompassing. Wolfe explicitly follows the on-site or close nearby delimitation (2008). In a range of decentralised technology descriptions he uses primarily what are defined here as individualistic technologies; production and usage within the boundaries of the property or building, with surpluses and shortages balancing through a (gas or electricity) grid. Heat networks are mentioned, but not discussed. Woodman and Baker, in the same issue of Energy Policy, use a similar definition that includes on-site or close by generation, citing the Renewable Energy Strategy consultation (2008). However, they extend their considerations to the purpose of the use of energy to include the generation of energy into transmission networks, so generation onsite, but potential usage off-site (presumably through something like bidirectional electricity grids). It seems this is done primarily so large- or mid-scale schemes by "large incumbent energy companies" can be included (ibid: 4527). This provides a broader definition, and balances potential (renewable) electricity projects better to the scale of CHP and district heating and cooling. However, it is decisively less clear delimitation regarding what the maximum scale of decentralised energy would be.

It seems the difficulty in delimiting the maximum extent of 'local' and 'near', especially when it comes to electricity conversion, means nearly all confident examples and applications of decentralised energy use a very narrow interpretation. Devine-Wright and Wiersma review the shortcomings of the concepts of community and decentralised energy, focussing on the spatial ambiguity that words like 'local' and 'near' cause (2013). Their work situates decentralised energy very closely to community energy, particularly in recognising that decentralised energy can occur at the neighbourhood level in both the electricity and heating sector. More importantly, by showing that a more sophisticated understanding of decision-making, local appropriation, and the general understanding of 'local' is necessary in order to understand the scope of both community and decentralised energy, it becomes possible to better integrate non-household based actions into decentralised energy thinking. That having been said, their focus is on the organising process and 'instigating actors' of community interventions, so most of the projects are still household or building-scale technologies (or behavioural interventions) deployed in a neighbourhood scheme, or district heating (ibid). This means that while the predominant technologies used were still primarily limited to individualised electricity generation and CHP/district heating, their integration of decentralised energy with community energy adds to the understanding of decentralised energy in a broader sense than merely the implementation of these few technologies.

Combined, these interpretations mean that often CHP and district heating are often the only 'community' scale technologies that are employed within a decentralised approach, which seems both limited and skewed. The implicit question becomes whether there are any other 'community' scale technologies that can be implemented in the (renewable) electricity sector, and if not, what the fundamental differences are between them and CHP – in terms of both locality, decision making processes, and effect on the electricity system at large. This in itself implies having a more sophisticated understanding of what decentralised and centralised energy is, based on the concepts they represent rather than exemplary technologies. In order to better be able to understand and define decentralised from a system point of view, it seems appropriate to step back and look at the understandings of the energy system at large, before ascertaining which technologies can or cannot be considered decentralised.

Smart Energy Systems

There have been several pieces of work that look towards 100% renewable, smart energy systems, which are helpful in building a general understanding of a (smart) energy system. Smart is the new cool: it is widely used to indicate a different, better approach in a huge variety of fields, but is poorly defined. However, as work is being done (especially in light of smart cities), several key characteristics arise. Firstly, there is the idea that as ICT allows for better control, linking and connectivity of systems, the barriers between disciplines and industries can be reduced (Hollands, 2008; Kominos, 2002). This is especially interesting as we explore the synergies between the various elements of the energy sector, such as electricity, transport, and heating. The potential benefits of interconnectivity make it important to focus on both electricity and heating within the energy sector – and keep the energy needs of the transport system in mind. The synergies that smart energy can create, especially in terms of flexibility and energy storage, will be a key characteristic to consider.

Secondly, smart is generally associated with an increased connectivity between the private sector and the public sector. This can be a delicate issue, as some see pro-business environments as the only way to raise capital for further research and development, while others now see the smart label merely as a euphemism for neo-liberal state retrenchment (Hollands, 2008). However, different structures within the UK energy system are likely to require different planning, funding and implementation models (Walker & Devine-Wright, 2008). The argument can also be overturned to imply that if the private sector wants to act, they must have a level of local participation and possibly ensuring local benefits in order to be considered smart. Newer, smarter organisation models can be worth exploring as the energy system is restructured.

The third characteristic involves an element of capitalising on the knowledge, education, consumption patterns and leadership of people in a society (Nam and Pardo, 2011; Shapiro, 2006). Thinking about people and their smart behaviour can be especially interesting when we start considering how change can occur, and what role people as individuals and collectively can have. Additionally, it plays into the idea that rather than individuals making decisions, technology that is able to aggregate and look at the collective may be better placed to fully exploit synergies. The ideas of human capital, collective intelligence and city-wide benefits of a 'smarter' city are especially relevant if it becomes more important to look towards a more diverse and more engaged model of local energy conversion.

Much like the word smart, the term smart energy is loosely used and interpreted by different people and streams of thought. However, through an increasing body of work, often in conjunction with the EnergyPLAN model, a comprehensive Smart Energy Systems concept has been developed. The general principles are summarised and outlined in Connolly et al., but also exemplified in Lund et al., Mathiesen et al., and extensively in Lund's book (2013; 2012; 2015; 2010). Figure 1 overleaf characterises the different resources available, conversion options, and demands that need to be fulfilled in a Smart Energy System as it will be used and applied in this project. In short, the Smart Energy Systems concept can be characterised as maximally renewable, minimising biofuels, with generally a non-nuclear character. The focus of the system is on integrating renewables through system flexibility and storage, without compromising on affordability. The Smart Energy Systems concept has been applied within a variety of different countries, and, because it focusses primarily on the integration of various smart grids, can be used fairly flexibly and adjusted to be optimised within a given context. Because of the socio-technical nature of the energy system, the Smart Energy Systems concept simultaneously recognises the need for the design of business models, policies, and infrastructure in order to be able to achieve the technical integration and optimisation.

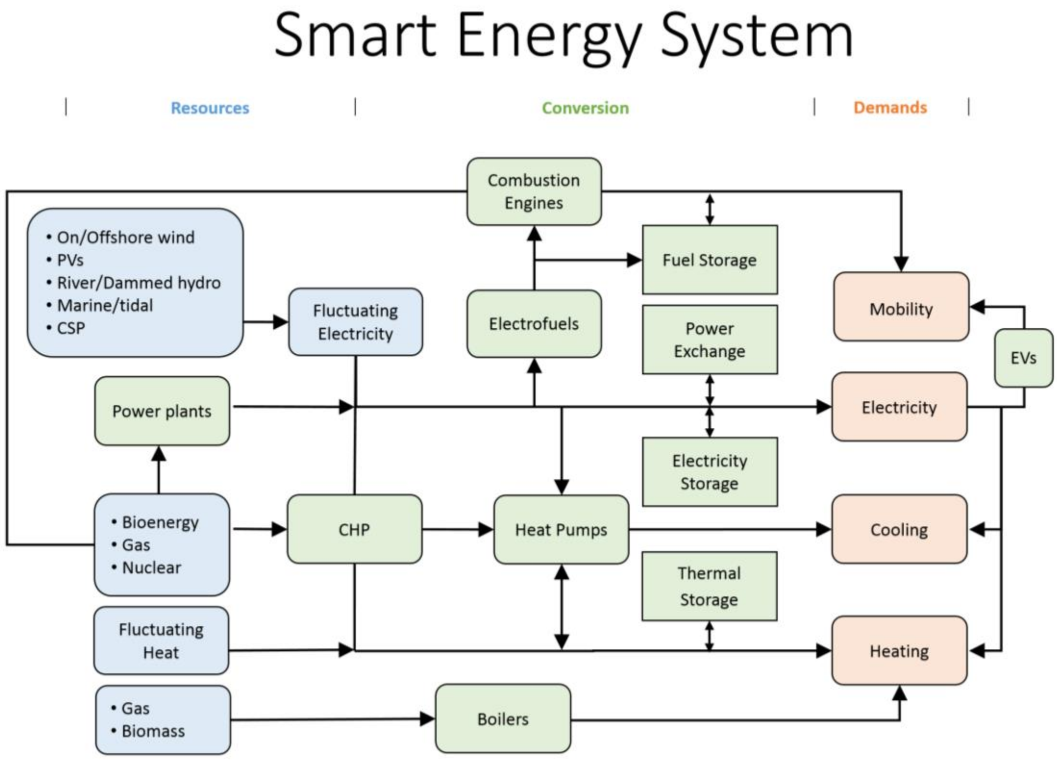

Figure 1: Representation of a smart energy system, including available resources, conversion options, demands, and connectivity between the separate elements.

A key, yet sometimes implicit aspect of the discussion of the Smart Energy System concept is that it is maximally renewable, with a minimal use of biofuels. The reasons for which a renewable energy system would be preferable are in relation to the increased understanding and salience of the effect of fossil fuel CO_2 emissions on the environment and the long-term viability of our wellbeing. The redesigning of systems towards local, renewable energy sources is also increasingly validated by geopolitical concerns, and countries' ambitions to achieve a certain level of energy autarchy and energy supply continuity (Winzer, 2012). While the UK has substantial natural gas reserves it is increasingly gas vulnerable, and the question of energy security emerges with relation to diversified energy sources (Bhattacharyya, 2009; Rogers-Hayden, Hatton and Lorenzoni, 2011). Even on a supra-national level, this has been exemplified by the EU energy stress tests in 2014, and the shaping of the Energy Union this year (EC, 2014; EC, 2015). Lastly, renewable energy is seen as a way to develop local or domestic employment. The underlying principle is that as (proportionally) less money is used on fuel, the full investment costs are reinjected into the economy by local design, construction, etc. and a (fiscal) multiplier effect occurs (Connolly et al., 2013). There has been some UK specific exploratory modelling that explicitly links 'green growth' (or carbon decoupled growth) to investment in green infrastructure and services, specifically linked to community energy projects, activities, and organisations (Jackson and Victor, 2011). In this way, renewables are not only used because of their climate neutrality, but also because of the security and socio-economic externalities that occur.

Biofuels are often an underpinning part of 100% renewable scenarios – especially if transport is considered (Lund, 2010; Mathiesen et al., 2015). Biofuels (whether solid, liquid, or gaseous) function like traditional fuels in many aspects, specifically in the manner in which they are stored, the way they can be transported, and in the way they allow us to choose when and where to burn them, and thus release their energy. Especially in light of an increasingly intermittent renewable system, this is an important characteristic, because the level of control allows biofuels to be an important grid-stabilising source of energy.

However, there is a high opportunity cost to using biofuels in the electricity and heating sector, as they are likely to be much more valuable in the transport sector. Wenzel points to the many transport and industry uses that will require biofuels, and a comparison with available bio resources emphasises the need to –especially in the long term – move away from biofuels in the energy sector (2010). An overview of Figure 1 shows that while there are many alternative fuels and technologies for the former, biofuels seem like the only currently widespread option for the latter sector. In other words, a transition to a Smart Energy System allows for many different possibilities to replace traditional fuels in the electricity and heating sector, but biofuels may (initially) be the only available substitute for the transport sector. This means that in a Smart Energy System, the use of and dependence on biofuels in the electricity and heating sector should be minimised, allowing them to be put to better use in the transport sector.

There is also a sustainability argument to try and minimise the necessity of biofuels. A primary concern with biofuels is the close interaction between biofuel markets and agricultural markets. The expectation is that as crops (or arable lands) are used for biofuel production rather than food production, scarcity will drive up food prices. In addition, high oil prices will mean a greater demand for biofuels. High oil prices also drive up the price for food due to the energy needed for agriculture, exacerbating the problem. Specifically, in light of the volatility of oil and food prices in 2008, there have been an increasing number of calls to coordinate policies aimed at biofuel targets with food security targets (Mandil and Shihab-Eldin, 2010; Rosegrant, 2008). However, more recent reviews consider that the food price spikes of 2008 were not only (or even largely) to blame on an increasing demand for biofuels. The co-dependency of food prices on oil prices, and the structuring of global agricultural markets with regards to subsidies and trade restrictions have a much larger impact on volatile and heightened food prices, although biofuels are not without impact (Ajanovic, 2011; Zilberman et al., 2012). However, the arguments do lay out the concern that biofuels are not necessarily sustainable – specifically when considering the need for (socially and environmentally) sustainable practices in global agriculture.

Additionally, there are concerns that if the biofuel (or substituting alimentation agriculture) is not produced in an already existing excess cropland, the conversion in land use will release sequestered CO_2 from the ground (Searchinger et al., 2008). In other words, the additional land must sequester more GHGs as cropland than it did previously, for there to be an actual net decrease of GHGs in the atmosphere – a period which was found, for an ethanol increase in the U.S., to be around 167 years (ibid). The uncertainty that surrounds the links between increased agriculture, the agricultural systems, and the soil systems provides even more impetus not to be overly reliant on biofuels as a way of decarbonising the energy system, lest they carry their own externalities or do not achieve the goal of decarbonisation. In conclusion, a smart energy system seeks to minimise the use of biofuels, and prioritise them for the transport sector, where they can be put to better use. This results in a need to divert the electricity and heating sectors from biofuels, to the largest extent possible.

The amount of biofuels available in the UK in 2050 is difficult to estimate. The geographical mapping for the future is difficult, in part because the understanding of how forestry and agricultural biomass is currently used is incomplete (Connolly, Hansen and Drysdale, 2015). Their results show reasonable straw potential (primarily in the Midlands, and along the east coast), and relatively high potential for biomass from forestry throughout the UK. However, the results only show a potential of almost 26 TWh/year from biofuels. This means that in addition to sustainability concerns, there are concerns about resources being used to import fuel; these work contrary to the multiplier effect described in the allocation of resources toward (intermittent) renewables.

Nuclear energy

Nuclear energy and its relationship to renewability (and sustainability) is not an easily navigated issue. Lund explicitly points out that through the use of uranium, nuclear is technically not renewable – nor is the exploitation of uranium necessarily sustainable (2010). While uranium gathered from sea water is considered to be "almost inexhaustible", and lower grade sources can be explored, these technologies are by no means mature and per definition not renewable (Adiamantiades and Kessides, 2009: 5156). Nuclear waste storage, especially spent fuel and high-level waste, remains a problem for which the best current solution is literally to put it away and hope it solves itself (ibid). Even before the Fukushima Daiichi disaster in 2011, public concerns about safety were widespread, with the accidents at Three Mile Island and Chernobyl never truly leaving public perception (Adiamantiades and Kessides, 2009; Wittneben, 2012). Nuclear energy remains a dividing issue.

However, before the events in Japan, nuclear energy was experiencing a 'renaissance' (Joskow and Parsons, 2012; Adiamantiades and Kessides, 2009). The ability to generate power in a very traditional, central power plant without the emission of CO_2 explains the appeal of nuclear power as a technology for the future. The low sensitivity to price fluctuations (and avoidance of fossil fuel price fluctuations), the energy security nuclear can bring as a consequence of relatively easily procured and stockpiling uranium, and the avoidance of airborne pollutants (including CO_2) provide for an attractive alternative (Adiamantiades and Kessides, 2009). Generation III reactors are considered a key part of this renaissance (Joskow and Parsons, 2012). Generator IV reactor designs, to which the UK government is a collaborative research agreement signatory, promise radically improved safety, availability, productivity, and cost reductions (Adiamantiades and Kessides, 2009). In addition, boiling water reactors already provide a more flexible, demand-response production patterns. Within the last decade, nuclear interest re-emerged, with several European countries extending the lifetime of their plants and re-considering or overturning their nuclear phase-out policies, turning to nuclear to provide reliable, climate-neutral electricity.

The UK has proven to be one of the countries that has not been discouraged from proliferating their nuclear programme by the catastrophe in Fukushima. Media attention was lower, and in contrast to Germany, the public reaction was nor as emphatic nor as organised (Wittneben, 2012). The decision making processes concerning the replacement of current nuclear reactors does not seem to have been influenced by the Fukushima disaster nor the European mandated stress-tests that resulted: nuclear energy is still seen as a viable way to achieve both climate and energy security goals (Joskow and Parsons, 2012; Rogers-Hayden, Hatton and Lorenzoni, 2011). However, investment consortia have been rattled, but the Government is trying to improve the regulatory framework for nuclear as a non-carbon emitting energy source (ibid). It is impossible to fully predict if Fukushima has impacted the expected pathway, but the indication is that in the UK, nuclear energy is still perceived as a valuable and inomissible part of a potential renewable energy mix.

For this reason it seems unnecessary to exclude nuclear from a smart energy mix, but with the understanding that this is only because of the application to a country that is actively planning to use nuclear as part of a renewable energy mix, and a country where the safety and ethical concerns have been outweighed by the value of base-load, carbon-free energy. However, it does seem imperative to understand to what extent the energy system is reliant on nuclear, and what a potential backlash and phase-out would mean, if this is even possible.

Intermittent renewables

What remains to discuss are the renewable resources in Figure 1. Aside from geothermal energy, they are characterised by their intermittency. Simultaneously, demand patterns fluctuate. As Connolly et al. point out, the primary challenge is to make the system flexible enough to be able to absorb these intermittent energies and be able to provide them (in sufficient quantity) when we demand so (2013). In other words, integrating renewables does not only have a quantity aspect, but also a temporal allocation aspect, ensuring demand and supply overlap both in quantity and in timeliness, while still maintaining grid stability.

The way this is achieved within the Smart Energy System concept is through storage and connectivity. Connectivity involves being able to fuel independent grids gas, electricity, and thermal grids with different sources of energy, and bi-directionally. Crucially, connectivity also means connecting the grids: achieving the integration of sectors that is key for a smart system. This is clear from Figure 1, which shows what technologies are crucial in order to link these infrastructures. Additionally, different forms of storage are necessary, and their use can be enhanced by the connectedness of the system. Especially in the final stages of the system transformation, maintaining grid stability becomes one of the central challenges (Lund et al., 2012). A good regulation system, presumably ICT driven, is imperative to maintain a regulation hierarchy and achieve full connectivity.

In order to illustrate the connectivity of the system (even without the inclusion of the transport sector), consider the hypothetical of a high wind, low electricity demand, low heat demand period, such as during a windy night. Electricity generation from combined heat and power plants (CHPs) is minimised, and electricity from wind turbines is prioritised to use whatever electricity demand does exist. This is only possible if the CHPs are small and flexible enough to be regulated in this way. Excess electricity from wind production is used to power large (or small) scale heat pumps, which convert the electric energy to thermal energy. This can be used for the (low) immediate thermal needs, and then placed in short storage to be used in the morning, when the heating is turned on, everyone wakes up, showers, and thermal demand peaks. A local, decentralised system is necessary for this, in order to be able to store and distribute the heat effectively. Following this, long term thermal storage and electricity storage become options, with the potential for hydrogen energy storage to become available in the future. It is important to note that the opportunity cost is to either provide heat with a separate system (be that a boiler-only thermal or gas grid), and either trade the excess electricity production from the wind (or solar) turbines, or forgo the electricity generation in favour of maintaining grid stability. The connectivity, and flexibility through scale and decentralisation, allows for a higher level of integration of intermittent renewables, if desirable.

There are several aspects of the Smart Energy System that are relevant to consider. Firstly, there is a high likelihood that the technologies considered in this modelling will be fully developed by 2050, in large part because many of them are in use today. This means the scenarios present a trajectory that favours certainty over risk. Electrical storage shows huge potential in high value applications, but is also more uncertain in terms of costs and performance in the long run (Østergaard, 2012). As such, the system prioritises thermal storage over electric storage. This presents a precautionary view: if technological developments do move, which is very possible looking 35 years into the future, the analysis has not overestimated the benefits of a Smart Energy System.

