# DEEP DECARBONIZATION SCENARIOS OF THE UK ENERGY SYSTEM WITH DEMAND-SIDE OPTIONS AND RENEWABLE ENERGY

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With a legally binding commitment of 80% CO2e reduction by 2050, UK's energy system warrants a deep decarbonisation drive within decades. Past UK energy system transition scenarios approached this transition with a supply-centric approach. In electricity that often meant centralized low-carbon generation options, such as nuclear power plants and offshore wind farms, meeting majority demand. In this study, using a suite of bespoke end-use demand and energy supply infrastructure expansion planning models, we present two transition scenarios aimed at decarbonisation. The first scenario envisions high electrification of heating and transport services and powering the energy system with low carbon electricity, while the other envisions a balanced uptake of energy conservation and efficiency, electrification, microgeneration and large-scale renewable energy. The analysis focused on electricity and gas demand and supply in the island of Great Britain within the UK. When compared with a reference scenario, the balanced approach is found to have the higher potential to reduce overall energy demand along with the demand for electricity and gas, whereas the electrification approach increases total and peak electricity demand by 35% and ~90% respectively over reference by 2050. Supply side implications to meet the demands are tested with nuclear, CCS, offshore wind as well as a balanced mix of major supply-side options. The chosen mixes in the two scenarios could largely meet the power sector decarbonisation goal with varying cost, stranded asset, governance and supply chain implications.

**Keywords**: decarbonisation, demand-side management, renewable energy, modelling, scenarios

## INTRODUCTION

UK has one of the world's most ambitious GHG reduction targets with a legally binding commitment of 80% reduction by 2050 relative to its 1990 level. UK Committee on Climate Change (CCC), government's advisory body, has set carbon budgets to meet the carbon target. In its 4$^{th}$ carbon budget, it suggests a 60% reduction using 'domestic action' by 2035 with deep cuts through 2020s onwards. Also as a member of the EU, UK has a number of energy efficiency, vehicle emission and renewable energy targets for 2020/2030. Since the industrial revolution, UK has managed dramatic transformation of its energy system a number of times. However, moving away from the incumbent fossil fuel dominant energy system to meet multiple current targets while maintaining a supply secure and affordable energy system would be a much more challenging transition. The constantly evolving global energy technology and market dynamics and increasing import dependence of key fuels are also adding to this immense challenge.

A number of government and academic studies have investigated plausible pathways to decarbonise the UK energy system. Most studies have focused on the supply side of the energy system with limited emphasis on the demand-side options. However, recently there is an increasing emphasis on the role of demand-side transition options across key economic sectors along with known supply-side options in plausible transition pathways. Alongside, in a world where many long-term costs of transition options are highly uncertain and the multi-objective nature of the transition may need policies beyond a cost/price focus, there is an increasing emphasis on identifying robust transition options and pathway(s) along with often-modelled cost minimal pathways. This is also in light of the need to minimise the uncertainty in volatility of energy demand/price and to maintain a high level of energy security.

This paper presents part of the analyses and results from a consortium aimed at providing critical insights to deliver robust energy system transition strategies for the UK to meet its triple objectives of energy security, affordability and sustainability under an increasingly uncertain future of socio-economic growth. With an energy infrastructure transition perspective, the analysis focuses on two major energy carriers in the UK, electricity and gas. Currently ~285,000 km of gas distribution pipelines, 7800 km of gas transmission pipelines, 4800 km of oil distribution pipelines and 8500 petrol filling stations meet the major energy needs of the UK. Emission results presented in this paper focus on the emission intensity of the power sector by 2050.

Due to data limitation the analysis is carried out for the island of Great Britain (GB) which is responsible for 97% of annual energy consumption in the UK in 2012 [1].

## METHOD AND DATA

### Modelling framework

The analysis involves a suite of models soft-linked by a system-of-systems framework [2][3][4]. Explicit sector models and different modelling approaches are integrated by harmonising key linking points, using standardised common input data of major external drivers (gross value added, energy price, demographics etc.) and using a top-down approach to first define policy aspirations and then translating these to strategy narratives and model level values of transition options.

