Flexible Demand in South Africa's Energy System – Addressing System Modelling Needs and Challenges

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ABSTRACT

Energy systems across the globe are continuing their rapid evolution in the production, consumption, storage, and management of energy. This evolution is taking place within the context of shifting end-use requirements, pressing environmental and climate concerns, economic drivers, and lingering (or growing) energy poverty. At the same time energy system planners, power generators, system operators, distributors and consumers are trying to keep up with increasing shares of variable renewable electricity generation, shifting economics and market structures of energy systems, and innovative approaches to managing system demand. Many energy systems models in South Africa have been developed for the purposes of long-term infrastructure planning, and are equipped to interrogate risks and opportunities associated with certain technologies, links to socio-economic objectives, and to manage uncertainty around input assumptions. Flexible Demand is perhaps the most recent addition to the overflowing complexity facing energy system planning, and it is important that long-term energy modelling stays ahead of the game so that the introduction of evolving flexibility can be adequately modelled, evaluated, and planned for. The ultimate goal is to ensure that the inclusion of flexible demand into our energy systems accrues the maximum system benefits, ensuring that the energy systems are planned to be economically, environmentally and socially optimal. The purpose of the paper is to define what the potential considerations of Flexible Demand are for the South African energy system, and the resulting implications for energy systems models. It is intended to elucidate the potential benefits for flexible energy demands in the country, and to make recommendations on how the current modelling paradigms need to be continually updated to be more inclusive of newer demand-side energy resources. The paper also discusses several capabilities of the South African TIMES model (SATIM) in addressing some of the defined focus key areas.

1. Introduction

Power and energy markets continue to evolve in response to economic, social, environmental and technological pressures. The transitioning paradigm of the energy systems in turn leads to associated energy systems modelling challenges.

One manifestation of this evolution is the observable transition toward energy systems characterised by increased demand-side influence and increased shares of variable renewable energy resources in response to climate constrained energy targets. The presence of grid-based renewable power generation has meant that power system operators have effectively been implored to relinquish a degree of control of when generation happens (Samad, 2016). We are also entering era of "base-cost renewables" (Liebreich, 2017; Bloomberg, 2017) where wind and solar are cheaper than any other sources of electricity in many electricity systems globally, but are for the most part variable, and therefore require the presence of other technologies on the supply side, and flexible load on the demand side in order to fully integrate them effectively (Göransson, 2014; Zerrahn, 2015). These enablers of a renewable-powered and cost-optimised energy system include wide-ranging demand response options, power storage technologies, flexible fossil-fuel plants, non-power alternatives to meet end-use requirements, and interconnections with neighbouring systems. These options have inherent costs that need to be included in the maximisation of welfare and the minimisation of the cost of energy systems and the costs of energy infrastructure investments. The presence of uncosted externalities associated with various power supply options render unavoidable one or more elements of subsidy, market protection, or externality-inclusive cost evaluation.

The notion of demand flexibility is not a new one. Internationally and in South Africa, demand-side management, peak-shaving and load-shifting have long been a part of the suite of tools available to power system operators and utilities to improve system economics and stability. What the current wave of research – the part which can be classified under the broad umbrella of flexible demand and demand response – is now paying attention to, is the value of these resources in creating a more optimised power system. South Africa has abundant supplies of renewable energy, alongside a prevalence of suppressed demand and a need for energy to stimulate economic development. If the energy system could incorporate greater flexibility, it would make a stronger case for the accelerated uptake of the cheaper renewables resulting in decarbonisation of the grid, alleviation of energy poverty the provision of much needed economic stimulus. As reported internationally, these objectives can be achieved

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through flexibility-induced reduction of the overall electricity price, minimised peaking plant utilization, reduced or delayed infrastructure capacity requirements, reduction of transmission and distribution congestion, reductions in emissions and improved overall economic efficiency (Albadi, 2008; O'Connell, 2014).

Models used for decision support and policy-making under the new energy paradigm need to address flexibility while continuing to pay attention to physicality and economics (EU JRC, 2015). The recognition that more flexible energy systems are required has precipitated several questions related 1) maintaining or enhancing system reliability and adequacy, 2) the need for rules governing curtailment and storage and 3) the types of dispatchable backup that are best suited to the system.

Electricity supply options differ not only in terms of cost and carbon intensity but also ancillary services related to reliability, response speeds, abilities to ramp up / down. The ultimate goal is to create the optimal energy portfolio (Liebreich, 2017). New communication and control capabilities of the so called 'smart-grid' have allowed Demand-Side-Management (DSM) interventions, in particular, Demand Response (DR), to alter the electrical load to achieve a number of valuable benefits in energy systems.

Furthermore, the new paradigm presents numerous modelling challenges, including linking energy system models with sectoral energy models, uncertainty related to renewable capacity, and inclusion of flexibility and technical constraints in power systems. And while the planning and modelling paradigms are evolving, there are already numerous bottom-up innovative technologies that are percolating into the system (including smart meters, energy management apps and related data). Energy system planners do not necessarily drive the uptake of these technologies; however, they do need to incorporate the role of end-users and their interactions with the energy system.

To further the discussion around flexible demand in South Africa and the resultant energy systems modelling implications, the remainder of this paper proceeds as follows. Firstly, the prevailing literature in relation to flexible demand (largely developed world focused) is summarised including definitions, program classification, potential benefits and challenges. The second section discusses the general implications of developments in flexible demand for energy systems modelling and provides a brief overview of attempts to incorporate flexibility into the energy and/or power system models. The two sections that follow mirror those that precede it, but they focus the attention on the relevance for the South African energy context and associated modelling implications respectively. The paper concludes with some guidance on how energy systems models can begin to address the current flexibility options as well and prepare for the tendency toward a more flexible and dynamic future South African energy system.

