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Review

Demand-Side Management as a Network Planning Tool: Review of Drivers, Benefits and Opportunities for South Africa

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Abstract: The reliability and security of an electric power supply have become pivotal to the proper functioning of modern society. Traditionally, the electric power supply system has been designed with the objective of being able to adequately meet present and future demand, with efforts to maintain supply reliability being focused primarily on the supply side. Over the decades, however, the value of demand-side management—efforts focused on enhancing the efficient and effective use of electricity in support of the power system and customer needs—has been widely acknowledged as being able to play a greater role in ensuring that the key objectives of power system operation are satisfied. This article presents a study of demand-side management and opportunities for incorporating it into network planning as an effective means of addressing supply capacity constraints in the South African electric grid. The main drivers, benefits and potential barriers to the effective implementation of demand-side management are examined, along with the main enabling technologies. The key finding of the study is that the effective integration of demand-side management into network planning requires a shift from the traditional network planning approach to one that is more suited to fully exploiting the flexibility resources available on the demand side of the network.

Keywords: demand-side management; DSM drivers; enabling technologies; network planning

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1. Introduction

The electric power supply system serves a critical functionality in modern society. Its primary operational objective is to be able to match the generated power to the load demand at all times. Secure, reliable, economic, efficient and sustainable operation are other key objectives for power system operation. Traditionally, efforts to realize these technical and economic operational objectives have almost entirely concentrated on the supply side of the power system, that is, the whole electrical infrastructure that is involved in the generation, transmission and delivery of electrical power to the end-users [1]. Over the past few decades, however, attention has increasingly been given to the potential role that the demand side (i.e., the consumer of electricity) can play in the secure, reliable and efficient operation of the power system. The concept of demand-side management (DSM) largely originated in the U.S.A. in the 1970s, in response to growing energy security concerns as well as the environmental impact of electricity generation, especially nuclear power [2]. Its evolution was influenced by a combination of political, economic, social, technological and resource supply factors that significantly impacted the electricity sector's operating environment and its outlook for the future [3]. The ensuing decades witnessed many developments, including the deregulation of the electric power supply industry that introduced competitiveness and a heightened focus on greater efficiency and economy of operation, the proliferation of decentralized and variable renewable energy generation integrated into the distribution network and technological advancements that spurred efforts to evolve the legacy electric grid into a modern smart grid [4–6]. In this context,

DSM has been viewed as having the potential to play an increasingly important role in supporting the electric grid modernization efforts [7].

DSM refers to a variety of schemes and mechanisms, mainly implemented by the electric utility, meant to influence customers' energy use patterns in an effort to achieve a more desirable utility's load shape, in terms of the load's time pattern and/or its magnitude [3]. Electric power systems in many parts of the world are faced with a variety of challenges. Growing energy demand coupled with the increasing cost of building new generation, transmission and distribution infrastructure is compelling many system operators to operate the power system closer to the system capacity limit. This leads to the system being overstressed and increases the cost of the electricity supply due to the need to frequently run expensive peaking generation [1]. The increased uptake of variable renewable generation at large scales due to environmental and energy security concerns is having a significant impact on the dynamics of power system operation, leading to a greater need for operational flexibility and control. DSM is anticipated to play a greater role as a flexible resource that can support the system operator in addressing these and other challenges to ensure the system is operated as reliably, efficiently and economically as possible [8]. DSM programs are mainly aimed at modifying the behavior of electrical loads of the various customer types (industrial, commercial and residential) in an effort to optimize energy production costs and enhance energy utilization, leading to improved system reliability. They may even enable the deferring of network reinforcement by diminishing the peak capacity requirements of the network when managed effectively [9].

This article presents a literature survey of various aspects of demand-side management. An overview of demand-side management is presented in Section 2, outlining the historical development of the concept and the implementation aspects as well as highlighting the drivers, benefits and potential barriers to the implementation of demand-side management. The effective implementation of demand-side management requires a variety of supporting structures, which are discussed in Section 3. Section 4 then presents a sample of examples of demand-side management initiatives from different parts of the world, as have been reported in the literature. The impact of demand-side management on network planning is the focus of Section 5, which also discusses how it could serve as an effective mechanism for addressing the growing challenge of the electricity supply shortage in South Africa. Section 6 concludes the review with a summary of the key points and some recommendations for further study.

2. Overview of Demand-Side Management (DSM)

2.1. Historical Development of DSM

Demand-side management, as an alternative to supply-side management for the purpose of achieving least-cost electrical energy provision, grew steadily in the U.S.A. in the 1970s out of increasing concern over the reliance on foreign sources of fossil fuels and awareness regarding the environmental consequences of electricity generation [2]. The growth and popularity of DSM programs among U.S.A. electric utilities were largely fueled by favorable regulatory policies that provided the regulatory environment and incentives that encouraged the pursuit of least-cost or integrated resource planning principles on the part of the utilities. The development and evolution of DSM over the decades has been highly influenced by political, economic and regulatory factors, as well as public–private interests of the stakeholders.

Although the importance of influencing consumer energy use behavior (by means of the proper choice of energy-consuming devices and appliances and their appropriate usage) was long recognized, a holistic approach in the form of a DSM framework had not really been developed until the late 1970s. The development of this framework enabled addressing such questions as [3]:

- Considering the current set of resources available or under consideration, what changes in consumer demand patterns would be of benefit to the consumers and to suppliers?

- Which end-use technologies or changes in consumer behavior are likely to yield those changes?
- What market implementation methods would be needed to influence consumer preferences and behavior to produce the desired result?

Thus, rather than look at energy efficiency, load management and other related initiatives as independent tools, the DSM framework would provide a holistic and logical approach to implementing all initiatives meant to positively influence electricity consumption behavior in order to achieve the desired objectives. Early attempts to manage demand for electricity included the use of price as an incentive (i.e., time-of-use pricing), technologies such as thermal energy storage (i.e., storage water heating) and direct load control, being one of the most prevalent [10].

South Africa has historically enjoyed an abundant electric energy supply, but early in 2008, the country was faced with an acute power supply deficiency problem caused by a combination of supply-side problems that included coal availability, maintenance needs and unplanned outages, leading to a drastic fall in reserve margins. Energy efficiency and demand-side management measures were identified as an immediate and effective means of addressing the power supply inadequacy problem [11]. Indeed, a number of policies have been formulated in the recent past that were directly intended to address the issue of energy efficiency and demand-side management. For example, the "Regulatory Policy on Energy Efficiency and Demand Side Management for South African Electricity Industry" of 2004 [12] provided the regulatory framework for the implementation of energy efficiency and demand-side management as a means of addressing the anticipated peak generation capacity constraints. As the power supply shortages have intensified in recent times, Eskom (the national electric grid operator) has been placing greater emphasis on demand-side management, seen to be a "win-win situation—reducing pressure on the power system and enabling customers to realize cost savings by being more energy-conscious and reducing their consumption without affecting business productivity or quality of life" [13].

