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Executive summary

SA Power Networks (SAPN) is seeking to develop (and subsequently implement) a strategy for the efficient management of its Low Voltage (LV) network. The development of this strategy entails a cost-benefit review of a number of potential strategic options that could be used to manage the LV network in order to determine which delivers the greatest value to all stakeholders.

It was determined that an appropriate way to formulate and test strategic options was through the development and use of the Transform Model® for SAPN. The Transform Model has been used extensively around the world to support strategic decision making for network businesses and to inform regulatory submissions.

Predicting the speed and geographic spread of uptake of DER is inherently challenging; what is certain is that the uptake will not be uniform across the state and these technologies will have different impacts for different network types (such as those in a rural or urban context). The decisions taken by a network operator in the next few years can have a material impact on the ability of the networks to take advantage of the opportunities and respond to the challenges and the associated costs of so doing.

This report describes the development of the Transform Model for SAPN; a comprehensive model that is designed to assist key stakeholders in the evaluation of options to address uncertainties and to allow exploration and quantification of many 'what-if' scenarios with regard to future network demands and DER uptake scenarios. The purpose of the model is not to provide a single definitive answer to the question of the level of investment driven by DER in the LV network, but rather is to provide a framework for the evaluation of options and to form a basis for strategic decision-making.

A separate document describes the pre-cursor to this work where various real networks from SAPN's distribution area were modelled to create the parameters that would inform the development of the Transform Model[1]. Both of these documents should be viewed as annexes to the main document which describes the selection and justification of the most appropriate LV Management Strategy for SAPN to pursue to ensure value to all of its customer base.[2]

The ongoing use of the results of this model and further analysis of different scenarios can be used to directly inform SAPN's business planning and strategy for accommodating the increase in DER in an economically efficient manner, thus delivering value for customers while not compromising the integrity of the network from an engineering perspective.

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[1] "LV Management Strategy Annexe 1: DER Hosting Capacity Assessment", EA Technology (November 2018)".

[2] "LV Management Strategy", EA Technology (November 2018)

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1. Introduction

1.1 Context

As part of its approach to the next regulatory period, SA Power Networks (SAPN) is seeking to develop (and subsequently implement) a strategy for the efficient management of its Low Voltage (LV) network that will deliver the best outcomes for its customers. The development of this strategy entails a cost-benefit review of a number of potential strategic options that could be used to manage the LV network in order to determine which delivers the greatest value to all stakeholders.

In order to do this, it is necessary to understand in greater detail the likely changes to customer demands that will be brought about through increased penetration of distributed energy resources (DER). In this way, it will also be possible to gain an appreciation of the way in which network demands will evolve and how best to ensure the network is equipped to meet the needs of customers both in the short-term, and also longer-term future.

To help achieve this, SAPN commissioned EA Technology to investigate the likely uptake levels of various technologies and examine their effects on the network in the context of their potential to breach network limits, and hence determine the levels of investment that could be driven by the uptake of such technologies. In order to do this, EA Technology has created a South Australia version of its Transform Model (a tool that has already been extensively used in Great Britain, Northern Ireland and in New Zealand) to quantify the challenges associated with the increased uptake of DER.

1.2 Aims and objectives

This report aims to provide a comprehensive understanding of the Transform Model philosophy. It should be read in conjunction with the main LV Management Strategy document[2] and also takes inputs from the Hosting Capacity Study[1]. Specifically, this work can be divided into two main objectives:

- To develop the Transform Model for the electricity distribution network in South Australia.
- To identify, quantify and assess the effects of DER on the future planning and operation of the SAPN electricity distribution network.

1.3 Scope of work

This work evaluates future investment requirements in distribution network assets associated with the integration of DER as a result of customer behaviour changes. In this respect, this work does not consider any other types of load-related expenditure (e.g. primary reinforcement schemes, fault level reinforcement, etc.) nor core network investment expenditure owing to asset renewal, refurbishment, civil works, etc.

The strategic investment planning assessment of SAPN’s electricity distribution network is performed on distinct scenarios representative of the future growth of DER in South Australia, taken from forecasts by the Australian Energy Market Operator (AEMO).

1.4 Structure of the report

This report details the method, impact analyses and key findings applied and developed by EA Technology in this work. The structure of this report is as follows:

- Section 2 presents the main structure of the Transform Model used in this work for the strategic distribution network investment and planning assessment of the electricity distribution network in South Australia.

- Section 3 briefly introduces the scenarios describing the future growth of DER in South Australia.
- Section 4 provides an overview of the process adopted to develop a representative network of the SAPN electricity distribution network.
- Section 5 details the sets of engineering solutions/technologies that can be deployed to resolve network constraint problems.
- Section 6 briefly examines some of the key other modelling considerations within the development of the Transform Model
- Section 6 summarises concluding thoughts and signposts a reader as to where to examine the outputs from the analysis conducted through the Transform Model

2. The Transform Model

2.1 Structure of the model

The demand for electricity on the distribution network is changing as new technologies (e.g. electric vehicles, solar photovoltaic, etc.) become an integral part of customers' lifestyle and behaviour. The increasing presence of these distributed energy resources (DER) in the electricity distribution networks, with fundamentally different technical and operational characteristics, will drive a dissimilar impact to that of the incumbent technologies. Hence, there is a need for SAPN to understand the resulting technical effects (e.g. circuit overload, circuit under or overvoltage, etc.) of the integration of DER into the distribution network, the associated economic effects (e.g. overinvestment, stranded assets, ineffective risk management, etc.) for the business and as a result to establish how these new distributed generation and demand technologies should be treated in the strategic planning of the distribution network.

In response to these challenges, the Transform Model will assist SAPN to accomplish effective strategic decision making in respect to network planning and investment by projecting distribution network expenditure owing to increasing growth of customer uptake of DER and distributed generation[3]. Moreover, the Transform Model will also support SAPN in the risk management practices within the business. Figure 1 depicts a schematic representation of the Transform Model.