Secondly, CHPs, large scale heat pumps, and district heating are inherently decentralised due to the flexibility that is required of them, and the local nature of heating networks. Centralised large scale power plants (especially nuclear) can maintain a stable base-load, but are not as effective as dealing with fluctuations. While the Smart Energy System excels at integrating fluctuating electricity production, the conversion between electricity and heat (be that directly through heat pumps, or indirectly through reduced CHP production) is likely to perform better in a decentralised system, because it provides more types of connections and connections at different scales; through the combined use of CHP, large-scale heat pumps, and residual heat pump use in rural areas.

The more substantial implication in terms of the socio-technical aspect of an increasingly connected energy system is that as the system becomes more integrated, the externalities of technology choices grow. As the system becomes more interconnected, an action in one part of the system is increasingly likely to have (external) effects on the system that represent costs or benefits to others. This is exactly what creates the synergies of a Smart Energy System, however, it does have implications for how we approach the individual decision making for both the choice of technology and for the use of the technology. This can be a technical challenge, particularly in the system control, which is why ICT can have such a large potential. However, it is also socio-technical challenge, because it will concern the extent to which we are able to internalise the costs and benefits of the system effects, and allow for choices that are optimal not just to the individual but also to the system. Secondly, a smart system may require the relinquishing of individual choices or control over parts of the energy system, which can pose a policy and social challenge.

Capacity and point of conversion

The relevance of the above is in part to guide how a system should be optimised, and what features an energy system has, but also to have a starting point in differentiating between centralised and decentralised technologies and systems. Because energy systems are per definition complex, interdependent, and depend on an interplay between supply and demand, this can be difficult. However, the point of energy conversion can be used to delimit where 'energy is produced'. Lund works with definitions that distinguish between energy demand and end use demand (2010). This seems like a useful and pragmatic way to delimit how and specifically where we expect energy to be 'made'. End use demands are defined as "room temperature, transportation, and heat" (ibid: 8), which are inherently confined to the individual building or situation in which they are used. They represent the energy we functionally use – but less the energy that is provided by the system at large. The more interesting concept regarding the structure of an energy system is the energy demand, which consists of the demand for the energy forms of heat, electricity and fuel. The way in which we supply these energy forms is more variable – both in spatial location, but also in terms of the different scales of technology that can be employed to satisfy these demands. This conversion point (from fuel to warm water; from wind to electricity; from fuel to electricity) is a clearer boundary to understand how the energy system functions as a utility to supply people with energy. Considering the point where energy is converted or produced into these forms can then become a useful delimitation to define where in the system technologies are (physically) situated and which technologies in the system can be structurally changed– while recognising the interconnectedness of the system.

The physical point of conversion, linked with size, can be a first step in differentiating between a centralised and decentralised technology within the system. Determining the size and design applicability of the technology seems like a very obvious first step. What capacity minima and maxima try to express is the extent to which energy is distributed throughout the community, based on the spatial locality of the point of conversion. Size is an especially helpful parameter to determine which technologies can be considered 'household scale' technologies. These are individual-scale technologies, they are designed to provide end use demands for an individual household, business, or service, and to that end the energy demand is in the building and the technology building-sized. While these individual building scale technologies are easily defined, the 'size' requirements for decentralised technologies, such as district heating, or non-building sized renewables, is less obvious. This is likely why these individual-scale technologies have been at the centre of previous attempts to define decentralised; because they are, per nature, clearly confined and thus defined.

Although any size parameter for mid- and large-scale technologies is arbitrary, it is clear that there is a subjective concept of locality to decentralised energy, that is not building sized, but also smaller than the energy merely dissipating into the national grid without any spatial connotation to where it was converted at all. For some decentralised energy technologies this seems obvious; heat cannot be transported over extreme distances without inefficient network losses, so the heat must be consumed relatively locally. However, for electricity generating technologies this may be less obvious, because the basis of a flexible system is a grid that can use intermittent renewable resources in many ways. The judgement must then be made if there is a likely relationship between local generation and local use. For example, electricity generated by an offshore wind turbine farm is unlikely to be used locally, merely because it is physically placed outside of an energy-demanding community, and the amount of energy that is generated at full capacity is likely to be so large, it must be dissipated throughout the system or lost. However, this is a generalisation; if a coastal city has a dozen offshore wind turbines that are used primarily to power the harbour and associated businesses, this could be seen as a decentralised approach.

Although size alone is used to limit the idea of decentralised energy by some (e.g. Williams, 2010), the rare size limitations that do exist for decentralised energy (for example, the capacity ceilings for Feed-In-Tariffs), seem rather arbitrary, both to Government and stakeholders (DECC, 2013). Size can inform, but is too simplistic a measure to capture the larger, socio-technical implications of what decentralised energy actually means in the vernacular. Due to the nature of a socio-technical system (and a socio-technical distinction between centralised and decentralised), the size and locality of the technology alone cannot be iron-set rules of distinction between centralised and decentralised, but rather guidelines to interpretation that represent subjective judgements. This makes defining centralised and decentralised energy less positivistic, but does better reflect the nature of the energy system

From this, it seems that there is an element of size and of locality can be considered, but not alone. Following Lund's differentiation between end-use and demand to determine a point of conversion, several distinctions can be made. On the one hand we can imagine centralised, large scale conversion, without explicit or exclusive (supply) links to the local areas, aimed at providing national networks. Examples could be large scale power plants, which may supply electricity to local inhabitants, but are also designed to power the grid in a much more significant way. Offshore wind turbines, which convert energy in a centralised (distant) area, and transmit their energy into the national grid are similar in nature.

On the other hand, and complementary to these national-scale distribution technologies are individualised conversion points; where conversion takes place within the building, using centralised, near-universal national infrastructure such as the electricity and gas networks. These individual-scale technologies can be considered decentralised because they are not large, huge installations. However, at the same time the clearest distinction the point of conversion makes is between individual-scale technologies and other decentralised technologies such as CHP and onshore wind turbines, so it seems counterintuitive to place them in the same category.

Rather, the individual-scale and large centralised technologies are seen as complementary. In a way the centralised system relies on both individual technologies, and severely centralised technologies. There are two reasons these are combined in a centralised system. Firstly, individual technologies alone would not be able to comprise a system in the sense that we know it; if every household, business, and public building supplied and converted their own energy on-site, what would remain is a collection of (off-grid), unconnected elements, which would not represent a system with interactions, dynamics, and relations. Secondly, the way individualised technologies are expected to work in the current system is complementary to heavily centralised conversions and structures. Without constant, self-balancing centralised electricity grids and supply, individual technologies like heat pumps cannot function; individual intermittent renewables rely on the electricity grid for balancing purposes. Similarly, gas-fuelled individual technologies rely on the national gas grid, a public works infrastructure, to be able to convert within the home. In this way, the centralised system is one where individual technologies interact with centralised. This means that while centralised and individual technologies are different in their conversion points, they can be seen to be different sides of the same coin, and together form a centralised system. As the social elements of the socio-technical system are added, this complementariness will become clearer.

The intermediary then is decentralised, where size and locality are more balanced. Conversion takes place distinctly outside of the building; but at a neighbourhood, city or area region. The scale is larger than aiming to heat merely the individual building, but is not large enough to provide energy for more distant regions of the country. This distinction sounds and is rather subjective, but as the literature rightly points out decentralised energy is more diverse, and more often a case-by-case understanding than conventional energy. However, an understanding of the basic scale, intended use, and locality of the technologies can help garner an understanding both of what its role in the Smart Energy System is when it comes to conversion and interconnecting energies and exploiting synergies of scale, while also being an indicator of what kind of system the technology functions in, with regards to centralisation and decentralisation.

Choice and (de)centralisation

Understanding energy systems, especially the concept of decentralised energy systems, means recognising that energy is not only a technology distinction – but also the "particular social arrangements" that surround the implementation of it (Walker & Devine-Wright, 2008: 498). This in part means that the classifications and understandings of centralised, decentralised, and community are dependent on the social and institutional contexts, and re-evaluations are very much possible. Understanding the choices made in the energy system allow for a better understanding of how to change it – but also for a differentiation between centralised and decentralised energy systems.

An energy system, including a Smart Energy System, is both technical and social. It is in essence an infrastructure system, consisting of fuels, production units, transmission technologies, convertors. This incredible variety allows the use energy in the instantaneous and versatile manner, often without even making a conscious effort. There is a fundamental social aspect to the energy system and the influence which it has on our way of life, the expectations and associations we have and create, and the extent to which we take responsibility for it. Aside from its technical components, individuals and the institutions that surround us have an undoubtable influence over how we define and understand the energy system. Recognising that it is both a social and a technical system allows for a better understanding of how it works and can be classified, as well as how it can be influenced and changed.

The way that the physical part of the energy system is created, maintained and sustained is through the choices of technologies that are used and implemented. The kind of technologies we choose to provide the energy we need, the amount of energy, and the allocation of energy become the components of an energy system. Because of the variety of available technologies and the social impacts of the functioning of energy system, the technological choices that are made are informed not only by cost and performance, but also by a variety of factors that represent the larger impacts and perceptions of the energy system. This is why the decision making that surrounds the technical implementation of the energy system represents such an important issue to fathom. To both understand why the system exists as it does, and what change is possible, it is key to understand how and why choices are made, and what is necessary for socially optimal choices to be made. Additionally, understanding the choices is key to understanding how choices for centralised and decentralised energy differ, and what the distinctions are.

Within a classical market understanding, the assumption is that bringing more, different, and specifically better forms of production to the market will lead to better choices and a better functioning market. As more energy technologies appear on the market, consumers can choose between a wider variety of energy technologies, and energy technologies will be forced to operate competitively. This is the idealistic and purely theoretical understanding of the market: it is an assumption that carries huge caveats because it involves a complete and completely understood reflection on the consequences of the choices. The preconditions of this market mechanism working is consumers being fully informed, all externalities accounted for, consumers acting rationally (also towards the long term), having investment capital, etc. Applying the understanding of choices and the resulting market transactions that determine technologies and the energy system, it becomes clear that choices of energy technologies are not made optimally. This constitutes a market failure, as choices are made that do not provide the most optimal system in terms of allocation, energy efficiency, cost, and sustainability.

These market failures result from the way that choices are made – and who is making them. The underlying assumption is that for different energy systems, different market failures occur. A decentralised energy system should be characterised by a distinct set of ways that decisions are being made, and certain market failures that are inherent to them – in the same way we expect the market failures of a centralised energy system to be characteristic in some way. This means an understanding of the choices being made can help differentiate between centralised and decentralised energy.

The choices that occur in an energy system occur very much within the social and institutional construct of the energy system, so it is especially important to understand who is actually making the decision, based on what kinds of considerations, and what kind of choices they have. Without an understanding of who the actual decision maker is, it is difficult to formulate interventions or policy that can adequately address the decision makers and their choices.

Lund discusses the theories of 'Choice Awareness', distinguishing between choice at the individual level and choice at the societal level, which recognises the idea that individual consumers do not necessarily have influence at all (2010). This theory raises an important point to consider: that in situations where there is a perception that there is no (or no good) choice, the awareness of choices should be raised. He uses the argument primarily for decision making at a societal level, arguing that a strategic shift is often necessary for (local) governments to start thinking creatively and including better, more renewable, but possibly less conventional options. However, the theory seems specifically apt for the individual decision making. Renters often feel they have no choice in their energy provision technologies, while landlords may have little incentive or knowledge to be fully aware of all choices and possibilities. Additionally, the knowledge of individuals is often neither as sophisticated nor as strategic as would be ideal. In practice, it is likely most heating installations are decided upon as a direct replacement for the broken previous one, with time a more important factor than a wholly aware and inclusive decision making process.

The implicit question is what kind of knowledge and agency individuals, organisations, government, and others then have in the decision making process. All actors should be included in understanding decision making. This limitation in individual decision making is often framed within a context of what we can expect to know or want within societal constraints. Theories concerning socio-technical regimes and lock-in have tried to address the importance of social perceptions, information, expectations, and agency to explain why the creation of better alternatives does not precipitate the making of better choices (Unruh, 2000; 2002). We know our current choices (be that the decision to build a new fossil fuel power plant, or even installing a condensing boiler in a household) are both unlikely to be ideal, unlikely to have been precipitated by an imagined aggregate of consumers, and unlikely to substantially change the form of the energy system (Lund, 2010: Unruh, 2000; 2002). The appeal of a socio-technical system is that it addresses the different roles of the aggregate consumers and producers, the government, companies, and even the frameworks of individual consumers' norms to understand the way that they form institutionalised processes which are radically different from what puritan economic theory describes. It addresses both the underrepresentation of better, ulterior choices, and the idea that society at large must change – rather than merely trying to inform and incentivise individual people.

It is important to consider both perspectives: both Lund and various socio-technical/lock-in approaches proceed to immediately exclude consumer choices as a valid way of conceptualising change and focus only on the societal decision making. However, the (individual) consumer remains important for two reasons. Firstly, individual decision making does happen and is often given some (ostensible) role in changing the larger energy system, so it is difficult to ignore. There remain cases in which consumer decisions are being made, and considering strategies to ameliorate or optimise these decisions remains necessary, in conjunction with changing the social constraints consumers face. Even if the power or range of these changed decisions is very limited in terms of effect or even a larger system change, there is a possibility that they can contribute. While it is not within the scope of this paper to pass on advice aimed at specific individual household solutions, including the perspective of the consumer may help raise awareness of the choices they can make. Secondly, an in depth understanding of how, why, and to what extent individual consumer decision making is effectual in catalysing change can strengthen the argument for a larger regime change.

Blending both the individual choice perspective and the role of the socio-technical surrounding does not create an especially clear framework of understanding, but does allow for the flexibility that is necessary in order to understand decisions being made in all parts of the energy system. This is especially important as there becomes a 'need' for consumers to actively choose community solutions; be that directly (for example by connecting to a district heating grid) or by working towards community wind power, solar power, or other decentralised solutions, in order for them be perceived as viable. It is important to ascertain where the choice is (or is not) being made, in order to be able to understand what effect they have on the system and how to influence these choices.

The importance of ascertaining who the decision maker is and how the decision is being made is then an indicator of what kind of (socio-technical) system is being implemented. Walker & Devine-Wright characterise a decentralised system as open and participatory, whereas the centralised decision-making is largely closed and institutional (2008). While these characteristics do not seem appropriate for a continuous scale or indexation, they are apt descriptions of how decisions are being taken, and who has influence. Conceptually, they allow for a clear distinction between centralised and decentralised.

For decentralised decision making, it seems obvious that the necessary collaboration, coordination, and convincing, while costly and time consuming, leads to a fairly open and participatory discussion. Because a collective consumption or demand decision must be made, the likelihood of these processes being open and accessible to others is high, after all, the work is often based around gathering support and investment. It appears undisputed that there is a need for a (legal) entity, company, group, charity or organisation to represent the individuals and act on their behalf when it comes to community energy, although the nature may differ (Walker & Devine-Wright, 2008; DECC, 2014). It should be clear that this represents a transaction cost; people must be willing to invest their time, effort, learning and knowledge into these processes, which can represent both costs and barriers (for example, if the knowledge is not present) for decentralised decision making. The processes of aligning people within these organisations, sometimes creating such organisations, aligning organisations, and working with them inherently requires a certain degree of cooperation, discussing, and deliberation.

Conversely, centralised decision making is associated with closed and institutional processes (Walker & Devine-Wright, 2008). Again, this description is apt for both the decisions that are made at a (national) government level, far from our beds and understanding, and those that are made by the building owner or tenant, and remain largely invisible for the rest of society. In the first case, the reference is primarily made to decisions to build large-scale infrastructure or conversion points, without an extensive local engagement to all who will use and apply their end result. The empirical examples in Lund's book on Choice Awareness Theory are clear descriptions of cases where choices are made without consideration of alternatives, with pre-assumed solutions, and without acknowledgement or openness towards others' involvement and ideas (2010). This kind of decision making can have an element of public consultation or participation, especially if there is a formalised impact assessment involved. However, even in the UK, the vague role of what participation actually means in the IEA or SEA process does not fully ensure an actual sense of partnership or citizen power (Arnstein, 1969; Bond, Palerm and Haigh, 2004; Glucker et al., 2013). There is no inherent need for a social conversation about how improvements can be made, what is optimal, or peoples' collective ideas and engagement. There is not necessarily a sense of accessibility, sense of equal negotiation, control, or ability to tangibly influence decisions. In this way, the decision-making behind large, centralised projects can be closed and institutional.

In a similar way, the choices that are made at the individual building level are not openly discussed, or part of a meaningful discussion that allows for community influence. To the contrary – the nature of decisions made regarding individualistic choices is the essence of a closed decision, because no one else has any legitimate influence or standing. Market failures abound, especially when it comes to the purchase of gas boilers, microgeneration technologies, and other individualistic technologies, which can involve knowledge gaps, grid access, externalities, or a lack of capital (Allen, Hammond, and McManus, 2008). There are (market-based) efforts to encourage people and incentivise them to make certain decisions, but these efforts can only ever be that – an incentive or encouragement. If the decision is being made by the individual and the individual alone, in absence of larger cooperation and coordination, it is inherently difficult for decentralised decision to take place.

Because of these differentiations, it remains important to understand who is making the decision and how – both to understand the different characteristics of centralised and decentralised energy systems, but also to have a more sophisticated understanding of how decisions are made in order to influence them.

Who does the choice affect?

One of the difficulties of trying to make distinctions in the energy system is the very interconnected, interdependent, and entwined nature of the system. Actions have effects, knock-on effects, and influence the working of the system at large, especially as it becomes more interconnected and interdependent. The underpinning idea of a successful Smart Energy System is that interconnectivity allows for the absorption of intermittent renewables, so it is likely that increased interconnectivity will also mean increased interconnectivity between the decision making processes. One of the key questions that has to be considered, is who is affected by a choice. This is a common consideration, also in the idea of decentralised or community energy (Walker & Devine-Wright, 2008). It involves looking at the outcome, otherwise termed, for whom is there an incentive/disincentive for this to be realised? On whom do the benefits accrue that justify/outweigh the barriers?

The complete internalising of external benefits is often one of the underpinning ideas of community energy; to ensure that all benefits are retained and fall to the local people. Ideas of community energy often insist that the profits must be entirely local, and that there must be external social benefits (Walker & Devine-Wright, 2008). However, this can exclude companies that want to build 'community' scale installations, because they are not locally, charitably, or publicly owned. For decentralised energy, this seems too severe in terms of assessing only the social setting of the energy technology. The community is still receiving energy, and presumably at a more competitive price. Shared, localised ownership of the decentralised energy should not be necessary to accrue some benefit, and taking the full capital risk of owning an installation could be encouraged, but should also not be necessary for decentralised energy. The point is to transfer the benefit to the consumer; whether that is done through an ownership model, or through reduced prices through competition is less salient than it is for the concept of community energy. Community energy is likely to be decentralised, but to confine decentralised energy to community energy seems too stringent.