2.2. Implementation of DSM

DSM encompasses a variety of (largely) utility-centric initiatives that range from educating and sensitizing customers regarding the efficient and conscientious use of energy to offering a variety of incentives that are aimed at realizing an improved load shape. The main categories of DSM programs are [2]:

- General information educating customers regarding the effective use of energy
- Advisory technical support, including energy auditing and making recommendations for improvement in energy use
- Financial assistance in the form of loans or direct payments to support investment in energy-efficient technologies
- Direct or free installation of energy-efficient technologies
- Performance contracting, whereby customers get into contracts with utilities to guarantee a certain level of energy performance
- Load control or load shifting, where customers consent to having their energy-consuming devices remotely controlled by the utility in return for financial incentives
- Innovative tariffs, such as interruptible rates, time-of-use rates and real-time pricing, which are meant to improve the levelized cost of electricity supply

The choice of which of these DSM programs to implement in any given context is largely a function of political, socio-economic and regulatory factors, among other considerations. Some DSM programs are geared towards promoting energy efficiency; others target achieving desired load shapes, such as peak-load reduction or load shifting. Broadly speaking, DSM initiatives can be classified into two main categories, based on how load changes are induced [14]:

- Incentive-based DSM schemes are programs facilitated by utilities or energy service providers, which essentially incentivize customers to reduce their energy demand,

who then receive compensation for their participation. Reliability conditions or price conditions may trigger the need for load reduction.

- Price-based DSM schemes attempt to induce changes in customer energy usage patterns by means of changes in the price of electricity. This encompasses real-time pricing, critical peak pricing and time-of-use rates. The premise for the use of price-based DSM schemes is that if the price differentiation for different time periods is significant enough, the customers are likely to respond by altering their energy use so as to take advantage of lower-priced periods, thereby reducing their energy bills. Of course, customers may also choose to continue with their normal routine of energy consumption, so participation in this type of DSM is categorized as voluntary.

2.2.1. Incentive-Based Schemes

- Direct load control (DLC) is a program whereby the system operator remotely controls the on/off state of a customer's electrical equipment (e.g., space heating, water heater, air conditioner) on short notice. These programs are primarily implemented in the residential and small commercial customer segments
- Interruptible/curtailable programs offer customers a rate discount or bill credit for agreeing to reduce the energy demand during system contingencies. The customer usually incurs penalties for failures to adhere to the curtailment arrangements. These schemes are typically implemented in large industrial and commercial customer segments

2.2.2. Market-Based Schemes

- Demand bidding enables customers to offer bids to curtail their energy demand based on the wholesale electricity market prices or the equivalent. This scheme is normally open to large industrial customers with a high demand (i.e., with a megawatt (MW) demand threshold specified by the system operator)
- Emergency demand response (DR) participation is offered to customers who can effect load reduction in exchange for agreed-upon incentives during periods of system constraints, such as reserve shortfall, which may endanger the security of supply
- Capacity markets are where customers offer load curtailment as a system capacity to substitute for conventional generation or a lack of transmission capacity or other delivery resources. Prior arrangements are usually made between the system operator and the customer in terms of when the service might be required. Failure on the part of the customer to deliver the service as per the contract usually incurs penalties
- Ancillary service markets are programs where customers bid load curtailments in the ISO/RTO (independent system operator/regional transmission organization) markets as operating reserves. If their bids are accepted, they are paid the market price for committing to be on standby. If their load curtailments are needed, they are called upon by the ISO/RTO to deliver and may be paid the spot market price for the delivered energy

2.2.3. Price-Based Schemes

- Time-of-use (TOU) pricing applies rates with different unit prices for energy consumption at different times. This is usually pre-determined for a 24 h day. TOU rates are meant to reflect the average cost of generating and delivering power during different periods of time
- Real-time pricing (RTP) is a form of rate in which the price of electricity tends to fluctuate at a predetermined time interval (usually hourly), reflecting changes in the wholesale price of electricity at different times of the day. The RTP prices are normally communicated to the customers ahead of time, which could be on a day-ahead or hour-ahead basis
- Critical peak pricing (CPP) rates combine the TOU and RTP rate designs. TOU constitutes the base rate structure, and a provision is made to replace the normal peak price with a much higher price under specified anomalous conditions (e.g., when

there is a threat of system reliability being compromised or when supply prices are excessively high)

- Extreme day pricing (EDP) is similar to CPP (in having a much higher price than normal) and differs in the sense that EDP is in effect for the whole 24 h of the extreme day and is unknown ahead of time [15].

2.3. Drivers for DSM

The primary driver for demand-side management is to enlist the support of customers in optimizing electric energy production costs and enhancing energy utilization, which in turn contributes to energy security and reliability. There are, however, many other factors that may act as drivers for the implementation of demand-side management, some of which are listed in Table 1 [1]:

Table 1. Drivers for demand-side management.

Driver	Description
Economical	The opportunity to exploit demand elasticity to reduce electricity prices
Social benefits	Efficient end-use of energy can have many benefits for the public
Environmental	Enhanced energy efficiency and energy resource utilization can help reduce greenhouse gas emissions and the overall negative ecological impact of energy production and utilization
Customer choices	Providing customers with additional choices and opportunities to take an active part in network management can have both technical benefits for the network and economic benefits for the customers
Enabling technologies	Technological advancements facilitate the effective implementation of demand-side management and thus encourage its full exploitation
System stability	The need to more effectively manage the growing share of non-controllable generation in the network requires the flexibility that can be provided by demand-side management
Network	The opportunity to address network constraints with the aid of demand-side management
Educational	The opportunity to educate energy consumers about the technical and economic aspects of energy production and delivery, and the positive contribution they can make to managing the system more effectively

2.4. Benefits of DSM

The electricity supply sector has many stakeholders, including transmission and distribution system operators, electricity market operators and balance responsible parties (BRP), energy service providers, energy traders, suppliers, traders and retailers, manufacturers, customers, policymakers and regulators, among others. All these stakeholders can derive benefits from the effective implementation of demand-side management:

