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# Modelling Requirements for Low Carbon Electricity Systems: New Robust Models of Demand, Generation, Energy Storage and Demand Side Management in Static and Dynamic Studies

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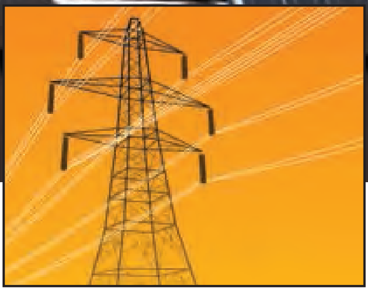

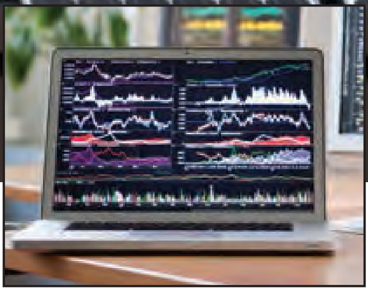

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# About this report

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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# Modelling Requirements for Low Carbon Electricity Systems: New Robust Models of Demand, Generation, Energy Storage and Demand Side Management in Static and Dynamic Studies

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## EXECUTIVE SUMMARY

This paper presents modelling, input data and software aspects of the low carbon technologies and new 'smart' solutions that are going to be a part of business-as-usual within future distribution and transmission companies. The main objectives are evaluation of modelling requirements and capabilities for studying future electricity distribution and transmission networks, identification of gaps in existing modelling capabilities and currently available input data and critical assessment of the impact on GB power system performance and stability/security. Modelling of future distribution networks requires integration of new low carbon technologies, such as solar and wind generation, electric vehicle and heat pump demands, and energy storage, as well as 'smart' network solutions including demand side management and response. Future distribution and transmission companies will have to apply a number of dynamic and steady-state power system studies to assess technical feasibility of the envisaged network solutions designed to deal with new low carbon technologies.

Several modelling and input data gaps are identified. Adequate dynamic models, which account for both non-electrical and electrical processes, do not exist in the currently used power system analysis tools for electric vehicles, heat pumps, demand side management, solar generation and all types of energy storage. Similarly, dynamic frequency control blocks are not developed for all considered demand and generation categories and need to be designed from scratch by the user. Situation with steady-state, 'single snapshot' models is slightly better, however there are no adequate models for electric vehicles, batteries, compressed air, flywheel, super-capacitor and superconducting magnetic storage. Static hourly profiles, which are required in sequential studies, do not exist for electric vehicles, heat pumps, demand side management and response, compressed air, pumped hydro and battery storage. Currently available reliability analysis engines cannot adequately model solar and wind generation, as well as compressed air, pumped hydro and battery storage. Data on harmonic current injections and reliability data are not available in all studied cases.

The first recommendation is that development of models for new low carbon technologies and 'smart' solutions should be done by co-ordinated action of all distribution and transmission companies, as well as other relevant parties, such as academia and commercial software providers. A common database of all 'in-house' developed models and software scripts should be established and managed by a single party. Next, new models will have to be populated with real-life data and distribution & transmission companies need to establish internal processes to gather various types of modelling data from manufacturers and suppliers of new technologies. This is particularly important for distribution companies because they are currently not doing dynamic studies and some of static studies, and the amount of data to be gathered is 'huge' due to network dimensionality and large number of 'small' new connections. The populated new models will be applied within the whole suite of power system studies. In that respect, new functionality of the existing software tools will be required. To mention a few, multi-stage (i.e. sequential) load flow, optimum power flow with 'appropriate' objective function and/or security constraints, new network equivalencing models for steady-state and dynamic studies, distribution network reconfiguration and restoration functions and new reliability analysis tool based on sequential Monte Carlo simulation will need to be developed. Distribution and transmission companies should go for the unification of power system software tools, which would provide simple and quick access to input data, internally developed models and various reports. Finally, companies will have to undertake appropriate staff training to be able to cope with new challenges, whilst academia will provide adequate education of the new generation of power systems engineers.

## 1. BACKGROUND

The IET Power Network Joint Vision (PNJV) initiative recently concluded that there were significant concerns relating to the secure and co-ordinated operation of the GB power system as a result of current and future operational challenges. An important area for further investigation is the ability to model the emerging power system and to understand the system phenomena from planning and operational perspectives. The Council for Science and Technology (CST) has approved the project ‘Modelling Requirements to Assess the Resilience of the Electricity System as it is Adapted to Deliver Low Carbon Transition’ to assess the modelling requirements and existing capabilities for the GB power system. An IET and CST/GO-Science Steering Group has been formed to lead this work.

The purpose of the project is to assess the modelling capability required to enable a full understanding of the future behaviour of the GB power system developed to meet the challenges of low carbon transition. The GB power system is defined as the physical infrastructure comprising onshore and offshore generation and transmission with associated interconnections, distribution, storage, and demand-side systems for electrical energy. The project will review the level of modelling required to demonstrate that the networks are fit for purpose and identify any modelling capability gaps that need to be filled, in order to provide stable and secure performance of the GB power system. This is required for both shorter operational time frames and in longer investment time frames in line with the wider questions of energy system security now and in future. The modelling referred to is computer simulation of Britain’s electrical power systems including its demands, the physical equipment, systems and sub-systems, and its operation in a commercial context. The project is intended to inform Government, power system operating companies and other stakeholders of the modelling requirements, capabilities and emerging needs for power system modelling tools, platforms, methods, models and data.

The IET/CST Steering Group will lead the project but expert support will be provided to undertake the specialist tasks. The support is required to have expert-level domain knowledge addressing the scope and have real experience of power system modelling activities. The approach to delivering the project is by commissioning several papers to provide evidence to the CST/IET Steering Group about the level of readiness of modelling capability required to give visibility of system challenges and thus underpin continued delivery of performance and security from the GB power system.

# 2. POWER SYSTEM MODELLING REQUIREMENTS AND AVAILABLE SOURCES OF INFORMATION

Modelling requirements for new low carbon technologies (LCTs) related to electricity demand and generation are presented first. Following LCTs and related 'smart' solutions are analysed:

1. Electric vehicles (EVs) and heat pumps (HPs).
2. Different types of demand side management (DSM) and demand side response (DSR).
3. Solar (PV) generation and wind generation.
4. Energy storage in compressed air, pumped hydro, flywheels, batteries, super-capacitors, super-conducting magnetic and hydrogen – fuel cells.

Modelling requirements are presented for multiple power system analyses, which are defined in the recently initiated 'smart' network study [1], more specifically: load flow and optimum power flow studies, fault/short-circuit study, frequency response and whole system balancing study, reliability study, dynamics studies, harmonics – power quality and protection studies.

The modelling requirements are compared with existing modelling capabilities in the second sub-section and modelling gaps are identified. Assessment of the impact of new LCTs on the GB power system performance is given in the final, third sub-section.

## 2.1 Power System Modelling Requirements

Modelling requirements are presented for the above power system studies, for each new LCT in turn.

### Electric Vehicles

Electric vehicles (EVs) can be classified as battery electric vehicle (BEV) using electrical traction only, hybrid electric vehicles (HEV) using electrical power train and an internal combustion engine (ICE) and plug-in hybrid electric vehicles (PiEHV) that can also run using the electrical drive only. Several charging modes can be specified, e.g. slow residential, slow public and fast public.

Full dynamic simulation models of HEV and PiEHV are given in [2-6]. They are based on object oriented approaches, with the models of ICE, transmission-gearbox, electric machine, inverter and the pack of batteries. The electric drive model comprises dynamic models of induction machine, inverter and the voltage map for a battery pack showing relationship between voltage, state-of-charge (i.e. percentage of remained energy in the battery) and the charge/discharge rate [5, 6]. HEVs can be run in the ICE and hybrid modes, whilst IEC, electric and hybrid modes can be set at PiEHVs. The battery pack can be charged from the power grid requiring modelling of the inverter and batteries, or from the IEC and the electric drive when the whole system needs to be modelled.

Enhanced modelling of Lithium-Ion batteries in HEV and PiHEV, taking into account temperature effects, is presented in [7, 8]. Temperature dependent state-of-charge is proposed in [7], whilst a combined electro-thermal model is developed in [8]. Dynamic modelling of the EV electric mode is also done in [9] using the VHDL-AMS modelling platform. The main components are the vehicle dynamic model, inverter model, permanent magnet synchronous machine model and control strategy. Finally, a dynamic battery model capable of reproducing state-of-charge, I-V characteristics and dynamic behaviour of different battery types is proposed in [10,11]. It is used as an electricity source in the full PiHEV model encompassing battery storage, electronic drive and motor, vehicle transmission and dynamics and a speed controller [19].