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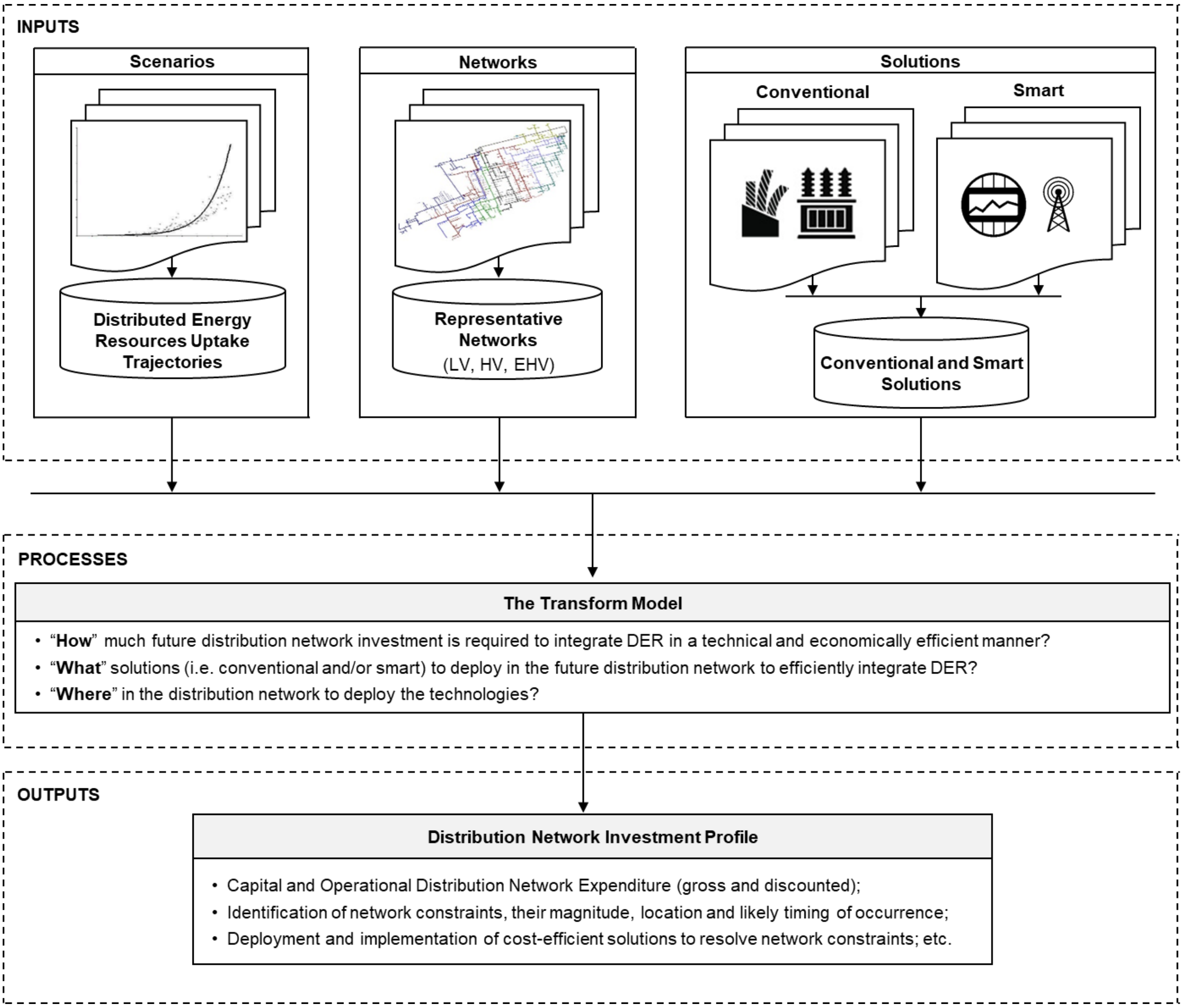
[3] It is noted that the Transform Model does not assess any other category of load-related expenditure such as zone reinforcement schemes, fault level reinforcement, network connections, etc. Similarly, the Transform Model does not assess distribution network expenditure relating to asset replacement, refurbishment, civil works, etc.



- "**How**" much future distribution network investment is required to integrate DER in a technical and economically efficient manner?
- "**What**" solutions (i.e. conventional and/or smart) to deploy in the future distribution network to efficiently integrate DER?
- "**Where**" in the distribution network to deploy the technologies?

- Capital and Operational Distribution Network Expenditure (gross and discounted);
- Identification of network constraints, their magnitude, location and likely timing of occurrence;
- Deployment and implementation of cost-efficient solutions to resolve network constraints; etc.

Figure 1 **Schematic representation of the Transform Model**

Scenarios

Scenarios are used within the Transform Model to represent projections of the future electricity outlook under an uncertain landscape that is broadly driven by political, economic, social, technological and other types of uncertainty. These alternative projections of the future will enable SAPN and other stakeholders to better understand the effects of uncertainty and identify credible, plausible outcomes for the future of the electricity distribution network in South Australia.

As part of this work, scenarios have been taken from AEMO and sensitivities assessed where relevant. The development of these scenarios is discussed further in Section 3.

Networks

Real distribution systems are characterised by a vast diversity of topologies, customer densities and ratings of the feeders resulting in every feeder being different in some detail to every other feeder, even if only slightly. Attempting to model such an extensive distribution system on a circuit-by-circuit basis to assist the strategic decision-making process of distribution businesses becomes an impractical task. Accordingly, the Transform Model relies on the concept of 'representative' networks to create a number of 'typical' feeders that constitute a best fit to a specific group of real feeders. Representative feeders were initially defined for SAPN based on real feeder data. Then, these local representative feeders were combined and replicated in the appropriate proportions, to create an overall network that is a reasonable approximation of the SAPN distribution network. The development of the representative networks, that forms the SAPN electricity distribution network, required the collection of appropriate numerical data and set of construction principles, based on standard design practices that were provided by SAPN. The attractiveness of the approach described is partially attributed to the fact that the required data sets are either available or could be made available with reasonably low effort.

Solutions

Networks are made up of a range of technologies and commercial arrangements that are applied in different combinations and at different geographical scale to enable the transfer of energy from grid exit points to consumer load points. The solutions deployed by the Transform Model to resolve network constraint problems comprise two distinct types:

- **Network solutions**: refers to technological network solutions that are used in the design, operation and management of networks. These include conventional solutions for network augmentation, such as laying new cables, replacing transformers, etc. and also considers smart grid technologies such as rebalancing loads on feeders or dynamically managing the network voltage.

- **Non-network solutions**: refers to customer-side solutions whereby network constraints are alleviated through customer response to signals, which may be pricing signals through tariffs or may be through contracts for voltage support at certain times etc. These solutions are more commercially based rather than technologically in comparison with the network solutions described above.

Model engine

The Transform Model is a techno-economic modelling tool to assess strategic investment decisions in electricity distribution infrastructures that enable the cost-efficient and secure integration of DER in the SAPN electricity system of the future. The Transform Model provides an in-depth understanding of:

- "**How**" much future distribution network investment is required to integrate DER in a technical and economically efficient manner?

- "**What**" solutions (i.e. conventional and/or smart) to deploy in the future distribution network to efficiently integrate DER?

- "**Where**" in the distribution network to deploy the solutions?

Outputs

The main output of the Transform Model is a network investment profile, indicating the level of expenditure required on a year by year basis to accommodate DER in a cost-efficient manner whilst ensuring security and quality of supply as well as value for customers. The investment profile indicates the necessary capital expenditure and direct operational expenditure (such as inspection and maintenance, rental of communications channels etc) and is displayed in both gross cumulative and discounted terms to allow for ease of use when feeding into business planning. The model does not address wider requirements for investment such as asset renewal and underlying demand growth.

The Transform Model also provides numerous additional outputs such as: the identification of network constraints, their magnitude, location and likely timing of occurrence; the deployment and implementation of cost-efficient solutions to resolve network constraints; a data base of innovative network and non-network smart solutions and conventional solutions; the identification of the optimal timing for implementing these solutions; cost-estimation of the deployment of solutions in the network, etc.