- Transmission and distribution system operators can take advantage of the flexibility provided by the demand response to realize improved system stability in the face of the higher penetration of variable renewable generation, improved congestion management and a decrease in network bottlenecks that may be caused by sustained peak demand. Demand-side management may also contribute to improved voltage regulation and overall power quality
- Electricity market operators may encourage customer active participation, which would lead to more efficient market operation, lower electricity prices and greater innovation in the way of supporting technologies to enhance market operations. Balance-responsible parties may also welcome the opportunity to engage active customers in the balancing markets

- Energy service providers, traders, suppliers and retailers may benefit from providing customer access to the electricity markets in the form of platforms, technologies and products that enable customer participation in electricity markets
- Customers may derive economic benefits from demand-side management, which makes a variety of choices available for better managing energy usage, as well as actively participating in network management by means of taking part in various system operator-driven demand-side management initiatives
- Manufacturers may benefit from the opportunity provided by demand-side management to develop new products and technologies in support of the effective implementation of demand-side management
- Policymakers and regulators have a major role to play in the realization of demand-side management initiatives. They may also benefit when the successful implementation of these initiatives leads to technical, economic, social and environmental benefits, which is their ultimate goal
- Demand-side management may also offer an opportunity for new entrants in the electricity supply sector, as new and innovative paradigms are discovered for the most effective means of exploiting demand-side resources. For example, aggregators, advanced ICT and advanced metering infrastructure service providers will play an increasingly greater role in the actual implementation of various smart grid initiatives, among them being demand-side management and the demand response.

With so many stakeholders and potential benefits, the main challenge regarding demand-side management may lie in the development of business cases that properly weigh all the costs and benefits of implementing demand-side management, also considering the possible impact of the market structure and other supporting infrastructure. This is likely where policy and regulation may play a pivotal role, although there are many other factors that may be equally decisive in the development and effective implementation of demand-side management. Some of these are highlighted in the following section.

2.5. Barriers to the Effective Implementation of DSM

A number of factors can act as barriers to the effective implementation of demand-side management, and include technical, structural, regulatory, educational and financial/economical barriers, as further elaborated on in Table 2 [1].

Table 2. Potential barriers to the effective implementation of demand-side management.

Type of Barrier	Description
Technical	• Lack of suitable technological infrastructure (e.g., control, monitoring and advanced metering infrastructure) • Rapid changes in technological innovation may lead to uncertainty in terms of the most appropriate time to invest • The heterogeneity of technologies makes integration challenging, especially with the need for a high degree of integrity in electric energy systems • Lack of standardization of communication, grid–code interconnection and other relevant standards (e.g., metering infrastructure standards)
Structural	• Form of market structure that may be unconducive for promoting demand-side management (e.g., a traditional vertically integrated market structure) • Poor accessibility of small customers to electricity markets; this may be tied to the non-availability of new types of stakeholders, such as aggregators and energy service companies • Lack of suitable business models which may exploit available demand-side resources

Table 2. *Cont.*

Type of Barrier	Description
Regulatory	• Inadequacy or a lack of a regulatory framework may impede the development of demand-side management • Lack of relevant business support structures backed by regulation may also adversely impact the development of the business case for demand-side management
Educational	• Lack of awareness on the part of customers regarding the opportunities for monetizing demand flexibility, or a lack of understanding of the potential financial and technical benefits of exploiting such flexibility
Financial/economical	• Absence of economic incentives (or the unattractiveness thereof) which would encourage customer participation in demand-side management initiatives • Lack of understanding of the compensation structures in place for participation in demand-side management
Traditional	• Belief that the demand-side resources are not as effective in providing system services as supply-side resources are • Insufficient knowledge and understanding on the part of customers regarding new technologies employed in demand-side management, the workings of rate structures and related services

3. Supporting Structures for the Effective Implementation of Demand-Side Management

3.1. Enabling Technologies

Demand-side management as a technological evolution can be viewed in the larger context of the smart grid. A smart grid has been defined by the European Commission's European Technology Platform [16] as: "An electricity network that can intelligently integrate the actions of all users connected to it—generators, consumers and those that do both—in order to efficiently deliver sustainable, economic and secure electricity supplies." Many other authoritative bodies and organizations in the electric power system sector have given other variants of the definition of the smart grid (e.g., the International Electrotechnical Commission (IEC), the Institute of Electrical and Electronic Engineers (IEEE), the US Department of Energy, etc.) At the core of the smart grid is the use of Information and Communications Technologies (ICT)-based innovative technologies to provide the electric power system with the intelligence necessary to effectively integrate the heterogeneous components (among them, demand-side resources) that need to seamlessly interoperate in order to deliver electricity reliably, securely, affordably, efficiently and sustainably. Some of the key enabling technologies include [17]:

- Information and communication technologies (ICT)
- Grid monitoring and control technologies
- Advanced metering infrastructure and smart meters
- Smart sensor and actuator networks
- Intelligent electronic devices

Information and communications technologies, as well as grid monitoring technologies, are briefly discussed in the following sub-sections.

3.1.1. Information and Communication Technologies (ICT)

The realization of demand-side management objectives, such as flexible consumption patterns responsive demand behavior and active demand participation in energy markets, requires the evolution of new metering, control and information management technologies that will support the needed functionalities. By availing customers with information such as near-real-time meter readings and real-time pricing data, they can become more aware of the relationship between the level of demand and the cost of electricity supply, on the basis of which they can decide whether to modify their energy consumption patterns or

to carry on as normal. ICT technologies facilitate the implementation of DSM schemes in the sense that automated systems can be used to make consumers aware of opportunities to participate in such schemes, and their response or participation can also be automated or carried out manually. The main functionalities required to be provided by the ICT infrastructure for the purpose of implementing DSM include [1]:

- Notification
- Measurement
- Compliance
- Settlement
- Automated controls

Some form of notification is required to make consumers aware of opportunities to participate in DSM. These notifications may take many different forms, direct or indirect, passive or active. The medium of delivery of the notifications has to take into account such factors as the volume of notifications that must be delivered (i.e., the number of participants and their geographical spread), the speed at which the notifications have to be delivered and the extent to which customer responsiveness is required (for example, whether it is voluntary or mandatory). Manual notification systems (such as telephone calls or electronic messaging) have traditionally been used for some DSM schemes in the past. These may be suitable when the speed of response is not required to be very fast, and the level of customer participation is low to moderate. In cases where the participant count is very high, however, an automated notification system may be more convenient and more effective. Technological advancements in the way of information and communications technologies are facilitating the implementation of such automated systems, which would otherwise have been technically difficult or economically prohibitive to implement in the past. Automated systems also facilitate improved record-keeping and tracking of how effective the schemes are in engaging customer participation and are especially useful where mandatory compliance may need to be enforced.