However, even is a decentralised energy technology is only owned by one entity, this does not exclude benefits and costs accruing on separate parties – especially as systems become more interconnected. Within economics, the concept of externalities is widely used to denominate such external effects. Externalities occur when benefits or costs are accrued outside of the consumption or production of goods and services; in other words, when positive or negative impacts occur on others, but this is not included in the transaction pricing (Laffront, 2008). This is relevant for technologies such district heating, which, by using CHP production and the associated flexibility, allow for better integration of intermittent renewables. Both the consumer and producer are not priced or remunerated for this effect directly, but it does occur and brings about wider benefits to society. Similarly, the implementation of an onshore wind turbine is likely to have both negative and positive externalities, when people who are not directly involved with the implementation or beneficiaries of its energy view it as a nuisance, or view it with pride.

Within systems thinking, externalities are loosely linked to the idea of synergies (Meadows, 2008). Synergies are situations where over time, $1+1\neq2$; the outcome is not merely the sum of its parts (Connolly, 2014). Synergies are an expression of the idea that there are emergent properties; effects occur outside of the immediate action or implementation. While externalities need not have the same feedback effect that is often associated with synergies, they both convey the idea that indirect effects occur, which can bear costs or benefits. When looking at systems, synergies and externalities are seen as being an indicator of a dynamic, complex system (Meadows, 2008). Figure 1 representing the Smart Energy System is in effect the visual representation of this; as the system becomes more intertwined and connected, the likelihood of a change in one part affecting a different part is larger. For this reason, it seems that a decentralised system, and technologies associated with it, are likely to display an array of externalities and synergies.

The presence of externalities can be a problem because as the benefit (or cost) is not covered in the initial transaction, the market is likely to under or over produce. To continue the example, if the implementation of CHP leads to a cheaper overall electricity system (because intermittent renewables are better integrated), but this benefit is not shared with the producers and consumers of CHP and district heating, they will not implement as much district heating as is actually necessary for the market to work optimally; i.e., at its cheapest level for the system overall. Crassly, if people are not paid for their beneficial actions, they will not do it. This has been one of the main arguments for government intervention in the market. The primary incentive for the government is to correct the market failure; to ensure that the good with positive externalities (or a positive synergistic effect) is provided at the level that it optimum for society at large, or that the good with the negative externality (or negative synergistic effect) are provided at a (lower) level that is efficient for society at large. Sometimes, intervention is drastic, such as weapon bans, drug bans, or mandatory vaccination This is generally done through subsidies or taxes; the understanding being that after the subsidies and taxes are implemented, the market functions more optimally, and the taxes and subsidies are recuperated by society.

The direct implications for this project are two-fold. Firstly, as the methodology will elaborate on, the costs for the modelling will be made for society at large, which means the merits and drawbacks of the systems modelled will apply to society at large, and not individual parties. More importantly, the presence of externalities makes socially efficient implementation more difficult, and for many (centralised and decentralised) technologies, the presence of complex externalities and synergies explains why, even though they can be hugely more efficient, implementation proves so difficult. This is especially likely to be the case in the decentralised, heavily interconnected, complex system, where decisions are made on a more collective basis than the centralised system, and which uses more technologies that depend on shares externalities and synergies. Being aware of where these externalities and synergies occur, and what effect they have, is an important part of understanding the implications of the various energy systems, and will be an underpinning part of the discussion.

Chapter summary

A literature review of the current understandings of decentralised energy showed that elaboration was necessary in order to be able to construct a decentralised energy system. The idea of a 'decentralised energy system' is easily lauded, but ill-defined. Most understandings of decentralised energy are very clear in including individual-scale renewables and energy efficient measures, CHP and district heating, and often an obligatory mention of community energy. However, these definitions merely mention several technologies, and fail to actually create a decentralised energy system. Additionally, there is little conceptual work on why technologies are or are not decentralised, leading to unclear delimitations.

In order to differentiate between a centralised and decentralised system, the concepts of the Smart Energy Systems and the decision making surrounding the implementation of energy technologies are useful. The recurring theme is the level at which targets are achieved. In the consideration of the technical aspects of a better energy system the scale and locality are given by the point of conversion. The issue of choice and agency revolves around the level at which decisions can be made, and how accessible these processes are. The extent to which externalities are present and accounted for is important to understand the role of decentralised energy in a larger system, and what implications are likely.

A decentralised energy system, and the technologies that fit within it, then becomes clearer. Decentralised technologies cannot be chosen for and installed by a single entity without the possibility of influencing the decision, and without affecting the local energy system. Additionally, decentralised energy should have some decentralised impact in terms of where the benefits and costs accrue; they cannot simply be kept within the household or dissipate into the national energy system. This excludes both individual-scale technologies, which are chosen for/by building owners of managers, and which use the centrally provided gas and electricity grids. This also excludes large, institutionally decided for, installations that aim to power the national grid, without explicit aims for the local surroundings. It does not necessarily mean that decentralised installations cannot be owned by a single entity, but it does mean that the decision process must be open and accessible enough for the local impacts to be discussed and treated in a collaborative, cooperative way. This understanding is less positivistic than naming several technologies, but will provide a better framework within which a decentralised energy system can be built.

This decentralised energy system is contrasted with a centralised energy system. The point of conversion is either at the building level, and the size of the installation indicates it is primarily used to fulfil the demand within that building. Alternatively, the point of conversion is so remote and the capacity so large that there is no longer a tenable connection to the area, and the technology mainly serves to power the national, centralised grid. Centralised technologies are chosen through closed, institutional processes; both in the case of individual-scale and large centralised technologies. For the purpose of this systems analysis, these two are considered to be used in a complementary way to make up a centralised energy system. This leads to a workable definition the characteristics of a decentralised and centralised energy system, based on a wider understanding of what energy systems are and what makes them successful. Using these, the systems can be modelled and compared (with each other and a BAU scenario), to better understand the implications of a decentralised energy system.

3. METHODOLOGY

In order to be able to understand the implications of different energy systems towards 2050, they must be modelled. To compare a centralised and a decentralised system, both must be designed, modelled, and optimised. The scenarios must be both designed according to the technical possibilities and limitations of the used technologies, their capacities, and their costs. The scenarios are also designed according to the understanding of the prioritisation of certain technologies and their composition, in order to be able to create centralised and decentralised scenarios that are congruent with the understanding of these energy systems. The scenarios are not modelled with an assumption that some technologies are available and some are unavailable; rather, with the understanding that in a decentralised scenario, certain technologies are preferred over others, while certain others are prioritised in the centralised system. Additionally, a business as usual (BAU) scenario is included in order to put the scenarios in perspective.

In terms of assessing success, there are several parameters that are important to consider, including the energy in the system, the cost of the system, and the environmental impact of the system. The application of these three aspects of success is reminiscent of the Smart Energy Systems concept, and have (with variations) been used in the context of EnergyPLAN scenario modelling, including for STRATEGO (Connolly et al., 2015). Firstly, the use and source of energy is an indicator of how the energy system is performing. There are several measures of this. Primary Energy Supply (PES) is the energy required for the system before any of the conversion processes take place; a decrease in PES generally indicates an increase in efficiency, because it takes less energy input to be able to achieve the same level of final provision. The level of consumed renewables – especially intermittent renewables – is also important to look at. As outlined in the context of a Smart Energy System, there are several drawbacks to being overly reliant on biofuels in order to achieve decarbonisation; this means part of the success of a system is the extent to which it is able to integrate intermittent renewables. While the absolute amount of renewable energy is relevant, a percentage (of PES) is especially indicative of the overall flexibility of the system.

Secondly, costs are a crucial parameter to consider. The costs of the system are considered from a real equilibrium point of view; this means subsidies, taxes, and externalities are disregarded. The costs represent the bare, simple, actual, tangible cost of having or ceasing a certain technology, without representing changes to market structures, or being indicative of what actual consumers would necessarily pay for the service. It also means that externalities are not accounted for, although a carbon price is used in accordance to carbon market values. This equilibrium pricing is in part used through necessity, because it is impossible to accurately predict what kind of policies and incentives will exist regarding different energy sources in 2050. More importantly, it is also likely to be the most useful for energy planners and policy makers, because it represents the actual cost of having the system. The desirability, and need for incentivisation of aspects of the energy system can then form the basis upon which subsidies and taxes can be designed and costs redistributed. In this way the costs are helpful to inform decision making and future policy – but say little about the market prices and immediate costs to consumers now or then. Additionally, costs are annualised in order to be able to compare different scenarios with different technology lifetimes. As such, the costs of the systems should not be seen as the value of money necessary to 'build' or implement the system – rather, it should be seen as the costs that are necessary (every year) to have the system and perpetuate it.

In terms of what success is, it is easy to say that less costs are better. Nevertheless, the way the costs are distributed can be an important parameter to consider. For example, it is generally less desirable to spend a larger proportion of the costs on fuels, than on (infrastructural) investment or variable costs. This is because for these latter two forms of spending, the multiplier is generally higher when it comes to the wider economy, as it is spent on (domestic) labour, design, and materials, and then continues to circulate within the (local) economy. However, it is also necessary to think about who is making the investment, and what implications that has for individual households, governments, and others. Some entities have easier access to up-front capital or loans than others. As a consequence, the costs structure is relevant because high investment costs may indicate high upfront costs. This may not necessarily have a bearing to the extent to which the system itself is successful, but does become relevant as the discussions turns towards implementing the system, and its achievability.

The last parameter of success is the level of decarbonisation achieved, which is most easily expressed in CO_2 emissions per year. The need to do this is clear: in essence, the aim of the game is to achieve as many carbon dioxide reductions as possible, for the least cost. To sum up, in order to understand the impacts of a centralised versus decentralised system, and be able to compare them to a BAU scenario, it is necessary to model them, and understand how the systems act in terms of energy, cost, and decarbonisation.

Systems modelling

Modelling the scenarios was done in the EnergyPLAN programme, a publicly available programme developed at Aalborg University which combines all sectors of the energy system. Through the hour-by-hour calculation, it is extremely effective in understanding what the realistic possibilities are for alternative and renewable resources. In addition to STRATEGO, it has been used throughout the Heat Roadmap Europe projects, in the Danish context through the Danish Society of Engineers (IDA) Climate Plans, and a variety of developed and developing countries (Connolly et al., 2013; Connolly et al., 2013; Mathiesen, Lund and Karlsson, 2009). EnergyPLAN is specifically helpful because it allows for the incorporation of the synergetic effects of a Smart Energy System. This means the implications of a centralised/decentralised heating, cooling, and electricity system will be represented in a more meaningful way than with models that treat these sectors or technologies separately, or with larger time steps in the modelling.

The modelling work for this piece of research, especially in the heating sector, is largely based on the STRATEGO project, in particular the development of national heating plans in WP2 (Connolly et al., 2015). The European Union Energy Efficiency Directive of 2012 mandates Member States to seriously assess the opportunities for efficiency in the heating and cooling sector (EC, 2012). STRATEGO aids in this by combining, on a national level, a geographic assessment of heating demands and sources (thermal mapping) with hour-by-hour energy modelling and analysis for the heating sector. More specifically, STRATEGO WP2 has looked at what the optimal level of cogeneration and district heating/cooling is, while also balancing heat demand reductions and individual heating options. The aim of STRATEGO is to link these national heat atlases and understandings to local planning, strategic capacity, and provide support for the tangible implementation of priority area projects.

Being able to use the STRATEGO models and data has been invaluable to the quality of the scenarios for a variety of reasons. Firstly, the combination of EnergyPLAN cost databases and the UK specific data and data distributions which were gathered and created throughout the STRATEGO project mean that the inputs for the scenarios were easily accessible and validated. The EnergyPLAN database is publicly available, and checked, edited, and ameliorated on a regular basis (EnergyPLAN, 2015). The background reports of STRATEGO collate the relevant findings regarding the necessary data for the energy systems, with input from the national partners of the project. The background reports, but also the executive summary, country summaries and main reports for all these are available from the STRATEGO website. This research benefits directly from the extensive and collaborative data gathering that has been done in the STRATEGO project.

Secondly, this research occurs under many of the same assumptions that were made for the STRATEGO scenarios. The decentralised scenario is in essence an elaboration of the STRATEGO Heat Roadmap scenario which has incorporated energy efficiency changes with a ready optimised, decentralised heating and cooling sector. The centralised scenario is a more severe modification of the BAU-based scenario, where energy demand savings were incorporated. For those taken from the STRATEGO modelling, the underlying assumptions have been carefully considered, argued, and sourced in the STRATEGO reports (Connolly et al, 2015; Connolly, Hansen and Drysdale, 2015). This allows this research to build on the expertise and experience of others, although some assumptions will be more fully discussed. Hopefully, in the dissemination process, the congruence between the projects will contribute to the continuity between the outcomes and allow planners to understand the implications, possibilities, and limitations of the wider energy system in relation to STRATEGO outcomes.

Designing the scenarios

The primary aim of creating the two scenarios is to understand what the implications are for the UK if, over the next 35 years, a more centralised or decentralised energy system is implemented. The BAU comparison exists as a model of no directional change: the result of making improvements, but staying on the current pathway. Both the centralised and decentralised scenarios are optimised to the best possible point within their constraints, in line with the Smart Energy Systems concept. While the two scenarios represent different worlds, they are both the best of their respective worlds in terms of integrating renewables at a reasonable cost.

Both scenarios have a similar starting points, which coincide with the STRATEGO starting points. The forecasting towards 2050 in terms of population, electricity demand, housing stock, and BAU technologies is based on the “Trends towards 2050” report written for the European Commission (Capros et al., 2014). This is also the source for fuel costs, carbon costs, and includes the assumption that legally binding targets are achieved within the appropriate timeframe (ibid). Aside from showing the result of current trends, the second explicit purpose of the document is also to function as a bench mark for concurrent or alternative approaches toward the energy system, and how the results can be used. This is why it is included in the analysis: to allow for comparison with the centralised and decentralised energy systems.

A discount rate of 3% is used throughout the projects, again based on STRATEGO. This is not very high, but in line with the Treasury’s recommendation for projects of 30+ years (HM Treasury, 2003). Because the STRATEGO is a European project and discussed primarily Eurozone countries, the currency denomination is in euros. This is unfortunate for dissemination purposes, but increases the reliability of the data. A final important assumption in both the scenarios is the application of 40% heat savings in the UK between now and 2050. A more detailed discussion how this figure was arrived at and the corresponding validity is found in the main STRATEGO report and Background Report 3b (Connolly et al., 2015; Connolly, Hansen and Drysdale, 2015). An important point to take away from these numbers is that while the increased implementation of heat savings does display a diminishing rate of return, this 40% figure is likely to both represent the cost optimal level while still being extremely ambitious – and more optimistic than several estimates.

This heat demand reduction (and electrical efficiency gains from the BAU scenario) results in an electrical demand of 407.91 TWh/year, a heating demand of 284.33 TWh/year, and a cooling demand of 5.7 TWh/year. Industrial and transport energy requirements are included in the energy system, but these sectors are held constant throughout the scenarios, so are not discussed at length. This does mean that in the results, there will be a substantial amount of 'other' fuels – mainly coal, oil, jet fuel, diesel, LPG, and a variety of biomasses that are used in these sectors.

The main differences between the two scenarios are the extent to which different technologies are used, to create the systems with different natures according to how they have been explained in the preceding chapter. The following sections will both describe why certain technologies have been prioritised to create the decentralised and centralised characters of the energy systems, while also explaining how and with what specific data the scenarios were modelled.

The decentralised scenario

The decentralised scenario aims to create a Smart Energy System where technologies that fit the nature of a decentralised energy system are prioritised over centralised technologies. This distinction is made based on where the point of conversion is, size, who makes the decision an in what kind of process, and what kind of externalities are present. Based on the theoretical discussion, decentralised technologies are larger than building scale, but not so large that their purpose is the national grid only. They cannot be implemented by a single entity without collaboration and input, in part of because of the impact they have on their surroundings. Lastly, they are likely to contribute to the interconnectedness and interdependency of the system, and carry externalities.

The decentralised scenario takes its starting point from the STRATEGO WP2 Heat Roadmap model. This is the optimised, decentralised heating scenario STRATEGO created. In the heating sector, district heating is implemented to satisfy 70% of the heat demand after reductions (Connolly et al., 2015). The district heating level and supply was determined and optimised following roughly the same success parameters as used in this report in STRATEGO, based on the results of the thermal mapping and EnergyPLAN modelling. The remaining heat supply is the rural areas for which it is not viable to have a gas or heating network connection; here, heat pumps were implemented. Cooling is provided by district cooling where viable, and electrically provided in other cases.

This scenario in effect represents a case where district heating and cooling (based on as many surplus, efficient, and renewable sources as possible) is decentralised to the most efficient point. District heating and cooling provides the end demands (change in temperatures) in homes and buildings), but moves the point of energy conversion to a more centralised base, where it can benefit from access to cleaner or cheaper energy sources. Additionally, the combination of storage with a CHP plant or large scale heat pumps allows for a higher level of integration of intermittent renewables. A district heating system requires a different kind of choice: the energy source and network cannot be organised by one individual, but must be done at a reasonably local level. Because they convert energy outside of the building, cannot be implemented by an individual in isolation, and bring wider benefits to the energy system at large by linking the electricity and thermal sectors, and allowing previously un(der)utilised sources to be included, district heating and cooling seem like the ideal decentralised solution for the heating sector.

In order to supply the district heating optimally, while respecting the geographical considerations of the mapping that took place for the UK, the Heat Roadmap for STRATEGO has been wholly implemented, with small boiler capacity and storage capacity optimisations after the electricity modifications. Combined Heat and Power (CHP) plants are used to supply 120.54 TWh/year of the thermal network heat. Figure 2 below shows the development of CHPs in Denmark, and explains in a very visual way why the implementation of CHPs is seen as a decentralisation process, even though ostensibly it 'centralises' peoples' heating supply. For the energy system, a move is made from few and central electricity conversion points to many, multifunctional conversion points. Both in Danish, and some British literature, CHPs are seen as a key aspect of a decentralised system, specifically because of their inherent connection to district heating, and their smaller nature, leading to a system with more, but smaller energy conversion points. In many ways, the considerations for CHP are becoming key when it comes to integrating more energy efficient and renewable heat supplies into the thermal network.

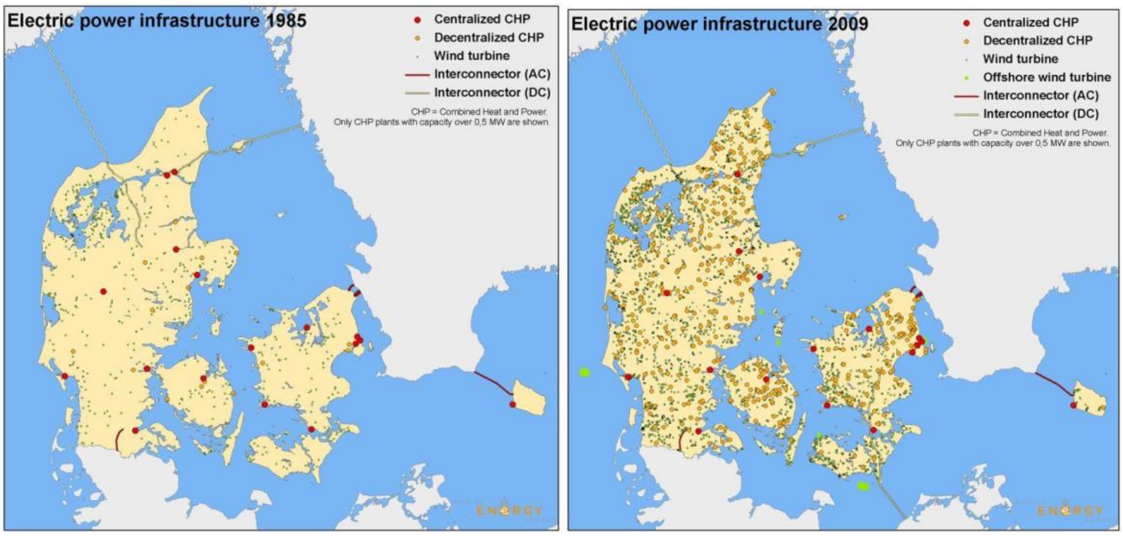

Figure 2: The development of electric generation in Denmark, and the (geographical) prevalence of small, decentralised CHPs. Taken from ENS, n.d. Energy Info Maps, available at http://www.ens.dk/en/info/facts-figures/energy-info-maps/download-premade-maps. Accessed May 2015.

