Modelling of Smart Low-Carbon Energy Systems

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In this document we describe models developed by our research group, namely: Whole electricity System Investment Model (WeSIM), Stochastic Unit Commitment (SUC) model, Price-based Demand Side Participation Model (PriceDSP), Dynamic Transmission Investment Model (DTIM), Distribution Network Planning Model (DistPlan), and Combined Gas and Electricity Network Operation Model (CGEN).

1. Whole-electricity System Investment Model (WeSIM)

WeSIM is a comprehensive electricity system analysis model simultaneously balancing long-term investment-related decisions against short-term operation-related decisions, across generation, transmission and distribution systems, in an integrated fashion. In this context, WeSIM is a holistic model that enables optimal decisions for investing into generation, network and/or storage capacity (both in terms of volume and location), in order to satisfy the real-time supply-demand balance in an economically optimal way, while at the same time ensuring efficient levels of security of supply. A key feature of WeSIM is in its capability to simultaneously consider system operation decisions and infrastructure additions to the system, with the ability to quantify trade-offs of using alternative smart mitigation measures, such as DSR, new network technologies and distributed energy storage, for real-time balancing and transmission and distribution network and/or generation reinforcement management. The model also captures potential conflicts and synergies between different applications of distributed resources (e.g. demand side response - DSR) in supporting intermittency management at the national level and reducing necessary reinforcements in the local distribution network.

The objective function of WeSIM is to minimise the overall system cost, which consists of cost of investment in generation, network, interconnection and emerging flexible network, storage and DSR technologies and cost of operating the system, which includes generation operating cost and cost of supply interruptions. The problem is subject to power balance constraints, reserve and adequacy constraints, carbon emission constraints, power flow limits in transmission, distribution and interconnection, generation plants' dynamic characteristics, and DSR and storage operational constraints. The structure of WeSIM is shown on Figure 1.

WeSIM can be used to assess the electricity infrastructure development and system operation within UK or EU. Different network topologies are generally used to balance the complexity and accuracy of modelling. Different levels of market integration can be modelled in WeSIM through distinctive levels of energy exchanges cross-border, sharing of security or various operating reserves, e.g. country, regional, EU levels. WeSIM optimises the generation, storage, and DSR dispatches taking into account diversity of load profiles and renewable energy profiles (hydro, wind, PV, CSP) across Europe, in order to minimise the additional system capacity to meet security requirements.

