The Institution of Engineering and Technology

# Modelling Requirements for Least-Cost and Market-Driven Whole-System Analysis

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**Paper 14 of 15, Part 3:** IET Special Interest Publication for the Council for Science and Technology on "Modelling Requirements of the GB Power System Resilience during the transition to Low Carbon Energy"

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# About this report

The Institution of Engineering and Technology was commissioned by the Council of Science and Technology (CST) to research the emerging challenges for modelling electricity systems and how Britain's capabilities would need to be adapted to assess electricity system resilience as GB makes the transition to a low carbon electricity system.

This project commissioned, and received, fifteen individual papers from GB-based specialists of international standing in power system modelling. The authors of the papers worked with a wide stakeholder base of network companies, academics and others, who provided review and challenge. Professor Graham Ault CEng FIET was contracted to provide technical co-ordination and drafting. The emerging conclusions were further validated by means of an industry and academic workshop sponsored by Government Office for Science. The entire project was conducted under the direction of an independent steering committee composed of senior IET Fellows, two of whom were also CST nominees.

**The report is composed of three parts:**

- Part 1: Main report
- Part 2: Summary of Commissioned Papers
- Part 3: IET Special Interest Publication – Academic & Industry Papers

All three parts of this report are available from the IET website at:

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## EXECUTIVE SUMMARY

Development of holistic modelling approaches of the whole electricity system chain (generation, transmission, distribution) across both operation and planning time horizons will be essential, as the historical, individual sector centric approaches are no longer sufficient to facilitate cost-effective operation and development of the system. The whole-electricity system modelling should consider all sectors concurrently as new technologies, such as demand side response or distributed storage will simultaneously impact distribution, transmission and generation sectors. In this context consideration of national level objectives will need to be included in modelling of operation and design of local distribution networks, which is in stark contrast with the established models currently used. Furthermore, given that substantial asset replacement will take place in the next 20 years, it will be important to replace the incremental, like-with-like network replacement approach, with a whole-system, strategic development paradigm, accounting for the impact of alternative emerging smart grid technologies. It is important to stress that development of whole-electricity system models is in early stage and that there is a very significant scope for further improvements.

Furthermore, a new generation of models is needed to understand responses of market participants to alternative future market designs and regulatory and commercial incentives, across all time scales from real time operation to long-term investment. Significant changes in the commercial framework will be needed to support efficient operation and investment in the context of whole-electricity system paradigm. Given the growing requirement for flexibility, there is a need for new market modelling techniques to be developed, to optimally allocate available supply and demand side resources including network capacity, to ancillary services and energy markets, considering participation of both traditional and new players. The roll-out of smart metering is expected to enable millions of small-scale participants to participate in electricity markets and provide system management services. The traditional centralised operation paradigm will no longer be applicable and distributed coordination models will be therefore required to facilitate the interaction between all supply and demand side market participants, while considering simultaneously distribution and transmission network infrastructure constraints. Modelling activities in this general area have only started recently and significant development is required to address the growing challenges.

Finally, an integrated approach to electricity system modelling within the entire whole-energy system context is becoming essential given significant interactions between different sectors in achieving the national carbon reduction targets. A number of comprehensive multi-energy models (e.g. TIMES/MARKAL, MESSAGE and ESME) have been enhanced recently, although time and space resolution of these models may not be adequate for future low-carbon energy systems, in the context of capturing the phenomena in real-time operation and across different locations in energy networks. Key challenges in this respect are associated with the complexity of representing the multi-energy system with sufficient granularity, in order to capture the key phenomena and interactions across different locations and energy infrastructure operation and design.

## 1. BACKGROUND

The UK energy system is facing challenges of unprecedented proportions and will require radical transformation of all energy sectors, i.e. electricity, heat, gas in terms of technology and associated infrastructures, as well as in the way the energy is supplied, managed and consumed across all energy intensive activities, in order to facilitate a cost effective evolution to a low carbon future.

Given the ambitious UK decarbonisation agenda **[1]** with more than 30% emissions reduction by 2020 and 80% emissions reduction by 2050 (from 1990 levels), there is a need for a profound restructuring of the energy sector, while at the same time maintaining the critical energy policy goals including security of supply and affordability **[2]**.

Decarbonisation of supply system is under way through the large-scale penetration of renewable and low-carbon generation. However, the largest part of these sources is characterized by limited predictability and controllability, increasing the need for low utilisation flexible generation to cope with demand-supply imbalances. The decarbonisation of energy demand is expected to grow beyond 2020 with the electrification of segments of transport and heat sectors. However, analysis of the transport and heat consumption patterns reveals that such electrification will yield disproportionately higher demand peaks than the increase in overall energy consumption, potentially driving significant investments in generation and network capacity. In this context, the role of new technologies, in the form of generation-led and demand-led demand side response (DSR) and energy storage becomes crucial for the cost-efficient decarbonisation of the GB energy system. The flexibility of their operation can mitigate system imbalances and reduce new demand peaks, limiting the extent of inefficient operation of the generation system and the need for capital intensive investments **[3]**.