2.2 Framework for distribution network investment

The Transform Model is used to quantify and assess the impacts associated with the integration of DER in the development of electricity distribution infrastructures. The Transform Model uses the concept of 'headroom' to capture these impacts in a consistent manner. Headroom refers to the difference between the load experienced on a network or asset, and the rating of that network or asset. If the rating exceeds the load, then there is a positive amount of headroom and investment is not required. However, once load exceeds the rating then the headroom becomes negative and investment to release additional headroom must be undertaken. For the purpose of this project, the Transform Model evaluates three different types of headroom:

- **Thermal headroom**: difference between the circuit load and the thermal rating of the circuit;
- **Voltage headroom and legroom**: headroom relates to the difference between the circuit voltage at the highest point (e.g. the transformer infeed) and the upper statutory limit. Legroom relates to the difference between the circuit voltage at the end of a feeder and the lower statutory limit. Generally, the upper and lower voltage statutory limits differ by voltage level.
- **Fault level headroom**: difference between the fault level experienced at a busbar and the associated fault rating of the switchgear at that busbar. Generally, the fault level ratings differ by voltage level.

The advantage of using this concept of headroom is that it allows thermal, voltage and fault level to be discussed simultaneously on a common base. For instance, if a particular DER contributes to a reduction in both thermal and voltage headroom then this can be easily identified.

The increasing presence of DER (as well as any organic growth in demand) generally leads to a reduction in headroom on each feeder. When thermal, voltage or fault level headroom (or voltage legroom) on a feeder reaches a pre-specified threshold (i.e. intervention threshold), the Transform Model looks to deploy the most economically efficient network solution (i.e. conventional or smart) to increase the available headroom to adequate levels. Figure 2 provides an illustration of this process. It is noted that, while the diagram only indicates thermal headroom, the Transform Model will simultaneously be ensuring that voltage headroom (or legroom) and fault level headroom are within acceptable limits.

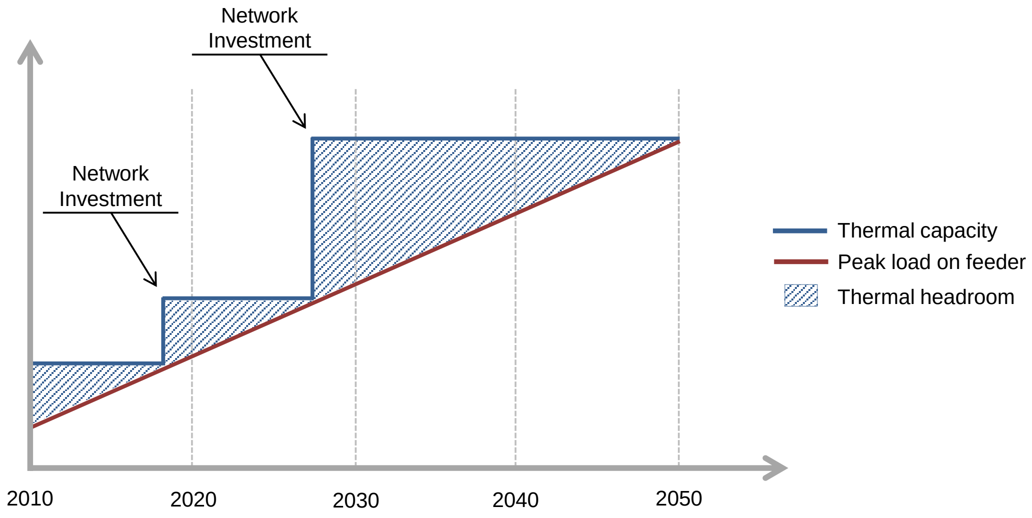


Figure 2 **Illustration of the network investment process**

The development of future electricity distribution networks is likely to be achieved through a mixture of network and non-network solutions that are deployed in different combinations and at different geographical locations to enable an economic efficient and secure delivery of electricity to customers. In this context, the Transform Model considers a blend of conventional solutions and smart solutions to ensure customer value is achieved.

2.3 Provenance of the Transform Model

2.3.1 Initial development

The Transform Model was originally conceived through a project carried out for the Smart Grid Forum in Great Britain. This forum, chaired by the UK Government's Department of Energy and Climate Change (DECC) and the energy regulator, Ofgem, has a number of workstreams that seek to determine how to make the transition to a smarter grid across the entire electricity sector.

Workstream 1 constructed scenarios for potential uptake rates of different low carbon technologies. These uptake scenarios were then used in Workstream 2 to determine where across the value chain of the electricity sector the costs and benefits of moving to a smarter grid lay. A basic model of networks was constructed to help determine theses costs and benefits and a key conclusion from this work was that the area of the value chain that would experience the greatest level of impact was likely to be the distribution sector.

As a consequence, Workstream 3 (facilitated by Energy Networks Association) set out to create a model to determine how distribution networks would need to respond to the likely increased levels of low carbon technologies connecting over the medium – longer term. This work was supported by Ofgem and UK Government, together with all of the British distribution businesses.

Having completed the construction of this model for all of Great Britain (which came to be known as the Transform Model), further work was then undertaken to create instances of the model for each of the 14 individual distribution licence areas in Great Britain. This provided the network businesses with a tool to be able to forecast the necessary investment to accommodate LCT growth over any given timeframe, something which then lent itself to strategic business planning.

2.3.2 Use in business planning

Previously the network operators had not had the facility to determine the level of expenditure that would be required to accommodate technologies such as electric vehicles on the network for two reasons. Firstly, such considerations had not been necessary in previous price control periods, and secondly, the uncertainty associated with where the technologies would connect, and the precise rates of uptake meant that traditional approaches to network investment planning were not particularly well suited to this sort of problem.

So as to ensure distribution network operators could adequately support the likely uptake of such DER over future regulatory periods and thereby positively contribute towards promoting customer access to the network and decarbonising the economy, the Transform Model has become a tried and tested method for this exercise. It has to date been used to inform business planning and regulatory submissions in Great Britain, Northern Ireland and New Zealand before this work in Australia.

2.3.3 Ensuring the model is robust

When the Transform Model was first developed, EA Technology led a team of expert parties in its construction including those particularly experienced in understanding how load profiles will change over time, demographic effects, and also those with significant economic expertise.

The various solutions used within the model each require costs and benefits to be attributed to them for the model to function. These were originally defined by EA Technology working in partnership with the network businesses and taking knowledge gained from trials of those solutions. In order to ensure the figures determined were sufficiently representative, an independent third-party consultancy was employed to review and validate the assumptions contained within these elements of the modelling.

Further quality assurance was also carried out by UK Government, a licensed user of the model, who employed a different independent party to review all of the software models that the relevant department within Government uses for different purposes and this included a review of the Transform Model. UK Government has since gone on to use the model to evaluate the impact of potential policy decisions (e.g. to investigate the network costs associated with greater incentivisation of heat pumps).

The model has therefore been endorsed by government and also by regulatory bodies, including Ofgem who describe it as 'world-leading' in its approach to this challenging area.

2.3.4 List of Users

The following is a non-exhaustive list of users who have active Transform Model licenses, split by the sector in which they operate.