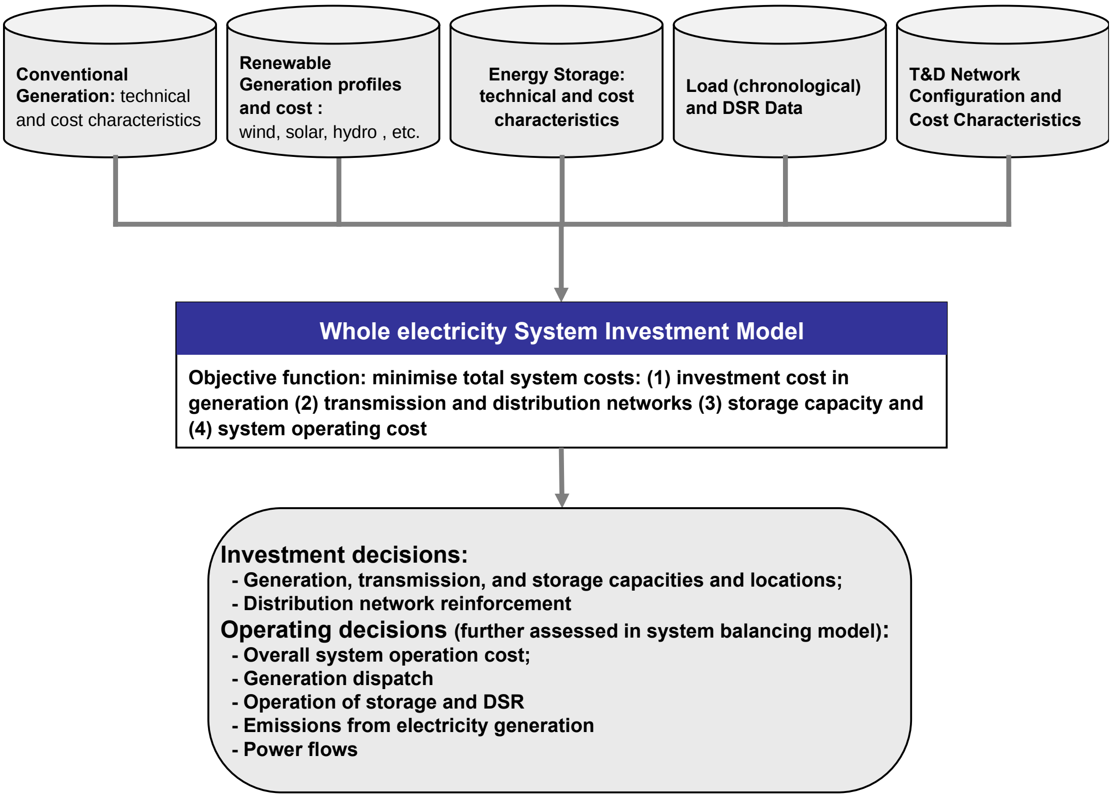

Figure 1: Structure of the WeSIM model

Regarding the local distribution networks, WeSIM uses a set of representative networks that follow the key characteristics of different type of real GB (and EU member states) distribution network. These representative networks are calibrated to match the actual electricity distribution systems. The mismatches in control parameters between the actual GB and representative networks characterised using this process, are less than 0.1%.

Regarding DSR modelling, WeSIM broadly distinguishes between the following electricity demand categories: (i) weather-independent demand (ii) heat-driven electricity demand (space heating / cooling and hot water), (iii) transport demand and (iv) smart appliances' demand. Different demand categories are associated with different levels of flexibility. Losses due to temporal shifting of demand are modelled as appropriate. Flexibility parameters associated with various forms of DSR are obtained using detailed bottom-up modelling of the different types of DSR.

2. Stochastic Unit Commitment Model (SUC)

For the purpose of assessing the operational costs associated with balancing demand and supply in real time in future systems with significant contribution of renewable generation, and quantifying the value of various emerging technologies that offer different types of flexibility, time-domain generation scheduling models are required. This is because of the need to capture complex inter-temporal constraints that limit the balancing actions of the thermal plant, storage, and demand-side measures. For this purpose, we have developed a stochastic unit commitment (SUC) with rolling planning. The structure of the SUC model is presented in Figure 2.