Apart from the integration of these new technologies, meeting the economy-wide decarbonisation targets cost-efficiently requires a paradigm change in energy system modelling. First of all, these technologies can improve the efficiency of different sectors of the electricity system, i.e. generation, transmission and distribution, across different timescales, from real time operation to multi-year planning. Therefore, modelling tools should not consider the impact on each of these sectors and timescales in isolation, but adopt a more integrated approach, able to capture relevant interactions and reward different resources for their whole-system value.

Modelling efforts should also focus on capturing changes in commercial arrangements that will be needed to support cost effective decarbonisation of the system. These will include the development of new markets for flexibility provision, the aggregation of small-scale demand side response resources, the balancing between national and local value streams, and the harmonisation between system cost minimising solutions and individual market participants' objectives. Furthermore, modelling approaches should represent the shift from traditional centralised operation to a distributed coordination paradigm, as the roll-out of smart metering is expected to enable millions of small-scale players throughout the UK to participate in electricity markets and system management.

Finally, an integrated approach to electricity system modelling within the wide whole-energy system context is becoming essential given significant interactions between different sectors in achieving the national carbon reduction targets. For instance, the deployment of heat networks coupled with thermal energy storage, including CHP or large-scale heat pumps that may supply these networks, could support the integration of wind in the electricity system. Similarly, the substitution of fossil fuel-based road transport with electric vehicles when coupled with low-carbon electricity generation (i.e. renewables, nuclear and CCS) could potentially deliver significant carbon reduction at the national level. Likewise, the interaction between gas and electricity infrastructures may be significant and an integrated approach to operation and infrastructure designs could bring significant benefits.

Although a number of modelling platforms that are emerging are increasingly focusing on integrated energy system analysis considering the impact of new technologies, a number of potential areas for future developments are identified in this paper. In addition to incorporating aspects such as uncertainty, location, chronology and distributed operation in least-cost whole-system models, significant effort is required to develop models capable of investigating whether the market design and regulatory and commercial framework will provide adequate incentives to deliver the necessary investments in technologies and solutions to support a cost-effective and secure transition to a low-carbon energy system.

## 2. WHOLE ELECTRICITY SYSTEM MODELLING

Existing studies have investigated the impact of emerging DSR and storage technologies on isolated sectors of the electricity system chain and isolated timescales. Examples include the impact on generation system operation [4]-[7], the impact on generation expansion planning [8]-[15], distribution network planning [16]-[19] and transmission network planning [20]-[23]. Recent publications [24]-[26] demonstrate the limitations of established modelling approaches that are unable to consider interactions between electricity sectors, i.e. generation, transmission and distribution, and are not capable of reflecting the interaction across different time-scales, from real time balancing to long term infrastructure planning.These studies, based on the integrated whole-system electricity infrastructure modelling methodology, have clearly revealed that applying DSR and energy storage technologies to support generation, transmission or distribution sectors in isolation, will significantly underestimate the potential benefits of flexibility provided by these technologies, particularly in the context of future lower-carbon electricity system. It was further shown that time and location effects need to be given adequate consideration: time horizons covering investment and operation time scales, as well as the impact that flexible technologies have depending on their actual location within transmission and/or distribution network.

As an example, the whole-system benefits of energy storage and DSR identified in these studies are split across different segments in the system – generation and network investment and system operation. However the electricity generation and electricity transport sectors (distribution and transmission networks) are operated by different commercial organisations and the level of coordination is currently very limited. Hence the use of flexible technologies such as DSR or distributed storage is devoted to a particular application within a single sector.

To illustrate the limitation of this approach, an example is introduced that contrasts the cost and benefits of applying whole-systems approach against the DNO centric approach for designing future distribution networks, under two different scenarios of generation flexibility; Figure 1 presents the total cost difference obtained by the whole system approach and by the DNO centric approach (considering a single DNO licence area) for a system with flexible and inflexible generation portfolio in a future with significant contribution of intermittent renewables. If the cost difference is positive, it means that the cost for that particular sector in the whole system approach is higher than the cost proposed by the DNO centric approach. On the other hand, if the cost difference is negative, it shows the savings generated by the whole electricity system approach.

The results demonstrate that the whole system approach proposes larger investment in distribution networks compared to the one projected by the DNO centric approach. This additional distribution network investment enables the flexibility of DSR to reduce primarily the operating cost and generation CAPEX.