2. Flexible Demand

2.1. Definition, overview, and international experience

From the literature surveyed for this review, no uniformly consistent classification can be found for demand response. Flexible Demand (FD) is not distinct from the notion of Demand Response (DR) or Transactive Energy (Chen & Liu, 2017), and these ostensibly include the longer established range of options falling under the banner of Demand Side Management (DSM) (Samad, 2016). DSM is a more general term that encompasses DR and other methods that modify consumer demand (e.g. energy efficiency and behaviour change programmes). Other reports have referred to Demand Flexibility (Dyson et al, 2015) which does not appear to be distinct from FD or DR. Regardless of the terminology, these notions in the context of the power sector refer to the intentional change in consumer's electrical demand profiles either in response to a changing electricity price or to load control signals with prior agreements. The discussions in the remainder of the paper will refer interchangeably between FD and DR, with the understanding that FD includes options such as DR and DSM.

Automated Demand Response (ADR) is a form of DR where the signal is received by control equipment at the customer's facility. ADR has proved its worth in ensuring that keeping up with electricity demand, while ensuring larger proportions of renewable generation and maintaining grid reliability. The key feature of ADR is that decisions to shift or curtail load are carried out intelligently and without the need for intervention by the system operator or end-user. The approach has applications in all sectors (Samad, 2016) recently including grid-integrated buildings and micro-grids leading to increasingly sophisticated management of demand-side load profiles.

The presence of storage devices (including electric vehicles) and onsite power generation can be regarded as energy assets that now occupy the demand side of electrical power systems. The uptake of such technologies has been spurred by energy storage technology, decreased costs of small-scale renewables, energy policy and moves by end-users towards energy independence. In DR, the System Operator (SO) or utility aims to modify customer load profiles to mitigate grid-side issues. Incentives are offered in lieu of response to signals or through direct load control from the SO or curtailment of load is executed according to contracts.

In brief, flexible demand could refer to any of the following practices:

- Using alternative energy sources, carriers, or technologies to meet the same demand.
- Shifting the time at which the energy service is required.
- Foregoing the service, voluntarily or through external control.
- Inter-sectoral linkages: such as flexible charging of electric vehicles, or flexible production of hydrogen through electrolysis for use in power-to-gas, power-to-power, or power-to-liquids applications.

2.2. Classification of demand response programmes

(Li, et al, 2016) present DR options as ranging from controllable loads, to generalised demand resources (GDR), where the latter includes distributed generation (DG) and electric energy storage (EES). One possible classification that covers the various options from a power systems perspective consists of two categories, with subcategories summarised as follows overleaf:

1. Price-based / distributed control
    a. Time-of-use tariff
    b. Critical peak / extreme day pricing
    c. Real-time pricing
2. Incentive-based / centralised control:
    a. Direct load control
    b. Interruptible / curtailable load
    c. Ancillary services

When classifying programmes that are designed to incentivize and enable actors to participate in providing flexible demand, it is necessary to specify who the programme's participants are on the demand-side. Individual consumers (large and small), whole sectors, geographically aggregated groups of users, and third-party market intermediaries are all potential players in the market. The potential for aggregating responses of individual end-users or of individual types of appliances held by multiple end-users will depend on the practical potential for DR in a particular group, in combination with a consideration of the techno-physical needs or constraints of the system. Broadly, examples of sectoral aggregation for flexible demand purposes according to buildings, industrial, and transportation sectors. Aggregators can also be specific categories of private sector end-users or public entities such as municipalities.

3. Benefits, challenges and enablers of flexible demand

The benefits of energy efficiency in general are widely regarded as being plentiful and of "no regret" to energy systems planners. Flexible demand is expected to able to achieve similar outcomes, but in a more focused manner (Baatz, 2015). Some of these benefits include avoided costs (energy, capacity, transmission and distribution, ancillary services, environmental compliance), demand reduction induced price effects, and others. From an energy system planning perspective (Albadi & Saadany, 2008) were early proponents of the idea that DR might be a cheap resource available for operating energy systems than, say, investing further in additional generation or transmission infrastructure. The section concludes with some of the challenges related to DR, as well as some emergent enablers.

3.1. Operational benefits

One of the largest drivers for DR is that of adding flexibility to integrate higher penetrations of variable generation such as wind and solar into the system with increased stability and reliability. Typically, this requires fast responding flexible generation or energy storage to account for fluctuations, however DR has been shown to present a significant opportunity to provide this flexibility at low cost (US DoE, 2005; Milligan, 2010).

These DR benefits, often classed as ancillary services, would otherwise require expensive open-cycle gas turbine generators with very fast response times and ramp rates, in the limited presence of hydro and pump storage, as is the case in South Africa. Alternatively, providing these services often requires generation plants to run at partial load levels allowing upward output ramping and cycling between levels. Running plants at lower than rated capacity and continuously cycling their output incurs efficiency losses, increased degradation of plant and increased emissions (Troy, 2012; Leuken, 2012). DR services are thus able to increase overall system reliability, reducing the likelihood and severity of load-shedding events and outages and the associated economic losses (Albadi, 2008; O'Connell, 2014).

Thermal end-uses in particular have the ability to alter their load almost instantaneously with minimal disruption to activities, and therefore provide a significant opportunity for providing ancillary services at low cost (Nolan, 2015; O'Connell, 2014).