Residential, services and industry sector energy consumption models employ a simulation-accounting approach. More than 160 energy efficiency, conservation, fuel switching and distributed generation technologies and management options are represented at major end-use and/or sub-sectoral level. With a perfect foresight back-casting approach, yearly uptake of each transition option is applied with a S-curve model to estimate the changes in end-use fuel consumption relative to the base year level. In transport, elasticity of transport services demand to changes in population, GVA per capita, travel cost and travel speed are used to compute utilisation factors of different travel modes and respective energy consumption. Further descriptions of the model methodologies are available in [2].

Electricity supply analysis is carried out by an optimisation based combined gas and electricity network expansion model CGEN+ [5]. Gas and electricity infrastructure expansion capital costs, operation costs and costs of energy unserved are simultaneously minimised (subject to constraints in gas and electricity networks) to arrive at optimal capacity and related infrastructure mix.

CGEN+ needs electricity and gas peak load as inputs. Electricity peak load is estimated at national level by adding impacts from electric vehicles, electric heating and demand response offsets to a reference peak load. Gas peak load is harder to predict and an empirical method based on historical data is employed. National level loads are disaggregated at CGEN level electricity bus and gas nodes using an empirical approach. More details can be found in [6].

## Base year data and socio-economic projection

Base year (year 2010) assumptions for the models are collected from variety of sources including [7] for sectoral, end-use and fuel level energy consumptions, UK Department for Transport's Annual Average Daily Flow data for road traffic, [8][9] for gas and electricity infrastructure capacities and [10] for electricity generation technology costs.

Population and household growths are assumed to be 79 million and 40 million respectively by 2050 – these were 63 million and 26 million respectively in 2011(census data). GDP is projected to be £3 trillion by 2050 (2009 prices). Costs of fossil fuels are assumed at $245/bbl for oil, 183 p/therm for oil and £199/tonne for coal by 2050 [4].

## SCENARIOS AND ASSUMPTIONS

### Brief profile of energy demand and supply in the UK

Heating and transport are major end-uses in the UK energy system – the former consumes 78% of annual energy consumption excluding transport and the later consumes 38% of UK's annual consumption. Both end-uses are currently dominated by fossil fuels – gas's share in space/water heating is 70-80% and oil is the major fuel in transport (97% share). One major area of focus for decarbonisation (and more so in an electrification centric pathway) is the power sector – currently, gas and coal dominate power production in the UK (~28% and 40% respectively in 2012). Renewable electricity account for ~12% of total generation. Government envisages total power sector decarbonisation (~50 gCO2e/kWh) by 2030 and beyond.

In this study, we test two scenarios and a reference scenario for our analysis. Each scenario consists of a narrative that outlines demand-side transitions envisioned to 2050. Each demand-regime obtained with these options is then tested with a single or a number of supply-side transition pathways envisioned in the narrative. The investigated scenarios are briefly described below. Detailed description of scenario narratives and assumptions can be found in [6].

### The scenarios

| Scenario >> | MPI | EHT | DDBT |
|---|---|---|---|
| Energy conservation | | | \|\|\|\|\|\|\|\|\|\| |
| Building envelope efficiency | \| | \| | \|\|\|\|\|\|\|\|\|\| |
| Appliance/other efficiency | \| | \| | \|\|\|\|\|\|\|\|\|\| |
| Heat electrification (e.g.HP, EAF) | \| | \|\|\|\|\|\|\|\|\|\| | \|\|\|\| |
| CHP | \| | \|\| | \|\|\|\| |
| Biomass systems | | | \|\|\|\| |
| District heating | | | \|\|\|\| |
| Solar thermal | \| | \|\| | \|\|\|\|\|\| |
| Solar PV | \| | \|\| | \|\|\|\|\|\|\|\|\| |
| EV/PHEVs | | \|\|\|\|\|\|\|\|\|\| | \|\|\|\|\|\| |
| Demand response | | \|\| | \|\| |

Fig. 1. Schematic representation of the uptake of major demand-side options in the scenarios.

As the name suggests, *Minimum Policy Intervention* (*MPI*) scenario envisions minimal intervention of relevant policy measures and assumes that there is only ~10% uptake of economic/technological potential of efficiency, fuel switching and distributed generation options by 2050. No conservation effort is assumed. On the supply side, MPI demand regime is met with two supply-side mixes obtained with or without a carbon price floor (*MPI* and *MPI (no carbon cost)*). Carbon price floors are set at values announced by the UK government at £16/tonne in 2014, £30/tonne in 2020 and £70/tonne by 2030 and beyond.