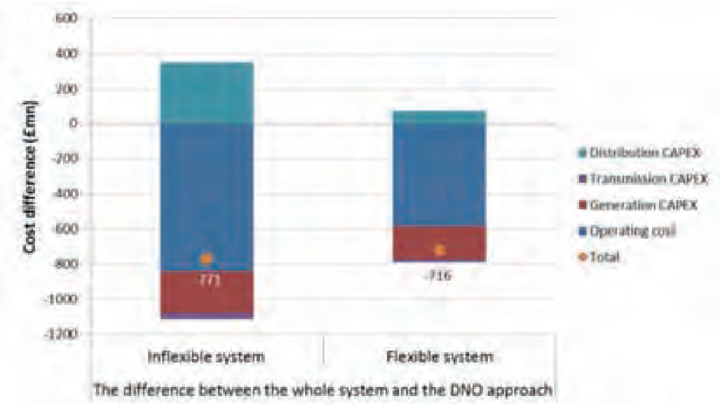



**Figure 1: Impact of generation flexibility on the role and value of DSR.**

As the system used in the study is relatively constrained and not able to absorb the output of renewables, the DSR can provide flexibility needed to reduce the curtailment of wind power output. Consequently, DSR will also reduce the requirement for CCS capacity, which would otherwise need to be built to displace the curtailed wind output and meet the emissions target.

The results demonstrate that in the inflexible system, the whole system approach proposes more than £340 million more investment in the local distribution network in order to accommodate higher DSR driven peak load. With higher distribution network capacity and DSR, electrical loads can be controlled to follow the wind power output in order to improve its utilisation otherwise the output needs to be curtailed. Curtailment is costly not only in operational terms, but also in investment terms as reduction in wind energy absorbed will trigger investment in low carbon generation (SSC in case) needed to meet CO2 target. In contrast, the DNO centric approach will prioritise the use of DSR for peak load reduction in order to reduce the distribution network reinforcement cost despite the value of DSR for system balancing purpose. It is important to note that in the DNO centric approach, DSR is also be used for system balancing purposes as long as it does not trigger increase in the peak load.

In the case of more flexible generation system and enhanced interconnection, the need to use DSR for system balancing will be reduced. Therefore, as demonstrated in Figure 1, the additional investment in the local distribution network proposed by the whole system approach, i.e. £70 million is significantly lower than the additional investment proposed in the case of inflexible system (£340 million). Thus, the role of DSR in the flexible system is closer to the role of DSR in the DNO centric approach; this shows the shift of the focus of DSR applications depending on the system needs.

The results of the study demonstrate that the additional investment in the local distribution network to allow DSR to support national level balancing, can be justified since the benefits in the forms of savings in OPEX and generation CAPEX exceed the cost of reinforcement of this particular DNO area. In both cases, the cost obtained by the whole system approach is less by approximately £716 million to £771 million[1]. The savings are not insignificant and should be pursued to reduce the overall electricity cost to consumers. This clearly demonstrates that a coordinated whole-system approach to distribution network design will be important, and will require the consideration of national level objectives when designing local distribution networks, which is in stark contrast with the present approach. These effects are clearly not within the scope of presently established sector centric modelling tools and the present market, commercial and regulatory framework, does not yet support the whole-system paradigm.

There is however significant scope for further improvement of the whole-system modelling. Due to very large scale of the problem, extending its scope to deal with uncertainty in a multi-year time horizon is the key remaining challenge.

[1]We observe slight increase in benefits in transmission network investment under the whole system approach (note that the transmission network investment is predominantly driven by out of merit generation costs).

Furthermore, traditional distribution network design has been driven by requirements of delivering reliability and continuity of supply. This has not explicitly included electricity losses, their economic and carbon emissions impact. However, consideration of network losses in network planning clearly demonstrates the importance of shifting from the present peak demand and minimum network asset based design / reinforcement philosophy to a loss-inclusive network planning approach in order minimise the total system costs. This demonstrated that this approach is not optimal and that loss inclusive network design would lead to a very significant reduction in peak utilisation of LV and HV circuits in particular as shown in Table 1.

| Under-ground Cables | Peak Utilisation(%) | Ratio of peak capacity and peak demand |
|---|---|---|
| LV | 12 - 25 | 4.0 – 8.3 |
| HV | 14 - 27 | 3.7 – 7.1 |
| EHV | 17 - 33 | 3.0 – 5.9 |

**Table 1: Peak utilisation and the ratio of peak capacity and demand on the inclusive network design.**

This analysis demonstrates that following the present minimum distribution network cost based design approach, would lead to inefficient investment in generation (size of a typical nuclear power plant) that would need to be built and operate only to supply increase in losses in HV and LV distribution networks above the efficient level, which would ultimately lead to unnecessary increase in cost to future consumers.

