

Approaches in modelling a resilient energy scenario in UK MARKAL Elastic Demand (MED) version

Ramachandran Kannan

King's College London, Strand, London WC2R 2LS, United Kingdom
Email: r.kannan@kcl.ac.uk / r.kannan@email.com

Abstract

The UK government sets a legally binding greenhouse gas emission reduction target of 80% by 2050, while ensuring a secure and affordable energy supply. Under the UK Energy Research Centre (UKERC) Energy 2050 project, four core scenario analyses have been undertaken to explore the pathways to a low carbon and resilient energy system. A resilience energy system is defined as the set of technologies, physical infrastructure, institutions, policies and practices located in and associated with the UK which enable energy services to be delivered to UK consumers. A number of models and analytical tools have been used for the resilient energy system analyses, and MARKAL model is one amongst them. Within the analytical framework of the UK MARKAL elastic demand (MED) model, the resilient energy system has been characterised through diversity in energy supply and reducing the final energy demand. A set of user-defined constraints have been chosen to model the resilient scenario in MED. The MED analyses try to seek answers to: Will investing in a resistant energy system make it easier or more difficult to reduce CO₂ emissions? What is the additional cost of investing in resilient energy system compared to a low carbon energy system? The analyses show that a resilient energy system reduces CO₂ emissions, but does not go far enough to stay on the pathway to the 2050 80% reduction target. This paper presents the type of constraints used in the MED analyses and key insights from the parametric analyses.

1. Introduction

The UK government sets a legally binding target of 80% cut in GHG emission by 2050 from the 1990 level (CCC, 2008) while ensuring a secure and affordable energy supply (DBEER, 2007). Under the auspicious UK Energy Research Centre (UKERC) Energy 2050 project scenario analyses have been undertaken using a number of models and analytical tools (UKERC, 2009). The UK MARKAL energy system model (Kannan, 2007) has been used to explore cost of moving to a low carbon and resilient energy system. The concept of *resilience* has had relatively little usage in the energy domain though the concept of *energy security* and *security of energy supply* are frequently (and often loosely) used. For our analyses, we defined a resilience energy system as *the set of technologies, physical infrastructure, institutions, policies and practices located in and associated with the UK which enable energy services to be delivered to UK consumers* (Jim et al, 2009). This definition covers all of the equipment along the energy supply chain that is located in the UK – extraction of non-renewable resources, electricity generation, energy conversion, transportation, transmission, storage, distribution and end-use equipment. It excludes physical infrastructure located outside the UK. It covers UK institutions (government at the national, regional and local levels, other statutory and non-statutory

public bodies and private companies), UK policies, regulatory frameworks (economic and environmental) and operating practices.

The advantage of focusing on *resilience* as the key concept is that it can be seen as an intrinsic characteristic of the energy system itself. It does not require us to think about the underlying causes of a particular shock, for example a prolonged interruption of gas supply. We only need to know that a particular kind of shock is possible.

The definition is built round the concept of delivering *energy services* to consumers rather than energy *per se*. This allows for the fact that technologies and practices on the energy demand side can help to ensure a reliable supply of energy services. For example a well-insulated house will make the occupants more resilient against supply interruptions during cold weather. The following three models with complementary characteristics have been used to explore the cost and benefits of the resilient energy system.

1. *MARKAL Elastic Demand* (MED) model of the entire UK energy system
2. *Wien Automatic System Planning* (WASP) model which determines electricity generation expansion plans at the national level
3. *Combined Gas and Electricity* (CGEN) model which determines geographically specific investments in new gas and electricity infrastructure (gas pipelines, terminals and storage facilities; transmission lines; and power stations)

These models have been soft-linked, i.e. the output of one model has been used as input to another rather than attempting to solve the models simultaneously. Figure 1 shows the dataflow between the models. The focus of this paper is on MARKAL MED analyses, while the other modelling analyses can be found in the UKERC working paper (Skea et al, 2009).