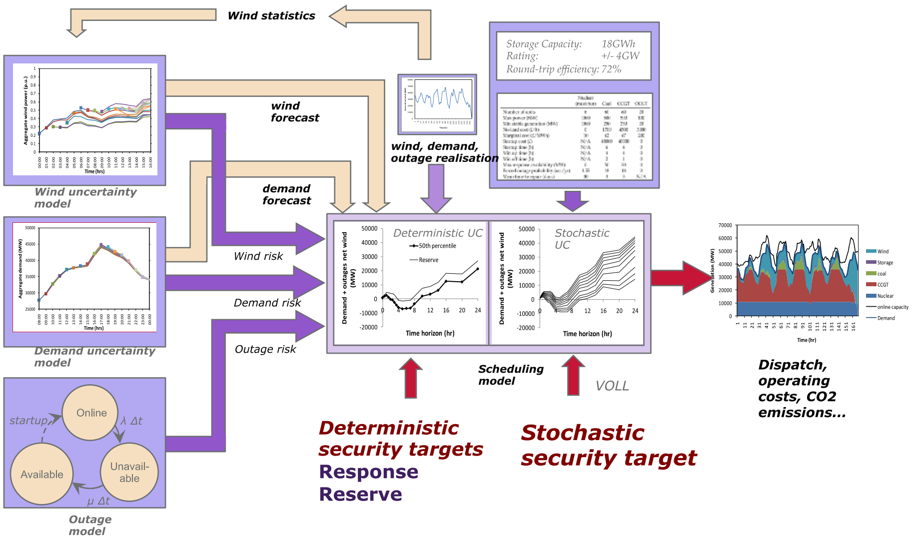

Figure 2: Structure of the SUC model

SUC contains a number of models including short-term aggregated time series model to account for all the correlations that are needed to produce synthetic, unbiased wind power forecasts and associated risks that evolve in a realistic way. The quantile-based scenario tree methodology applied has the ability to capture the worst-case tail of the distribution, thus allowing the scheduling decisions to be optimised in a wind-integrated system using the value of lost load (VoLL) as the only security parameter. One of the key features of the SUC model is in its ability to schedule both primary and secondary reserves considering wind, demand and generator outage uncertainty. This is critical for allocating storage or DSR resource between energy arbitrage (wind following) and the provision of ancillary services. It is clearly very important to optimally allocate the energy storage and DSR resource between providing reserve and conducting energy arbitrage, which only stochastic scheduling model can facilitate. SUC therefore optimises the allocation of storage resources between energy arbitrage and reserve, which varies dynamically depending on the system conditions.

3. Price-based Demand Side Participation Model (PriceDSP)

Coordination of flexibility at the demand side with system objectives and requirements can yield significant benefits in term of capital and operating costs across generation, transmission and distribution sectors. In traditional centralised coordination approaches, flexible loads communicate their economic and technical characteristics to a central entity (supplier, system operator or DNO, according to the application), which solves a global optimization problem and posts according direct control signals to the flexible loads. Under a large-scale penetration of such loads, this centralised coordination paradigm will face communication and computational scalability limitations. Furthermore, consumers are likely to raise privacy concerns, as they are not generally willing to reveal their individual properties and be directly controlled by an external entity.

In this context, we have developed an alternative decentralised demand coordination mechanism, in the form of the Price-based Demand Side Participation Model (PriceDSP). This model is designed to optimally coordinate demand flexibility with system objectives and requirements, without requiring centralised knowledge of individual loads' characteristics. The model is founded on dual decomposition principles, involving a two-level iterative process, consisting of a number of independent local optimal price response sub-problems - expressing the participants' choices according to the posted prices and their own objectives and constraints- coordinated via a price update algorithm to ensure that system requirements are satisfied (Figure 3).