Further development of the whole-electricity system modelling beyond the current state of the art should include consideration of the evolution of the system, differentiating between incremental and strategic investment. In this context for example, distribution network planning is currently based on like-with-like replacement, which is unlikely to be optimal for the 21st century as the present distribution networks were designed in late 1940s or earlier. Given the significant interest in connecting low carbon demand and generation technologies, combined with substantial asset replacement programmes in the next 20 years, it will be important to replace the like-with-like network replacement approach, with a whole-system, strategic modelling paradigm, accounting for the impact of alternative emerging smart grid technologies. Similarly, there is a significant opportunity to strategically integrate development of onshore and offshore transmission grid and interconnection by departing from the present member-state centric approach and adopt a EU wide approach, which would result in very significant savings through integration as recently demonstrated in [27].

Furthermore, modelling of uncertainties, particularly in cost and technical characteristics of emerging technologies is critical for developing robust strategies for infrastructure development. In this context there is also a growing need to understanding of DSR capability in the context of whole-electricity system modelling taking into account consumer interests and behaviour, (e.g. [28]-[29]), which is particularly relevant for supporting cost-effective decarbonisation.

## 3. MODELLING OF FUTURE MARKET AND COMMERCIAL ARRANGEMENTS

The shift to a low-carbon power system requires suitable changes in commercial arrangements to fully recognise and reward the value of new flexible technologies. In this context, modelling efforts should focus on (A) recognising the value of flexibility, (B) capturing synergies and conflicts between the value streams of these technologies, (C) deriving commercial arrangements harmonising the social welfare maximising solution with the objectives of individual market participants and (D) representing the shift from centralised to distributed coordination.

### a) Modelling of integrated energy and ancillary services markets

At present, the value of providing flexibility, within the established ancillary services markets, is a small fraction of the volume of the energy market. Recent analysis demonstrates that the importance and volume of balancing markets will radically increase, and that generating plants with enhanced flexibility will be critical in supporting the integration of less flexible low carbon generation, such as nuclear and wind. However, the present market design rewards energy production and capacity rather than flexibility, and investment in low cost, inflexible plants (primarily gas fired plants) could lead to a significant increase in balancing costs and C02 beyond 2025. There is a need to develop new models to recognise the problem that investors in conventional generating plants, DSR and energy storage technologies will face, and to quantify the economic benefits and C02 implications of coordinating energy and ancillary services markets in future systems with significant contribution of low carbon generation.

This modelling effort will be essential for the development and design of new ancillary services markets [30]-[31].

Furthermore, current transmission network operation and design models do not take into consideration sharing of a range of ancillary services across the network. Recent work suggests that given the growth in renewable generation and consequent increase in the requirement for various forms of reserve, explicit consideration of the impact of network constraints on the allocation of spinning and standing reserves across the system will become important [32]-[33]. However, the present market and commercial framework does not explicitly recognise flexibility products that could be exchanged or traded across transmission networks and interconnection. New modelling approaches need to be developed to optimally allocate network capacity between energy and reserve provision and support development of coordinated energy and ancillary services markets.

### b) Realising the whole-system value of new technologies

As discussed above, the whole electricity system modelling approach reveals that demand side and energy storage resources could bring significant benefits to several sectors of the power system. However the energy supply sector (generation) and energy transport sectors (distribution and transmission networks) are operated by different commercial organisations and the level of integration and coordination is currently limited. In order to facilitate distributed generation- and demand-led flexible resources to provide system wide services, a form of coordination is required. The recently developed concept of Virtual Power Plant (VPP) [34]-[36] would enable distributed resources to access national wide markets, and provide both energy and ancillary services.

In order to optimally balance conflicts and synergies between provision of national wide and local services, a Distribution System Operator (DSO) paradigm should be explored, which will require new modelling capabilities to be developed. The DSO will adopt a fully active role at the interface between distribution and transmission networks and coordinate service provision by distributed energy resources to the transmission network.