Simplified steady-state modelling of EVs is used within the multi-stage optimisation model for optimising interaction between EVs and renewables [12]. EVs are modelled with the aid of charge and discharge active powers within time intervals, however energy stored in the EV batteries and their capacities were not applied. Impact of PiHEV charging on Brazilian distribution networks is studied in [13]. Theoretical charging curves of batteries giving relation between charging current and state-of-charging [14] were used. Battery capacity and state-of-charge were applied because network loading depends on the battery voltage and current values. The simulations considered two charging behaviours: single-phase, low-voltage slow- and fast-charging, as well as three-phase, low-voltage fast charging. Recharging can be done using slow residential and/or public chargers, as well as fast public chargers.

Three PiHEV recharging profiles were considered: uncontrollable profile predominant over peak demand intervals, dual-tariff profile with the presence of an extra peak-demand tariff, and controlled recharge profile. The work has been extended in [15] to account for stochastic evaluation of the EV impact on the distribution networks.

Impact of PiHEV charging on distribution networks is studied in [16, 17], whilst a multi-stage optimisation model is proposed in [18] to investigate uncontrolled and controlled charging. PiHEV charging over consequent time intervals was modelled using the constant active power within each hourly interval. Battery capacity and state-of-charge are the remaining electrical quantities used, whilst plug-in time (i.e. last trip arrival time), departure time of the first trip in morning, energy consumption per mile, distances travelled, etc. are the applied non-electrical quantities. A stochastic simulation model based on Monte Carlo approach is developed in [19]; active powers of PiHEV charging over time intervals and capacity of batteries are used to simulate PiHEV loading in business, retail and commercial areas.

### Heat Pumps

Heat pumps can be classified as air-source, ground-source and water-source pumps. They can be used for cooling and heating of air, water heating, etc. Different types of motors, most frequently single-phase and three-phase induction motors, can be used within heat pumps. Different control techniques, e.g. fixed- and variable-speed drives, can be applied to heat pump motors.

A dynamic thermo-electrical model of the heat pump system was proposed and compared against test results in [20, 21], in order to control the load and contribute to the reduction of capacity of electricity storage. The system consists of a three-phase motor, compressor, air heat exchanger, water heat exchanger and a control system. When the power consumption of the heat pump is changed from minimum to maximum value, the rate-of-change is strongly non-linear. The dynamic power consumption model was based on the heat pump's coefficient of performance (CoP) characteristics, relating the CoP to power consumption and temperature difference between outside temperature and the water/air temperature, single first-order delay element and a dead-time element.

'Similarly', a dynamic thermo-electrical model of air-source heat pump was developed in [22, 23] to study complete building/housing systems. It consists of a compressor (gaseous refrigerant is pressurised), condenser (high pressure, high temperature refrigerant is converted from gaseous to liquid state – water cycle), an expansion valve (changes into low pressure, low temperature liquid) and evaporator (liquid refrigerant is converted back to gaseous state – air cycle). Simplified thermo-dynamical differential equations of individual components were developed using the CoP which depends on the outside air temperature and the condenser outflow temperature.

A dynamic model of the variable speed heat pump (VSHP) in a commercial building that responds to direct load control has been developed in [24]. The main components of the VSHP are an evaporator, a compressor, a condenser, and an expansion valve, whilst the whole system consists of a variable speed drive-controlled squirrel cage induction motor that drives the VSHP, a VSHP, experimental building room and a power/temperature controller in the building. The input and output characteristics of the VSHP, in both transient and steady-state operation, were extracted from the non-linear differential equations [25]; indirect torque controller with a constant flux linkage was used as the dynamic model of the variable speed drive-controlled induction motor, as well as the dynamic thermal model of the experimental building. Another dynamic model of the variable speed drive controlled induction motor, comprising compressor motor, power converter and variable speed controller, is presented in [26]. The drive is used for water source heat pumps (WSHPs) and takes into account working principles of the controlled induction motor and compression process. The motor and compression characteristics of the WSHO were developed to model the coupling between motor speed and the torque and compression characteristics.

Modelling of ground source heat pumps was done in [27, 28]. The thermo-dynamic model developed in [27] predicts the house indoor temperature when heat pump electrical power and outdoor temperature are known. A reliability model of the underground heat exchanger is proposed in [28]. Both dynamic and steady-state models of heat pump *load* were developed and validated against experimental results in [29] to find impact on low-voltage networks. The dynamic heat pump load model includes single-phase induction motor and a soft-starter. Active and reactive powers of the heat pump (steady-state model) are then modelled as functions of voltage and frequency at the load terminal in order to replicate the experimental results.

Measurements of daily profiles of several types of heat pumps are compared and analysed in [30] to find impact on distribution networks in system planning. The heat pumps have three major components: the first compressor step is used for space heating, the second for water heating, whilst the resistive element is used for additional heating on cold days. The hourly profiles of electricity consumption in kW are obtained in four steps: heat demand for space and tap water heating are derived from the thermal heat demand profiles, the heat demand is converted into the electric energy demand for one or two compressor steps and the resistive heating element, individual profiles are then constructed and aggregated.

A stochastic Monte Carlo method is proposed in [31] to study impact of uncontrolled human behaviour on low-voltage networks. Three typical HP electricity profiles were developed and randomly assigned to low voltage customers with HPs. These profiles were calculated from hourly thermal demand profiles, which are classified by occupancy types, seasons of the year, build periods and types of the houses, and whose granularity was increased to one minute to adequately capture the HP demand.

### Demand Side Management and Demand Side Response

In this paper, classification of demand side management (DSM) and demand side response (DSR) is based on the U.S. Department of Energy approach [32]. DSM refers to the demand that can be directly curtailed either remotely from the control centres or locally when installed in appliances; it is also called direct load control and is of deterministic nature. Two types of demand side response (DSR) are distinguished. The first is incentive based option [33] and it refers to interruptible contracts which are usually activated in system emergencies when the control centre 'asks' the customer to reduce its consumption. Probability of this load curtailment is high and it can be treated as (quasi) deterministic quantity. On the other hand, DSRs to critical peak pricing, real-time pricing and time-of-use pricing [33] are of stochastic nature and need to be assessed from the demand elasticity to price variation, where elasticities can vary in a wide range. There is currently around 0.5GW of DSM in the UK, which are mostly call-off contracts with industrial users.

The conventional load-frequency model for frequency control of a single-area power system has been extended with an additional DM control loop in [34]. The overall approach is based on the synchronous machine rotor motion equation, in which DM is modelled as an independent term. The additional control loop comprises a controller and the DM communication delay, and its input is frequency deviation. Another investigation of aggregated air conditioners in frequency regulation and peak load reduction is presented in [35]. A second-order equivalent thermal parameter model of home heating/cooling system is developed first, a general aggregated model next, which is followed by a novel control scheme that captures compressor time delay and controls the individual house loads.

An aggregated reduced-order dynamic model is proposed in [36] for a class of second-order thermally controlled loads. The individual device model is based on the equivalent thermal parameter model that describes thermo-dynamics of individual loads. Aggregation of individual load models is done for homogenous and heterogeneous loads, and a novel model reduction technique is proposed to get the final reduced-order aggregated model. Next, a simplified dynamic electrical load model of a chiller for use in demand response applications is presented in [37]. The coupling of a building's electrical and thermal characteristics is captured using a dynamic model.

Development of controllable residential load models at the appliance level is presented in [38]. These include space cooling, space heating, water heating, clothes dryer and electric vehicle charging. Space cooling/heating and water heating were modelled using thermal models coupled with electricity consumption, clothes dryer with the aid of electrical power, and electric vehicles model was based on essential battery characteristics and electricity consumed. The developed models were than aggregated to generate controllable load profiles. A static distribution feeder model including multi-state models of residential appliances, such as electric dryers, dishwashers, hybrid water heaters, refrigerators and clothes washers was used to examine the aggregate response of demand response enabled appliances in [39].

Another important aspect of DSM and DSR is load recovery following the completion of load shedding, and it is studied in [40-42]. Recovery models for air-conditioners and water heating devices were developed in [40], refrigerators were treated as frequency response capacity in [41], whilst the economic model of load recovery following demand response and its impact on DR scheduling was studied in [42].