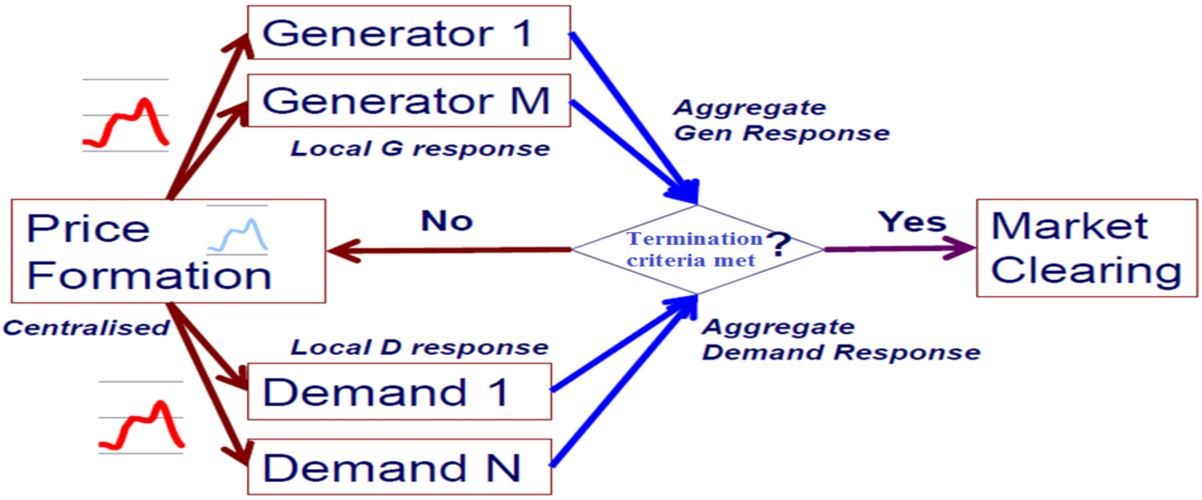

Figure 3: Structure of the PriceDSP model

However, naïve application of price-based coordination in combination with the envisaged automation in demand response leads to serious loss of diversity and demand concentration effects, as flexible loads attempt to consume as much as possible at the lowest-priced periods. These effects create significant new demand peaks with adverse impacts on the economic and technical performance of the system. In order to address these effects, three different measures have been developed and incorporated in PriceDSP:

- applying relative flexibility restrictions to flexible loads

- applying non-linear prices, penalizing the extent of flexibility utilized by flexible loads

- randomising the price signals posted to different flexible loads

4. Dynamic Transmission Investment Model (DTIM)

Dynamic Transmission Investment Model (DTIM) is a cost-benefit analysis based electricity transmission expansion planning model that optimises the timing, capacity and location of the transmission investment. The model also provides minimum cost generation dispatch decisions including the use of out of merit generation, including wind generation curtailment (if necessary), preventive and corrective control techniques to manage network congestion. DTIM balances costs of network constraints with costs of network reinforcement, minimising the overall cost of power system operation and expansion over a given duration.

Throughout the optimization period the model determines when, where and how much to invest into transmission network considering demand forecasts, current and future fuel costs, evolution of installed conventional generation capacity, the location and quantity of new wind generation capacity, transmission and generation maintenance plans, etc. DTIM is capable of capturing inter-temporal changes in generation and demand thus optimizing both the amount of transmission capacity and the timing throughout the modelling period. In addition to the transmission planning capabilities, DTIM can be used to calculate welfare functions, energy market prices, locational marginal process, constraint costs, losses, generation dispatch patterns and transmission power flows.

Given the need to determine the economically efficient level of transmission network security, DTIM is developed within a probabilistic framework that incorporates various operational measures based on alternative smart grid concepts which allow generation, transmission, and demand corrective actions to be coordinated in both pre- and post-fault time windows. This is particularly relevant for the future GB system as the significant network reinforcements driven by the increase in on- and off-shore wind generation, could be partially substituted by a number of cost-effective, smart grid operational measures.

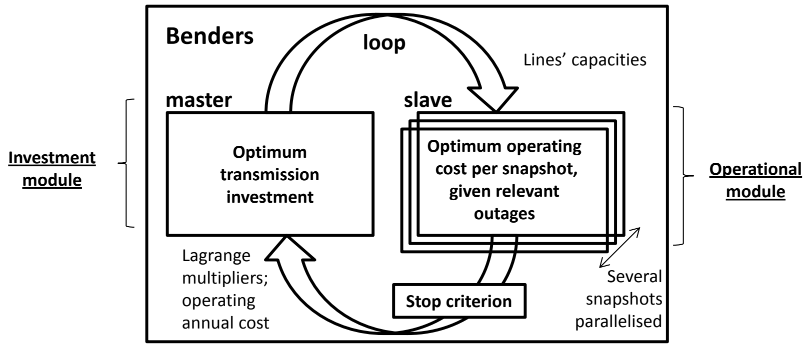

Figure 4: Structure of the DTIM model

DTIM is composed of operational and investment modules that are presented in Figure 4. In the operational module, the optimal network utilisation over a given operating condition is determined when considering the use of an array of smart grids technologies that allow generation, transmission, and demand corrective actions. The investment module, supported by multiple executions of the operational module over a variety of operating conditions, determines the optimum network investment in a year. The operating and investment decisions are coordinated through a Benders decomposition algorithm.