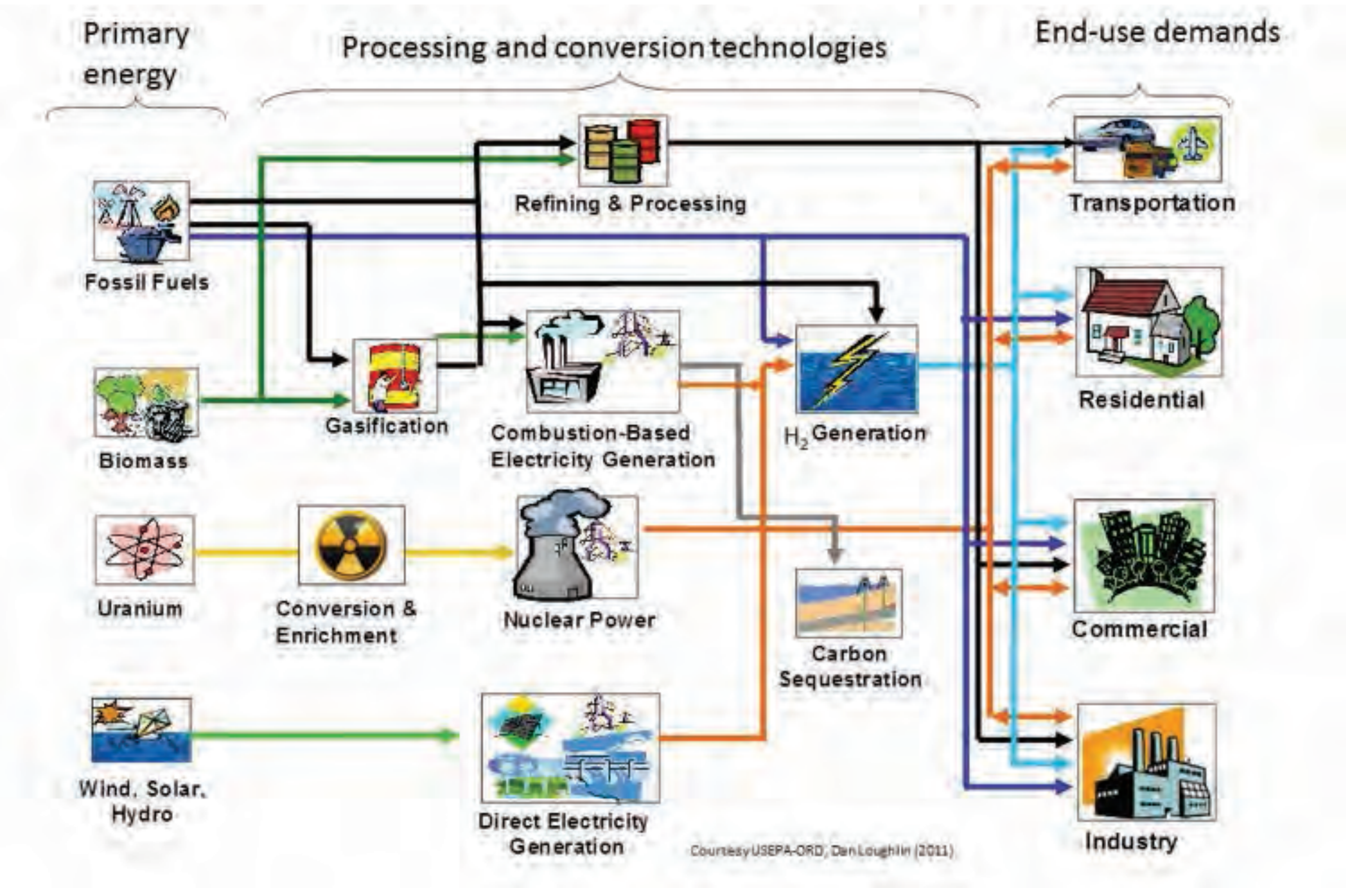



**Figure 2: MARKAL/TIMES Energy System Model.**

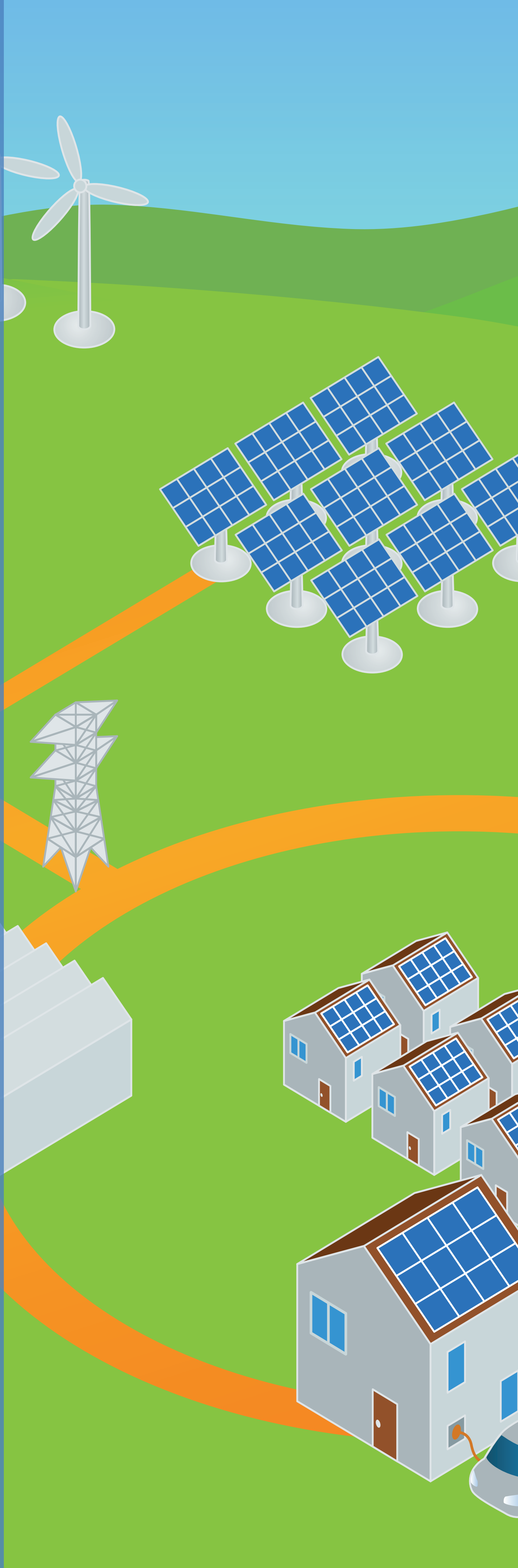
This will in turn require development of new commercial arrangements between the service providers (VPP), DSO and Transmission System Operator (TSO) that will enable a shift from the separate, isolated operation of energy supply, transmission and distribution sectors to a fully coordinating approach, and subsequently lead to the realisation of the maximum overall economic value of distributed energy resources considering both national and local objectives.