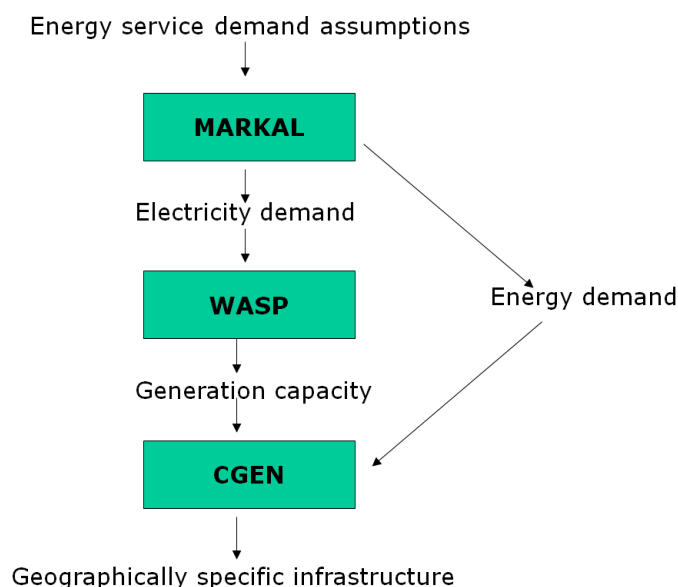


Figure 1: Model linkage in resilient energy system analyses

Within the analytical framework of the MARKAL model, the resilient energy system has been foreseen as diversity in energy supply and reducing energy intensity (ratio of *final energy demand to GDP* ($PJ/£_{GDP}$)). With these criteria, a number of parametric analyses have been undertaken by applying constraints on primary energy supply, electricity generation mix and installed capacity and the final energy supply. Based on the insights from these parametric analyses, a set of constraints have been chosen to characterise the resilient energy system. In the MED analyses we tried to seek answers to: Will investing in a resistant energy system make it easier or more difficult to reduce CO₂ emissions? What is the additional cost of investing in a resilient energy system compared to a low carbon energy system? The methodology of implementing the constraints and results from the parametric analysis are discussed in this paper.

Section 2 elucidates analytical framework of the UK MARKAL model. Section 3 describes the parametric constraints and with their results. Section 4 defines the final set of constraints, which characterise the resilient energy system. The key conclusion from the resilient energy system analyses is highlighted.

2. UK MARKAL model - Overview

MARKAL portrays the entire energy system from imports and domestic production of fuel resources, through fuel processing and supply, explicit representation of infrastructures, conversion to secondary energy carriers (including electricity, heat and hydrogen), end-use technologies and energy service demands of the entire economy. As a perfect foresight partial equilibrium optimization model, standard MARKAL minimizes discounted total system cost by choosing the investment and operation levels of all the interconnected system elements. The UK MARKAL model optimally solves from year 2000-2070 in 5-year time steps. The model is calibrated in its base year (2000) to data within 1% of actual resource supplies, energy consumption, electricity output, installed technology capacity and CO₂ emissions (DBEER, 2006). A first key input parameter is resource supply curves (Table 4 in Anandarajah et al., 2008). From these baseline costs, multipliers are used to generate both higher cost supply steps as well as imported refined fuel costs.

A second key input is dynamically evolving technology costs which are based on expert assessment of technology vintages or for less mature electricity technologies via exogenous learning curves derived from an assessment of learning rates combined with global forecasts of technology uptake (Kannan, 2009).

A third key input is an explicit depiction of infrastructures, physical and policy constraints. A wide range of peer reviewed data sources inform the model and have been supplemented by a series of stakeholder workshops. A complete description of all input parameters is given in the model documentation (Kannan et al., 2006). All costs are in 2000 British Pound (£₂₀₀₀). The model uses a global discount factor of 10% to reflect commercial UK market rates of return. The model uses a

higher hurdle rate for advanced end-use technologies like plug-in hybrid/hydrogen vehicles and heat pumps. All currently UK legislated environmental and economic policies as of 2005 are included (DEFRA, 2006). In addition, considerable attention is given to near-term (2005-2020) convergence of sectoral energy demands and CO₂ emissions within the econometric outputs of the DTI energy model. The imposition of a range of policy and physical constraints, implementation of all taxes and subsidies, and inclusion of base-year capital stocks and flows of energy, facilitates realistic evolution of the energy system under alternate scenarios.

Final key inputs for the UK MARKAL model are exogenous demands for energy services. MARKAL elastic demand (MED) version is used to account for the response of energy service demands to prices. This is implemented at the level of individual energy service demands using linear programming. Hence, each demand has a constant own-price elasticity. The MED model calculate welfare losses from reduced demands - i.e. if consumers give up some energy services that they would otherwise have used if prices were lower, there is a loss in utility to them which needs to be accounted for. The sum of consumer and producer surplus (economic surplus) is considered a valid metric of social welfare in microeconomic literature. A full description of MED function and its input assumptions are given in the low carbon pathway report (Anandarajah et al., 2008). A full description of the UK MARKAL model is given the model documentation (Kannan et al, 2006).