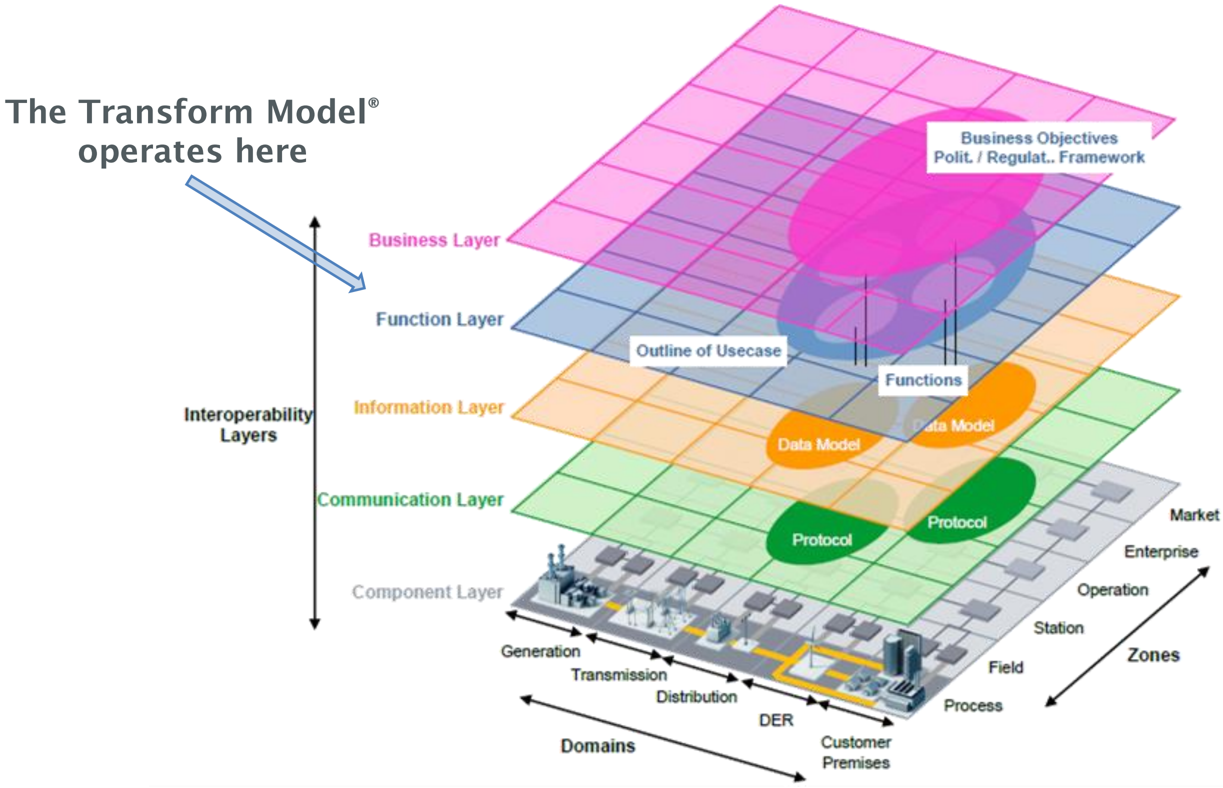
- Government
    - UK Department of Business, Enterprise & Industrial Strategy (BEIS); previously the Department for Energy and Climate Change (DECC)
- Regulators
    - Ofgem
    - Utility Regulator (Northern Ireland)
- Distribution Network Businesses
    - Electricity North West
    - Northern Powergrid
    - Scottish Power Energy Networks
    - Scottish and Southern Energy Power Distribution
    - UK Power Networks
    - Western Power Distribution
    - Vector
    - Alpine Energy
    - Buller Electricity
    - Powerco
    - The Lines Company Ltd
    - Top Energy
    - Waipa Networks
    - WEL Networks
    - NIE Networks

2.4 A strategic tool

It is important to note that the Transform Model is used to inform strategic, rather than tactical, business decisions. A useful visualisation of this involves the European Smart Grid Architecture

Model (SGAM)[4], which describes a smart grid approach as being made up of several ‘layers’, as shown in Figure 3.

The lower layers deal with the assets installed and the way in which communication occurs between these assets. The Transform Model is not prescriptive regarding the communication medium used, or the level of data warehousing that is employed, for example. Rather, the Transform Model operates at the ‘function layer’ providing an overall view of the way in which a smart grid should be developed to meet the needs of stakeholders and giving strategic direction to a network operator to help them achieve this.



The Transform Model® operates here

Figure 3 **Smart Grid Architecture Model illustrating that the Transform Model operates at the Function Layer**

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[4] http://ec.europa.eu/energy/gas_electricity/smartgrids/doc/xpert_group1_reference_architecture.pdf

3. Uptake Trajectories for Distributed Energy Resources

The evolution of electricity demand and potential network constraints and/or expenditure in SAPN's electricity distribution system is expected to be strongly influenced by the uptake of DER. SAPN already experiences amongst the highest levels of rooftop-connected PV globally, and this brings with it associated challenges. When this is coupled with anticipated increases in domestic behind-the-meter storage systems, the issue becomes more complex and the need to have a coordinated LV Management Strategy that facilitates customer choice while keeping bills low becomes even more critical.

This section presents a set of DER uptake scenarios used within this work, taken from published data from AEMO. The modelling can be conducted across any period to 2060, but the focus here has been on the period to 2035.