Measurement of customer participation in (i.e., their contribution to) DSM is important, both for assessing compliance (where there are contractual obligations) and facilitating settlement for the rendered service. The measurement mechanism has to enable differentiating between the "normal" consumption and the DSM-induced consumption modification, on the basis of which the customer has to be compensated. This depends on the design of the DSM scheme, as not all DSM schemes involve direct compensation. In a time-of-use rate or real-time pricing DSM mechanism, for example, it is the customer's energy use pattern modifications that will directly impact the energy bill, without the customer having to receive direct compensation for participating in the DSM scheme. Measurement can take many forms and will depend on requirements such as volumes of data, the frequency of data transmission, the granularity of data (in terms of time intervals) and the desired speed of response.

A means of assessing compliance is needed in order to establish the performance level of the customer and to determine the extent to which they are honoring their contractual obligations, where this is applicable. One methodology used in establishing compliance is referred to as the baseline methodology, which involves estimating customer "normal" consumption and then compensating them on the basis of the variation between the estimated "normal" consumption and the actual consumption (assuming there is a reduction in the actual consumption relative to the one deemed normal). In the case of on-site generation that the customer wishes to bid as a demand-side resource, it is common to use a direct meter that measures the generator's actual output, which is then used to determine compliance. Where real-time pricing is used as the DSM mechanism, compliance is not necessarily required to be determined, since this is a more direct mechanism for inducing customer energy consumption modification, and the customer is simply charged the hourly energy price based on their magnitude of consumption.

A settlement system is required, which acts as a means to credit the customers participating in the DSM schemes. The system provides facilities for the maintenance of

meter usage, market pricing, event compliance levels and individual contract terms. Large consumers who have direct access to the wholesale electricity markets receive a direct settlement from the wholesale market. For the majority of DSM participants, however, their participation may be facilitated by such entities as aggregators, distribution companies, or energy service providers, among others. Settlement for the rendered service in that case is a two-step process: from the wholesale market to the DSM scheme facilitator (e.g., aggregator), and then from the DSM facilitator to the participating consumer. The settlement system design has to provide for delineating between these stages of settlement.

Automated controls enable DSM schemes where the utility operator or other service provider is able to remotely and automatically control predetermined loads. This is commonly applied in the residential demand sector. The loads that are typically controlled this way include heating, ventilation and air conditioning (HVAC), electric water heaters, pool pumps and lighting. Automated controls may also be found to a somewhat lesser extent in the commercial sector, with the typical remote load control technology being lighting control. Building automation control technologies exist, which enable systems to be programmed so as to respond to electricity price signals rather than simply demand levels. Thus, they are able to adjust the energy consumption levels at times when the predetermined settings indicate that electricity prices are in excess of predefined thresholds.

3.1.2. Grid Monitoring and Control Technologies

A modern integrated power system requires high-level surveillance, monitoring and control in order to maintain the desired level of security, reliability, efficiency and quality of power supply. The main components of the modern power system include the bulk generation, transmission and distribution systems, as well as electricity markets, operations, utilities and end-consumers. Grid monitoring and control requirements are differentiated by the part of the system of interest. The transmission system, as the backbone of the entire interconnected power system, for example, requires advanced technological tools for various analytics such as real-time stability assessment, robust state estimation, dynamic optimal power flow, contingency analysis and security assessment. Key technologies employed in these analyses include phasor measurement units (PMUs), state estimators, advanced metering infrastructure and smart meters, smart sensors and actuator networks and intelligent electronic devices (IEDs). The distribution system acts as the interface for industrial, commercial and residential consumers of the bulk electric power supply system. The main monitoring and control needs at this level include smart metering, automated meter reading and automatic billing, fault detection, isolation and service restoration, feeder reconfiguration, voltage optimization and demand-side management. The key objective in the implementation of advanced technological and analytical tools in the entire electric power supply chain is to realize a self-monitoring, self-healing and resilient smart grid network that is self-aware and is capable of taking actions independently on the basis of situational awareness.

3.2. Market Structures

An electricity market structure refers to the way in which stakeholders in the electric power system interact to produce and deliver electricity to the end customer. The key stakeholders or sectors in the electric power supply chain are generation, transmission, distribution, system operations, wholesale markets and retail supply. Four main market structures can be identified, which are [18]:

- Vertically integrated monopolies
- Unbundled monopolies
- Unbundled electricity market, with limited competition
- Unbundled electricity market, with full competition

The vertically integrated monopoly structure is the traditional system where the electric utility controls and undertakes all of the functionalities of the electric power supply system, including generation, transmission and distribution. The structure does not have

an open electricity market, meaning there is no competition in the delivery of the various electricity supply-related services.

An unbundled monopoly is similar to a vertically integrated monopoly, the main difference being the separation of generation from all other functions of electricity supply (i.e., transmission, distribution and wholesale and retail markets). This structure also does not encourage competition, except at the generation level, where large generators can compete to supply to distribution companies, and perhaps large industrial consumers as well.

An unbundled electricity market with limited competition introduces a competitive wholesale electricity market, where many different generation companies bid to supply to electricity distributors, and possibly large industrial customers as well. In this structure, generation companies have open access to the transmission and distribution systems, and there is competition for the supply of generation at the marginal cost of supply. Depending on the size, the wholesale market may also be open to self-generating large consumers and independent power producers.

In an unbundled electricity market with full competition, all the major sectors of the electricity supply system (i.e., generation, transmission and distribution) are separated, and there is competition at all levels, that is, wholesale and retail markets. This structure is considered to be the most advanced in terms of embodying the objectives of modern deregulated power systems with open access to electricity markets [1].

The market structures described above can be distinguished by the degree of unbundling and the extent of competition in the wholesale and retail electricity markets. In terms of the implications for demand-side management, the unbundled electricity market with full competition is the one that is most likely to fully exploit the potential of demand-side management to contribute to efficient network operation. Power systems in developed countries such as the U.S.A. and European countries have largely reached this highest level of unbundling and competitiveness of electricity markets.