In terms of renewable and highly efficient heat for the district heating system, STRATEGO has identified the use of 37.29 TWh/year of industrial excess heat, and 9.46 TWh/year of heat from (geothermal) absorption heat pumps, at a coefficient of production (COP) of 3. Compression heat pumps (also COP of 3) were added to supply a combined 29,639 MJ/s of heat, and (large-scale) solar thermal provides an additional 11.78 TWh/year of heat to the district heating system.

The use of industrial waste heat is a prime example of smart, decentralised energy use. Firstly, it implies using energy that is otherwise already converted at a central point, in a localised manner. As a general rule, the marginal production cost will be zero or close to zero. Using waste heat is one of the prime ways that PES can be reduced, because it involves using waste heat to displace other ways of supplying heat; it creates a synergy. Secondly, the challenge of using industrial excess heat in order to heat homes and buildings capitalises on synergies that can emerge when (private) energy-intensive industries cooperate with heat supplies; whether they be private or (partially) public. Neither the district heating company nor the industrial company alone can made the decision to capitalise on the excess heat; there has to be a level of organisation, cooperation, and negotiation that is typical of more complex, inter-sectoral, decentralised technology uses.

A similar situation exists for geothermal and large-scale heat pumps, and the collective use of solar thermal energy. Previous analysis has shown that in the same way large gas boilers are cheaper than individual boilers, the large-scale application of heat pumps is cheaper than at the individual building level; primarily as large scale installations provide an economy of scale (Paardekooper, 2015). However, it is exactly the type of choice that an individual cannot make alone, because in order for the large production to be viable, a thermal network must be available, a minimum amount of customers must be assured, and often a certain level of capital backing must be available or guaranteed. However, when cooperation and coordination do occur, the benefits are not only the successful use of a (carbon efficient or carbon free) thermal network and supply, but also create possibilities for future network expansion, putting neighbours in a better position in terms of available options. Large-scale heat pumps have a specific additional externality that is key in Smart Energy Systems; namely that their link between the thermal and electricity systems can hugely contribute to the integration of intermittent renewables, especially in combination with large-scale thermal storage. In these ways, it is not only the thermal network itself which fits well with the decentralised energy system characteristics, but also the highly energy efficient and renewable thermal supply technologies that fully congrue with the understandings of a decentralised energy system.

For the remainder individual scale heating, heat pumps were used in following of the STRATEGO methodology. Their analysis showed that in terms of costs, biomass boilers, oil boilers, and electric heating were so close in system costs that the decision was made to implement heat pumps nearly universally in non-thermal network connected buildings, because of their efficiency (in reducing PES) and external benefits (towards the linking of the thermal and electric networks, and allowing intermittent renewable integration) (Connolly et al., 2015). This leads to heat pumps satisfying 81.02 TWh/year, and biomass boilers 4.26 TWh/year of thermal demand.

Having optimised the heating and cooling sectors, the electricity sector is optimised to best represent a decentralised system. To do so, technologies that generate electricity in a way a decarbonised as possible, while providing neighbourhood, community, or organised production are favoured, that need a level of organisation, coordination and cooperation to implement, and which carry externalities and effects on more than those who merely use the technology. Onshore wind is implemented to the point of lowest cost, while respecting the technical capacity for onshore wind in the UK, which was found to be 27,334 MW in the STRATEGO project (Connolly, Hansen and Drysdale, 2015). Interestingly, the cheapest technical option was found to be around 37,000 MW capacity, so while only 27,334 MW was implemented in this system, any increased potential to place on-shore wind in the UK could easily be capitalised upon.

In terms of decentralised electricity generation, onshore wind turbines provide a much more decentralised solution than offshore wind turbines, typically gathered together in farms, do. While still affected by geography (and surrounding structures), they are modular and can be placed in a wide variety of places, not only in coastal areas. This means they do not require large transmission grids, because conversion takes place outside of the individual building unit but not in a remote area that requires transnational transmission (ENS, 2014). Additionally, they are larger than the micro-turbines (>5 kW) that can be installed on (rural or highly suburban) private properties, so they are not technologies that can simply be installed based on one person's decision. In the UK, community owned onshore wind farms are scarce and hard to achieve, but smaller farms (with less turbines) are generally more accepted, and can bring about other social developments (Warren and McFayden, 2010). More poignantly, community ownership or shares and local government involvement are hugely important in actually bringing the onshore wind turbines to fruition, indicating that a level of careful organisation, coordination, and collaboration between various people is necessary (ibid; Toke, 2005). This, in addition to the conversion features, is characteristic of the decentralised energy technologies the scenario aims to prioritise.

Following onshore wind, dammed and river hydro power were maximised to the lowest cost, while respecting technical implementation limits. Both dammed and river hydro were implemented to the highest of their technical capacity, at 1,497 and 1,769 MW respectively. Again, if it were possible to implement more (although this is presumably considerably more difficult than with onshore wind), costs would continue to decrease. The river hydro showed almost no evidence of any decreasing returns to scale, even when capacity was quadrupled over the final number. In terms of a decentralised system, river hydro is prioritised because it exhibits many of the same characteristics of onshore wind turbines. The capacity is per nature very localised, but they do not occur within the confines of one building or even one property. Small-scale is usually less than 10 or 25 MW, depending on the definitions, and while much of the potential capacity is in Scotland and Wales, there are conservative estimates that England also has at least 50MW capacity (Paish, 2002). Hydro can have the potential to hugely contribute to the regulation and flexibility of a system, but its implementation generally requires coordination of inhabitants, users, investors accommodating for long lifetimes, and a consideration of the other functions of the fiver and surrounding areas (ibid). As such, it can easily be considered part of a decentralised energy system, where aggregation leads to efficiency.

At this point, the renewable energies that are lesser-prioritised in a decentralised energy system are added and optimised. Both marine and wave energy are not viable at this point; the cheapest level of implementation is zero. This means that the value of the energy produced does not offset the costs of implementation. The same result was found for (household) photovoltaic power. Offshore wind, however, was found to be able to make a contribution, at 35,000 MW installation, which is significantly less than the maximum capacity in the UK (67,334 MW, based on STRATEGO). It does show poignantly that the use of different technologies can be seen on a continuous spectrum of centralised and decentralised systems; just because offshore wind is a technology that characterises a centralised system, does not mean it cannot contribute to a decentralised system and has no place in it whatsoever; it merely emphasises that the system should be seen as a whole, and prioritised in such a way.

After the integration of the optimal amount of renewables as described above, nuclear was added to the point of optimal cost, while disregarding any Critical Excess Electricity Production (CEEP) this brought into the system. CEEP is clearly inefficient – energy is being produced, but not used, not exported, and wasted. The decision to increase capacity – at lower cost – or reduce CEEP through less capacity is then a subjective decision between cost and energy efficiency. However, the decision to implement at lowest cost has been applied throughout, including the intermittent renewables, so lowest costs are maintained. However, a note of final CEEP and a consideration of its implications is a necessary part of analysis. With this understanding, nuclear power was found to be cost optimal at 39,500 MW capacity, operating at 33% capacity and far below the maximum capacity of 75GW determined in the STRATEGO project. Remaining electrical demand was met through 43,500MW gas-fired condensing power plants, with a 55% efficiency.

The centralised scenario

The centralised scenario aims to combine both the highly centralised elements of energy planning, characterised by large volumes of conversion centrally; government or institutionally planned technology implementation; and an elaborate distribution system that impacts many, but fairly indirectly. This is combined with the application of individualistic technologies, those that can only supply one building or household (sometimes using a fuel or energy that is distributed from a centralised source); where the individual is expected to make the implementation decision (and any investments); and where the interconnection with the (centralised) grids is necessary. In order to model this towards 2050, and be able to compare it to a decentralised scenario, several steps are taken.

To fulfil heating demands, priority is given to individual-scale solutions. District heating is, per nature, a regional and decentralised solution, so is discouraged. However, thermal networks have lifetimes of 40+ years, so are unlikely to completely disappear; to this end district heating is kept at the level of BAU looking towards 2050. This represents 4.31 TWh/year of heat demand. Of that, all is produced through 7.16 MW of gas-fuelled CHPs.

All other heat is satisficed using technologies that convert energy on-site, such as heat pumps, biomass burners, and natural gas condensing boilers. These technologies are all closely associated with (centralised level) distribution networks: heat pumps rely on the electricity grid (and centralised electricity production); biomass burners, especially in urbanised areas, rely on a centralised system of biomass growth or procurement and distribution, and natural gas burners rely on a centralised gas distribution and procurement system. It means that there are nation-wide, centralised distribution networks for fuel, while allowing the choice of conversion mechanism and the conversion to take place within the home or building. This in itself is an example of how systematically complementary the centralised and individual scale technologies are.

In order to create the individualised and centralised heating scenario, a mix of these technologies was used. Part of the advantage of individual heating options is that different buildings, with different characteristics, often have their own individualised optimal solutions; however, this means predicting individualised heating solutions without extensive modelling and discussion of the housing stock is difficult. In order to broadly shape the different technology choices, the building stock was divided into multi-family buildings, individual (single family) homes, and service buildings (Entranze, 2013 in Connolly, Hansen and Drysdale, 2015). To broadly generalise, the first is roughly considered to be urban area, while the latter two are roughly considered to be sub-urban or rural. The number of heated buildings were then used to determine both the numbers of each technology that were required in the implementation, the necessary substations, and the necessary central heating (radiators, internal distribution system) and the proportion of fuels needed to create the heating side of the centralised system.

To start with service buildings, the district heating was left at BAU, although it should be noted this is an increase in comparison to 2010 data. Biomass burners and heat pumps were implemented to the point that STRATEGO had found them viable outside of district heating. The remaining service buildings were supplied with an equal proportion of air-to-water and water-to-water heat pumps. For single family homes, a similar logic was used, where residual district heating is used in a BAU fashion, biomass boilers are used where they are found optimal by STRATEGO in a district heating scenario, and air-to-water and water-to-water heat pumps are used equally to satisfy the full demand.

Heat pumps are an additional attractive option for the potential renewable heating of buildings. Coefficients of performance in 2050 are estimated between 4 and 4.5, so their highly efficient use of energy can be a key step to decarbonising the system (ENS, 2014). Heat pumps come in many different forms: air-to-air heat pumps for rooms and smaller apartments, and air-to-water and brine-to-water (ground source) heat pumps for full domestic hot water (DHW) and heating demands (ibid). This versatility makes them attractive for individual home and building owners, although their compatibility with an urban environment has been contested (ENS, 2014; Paardekooper, 2015). The main reason they are preferred over biomass boilers is because of the system effects they can have. Because they form a link between the electricity grid and thermal provision, they can play a key role in integrating intermittent renewable electricity sources. Even a small amount of storage can allow for the short term absorption of (relatively abundant) renewable electricity when the wind is blowing or the sun is shining – removing the need to use electricity when the intermittent renewables are scarcer. This means that as individuals install heat pumps, the wider system enjoys a benefit, creating a positive externality. This is one of the reasons heat pumps are generally preferred over biomass boilers in a centralised scenario that seeks to minimise carbon emissions.

For multiple family homes, a slightly different approach was chosen. BAU district heating was retained, while biomass burners, air-to-water and water-to-water heat pumps were implemented to the extent that STRATEGO found viable and optimal in a district heating scenario. However, a previous study found that in urban areas, or areas with as high a heat demand as multi-family buildings are likely to have, heat pumps cannot provide a viable alternative to gas networks. While they are slightly more fuel efficient, the costs are so significantly higher (about 20% system-wide), that it seems unrealistic to assume that the city-wide implementation of heat pumps is possible, especially in multi-family buildings (Paardekooper, 2015). To this end, condensing gas boilers and a gas distribution networks were maintained for these areas. This would not fit in a 100% renewable Smart Energy System, but given that decarbonisation and affordability are both success parameters, and gas is used not only in the combined heat and power plants of the decentralised system, but also within the electricity system, it seems a defendable trade-off.

The resulting heating system that is not supplied by district heating depends for 97.7% on heat pumps, 1.5% on biomass boilers, and on 0.8% condensing gas boilers. This, in addition to the 4.31 TWh/year of district heating, results in 2.07 TWh/year of heat from gas boilers at an 85% efficiency, 4.10 TWh/year from biomass burners at a 65% efficiency, and 262.98 TWh/year from heat pumps with a COP of 3. This means that while biomass and gas are present, the system overwhelmingly uses heat pumps which are highly efficient and can aid in integrating intermittent renewables. Individual building owners and residents can choose what kind of application they prefer and what is most effective for their specific building type, behaviour, and preferences. In addition, the energy, which comes from a national grid, is converted within the building.

Moving into the electricity sector, priority was given to capitalising on offshore wind resources. Offshore wind turbines, especially if implemented as wind farms, provide the intermittent renewable priority of a centralised system. The renewable energy is converted, literally, offshore, and distributed to the mainland, where it dissipates into the national electricity grid. The decision is often made centrally, and in a fairly institutional manner, because of the capital funding required but also because the Crown holds ownership rights to the seabed (Johnson, Kerr and Side, 2012). Because other than environmental concerns, there is less likelihood of local noise or visual disturbance. There is a perception that offshore wind farms are more socially accepted, because they do not impact people directly, although this perception may be an oversimplification on the part of decision-makers part (Devine-Wright, 2005). This also touches upon the extent to which offshore wind externalities are socially mitigated; out of sight could mean out of mind, and this is likely to dampen public discussion and participation in decision making. Based on this, offshore wind turbines were the first priority in terms of the electricity sector. They were implemented to the point of cost optimality, at 33,300MW capacity.

The second priority in terms of centralised renewable technologies are photovoltaic converters, sun panels. These are on the other side of the centralised spectrum; the point of conversion is delimited to within the household or building, the decision can only be made by the owner, and the larger, participatory discussion about the value and drawback is largely sidestepped. The regulation mechanism comes primarily from the electricity grid; the PVs as intermittent renewables have little stabilising effect in themselves, so this means that that a reliable, flexible electricity grid is necessary to be able to accommodate them. This means that the hyper-individualistic PVs are in a way complementary to a centralised decision making system, and a national grid that can absorb the intermittency. At cost optimal, PVs were implemented to their full possible potential at 9,193MW. I should be noted that this is their maximum potential in terms of what is possible in the UK: as with onshore wind turbines and hydro in the decentralised system, the actual most cost optimal capacity was far higher, with a slight trend of diminishing returns. Again, this means that if there are ways to increase the physical potential to implement PV, this could be a cost-effective way of facilitating the expansion of these intermittent renewables.

Marine and tidal power shows several similarities to offshore wind in the reasons that they can be categorised. Firstly, the point of power conversion is very similar, in that it is inherently more difficult to embed within a community or society, given the spatial distance between the point of conversion and the point of actual end-demand. Secondly, while the decision-making structures are still falling into place (given the infancy of the sector), a centralised decision making governance model is emerging (Johnson, Kerr and Side, 2012). Again, the seabed and rights belong to the Crown for exploitation, but additionally the resource is seen as contributing to all of society equally, without local delimitations (ibid). However, while prioritised under a centralised scenario, the implementation of neither wave nor tidal energy was found to be cost optimal, so no capacity was installed.

Following marine and tidal energy, dammed and river hydro were prioritised. These can easily be considered decentralised technologies, but depending on the decision making process, and who effectively chooses to implement the solution, it is possible to imagine dams and river turbines within a centralised scenario. Maybe more so in developing countries, where hydropower potential is at its highest, decision-making can be described as centralised, institutional, and even “secretive” (Merme et al., 2014: 28). A case by case, qualitative approach is necessary, using the framing questions of the theoretical discussion. For this reason, both dammed and river hydro are not first priorities – but they are considered in the centralised scenario. Both were optimised for cost; again, the full capacity was used at 1,407 MW and 1,769 MW respectively.

Nuclear was added to the point of optimal cost, having exhausted renewable options (offshore wind was found to be unviable). Nuclear power was found to be cost optimal at 22,800 MW capacity, once again operating at 33% capacity and far below the maximum capacity of 75GW determined in the STRATEGO project. The remaining electrical demand was provided by 64,175 MW gas-fired condensing power plants.

Sensitivity analyses

Firstly, a sensitivity analysis was carried out to discover to what extent nuclear power was appropriate in both the decentralised and the centralised system. In order to do so, alternatives were created where the power provided by nuclear (in both respective scenarios) was replaced by gas, and one where the nuclear power was replaced by biomass.

In the decentralised scenario, with gas as an alternative to nuclear power, this involved a total condensing gas power plant capacity of 69,500 MW, which is 26,000 MW more than under the nuclear based scenario. In the decentralised biomass alternative, this additional 26,000 MW capacity was fuelled by biomass in 35% efficiency power plants. In the centralised gas alternative, a total of 77,500 MW condensing gas boilers was necessary, involving an additional 13,325 MW of capacity. The centralised biomass alternative was created in the same manner, by substituting biomass as a fuel (at 35% efficiency) for this additional capacity. The results are discussed at greater length in the following chapter, but confirmed the nuclear powered scenarios as the most optimal to continue further analysis with.

The above described sensitivity analysis comes with a very specific caveat. Namely, EnergyPLAN is a static modelling programme when it comes to pricing; that is to say, the fuel (and investment price inputs) remain constant, regardless of the quantity of that specific element modelled. The implication of this is that the model does not consider the effect that different variables have upon one another, especially in expected costs. For example, for most infrastructural technologies, it is likely that there is an economy of scale; the amount that is planned for 2050 is likely to influence the cost of building that technology. If investment in nuclear power is extremely low over the next 35 years, the expected cost of implementing it in 2050 will be higher than if it continues to be deployed or is deployed at higher levels than now: there are regular investments to improving nuclear power efficiency and building approaches, investment are made into developing at lower costs, and know-how is retained. Similarly, economic theory would predict that as the usage of gas drops and drives down demand, the price would also be reduced. While the EnergyPLAN cost database uses references and validated expectations, they remain only that: expectations. It is valuable to see, specifically when choosing the type of fuel for power plants that underpin the electrical sectors outside of the renewables, what effect price fluctuations have.