3. Resilient parametric analyses

3.1. Definition of constraints

Building in resilience can be achieved only by bringing together a number of different mitigating measures. Broadly, these involve bearing down on energy demand, ensuring adequate capacity, diversifying supply and making greater investments in infrastructure. The value of different mitigation measures obviously depends on the nature of the contingencies for which we are preparing. The focus of the MARKAL analyses is on diversity in energy supply and reducing final energy demand. A number of user defined constraints are defined to reflect the resilient characteristic. The diversity constraint is focused to promote diversity in overall energy supply, i.e. the primary energy. Since electricity is one of the main final energy carriers, the diversity constraint is also applied to the power sector. The list of parametric constraints used in the MED analyses is given in Table 1. The constraints are systematically applied to a reference scenario (REF) which includes legislated policy measures as of 2005, including the projected uptake of conservation measures through 2020, climate change levy, electricity and transport renewable obligations, EU-ETS and so on. However, no new future policies or measures would be enacted to reduce energy use or CO₂ emissions. In the reference scenario, diversity of primary energy (just) meets the resilience criteria but the generation mix does not. In the low carbon scenario, diversity of primary energy fails to meet the resilience constraint but electricity generation mix is most diverse because of the uptake of nuclear power. The results of the reference and low carbon scenarios can be found in Anandarajah et al. (2009). Insights from the resilient parametric analyses is summarised in the next sub sections.

Table 1: List of constraints used for the parametric analyses

Criteria	Rationale	Name and description of constraints	
Diversity in primary energy supply	This criterion is intended to promote supply diversity in overall energy system.	R_PE	A maximum market share of 40% ¹ is applied ² to each fuel type. Import and domestic fuels are aggregated as a single category. Uranium for nuclear power generation is excluded in this constraint but nuclear generation is constraint through diversity in power supply.
Diversity in power sector	This criterion is intended to promote supply diversity specifically for the electricity sector.	R_P (PJ): Diversity in electricity generation mix	A maximum market share of 40% is applied ² to electricity generation from each fuel sources. In general, fuel sources are aggregated as coal ³ , gas ³ , nuclear ⁴ and renewable ⁵ .
		R_P (GW): Diversity in installed capacity	Similar to the diversity of electricity generation mix constraint R_P (PJ), but applied to installed capacity.
		R_POW: Diversity in both installed capacity and generation mix	Combination of the above two constraints, R_P (PJ) and R_P (GW)
Reduction of final energy demand	This criterion is intended as proxy for expenditure on final energy that would reduce the UK's economic exposure to volatility or enduring rises in global energy prices.	This final energy intensity constraint is aimed to reduce the final energy demand. The final energy intensity is unconstrained ² up to 2010 and then falls ⁶ at the following annual rates.	
		R_FE-A	2.4% per annum
		R_FE-B	2.8% per annum
		R_FE-C	3.2% per annum ⁷
		R_FE-D	3.6% per annum.
<p>¹ The 40% threshold is derived from an equivalent Herfindahl-Hirschman Index (HHI) of 30%. HHI is used by the Office of Fair Trading to measure excessive concentration when considering mergers and acquisitions</p> <p>² Due to the existing capital stocks and near term policy constraints, all the above constraints are implemented from 2015</p> <p>³ Coal/gas with and without CCS is aggregated</p> <p>⁴ only to new build nuclear plants</p> <p>⁵ offshore wind, tides, marine and wave</p> <p>⁶ In the reference scenario [REF], energy intensity reduces between 1.79% and 2.74% per annum during 2010-2050 (Anandarajah et al, 2008).</p> <p>⁷ The objective of the EU Energy Efficiency Action Plan (EC, 2006) is "to control and reduce energy demand and to take targeted action on consumption and supply in order to save 20% of annual consumption of primary energy by 2020 (compared to the energy consumption forecasts for 2020). This objective corresponds to achieving approximately a 1.5% saving per year up to 2020." It is difficult to compare this with the energy intensity that has been imposed in the Resilient scenario, but, with an assumed economic growth rate of around 2%, a 3.2% reduction in energy intensity is at least comparable to a 1.5% p.a. reduction in energy use. It is likely therefore that the Resilient scenario achieves or comes close to achieving the EU energy efficiency objective, whereas the Reference scenario does not</p>			

3.2. Diversity in primary energy supply

With the primary energy diversity constraint (R_PE), the share of coal reduces to 31% (vs. 39% in the reference scenario) (Figure 2). The reduction in coal demand is driven by changes in the power sector. The coal based electricity generation is reduced to 57% from 81% in reference scenario. In turn, nuclear power generation contributes to 18% of the total electricity generation compared to none in the reference scenario. It illustrates that the power sector is the cheapest sector to enhance diversity in primary energy supply. The high cost nuclear electricity (with respect to the cheaper coal) induces demand side response, particularly in the residential and service sectors. The restriction of coal also reduces direct use of coal in the industrial sector. The total primary energy supply in 2050 reduces to 7751 PJ from 8243 PJ in the reference scenario. The diversifying the primary energy supply reduces the CO₂ emission by 26% in 2050 from the reference scenario or 16% from the 1990 level, but at a welfare cost of about £ 3.5 billion in 2050.