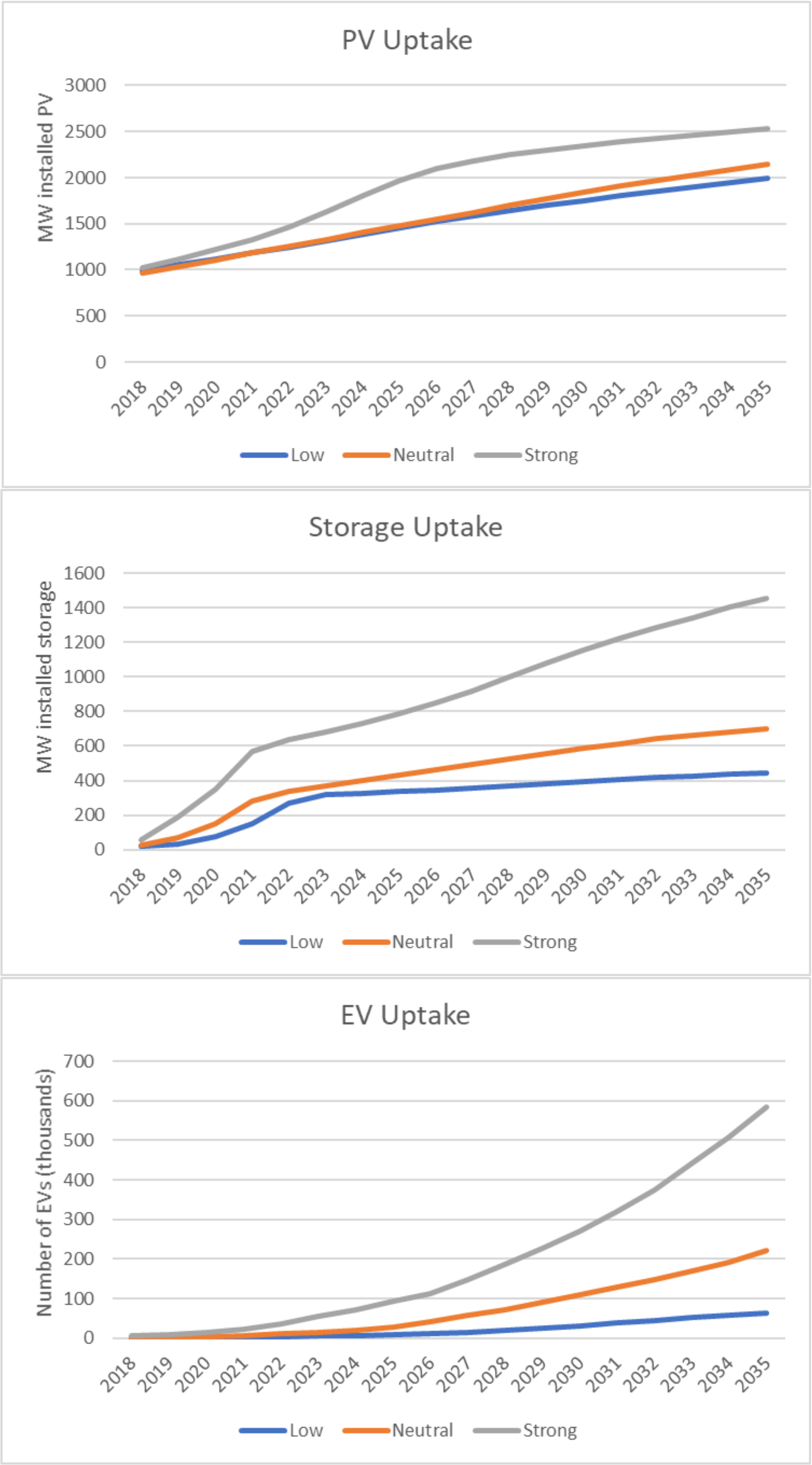

Figure 4 **AEMO DER uptake scenarios**

Table 1 explains where the curves from within Figure 4 have come from and their justification.

Table 1 **Source of growth assumptions**

Case	PV installed capacity	EV forecast (Number on road)	Energy Storage
Base Case	AEMO ISP 2018[5] **neutral** growth forecast (installed capacity (MW))	AEMO ISP 2018 **neutral** forecast (electric vehicles on the road)	AEMO ISP 2018 **neutral** with the assumption of 40,000 state government batteries staged as per current plans (installed capacity (MW))
PV Strong	As above	AEMO ISP 2018[6] **weak** forecast (electric vehicles on the road)	AEMO insights 2017[2] **weak** with the assumption of 40,000 state government batteries staged as per current plans (installed capacity (MW))
VPP Strong	AEMO ISP 2018 **strong** growth forecast plus additional PV to be installed under the Tesla VPP project (installed capacity (MW))	AEMO ISP 2018[7] **neutral** forecast (electric vehicles on the road)	AEMO ISP 2018 **weak** plus 40,000 state government batteries and 50,000 Tesla batteries staged as per current plans (installed capacity (MW))
Weak Uptake	AEMO insights 2017[2] **low** - shifted forward 2 years to reflect actuals for FYE 2018	AEMO ISP 2018[8] **weak** forecast (electric vehicles on the road)	AEMO insights 2017[2] **weak** with the assumption of 40,000 state government batteries staged as per current plans (installed capacity (MW))

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[5] https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Electricity-Forecasting-Insights/2018-Electricity-Forecasting-Insights

[6] https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Electricity-Forecasting-Insights/2018-Electricity-Forecasting-Insights

[7] https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Electricity-Forecasting-Insights/2018-Electricity-Forecasting-Insights

[8] https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Electricity-Forecasting-Insights/2018-Electricity-Forecasting-Insights

4. Representative Electricity Networks

This section provides an overview of the process adopted to develop a representative network of the of the low voltage distribution network in South Australia. It details the key characteristics and parameters of the representative feeders and discusses the way in which loads of the representative feeders were determined and examined.

4.1 Framework for representative feeders

Real distribution systems are characterised by a vast diversity of topologies, customer densities and ratings of the feeders resulting in every feeder being different in some detail to every other feeder, even if only slightly. Attempting to model such an extensive distribution system on a circuit-by-circuit basis to assist the strategic decision-making process of distribution businesses becomes an impractical task. In this respect, the framework adopted to classify and characterise networks uses the concept of 'representative' networks to create a number of 'typical' feeders that constitute a best fit to a specific group of real feeders. Representative feeders were initially defined based on the real feeders found in SAPN. Then, these local representative feeders were combined and replicated in the appropriate proportions, to create an overall network that is a reasonable approximation of the entire SAPN distribution network.

The concept of 'representative' networks enables the grouping of a set of real networks of similar inherent parameters such as the feeder length, configuration, construction, number of customers, etc., into a single network now characterised by 'typical' parameters such as average feeder length, average number of customers, etc. The framework creates a different representative network when a set of real networks have relatively different parameters since the mix and make-up are likely to be different. The use of this parametric approach, in contrast to a nodal approach, permits significant reduction of the number of feeders to model and the computation of load flows in large distribution systems. Parametric and nodal models can be defined as follows:

- **Parametric model**: uses a high level of abstraction to classify and characterise networks through their structural (e.g. construction: overhead, underground; configuration: radial, meshed; etc.), electrical (e.g. thermal rating, voltage rating, etc.) and population (e.g. urban, rural, etc.) attributes. It generally uses various types of 'headroom' to assess the performance of the network. Headroom is the difference between the actual power flows, voltages and fault levels and the limits set by network design, equipment ratings, or legal/regulatory requirements. Parametric models usually provide a high level of understanding and are especially well suited for strategic planning activities.

- **Nodal model**: enables the representation of a network through the detailed specification of the electrical properties of all its components through their equivalent circuit model. The performance of the network is assessed through the computation of a full load flow where the power injected in the network is directed to serve the load points.

It should be stressed that this framework allows for the representation of a 'typical' distribution network. It does not encompass every possible condition or topology that may occur in South Australia. The development of the representative networks was driven by the data provided by SAPN, together with the experience of EA Technology and is considered to be a sufficiently accurate representation of the network for strategic, rather than tactical, planning.

4.2 Definition of representative feeders

Representative feeders (also referred to as typical feeders) were developed such that each typical feeder is the most appropriate representation of the characteristics of a group of real feeders of the SAPN distribution network. The process followed to create representative feeders can be divided into three key steps: (i) real feeder classification; (ii) representative feeder classification; and (iii) representative feeder parameterisation.

- **Real feeder classification**: this step classifies and characterises the real network feeders found within SAPN through structural (e.g. construction: overhead, underground; configuration: radial, meshed; etc.), electrical (e.g. thermal rating, voltage rating, etc.) and population (e.g. urban, rural, etc.) attributes. This step allows incomplete datasets at LV, which are common among DNOs worldwide, to be modelled without a very expensive data collection and processing system. The process is driven by the data made available by SAPN.

- **Representative feeder classification**: this step creates a typical feeder that best represents the characteristics of a set of real feeders. In principle, each set of real feeders contains feeders which, although clearly not identical, are 'similar'. The similarity is determined by the defined range of the relevant structural, electrical and population attributes. It is noted that this step is a very crucial part of the process since if this range is too small, the number of representative feeders will become very large and the behaviour of the typical feeder could be rather dissimilar to the real feeder; but if the range is too large then the process clearly becomes more complex and difficult.

- **Representative feeder parameterisation**: this step establishes the final reduced set of typical feeders that best represent the real feeders of the SAPN distribution network. Each typical feeder can be viewed as the average feeder of a particular set of similar real feeders. Furthermore, the process decides and defines the quantitative values of the inherent attributes/parameters of the typical feeder that represents the set of the real feeders.