### c) Consistency between system cost minimisation and market participants' objectives

There has been significant interest in the co-existence of markets and low carbon agendas with particular concern as to whether the market and regulatory framework will provide appropriate incentives to all market participants to deliver the cost-minimising system operation in the short-term and bring efficient infrastructure investment in the long-term.

In the short-term operation time scale, a wide literature has demonstrated the inability of simple marginal pricing arrangements to support the cost-minimising solution in a liberalised market context, due to the complex operation characteristics of generation units, including binary (on/off) commitment decisions, fixed and start-up/shut-down costs, presence of minimum stable generation constraints, and minimum up/down times **[37]-[42]**. Recently, given the interest in DSR technologies, similar complexities associated with the demand side of the market have been identified and analysed **[43]-[44]**. This drawback of marginal pricing practically means that market participants cannot recover their incurred costs, and hence different approaches based on uplifts and differentiated and non-linear pricing to address this effect and achieve cost recovery have been proposed **[38]-[42]**. However, significant further effort is required to model and include the operational characteristics and of DSR and storage technologies in these approaches while incorporating trading of ancillary services and considering the impact of network constraints.

In the long-term time scale, a particular concern in the context of low-carbon electricity systems is the compatibility between market mechanisms and the low-carbon agenda: will the market provide signals to invest in appropriate technologies and solutions that will facilitate efficient and secure transition to a low-carbon future?



In this context, established modelling tools, including Dynamic Dispatch Model (DDM), Aurora and Plexos, enable the analysis of real-time operation and investment decisions in generating capacity to be carried out [45]-[46]. The electricity demand and supply are considered on a half hourly basis, typically for a number of sample days. Investment decisions are based on projected revenue and cash flows, allowing for different market designs to be analysed. The full lifecycle of power generation plants is modelled, from planning through to decommissioning and risk and uncertainty involved in investment decisions is accounted for. These models ensure that the long-term investment decisions are commercially consistent with prices and revenues that are generated in the short-term market. Although these modes can in principle answer the question regarding the extent to which a particular market design will deliver the cost-minimising solution, there is a significant scope for enhancement regarding the modelling variability and unpredictability of renewable generation and incorporation of demand side response and energy storage technologies. In this context there has been significant recent academic activity with a number of advanced modelling approaches dealing with uncertainty in operation and investment timescale [47]-[74].

Modelling of responses of network companies to different regulatory frameworks and incentive regimes is still underdeveloped. In GB, the new RIIO price control[2] will set the outputs that the Distribution Network Operators (DNOs) need to deliver and the associated revenues they are allowed to collect for the regulatory period. The most recent actions imposed by Ofgem, that force DNOs to make additional savings in their planned expenditure, clearly demonstrate weakness of this regulatory model, as the existing incentives do not align profit maximisation objectives of DNOs with the goal to maximise the value for network users. Another problem with the present regulatory regime is that it only considers incremental, like-for-like network reinforcements and it is unable to facilitate strategic investment when economically justified. However, modelling that would help informing the responses of network companies to different regulatory regimes is yet to be developed. Furthermore, the focus on minimising distribution network investment costs without considering the impact of reinforcements to the whole electricity system chain will lead to increased costs for consumers in the long run. In principle, such concerns could be addressed through developing whole-system market models. Finally, there is no appropriate scope to invest in network solutions that would provide flexibility to cost effectively deal with significant uncertainties in future developments, as discussed in [27]-[28], [74] in the context of integrated offshore network and interconnection. Similarly, future market-driven investment models should also have the capability to quantify the option value of alternative propositions and support robust decision-making under uncertainty.

In both short-term and long-term time scales, the individual objective of market participants lies in maximising their own profits, which is not always in line with system-wide objectives. Participants with material market shares or located at strategic positions may have the capability to affect market prices in order to increase their own profits and thus exercise market power. In this context, a large number of studies have investigated the effects of non-competitive market behaviour, mainly through game-theoretic and agent-based learning approaches [75]-[87]. However, the focus of this work is mostly on supply side, while the exercise of market power by aggregated populations of new demand side response and storage participants is still unexplored and constitutes a significant area for future work.