3.3. Policies and Regulation

One of the major issues or challenges in the development and implementation of DSM is the implementation of various policies and regulations. Establishing a unified standard policy system that addresses various aspects of DSM development has been a challenge because of the variation noticeable in regions. The imbalance in the regional development of DSM can be attributed to different key factors. First, there are significant disparities in economic development and energy utilization across different regions, leading to variations in the progress and implementation of DSM initiatives [19]. Second, there are notable variations in the development of DSM across different industries. DSM encompasses multiple sectors, with heavy industry being a major consumer of power and a key focus area for DSM implementation [20].

Due to the regional imbalances in DSM development, it is challenging to establish a unified DSM mechanism and formulate standardized policies. Power grid companies often face resistance from local governments when implementing DSM due to the lack of a cohesive approach. Addressing the imbalance in short-term development is difficult, necessitating a long-term vision. Consequently, it is crucial to establish a long-term DSM policy mechanism that gradually promotes the balanced development of DSM across regions. These policies create a favorable environment for DSM development and play a significant role in facilitating and guiding the implementation process. Countries such as China have formulated new policies to support the development of DSM. One such regulation was the Power Demand Side Management Regulation, which provides clarity on the scope of work and identifies the primary implementing body and liability subject for Demand-Side Management (DSM). It also addresses organizational management, technical measures, power pricing, funding sources and other relevant aspects. The regulation's provisions ensure the smooth implementation of DSM initiatives [20].

3.4. Demand-Side Resources

In principle, demand-side management is aimed at somehow shaping the load profile in a way that leads to an improvement in the technical and economic operation of the power system and increases the security and reliability of supply. This is mainly achieved by inducing energy consumers to modify their energy consumption behavior so that the load can "follow" the generation to some extent, which is the opposite of the traditional approach to supply–demand balance, where the generation has to follow the load.

Demand-side resources encompass more than just energy-consuming devices and equipment. With the significant progress made in the integration of distributed energy resources into the distribution systems, these are generally considered to form part of demand-side resources, to the extent that they are largely not under the direct control of the utility operator. Distributed energy resources (DERs) comprise conventional and non-conventional distributed generation, renewable energy sources (such as photovoltaic and wind) as well as energy storage [21]. DERs are anticipated to have an increasingly large contribution to distribution system operation. The high penetration of distributed generation—and especially variable renewable generation—in the distribution network is another factor that increases the need for flexibility resources in the network. This is mainly due to the fact that the DERs are not under the direct control of the utility operator, and thus they are considered to be non-dispatchable in the traditional sense of dispatchability. In other words, their behavior is to a large extent unpredictable, at least from the perspective of the utility operator. Moreover, for variable renewable generation, such as solar and wind generation, the output is intermittent and cannot be accurately predicted ahead of time. Thus, by implementing effective demand-side management and demand responses, the potentially adverse impacts of the DERs on network operation can be partially alleviated, in addition to the main objective of load shaping and load levelling that demand-side management is intended to accomplish [3]. This in turn can enable the integration of more variable clean energy into the electric grid, which is one of the main objectives of modernizing the electric power system, leading to higher energy security and an environmentally sustainable energy supply [9].

4. Some Examples of Demand-Side Initiatives around the Globe

4.1. State of the Art in Demand-Side Management

Utilities can improve their ability to regulate energy consumption, ease peak demand, incorporate renewable resources and ensure grid reliability by categorizing DSM programs based on the technology they use and the accompanying grid services they provide. This strategy not only allows customers to be active participants in energy management, but it also lays the groundwork for a more sustainable and resilient energy future. As technology advances, so does the possibility for novel DSM solutions that form a more sustainable and efficient energy landscape. These programs have been categorized as:

- Energy Efficiency: these are DSM programs that are designed to promote the adoption of Energy Efficiency (EE) technologies and behaviors that provide incentives for the utilization of energy-efficient equipment, such as HVAC systems, lighting and appliances. These incentives can be in the form of rebates offered at various stages of the supply chain, including upstream, midstream and downstream. Moreover, there are additional EE initiatives encompassing personalized rebates, programs centred around behavioral changes, strategies for retro-commissioning and approaches for new construction projects.
- Demand Response: an end-use load profile can be adjusted in response to system requirements by the end-user, a third party or a utility, frequently in exchange for economic incentives such as payments or changing rate structures. This mechanism entails the use of control technologies such as smart thermostats, direct load control switches, plug load controls or automated demand response (ADR) technologies, as well as behavior-driven demand response (DR) programs. While the bulk of DR programs are primarily concerned with regulating heating and cooling use, some

utilities offer bespoke rebates to business clients that implement other ADR-enabled solutions and commit to participating in DR programs. In addition, behavior-based programs are offered in the menu of options.

- Distributed Generation: these programs provide financial incentives, rebates and grants to utility customers who install Distributed Generation (DG) technologies on their premises. These technologies include photovoltaic (PV) systems, fuel cells, combined heat and power (CHP) systems and small wind turbines. The aim is to encourage the adoption of clean energy solutions and decentralize power generation.
- Electric Vehicle: these initiatives offer incentives, rebates or specialized time-based rates to promote the adoption of Electric Vehicles (EVs), EV chargers and grid-integrated smart chargers. Additionally, they encourage specific charging behaviors that mitigate the load impact on the distribution system. The focus is on encouraging sustainable EV charging practices while also optimizing grid management.

Several of these initiatives incorporate storage technologies and Time-Based Rates (TBR) to optimize energy management. The success of implementing these programs has effectively addressed certain market and policy obstacles that previously impeded the adoption of Demand-Side Management (DSM) strategies. These barriers included challenges related to securing program funding, dividing program administration responsibilities, synchronizing program cycles, establishing consistent cost-effective methodologies and overcoming resistance to participating in Demand Response (DR) efforts. The triumph of these programs has demonstrated the capacity to surmount these hindrances and promote effective energy management practices.

4.2. Demand-Side Management Initiatives around the Globe

4.2.1. Europe

The European Union has long recognized demand-side flexibility, empowered through demand response, as a critical resource for achieving a low-carbon, efficient electricity system at a reasonable cost [22]. This recognition has led to the Union developing a number of policies in support of demand-side management and energy efficiency, such as the Energy Efficiency Directive. Demand response is viewed as an important enabler of the security of supply, the more effective integration of renewable energy, improved market competition and customer empowerment. It has consequently become an integrated component of Europe's efforts to lower energy costs, support clean energy resources and address climate change concerns. There are wide-scale efforts to support the development and implementation of demand-side management in Europe at a national level. As a representative example, the United Kingdom (UK) is considered in this section.