The key structural, electrical and population attributes of feeders considered in the 'typical feeder classification' process include:

- Voltage: Low Voltage (LV ≤ 1kV), High Voltage (11kV), Extra High Voltage (33kV);
- Geography: rural, suburban, urban;
- Construction: overhead, underground, mixed;
- Feeder thermal rating;
- Feeder length;
- Peak load; and
- Number of customers.

4.2.1 Real feeder classification

The information and data relating to the real network feeders as well as their respective structural, electrical and population attributes were provided by SAPN. Table 2 summarises key characteristics of the SAPN distribution network as provided.

Table 2 **Key characteristics of the SAPN network**

Networks	Number of Substations	Number of customers
High Voltage	342	869,679
Low voltage	75,530	

At a number of workshops, EA Technology liaised with SAPN to define the appropriate feeder classes that would allow all elements of the SAPN distribution network to be considered. It was agreed that LV networks would be categorised by transformer as good data was available at this level. HV networks would be categorised by feeder, as good data was available on a per feeder basis for HV networks. This then allowed for analysis of the network data that SAPN would provide into these various classes. SAPN then provided example networks of each type which were modelled in Power Factory to determine network hosting capacities.

4.2.2 Representative feeder classification

Having examined the data and thus derived the basic parameters for the representative feeders, the various feeder classifications can thus be summarised. The following tables illustrate this classification, providing the rating, length, peak load and number of circuits for each class across all three voltage levels.

Table 3 Representative feeders of the HV distribution network in South Australia

Feeder	Feeder definition	Number of networks
HV1	CBD	124
HV2	Urban UG	109
HV3	Urban Mix	229
HV4	Urban OH	142
HV5	Urban Fringe	27
HV6	Rural Dense	152
HV7	Rural Sparse	273
Total		1,270

Table 4 Representative feeders of the LV distribution network in South Australia

Feeder	Feeder definition	Number of networks
LV1	CBD	551
LV2	Single Customer Commercial	1,717
LV3	Majority Commercial	3,589
LV4	Mixed Customer UG	699
LV5	Mixed Customer OH	1,840
LV6	New UG	5,487

Feeder	Feeder definition	Number of networks
LV7	Old UG	316
LV8	Small OH	882
LV9	Medium OH	4,002
LV10	Large OH	1,208
LV11	Single Rural	14,294
LV12	2-4 Customer Rural	13,037
LV13	Rural Township	8,790
LV14	SWER LV	430
LV15	SWER Township	20

Note that detailed load modelling for LV1 has not been carried out due to the unique nature of each CBD circuit and the perceived low likelihood of CBD circuits attracting large amounts of DER. Therefore, the CBD circuits were considered out of scope for the CBA.

4.2.3 Representative feeder parameterisation

Information pertaining to network topology and intervention thresholds for the different types of headroom and legroom were derived from the information and data provided by SAPN and discussed during the workshop phase and are presented in Table 5 for different network voltage levels.

The column fields of **Error! Reference source not found.** are briefly defined here.

- **Substation Capacity:** This refers to the amount of power in kW that can flow through the substation for a given network type before SAPN would seek to reinforce. It is based on the typical transformer size for that type of network.

- **Thermal Conductor Capacity:** This refers to the amount of power in kW that can flow through the cable/overhead line system for a given network type before SAPN would seek to reinforce. It is based on the results of the Power Factory modelling for those circuit types.

- **Voltage Upper Headroom Limit:** This is the percentage amount the voltage could rise over a circuit before customers started to experience issues. This was set having been advised of the tapping of transformers by SAPN and analysis of voltage shifts on 11kV circuits.

- **Voltage Lower Headroom Limit:** This is the percentage amount the voltage could drop over a circuit before customers started to experience issues. This was set having been advised of the tapping of transformers by SAPN and analysis of voltage shifts on 11kV circuits.

- **kW/%:** This is the amount of power (in kW) required to cause the voltage of the circuit to rise or fall by 1%. This was based on the Power Factory analysis.

- **Number of Customers:** This is the average number of customers connected to that network in Transform. It was based on an analysis of the categorised LV transformer data provided by SAPN, which included the number of customers for each transformer.

Table 5 Network Parameters

	Substation Capacity (kW)	Thermal Conductor (kW)	Voltage Upper Headroom Limit (%)	Voltage Lower Limit (%)	kW/%	Number of Customers
LV1 CBD	650	395	1%	12%	65	10
LV2 Single Customer Commercial	390	395	1%	12%	65	1
LV3 Majority Commercial	390	395	1%	12%	65	12
LV4 Mixed Cust UG	260	339	1%	12%	65	36
LV5 Mixed Cust OH	260	237	1%	12%	35	45
LV6 New UG	195	373	1%	12%	65	25
LV7 Old UG	195	200	1%	12%	29	53
LV8 Small OH	130	291	1%	12%	35	9
LV9 Med OH	260	278	1%	12%	33	51
LV10 Large OH	410	548	1%	12%	61	72
LV11 Single Rural	13	100	2%	12%	2	1
LV12 2-4 customer rural	75	359	2%	12%	7	3
LV13 Rural Township	195	328	2%	12%	38	21
LV14 SWER LV	1300	359	4%	12%	36	47
LV15 SWER Township	1300	359	4%	12%	36	47

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4.3 Representative distribution network

The representative feeders of the South Australia distribution network are combined across the different voltage levels existing in the real South Australia distribution network to form a representative network of the entire SAPN distribution network. Figure 5 depicts an overview of the three-tiered network that exists within the Transform Model, showing that connections are made between the EHV, HV and LV voltage levels such that the aggregation of loads at the lower voltage levels can be calculated higher up the network, thus allowing examination of the loads that will occur on all feeders at all voltage levels over the modelled period.