5. Distribution Network Planning Model (DistPlan)

In order to calculate the impact of low carbon demand and generation technologies on distribution networks, the Distribution Network Planning (DistPlan) model has been developed. The model determines the timing, capacity and location of distribution network reinforcements yielding the minimum overall cost (considering cost of reinforcement, cost of network losses and cost of flexible network, flexible demand and storage technologies).

As the impacts of local demand and generation depend, among others, on the topology and characteristics of the distribution networks, it is important to model distribution networks with different characteristics, e.g. urban, semi-urban, semi-rural, and rural networks and different voltage configurations (Figure 5). A number of such networks with different characteristics are developed, representing different mixtures of overhead and underground lines, different load density and number and mixture of customers, in order to map the GB electricity distribution networks.

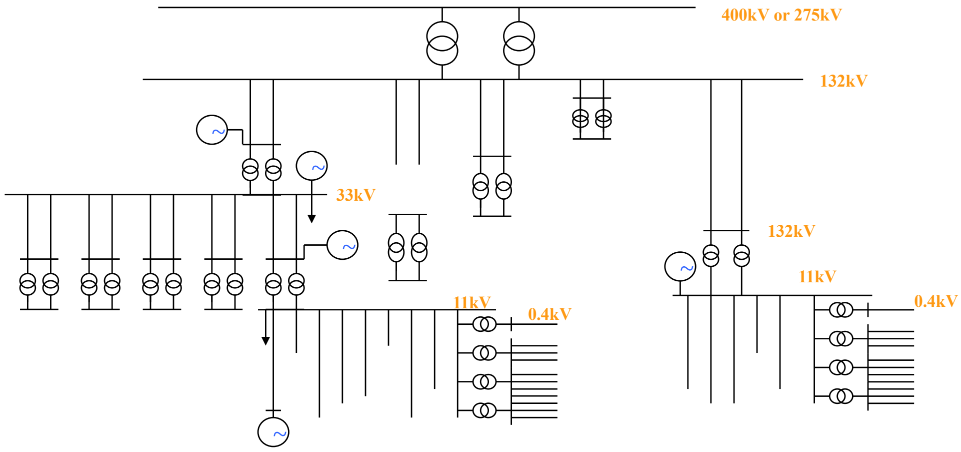

Figure 5: Configuration of representative regional distribution network model

The model is capable to represent and quantify the impact of different smart flexible technologies, including demand side response, energy storage and smart network technologies (such as voltage regulation, normally-open points) on the required upgrade of the distribution infrastructure.

6. Combined Gas and Electricity Network Operation Model (CGEN)

CGEN is a modelling and optimisation tool for the gas and electricity transmission infrastructure. CGEN model minimises the total operational cost of the combined gas and electricity system including the costs of gas supplies, gas storage operation, power generation and load shedding over the entire time horizon while meeting gas and electricity demand. Technical limitations and detailed characteristics of components of both networks are considered as constraints of the optimisation.