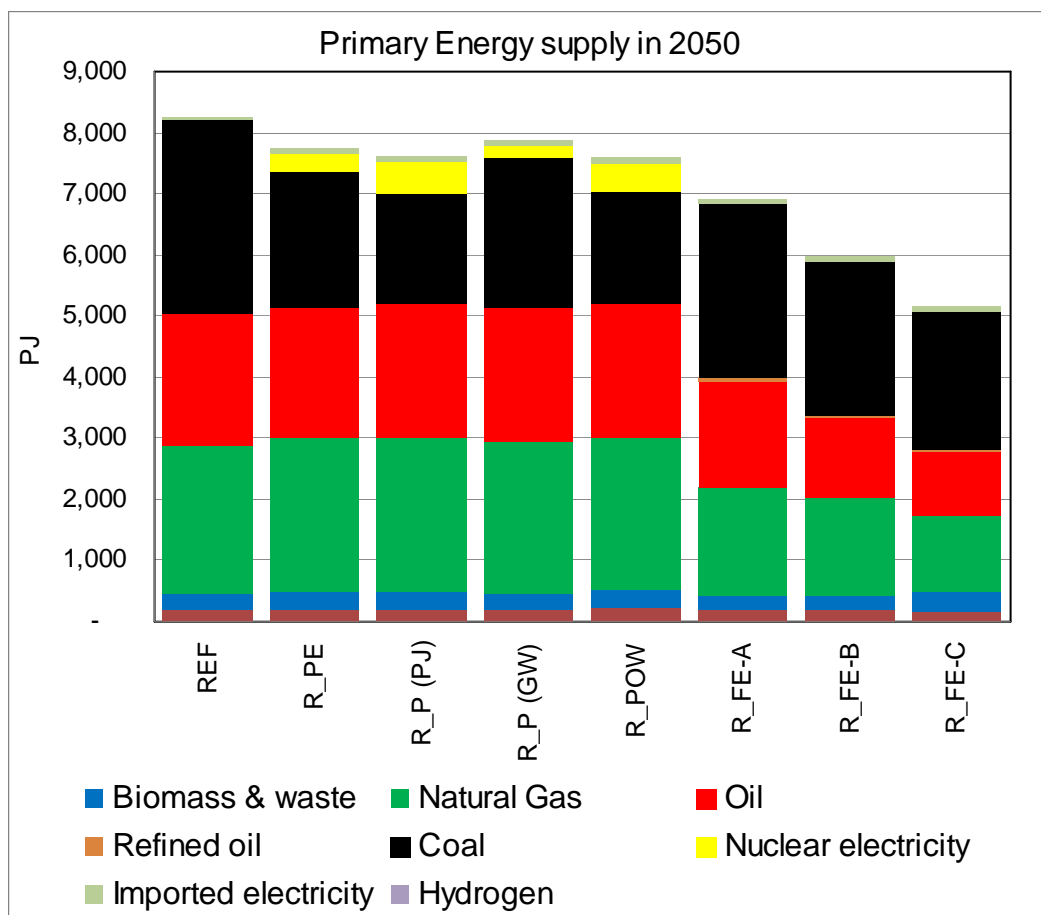


Figure 2: Primary energy supply in parametric runs

3.3. Diversity in power supply

3.3.1. Electricity generation mix

In the reference scenario, electricity generation mix is dominated with coal (54% in 2025 and 81% in 2050). With the R-P(PJ) constraint, the share of coal based power generation reduces to 40% in

2025 (vs. 54% in the reference) while gas based electricity generation increases to 31% (vs. 19% in the reference scenario).

In 2050, the coal-based electricity generation is reduced to 40%, and is replaced with nuclear of up to 33% of the total electricity generation (vs. non in the reference scenario). Figure 3 shows power generation mix in 2050. Diversifying the electricity generation from coal to nuclear increases cost of the energy system, and thereby induces demand side response. The combination of high energy system cost and losses in consumer surplus result a welfare costs of about £ 1.1 billion in 2025 and £ 4 billion in 2050. Nonetheless the diversification of electricity generation reduces the CO₂ emission by 22% from the 1990 level.