3.2. Economic benefits

Several economic benefits exist through DR, including the system wide reduction in the overall cost and cost volatility of electricity, achieved in part by using less energy provided by expensive power plants at peak times and the increased utilization of cheaper generating plants and renewables. This ability is especially valuable with large amounts of variable renewables contributing at times not coincident with high demand, reducing potential curtailment of renewables (Göransson, 2014; Nolan, 2015)

Overall economic efficiency can be achieved through implementing a real-time pricing (RTP) scheme. In a conventional flat-rate tariff structure, consumers often use low-utility appliances in high wholesale price times because they have no signal to do otherwise. Many of these appliances use can be easily shifted or interrupted without inconvenience, such as laundry or dishwashing or air-conditioning (O'Connell, 2014). Beyond short-term efficiency, economists have also predicted increased long-run efficiency of the overall economy through RTP that enables more efficient and fit-for-purpose capacity expansion planning (Borenstein, 2005).

Improved control over the time and targeting of electricity pricing allows for several disparate subsidisation improvement opportunities. Firstly, it allows the removal of the unintended cross-subsidization of users whose usage occurs mostly during peak times by those who generally consume during off-peak hours (Albadi, 2008; O'Connel, 2014). Furthermore, energy affordability could also be improved by implementing finer grained pricing for specific basic end uses and/or income groups enabling an interesting opportunity for targeted subsidies, for example providing basic lighting and cellular phone charging in addition to free-basic electricity (Welsch & Bazillian, 2013). Significantly cheaper electricity may also be possible if users are willing to use it during off-peak hours or accept a curtailable service for interruption tolerant end-uses such as battery charging. The added demand-side flexibility can reduce the needs of typically expensive large-scale centralised electricity storage by adapting to times of high, low or fluctuating renewable supply.

3.3. Planning and environmental benefits

Through reducing demand during peak hours, a delay or reduction in capital expansion investments for peak generating capacity can be achieved. The same is true for the transmission and distribution systems where spatially differentiated prices or control mechanisms can be implemented, network congestion alleviated and capacity upgrades delayed (Göransson, 2014)

Environmental benefits are achieved through the reduced needs for supply side and network capacity, and higher use of intermittent RE, resulting in a smaller overall system environmental footprint. Resultant benefits include the improvement of air and water quality and reduction of greenhouse gases and land degradation. These benefits are realised through reduced requirements for the running of generation plants and mining (Albadi, 2008). The resultant reduction in grid transmission footprint reduces land utilization, noise and sight pollution for people, and interference with the biosphere (Welsch & Bazillian, 2013).

The various benefits of DR are summarised in the table below:

Table 1 - Summary of flexible demand benefits

Operational Benefits	Economic Benefits	Planning and Environmental Benefits
Improved reliability and stability of electricity systems	Overall reduced electricity price and price volatility	Deferral/Reduction of generation and transmission capacity requirements
Ancillary services such as frequency and voltage support	Economic inclusion of more low-cost variable renewables	Higher penetrations of RE can lessen the burden of national contributions to global climate goals
Lessened need for peaking plants and spinning reserves	Reduced electricity storage requirements and cycling losses	Environmental and health benefits (GHG, land use, air, and water quality)
Reduced thermal plant cycling, lowering start up, ramping, and efficiency impacts	Energy affordability and global industrial electricity price competitiveness	Added flexibility adapting to unforeseen technological or global commodity costs or availability

3.3.1. Emerging DR enablers

While there are numerous challenges to the implementation of DR, enablers are emerging. Processes and architectures such as OpenADR are critically important for easing the implementation of micro-grids and ADR (Samad, 2016). Blockchain (Chen & Liu, 2017) is also emerging as a transaction enabler for assuring that energy systems are demand optimised while ensuring that agents are accurately remunerated for their contributions to systems services and/or provision of energy services in a cost-effective way (Pop et al, 2018). Blockchain has the potential to facilitate control of plug-loads in combination with advanced control strategies and efficiency investments (such as highly efficient, high-thermal mass buildings that reduce the costs of shifting loads) (Goldenberg & Dyson, 2018).

4. Sectoral Flexible Demand Potentials

4.1. Buildings

There is a predominance of focus in the literature on the buildings sector with transportation and industry having received less of the attention. This predominance need not be viewed as evidence for priority or potential of the sectors, but is rather a manifestation of the range of options in the buildings sector that are amenable to a demand-responsive system. In this sector initiatives can be tested on a smaller scale, for example an individual household or building, or on specific types of appliances within a sample of buildings. Of all the building types, commercial buildings have the greatest potential benefit (at least in the near term) from ADR. For example, case studies in China have reported pilot project savings in the range of 15-20% peak load reductions (Samad et al, 2016).

4.2. Industry

Globally, 75% of the energy used in industry is process heat, the remainder for mechanical work. Of the process heat requirement, 30% is low temperature, 22% is medium temperature, 48% high temperature. 10% of process heat is electricity-based (IEA, 2017)). GHG reductions in the provision of thermal services require bioenergy resource development, CCS and CCU (carbon capture and use). Role of renewable in industry has received less attention than in the buildings and power sector - with the majority of attention to-date focused on energy or emissions efficiency ("emiciency").