There are specific concerns with the estimated cost of nuclear. On the one hand, advances in nuclear science may decimate the costs of nuclear; alternatively, the next Fukushima could impose huge safety costs should nuclear wish to continue (Leibowicz et al., 2013). This is compounded by the fact that nuclear energy costs are notoriously difficult to find, let alone predict. A review of recent costs describes a range with a variance of almost 100% per kWh, depending on the place and plant, so specially if overruns and decommissioning are to be included, cost estimations are difficult (Kahouli, 2011; Leibowicz et al., 2013; IEA, 2015). Lastly, STRATEGO uses (country) energy balance boundaries which does not deal with end-of-life treatments that occur abroad, so the cost of disposing nuclear waste may not be fully accounted for, depending on where it takes place. With this in mind, a sensitivity analysis was run where both capital investment and O&M costs for nuclear were increased by 20%.

Given the drastic changes in fuel uses in the gas and biomass alternatives, similar sensitivity analyses were run for the biomass and gas alternatives. Theoretically, there is a correlation between the amount of fuel consumed and the price; however, EnergyPLAN does not reflect or change this. On the one hand this seems justifiable; while the UK both produces and consumes a lot of gas, it seems tenuous that changes in consumption patterns in the UK alone will lead to drastic shifts in global gas prices. Simultaneously, gas prices have traditionally been determined primarily by crude oil prices, and are expected to continue to do so (Asche et al., 2015; Panagiotidis and Rutledge, 2007). However, given the uncertainty over a 35 year time period, it is worth investigating if a lower gas (or higher biofuel price), in combination with a higher nuclear power price, can inform what kind of base-load power plants are preferable. In the gas alternative, prices were reduced by 20%; this follows the general understanding that less gas will be consumed (as gas boilers have been completely or mostly eliminated from the fuel mix), so prices drop. The biomass alternative represents a scenario where fundamentally more biomass is consumed than in the BAU scenario, so a 20% increase was implemented. In this way, the sensitivity analysis both tried to implement a dynamic element to the pricing of the base load power plants, while also investigating how close the different alternatives are in terms of substitution.

Chapter summary

This chapter has shown how the theoretical understandings have been used to create a centralised and a decentralised scenario for 2050, to be compared with the BAU scenario. For each technology, it has been explained why they were prioritised or less prioritised, and what the resulting optimal level of implementation was. In addition, the issue of base load electricity provision has been addressed by seeing if alternatives for nuclear are viable, and how robust these alternatives are comparatively. Having created and modelled the scenarios, it is possible to start comparing, and look at the implications of a decentralised energy system for the UK.

4. RESULTS

The objective of the modelling is to be able to compare a decentralised energy system to a centralised energy system and BAU scenario in order to be able to assess its impact. Understanding the theoretical and conceptual ideas of decentralised energy alone is limited, because it does not give any indication of the performance of the system. As outlined in the previous chapter, the immediate comparison is made along the lines of several parameters of success; fuel mixes, decarbonisation, and cost. These indicators allow for a better understanding of how the system works and what its implications are, but also to assess if a decentralised energy system is desirable at all. By understanding how a UK decentralised energy system performs, it is possible to start understanding the implications of such a system in 2050.

Fuel and CO_2

The first important comparison to make between the centralised and decentralised scenario is the fuel use of the energy system, and the CO_2 emissions that result from this. As becomes clear from Figure 3, both the centralised and decentralised scenarios provide an improvement to the BAU scenario when it comes to PES and CO_2 emissions. In terms of reducing PES, this improvement on both counts represents an increase in efficiency in the system; both use less fuel to be able to achieve the same output than the BAU scenario. For both systems, coal and oil have been removed from non-industrial energy and transport uses, which provides an efficiency increase as the substitutes are generally combusted in a more efficient way. In the decentralised system, the combined heat and power act highly efficiently while the use of heat pumps for individual heating provides efficiency in the heating sector of the centralised system. However, the relatively high use of (inefficient) nuclear power in the decentralised scenario compared to the (condensing) gas power plants in the centralised scenario mean that the centralised scenario is about 2% more efficient in terms of primary energy supply; 2181 TWh/year as opposed to 2140 TWh/year.

An additional important result when it comes to looking at the total fuel uses is that the centralised scenario has a Critical Excess Electricity Production (CEEP) of 17 TWh/year, while the decentralised system wastes over twice as much at 35 TWh/year. As a percentage of PES, neither of these are overly large, representing less than 1% and less than 1.5% respectively. However, because it means that in the decentralised system (even when optimised) energy is not being used because it is neither needed nor tradable at that point in time, storage technologies are likely to be able to contribute relatively immediately, because more energy is then available at no marginal production cost.

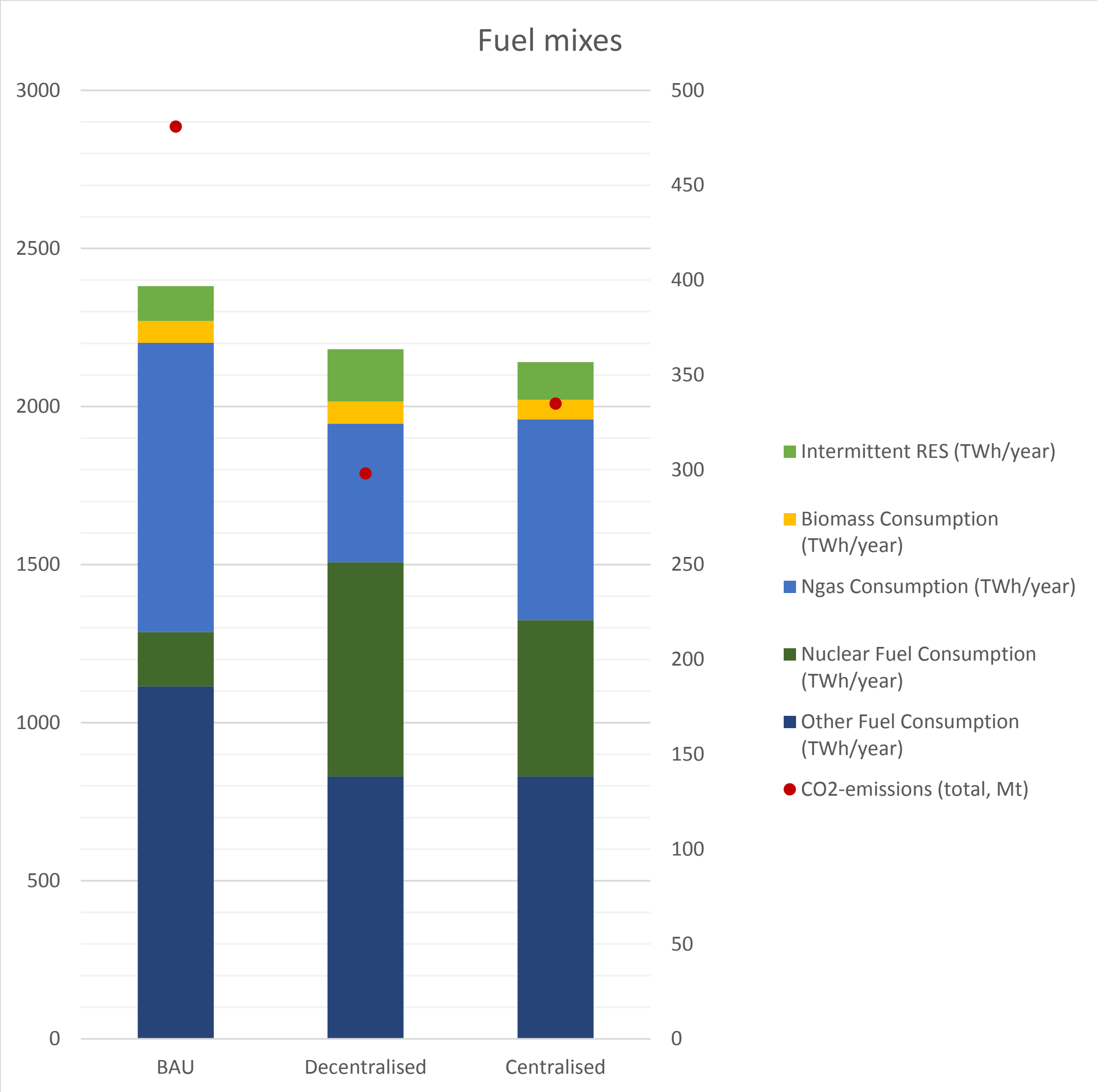

Figure 3: Fuels, fuel totals, and CO_2 emissions for the centralised, decentralised and BAU scenarios.

In terms of the intermittent renewable fuels used in the respective systems, again both the centralised and decentralised scenario provide an improvement over the BAU scenario, although the centralised scenario only presents a marginal one. While the centralised scenario can incorporate 119 TWh/year, the decentralised system uses 166 TWh/year of intermittent renewable electricity. This is important, because one of the aims of a Smart Energy system is the flexibility and ability to integrate the intermittent renewable electricity. This is one of the reasons that the CO_2 emissions for the decentralised system are significantly lower; 298 Mt versus 335 Mt per year.

The second reason the CO_2 emissions are significantly lower is the higher level of nuclear that is used in the decentralised system. This is again a reflection of the ability to fluctuate and integrate within the decentralised system. Conventionally, nuclear energy is used to cover the base load demand because of its inflexibility. Gas power plants are used to provide the flexibility to adapt to demand fluctuations, even without the presence of intermittent renewables. As renewables are integrated, additional flexibility is required. However, the centralised and decentralised scenarios also represent different kinds of intermittent renewables; because the centralised system relies predominantly on offshore wind production, the amplitude between the variations is much larger. This means that even though the centralised system uses less intermittent renewable energy, it needs more gas to be able to regulate the fluctuations. The decentralised system uses river hydro, onshore and offshore wind in a more balanced way. While each of these sources is intermittent, their intermittency is different and aggregated they provide a more stable supply, which means less gas-fuelled electricity production is necessary to regulate the system. In effect, the diversification of intermittent renewables that occurs in a decentralised scenario has the capacity to cancel out some of their intermittency. Ironically, this means that there is more of a base-load to be covered, and the cheapest point of implementation of nuclear power plants is higher. This also contributes to the low level of CO_2 emitted in the decentralised scenario, and its strength in achieving decarbonisation in the system as we look towards 2050.

A final point should be allocated to the level of biomass used. In the centralised system, this is 61.6 TWh/year; in the decentralised system this is 70.0 TWh/year. Compared to the other fuel uses, this is very little, however, the resource analysis in STRATEGO found the UK could only produce 26 TWh/year worth of biomass domestically; the remainder would have to be imported (Connolly, Hansen and Drysdale, 2015). This underlines the scarcity of biomass resources, and the importance of using intermittent renewables (and possibly nuclear power) to generate CO_2 free energy.

Costs

Aside from the energy and decarbonisation parameter, the costs of the system represent a major determinant of performance. Figure 4 shows the total costs for the respective systems, and the breakdown according to what type of cost they represent. The primary conclusion is that while the centralised and BAU scenarios cost almost equal amounts (281,021 and 283,518 million euro per year respectively), at 265,727 million euro the decentralised scenario presents a 5% reduction in costs overall in the entire energy system – including transport costs. This is significant: the savings per year would be almost 1% of current UK GDP (ONS, 2015; XE, 2015). This in itself, aside from any environmental or autarchy concerns aside, presents a reasonable justification for a decentralised energy system.

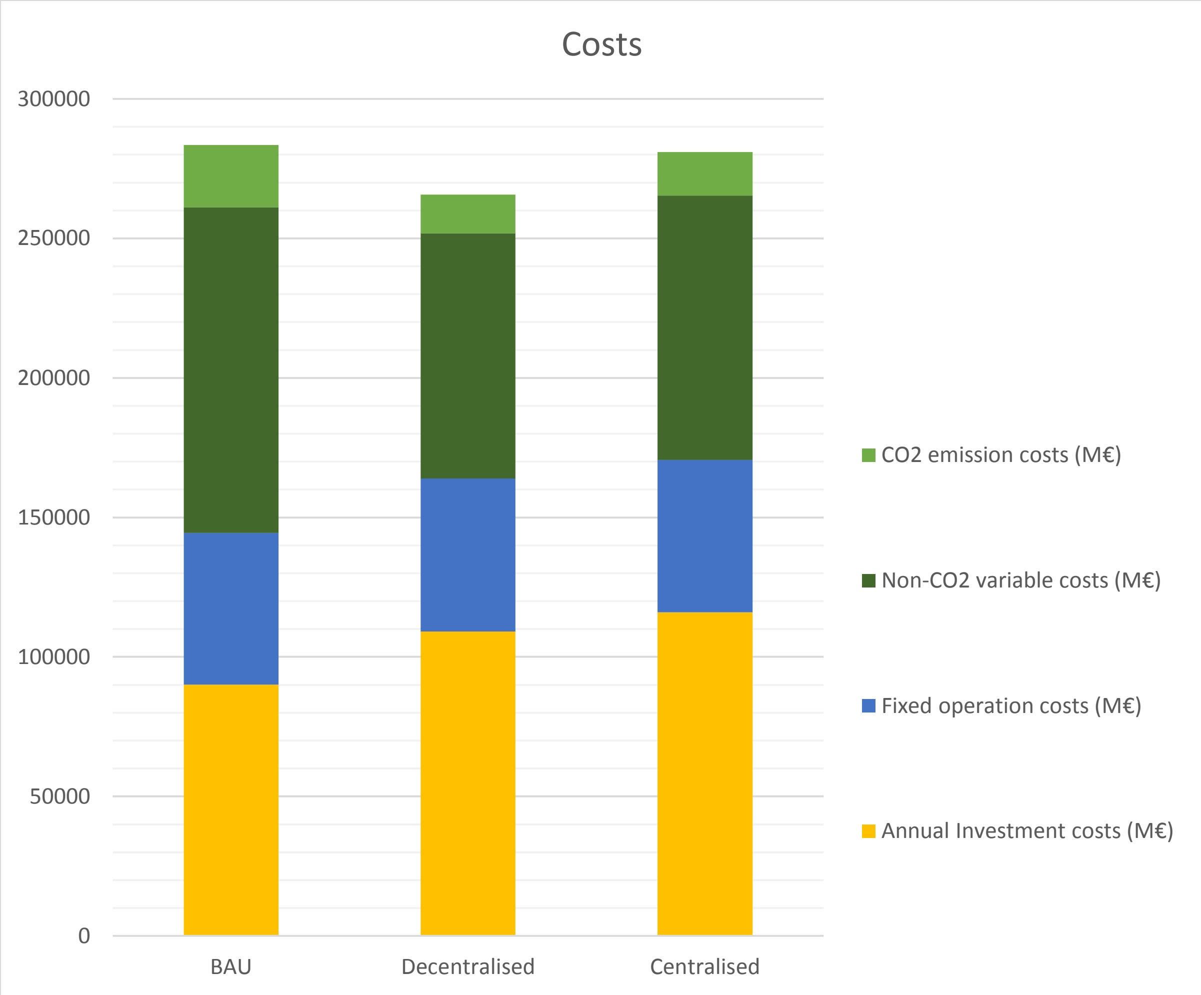

Figure 4: Costs and cost breakdown of the centralised, decentralised and BAU scenarios

When looking at the breakdown of the costs for the various systems, also represented in Figure 4, several things become apparent. Firstly, less money is spent compensating for CO_2 emissions in the decentralised scenario, because less carbon dioxide is emitted. Secondly, the variable costs in the decentralised system are lower than in the centralised system. Because biomass exchange costs are fairly similar between the two scenarios, this is primarily explained by the higher expenditure on natural gas exchange costs in the centralised system. High natural gas expenditure is not just a problem because it results in a more expensive system, but also because in the case of the UK, it is likely to represent an import cost. Either the gas is sourced within the UK, which means it cannot be exported, and an opportunity for foreign money to be injected into the UK economy is missed. Alternatively, and more likely as the UK gas reserves deplete, gas has to be imported and the money is spent abroad. This has a negative effect on the domestic economy not only because the expenditure represents an export, but it is also no longer multiplied within the local economy; it loses its potential for growth in the UK. Because of this, lower variable fuel costs are preferred, and the decentralised system represents a better opportunity to support the UK economy.

This understanding also feeds into the reason that it is preferable to spend money as annual investments, rather than as a variable cost. While the absolute level of annual investment is higher in the centralised scenario than the decentralised scenario, proportionally the two scenarios are almost identical (41.2% versus 41.0% respectively). Not only do both scenarios represent an improvement on the BAU scenario in that they retain more of the expenditure domestically, but also because investment in infrastructure, equipment, and conversion technologies represents an investment in local employment, local knowledge and local skills. This means that proportionally, annual investments are a better way to spend money than on variable fuel costs. While both the decentralised and centralised scenarios are an improvement on the BAU scenario, the decentralised scenario has lower variable (gas exchange) costs, and is more cost effective overall. These reasons alone are a strong impetus to move towards a decentralised system when looking towards 2050.

Sensitivity analyses: non-nuclear alternatives

The use of nuclear energy is not a typical characteristic of a Smart Energy System; as previously discussed, it is considered neither renewable nor is it characteristically flexible enough to allow better integration of renewables. Two alternatives were modelled for each scenario. One alternative replaces the use of nuclear energy by biomass burned in condensing power plants; the other uses natural gas to replace the nuclear energy. Again, the implications of the fuel compositions, CO_2 emissions, and the costs of the system are discussed.

Figure 5 shows the different fuel uses for the different scenarios and alternatives. The changes from the nuclear scenarios are clearly shown. Because nuclear energy is fairly inefficient in terms of converting Primary Energy into actual useable electricity, both the biofuel and gas alternatives have higher system efficiency overall, as the total fuel use (to satisfy identical demands) is smaller. Because the gas is converted more efficiently than the biomass, the gas alternatives are the most efficient. Comparing the centralised and decentralised systems, it becomes clear that the efficiency gains are larger in the decentralised scenarios, both in terms of absolute fuel savings and proportionally. Presumably, this is because more nuclear is being replaced.

The more interesting revelation is that while the gas alternatives are more efficient overall, they also have a fundamentally higher level of CO_2 emissions, although both alternatives still provide an improvement on the BAU scenario. This is in large part because there is less coal and oil in all the modelled scenarios, and the gas replacing them is both used more efficiently and has a lower carbon content. However, the additional gas used in the gas only alternatives means the system is not as successful in decarbonising as either the nuclear or the biomass systems.