The UK is one of the European countries that have made the greatest advances in the development and implementation of demand-side management and demand response. The country has a fully liberalized and privatized electricity market that can be regarded as being highly reliable [23]. A lot of progress has been made in incorporating demand-side flexibility into electricity markets. This encompasses flexible demand, energy storage as well as distributed generation. Demand-side flexibility is able to participate (either directly or via aggregation) in various electricity markets, including the balancing and capacity markets. Direct participation is possible for large industrial and commercial customers, which make up about 90% of the total estimated demand-side flexibility, whereas small to medium enterprises and residential customers may participate via aggregators [24]. The need for flexibility in the UK electric grid is increasing as renewable generation capacity has been growing at a rapid pace. The UK has the largest installed capacity of offshore wind generation in the world. The intermittency of this form of generation increases the need for flexibility resources, including demand-side flexibility [25]. Demand-side flexibility providers are able to participate in a variety of balancing markets, such as frequency response, reactive power services, short-term operating reserves (STOR) and demand-side response.

4.2.2. U.S.A.

The U.S.A. has been at the forefront of developments in demand-side management and demand response since the 1970s. The term demand response was popularized by the U.S.A. Energy Independence and Security Act, which was generally defined as including programs and activities that reduce peak demand via the use of dynamic pricing, advanced metering infrastructure and enabling technologies [3]. As per the estimates of the U.S.A. Energy Information Administration, over 9 million customers were enrolled in demand response programs in 2014, as depicted in Figure 1 [26]. Demand-side management and demand response initiatives have a significant impact on the peak demand in the U.S.A. Figure 2 depicts an estimate of the percentage peak demand savings from demand response in various U.S.A. electric utilities [27].

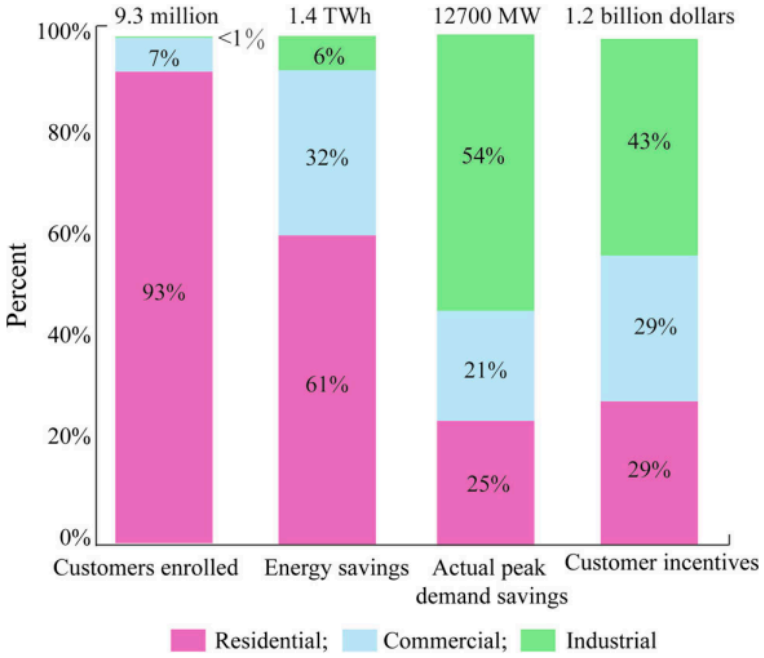


Figure 1. Sectorial composition of the U.S.A. demand response programs (source: [26]).

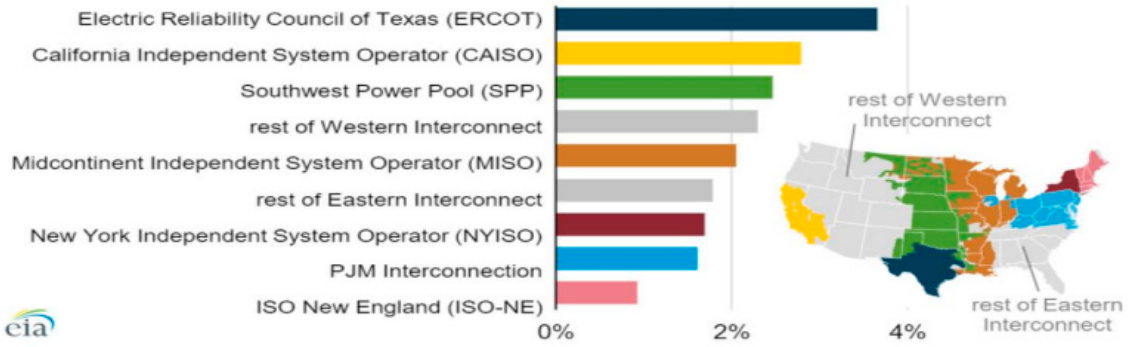


Figure 2. Percentage of total peak demand savings from demand response (source: [27]).

Among the U.S.A. utilities, the Pennsylvania–Maryland–New Jersey Interconnection (PJM) and the California Independent System Operator (CAISO) are considered to be among the pioneers of the implementation of various demand-side management and demand response programs [25]. The large share of variable renewable energy (mainly solar and wind) in the CAISO region has especially prompted a significant drive towards the full exploitation of demand response and energy efficiency as a means to support the transition towards cleaner, greener, environmentally sustainable and stable electricity supply. Some of the challenges to the full-scale implementation of demand-side management that have

been identified include market barriers, policy and regulation, customer behavior as well as infrastructure and technology. There are ongoing efforts on the part of the state to address some of these barriers through appropriate policy development and regulation [25].

4.2.3. South Africa

South Africa has been plagued with ongoing concerns regarding the sufficiency of its electricity infrastructure and energy policies, culminating in the energy crisis of 2007–2008 and subsequent supply shortages that have lasted until the present. The Department of Minerals and Energy (DME)'s 2003 White Paper On Renewable Energy [28] highlighted a reserve margin of 10% for South Africa's fossil fuels, which provide roughly 90% of the nation's electricity. The white paper stressed that the national utility would face challenges by 2007 if significant measures were not taken to encourage energy efficiency. This prediction proved accurate, as the country experienced a discord between supply and demand from 2007 to the present. The 2008 energy crisis in South Africa, arising from a higher demand for electricity compared to the available supply and a diminished reserve margin, has underscored the necessity for greater synergy between home energy management systems (HEMS) and supply-side energy management systems (SSEMS). Demand-side management (DSM) techniques have been scrutinized and validated as viable methods for regulating electricity consumption from the consumer side. However, the effectiveness of DSM hinges on the active engagement of willing consumers. Reference [29] highlights that the persistent enforcement of regulatory compliance has emerged as a core issue in South Africa's utility sector. This predicament cannot be merely a trade-off. Instead, it requires the establishment of institutional frameworks to enhance overall performance. It is noteworthy that the progress of the energy transition significantly relies on political processes.