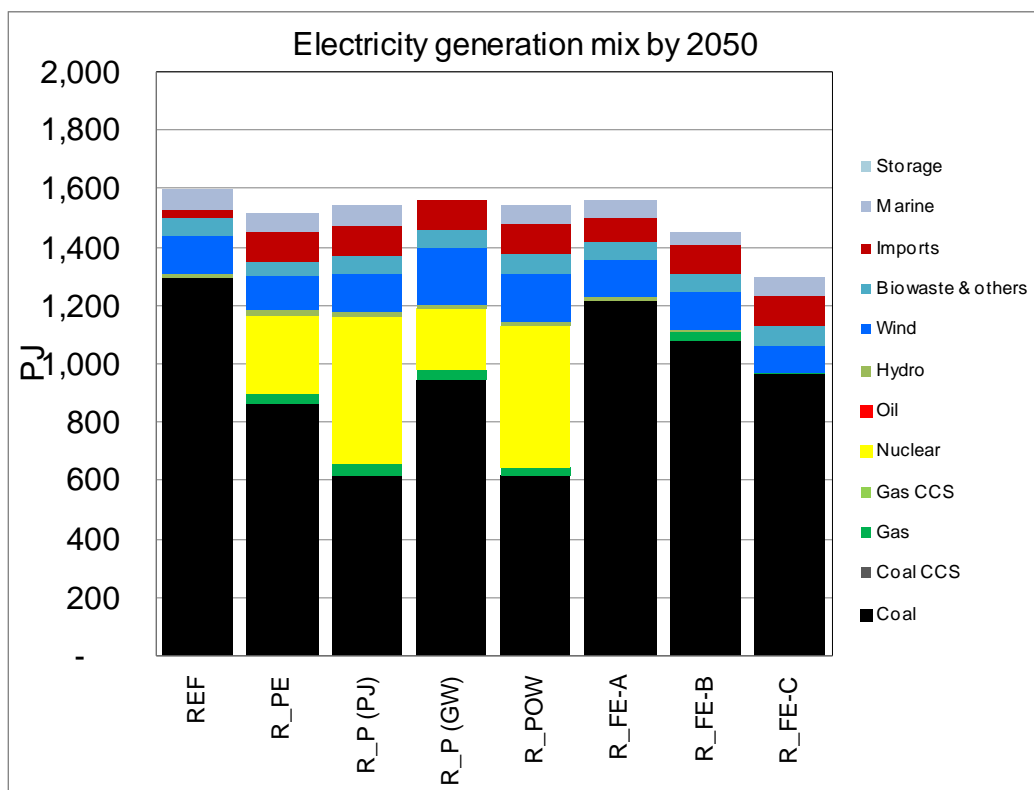


Figure 3: Power generation mix in parametric analyses

3.3.2. Installed capacity

Applying the capacity constraint [R_P(GW)] encourages investment in new gas capacity in the short term, and nuclear and wind in the long term. Installed capacity of gas plants in 2025 is more than doubled but gas based electricity generation is not increased more than 50% (Figure 4). This is mainly because the coal based generation is the cheapest. This infers that the investment in the gas plant is chosen only to fulfil the constraint as the capital cost of gas plant is the cheapest.

In 2050, installed capacity of coal plant is reduced to a two-third of the reference scenario, which stimulates new investment in nuclear plant for base load generation. The model chooses high wind capacity, which requires additional gas plant to cope with its intermittence nature. Thus, the investment in cheaper gas plant complements the intermittence wind capacity and also serves for reserve margin. Having the diversity in installed capacity, the electricity generation mix is still dominated with cheaper coal of up to 60%. Therefore the demand side response is relatively less than that in the R_P(PJ) run. Its welfare cost is £ 0.8 billion in 2025 and £ 2.5 billion in 2050.

3.3.3. Installed capacity and electricity generation mix

The R_P(GW) constraint chooses more coal based electricity generation (60%) and therefore it is not fulfilling the criteria for diversity in generation mix. On the other hand, the R_P(PJ) run fulfils the criteria for the capacity diversity to a large extent. Combining these two constraints produces more or less a similar results of the R_P(GW) run in short term and R_P(GJ) run in long term. Therefore its welfare cost in 2025 is slightly higher than that in R_P(PJ). But its CO₂ emission and welfare cost are similar to that of the R_P(PJ) run (Table 2).