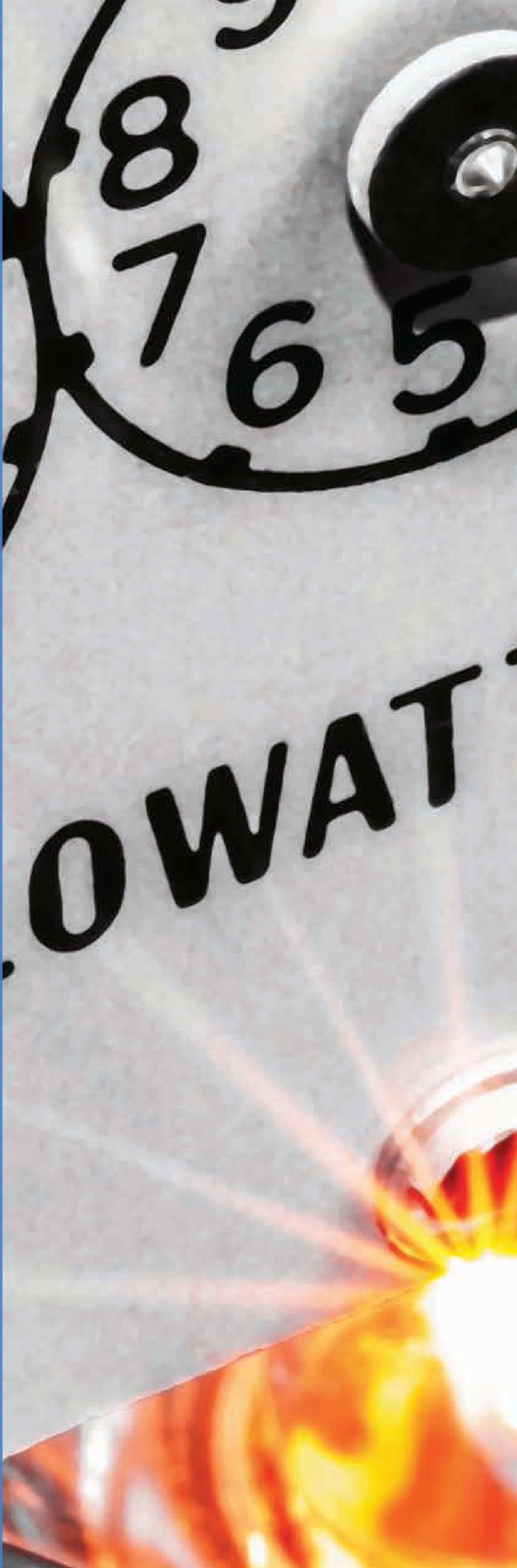
Several different aspects of DSM and DSR, other than load modelling, are studied in [43-51]. A demand response model based on customer behaviour, which is modelled with the aid of extensive demand-price elasticity matrices for different customer types, is presented in [43].

Both price-based and incentive-based DRs are modelled using the customer behaviour expressed through demand-price elasticity in [44]. Optimal demand schedule is calculated using the proposed optimum power flow that accounts for distribution network constraints and interactive communication between households and the load service entity [45, 46]. A demand response program that enables use of bidding of emergency residential load resources to respond to contingencies is presented in [47]. A novel DR scheme which does not require prediction of price elasticity of demand, but makes use of customers' submissions of candidate load profiles ranked in the preference order is given in **[48]**. Paper **[49]** presents a linear programming based optimisation model that adjusts hourly load levels of individual consumers in response to hourly electricity prices. Finally, papers **[50, 51]** investigate further impact of residential DR systems on distribution networks.

### Solar Generation

In-detail dynamic models of the photovoltaic system are presented in **[52, 53]**, and they are based on solar physics described in **[54, 55]**. The equivalent electrical circuit comprises photo current source, a shunt diode (there are also models with two parallel diodes **[56]**), a shunt resistor modelling leakage current to the ground, and a series resistor representing the internal resistance. The photocurrent generated by the photo current source is directly proportional to the solar radiation level in W/m$^2$ and the difference between the operating and rated temperature; the diode current is a function of diode saturation current, operating temperature and voltage across it. The resulting nonlinear (I-V) characteristic is then found using the parameters provided by manufacturers **[52]**. Further analysis of non-linear (I-V) and (P-V) characteristics where either solar irradiance or temperature level is parameter is done in **[53]**, showing that solar irradiance is the dominant parameter affecting the output current/active power. The one-diode model is applied in a slightly simplified form in **[57]** to investigate response of solar generation to changes in solar irradiance and consequent changes of grid AC voltage during disturbances. This is the well-known effect of 'cloud transients' that can produce substantial impact on low-voltage systems in terms of voltage sags and swells. Papers **[58, 59]** extend the work on I-V and P-V characteristics by using the maximum power point tracking control scheme to control power converter in order to get constant and maximum power output of a solar array.

A detailed solar irradiance model based on first principles is developed in **[60]** to simulate solar irradiance across the urban area throughout the day and asses the solar generating capacity in that area. The developed model can be integrated with a model of variable solar irradiation (i.e. 'cloud transients' model) to find the impact on distribution networks. Several approaches are proposed to model solar irradiation variability, for example **[61-63]**.



A steady-state solar generation model for state estimation is developed in [64]. It is based on the nonlinear relations for solar current and voltage obtained from the two-diode model, and their product is then multiplied by the inverter efficiency to get solar AC output power. A 'similar' model, where solar output power is a function of solar irradiation, operation temperature and solar-converter losses (i.e. efficiency), is developed in [65] to study impact of wind and solar generation on networks. Two further steady-state models can be found in [66, 67]. A model that can estimate hourly solar energy generation in different sunshine conditions is presented in [68]. The output power of the solar cell is dependent on solar irradiation, temperature of the solar cell and technical properties of the solar module. Solar irradiation was modelled using the measured hourly long-term irradiation and sunshine data; however, 'cloud transients' were not modelled.

A simplified steady-state model of the solar generation for steady-state systems studies is developed in [69]. Solar generators are modelled as a static generator that is a part of the DIgSILENT library. As the PV converters are significant source of harmonic currents, worst case current injections based on IEEE Standard 519 [70] were assumed. Even simpler approach to modelling solar generation with the goal to study impact on low-voltage networks is developed in [71]. The ideal AC voltage source at the inverter – grid side and a series inductance were used for this purpose.

### Wind Generation

The first wind farm concept is based on the fixed- speed wind turbine, where a squirrel cage induction generator is coupled with the wind turbine rotor through a gearbox [72]. The generator accepts only very small rotational speed variations defined by the cut-in and cut-off wind velocities. The next concept is variable speed – constant frequency wind generation using doubly fed (wound rotor) induction generator (DFIG); several schemes were developed, e.g. limited-variable speed, variable speed with partial (i.e. rotor) converter and variable speed with full converter (so-called fully converted machine) [73]. This concept can also make use of the brushless doubly fed generator (BDFG), which does not have slip rings and brushes. If a single BDFG machine is used, it is equipped with the main – generating winding and an auxiliary – magnetising winding on the stator, and the axially laminated anisotropy rotor [74]. In case of a cascade BDFG, there are two wound rotor induction machines on the same axis, with the windings on two rotors joined together with inverse phase order; the machines are called 'exciter' and 'generator' [75, 76].

A comprehensive dynamic model of wind generation for steady-state and transient analyses has been presented in [77]. The model is aimed at analysing fluctuating wind power generation, power quality of the grid connected wind-park and fault ride-through capabilities during low-voltage conditions. The major modelling blocks are dynamic model of the turbine rotor, mechanical transmission system comprising low-speed shaft, gearbox and high-speed shaft, standard induction generator and a local grid sub-model. The model can be integrated within common power system simulation platforms.

A model of variable speed DFIG based wind generation system is developed in [78] to investigate control strategy of the generator side inverter. Wind turbine is modelled in an approximate way, whilst full models of the drive train, DFIG, and voltage source converter connected to DFIG rotor terminals are presented. Paper [79] also deals with the control aspects of the variable speed DFIG based wind system. Models of turbine (simplified), DFIG, rotor side converter and stator side converter are developed. DFIG vector control is used to keep the rotation speed at the optimal value using the maximum power point tracking approach to extract maximum power.

Integrated dynamic models of wind and solar generation and energy storage are considered in [80]. The wind system model comprises wind gust model, turbine and turbine controller models, variable speed DFIG model, converter and electrical control models. Turbine and wind gust models are algebraic and include variations of wind speed, pitch angle and rotation speed; the turbine control model dictates the pitch control signal to limit mechanical power in over-rating conditions, or maximise the mechanical power in low-rating conditions.

Next, full nonlinear state-space modelling of a variable speed cage induction machine (i.e. fully converted machine) wind generation system is introduced in [81]. Models of individual components, that is, wind profile, wind turbine, induction generator and the pulse width modulation (PWM) converter, were developed and then aggregated into a single nonlinear model, which was subsequently linearised. Dynamic model of a variable speed DFIG-based wind generation system operating under unbalanced network conditions is presented in [82]. The DFIG-based models in the positive- and negative-sequence reference frames are developed; zero-sequence model is not needed because of the DFIG winding star connection.

Modelling of wind generation for active power – frequency control is presented in [83–86]. Fully converted machines do not contribute to the system inertia at all, whilst contribution of DFIG generators is very small and can be neglected [83]. Wind turbine manufacturers have come up with controllers that can provide inertial response and some governor response in cases of large frequency disturbances [84]. The controller response to frequency deviations is called 'artificial inertia', or 'simulated inertia', or, most commonly, 'synthetic inertia'. They provide extra active power immediately after a frequency disturbance and 'momentary increase' the total system inertia, which in turn substantially reduces the rate-of-change of frequency and gives time to governors to respond. The synthetic inertia controllers either extract 'hidden inertia', or make use of reserve capacity in pitch [83]. In the first case, kinetic energy from wind turbine rotating masses is utilised to produce extra power; operation of wind turbines on de-loading curves instead of maximum power point tracking with available power reserve is done in the second case. Full dynamic models of wind generation systems with 'synthetic inertia' controllers are developed in [84, 85, 86].