An *Electrification of Heat and Transport* (*EHT*) scenario assumes an ambitious electrification drive in heating and transport services. No energy conservation measures are assumed and efficiency measures are assumed at MPI level. For example, air-source and ground-source heat pumps replace 80-85% and 60-75% of space and water heating respectively in residential and services sectors by 2050. In industry, heat pumps reaches full potential, replacing 15% and 40% of gas demands in low temperature process heating and space heating respectively by 2050. In iron and steel sector, all remaining blast oxygen furnaces are replaced with electric arc furnaces. About 26 million BEV and PHEV cars ply the streets of Great Britain by 2050, with 20% charging from the grid (G2V) and 10% contributing to peak demand response (V2G) during peak hours. During peak hours, only cars are assumed connected to the grid for G2V and V2G purposes. Heat pumps (and electric resistive heating) meet all heating services demand during peak hours and do not use back-up heating systems (such as auxiliary gas boilers). Electricity demand in EHT scenario is met with three different supply-side mixes with carbon price floor enforced – a nuclear centric (*EHT-Nuclear*), an offshore wind centric (*EHT-Offshore*) and an incumbent fuel mix with CCS (*EHT-CCS*) centric pathway.

*Deep Decarbonisation with Balanced Transition* (*DDBT*) assumes ambitious uptake of efficiency and conservation measures and solar PV/thermal with balanced uptake of all other demand-side options including fuel switching. About 16 million BEV/PHEV cars ply the street of Britain with similar G2V/V2G and heat pump operating regime as in EHT scenario.

Figure 1 shows a comparative depiction of the uptake of major demand-side options in the three scenarios.

## RESULTS AND DISCUSSION

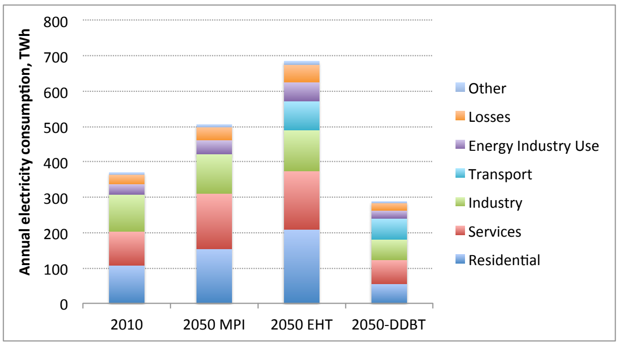


Fig. 2. Annual electricity consumptions in the scenarios.

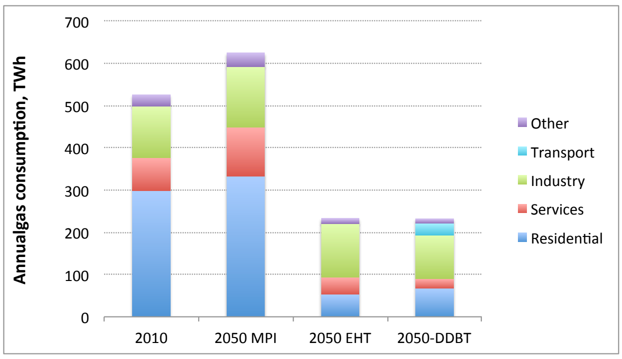


Fig. 3. Annual gas consumptions in the scenarios (do not include consumptions in electricity generation).

As seen in Figure 2, there is significant variation of annual electricity consumptions across the scenarios. DDBT scenario produces 40+% lesser consumption compared to the reference, whereas in EHT consumption increases by ~35%. On the other hand, both DDBT and EHT scenarios produced similar reductions in annual gas consumption (~62%) (Figure 3). Both EHT and DDBT scenarios could produce lower than reference overall annual energy consumption (for residential, services and industry sectors) by 2050, with DDBT producing largest reduction (55%) followed by EHT scenario (28%).