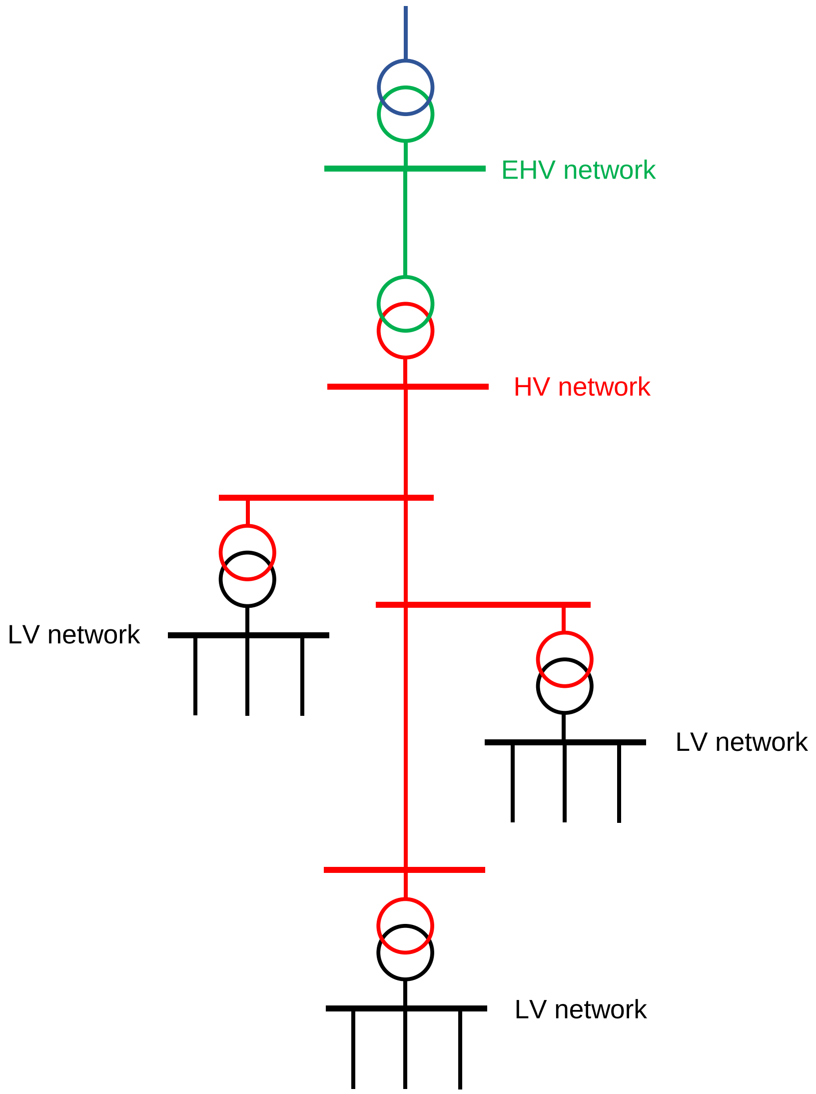

Figure 5 **Schematic diagram of the network**

In order to ensure that the loads can be calculated appropriately, it is important to establish which types of HV feeder are fed from which EHV feeders (and similarly which LV feeders are supplied from which HV feeders). In order to do this, a representation such as that shown in **Error! Reference source not found.** is developed. This allows the various parametric feeders to be combined to constitute a network which is representative of that found in South Australia

4.4 Feeder and network loads

The electricity demand of each representative feeder is characterised by the half-hour time series of load across representative days. For each year, six representative days are considered, i.e. an average 'summer' weekday, an average 'winter' weekday and a 'peak winter' weekday. SAPN used their data to construct typical load profiles for each of the different types of customers and for each of the representative days. Each transformer on the SAPN network had been categorised, into one of the feeder types in Table 4. The average number of customers from the available data on real transformers was used to set the average customer numbers in the model, which combined with those customers load profiles gave the load profile for the networks.

The loads obtained for the LV representative feeders were then used to build the loads for the higher voltage feeders (HV and EHV) through the 'bottom-up' approach inherent to the Transform Model.

5. Engineering Solutions

Networks are made up of a range of technologies that are applied in different combinations and at different geographical scale to enable the transfer of energy from grid exit points to consumer load points. The increasing presence of DER in distribution networks will cause thermal, voltage or fault level headroom (or voltage legroom) limits to change over time. The reduction of headroom levels to a pre-set limit will require the DNSP to intervene in the network in order to release headroom ensuring security and quality of supply.

The Transform Model selects the most appropriate solution in each modelled instance when a capacity constraint is breached.

Alternatively, the Transform Model developed for SAPN can be run in “static limits mode” or “dynamic limits mode” where DER are constrained to keep the network from breaching its limits.

5.1 Network Solutions

Network solutions refer to technological network-based solutions that could be used to increase network capacity. This includes some solutions that are used today, such as re-stringing overhead lines or adding infill transformers. It also includes some solutions that could be used in the future, such as the use of LV Statcoms. The solutions considered in the model are shown in Table 6.

Table 6 **Network solutions**

TF upgrades and infills	**Non-network solutions**
Upgrade distribution TF OH - 100kVA to 200kVA	Battery 100kW/200kWh -LV
Upgrade distribution TF OH - 200kVA to 315kVA	Battery 50kW/100kWh -LV
Upgrade distribution TF UG	Battery 25kW/50kWh -LV
Infill TX Small OH TF (<10kVA)	Battery 3MW/6MWh - HV
Infill TX Large OH TF (>10kVA)	Battery 1.5MW/3MWh -HV
Infill TX pad mounted	Customer inverter voltage support contract
Replace Tapless Transformer with tap changer (OH)	
Replace Tapless Transformer With new TF with OLTC (OH)	**Feeder reconfiguration**
Upgrade ~10kVA TF to include a tap changer	Split Feeder HV Urban
	Split Feeder HV Rural
Rebalancing and retapping	Re-String LV Urban
Load Transfers (LV)	Re-String LV Rural
Tapping of existing Dist TX	Re-String HV OH Urban
Further Tapping of existing Dist TX	Re-String HV OH Rural Short
Rebalance Phases OH	Re-String HV OH Rural Long
Rebalance Phases UG	Split Feeder HV UG
	Split Feeder HV OH Rural Long
Reactive power support (network)	Split Feeder LV UG
LV Regulator	Split Feeder LV OH Urban
LV Regulator Small Customer Numbers	Split Feeder LV OH Rural
HV Reactor Bank	
HV Regulator	**Substation upgrade**
Existing Regulator+LDC	Upgrade Zone Sub TF Urban
LV Statcom (Underground)	Upgrade Zone Sub TF Rural

5.2 Capacity increase

Solutions increase capacity of networks in the parametric model. Depending on which capacity has been breached the solution could increase either the thermal rating of the cable system, the thermal rating of the transformer, the allowable voltage rise, or the amount of power required to cause a voltage rise.

The extent to which solutions increase network capacity was determined by simulating the solution in Power Factory. Each solution would be modelled on a number of networks to get the range of values that the solution could provide. For example, for infill transformers the effect of adding an infill transformer was simulated on 4 networks giving increases in capacity of between 57 and 120% as shown below. As the 120% value was an outlier the increase in capacity entered into transform was 70%.

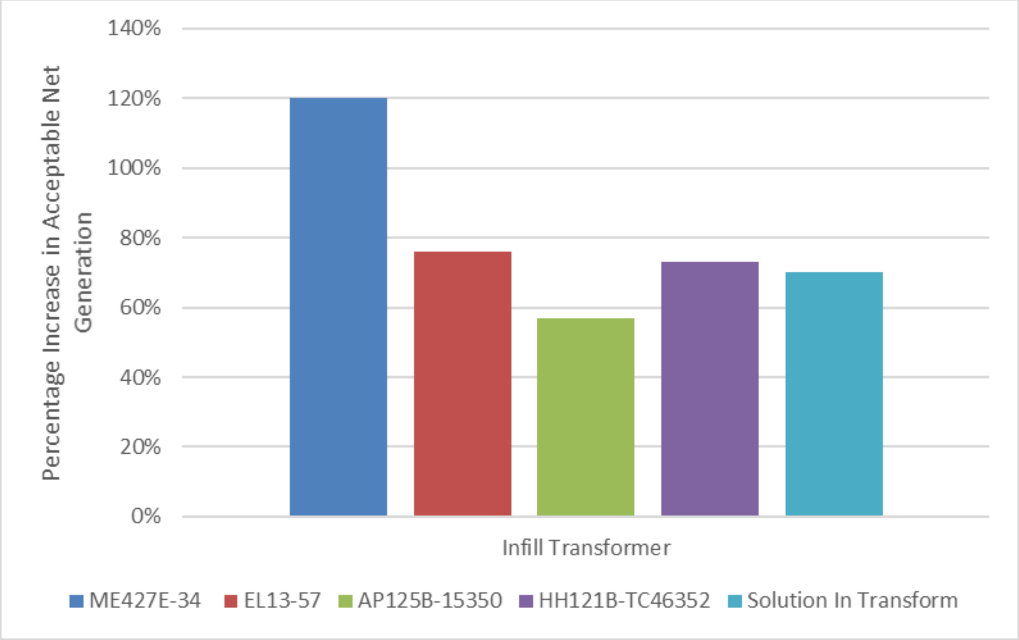

Figure 6 **Capacity Uplift for Infill Transformer**

5.3 Curtailment

In order to consider the ways customer DER could be managed a curtailment mode was created for SAPN. Instead of the dynamic curtailment included in the network solutions list which was compared dynamically to other potential solutions the curtailment mode assumed that all LV constraints would be addressed via the curtailment of generation or energy storage.