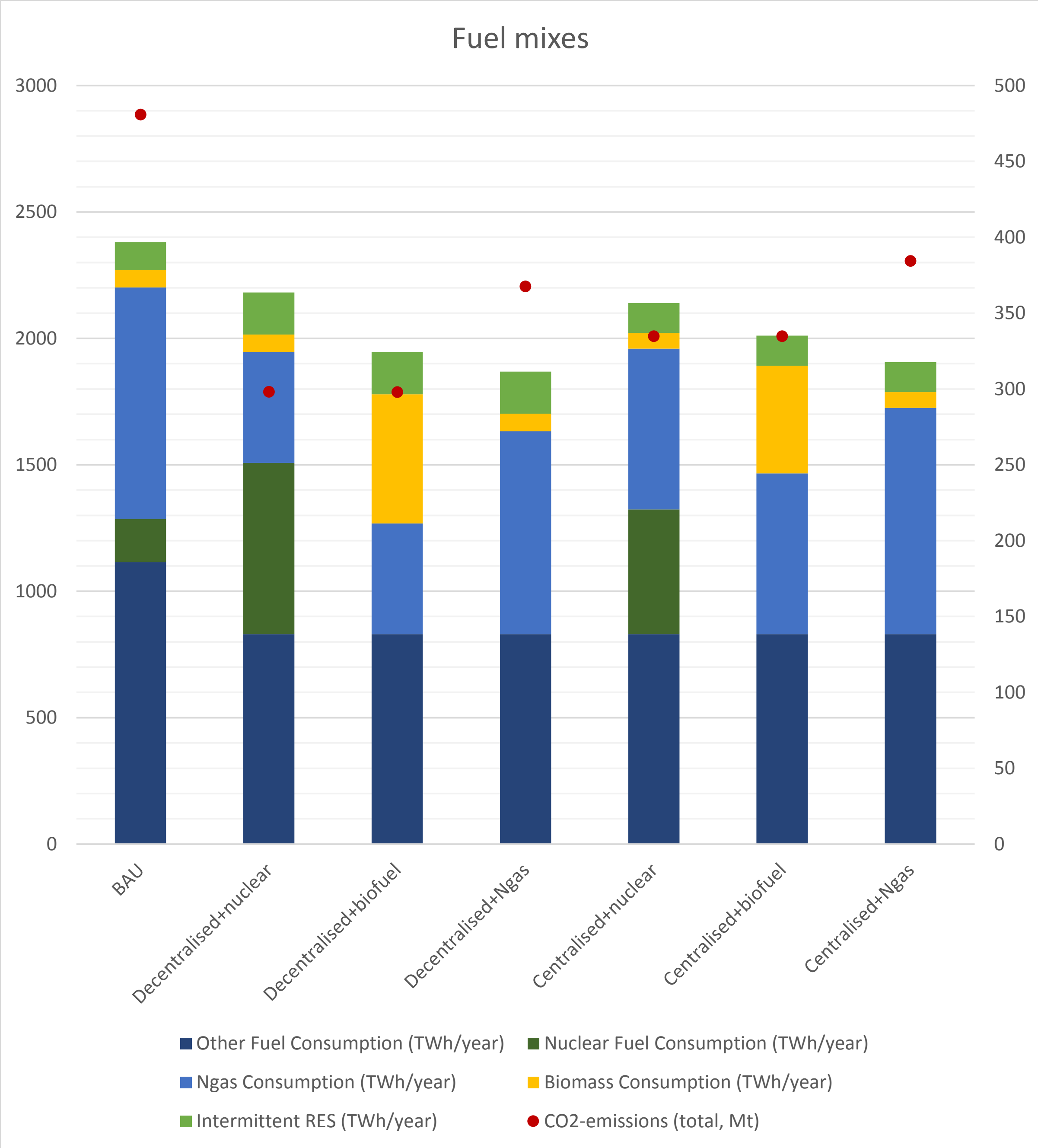

Figure 5: Fuel uses in the centralised, decentralised, BAU and non-nuclear alternative scenarios

When looking at the costs of the alternative scenarios, it becomes clear why the nuclear is included. Figure 6 shows both the centralised and decentralised scenarios the scenario that includes nuclear power results in the cheapest system. While the biomass and gas alternatives have lower annual investment costs, the higher fixed and variable costs result in more expensive system overall. This is in large part because more physical fuels are being used that have to be traded; in the biomass alternatives, the exchange costs rise from 1,965 to 16,694 million euro in the decentralised and 1,955 to 14,106 million euro in the centralised scenario. Again, the domestic potential for biomass production is not very large; already in the nuclear scenarios over half of the used biomass is being imported. In the gas alternatives, natural gas exchange costs rise from 101,815 to 114,009 million euro and 110,461 to 119,068 million euro respectively, while also increasing the costs necessary to cover CO_2 emissions in the carbon market. This means that under the given assumptions, the scenarios that include nuclear provide the best prospect in terms of being able to decarbonise in the most cost-effective way, and minimises the expenses that are likely to be directed abroad.

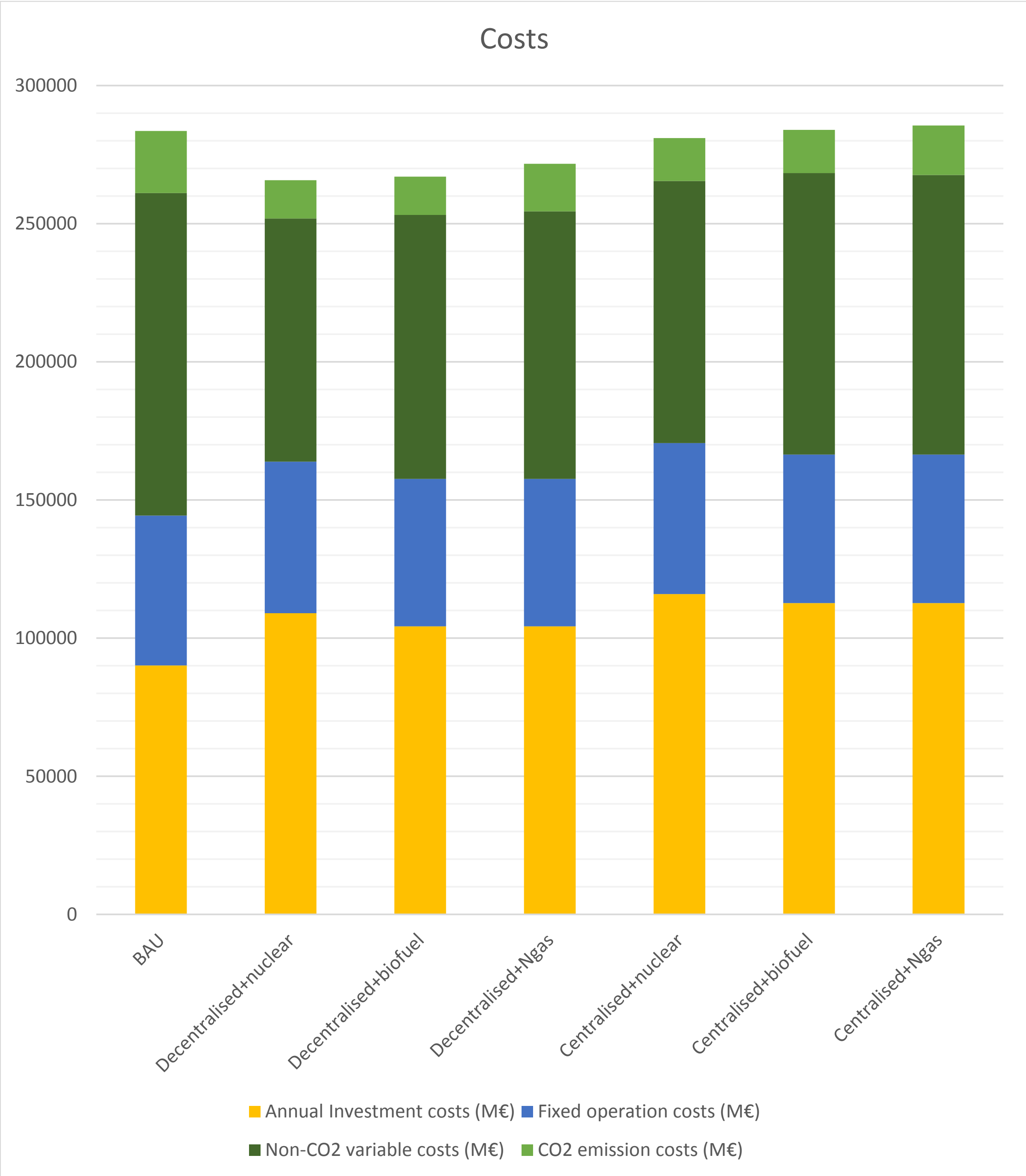

Figure 6: Cost breakdown of the centralised, decentralised, BAU and non-nuclear alternative scenarios

Robustness in the non-nuclear alternatives

For reasons set out in the methodology, it is important to understand the robustness of these findings. Due to the static nature of EnergyPLAN, changes to the investment and O&M costs of nuclear power, and fuel costs of biomass (an increase of 20%) and gas (a decrease of 20%), do not affect the fuel uses, PES and carbon emissions of the scenarios. However, an overview of the differentiation between the total costs is given in Figure 7. Several things become clear. Firstly, the decentralised scenario remains cheapest, considering all the alternative. The most expensive decentralised scenario, the gas based alternative, is less expensive that the cheapest centralised alternative, which is the reduced-price gas scenario (271,623 and 277,938 million euro respectively). This in itself speaks for the robustness of the advantages of the decentralised system in terms of cost; changes in expectations regarding investment costs and fuel costs of the base load providing technologies are unlikely to make the decentralised scenario less attractive overall.

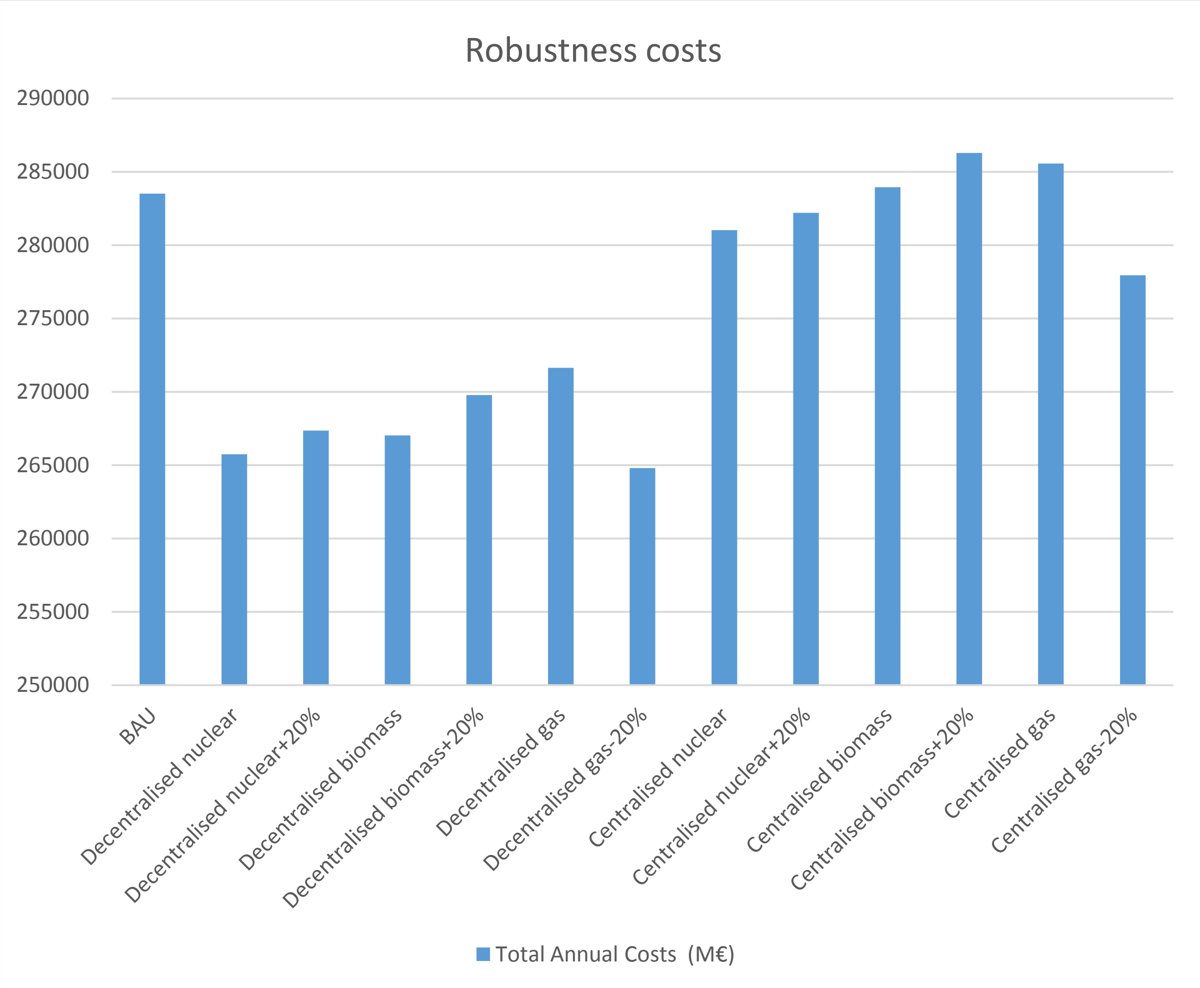

Figure 7: Costs of the centralised, decentralised, BAU, non-nuclear alternative and adjusted non-nuclear alternative scenarios

Concerning the specific technology to be used for the base load, the results are more ambiguous. For both the centralised and decentralised scenarios, a gas based system was the most expensive; but a 20% decrease in gas prices results in the cheapest variant of the different alternatives modelled. In addition, while the changes between the nuclear-fuelled and biomass-fuelled alternatives are fairly modest, the gas price reduction also has the greatest effect of the different sensitivities modelled, in both the centralised and decentralised scenario. This would indicate that an energy system based on gas, whether centralised or decentralised, is price sensitive, and its final performance is likely to depend on how fossil fuel prices develop in the future. As the sensitivity analysis shows, this could be beneficial if prices develop to be lower than expected; but if they do not, the system is unlikely to be cost efficient, whilst also being less optimal in terms of fuel, as discussed earlier.

Regarding the robustness of the nuclear and biomass in the centralised system, an increase in nuclear investment and O&M costs by 20% does not drive the costs up far enough to exceed the biomass alternative. However, it should be noted that a 20% increase in biomass costs does result in the system costs exceeding that of the (unchanged) gas scenario. Again, this points towards a fuel sensitivity in the centralised system.

In the decentralised system, a different dynamic can be observed. Here, the increased price of biomass does not result in an overall cost ride that exceeds that of natural gas; if natural gas prices remain as expected, biomass will be a cheaper option even if prices increase. However, if the cost of implementing nuclear does rise while the price of biomass remains stable, it would be more optimal to implement a biomass-fuelled decentralised system, based on costs alone. However, the difference would represent about 300 million euros – a hardly resounding conclusion in either direction. The implication of this is that the costs for nuclear power, biomass fuels, and gas should be closely monitored. The decentralised system is the cheapest and most robust option, regardless of the various sensitivity alternatives. The volatility in gas can either reduce costs to the point of efficiency – or make it the least attractive option available. An underestimation of the investment necessary to implement nuclear power could lead to an opportunity cost, as biomass fuels could provide a slightly more viable option, if fuel prices remain equal. While nuclear remains the assumed technology, it should be understood that if prices do not develop as expected, this could become an uncertainty.

Chapter summary

The aim of modelling the decentralised system in a comparison with a centralised and BAU scenario was to be able to see what the implications would be for such a system in 2050. By prioritizing different kind of technologies (based on how well they fitted in a centralised or decentralised system) two very distinct systems were created, with different technology mixes, primary energy supply, fuel mixes, carbon emission levels, costs and cost structures.

Both systems provide an improvement on the BAU scenario. This is a significant point to reiterate after extensively comparing the centralised and decentralised energy systems, because it shows that even the less-optimal version of a Smart Energy System is better at decarbonising the system at a reasonable cost than our current trajectory is. This also adds to the need to actively reform the energy system, because the current trajectory is simply not good enough; for a similar cost, a Smart centralised Energy System could be providing better options. By modelling and looking towards 2050, it becomes clear that change is needed in the current pathway.

Comparing between the centralised and decentralised system, it overall becomes clear that the decentralised energy system if preferable for a variety of reasons. While the decentralised energy system is almost similar to the centralised energy system in terms of PES reductions, it integrates a far higher level of intermittent renewable energy. Additionally, while biomass levels are very similar, the decentralised energy system uses less gas and more nuclear energy than the centralised system. Combined, this means the decentralised energy system reduces CO_2 emissions to a much larger extent than the decentralised energy system does.

In terms of costs, the decentralised energy system is also preferable over both the centralised and the BAU scenarios. The decentralised energy system represents a saving of over 15 billion euro per year. Additionally, proportionally less is spent on fuels and compensating for CO_2 emissions in the decentralised energy system, which means more is being spent on structural investment and infrastructure. This represents a better way of spending money, because it is more likely to contribute to the UK economy at large, rather than being exported. While both systems are an improvement on the current trajectory, the decentralised energy system represent a cheaper, greener option because it is better at capitalising on the synergies that occur within the system to enhance flexibility to integrate intermittent renewable sources, and reduce costs.

In terms of allowing nuclear into the fuel mix, it seems that while it is nor renewable nor undisputed, there is a large potential for it to play a contributing role. Excluding nuclear as a base load technology in these scenarios would either involve importing large amounts of biomass, or using carbon-emitting gas as an alternative. Both these options come at a higher cost, although a steep increase in nuclear investment prices could make a decentralised biomass system competitive. If gas prices are drastically reduced, a gas-based decentralised energy system would become a cost effective alternative, but this would have implications for CO_2 emissions. However, the sensitivity analysed show that all decentralised energy alternatives remain cheaper than any of the centralised energy alternatives, reiterating that the decentralised energy system is a more cost effective way of decarbonising the energy system.

5. DISCUSSION AND CONCLUSION

The implications of defining 'decentralised'

In order to be able to compare the impact of a decentralised system with both a centralised system and BAU, it was firstly necessary to understand what a decentralised and what a centralised system are. While most discussions of decentralised energy had common technologies and lines of thinking, there was a surprising lack of specificity, clarity and development of literature on this topic. Both in policy papers and in the academic realm, the focus was primarily limited to individual-scale renewables generation and heat solutions, in combination with district heating and CHP. Because a decentralised (and centralised) system had to be developed, it was important to understand what makes a technology centralised or decentralised. To this end, the influence of the point of conversion (and size), the decision making process, and the extent of the externalities was considered to understand how central or decentralised technologies were. The way decentralised energy has been interpreted in this research may be closer to community energy, in that it focusses on the mid-scale and includes both the technical and social factors. However, decentralised energy is less focussed on generating local social benefits and less explicitly stringent on local actors' involvement and ownership models (DECC, 2014; Devine-Wright and Wiersma, 2013). Rather, it recognises that the power to decide and implement decentralised energy projects does not lie solely with or concern a single entity – be that the individual or the centralised authority.

Individual technologies have been excluded from the understanding of decentralised energy; because their spatial and size connotations are so different, the decision-making process for implementation is fundamentally dissimilar, and their externalities and further social implications differ from those in the decentralised system. In the heating sector, this has made a huge difference, because while most other considerations of decentralised energy do explicitly mention district heating, they are also content to include heat pumps, biomass boilers and solar thermal solutions (Devine-Wright and Wiersma, 2013; LCG, 2007). While these still exist in the decentralised scenario, they are not prioritised. This differentiation and prioritisation between individual and decentralised technologies, specifically in the heating sector, has created two very distinct scenarios; a centralised system based on individual solutions, and a decentralised one based on district heating, even though others would consider these all decentralised. In the heating sector, this is an especially important distinction to make. One of the main messages of STRATEGO is that district heating can be expanded to 70% of total heat demand in the UK; this is phenomenal and the implementation challenge that will follow from this heat mapping is immense. The viability of either district heating or individual solutions is based on the density of the heat demand; individual solutions in rural areas and district heating in the denser areas. This distinction needs to be further integrated into planning policy; and putting all these solutions under the name of decentralised does not contribute towards that.