Sources of emissions in industry (and consequently the potential for reductions) extend beyond the pure energy-related emissions and include combustion and process emissions from cement manufacturing, iron and steelmaking, and chemical production. According to the IEA (2017), reducing long-term greenhouse gas (GHG) emissions of the industry sector is one of the toughest challenges of the energy transition. However, the IEA also reports that rapid cost reductions in solar photovoltaics (PV) and wind power may enable new options for greening the industry, either directly from renewable electricity or through the production of hydrogen (H)-rich chemicals and fuels. Electrification of industrial processes, which typically have high demand capacities, offers new flexibility options to better integrate large shares of variable renewables into power grids. The 2017 report concludes that a combination of direct process electrification and use of storable hydrogen-rich chemicals and fuels manufactured from electricity may offer the greatest potential for proliferation of renewables. Electricity is costlier to store than heat, but is much easier to transport if connected to the grid. Hydrogen-rich chemicals are easier to store and transport than both heat and power, and this advantage may compensate for the energy lost transforming into these carriers.

The policy and market considerations for accelerating RE uptake in industry include national or international barriers to deployment of RE. Considerations that are of a domestic nature include energy supply regulatory regime, grid access, investment risk-reduction, mandates to utilities, technological warranties, financing of pilot projects and research and development awareness. Internationally, global agreements and co-ordination are required, but are politically challenging to implement; affordability of CO_2 emissions reductions will vary between countries. The opportunities that exist are dependent on bilateral and multilateral agreements and restrictions on trading of materials based on their associated upstream emissions.

Large power users such as aluminium smelters using electrolysis have the potential for short duration DR at low cost (with longer interruptions being intolerable) (Milligan, 2010; IEA, 2017). Power purchases account for roughly one third of the production cost for aluminium, so the presence of surplus renewables in a system can also act as a driver for new smelting processes that do not require constant power levels. Examples of applications include the US (Samad & Kiliccote, 2012) where aluminium processors can provide ancillary services through automated control (up to 70 MW of regulation) using cycling and voltage control strategies (with a estimated investment of $700,000 and return on investment in 4 months).

Storage can also help decouple power consumption from operations in the industrial sector. Various types of storage exist including electrical (batteries, flywheels, pumped hydro), thermal storage (preheating and precooling using, say ice slurries), and inventory storage (e.g. cement factories stockpiling crushed rock so that production is not affected). Of these, inventory storage is particularly useful for industrial applications where loads can merely be rescheduled, or temporarily curtailed.

4.3. Transportation

The principal focus of DR in relation to the transportation sector is on the potential related to electric vehicles. Electric vehicles are deemed to offer a highly responsive end-use, not only because they assist with integration of renewables into a grid, but also for the value in providing ancillary services. The anticipated transition to next-generation mobility depends largely on the electrification of motor vehicles and buses. While commuter and freight rail will continue to rely on grid-supplied electricity, it is the proliferation of electrical infrastructure for charging EV's that offers the most possibilities for maximising the potential benefits of energy systems that are more responsive.

In addition to offering potential GHG emission reductions (if coupled with appropriate electricity generators) and improved local air quality, EVs also offer the additional utility of electricity storage. EVs can function as a class of distributed pumped storage supplying electricity directly to distribution networks when stationary. Foley et al. (2013) ascribe EV charging into three main categories:

- Peak charging; which is uncontrolled or unconstrained and assumes vehicle owners will charge their cars immediately after arriving home from work coinciding with peak electricity consumption.
- Off-peak charging; which is controlled or delayed and assumes vehicle owners will charge their cars later to use of cheaper electricity tariffs or utility companies will use smart metering to control the charge of EVs.
- Opportunistic charging; assumes vehicle owners will charge their cars in a continuous or stochastic manner.

Charging and discharging behaviour (i.e. driver behaviour) and its concomitant effects on distribution networks is therefore important to understand and has been the subject of numerous studies (Kempton et al. 2001; Paevere et al. 2012; Ogden 2014; Markel 2015). These studies have demonstrated the value of a more detailed energy consumption time profile representation and should be pursued further in future.

4.4. Other cross-sectoral potentials and "power-to-x"

Other opportunities for flexible demands include further coupling between sectors through increased electrification of the energy system, and opportunities for producing "power-to-x" such as power-to-gas, power-to-chemicals, or power-to-liquids ("electrofuels"), using opportunistic cheaper electricity available during periods of excess renewable generation from wind and solar, often using hydrogen produced from electrolysis as the basis (Göransson, 2018; Ridjan, 2016, Tremel, 2015).

Power-to-Heat is a common candidate for coupling in countries that have high heating demands met by direct thermal fuels, while cooling using absorption chillers, and even solar thermal cooling are also gaining attention (Bloess, 2017; Yilmaz et al., 2017, IEA, 2012).

Hydrogen has also been identified as a strong candidate for reducing the carbon intensity of steel production, which in most cases uses coal both as a reduction agent and a heat source. Reduction reactions are said to contribute roughly 90% of total CO2 emissions in the ore-based steel-making production chain (HYBRIT, 2016). This method is however still largely unproven at scale and further research and development is needed.

Finally, another interesting potential for sector coupling is the flexible operation of electric loads in the water sector. Large scale desalination, water pumping, and purification/treatment all pose strong potential sources of electrical demand flexibility with the ability to assist in integrating large shares of variable renewables and reduce their significant energy related costs. (Novosel et. al., 2015; Tsai, 2016)

5. Implications of flexible demand for energy systems modelling

As flexible demand resources emerge in energy systems planning, the associated challenges of consumer behaviour, energy storage technology advancement, and intersectoral demand response linkages are attracting more attention in the literature. The ubiquitous importance of energy systems modelling as an aid to planning and decision-making is bolstered and challenged even further by the introduction of demand flexibility.

A lack of implementation experience, available data and modelling representations lead to challenges with accurately quantifying the full potential of flexible demand-side resources. Therefore, experimentation with modelling that makes provision for FD is vital to justify the cost of physical control device installation, system upgrades, market modifications, incentive design and policy measures. Such studies should not be done in isolation from overall planning and policy developments and assumptions must be continually updated and improved upon as new data and experience become available.