Modelling of wind generation in load flow, fault level and dynamics studies was investigated in [87]. In the load flow study, operating constraints of synchronous generators, winding parameters of induction generators and control strategy of converter controllers (e.g. constant power, or current, or power factor) are modelled. Higher accuracy was required in fault level calculations, so that fully developed models of synchronous and induction machines using transient and subtransient components, were applied. Besides, it was assumed that converter controls limit the converter fault current contribution to the full load values. User-defined dynamic models of controllers were developed and integrated with machine dynamic models to study transients. Both fixed pitch and variable pitch turbines were modelled.

A steady-state, sequence frame-based model of the variable speed wind generator (with partial convertor) for three-phase load flow studies is developed in [88]. The positive-sequence model is either a constant power source (PQ mode with constant power factor), or a constant voltage source (PV mode with constant terminal voltage). The negative- or the zero-sequence counterpart comprises a shunt combination of a controlled current source and fictitious impedance. Extension of the model towards the sequential load flow is done in [89]. Three-phase modelling of the voltage-sourced converter (VSC) for load flow analysis of the VSC-interfaced wind generator (i.e. fully converted machine) is done in [90]. The sequence component models are developed and they account for balanced and unbalanced conditions, various VSC control strategies, etc. Next, modelling of the HVDC connected off-shore wind generators within the multi-stage OPF was done in [91] using the DFIG's capability curve, which is available in DIgSILENT library as a 'static generator' option.

Simple PQ and RX steady-state models of wind turbines were used in [64] for state estimation modelling. The PQ model refers to constant active and reactive power modelling, whilst RX model denotes the steady-state equivalent scheme of an induction generator.

Several probabilistic wind turbine models are proposed for reliability studies. Most accurate models apply either non-sequential or sequential Monte Carlo simulation [92-95]. Different analytical models have also been developed. Stochastic characteristics of wind are combined with Markov model for wind turbines in [96]. A common wind-speed model, based on annual wind speed mean and standard deviation, is combined with multi-state wind turbine model in [97]. Paper [98] presents a simplified model whereby conventional multiple generation capacity states are integrated with wind availability levels that are sampled from the historic profiles. Reliability models of large wind farms for use in generation planning studies are given in [99]; the main contribution is modelling of mutually dependent wind turbine outputs due to dependence on the same energy source, the wind.

### Energy Storage

Several types of energy storage are presented below. They can be broadly classified in the following groups:

- Mechanical storage systems: compressed air storage, pumped hydro storage and flywheel energy storage.
- Electrochemical energy storage: storage in several types of batteries, such as Lithium Ion, Nickel Cadmium, Sodium Sulphur, Vanadium Redox, Nickel Hydride, etc.
- Electrical energy storage: storage in super-capacitors and super-magnetic materials.
- Chemical energy storage: storage in fuel and hydrogen cells.
- Thermal storage systems.

The only commercially utilised energy storage in the GB power system is currently pumped hydro storage.

However several research projects investigating other types of energy storage are under way, such as lithium-ion (LI) and sodium-sulphur (NaS) batteries, large-scale compressed air storage and domestic hot water storage.

### Compressed Air Energy Storage

Compressed air energy storage system (CAES) consists of a compressor, a reservoir (either underground, or tanks on ground), a gas turbine and a generator. It is a relatively mature technology having an operational history of around 30 years. CAES can be considered as a good large scale storage option with long life expectancy, large power capacity for long time, good dynamic properties and high efficiency. The main drawback is the thermodynamic restrictions to keep the process isothermal.

Detailed dynamic models of CAES systems have been developed in [100, 101] and they represent full thermodynamic cycle. Such detailed models are of high complexity and may prove to be bottleneck to conduct extensive grid level simulations for generation planning [102].

A CAES system for wind turbines is proposed in [103, 104] in order to capture excess power prior to electricity generation. A hydraulic pump is attached to the wind turbine rotor and it drives a shaft with a hydraulic pump/motor, a liquid air piston compressor/expander and an induction generator. Energy is stored/extracted in/from the storage vessel containing both liquid and compressed air at the same pressure. The full dynamic model of this system is developed. Full dynamic model of another hybrid CAES based on compressed air and super-capacitors, which converts excess energy from the power supply to stored pneumatic energy using a compressor, is presented in [105].

A simplified state-space model of CAES technology is developed in [102] and it captures the essential dynamics related to mass flow rates in and out of the reservoir and reservoir internal pressure. These two parameters bear direct effect on the storage reservoir power intake and output. The state-space model is a simplified version of the full scale model, with the compressor and gas turbine operations represented by discrete steady-state equations, that is, state in the next interval is a function of state in the previous interval.

A simple steady-state model of the CAES system presented in [106] makes use of the charge and discharge power balance equations constrained by power limits.

### Pumped Hydro Storage

Pumped hydro storage is probably the most important storage technology today. The pumped storage plant generates electricity during peak load hours and system emergencies, and pumps the water from the lower to the upper reservoir-lake during night hours of low consumption. It can be realised either with two separate turbines (one for pumping, the other for generation), or with a single reversible pump/turbine that can operate both ways. There is currently around 3GW of pumped storage in the UK, out of which 'Dinorwig' plant can provide 1.8GW.

There are several papers which address the full dynamic modelling of hydraulic turbines, e.g. [107-109]. On the other hand, although there are numerous papers describing hydraulic pumps, there is very few modelling of pumped storage plant operating in the pumping regime. Similar situation is with modelling of reversible turbines.

A full dynamic model of the reversible pumped storage station is developed in PSS/E [110] to simulate operation of the station in both ways. Models of the reversible pump/turbine, conduit system and motor/generator are integrated into a single model. Another full dynamic model of pumped storage hydro-plants, taking into account rigid and elastic dynamic models of water tunnel penstock configurations, hydro-turbine, pump head-flow curve, gating effects and generator/motor, is developed in [111]. A slightly less accurate dynamic model, considering separate models for turbine-generator governor and pump-motor, is presented in [112].

Even simpler approach to modelling the turbine and governor, but with detailed modelling of the DFIG is given in [113]; the main goal is derivation of the model of doubly-fed adjustable-speed pumped storage unit.

Simple steady-state models of pumped storage turbines and pumps are presented in [114]. They are modelled using the maximum and minimum generating and pumping capacities in the stochastic optimisation model that takes into account 'previous' reservoir states (i.e. conservation of water flow) and reservoir lower and upper limits. 'Similar' approach is applied in [115] within sequential Monte Carlo simulation for production costing. A slightly more complex approach, based on the generating/pumping power dependence on water discharge and head, addresses medium- and long-term optimal operation of a reservoir [116].

### Flywheel Energy Storage

A flywheel energy storage system (FESS) is relatively new technology where an electric supply charges the flywheel which stores energy in the form of kinetic energy. As the stored energy is required, the flywheel starts to discharge its kinetic energy. The main components are flywheel, motor/generator, power converter and controllers. The main advantages are fast charge/discharge, high energy storage and power density, low risk of overcharge or over-discharge and long life cycle [117-119]. Two basic FESS schemes were developed: low-speed flywheels with speeds up to 10,000 rpm in which steel rotors are used to increase inertia with conventional bearings, and high-speed flywheels with speeds up to 100,000 rpm where rotor is made of composite materials and magnetic or superconducting bearings resulting in a compact FESS [120].

Some of the reports on very diverse flywheel systems are presented in [121-125]. A system for US Navy combat ships is used to control voltage sags and power quality [121, 122]. A flywheel is attached to the induction motor shaft, which is connected to a series transformer via two voltage source converters. The power electronic interface facilitates bi-directional flow of power for charging and discharging the flywheel through the induction machine. The full dynamic model was developed in PSCAD/EMTDC. Another FESS, consisting of a flywheel attached to the permanent magnet synchronous motor and an AC power converter employing space vector pulse width modulation, is reported in [123]. The flywheel is modelled with the aid of inertia and stored energy, whilst full dynamic models of the motor and converter are also presented. A model of a 'similar' FESS with the permanent magnet machine is developed and used as a fast-response energy storage device during ride-through events related to variable wind power [124]. Finally, application of a flywheel attached to an induction machine that is connected to the grid-side converter of the off-shore winfarm HVDC link is used to balance the DC link voltage rise during AC faults [125].

### Battery Energy Storage

Battery energy storage is considered one of the best future storage techniques [126, 127]. In batteries, electrical energy is stored in electrochemical form by creating electrically charged ions. Batteries can be classified according to the electrode material and the electrolyte [126]. The most commonly met batteries are lead-acid, nickel-cadmium, nickel-metal hydride, sodium sulphur and lithium-ion; some of their properties can be found in [120, 130].