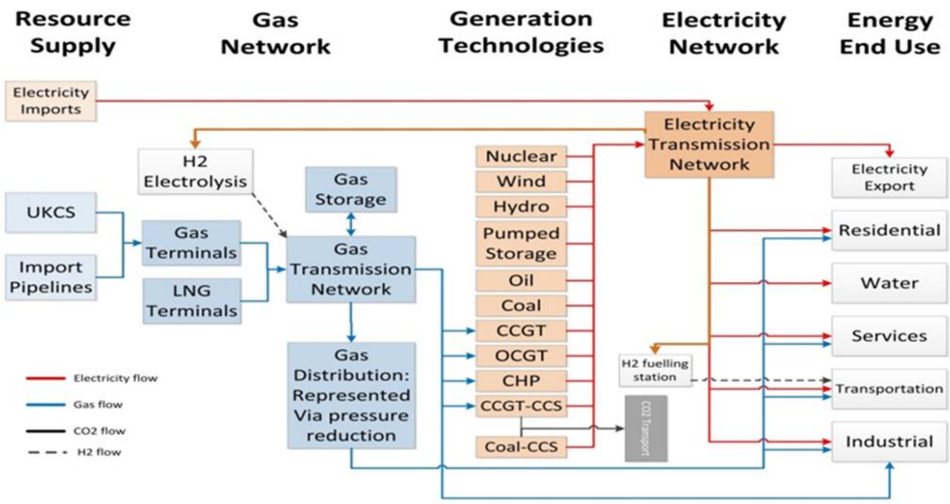

Figure 6: Flow diagram of gas and electricity system considered in CGEN

CGEN is capable of modelling networks with different level of spatial details (e.g. from a simplified cross-region gas network to complete National Transmission System). In terms of temporal granularity, CGEN is flexible to model operation of networks over a time horizon from a day to a month with time steps from 30 minutes and longer.

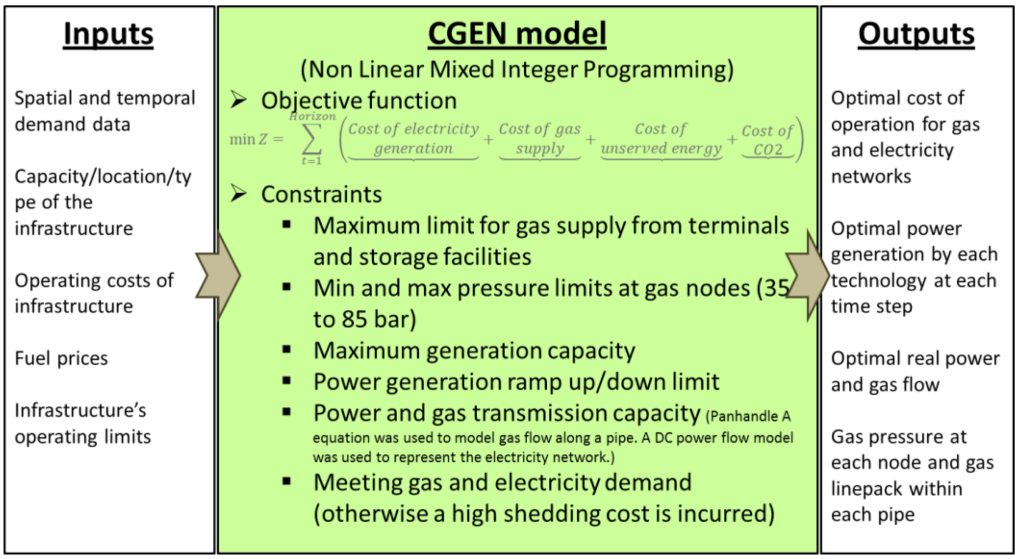

Figure 7: Overview of CGEN model's inputs and outputs

Detailed description of CGEN can be found in the following references:

1. M. Chaudry, N. Jenkins and G. Strbac, Multi-time period combined gas and electricity network optimisation, Electric Power System Research, Volume 78 (2008) 1265 - 1279
2. M. Qadrdan, M. Chaudry, J. Wu, N Jenkins, J. Ekanayake, Impact of a large penetration of wind generation on the GB gas network, Energy Policy, Volume 38 (2010) 5684-5695.
3. M. Qadrdan, J. Wu, N. Jenkins, J. Ekanayake, Operating strategies for a GB integrated gas and electricity network considering the uncertainty in wind power forecast, IEEE Transaction on Sustainable Energy, DOI: 10.1109/TSTE.2013.2274818.