Three different curtailment modes were considered with increasing levels of refinement and granularity:

- Static Limits
- Dynamic Limits (Informed by a template network model)
- Dynamic Limits (Informed by a full network model)

“Static Limits” assumes a fixed amount of generation can be allowed to export to a particular network. A static zero export limit is then applied to all new DER connected to that network. The “Dynamic Limits informed by template model” creates seasonal limits which set a limit on the total amount of power that can be generated per installed kW of capacity per season and curtails all energy generated above that limit. The “Dynamic Limit informed by full network model” evaluates how much excess power above the network’s hosting capacity is generated each half hour and curtails only that.

All calculations were carried out independently on a per simulated network basis. For example, the calculations for “Large Overhead” networks were independent of the calculations for “Small Overhead” networks.

5.4 Framework for the deployment of distribution network solutions

The presence of DER in distribution networks will cause thermal, voltage or fault level headroom (or voltage legroom) limits to change over time. The reduction of headroom levels to a pre-set trigger limit will require the DNSP to intervene in the network in order to release headroom ensuring security and quality of supply. In this respect, the Transform Model seeks to select and deploy smart and conventional solutions to resolve network constraint problems through a variable ‘merit order stack’. The merit of each network solution is characterised by a ‘cost function’ of the following elements:

- **TOTEX**: the sum of capital expenditure (CAPEX) plus the net present value (NPV) of annual operating expenditure (OPEX[9]) over the life of the asset
- **Life expectancy**: this considers the residual life of the asset at point *n* in time (where *n* is set to be the number of years forward in time for the model to resolve a problem, following a breach of headroom)

These elements are then combined to obtain the merit cost of a particular solution as follows:

$$Solution\ Merit\ Cost = \left(\frac{n}{Life\ Expectancy}\right) \times (TOTEX)$$

It should be noted that the ‘solution merit cost’ is different from the cost of the solution (i.e. TOTEX) and it is only used for the purposes of ranking different solutions against each other in a comprehensive and consistent manner.

The Transform Model selects the combination of solutions that solves the network constraint (up to a maximum of 5 solutions used in parallel). The approach credits solutions that are deployed to resolve one network constraint type (e.g. voltage legroom) that has an impact on other network constraint types (e.g. the solution deployed to resolve a voltage legroom violation may also increase thermal headroom).

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6. Other Modelling Considerations

6.1 Clustering of DER

It is well-documented that the penetration levels of DER are not uniform across a distribution network. (If they were, then the accommodation of such DER would be far more straightforward.)

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[9] It is important to note that while OPEX does include well-established costs (such as those associated with maintenance), it also allows for other costs associated with smart solutions, such as the rental of communications channels. However, it does not include indirect opex costs such as those associated with design, project management, back-office etc.

Rather, there are certain portions of the network that experience significantly greater amounts of DER (they are more highly clustered) than other network areas.

The Transform Model accounts for this by taking ten variants of each of the representative networks and applying different levels of clustering of DER to these networks. The data to inform the degree to which this clustering occurs was taken from SAPN information on the level of DER installed per distribution transformer.

In this way, the representative feeders more accurately reflected the variation that one might expect to see between two electrically similar feeders that might exist in different geographical areas or have customers of different demographic groups whose propensity to install DER would not be equal.

6.2 Phase imbalance

When considering the ability of the network to accommodate DER, the more balanced the network, the greater the level of DER that can be tolerated before network breaches occur.

In many cases, precise phasing information of customers is unknown and there are weighting factors within the model that can be used to account for this uncertainty. In this case, when conducting the Power Factory modelling, unbalanced load flows were carried out with three phase models created and customers connected to a specific phase. This was utilised as a more accurate method of understanding the capability of the network to accommodate DER through anticipated levels of phase imbalance.

More detail on how this modelling was performed can be found in the associated report.[1]

6.3 Discount rate

The Transform Model uses a discounting procedure to compare costs and benefits that occur in different time periods. The concept of discounting is based on the ‘time preference’ principle where people, generally, prefer to receive goods and services now rather than later.

The discount rate can be varied to be any figure that a use requires and can also change over time (i.e. a discount rate of 4% could be applied for the first ten years and then changed to, say, 3.5% for the next ten years if so desired). In the modelling performed for this work, the discount rate has been held constant at 3.41% following discussion with SAPN.

6.4 Look-ahead period

The Transform Model employs a perfect foresight approach to network investment. Thus, distribution network investment decisions are made with a perfect view of network loads in the forward years. Solutions are therefore selected on the basis of them being able to cater for the network demand over the coming years, and this number of years, which can be thought of as a network planning horizon or a look-ahead period, is set as a default to five.

If this look-ahead period were to be altered, then some of the results would change as the model would favour different solutions. For example, opting for a look-ahead period of one year would drive investment decisions to accommodate short term growth of DER based on the deployment of low-cost solutions that release low levels of headroom. This is likely to become cost inefficient in the long term as these solutions will need to be replaced by those that have significant ability of releasing larger volumes of headroom.

Conversely, taking a longer look-ahead period could drive the model towards the selection of longer-life asset-based solutions as these tend to deliver larger step-changes in headroom for an up-front capital investment. Hence if the look-ahead period is significantly extended, the model will favour these solutions as offering ‘value’ by the virtue of solving the network problem and avoiding the need to revisit that network for many years or decades.

A look-ahead period of five years has been used for this work as it aligns with standard business panning timescale sand strikes an appropriate balance between the two extremes outlined above, thus providing a more balanced investment decision that is likely to deliver more economically efficient decisions and provide long-term value to customers.

7. Results and Conclusions

The Transform Model for SAPN has been created to be a representation of SAPN’s distribution network. It is a tool that can be used to support strategic business decisions, particularly in relation to the LV network, and can be updated over time as required by users.

The Transform Model was executed over a range of potential DER uptake scenarios as discussed in this document. This produced a number of outputs including:

- capital expenditure
- operating expenditure
- level of curtailment imposed on customers
- volumes of different engineering solutions deployed
- amount of non-network alternatives that could be utilised to mitigate the network issues.

These results were then subjected to some post-processing to formulate them into strategy options for the LV Management Strategy development. The overall results and the conclusions drawn from this in terms of the preferred LV Management Strategy moving forward are fully discussed within the detailed report examining the strategy development.[2]

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