In general, accurate battery models tend to be overly complex mathematical formulations due to highly non-linear operation characteristics. Most common approach in network simulations is to use equivalent circuit models, which need to be dynamic in order to accurately represent operation of batteries [130]. This approach has also been used to model charging of EV batteries.

A vanadium-redox battery system is studied in [128], because it can be used for large capacity energy storage. Positively and negatively charged vanadium electrolyte is stored in two tanks and a pump is used to circulate the electrolyte from the tanks to the cell, in which electrodes and an ionic membrane are placed and where chemical reaction takes place. The equivalent circuit model of the battery, accounting for electrical and chemical factors is developed. It contains a controlled voltage source, a controlled current source, an electrode capacitance and the equivalent internal and parasitic resistances. A system describing dynamic models of the DFIG-based wind turbine with lithium-ion battery storage is presented in [129]. The battery is modelled using the equivalent circuit whose components are a voltage source dependent on the state-of-charge, and series resistances in parallel with capacitors which are all function of the state-of-charge. The modelling is done in DIgSILENT environment.

A survey of battery storage systems and modelling techniques is given in [130]. Electrochemical models are designed to account for chemical, thermodynamic and physical characteristics of batteries. Several equivalent circuit models of different complexities are presented and discussed; they are not presented further in this paper.

### Super-capacitor Energy Storage

Super-capacitors (or ultra-capacitors) are electric double layer capacitors that have very high capacity and charge/discharge current. They have long life, high number of cycles, fast response and long-time energy storage; the main drawback is low energy density [131–133].

Some of the applications of super-capacitor energy storage are reported in [134–137]. A power system of a metro is modelled in [134], where the super-capacitor-based energy storage is used to store energy from electromagnetic braking instead of consuming it by the breaking resistor. Similarly, a full dynamic model is developed for trams in which kinetic energy from braking is stored in a super-capacitor based system [135].

Modelling and design of transmission ultra-capacitor systems that integrate voltage source converters and ultra-capacitor storage units is described in [136].

Finally, a hybrid battery-supercapacitor energy storage system connected to the rotor side of a DFIG to get smooth output from the wind-farm is modelled in [137].

### Superconducting Magnetic Energy Storage

Superconducting magnetic energy storage (SMES) is designed to store energy in the form of magnetic field. A SMES system comprises superconducting coil and bi-directional converter for charging/discharging the coil. It is a very fast system and suitable for high power, short time applications; however it is still very costly [138–140].

The energy charging, storing and discharging characteristics of a magnetic storage system have been analysed in [141] to develop an integral approach to dynamic modelling of SMES systems. A permanent magnet synchronous generator for wind generation fed by a current source converter with a SMES coil in the converter DC link is studied in [142] using the full dynamic models of all components. Another application is power control of a superconducting magnet with the aid of a current source converter [143]. Paper [144] investigates integration of a SMES system into the control reserve for transmission system emergencies. The SMES system comprises super-conducting coil cooled by the cooling unit, power converter, controller and a transformer. Finally, impact of a SMES system on frequency stability in an isolated power system is studied in [145]. The SMES system has a superconducting magnetic coil, damp resistor, power converter with controller and a transformer; in-detail dynamic models are developed.

A number of papers deal with numerical aspects of calculating magnetic fields in the SMES systems; they are not studied in this paper.

### Hydrogen and Fuel Cells

Hydrogen is a clean, efficient energy storage medium that is mainly used with fuel cells. Its main drawback is low energy density [146, 147]. There are various applications of this technology; they are not further investigated.

## 2.2 Critical Assessment of Power System Modelling Capabilities

Critical assessment of existing power system modelling capabilities is presented by types of new LCTs and ‘smart solutions’.

### Electric Vehicles

Full dynamic models of EVs, which take into account ICE, gearbox, electric machine, inverter and the pack of batteries, are not required when considering distribution network aspects of the EVs. Modelling of EV charging modes is relevant for the impact analysis. In that respect, dynamic models of batteries and converters are required for the simulation of transients. Dynamic models of batteries are usually based on equivalent circuits that are derived from curves giving the relationship between battery current, voltage and state-of-charge. Standard dynamic converter models can be used for modelling EV converters.

Steady-state modelling of EV charging usually makes use of constant power with pre-specified power factor usually equal to unity. Besides, EV charging profiles for different charging modes are required to execute the sequential load flow. These profiles can be affected by adopted electricity pricing policies.

The following EV modelling gaps were identified considering the whole suite of power system studies:

- There are no dynamic models of EV batteries in the currently used software packages. They need to be combined with existing converter models to develop the EV dynamic charging models.
- There are no dynamic models which would address frequency response of EVs to frequency variations. Such control systems and corresponding models need to be developed. The preferred approach is to have separate EV and frequency control modules that can be integrated into a single dynamic model.
- Aggregated dynamic models of EVs need to be developed for studying higher voltage levels, such as 11kV and 6.6kV.
- There are no steady-state load models which represent (I-V) characteristics of batteries. These models will have to account for the state-of-charge of batteries.
- There are no hourly load profiles for the sequential analysis of different EV charging regimes. The so-called controlled charging regimes need also to be developed. The charging regimes are required for sequential load flow, multi-stage OPF, sequential reliability analysis and market – economic studies.
- There are no data on harmonic current injections of EV loads. They have to be either estimated, or some recommendations from international standards taken.
- Modelling aspects of EV storage were not considered in this paper. It is likely that the similar models should be applied ‘in reverse direction’.

## Heat Pumps

The full dynamic thermo-electrical model of a heat pump should be built in accordance with the corresponding pump design, e.g. whether it is used for air and/or water heating, air cooling, etc. A typical model shall integrate dynamic models of a motor, a compressor, an air heat exchanger, a water heat exchanger and a control system. Such a model can be simplified to account for the most important thermo-electrical quantities, such as coefficient of performance, air/water temperature, motor torque, etc.

Dynamic performance of heat pumps can be further simplified by full modelling of the electrical part (i.e. motor, power converter and controller) and equivalent characteristics of the thermal system. In that respect, coupling between the motor speed, torque and compression characteristics needs to be established.

Steady-state modelling of HPs can be done by using the equivalent motor schemes/circuits, or constant active and reactive power approach. In sequential studies, hourly load profiles are required since HP consumption depends on the thermal parameters.

The following HP modelling gaps were identified considering the whole suite of power system studies:

- The full thermo-dynamic models of different types of HPs do not exist in the currently used power system analysis tools. They can be replaced by simplified dynamic models that take into account major thermal parameters.
- Although frequency dynamics of motor loads has been widely studied, frequency response of HPs needs to be developed and modelled because it is dependent on thermo-dynamic characteristics. Modular approach is again the preferred option.
- Aggregated dynamic HP models need to be developed for studying higher voltage levels, such as 11kV and 6.6kV.
- Fault level contribution from HPs need to be understood and adequately modelled within dynamic models.
- The steady-state hourly profiles of HPs need to be developed and applied in sequential studies, such as load flow, OPF, sequential reliability analysis, market studies, etc.
- Where HPs are equipped with power converters, data on harmonic current injections need to be provided. Currently, they can only be assessed.

## Demand Side Management and Demand Side Response

Full dynamic models of different types of loads (e.g. electric dryers, dishwashers, water heaters, refrigerators and clothes washers), have been developed and integrated within different DSM and/or DSR schemes. These models are often based on non-electric parameters, whose values need to be assessed and input into computer simulations. Two types of simplifications can be done: the first is model reduction using an approach for reducing the order of differential equations. The second is modelling the electrical part of the system in full and approximating the non-electrical processes.

Aggregation of some of ‘responsive’ load types into a single dynamic model has also been studied. The aggregated dynamic models are usually of reduced order and can account for several non-electric parameters.

Another very important aspect of load modelling is the frequency response during system emergencies. Substantial investigation into frequency response characteristics of different load types has been done. Since load disconnection is the principal means to avoid frequency collapse, DSM and DSR of different load types can further contribute to restoring the system stability-security. All loads that remain in-service also participate in the frequency response in accordance with their power-frequency characteristics.

Steady-state modelling of DSM/DSR load curtailment is usually done using a fictitious constant active/reactive power generation attached to network nodes. In optimisation models, DSM/DSR load curtailment is a variable limited by physical load constraints.

Load recovery (or deferred load pickup) needs to be modelled in sequential power system studies. Several models for different load types were developed based on real-life measurements.

The following DSM/DSR modelling gaps were identified considering the whole suite of power system studies:

- Load curtailment components do not exist in currently used power system analysis tools. The user has to find her way around the problem and apply some ‘adequate’ load or generation models that are available.
- Full dynamic DSM/DSR (or load curtailment) models do not exist; furthermore, dynamic models of different load types are limited to motor models, without modelling the non-electric processes.