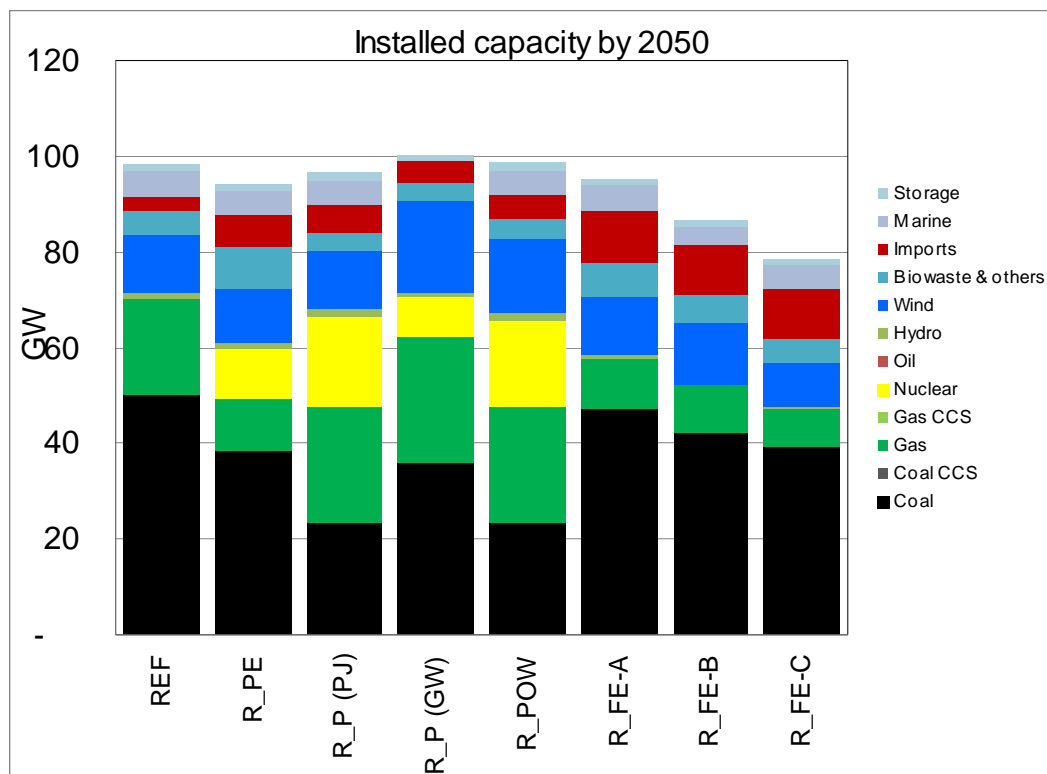


Figure 4: Installed capacity in parametric runs

3.4. Reducing of final energy

Compared to the supply diversity, reducing the final energy demand is the hardest¹. All the end use sectors responses to the final energy constraint through a combination of energy efficiency improvement, fuel switch and demand side response. However, the demand side response is the most significant. For example, the residential heating demand is reduced up to 25% in 2025 and 47% in 2050 (Figure 5).