(DeCarolis et al, 2017) provide a timely reminder that model selection and/or design should be driven by the motivating questions. In addition, they emphasise the importance of transparency (of models and data), and the need to consider endogenous and exogenous uncertainties (with the associated impacts on conclusions drawn from the models). These questions should be the starting point rather than the pre-existence or particular functionalities of particular models being used to motivate the choice of problem to analyse. In the case of flexible demand, models need to be built based on the need to incorporate flexibility, and to evaluate flexibility options (or both). It may be that completely new modelling approaches are required to meet complex research challenges, and flexible demand is a good contender for testing this need.

5.1. Challenges in resource valuation and quantification

Although flexible demand, and in particular electrical demand response is increasing in popularity, challenges exist regarding its rollout, including for example how to determine its actual expected system value and quantify the expected total extent of the demand "resource" itself (Nolan, 2015).

Many studies investigating the benefits of demand response have investigated the integration benefit of different demand flexibility sources separately, or only for electricity in isolation from rest of the energy system. Such approaches do not reveal the inter-relating effects of programs on each other, as well as competition between alternatives such as storage, fuel-switching, or the feedback impacts from future system evolutions.

Although more complex and time consuming from a modelling perspective, it is therefore necessary to include a varied portfolio of DR resources in an evaluation study to more accurately determine impacts and benefits in a holistically integrated energy system model (Nolan, 2015; Göransson, 2014; LBNL & Olsen, 2013).

It is also necessary to incorporate the long-term planning effects and interaction with the wider energy system (not only the electricity sector), and to include future alternatives that could in-fact reduce the total availability of particular flexible demand-side resources. For example, industrial process heat requirements can make use of either grid power or alternative primary fuels. Electric water heating is a potential candidate for demand flexibility that could also be replaced with solar water heaters, or alternative heating sources such as LPG (or various combinations of these options). The same is true for potential fuel switching to gas from electricity for residential cooking or process heat for industrial uses. In northern countries, gas end-user can compete over limited resource availability with conventional flexibility provided by gas-fired generators.

The full exploitation of DR can also be limited by human behaviour (Samad et al, 2016). Demand Response "events" may result in rebound effects, where consumption in advance of the allotted down-time increases, then drops below the normal peak, then rebounds at the end of the DR event (Samad & Kiliccote, 2012). Research is consistent regarding some of the obstacles to the application of DR including operation strategies, market frameworks and lack of experience (O'Connell et al, 2014).

Currently there is a need for establishment of reliable control strategies and market frameworks necessary to make optimal use of the resource. DR potential is stunted by the two-way dependency between uptake of DR and valuation methodologies has exacerbated the data-imposed limitations. Simultaneously, a modelling paradigm has emerged that is heavily reliant on speculative assumptions (O'Connel et al., 2014).

5.2. Energy system models versus power system models

Options for extending the modelling paradigm to incorporate flexible demand include increasing computational power / efficiency, soft-linking, hard-linking different models, and heuristic approaches that incorporate flexibility requirements with simplified complexity and acceptable trade-offs between accuracy and complexity.

There are typically two types of models that are used for the modelling of energy systems with different objectives and structures. On the one hand, large scale energy system models are used for long term energy and power system evolution scenario modelling and capacity expansion planning. On the other hand, there are detailed power system models investigating the changing system and market dynamics and techno-economic operation of the system (Pina, 2011).

Furthermore, energy and power systems are complex systems, in the fact that their functioning and behaviour cannot be adequately analysed or explained by investigating their components individually. Therefore, these systems must be investigated as a whole, and their complex interactions understood, to properly understand the interrelating effects and behaviour of the complete system (Deane, 2012).

Long-term planning models generally use coarser temporal and spatial resolutions and use simplifications of the power system with a smaller number of time slices, representative of typical days and seasons. This representation is most commonly achieved with modelling software such as TIMES, MESSAGE or Osemosys. Contrastingly, detailed power system models have significantly more detail of individual plants and their operational characteristics within the system. Dedicated power system models focus on modelling system dynamics, economic dispatch, system adequacy and reliability, and have a much higher temporal resolution with significantly more detailed constraints and rules. Traditional power system models typically need to consider parameters such as ramp rates, cycling costs, integer constraints (e.g. unit size), minimum up/down times, and minimum stable generation. Typical power system models include the likes of PLEXOS or GridView (JRC, 2015; Pfenninger, 2015).

As mentioned in the introductory part of this paper, challenges arise as the structure of many electricity systems is evolving to include increasing amounts of renewable energy resources. In order to ensure that adequate system capacity and flexibility is built to accommodate these fluctuating resources reliably and economically, the combined details of energy planning models and power system models are required (Deane, 2012; Welsch, 2014; JRC 2015). Fully incorporating the detail of a power system model into an energy system model usually renders the optimisation problem excessively computationally expensive (JRC, 2015).

There are generally three ways in which this can be solved:

- Significantly increasing computational power.
- Using heuristics that can incorporate system flexibility requirements with simplified complexity and acceptable trade-offs between accuracy and complexity.
- Combining or coupling different models together and feeding modelling results between them.

5.2.1. Increasing computational power

Achieving this usually involves using cluster-based computing where scalable hardware allows significantly more computational power to be utilized by adding more processing units and breaking up the problem into sub-problems that can be run in parallel.

Depending on the size or nature of the problem, possible non-linearities, or difficulty in sub-dividing the core computational problem to be run in parallel, this may still prove to be too large to justify the cost of using the required hardware resources. Applying this method may also require specialized programming expertise to achieve – which is often not the primary specialization of energy system modelers and infrastructure planners.