- It would be highly desirable to have aggregated dynamic load and DSM/DSR models dependent on non-electric parameters. Simplified, reduced-order aggregated models with approximate modelling of non-electric processes are also welcome.
- The full and/or aggregated load and DSM/DSR models should have adequate frequency response modelling which can be used in frequency response studies.
- Impact of the DSM/DSR on fault levels needs to be adequately modelled within dynamic models.
- Steady-state hourly profiles of different DSM/DSR strategies taking into account load recovery need to be developed.

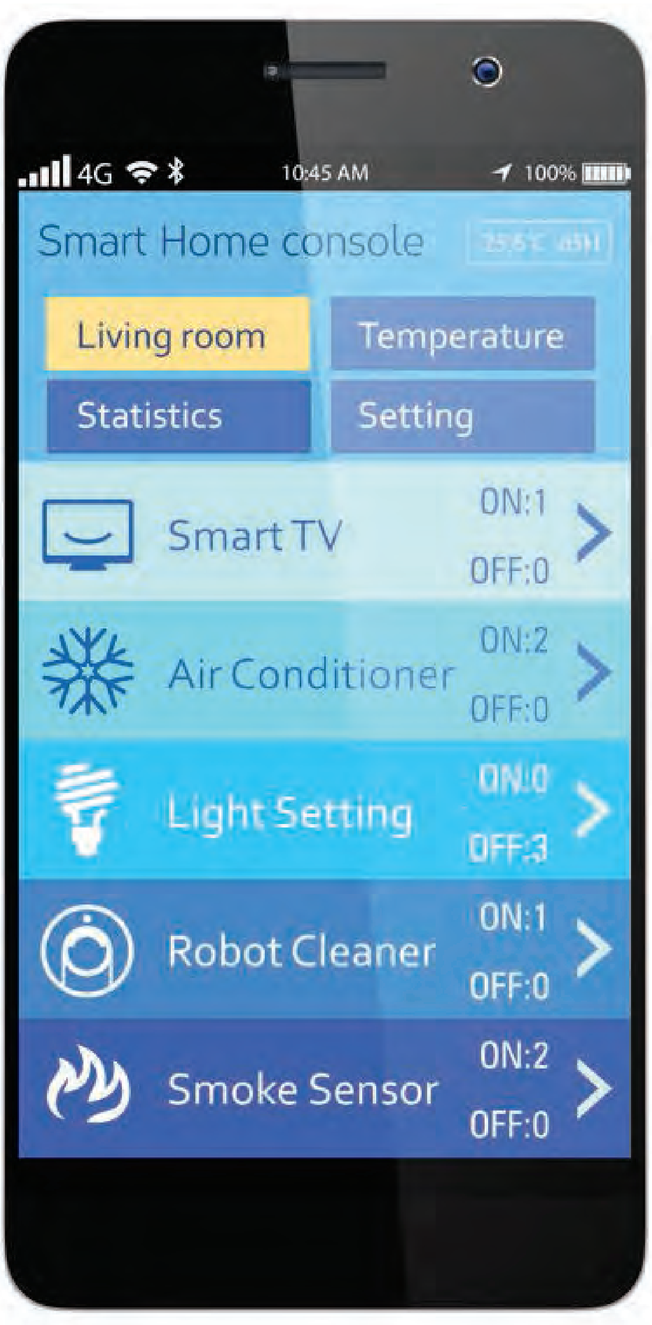
### Solar Generation

Dynamic models of solar panels are based on equivalent circuits and resulting highly non-linear (I-V) and (P-V) characteristics. Equivalent circuits of different complexity were developed. The models which account for solar irradiation as an input parameter can be combined with a model of 'cloud transients' in order to calculate the voltage variation range at solar terminals. They are then combined with models of power converters to get the full dynamic model of a solar system. Aggregated models of several panels were simply derived by multiplying the solar current by the number of panels.

In steady-state solar generation models, solar current and voltage are functions of solar irradiation, operating temperature and solar-converter losses. A simplified version makes use of the DIgSILENT 'static generator' library model.

The following gaps in solar modelling were identified considering the whole suite of power system studies:

- Dynamic models of solar generation are not present in the currently used power system analysis tools. The user has to develop her model using the equivalent scheme approach and available library components. However, the model cannot account for variable external, non-electric parameters. More specifically, potential variation of solar irradiation due to 'cloud transients' needs to be modelled in order to understand the impact on networks.
- Frequency response and control of solar generators has not been investigated and there are no appropriate dynamic models.
- There is no investigation related to the fault level contribution of solar generation. Current approach is to limit the contribution to the rated power of the solar system.



- Only the latest DIgSILENT version has several steady-state models of solar generation; however, they cannot be found in other software packages.
- Solar generation is a source of substantial harmonic distortion. There are no data on harmonic current injections and they have to be assumed in the power quality studies.
- Currently used reliability engines cannot adequately model solar generation. Namely, random sampling of solar irradiation and ambient temperature needs to be done, which is only possible in the sequential Monte Carlo simulation.

### Wind Generation

Full dynamic models of different types of wind systems should integrate turbine rotor, mechanical transmission, induction (or permanent magnet) generator and power electronics converter. Wind turbine is often modelled in an approximate way, using the power – wind speed relationship. The models are usually developed for balanced network conditions, whilst there are several recent attempts to model wind systems for unbalanced conditions with the aid of positive- and negative-sequence reference frame models.

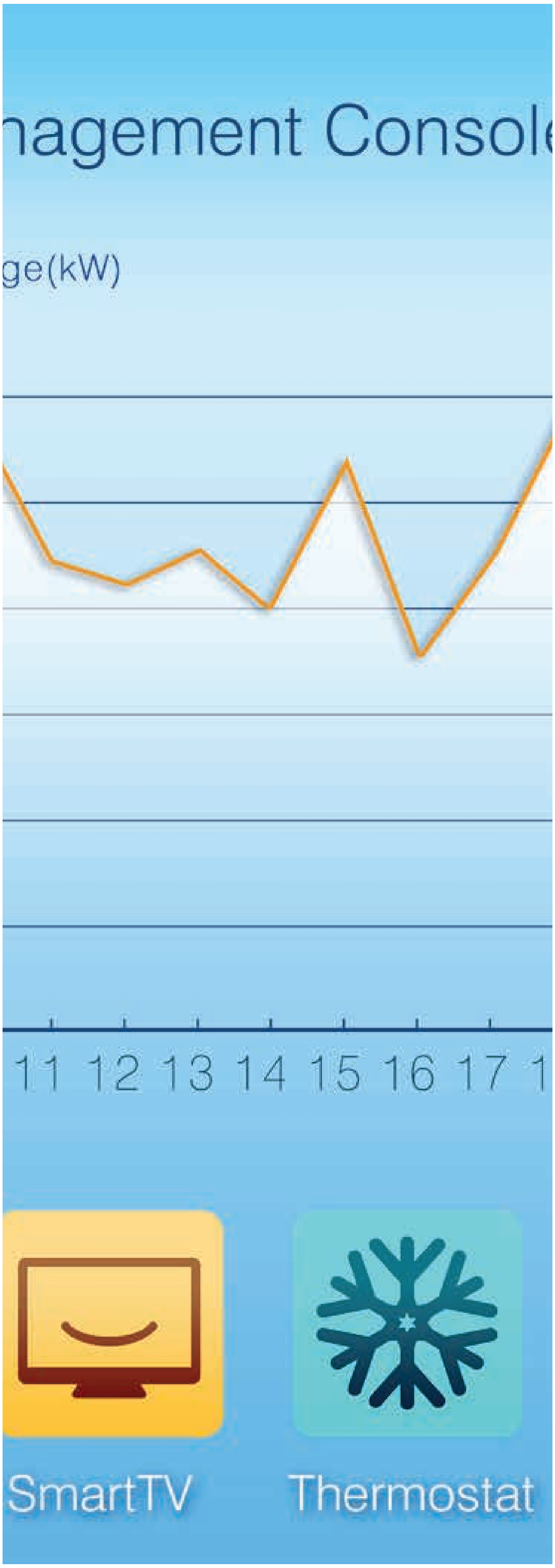
Steady-state modelling of fixed- and variable-speed (with rotor convertor) wind systems is done with the aid of the equivalent circuits of electrical machines. A 'static generator' model, as described in the DIgSILENT library, is used for fully converted machines, and for off-shore wind-farms connected to the network through an HVDC link.

Some optimisation models are based on even simpler representations using the active and reactive power model.

Stochastic steady-state models are usually based on the active and reactive power generation, where random sampling of wind is used to produce wind-farm generation profile.

The following gaps in wind modelling were identified considering the whole suite of power system studies:

- The aerodynamic and mechanical systems are usually simplified in the existing dynamic wind system models. It is not clear what the impact of these simplifications is and whether full models should be used instead.
- Full dynamic modelling of HVDC connected off-shore wind systems has to be done using the existing models of wind systems, DC network and power converters. It would be much simpler to have 'standard', integrated models.
- Full dynamic models of fully converted machines are not available, because manufactures do not disclose applied control techniques. These machines are modelled using the 'static generator' model, i.e. steady-state characteristics.
- Frequency control blocks are not available in the currently used software tools. They should be developed and integrated with existing wind system models. A good starting point could be development of 'synthetic inertia' controllers that are already manufactured for DFIG and fully converted machines.