### d) Modelling of distributed market place

The shift from centralised to highly decentralised paradigm will pose very significant challenges in future system operation and design. With the roll-out of smart metering, millions of small-scale flexible loads, distributed generators and storage devices, dispersed throughout the UK distribution network and owned and operated by self-interested market participants and consumers, will be able to participate in electricity markets and system management. In this context, the traditional centralised operation paradigm, where a central coordinator collects the cost characteristics and operational constraints of system participants and schedules them based on the solution of a least-cost optimization problem [88]-[90], will no longer applicable, due to communication and computational scalability as well as privacy concerns.

Dynamic pricing schemes [91]-[92] could deal with these limitations of centralised approaches, as end customers are incentivised to modify their consumption patterns according to the posted prices, without having to reveal their individual properties to a central entity. In these schemes however, the posted prices are not influenced by the resulting demand response close to real-time, leading to inefficient or even infeasible system outcomes, such as loss of diversity and synchronisation of demand response in the periods when the energy prices are lowest.

[2] RIIO: Revenue=Incentives+ Innovation+ Outputs.

A two-level modelling framework of distributed, market-based coordination of demand response has been recently developed, combining the cost efficiency of centralised mechanisms with the distributed participation structure of dynamic pricing schemes [93]-[95]. At the local level of the model, individual users optimise their production and consumption patterns according to their own objectives and requirements in the context of proposed energy prices. At the global level, the prices are updated in an effort to satisfy system-wide objectives and constraints. In order to avoid reduction in diversity and resulting synchronization phenomena, different measures have been proposed, such as the augmentation of the marginal prices sent to demand resources by response limits or non-linear pricing signals, as well as the randomisation of the communicated prices. This mechanism has been applied both to the wholesale market level to enable more efficient operation of the generation system [94]-[94], as well as the local distribution level to enable management of voltage and thermal constraints through locational pricing of both active and reactive power [95].

Furthermore, a very strong interest has been observed around the development of agent-based models, exploring the behaviour and interactions between a very large number of small-scale market participants [96]-[113].

Models that simulate fully decentralised system operation need to be further enhanced to deal with conflicts between supply side and network congestion management driven demand- and generation-led DSR response. Furthermore, the realisation of such a distributed coordination approach requires suitable two-way communication enabling the interaction between the dispersed demand resources and the market coordinator. In this context, significant effort is needed to model the technical capabilities of communication systems and understand the interaction between the efficiency of distributed coordination and the associated communication requirements, in terms of number and size of message exchanges. Furthermore, the reliability aspect of these communication systems should be explored, by investigating the impact of message delays and losses on the coordination outcome.

## 4. MULTI-ENERGY SYSTEM MODELLING

Multi-energy system models are becoming particularly relevant given the growing interactions between electricity, heat, transport, gas, hydrogen and water sectors, particularly driven by the low carbon agenda. The interfaces between different energy vectors and corresponding infrastructures are becoming increasingly important as the integrated approach is likely to deliver significant savings when compared with the traditional approach of considering individual energy sectors in isolation. For example, as research demonstrated, the heat sector may present substantial opportunities for energy storage and thereby support a more cost effective integration of intermittent and inflexible electricity generation [114]. Similarly, pumping operations in the water sector, aimed at filling reservoirs, could potentially provide very valuable flexibility and enhance efficiency of the real time balancing tasks in a future low carbon electricity system. Furthermore, recent research has clearly demonstrated that interaction between gas and electricity infrastructures may be significant and that an integrated approach to operation and infrastructure designs could bring significant benefits.

A number of whole energy system models have been used in practice. One of the most frequently applied tools for developing technical-economic models of global, regional, national and local energy systems is the TIMES/MARKAL framework developed by International Energy Agency (TIMES represents the recent evolution of MARKAL [115]-[117]). TIMES is a technology rich, bottom-up model generator, which uses linear programming to produce a least-cost energy system, optimised according to a number of user-defined constraints, over medium to long-term time horizons. The model configures the production and consumption of commodities and their prices so that the producer and consumer surpluses are maximised. The model also considers the price sensitivity of demand i.e. that the price of producing a commodity affects the demand for that commodity and vice versa. One of the limitations of the TIMES/MARKAL family of models is that they typically do not support spatial disaggregation of energy supply and demand, while the temporal resolution is restricted to time blocks rather than detailed real-time variations in supply and demand.

Another multi-energy system model based on a linear programming platform is MESSAGE, a model used for medium- to long-term energy system planning, energy policy analysis, and scenario development [118]. The model provides a framework for representing an energy system with all its interdependencies from resource extraction, imports and exports, conversion, transport, and distribution, to the provision of energy end-use services such as light, space conditioning, industrial production processes, and transportation. Similar to TIMES/MARKAL, the MESSAGE model is also limited in terms of spatial and temporal disaggregation of energy supply and demand.