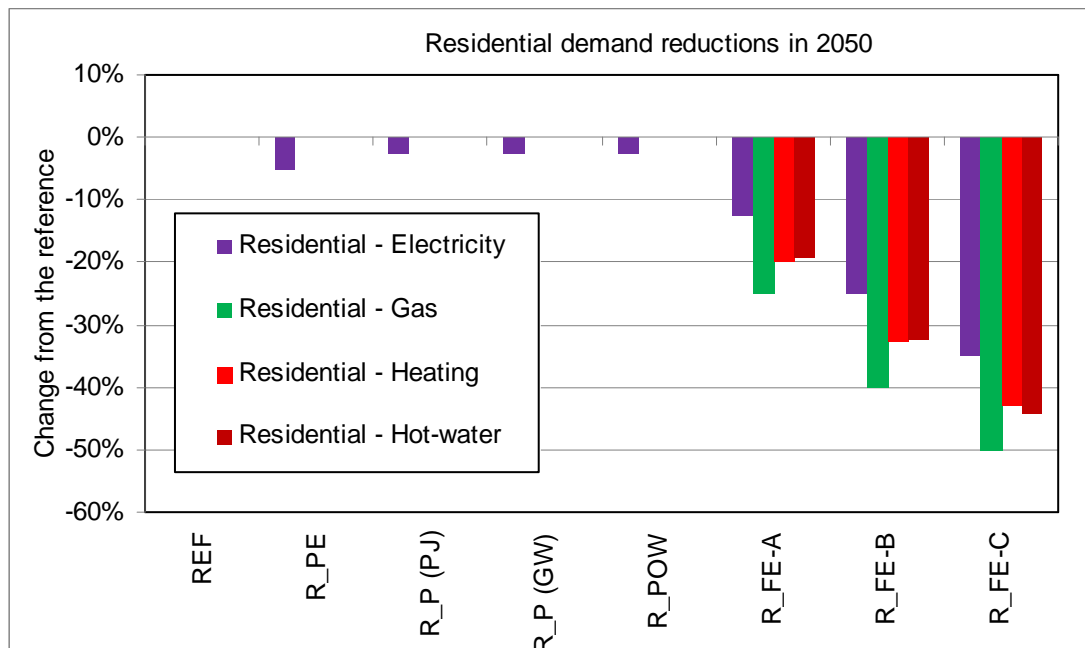


Figure 5: Demand response in the residential sector in parametric runs

Figure 6 shows the final energy demand. In general, constraining the final energy supply promotes the use of electricity due to high efficiency at end use technology. For example, gas based heating in the residential sector switch to efficient heat pumps. This fuel switch should have increased the electricity demand, but total electricity demand is decreased due to the demand side response. The demand reduction is very high when the final energy constraint becomes more stringent (Figure 5). The reduction in final energy reduces the primary energy supply, and the CO₂ emission up to 40% from the 1990 level. However, the high level of demand reduction results in high welfare cost, that varies between £ 10 and 45 billion in 2050 (Table 2).

¹ The annual energy intensity reduction of 3.6% (R_FE-D) gives an infeasible solution.

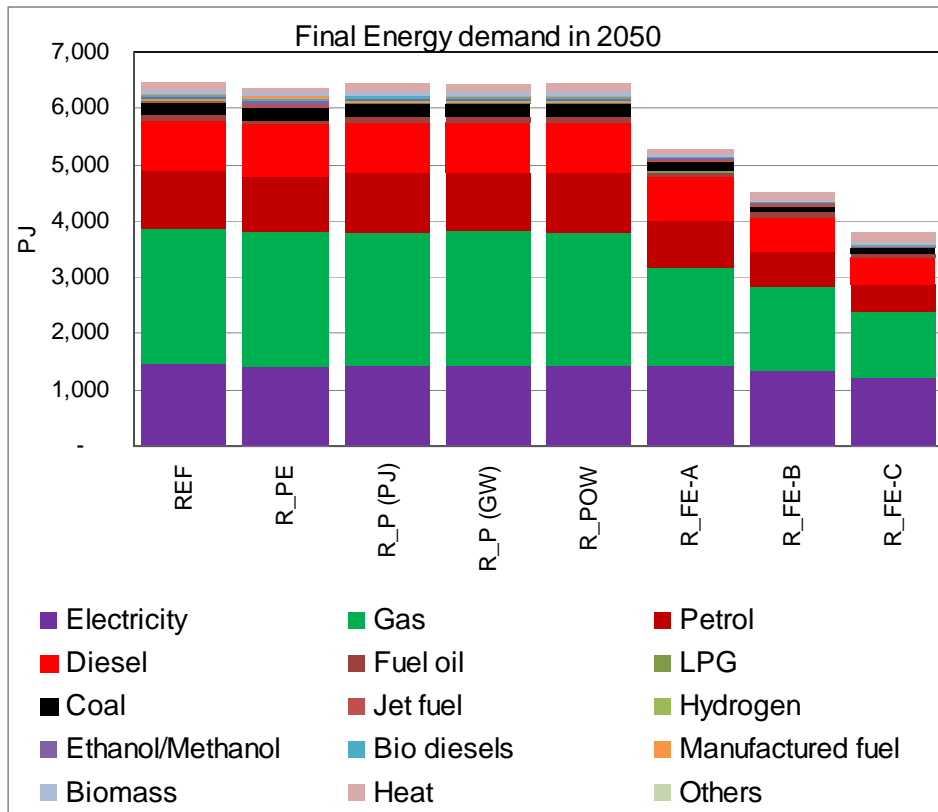


Figure 6: Final energy demand in parametric analyses

Table 2: Welfare costs in 2050 with respect to reference scenario in parametric runs

MED indicators	R_PE	R_P (PJ)	R_P (GW)	R_POW	R_FE-A	R_FE-B	R_FE-C
	<i>(in £ billion)</i>						
Change in energy system cost	2.52	3.68	2.18	3.77	-4.84	-7.74	-13.70
Change in consumer and producer surplus	-3.56	-3.99	-2.54	-4.04	-9.96	-24.38	-45.55