In the electricity sector, the differentiation between centralised and decentralised is less clearly defined. In many cases, this is because the way in which the technology is used, decided for, and the interpretation of locality of the technology. Including both the social and the technical aspects of the technologies and systems means that there is room for subjectivity. The centralised or decentralised classifications can be context dependant, however, this does not mean they should be excluded from the idea of decentralised energy. This is especially because a decentralised energy and electricity approach does seem to have had a measurable effect on differentiating the systems. The discussions in the methodology, the results in the previous chapter, and the discussion of the technical and policy implications further in this chapter will show that the differentiation that occurred in this modelling, based on this understanding of centralised and decentralised in the electricity sector, does fundamentally impact the system in its composition and also in how it performs. The differentiation that was used here led to different results, which gives credence to the idea that the classifications made were not random and have effect.

Within the centralised energy system, there may be a further need to distinguish between individualistic centralised technologies, and true centralised technologies. Part of the reason the concept of decentralised is so clouded is because it is taken to mean those things not centralised; and individual, household, business, or building technologies play an awkward role that is different from conventionally large centralised installations. The argument that they are complementary has been used here, because both the electricity and the gas grids have a very national, public works character that individual technologies cannot do without, and which drive the proliferation of individual technologies. However, true complementariness would mean that if the demand for one increases, the demand for the other also increases; the two technologies would be demonstrably linked. This analysis only compares systems: a deeper understanding of how (incrementally) increased building-based energy would affect the gas grid, the electricity grid, and the need for centralised energy production is necessary. This may then further the understanding of the relationship between individual technologies and the centralised system, and contextualise decentralised energy.

Technologies in the decentralised energy system

Before looking at the wider implications of the decentralised energy system, it is helpful to discuss the implications of a transition to a decentralised energy system from a technology point of view. The changes in the technology mixes, as well as what they mean with regards to the complexity, interdependency, and flexibility of the energy system must be understood in order to fully conceptualise the system and understand the social implications. The picture that emerges from building the centralised and decentralised systems is that many of the technologies occur in both; it is the proportional mix in which they occur that gives the system its character. This in itself is an important point to discuss, because it means that while technologies are prioritised one over the other, the implementation of a decentralised energy system does not necessarily provide an argument to drastically reduce or limit the technologies that are used within the system. It is a question of relative prioritisation, rather than outright exclusion.

While many technologies occur in both, the centralised and decentralised systems do provide very different results in terms of cost, renewability, and the kinds of energy that have been used. It is especially interesting to note the synergies that occur, providing flexibility for intermittent renewables to be integrated and cost reductions. More work could be conducted, looking at which technologies specifically within the decentralised system provides these benefits, and which technologies function especially synergistically. This would assist in understanding if there are any sectors that should be especially prioritised; for example, to what extent is the flexibility in the decentralised system dependant on the full 70% implementation of district heating? In what ways do onshore and offshore wind complement each other on an hour-by-hour basis? As decentralised energy becomes better defined, and the advantages of a decentralised energy system better understood, these questions become important in order to understand how the individual elements behave within the system, and how it differs from a centralised energy system.

The differentiation between the systems is primarily based on the extent of implementation, rather than totally excluding certain technologies. However, there are several technologies that are only viable in one system and not the other. In terms of absolute exclusion, gas boilers do not exist in the decentralised system, because urban networks for heating have become thermal rather than gas. The decentralised system has no photovoltaic power – simply because it was no longer viable. Conversely, the centralised system has no onshore wind power, because at that point in the pecking order, it is not viable. This shows how exclusion of technologies is not a priori, but as a result of the differentiated system costs, flexibility, and order of prioritisation.

While it is not reasonable to assume that these 'excluded' technologies will not be used at all in 2050, it is of note that they no longer contribute in an alternate system; money is more wisely spent elsewhere. If the ambition is to create a decentralised system, schemes to implement PV to the fullest possible extent may provide immediate benefit in terms of renewable electricity, but will not contribute (or pay-off without public money) in the long run. Investing time, money, and carefully designed policy into the components that do not contribute to the desired decentralised system represent an opportunity cost. This only makes it more imperative to have a clear, long term strategy when it comes to what the structure of the energy system should be.

The overlarge majority of the technologies that make up the energy system, are used both in the centralised and decentralised. For example, river hydro and dammed hydro are both used maximally; that is, to the extent that it is physically possible given the UK geography. Outside of the cities, heat pumps are still the primary recommended heating technology. Both systems still have a degree of district heating and CHP – which are both higher than current implementation. Both systems extensively use offshore wind turbines to generate renewable electricity. Both systems rely in part on nuclear energy, and in part on gas power plants to fulfil the base load of electricity demand. A transition towards a decentralised energy system does not involve extreme technological breakthroughs, or even an extreme change in what the technologies achieve. The technologies of the system are not fundamentally different – it is rather their proportional importance and constellation which provides the difference. When comparing the two systems, there are two technologies where their proportional prevalence is surprising and unexpected.

With offshore wind, in terms of sheer capacity the optimal amounts were found to be 35,000MW in the decentralised system, and 33,300 MW in the centralised system – even though in the decentralised system, offshore wind was only prioritised 5th, while it was the first choice of electricity generation in the centralised system. This seems like a paradoxical finding, because it means that if the aim is to use as much offshore wind power as possible, the better strategy is actually to implement a more decentralised system. Firstly, from the viewpoint of the sector alone, this implies that large amounts of offshore wind and a decentralised system are not incongruent. Moreover, this is an indication of the flexibility of the decentralised system; even though at this point 29,103 MW of intermittent renewables has been installed, it is still able to integrate offshore wind energy more cost effectively. This flexibility and ability to integrate renewables is also an indication of how the centralised and decentralised heating systems function. In the decentralised system, the rationale was that the combination of CHP, large-scale heat pumps, and thermal storage allows for the minimisation of electricity production and maximum use of excess electricity when a large supply of intermittent renewables is present; the centralised heating scenario relies on heat pumps to be able to absorb the excess electricity. Between the two, the extent to which offshore wind can still be integrated into the decentralised system speaks for the added value that a decentralised heating system brings to the energy system at large.

Similarly, the result for the different amounts of nuclear in the systems are interesting. The expectation was that nuclear power, with its inflexible nature, would be more difficult to implement in a decentralised system – especially as the decentralised system does use a significantly larger amount of (intermittent) renewables in its energy mix. However, the installed capacity in the centralised system is only 28,800 MW, while the decentralised system has 39,500 MW of nuclear power installed. This results in the decentralised system using 677 TWh/year of nuclear energy, while the centralised system uses only 494 TWh/year. In parallel to the discussion of offshore wind, a primary conclusion of this is that nuclear energy – even in relatively large amounts – is not incongruent with a decentralised system, and can actually be better deployed in an otherwise decentralised system. The underlying reasoning here is that because the decentralised system uses a more balanced variety of intermittent renewables, specifically both on- and offshore wind turbines, the fluctuations that characterise intermittent renewables still occur, but as they occur in different ways, they cancel each other out. In the centralised scenario, offshore wind represents over 75% of intermittent installed capacity (versus less than 55% in the decentralised scenario); this means the fluctuations in intermittent renewables at large are heavily dominated by the performance of the offshore wind turbines.

One reason that the decentralised energy system may perform better is because the renewables are diversified. This idea of aggregating various different renewables to decrease intermittence variance has been studied at times, primarily using the contrasting natures of wind, (wave) and solar powered technologies (Halamay et al., 2011; Chen et al., 2014). Given that it appears from this decentralised system that even two different kinds of wind technology can have a smoothing effect, there is a strong argument to better understand the synergies that can exist between different kinds of intermittent renewables better, and thereby create positive externalities. This is worth further studying and understanding, especially as the climatic conditions in the UK are likely to require UK specific data to fully understand the potential of diversifying and combining different renewables to create an optimally synergetic combination. The immediate implication is that creating a more decentralised and diversified system is likely to make the further implementation of renewables more viable.

Secondly, the implication of diversifying is that it is not sufficient for policy to merely prioritise and address one type of conversion technology. There has to be a balance in prioritising decentralised energy initiatives, while also ensuring that diverse decentralised energy initiatives are implemented. For example, when the Green Investment Bank started investing, it was very much focussed on a limited set of technologies, with offshore wind being the paramount in the energy sector (BIS, 2011). As such it was easy to perceive it as being primarily aimed at large, centralised projects – especially in the realm of energy. This of course would not contribute to a decentralised, diversified policy direction which would capitalise on the synergies possible between technologies; rather, a wider-cast, more comprehensive strategy is needed. This may not have the same communicability, but the synergetic effect intermittent renewables have on each other should endorse a decentralised, diverse policy approach rather than singular support for particular technologies. While prioritising, policy in a decentralised energy system would at the same time also have to ensure diversification.

A final more technical implication of the decentralised energy system is the levels of critical excess electricity production (CEEP), touched upon in the results chapter. To integrate intermittent renewable electricity, the Smart Energy System concept relies primarily on the flexibility that results from linking the heating and electricity sectors, and thermal storage. Although some electrical storage is present, it is not the cornerstone of flexibility, primarily because it has generally been considered too expensive, while the regulation of CHPs and thermal storage are proven, technically secure technologies which are much easier to extrapolate towards a 2050 scenario.

Improved battery and electrical storage performance could be of great importance in two ways, especially in a decentralised energy system. Firstly, reducing electrical storage prices could make it a viable option to utilise and capitalise on the CEEP that is already present, which would have more impact in a decentralised system, as there is more CEEP in the system. Secondly, a more ambitious Smart Energy System aims to integrate the transport sector into the flexibility and regulation of the energy grid (see Lund and Kempton, 2008; Mathiesen, Lund and Karlsson, 2011; and Lund, 2010). Improved electricity storage technology would make these options much more attractive and would improve the possibility to integrate intermittent renewables into the system, but have not been overly relied upon in this modelling.

Concerning the range of technologies used in this research, one option that would have been interesting to include is concentrated solar power or photovoltaic farms as a decentralised technology. Photovoltaic plants could be an extremely effective way of allowing people to invest and take part in renewable energy when their own homes do not allow for PV installation (be that technically, because of ownership/tenancy, or planning barriers). Additionally, in the same way large-scale heat pumps benefit from more optimal placement, CSP or PV plants could capitalise on efficient placement. Centralised solar power could be a great example of people forgoing individual solutions (such as solar PV), instead combining funds to collate the mirrored parabola that uses solar to power a steam turbine (and use residual heat for industry or district heating). These could be great ways of decentralising solar technologies, while also expanding the general capacity of both PV and intermittent renewable resources. However, average solar intensity in the UK is not high enough to make these CSP specifically viable on a grand scale, when doing national modelling (Connolly, Hansen and Drysdale, 2015). Several projects are currently under development in the UK; in areas like Devon and Cornwall, but surprisingly also in more northern areas (RES, 2015). A more detailed mapping and understanding of where solar intensity does make CSP possible is necessary; especially for the southern regions. Hopefully, the continued attention decentralised energy is receiving means other potentially decentralised options, like decentralised solar power, will receive more attention so they can be understood better.

Conceptualising a Smart decentralised Energy System

By creating and comparing centralised and decentralised energy systems for the UK it is helpful to summarise several aspects in order to conceptualise the decentralised system more clearly. Firstly, the decentralised energy system is preferable, because it is cheaper, and provides more environmental benefits. Secondly, in order to do so, it uses synergies and diversity that allow for increased flexibility and interconnectivity enabling it to integrate more intermittent renewables at a lower price. The key to this is interconnectivity, and making full use of the externalities that exist in the system.

Complexity and externalities require trust

Looking at the decentralised energy from the point of view of game theory may be beneficial, because it allows for a conceptualisation of the implications of a complex situation where externalities take place. Game theory "concerns the behaviour of decision makers whose decisions affect each other" (Aumann, 2008). In essence, it uses rational behaviour models to understand situations where people or entities act strategically towards each other, what different outcomes can occur, and how optimal they are. The decentralised scenario represents a world of complexity and interconnectivity; where individuals cannot as easily make their choices independently anymore, but choices are also no longer being made for individuals without impact. The synergies in the system mean that different elements and individuals involved in the energy system must rely on the services being provided by other parts – and will only be functional and profitable if this is the case. In both instances, a level of cooperation, coordination and trust is required, and this is true for the majority of the technologies that have a decentralised nature. A trust game, like the stag and hare game, can represent the implications of this kind of situation is in a simplified manner.

The stag and hare game was first described by Rousseau, and variations exist, but this version is summarised from Skyrms (2004). A number of hunters are out in the forest, where the only animals available is stag and hare. However, to catch a stag, they must cooperate as they lie in wait in their respective posts. Catching a hare is easier, and any of the hunters can easily shoot one by themselves – but the lack of cooperation eliminates the possibility of catching a stag. If the hunt is successful, two scenarios are possible: either one stag is shot, shared, and provides a certain payoff (x, where x>y) for each hunter. Alternately, a hunters can catch a hare (with payoff y), and no stag is caught. The share of stag being larger than a hare is crucial (x>y), otherwise, a different game is played. In this situation, the decision for any individual hunter is then to cooperate, lying in wait for the stag and the larger payoff, but risk having nothing if a different hunter goes after a hare. Alternatively, the hunter can ensure a catch by hunting his own hare - but thereby limit the catch of the others.

It should be clear that while one scenario (sharing the stag) is clearly preferable for everyone, there is no a priori 'better' or 'worse' action here for the individual, because the optimal decision depends on what the other hunters do. If the other hunters cooperate and wait, it is best if the hunter waits too, and gets a share of the stag. If the hunter knows or reasonably suspects the other hunters will hunt hare, it is best to hunt hare too and have a chance of catching one. Some not hunting hare while the others do is a suboptimal position, because it wastes time and effort, and some of the party are likely to come home without. The worst case scenario is not knowing; when the expectations and level of (dis-)trust is uncertain.

There is a parallel between the hunters' scenarios and strategies and the choice between a centralised or decentralised energy system. On the one hand there is the decentralised system, able to bring larger benefits for all if the gains are redistributed in a fair way (like the stag), but requiring cooperation, strategic coordination, and trust in order to incorporate all the synergies that are necessary. On the other hand, the centralised system, with individual choices but little ability to influence the closed and institution processes, represents the temptation to avoid risk and be secure, and have a hare. Cooperation, trust, risk, and gain; avoid risk, be independent, but be less well off. This parallel is useful, because it gives some insight into what the difficulties are in achieving a decentralised system, and several prerequisites.

Firstly, it should be clear that the stag has to be shared out. If the stag is caught but not shared there is no payoff for the cooperation of the other hunters; if the benefits that come from a decentralised system are not redistributed, there is little incentive for people and sectors of the energy system to start collaborating, and it is unlikely a decentralised system will be achieved. This need not necessarily be a fair share – for example, in a very trusting community, where stag are common, hunters may only receive the equivalent of a hare if a stag is shot, and be appeased. However, there should be at least an equal, likely higher payoff. The larger the difference between the payoff for everyone when a stag is shot (x) and a hare (y), the more likely hunters are to 'take the risk' and refrain from shooting hare, and wait for their share of the stag. For a decentralised system, this means that the larger the savings are, the more impetus people have to change, and trust in the change.

Secondly, the situation is likely to be repeated, so the decision made now is likely to be remembered in the future, and be influenced by past decisions. This effect, which makes the stag and hare game different from better known trust games like the prisoner's dilemma, is called 'the shadow of the future' by Skyrms (2004). If half the party disappear to shoot hare on the first day, it is unlikely there will even be an effort to shoot stag the next time without an organised, coordinating intervention. For example, if someone invests in an onshore windmill, and is not properly reimbursed on their investment, they are unlikely to repeat the decision. In energy systems, this is especially important when it comes to thinking about household and consumer decisions, because while installations like power plants and distribution infrastructure have long lifetimes, technology like condensing gas boilers, heat pumps, and PVs may not necessarily. Failing to adequately reward investment now may lead to a breach of faith and backlash in 10-15 years, making the implementation of a decentralised system even more difficult.

This 'shadow of the future' is important, because it gives a representation of the difficulty in building up trust, and the ease with which it is lost. The importance of trust, and fragility of it, has been raised in the context of community energy, and is by no means a given (Walker et al., 2010). Garnering the trust, through cooperation and coordination, is required to ensure the hunters do not go after hare. This is the aspect of the game that led Rousseau to write about it, and it has become an analogy in classical political philosophy, and a key point in much wider social contract thinking (Skyrms, 2004). The trust is a direct result of being dependant on the choices of others to be able to make our own decisions, and to ensure that if a cooperative decision is made, it pays out. That final aspect is, ostensibly, the easiest from a policy point of view; it requires creating and maintaining a long-term, stable strategy that will ensure that both individual consumers, businesses, investors, exploiters, and everyone involved in the hunt for decentralised energy knows what the aim is and how this will be achieved.

Creating and ensuring such a plan is a complicated task when it comes to strategic energy planning. Firstly there are external factors that can change the needs of the energy system; sudden geopolitical shifts in oil and gas exporting countries, financial crises or recoveries; nuclear reactor breakdowns. These make planning for the long term difficult, because they present immediate, debilitating challenges. The second is the continual game of political will, vested interests, viability, and consistency, which are expected to fluctuate over time. The problem with designing a long term, strategic approach toward decentralised energy is that it is not a target, or a benchmarking aim. Trying to achieve this kind of systemic change cannot be suspended or reversed for several years until the crisis passes, because that will undermine any trust that has been garnered, and affect the future decision-making – proportionally towards a scenario where cooperation and trust disintegrate, and the financial and environmental benefits of a decentralised scenario do not materialise. Policy makers will have to develop a strategic long term plan that is both ambitious enough to induce actual change, resilient in its design to be able to maintain itself in the face of changing geopolitical relations and economics, and negotiated to ensure political, corporate, and consumer support from all sides. Failure at any instance will have more effect than succeeding at multiple instances. This is the difficult art of social contract thinking – in an energy context – that is unlikely to be easy.

Market mechanisms to reallocate benefits

When it comes to redistributing the benefits of a decentralised energy system, as well as encouraging people to make choices that fit within a decentralised energy scenario, market mechanisms are one of the policy instruments at planners' disposal. Policy which aims at influencing consumer choices through market incentives, rather than outright choice intervention, seems the most feasible policy approach given the UK policy climate and cultural relevance: the UK has one of the most liberalised and competition-based energy markets of Europe (Toke, 2013; Bartle, 2002; Ofgem, 2015). The ability for consumers to freely switch suppliers, induce competition, and make real choices in the energy market has been the aim of successive energy policies, dating from privatisation in the '80s and '90s. The current Renewables Obligation mechanism (which is largely only available for corporate energy producers) is also very much a market-based approach. It seems likely that using market mechanisms to incentivise people to make choices that contribute to a better, decentralised Smart Energy System is the most politically feasible tool policy makers have.

As a first point related to the market workings of a decentralised energy system, it is important to understand that the modelling does not take subsidies into account for renewables of energy efficient technologies – or for fossil fuels. In the UK, these subsidies come in many different forms; direct transfer, indirect transfers, exploration aid, research and development contributions, tax concessions or exemptions, or even, arguably, the failure to tax externalities directly related to fossil fuel use (Whitley, 2013; Coady et al., 2015). Clearly subsidies are directly contrary to the concepts of an accessible, fair market for alternative, renewable and decentralised energies, the concept of 'polluter pays' as a mechanism for internalising the effects of harmful activities such as the widespread combustion of fossil fuels, and the basic aim to decarbonise the energy system and economy through market-based measures. Without adequately addressing these issues, there is a continual detraction from any serious effort to address the problems of a current energy system. Additionally, the decentralised energy system uses more energy from renewable sources, so would be proportionally more negatively affected by continued fossil fuel subsidies. Subsidies and market advantages for fossil fuels are not only contradictory to many energy policies, but would impact a decentralised system disproportionally.