- There is no fault level contribution of wind systems when the 'static generator' model is used for fully converted machines, or HVDC connected off-shore generation. The 'static generator' model should be modified accordingly.
- Harmonic current injections of different types of converters are not known. This is particularly important for fully converted machines and HVDC connected off-shore wind systems.
- Currently available reliability engines cannot model wind availability. Sequential Monte Carlo simulation procedure with pseudo-random sampling of wind profiles should be developed.

## Energy Storage

### Compressed Air Energy Storage

Detailed dynamic models of CAES systems representing the full thermo-dynamic cycle are of high complexity and computational requirements. Simplified dynamic models that capture essential dynamics related to mass flow rates and reservoir internal pressure may be preferred.

A simple steady-state model of a CAES system makes use of charge and discharge power balance equations constrained by limits on power consumption/generation.

The following gaps in CAES modelling were identified considering the whole suite of power system studies:

- Dynamic models have not been developed so far. The models have to take into account thermo-dynamic properties of the system. Simplified dynamic models are welcome.
- Contribution of CAES to frequency control can be modelled using the gas turbine and generator models (electricity generation) or frequency dependence of the motor model (electricity storage). It would be very convenient to develop aggregated frequency response blocks.
- Fault level contributions of CAES systems need to be understood and adequate models developed for both operating regimes.
- Steady-state models which take into account thermal parameters are not available. They are of particular interest in sequential studies.
- Hourly load and generation profiles of CAES systems need to be developed because they are dependent on thermal parameters. These models are required for sequential load flow, multi-stage optimum power flow, economic and reliability studies.
- Currently available reliability engines cannot model thermodynamic cycle of CAES systems. Sequential Monte Carlo simulation procedure should be developed.

### Pumped Hydro Storage

A full dynamic model of the pumped storage hydro-plant should have models of upper/lower water reservoirs, water tunnel and penstock, hydro-turbine and hydro-pump, generator and motor, governor and other control systems. Where reversible turbine is used for generating and pumping, a single model of reversible pump-turbine is required. The full model can be quite complex and it is often replaced with a reduced model in which hydraulic sub-system is simplified and electrical sub-system is modelled in full.

Steady-state models are usually based on active/reactive power generation and consumption in the two operating regimes. The power generation and consumption are limited by turbine/machine capacities in optimisation studies. Multi-stage simulation and optimisation studies also take into account essential hydraulic constraints, such as upper lake volume limits, discharge and pumping limits and water conservation equation.

The following gaps in hydro pumped storage modelling were identified considering the whole suite of power system studies:

- There are neither dynamic models of pumped storage hydro plants, nor of its components, such as water reservoir, water tunnel with penstock and hydro turbine, in the currently used power system analysis tools. The dynamic models of the generator, motor and control systems can be used, however it is not clear what is the impact of hydraulic system dynamics on the power system transients.
- It would be very convenient to have separate 'standard' dynamic models of hydraulic components and then to combine them with the models of electrical sub-system. Simplified hydraulic models can also be applied.
- There are no 'hydraulic' frequency control blocks in the software tools, and they have to be developed from scratch by the users. The library models of 'standard' frequency (and voltage) controllers would be much appreciated.

- There are no adequate steady-state models for sequential analyses by hourly intervals. These models will need to encompass essential hydraulic constraints, as specified above.
- Currently used reliability engines cannot model water inflow availability, hydraulic constraints and scheduling strategies. This can be done using the sequential Monte Carlo simulation.

### Flywheel Energy Storage

Basic modelling of a flywheel energy storage is done by entering appropriate data for motor inertia. Different flywheel energy storage systems are modelled using the dynamic models of all components, such as power converters, machine and controllers.

There are no reports on steady-state modelling of flywheel systems because they are used to improve system transients.

The following gaps in modelling flywheel energy storage were identified considering the whole suite of power system studies:

- Dynamic modelling of a flywheel energy storage system needs to be done by integrating models of individual components. This approach is probably adequate because there are no 'standard' flywheel systems.
- There are no reports and models of the frequency response characteristics of flywheel systems. These models are required if it is envisaged that flywheel systems will take part in the frequency control.
- It is not clear whether steady-state models are required or not.
- There are no data on harmonic current injections of flywheel systems with power converters.

### Battery Energy Storage

Full electrochemical battery models take into account chemical, thermodynamic and electrical characteristics of batteries. They are often too complex, and simplified models based on equivalent circuits of different complexity are used instead. Dynamic models of battery systems are then developed by integrating models of batteries, power converters and controllers.

Steady-state modelling of batteries is usually done using constant current or constant power sources.

The following gaps in battery storage modelling were identified considering the whole suite of power system studies:

- There are no dynamic models of batteries in the currently used software packages. Identical models of different battery types should be populated with battery-specific data. The developed models then need to be combined with the existing converter models to develop dynamic models of battery systems.
- There are neither reports nor models addressing the frequency response of battery systems during operating regimes with frequency drop/rise. It is likely that research in this area will be done in the near future.
- There are no steady-state models which represent (I-V) characteristics of batteries. These models will have to account for the state-of-charge of batteries.
- There are no hourly profiles for the sequential analysis of battery systems. The profiles are required for both battery charging and discharging, and they are dependent on battery characteristics. The profiles are required for sequential load flow, sequential reliability analysis and market – economic studies.
- There are no data on harmonic current injections of battery systems. They have to be either estimated, or some recommendations from international standards adopted.

### Super-capacitor Energy Storage

Dynamic modelling of super-capacitors can be based on either ideal capacitor, or 'real' capacitor with a resistor in parallel. Modelling of super-capacitor systems should consider models of super-capacitors, power converters and controllers.

There are no reports on steady-state modelling of super-capacitor systems.

The following gaps in super-capacitor storage modelling were identified considering the whole suite of power system studies:

- The 'standard' models of shunt components can be used to model super-capacitors. They need to be combined with the converter and controller models to develop dynamic models of super-capacitor storage systems.
- There are neither reports nor models addressing the frequency response of super-capacitor systems during emergency operating regimes.
- There are no data on harmonic current injections of super-capacitor storage systems.

### Superconducting Magnetic Energy Storage

Dynamic model of a SMES system can be developed from the shunt reactor model (superconducting magnetic coil), power converter model, user-specific controller model and models of other components.

There are no reports on steady-state modelling of SMES systems.

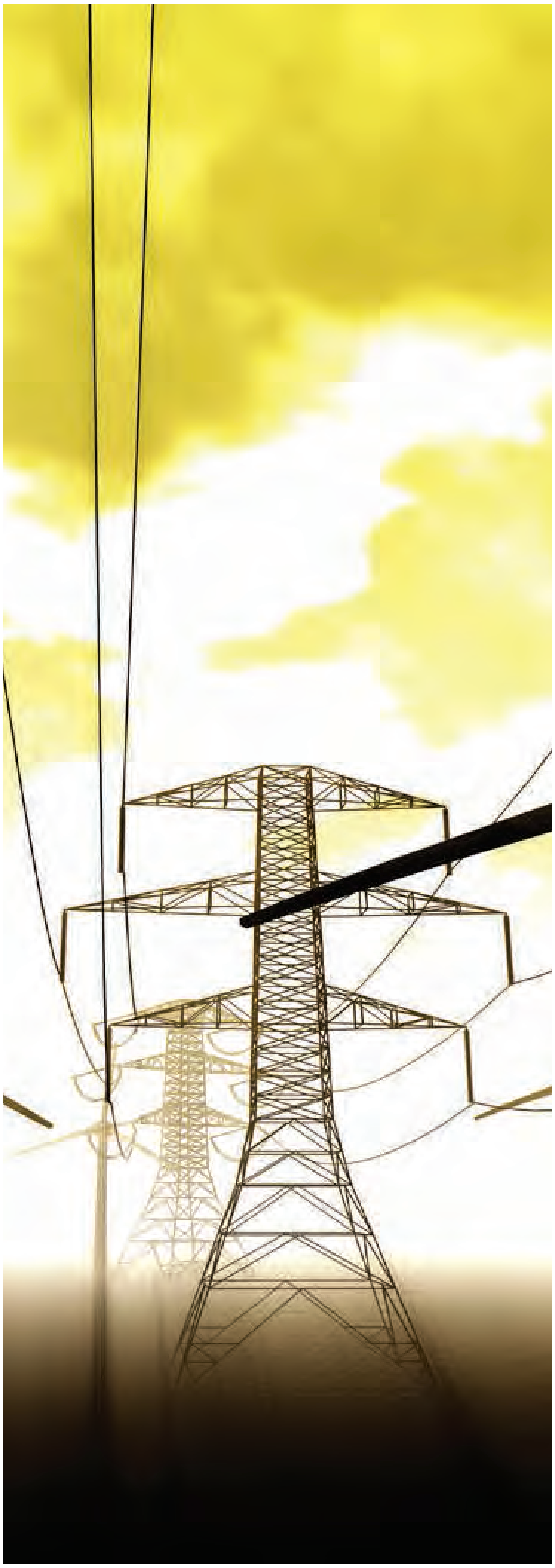
The following gaps in SMES system modelling were identified considering the whole suite of power system studies:

- The models of shunt reactors can be used to model superconducting magnetic coil. They need to be combined with the converter, controller and transformer models to develop dynamic models of superconducting magnetic storage systems.
- Only one report addressing the frequency response of a SMES system has been studied. This area and corresponding models need to be further investigated.
- There are no data on harmonic current injections of SMES systems.