5.2.2. Heuristics

Heuristic options include the use of ad hoc reserve requirements, capacity credits, LOLE calculations, stochastic programming, representative additional time slices (Poncelet et al. 2016), or relaxation of certain model constraints (JRC, 2015). Machine learning based clustering techniques used to determine representative days/hours/seasons have also been shown to be effective at reducing computation time while retaining solution accuracy, and present a strong candidate for adequately incorporating potentially decades of wind and solar data to address the issues of inter-annual variation of energy resources and demand profiles (Pfenninger, 2017).

Power plant ramp rates, cycling costs, integer constraints, minimum up/down time, minimum stable generation level requirements have been identified by many as strong candidates for details that may have minimal impact on model results, however with large impacts on computational requirements (JRC, 2015). These simplifications and their impacts, however, cannot be excluded as a rule of thumb as their impacts are invariably system specific, requiring the investigation of these constraints within each individual system context.

5.2.3. Model coupling

A technique that has been used recently to achieve the required modelling detail is that of model coupling through so-called "soft-linking" or direct integration (Deane, 2012; JRC, 2015). Typically, with soft-linking, separate models are run with the same basic data, load curve, technology costs etc., with one for long term system planning and another for short-term detailed power system flexibility analysis or any other specific sub-system focus. The long-term model is generally run first for specific years resulting in a capacity plan for that period, which is then implemented into the power system model.

The power system model then runs a more detailed analysis to check the adequacy of the system's installed capacity to meet flexibility requirements, include detailed plant operational costs and characteristics and make more accurate calculations of actual plant utilization and potential renewables curtailment. These results can then again be fed back to the system planning model to include actual expected plant run times, minimum reserve margins, resource capacity credits etc. This iterative process is carried out until results converge.

Examples of coupling include TIMES-PLEXOS Integration. The methodology implemented by (Deane et al, 2012) includes the "soft-linking" of a TIMES long term energy system mode and a detailed high-resolution power system model in PLEXOS.

Many other model-coupling implementations have been recorded in the literature, which have used numerous variations of model coupling and heuristic improvements. These can serve as a guide and methodological reference but it is important to note that results will be different for every system analysed, meaning that many simplifications and omissions that may have had little effect on accuracy may not hold for another system. Any simplifications made will have to be done weighing the potential for inaccuracy and ideally verifying all simplifications with a full detail model (JRC, 2015; Welsch 2014; Deane 2012, Seljom, 2015; Pfenninger, 2015).

The range of considerations in relation to modelling flexibility as evidenced by the detailed descriptions of the above are too numerous to describe in a brief review, however, some of the primary challenges encountered relate to (O'Connell, 2015; Brunnix, 2012):

- Mathematical representation of DR in models, for example treating demand as a negative generation asset or as a kind of proxy storage device.
- Pre-modelling concerns such as data sources, their availability and quality, and the modelling of uncertainty.
- Characteristics and physical constraints of specific demand-side resources such as energy shift limits or weather effects.
- Quantification of the available DR resources and expected market penetration/participation of programmes.
- Understanding the heterogeneity of DR resources, and grouping or clustering of demands with similar characteristics.

6. Opportunities for demand flexibility in South Africa

Advances in renewable energy technologies have created an opportunity for South Africa to transition to a low-carbon energy system without as significant of economic compromises as previously expected. This could have significant implications for future electricity generation in South Africa, where an ageing coal fleet and international climate change commitments requires the rapid scaling up of new and cleaner electricity generation capacity in the country – expected to compose largely of wind and solar PV, combined with flexible gas-fired generation and storage. While South Africa has developed a draft energy planning document for the country to 2050 (i.e. the 2016 Draft Integrated Resource Plan), the role of renewables in this is limited as a result of annual new-build limitations on solar PV and wind, particularly, as well as inadequate consideration of the rapid advances made in these renewable technologies, both globally and in South Africa. South Africa further possesses some of the best solar and wind resources in the world, with vast areas of the country suitable for generating electricity at low cost, particularly from solar PV, CSP, and wind technologies (Fluri 2009; WASA 2015; CSIR & Fraunhofer 2016).

South Africa's energy intensive industries are also being called upon to clean up their operations from an emissions perspective so will be seeking opportunities to benefit from and contribute to an energy market that is more flexible. To meet its commitments in terms of the Paris Agreement, South Africa will need greater shares of low-carbon electricity in its power system to compensate for other emissions intensive sectors e.g. coal-to-liquid fuels, iron and steel, non-metallic minerals, and the transportation sector where decarbonisation is expected to be more challenging and expensive. DR and other flexible demand resources are therefore key enablers for increased shares of renewable electricity, and therefore a low-carbon future energy system for the country.

6.1. Sectoral potentials

6.1.1. Buildings

Documented experiences with DSM, notably in the residential sector, date back to 1994 (van Harmelen et al, 1994) when innovations in decentralised energy controllers with adaptive learning, and remote ripple controllers were already being made. The aims of these innovations were to reduce the peak in the system load curve caused mainly by residential customers and avoid some of the effects of "cold load pickup". In recent years where load shedding was a concern, Eskom made use of a television-based "power alert" which communicated to residential users the need to curtail power consumption during peak periods by turning off unnecessary appliances. The incentive here was social i.e. to do what's best for the system rather than for monetary motivations at a household level. Such communication programmes are also a type of DR where the benefits can be evaluated in terms of avoided outages and reduced needs for expensive peaking generation, and the costs include customer dissatisfaction and the investment in the programmes themselves.