The subsidy-free way of seeing costs links to a wider implication that comes from the way costs are handled in this modelling. Because the costs are system wide, and not necessarily a reflection of the actual market price of the technologies (due to aforementioned taxes and subsidies, market distortions, etc.), the relationship between the cost of the energy system and the cost to the consumer is not necessarily clear or correlated. A decentralised energy system need not be explained or argued from an environmental or community-engaging point of view; a cost decrease of over 15 billion euros should make energy provision easier and cheaper for all. This implies that the benefits that arise from a cheaper (decentralised) system need to be redistributed throughout the population; the stag must be redistributed. This is a key part of incentivising and encouraging the implementation of decentralised energy; by ensuring that efficiency gains which are made are also effectively used to make the consumption of energy cheaper.

An additional aspect of this is specifically redistributing the benefits from the externalities that occur in the system, and internalising them in such a way that it encourages them. For example, in the decentralised system the heating sector – through its extensive use of CHP – ensures enough flexibility to be able to integrate intermittent renewables. Otherwise put, when someone chooses to produce CHP, and when someone chooses to use district heating, a benefit occurs that is external to both of them; the ability to actively integrate more renewable electricity falls on the producer of intermittent renewables. It would be both unfair and inefficient if the only actor to benefit from the flexibility would be the intermittent renewable energy producer; in part because the CHP would not be incentivised to actually provide any flexibility, but also because less people than optimal would choose CHP. This also means it is likely that the market alone will provide less than optimal CHP plants in the system, if no intervention takes place. To solve this, there are several options to internalise the externality; to balance the impacts over all affected. Either the intermittent renewable electricity company pays the CHP company for providing the flexibility services, which could then be redistributed to the consumer, who pays less for their heat. Alternatively, the CHP decides the benefits that result from their actions are so large, that adding a renewable intermittent component to the company (to use their own flexibility) would be profitable, and could reduce costs for consumers. Both solutions result in the CHP being incentivised to act optimally in terms of providing its services and in terms of providing flexibility for the intermittent renewable electricity sector. Additionally, customers having a lower heat price and so CHP will be more attractive, drawing more customers and expanding the system to a socially optimal amount.

A simpler example is a household scale heat pump, which features predominantly in the centralised scenario, but also plays a key role in rural areas in the decentralised system. The heat pump itself is relatively expensive for the consumer; the high efficiency does not, as a given, offset the investment costs over its lifetime (Paardekooper, 2014). However, it can provide a crucial role in the balancing of intermittent renewables, and in reflection of this it plays a much larger role in the (socially optimal) scenarios than would be the case if it were a system judged from the consumers' perspective alone. To encourage the uptake of heat pumps where they are appropriate, the customer should be compensated for some of the external benefit that their heat pump supplies for the larger system. The inverse is of course imaginable; that technologies which are less flexible are taxed because, through their unyielding nature, they provide an inefficiency and cost to society that could be avoided. Externalities should be accounted for; social costs or benefits should be reflected to ensure socially optimal choices are being made. This is part of the reallocation process, and part of the way in which society can agree to incentivise people to use technologies that fir in a decentralised energy scenario to build it.

Convincing consumers to alter their behaviour for reasons other than their own gain is difficult; even with full information, access to capital, and all other barriers removed it is difficult to convince people to do something that is better for society at large, but not optimal for themselves. At a minimum, there has to be an assurance that those people who are making choices that contribute to the synergetic efficiency of the system are (partially) compensated for their enabling actions. The fiscal options are endless, but the underlying point is that if a Smart (decentralised) Energy System avoids costs by capitalising on the benefits that arise with interconnectivity and synergies, these kinds of considerations will become much more common. Interconnectivity and interdependency is likely to require stronger regulation and a stronger energy 'social contract' to ensure better cooperation and coordination than is necessary in the BAU or a centralised energy system.

Using ICT driven 'smart' energy

When it comes to facilitating regulation, cooperation and coordination, the concept of ICT driven 'smart' energy and its acceptance by consumers could be extremely beneficial for a decentralised Smart Energy System. Firstly, the daily functioning and flexibility of ICT-driven 'smart' energy can hugely add to the functioning of a Smart Energy System: it is one of the crucial unspoken elements that regulates the CHPs, heat pumps, intermittent renewables, and grids. Secondly, it improves control predictability, and adjusts to unexpected circumstances with protocols and regulations. The stag and hare is a coordination and a trust game; if computers are coordinating each other's choices, the game is effectively playing itself. In a sense, a well-designed 'smart' system can alleviate the need for people to make decisions towards the cooperative and continual nature of the Smart Energy System in the short term. This effort to entice people to make choices that contribute to the system overall has the potential to tie in quite closely with the ideas of smart planning and smart use of ICT, connectivity between sectors, and using knowledge better.

For a Smart Energy System to be able to integrate and balance intermittent renewables, a level of continuous knowledge and control is assumed that does not directly involve the individual consumer. Even now, in the realm of 'smart' energy grids, these concepts are used to facilitate two-way flow electricity grids, demand-shaving, and using intermittent electricity availability to adjust the charging patterns of electric vehicles (EVs). Field tests for smart HVAC systems assume that as long as certain (indoor temperature) boundaries are respected, the appliance itself determines the optimal points of functioning and not functioning, resulting in better market functioning and better integration of intermittent renewables (Broeer et al., 2014). As an example, this also shows that there is a genuine expectation that as systems become smarter, they allow for better pricing to customers, better integration of intermittent renewables, but crucially also for consumers to give up direct control of their appliances.

The ultimate result of many of these efforts is for individuals to relinquish the control over the use of their appliances as long as they can still fulfil their basic function, based on the premise that they will become more energy efficient and/or cheaper. The underlying explanation could be that while customers care about their end demand (the pleasurable ambient temperature, the lighted room, the working stove, the moving vehicle), customers have less concern for how this is delivered to them (their energy demand), as long as it is as easy and as cheap as possible. The important point is that these people have already chosen which technology they are using; it is merely how it is being used that is relinquished. Extrapolating this to the choice of technologies that make up the energy system, people value the utility they derive from the product, and not necessarily the product itself. If the assumption holds, consumers may eventually be willing to also let 'smart' systems choose what technology is best for their building – as long as the end demand is satisfied in a cost-effective way.

As long as the package of energy technology and its regulation are provided by a transparent, trustworthy entity, function within the requirements to meet the consumers' end-demand, and result in an economically beneficial agreement, there is scope for this to happen. This would allow for both better services to consumers, but also better integration of intermittent renewables. It would make use of our immediate and enhanced knowledge of the energy market; it would require different sectors to work together, most likely both private and public. Most importantly, it would use the knowledge and intelligence that the energy sector has on demand, supply, transmission, integration, availability and consumer behaviour to provide a smarter and better service to the customer; it represents everything smart stands for.

The big question is if successful implementation of an energy system requires more trust than it can garner; especially if it is done by utility companies. Currently, trust, relinquishing control, understanding the needs and worries of consumers, and the necessity of introducing a whole new way of supplying energy is fickle, and uncertain, especially given the current climate in the UK. The past years have seen an unprecedented rise in peoples' surveyed distrust in energy supplying companies, that has not been resolved by consumers switching companies or taking their business elsewhere (Ipsos MORI, 2013). This is primarily because distrust and dissatisfaction with the services is equal for all companies; the market is not providing a clear 'better' alternative. The failure of the market to properly compete is such that is has led the market regulator, Ofgem, to refer a full-scale investigation of the current market to the Competition and Markets Authority (Ofgem, 2014). Most worryingly, this referral is also based on the inability to effectively combat high barriers of entry to the market, and suspicion about the similarity between companies' pricing behaviour (ibid). Options for alternative companies, which could possibly capitalise on even remotely decent customer service and relations, seem unlikely to gain access to the market in the near term.

Current consumer confidence in the energy sector is unlikely to make consumers feel willing to relinquish any control, unless energy providers manage to act in fundamentally different and more trustworthy ways than current utility companies. The question is if more trust is required to be able to establish 'smart' energy than it would create; in other words, what levels of trust are required for 'smart' energy to take off, and what effect that would have on peoples' general attitude towards energy. The question becomes to what extent people are willing to relinquish the choice of technologies –and to what extent we trust other entities to have control - in favour of a smarter, more synergetic, and cheaper energy system. The next question is if the current players in the market of supplying energy can establish such a model in a positive, fair way within the next 35 years. A decentralised energy system in 2050 would also imply a very different relationship between the customer and provider. If possible, ICT driven 'smart' energy could contribute greatly in a decentralised energy system, but this issue hinges on the trust, cooperation, and interaction between customers, companies, and planners.

Improved planning

It should be clear at this point that the implications of wanting to implement a decentralised energy system are not in the technical, but in the social and planning realm. This conclusion inevitably results in a need for better planning; both of a higher quality so it can induce trust and coordination, but also at a less central/more local level to reflect the nature of the technologies that are more prevalent in the decentralised energy mix. This is something that has to be recognised and treated seriously, because one of the implications of the stag and hare game is that both outcomes are not only possible, but completely rational and expected – no matter the payoff difference. In other words, without trust and cooperation, it remains possible and likely that a hare will be shot at, and there will only be hare-hunting hunting in the forest – even if the stag has golden antlers. Spending money, time, and energy is fully justified in order to still create a benefit overall. Based on the costs modelled, spending less than 15 billion euros per year on improved planning to ensure a decentralised energy system will still result in a cheaper system overall.

One of the challenges energy planning will have to face in order to improve public understanding, trust and cooperation is the way the public engages with energy and planning processes. As discussed in the theoretical overview, one element of smart planning is that it implies a level of cooperation between planners and other sectors, including the private sector. This goes further than merely in the smart use of technology, but also in the actual planning and implementation process. In his review of Divine-Wright's book, Pitt points out that many of the recommendations for better public engagement towards renewable energies are fairly incongruous with the way that private investors and corporations function (2012). Planning has to be a collective effort between the public, companies and the government. This is even more specifically the case if planning is to become less streamlined, and more (continually) adjusted to the specific understandings of place and the project potentials at hand, as is the underlying understanding of better participation. The necessity to have a continual cooperation between the private and public sectors in the planning and implementation process may provide an extra impetus for the public-private partnership nature of a smart cities, communities, and energy systems to take place.

Opponents to projects, especially wind, are rarely uninformed or ignorant, rather, a result of the complex interactions between place, planning and trust (Aitken, 2010). Especially if we acknowledge that companies, nor planners can ever truly achieve the complete and varied understandings of place, smart partnerships could play a large role in garnering acceptance. Specifically, this is the case for those companies which actively choose to incorporate collective or social intelligence in their decision making. Firstly, this can contribute to the complex, sophisticated communication and understandings that can help dissipate NIMBY-like resistance. NIMBY is as much a result of 'how' as 'what' (Devine-Wright, 2004). Secondly, one of the presumed barriers to decentralised energy is the barrier of necessitating cooperation and coordination: a more inclusive, open, participatory discussion about what options are available for energy may bring people to become included who are generally willing to pay or participate, but without the willingness or ability to act independently. Using collective knowledge in a smart public private partnership process can not only reduce resistance, but also improve on the participation rate, and provide a better solution for all.

There is another specific reason that the inclusive, participatory, and successful implementation of decentralised energy experiences is important. Research into the changing of people's (political and social) attitudes and prejudices show that while changing opinions is incredibly difficult, and general approaches such as priming, framing, and dispelling stereotypes may result in temporarily changed attitudes, but not necessarily in lasting opinion change (LaCour and Green, 2014). LaCour and Green contend that permanent change in attitudes can take place following face-to-face canvassing using scripts that involve a thoughtful discussion based on personal and acquaintance experiences and elements (without necessarily emphasising loftier or general moral sentiments). Most significantly, they found that while all canvassers reduce prejudice in a statistically significant way in the short term, canvassers who identified (to the subject) as being impacted or involved directly by the issue resulted in much more profound change – both in magnitude and length of opinion change (ibid). Additionally, this group of canvassers caused a spill over effect that was not seen with other canvassers (ibid).

There are several important elements to note from this with regard to reducing resistance and prejudice towards decentralised energy projects. Firstly, a participatory project should add to people's' knowledge, commitment, experience, and, with the fear of sounding lofty, to a sense of identity. There is some evidence that people who live directly next to wind turbines are slightly more positive about wind farms (Dulas Engineering, 1995 and Scottish Executive Central Research Unit, 2000, both in Devine-Wright, 2004). People who come out of the processing believing there is a tangible improvement that can be spread, and compellingly describing the impact of decentralised energy on their life, can be valuable assets. This is all the more important as there are indications that when it comes to renewable projects like onshore wind, the opinion of local familial and friendly networks is a high determinant of how the subject feels about the technology (Devine-Wright, 2004). Successful participatory processes can improve the outcome of planning processes.

Secondly, participation (and good experiences with participation) need not end when the project has been implemented. If people who have direct experiences can create rapport and are more effective persuaders, they can become a valuable part of the next step, whether formally or informally. Lacour and Greens research, while in a very different field, show that people who are directly impacted (for example, by the effective planning of a large-scale heat pump for district heating, or onshore wind turbine) are the best people to be able to change others' attitudes. Thirdly, the understanding of NIMBYism is difficult both because it is often place-bound and locally determined, but also because it has lacked serious interdisciplinary research free of typical biases (Pitt, 2012; Aitken, 2010). Using participatory processes to genuinely understand and learn more about how and why resistance takes place can make a valuable contribution to solving such problems. In other words, using collective intelligence within a smart framework can also mean using people's' experiences to alter perceptions, reduce prejudice, and garner support for subsequent projects.

Better understanding of participatory processes, and how they induce trust and cooperation into the energy system and the planning process are likely to be only part of the answer. As the technological challenges become less prominent, and the implementation challenges more poignant, it is important to remember that investing in implementation and planning is justified. This involves planning in better ways, and ensuring that the energy system is seen in a better, more trusted, more coordinated way. This can be by encouraging partnerships with all sectors, both to encourage ICT driven smart energy and to enrich the planning processes. It should also involve investing to gain a better understanding of what is needed in order to garner trust and cooperation in the energy system. Better planning, and even more expenditure can be justified in order to establish that it is appreciably less expensive and better for the environment – especially if it can ameliorate the way the energy system, in whatever form, is viewed and understood.

Conclusions

The need to continue looking for better energy systems in unquestioned, and in the UK, decentralised energy is gaining attention as a way in which to achieve such improvements. As the term becomes more frequently used in policy, literature, and by industry stakeholders, it becomes important to understand what the implications of a decentralised energy system would be for the UK, looking towards 2050.

The first implication of discussing decentralised energy is that a better definition and a more sophisticated discourse is needed on what decentralised energy actually is. This work has chosen to differentiate between centralised and decentralised energy based on technical and social factors of the energy system; the size and locality of the conversion technology, the decision-making process to implement technologies and systems, and the external effects that occur, and contribute to the synergetic nature of a Smart Energy System. Based on this, the decentralised energy system is understood as a system where individual or institutionally closed decisions are not possible, because of the impact of the system on others and because of the scale and locality of technologies implemented in it. Decentralised energy should be physically or conceptually linked to locality, but this is not as stringently applied as community energy concepts are. These understandings provide parameters which can be applied to technologies, projects, proposals or plans to assess to what extent they fit in a decentralised system or not.

Comparing a decentralised energy system to a centralised and BAU scenario, it becomes clear that a decentralised energy system could greatly contribute to the cost effective decarbonisation of the UK energy system. Both a centralised and decentralised energy system represent an improvement over the BAU scenario, but a decentralised energy system in 2050 integrates more and more diverse intermittent renewables, uses less gas, and emits 11% less CO_2 than a centralised energy system. At the same time, a decentralised energy system costs 5% less than a centralised scenario, saving over 15 billion euro per year. Proportionally more money is spent on activities that support the wider UK economy, while less is spent on fuel and compensating for CO_2 emissions. Many of the technologies in the centralised and decentralised system are the same; in part because the decentralised energy system is flexible enough to still be able to integrate centralised renewables after decentralised renewables have been optimised. The underlying explanation for the decentralised energy system's performance is that it is more interconnected and more flexible which allows it to capitalise on synergies both in the fuel mixes and in costs. The implication is that a decentralised energy system can add both to the cost effectiveness and the environmental impact of the energy system.

Based on these results, it becomes clear that a potential move towards a decentralised energy system in 2050 requires not only a technical change, but a much wider social change in the way we see and organise the energy system. More interconnectedness, interdependence and complexity require more and better planning and managing in order to be able to capitalise on the gains a decentralised energy system can provide. By looking at the energy system from the perspective of a trust game, where individuals' choices are affected by others choices, and coordination is required to be able to maximise returns, the implications of a potentially beneficial, but more interdependent energy system was further explored.

Using this analogy, the role of market interventions to redistribute the benefits of a decentralised energy system, and to ensure the internalising of the externalities has been discussed. Because the decentralised energy system is increasingly connected, and externalities are larger, market intervention is required to ensure that people are incentivised and rewarded by a decentralised energy system. Because a decentralised energy system is unlikely to be able to persist without these kinds of reallocations, a decentralised energy system is likely to require a higher level of market interventions.

Additionally, a decentralised energy system has implications for the role of ICT-driven ‘smart’ energy. Because of the high level of coordination and regulation necessary in a decentralised energy system, ‘smart’ grids, appliances and management have a huge potential to contribute to the effective management of an energy system, smooth decision-making and ensure the potential monetary and environmental gains. However, the need for people to relinquish the control of the functioning (and possibly choice) of their device implies that successful implementation of ICT-driven smart energy goes hand in hand with what a decentralised energy system needs; trust, transparency, and the potential to make energy more efficient for the end consumer.

The overarching implication of the decentralised energy system is the need for better, participatory, and engaging planning in order to garner the cooperation and trust required. Smart planning can contribute to it, if it effectively manages to enhance cooperation between the public, government, and private sectors. If done well, the effective use of knowledge and experience can not only make planning more effective, but also build larger public understanding and support for decentralised energy technologies and systems. A decentralised energy system not only implies the need for better planning and planning processes; because a decentralised energy system has the potential to be radically cheaper than a centralised energy system, a decentralised energy system would also imply an opportunity to continue investing in improved planning and innovative planning processes.

The decentralised, interconnected and interdependent nature of a decentralised energy system require a different prioritisation of the technologies that make up the UK energy system, but also a change in the way the energy system is organised and planned. Redistribution, trust, cooperation, participation and the better use of (local) knowledge can help not only achieve decentralised energy projects, but also build the larger support and trust required for its success. Because a decentralised energy system not only requires a larger proportion of investment in infrastructure, but also hinges on trust, transparency, coordination, cooperation, and implies a change in the way we organise the energy system. If it is possible to establish it, a decentralised energy system involves investing in infrastructure, people, and planning to have a cleaner, cheaper, and more open energy system for the United Kingdom.

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