## 2.3 Impact on the GB Power System Performance

Most important implications of connecting new LCTs and introducing 'smart' solutions on the GB power system performance are briefly summarised below:

- Demand and generation profiles will change due to electrification of transport (EVs) and heating (HPs) and connection of large amount of solar and wind generation. It is envisaged that variation of demand and generation is going to be significantly faster in future, and the GB power system will become substantially more dynamic.
- The power system stability and security will be adversely affected by new types of load and large proportion of intermittent generation. Furthermore, reliability of new 'smart' solutions is still unknown and it can further aggravate system stability and security. Here, reliability of software, communication and automation systems will play vital role.
- Operation of the electricity network will have to change in order to cope with the new LCTs and 'smart' solutions. System control engineers will have to cope with the substantially increased burden of system balancing under rapidly changing operating conditions.



- Processing of smart meter data in (near) real-time will further increase burden in control centres. Real-time and short-term operational procedures that make use of smart meter data will need to be developed taking into account realistic capabilities of control centres.
- The future permissible generation mixes will have to be carefully established on a locational basis using operational planning principles and system constraints. It is likely that generation constraining in both operation and planning/connection will happen.
- Amounts of the frequency response, emergency spinning and non-spinning reserve will have to be recalculated using new methods which can take into account high intermittency of wind and solar sources. The higher the intermittency of generation, the more reserve is needed.
- Low system inertia will become reality following connection of large amounts of fully converted generation, HVDC connected off-shore wind-farms and HVDC interconnections. It will be dealt with by very fast converter connected generation and/or storage and fast load shedding. The rate-of-change-of-frequency settings on generation protection will need to be changed.
- The conventional ‘critical’ operating regimes used in system planning are likely to change due to changed load and generation profiles. More specifically, sequential planning studies will need to be performed in future. For example, excessive voltages are already experienced on the transmission network during summer low-load conditions and adequate controls are needed to reduce them.
- DNOs will be faced with distribution systems of ‘transmission type’. They will have to cope with new technologies with shorter time constants, larger amounts of data that need to be processed in (near) real time and in planning stages, new software platforms and tools, etc. An example is new voltage control schemes, which will need to be developed and installed on DNO networks.
- DNOs will need to take part in system balancing, at least during system emergencies. In that respect, hierarchical control principles between National Grid and DNOs will need to be established and corresponding data exchanges initiated.
- ‘Appropriate’ market framework will need to be developed to allow the development of a more integrated system. For example, ‘low inertia auxiliary service’ can be introduced independently from the frequency response service. Participation of DNOs in different markets also needs to be developed.
- New ‘smart’ solutions can distort the existing auxiliary service markets. For example, large-scale compressed air storage could drive out of business existing pumped hydro storage.
- Developing the analytical base is one of key challenges.

## 3. CONCLUSIONS AND RECOMMENDATIONS

A brief summary the most important conclusions and recommendations is presented below.

### 3.1 Conclusions

A brief summary of identified gaps is given below by LCTs and new ‘smart’ solutions.

1. ***Electric Vehicles:*** there are neither dynamic models of EV batteries, nor dynamic models of frequency response of EV charging, nor aggregated dynamic models. Steady-state models based on EV battery (I-V) characteristics do not exist, and there are no hourly load profiles for different charging regimes. Data on harmonic current injections of EV loads and reliability data are not available.
2. ***Heat Pumps:*** there are neither full thermo-dynamic models of different HP types, nor reduced dynamic models in which thermal processes are simplified. Aggregated models of several HPs and dynamic frequency response models accounting for thermal processes are also missing. The steady-state hourly profiles of HPs need to be developed and applied in sequential studies. Data on harmonic current injections and reliability data are not available.
3. ***Demand side management and response:*** there are neither dynamic models of DSM/DSR, nor frequency response models associated with DSR/DSM. The full and/or aggregated load and DSM/DSR models should have a frequency response module. Furthermore, steady-state hourly profiles of DSM/DSR taking into account load recovery need to be developed.
4. ***Solar Generation:*** dynamic models of solar generation in the form of equivalent circuits, whose voltage/current sources are dependent on non-electric parameters,

do not exist in power system analysis tools. Similarly, there are neither models for 'cloud transients', nor dynamic frequency response models, nor methods for calculating solar fault contribution. Existing reliability methods cannot adequately model solar generation. Data on harmonic current injections and reliability data are not available.

5. ***Wind Generation:*** the existing dynamic models make use of simplified aerodynamic and mechanical sub-systems. Dynamic models of fully converted machines are not available; there are neither frequency control blocks (e.g. 'synthetic inertia' models) in the software tools. Fault level contribution of 'static' wind generators needs to be established. Currently available reliability engines are not capable of adequate wind-farm modelling. Data on harmonic current injections and reliability data are not available.

6. ***Energy Storage:*** identified gaps are discussed by storage types:-

**a)** ***Compressed Air Storage:*** there are no dynamic models that take into account thermo-dynamic properties of the system. Models for frequency control are neither available. Similarly, steady-state models with thermo-dynamic parameters, as well as load and generation profiles are not available. Currently available reliability engines cannot model thermodynamic cycle of these systems.

**b)** ***Pumped Hydro Storage:*** there are neither dynamic models of pumped storage hydro plants, nor of its components, such as water reservoir, water tunnel with penstock and hydro turbine. Similarly, there are no 'hydraulic' frequency control blocks in the software tools. Adequate steady-state models for sequential analysis by hourly intervals do not exist. Existing reliability methods cannot adequately model plants with hydro storage, nor pumped hydro storage.

**c)** ***Flywheel Storage:*** there are no models of the frequency response characteristics. It is not clear whether steady-state models are required.

**d)** ***Battery Storage:*** there are neither dynamic models of different types of batteries, nor frequency response models of battery systems in the software tools. Steady-state models based on (I-V) characteristics and the state-of-charge are not available; the corresponding hourly profiles need to be developed for sequential studies. Data on harmonic current injections and reliability data are not available.

**e)** ***Super-capacitor Storage:*** dynamic models considering frequency response during emergency operating regimes are not available. There are no data on harmonic current injections of super-capacitor storage systems.

**f)** ***Superconducting Magnetic Energy Storage:*** frequency control models are not available. There are no data on harmonic current injections.

### 3.2 Recommendations

1. Development of dynamic and steady-state models of new network components, such as EVs, HPs, solar and wind generation, under-frequency & under-voltage load shedding, as well as different types of storage and DSM & DSR is required. Reliability models of new components together with communication, automation and software systems need to be developed and integrated within the new power system reliability engine.

2. Some of the models will have to be developed outside the power system analysis tools using the 'in-house' approach. Co-ordination of the model development among DNOs, National Grid and other relevant parties (e.g. academia and software providers) is of prime importance. A common database of these models should be established, so that DNOs and National Grid can share the models and avoid unnecessary development costs.

3. It is likely that 'scripts' associated with currently used software tools will have to be developed to perform certain types of studies (e.g. sequential analyses). A common database of scripts should be established, and that scripts shared between DNOs and National Grid.

4. New models will have to be populated with real-life data. DNOs and National Grid should establish internal processes to gather and store various types of modelling data, which are currently missing. All required data shall be obtained from developers (new connections), equipment manufacturers and other relevant, third parties.

5. The new models will be applied within the whole suite of power system studies, namely sequential load flow, optimum power flow, fault/short-circuit analysis, dynamics simulations, frequency response and balancing, reliability analysis, harmonic/power quality analysis and protection study.

6. New functionality of power system analysis tools will be required in future. Some of the envisaged new functions are multi-stage load flow, optimum power flow with ‘appropriate’ objective function and/or security constraints, new network equivalencing models for steady-state and dynamic studies, distribution network reconfiguration and restoration functions and new reliability analysis model based on sequential Monte Carlo simulation.
7. Both DNOs and National Grid should go for a common software platform that will have desired functionality and models of new components. Unification of diverse power system analysis tools among DNOs is of prime importance.
8. The existing staff will need to be trained to perform new studies with new component models; however, it is likely that DNOs and National Grid will have to employ new, ‘properly educated’ generation of young engineers. In that respect, GB academia shall provide adequate education of students in power engineering. Specialised courses, delivered by academia and consultants, will be highly appreciated.

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