More recent studies show that DR is not restricted to grid-connected end-users. (Prinsloo et al, 2017) show novel approaches such as low complexity coordination framework, based on market principles, and demand response mechanisms for multi-priority grouping control of non-intelligent devices in off-grid rural village settings. Their paper considers transactive energy management principles for supply/demand coordination and demonstrates that the concept is effective in managing energy demand response and data flow dynamics in the context of rural community-based energy systems. This work shows that consideration of DR in combination with distributed renewables and microgrids in rural settings has the potential to limit the need for expanding grid infrastructure, thereby enhancing the efficiency of the energy system as a whole.

In addition to shifting the time of use of hot water load, other applications of ripple control include swimming pool pumps, streetlights and potable water pumps (Beute & Delport, 2012). Assuming such programmes are implemented with minimal inconvenience to end-users, these options have long been seen as a way of averting the need for new generation capacity, but it is not yet clear that these programmes can be implemented at scale, especially given the take up of alternatives to traditional water heating devices through the proliferation of heat pumps and solar water heaters. Regardless, as long as individual end-uses continue to require electricity, the role of load shifting options such as ripple control will continue to remain relevant.

South Africa's residential sector is also characterised by diverse groups of end-users, where energy needs and access to technologies and fuels differ dramatically between income groups. Low-income households have long been accustomed to curtailing their electricity consumption and switching to fuels such as paraffin or charcoal for cooking when they run out of money for electricity. Higher income households on the other have begun transitioning towards more efficient and grid-independent forms of water heating such as solar water heaters (with electric back-ups), heat pumps and LPG. Solar home systems, both grid-tied and off-grid with battery storage, are also increasing in their proliferation. With South Africa's high rate of electrification there exists the potential for more formalised, financially motivated programmes to involve aggregated groups of end-users in load shifting and curtailment once the technological and programmatic elements have been conceptualised.

6.1.2. *Industry*

The opportunities for DR in South Africa's industrial sector are not dissimilar from those referred to in the international literature identified earlier in this paper. To some extent these practices are already in place. Eskom already charges industrial and large commercial customers time of use tariffs as depicted by the time of use chart in Figure 1., which is already having an impact on the hourly pattern of consumption in some energy intensive sectors. Eskom has made agreements with large industrial users to curtail their load when the system is stretched to capacity (Deventer & Gaunt, 2015). However, further work can be carried out to assess the true value of these DR services to ensure they are accurately priced. There are also numerous opportunities for fuel switching in the short and medium term, as well as alternative energy storage options (e.g. ammonia and hydrogen).

Using flexibly produced electrolysis based hydrogen in direct iron reduction as mentioned above is also applicable to the South African iron & steel industry which is currently an emissions intensive sector when using coal in the process, combined with excellent solar and wind resources and potential periods of excess generation in high RE share future systems.

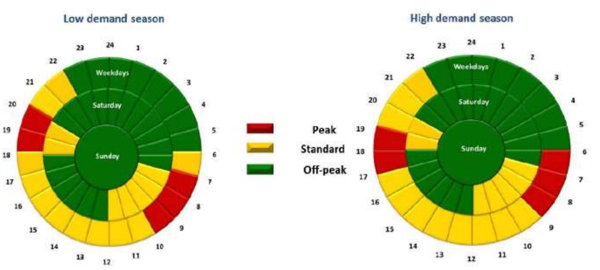

Figure 1 Eskom Time of Use Tarriffs Time Periods for Industrial and large Comercial customers

6.1.3. Transportation

With respect to DR, the main focus of attention in the transportation sector will be the role of electric vehicles. Electric vehicles charged from SA's national grid are still emissions intensive, but the flexibility of charging times also permits the inclusion of increased shares of grid-based renewables, as well as opportunities for stand-alone (non-grid) renewable installations for charging EV's. ERC modelling suggests that EVs could provide close to 20% and 5% of passenger travel and freight kilometers (predominately light commercial vehicles) by 2030 respectively with an increasing share approaching 2050 (Ahjum et al. Forthcoming).

The CSIR's (2017) comments on the Draft IRP 2016 included EVs as *"a demand side flexibility resource in the form of mobile storage"*. Modelled similarly to domestic Electric Water Heaters (EWHs).

6.2. Energy systems modelling in South Africa

This section provides a taxonomy of current energy system models in South Africa highlighting those that do or don't adequately address flexible demand, and demand in general.

Several energy models currently in use in South Africa. These include a TIMES model, which is used by the Energy Research Centre (ERC) called SATIM; PLEXOS, which is used at the Council for Scientific Research (CSIR), Department of Energy (DoE) and Eskom; and OSeMOSYS, which is used by a different division within the DoE. PLEXOS models used in South Africa are highly detailed models specifically applied to the power sector. These models contain higher time resolution for energy profiles and include detailed information on system constraints and reliability requirements. Given their fine time resolution and the focus on the power sector only, demand is often aggregated into total electricity demand, and therefore does not fully capture changes in the projected demand within individual sectors, behavioural responses to prices, or fuel switching. SATIM is a full sector energy model, which considers not only the demand for electricity and how this is met but also the demand for liquid fuels and other energy resources and how these impact the choice of fuels used within the electricity sector and vice-versa (for model and documentation: http://energydata.uct.ac.za/organization/erc-satim). In SATIM, the demand for energy services or useful energy (e.g. process heating), which has strong links to demand drivers (e.g. GDP and population), is specified. The final energy demand (e.g. the demand for electricity) is a result of the model, based on the least-cost demand technology mix (e.g. mix of boiler types or vehicle types). This provides a more holistic picture of the energy system and supply-demand interactions, allowing for endogenous fuel switching and the switch to more efficient technologies. SATIM, however, currently has a less detailed time resolution and does not currently account for certain technical constraints on the power sector such as ramp-rate constraints (although the model can be augmented to include this in future). SATIM can also be linked to an economy-wide model (eSAGE) in a version of the model called SATMGE. This allows for an analysis of the macro- and socio-economic impacts of energy decisions and investments on the South African economy. It also ensures that energy planning (in the modelling framework) accounts for the changing behaviour of agents in response to changes in the energy landscape (see Arndt et al. 2016 and Merven et al. 2017 for more details on the model).