A relatively recent tool developed by the Energy Technologies Institute is the ESME model [119], a national energy system design tool integrating power, heat, transport and infrastructure. Similar to TIMES/MARKAL and MESSAGE, the model finds a least-cost system design based on centralised optimisation. However, it includes a Monte Carlo approach to model uncertainties of key input parameters (e.g. fuel prices, technology cost etc.) and includes spatial and temporal factors in a more detailed fashion (although still not considering sub-hourly variations across multi-year time horizon). On the other hand, unlike TIMES/MARKAL, ESME does not factor in the demand elasticity.

One of the few multi-energy vector models that work with hourly resolution is the CGEN model, which has been developed to combine gas and electricity network expansion planning [120]-[121]. The model simultaneously optimises gas and electricity operational and network expansion costs, while optimising locations of planned power generation plants. The effects specific for gas transport systems are considered, such as the explicit modelling of line pack effects, which is needed for optimising the locations of gas power plants as well as of gas storage installations.

A related concept to integrated electricity and gas system planning is Power-to-Gas, which refers to technologies that convert electrical power to a gas fuel [122], which may become very relevant for future low carbon energy systems. However, there is a need for the development of detailed models with appropriate spatial and temporal resolution to fully understand the benefits of this technology.

Coupling of energy systems with their impact on environment and natural resources such as water and land is considered in the Foreseer tool [123]. It describes physical transformations of energy for other resources (such as energy use for water supply or irrigating and fertilising land) by technologies and physical activity.

The development of integrated multi-energy system models constitutes an emerging area of research and relevant literature is still in its early stages.

Further development of multi-energy models is clearly needed to enhance the spatial and temporal granularity and fully capture the interactions between different energy vectors. None of the major multi-energy models that are currently in use are characterised by adequate time and space resolution. In particular, the representation of the electricity system is generally not sufficiently refined in multi-energy models, i.e. they typically do not consider phenomena such as real-time system operation, maintaining sufficient reserves in the system, dealing with responsive demand and storage and with interaction between operation and investment timescales while considering local and national level infrastructures. Key challenges that need to be overcome are associated with the complexity of representing the multi-energy system with sufficient level of detail and capture the key phenomena and interactions. In order to deal with these challenges, it is envisaged that a number of different modelling approaches should be explored, each achieving a different trade-off between accuracy and computational requirements / complexity. The recently launched Whole Systems Energy Modelling (WholeSEM) research consortium [124] aims at addressing this very issue.

## 5. CONCLUSIONS AND RECOMMENDATIONS

Meeting the economy-wide decarbonisation targets cost-efficiently requires a paradigm change in electricity system modelling, so that the analytical tools adopt a fully integrated approach in order to capture growing interactions across different industry sectors. Development of holistic modelling approaches of the whole electricity system chain (generation, transmission, distribution) across both operation and planning time horizons will be essential, as the historical, individual sector centric approaches are no longer sufficient to facilitate cost-effective operation and development of the system.

Although several modelling platforms have emerged in the recent years that focus on integrated energy system analysis considering the impact of new technologies, a number of potential areas for future developments have been identified in this paper.

In addition to incorporating aspects such as uncertainty, location, chronology and distributed operation in least-cost whole-system models, more effort is required to develop models capable of investigating whether the market signals in a low-carbon economy will provide adequate incentives to deliver the necessary investments in DSR and energy storage technologies i.e. to support the cost-efficient transition to a low-carbon energy system.

Furthermore, novel modelling approaches are needed to establish whether the market arrangements and the related regulatory and commercial framework can provide sufficient incentives to the market participants in order to deliver the cost-minimising system operation and development in the low-carbon future. In this context, modelling of responses of network companies to different regulatory frameworks and incentive regimes is particularly underdeveloped. Changes in commercial and regulatory arrangements will be needed to adequately reward the value of new flexible technologies, which requires new whole-system models to be developed that are able to consider participation of both traditional and emerging new market participants, while optimally allocating network capacity between energy and ancillary services provision. Given the roll-out of smart meters, new models for simulating operation of fully decentralised energy and ancillary markets are needed to understand the ability of price based control to deliver energy efficiency and provide system management services. New modelling should deal with communication and computational scalability needed to achieve distributed coordination between market participants.

Traditional multi-energy models (TIMES/MARKAL, MESSAGE and ESME) do not use sufficiently refined spatial and temporal resolution required for future low-carbon energy systems. Further development in this area is therefore needed to extend chronological multi-energy models to include other vectors such as heat, hydrogen, mobility etc. Key challenges that need overcoming arise from the significant complexity of representing the multi-energy systems and interactions between different energy vectors.

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