The last decade has witnessed the introduction of numerous energy regulations by the government, further intensifying pressures on the energy industry. Reference [11] pointed out that several substantial challenges hinder the efficient functioning of DSM within South Africa's electricity sector, including the understaffing of Eskom's DSM group, non-pragmatic DSM frameworks, a lack of transparency in project and procedure approvals by Eskom and inadequate feedback due to the ambiguity in evaluation processes, with Eskom's evaluation teams disproportionately focusing on less crucial matters [30].

Regarding regulatory policies, the National Electricity Regulator (NER) in South Africa is tasked with ensuring sufficient generation capacity to meet future electricity demand. As Eskom's reserve margins decreased, the need for Energy Efficiency and Demand-Side Management expansion to ensure a secure supply, cost-effective energy services and improved sector efficiency was recognized [11]. In 2004, the NER introduced the Regulatory Policy on EE/DSM for the South African Electricity Industry, making EE/DSM planning and implementation a licensing requirement for major distributors. The policy outlines the responsibilities, obligations and roles of Energy Service Companies (ESCOs). The NER also established the Eskom EE/DSM Fund, administered by Eskom, with defined rules and procedures for implementation [11]. Policies such as the Electricity Regulation Act of 2006 and Energy and Demand Side Management (EEDSM) were implemented to provide a framework regarding EE and DSM interventions [31]. Figure 3 [32] represents the historical overview of the Eskom DSM program's evolution from 2001 to 2012.

According to [32], the integrated demand management (IDM) program has been able to achieve in excess of 3073 MW of demand savings, which is equivalent to about five thermal power generation stations being freed up. The IDM has encompassed residential, commercial and industrial energy efficiency improvements, notable among them being solar water heaters, compact fluorescent lamps replacing incandescent lights and industrial and mining process optimization and efficiency upgrades. Figure 4 [33] depicts the distribution of electricity consumption by sector, the main sectors being industrial, residential and services. The National Energy Efficiency Strategy policy document [34] envisaged an average demand reduction of 15% when all major sectors are considered.

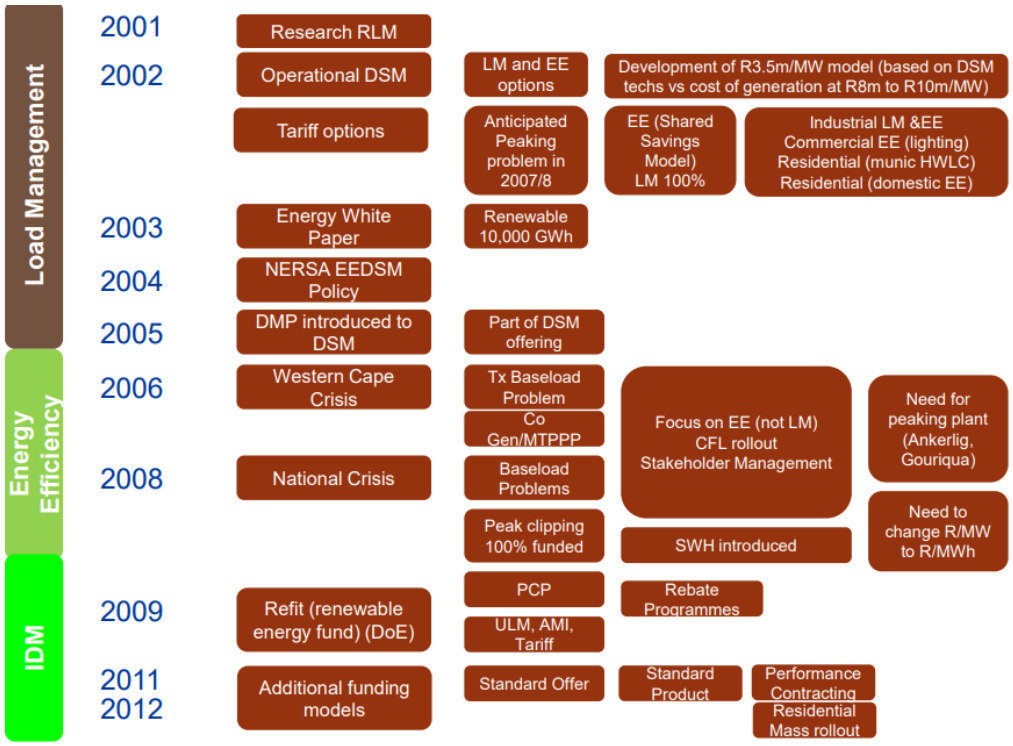


Figure 3. Eskom DSM programs: a historical overview (source: [32]).

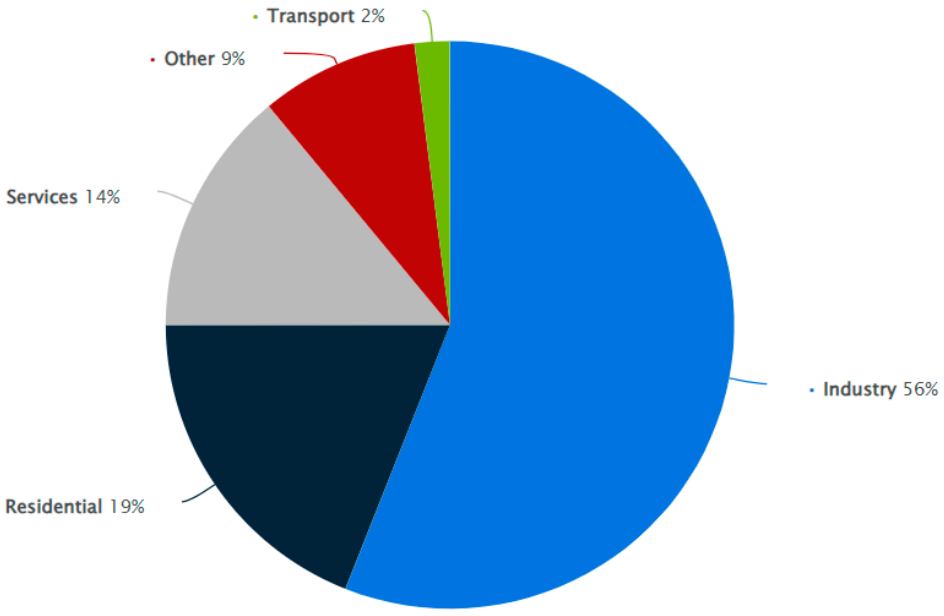


Figure 4. South Africa's electricity consumption by sector, as of 2019 (source: [33]).