Py-PSA-ZA is an implementation of the open source Py-PSA modelling framework focused on the South African electricity system context. It has detailed spatio-temporal representation of the power sector including spatially explicit transmission system expansion costing and optimization (Hoersch & Calitz, 2017).

These models have been used as a tool to combined Integrated Energy Planning (IEP) and Integrated Resource Planning (IRP) in South Africa. Other examples of energy models include municipal LEAP models that have been used to compile local government state of energy reports and citywide greenhouse gas emissions and scenario modelling.

SATIM potentially offers the scientific/research community a tool with unique benefits and capabilities in addressing this particular topic (likely the only model in Africa that deals with demand in sufficient detail, including disaggregated end-use useful energy demand projections while included in a full energy system planning model). Partially endogenous (supply and demand technologies), partly exogenous demand trajectory (driver-driven: GDP, population). However, SATIM would either need to be augmented with higher temporal resolution and operational constraints (e.g. ramp rates); or be used in conjunction with a more detailed power sector model, to be able to better quantify the potential value of increased flexibility for the South African Energy System. Having a good handle on the value of flexibility would make it easier to make investment and policy decisions that would support it.

6.3. Other potential considerations in South Africa

It is also worth mentioning the future system implications and opportunities as energy supply becomes more decentralised. Tendencies towards decentralisation and energy independence are particularly evident among South African municipalities who are pursuing waste to energy and wastewater to energy, installing renewable power generation at their buildings and facilities, greening of their municipal vehicle fleets, and shifting the load of high-capacity pumps to save on their operational costs in their water and sanitation infrastructure. They are challenging the current regulatory regime procuring their own renewable energy from IPP's, while paving the way for regulated embedded generation in households and commercial businesses. Local governments are set to become major participants in an energy system that is more amenable to demand flexibility. Municipalities are likely to be the actors that will be positioned to best understand the electricity demand requirements within their jurisdictions and would be key actors in incentivizing end-users to participate in demand flexibility programs. They can then also act as aggregators enabling them to provide predictions of firmly "dispatchable" demand resources to the centralised generation and transmission system operator.

Recent advances in distributed energy costs, mini-grid technology and innovative business models have made decentralised solutions a strong and economically viable opportunity for rural electrification as it avoids expensive MV network extension, purchases from Eskom and allows new smart-grid networks to be developed. The latter will increase the share of low-carbon electricity generation if renewable; provide local clean jobs; allow the potential for future grid-interconnection to strengthen end-of-grid networks; and allow flexible resources to balance supply (ERC 2017; Carbon Trust 2017).

7. Conclusions

One of the conclusions emerging from international research e.g. (JRC, 2015) is that there needs to be a mapping between flexibility needs and best practice for modelling in the context of rapidly evolving global energy system. The prevailing approach in recent years (although EU-focused) has been to combine large energy system models to sector-specific models, in spite of the technical issues and the need to manage trade-offs between model simplicity / coarseness and the accuracy and reliability of model results. Open source approaches and publicly available data are seen to be a key enabler of future model development. Further Investigation is required to determine the applicability of enablers such as blockchain platform for managing congestion, power quality and reliability.

Regarding the South African context, this paper has revealed the following research and modelling challenges. it is recommended that future areas of exploration include:
A full taxonomy of the range of fuel switching options in various sectors, as well as intersectoral linkages.

- Flexible electric load potentials and programme designs under a smart-grid paradigm.
- Behind-the-meter energy supply and storage technology investments and their impact on overall system efficiency, costs and equity.
- Electric mobility and impacts on the transportation sector.
- Interrogating the value and trade-offs of increased time slice resolutions when incorporating demand flexibility.
- Understanding the nature of feedback loops and causal dynamics that exist between flexible demand resources themselves, and to a system with increased shares of renewables.

This review has also reveals that that attempts to add flexibility to energy system models will add to the existing challenges that modelers face with regards to:

- Insufficient temporal and spatial resolution in their models
- Problems with data sources (accuracy, sample size, contextual applicability)
- Modelling multiple combined potentially competing or complementary flexibility options simultaneously with an appropriate level of scope and complexity.

Only after evaluating the expected achievable potential of demand flexibility in the full energy system, can justifications be made for large scale DR investment, program implementation and inclusion in long-term energy planning policy. A lack of experience in DR programs worldwide and the need for development of accurate system wide modelling representations still causes significant uncertainty of the value of potential DR programs (US DoE, O'Connell; 2014; Nolan, 2014; Nolan, 2015; Samad, 2015).

This paper has endeavored to provide an informed foundation upon which to build demand flexibility into energy systems modelling and analysis in South Africa. However, in order to realise the numerous claimed potential benefits of demand-side energy resources, ongoing work is needed to address the remaining challenges faced with appropriately quantifying the total resource potential. This includes understanding the technical characteristics of flexibility, as well as the how to incorporate these new resources in combined system value studies utilizing evidence based integrated energy system models.

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