4. Characterising a resilient scenario

From the parametric analyses, it is clear that none of the single constraints fulfils all the criteria for the resilient energy system (Table 1). In the power supply diversity constraint R_P(PJ), the primary energy supply exceeds the 40% market share (e.g. gas in primary energy supply is more than 43% in 2025). In the primary energy diversity constraint (R_PE) run, the share of coal based electricity generation (>57%) exceeds the threshold level of 40%. In neither of these run, the final energy demand is reduced to meet the EU 2020 final energy reduction target (see the footnote 8 in Table 1). The EU 2020 target is only achieved in the final energy constraint of R_FE-C, but the R_FE-C run does not fulfil diversity in power sector or primary energy supply. Therefore, for the core resilient

scenario three constraints namely, diversity in primary energy supply [R_PE], diversity in electricity generation mix [R_P (PJ)] and a reduction in final energy intensity of 3.2% per annum [R_FE-C] have been combined². These resilient constraints are applied to the reference and the 80% low carbon scenarios to produce a Resilient and low carbon resilient (LCR) scenarios. Table 3 summarises the key indicator from the core scenarios.

Table 3: Key indicators of core scenario in 2050 (from 2000 level)

2050	Reference	Resilient
<div style="display: flex; flex-direction: column; align-items: center;"> <div style="margin-bottom: 10px;">↓</div> <div style="writing-mode: vertical-rl; transform: rotate(180deg);">Low carbon</div> </div>	Primary energy supply: -4% Max share of primary energy: 38% (Coal) Electricity demand: +26% Max share of electricity generation: 81% (Coal) Max share of capacity: 51% (Coal) CO2 intensity of electricity (g/kWh): 591 Final energy demand: +4% Residential energy demand: -2% CO2 emission (from 1990 level): -2% Welfare cost: 0 £B	Primary energy supply: -44% Max share of primary energy: 28% (Gas) Electricity demand: +2% Max share of electricity generation: 40% (Coal) Max share of capacity: 27% (Coal) CO2 intensity of electricity (g/kWh): 352 Final energy demand: -38% Residential energy demand: -50% CO2 emission (from 1990 level): -52% Welfare cost: 49 £B
	Primary energy supply: -32% Max share of primary energy: 29% (Nuclear) Electricity demand: +39% Max share of electricity generation: 41% (Coal CCS) Max share of capacity: 25% (Coal CCS) CO2 intensity of electricity (g/kWh): 31 Final energy demand: -29% Residential energy demand: -55% CO2 emission (from 1990 level): -80% Welfare cost: 38 £B	Primary energy supply: -49% Max share of primary energy: 30% (Nuclear) Electricity demand: +16% Max share of electricity generation: 40% (Nuclear) Max share of capacity: 29% (Wind) CO2 intensity of electricity (g/kWh): 15 Final energy demand: -40% Residential energy demand: -50% CO2 emission (from 1990 level): -80% Welfare cost: 59 £B

5. Conclusions

The MARKAL model has been used to explore the cost implication of a resilient energy system in conjunction with other analytical tools. The MED parametric analyses produce very thoughtful insights. With the MED function, the model finds it easier to meet a number of constraints; otherwise the standard MARKAL model could have given an infeasible solution. However, it becomes more

² In the low carbon (LC) scenario, the residential heating switches to 100% heat pumps. Similarly in the R_FE-C run, the residential heating shifts to 100% heat pumps. Considering technical potential, market barriers and behavioural aspect of transition to heat pump technology, an additional constraint is imposed in the resilient scenario so that only a maximum of 30% of the residential heating demand can be met by heat pumps.

difficult to compare two variant scenarios in MED because of the difference in size of their energy system. To caveat these uncertainties, the systematic parameter analyses were helpful in understanding the drivers.

The resilient energy system reduces CO₂ emissions but does not go far enough to stay on the pathway to the 2050 80% reduction goal. There is remarkably little progress in electricity decarbonisation in the resilient scenario, and progress is slower if resilient constraints are added to the low carbon scenario. The diversity of power sector plays key role to diversity of primary energy supply. Cheap alternatives allow either diverse or low carbon generation mixes to make big contributions to overall goals.

Deduced energy demand, and thereby imports dependence, is the key to achieve a low carbon and resilient scenario. The low-carbon scenario contributes to reduced energy demands but it does not go far enough to meet the criteria for the resilient energy system. The demand reduction through behaviours changes is very important and the residential sector is critical in this regard. The resilient scenario requires a substantial change from demand side that incurs huge welfare cost.

6. References

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