In peak load (not shown here), gas peak demand follows similar trend (decrease) to annual demand in both scenarios. On the other hand, peak electricity demand jumps ~2.7 times the base year value in EHT scenario driven by higher annual consumption and peak hour use of heat pumps and charging of electric vehicles. In contrast, driven by efficiency and conservation, electricity peak load decreases below reference scenario level by

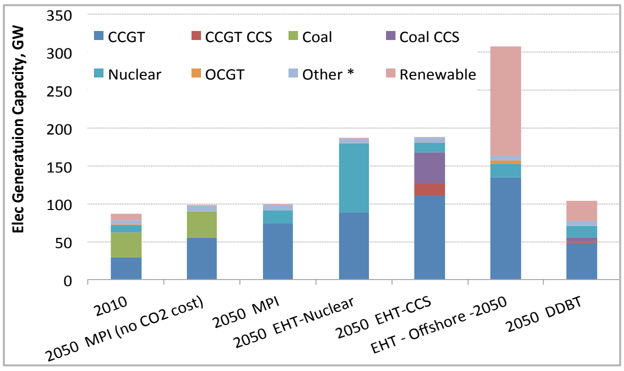


Fig. 4. Electricity generation capacity in the scenarios.

2050 after an initial increase in DDBT scenario. The peak load trend in initial years of both DDBT and EHT highlights the requirements for demand-side management measures in earlier years to minimize requirement of costly peaking plants (in comparison to MPI scenario). Our analysis finds that (not shown here), it is technically possible to lower the peak load to MPI or below base year level in both scenarios with the deployment of demand response measures enabled by a smarter grid (100% uptake assumed in both DDBT and EHT scenarios by 2020), such as from V2G, storage and auxiliary back-up systems in electric heat pumps.

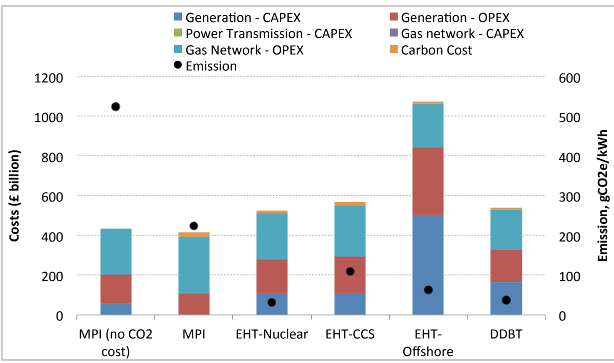


Fig. 5. Costs and CO2e emission in the scenarios.

Figure 4 shows the generation mix across the scenarios by 2050. DDBT scenario produced one of the lowest installed capacities with a balanced mix of mainly variable renewables (offshore wind, distributed solar and CHP), nuclear and CCGT plants. Both MPI supply-side scenarios produce similar capacity requirements, although with much higher proportion of CCGT and thermal power plants producing higher emission intensity as seen in Figure 5. Meeting high annual consumption and a much higher electricity peak load with variable offshore wind mean capacity and investment requirement in EHT-Offshore scenario is significantly higher and costly CCGT peaking plants with low capacity margin (~10%) are required to maintain system flexibility.

All supply-side pathways meeting EHT and DDBT demand regimes could reduce emission intensity significantly, with EHT-Nuclear scenario producing lowest emission followed by the DDBT scenario.

MPI scenario produces lowest cost with larger need for gas infrastructure in LNG plants and new interconnectors with Europe. The results show that investment requirement and breakdown would be similar across EHT-Nuclear, EHT-CCS and DDBT scenarios. However, unlike EHT and MPI scenarios, no new LNG infrastructure would be required in DDBT scenario (not shown here).

## BRIEF INSIGHTS AND CONCLUSION

The analysis suggests there are a number of options to decarbonise power in the UK. It also suggests that decarbonising the UK energy system would essentially involve decarbonising the gas grid and/or moving away from gas, and decarbonising transport. Options are limited in decarbonising the gas grid or transport in the UK context. Electrification of heating and transport services and powering it with low carbon electricity is one of the attractive decarbonisation pathways. However, without demand-side management measures in place, infrastructure and cost implications will be high in a scenario with variable renewables. Additionally, moving away from gas would mean disuse of a large part of the existing vast gas infrastructure in the UK – such impacts would need consideration in future studies for a full costing of transition pathways. On the other hand, a balanced DDBT-like pathway has the potential to both decrease energy imports and future price/demand volatility. To achieve required annual demand reduction for deep decarbonisation, fuel switching in key end-uses would be key as energy efficiency in lighting, appliances and industry would not be sufficient. The analysis enabled identification of a number of 'no-regret' options that are likely to incur comparatively lower investment costs, enhance energy security and would serve as enablers of other key options in any sustainability-focused pathway. Three such options identified are: (1) energy efficiency in buildings, appliances and industry, (2) transmission corridors connecting renewable resource-rich regions with demand hotspots and (3) smart meters with a smarter grid.

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