5. Impact of Demand-Side Management on Network Planning

5.1. Traditional Network Planning

Distribution network planning plays a pivotal role in achieving the main operational goal of the network, which is to maintain a safe, reliable and affordable electricity supply service, and in the process make as efficient use of existing electrical infrastructure as possible. Traditional network planning has focused on these aspects almost exclusively. With the changes occurring in the electric power supply sector, however, modern and forward-looking distribution network planning has to additionally consider grid modernization paradigms, such as technology-enhanced demand-side management, advanced

metering infrastructure, advanced distribution automation and the efficient integration of distributed energy resources [35].

The planning and design of the electric distribution system considers operation both under nominal conditions and under a number of credible contingencies. The main operational objective to be achieved is for the system to operate within well-defined ranges under nominal conditions and to be able to withstand contingencies with a minimal risk of contagions that may endanger the security, reliability or quality of supply. The key operational parameters of interest are the voltage magnitude and frequency, as well as the thermal loading of various network equipment, such as transformers and feeders [36]. The network planning problem can be formulated as an optimization problem with objectives and constraints that take into account the operational needs of the network and the practical limitations to which the network operation is subjected. Minimizing total lifetime capital costs and operational expenditures constitutes the primary objective when it comes to network planning. Constraints may include [1]:

- Technical constraints:
    - Equipment loading, losses, fault current levels
    - Required level of security and reliability of supply
    - Required level of voltage and power quality
    - Maintenance of nominal system frequency
    - Stability and dynamic behavior of the network
- Environmental impact
- Political/regulatory targets
- Future developments

Given the current state of the network structure, network planning and development seek to project the future requirements, in terms of the network infrastructure needed to cater for estimated future load development. The planning horizon can be short- (about one year), medium- (about five to ten years) or long-term (about fifteen years or longer).

The main distinguishing factors in the modern network planning and development approach relative to the traditional approach include the consideration of the impact of the liberalization of the electricity industry and the introduction of electricity markets, the need to consider distributed generation and distributed energy resources in network planning and operation and the role to be played by demand-side initiatives in enhancing network operation. The impact of demand-side management on network planning is of special relevance in this review and is considered further in the following section.

5.2. Impact of Demand-Side Management on Network Planning

Network planning and development are required to evolve in line with changes in the organization and operation of the power system. One of the most notable developments is the move towards a more deregulated electric power industry and the support of open electricity markets with diverse participants and stakeholders. The changing needs of consumers, and the widespread adoption of distributed generation and distributed energy resources, are other factors affecting network expansion planning [37]. These developments have meant that, from the network planning point of view, the network operation has become less predictable. Forecasts of future demand or the level of penetration of distributed energy resources are not so accurate. This leads to the need to adopt more probabilistic network planning methods, as opposed to deterministic ones. These probabilistic or stochastic methods are able to take a number of uncertainties into account, such as the uncertainty of consumer behavior and that of intermittent renewable generation output.

Demand-side management has traditionally not been taken into account in network planning. One reason for this is the relatively low perceived impact when compared with supply-side solutions for network planning and operation [1]. The perception has been changing, however, and there is wide recognition that demand-side management and demand response can make a major contribution to the achievement of the many

operational objectives of power system operation. In assessing the impact of demand-side management on network operation, the various technical and commercial considerations that are involved in its deployment need to be taken into account. In practical terms, however, the actual impact of DSM on network operation is in terms of affecting the effective demand seen by the supply side. On the one hand, DSM can be deployed to modify the load shape through such measures as time-of-use pricing, critical peak pricing or other DSM programs that seek to indirectly induce a positive change in energy consumption behavior on the part of the customer. Other than changing the load shape, DSM can also impact the load level, through a number of incentive-based DSM mechanisms, as discussed in Section 2.2. These changes then translate into:

- Optimizing network utilization by reducing peak demand, and improving the peak-to-average ratio, thereby leading to a flattening of the load curve
- Contributing to network congestion relief
- Helping to balance intermittent renewable generation, which then increases the network's capacity to host a greater amount of renewable generation
- Enabling the deferment of network expansion or network reinforcement as a way of managing supply capacity constraints
- Creating opportunities for new operational paradigms, such as aggregators that can aggregate various demand-side resources (distributed generation, energy storage and flexible demand) into Virtual Power Plants (VPP)

The key to realizing these positive impacts of demand-side management on the network is to be able to effectively integrate it into network planning. This is discussed further in the following section.

5.3. Integration of Demand-Side Management as an Integral Component of Network Planning

Distribution networks are evolving from the traditionally passive delivery systems that have simply connected end consumers to the bulk generation and transmission system to actively managed distribution systems that fully exploit distributed resources such as distributed generation, energy storage and demand-side management. This development is embodied in the concept of the Smart Grid, as was defined in Section 3.1. The emphasis in active distribution systems is to take full advantage of state-of-the-art technologies to implement intelligent distributed control throughout the electric power supply system, not just generation and transmission levels, as has been the case in the past.

Demand-side management has a central role to play in the future smart grid. This necessitates the development of methods and strategies for explicitly integrating it into the utility's network planning and expansion framework. The traditionally deterministic approach of network planning has to give way to probabilistic and stochastic techniques that are able to appropriately represent the uncertainty embedded in distributed resources such as variable renewable generation and demand-side management. The incorporation of demand-side management into network planning also requires the consideration of its impact on the operational, economic and other aspects of the network, including:

- Technical constraints (e.g., impact on power flows and voltage regulation)
- Costs of deployment, which may include investment, tariffs, regulatory obligations, and economic benefits
- Control and protection of the network
- Reliability and power quality
- Uncertainty of consumer behavior, and how it may impact network operation and control

Besides the considerations highlighted above, the full exploitation of demand-side management further requires the development of new analytical and other technological tools that facilitate the effective study, development and implementation of the resulting network planning solutions that are aimed at making full use of DSM. These tools include:

- Probabilistic Analysis (e.g., Probabilistic Load Flow)
- New scheduling algorithms that can coordinate the operation of distributed resources

- Innovative control concepts that seek to maximize the contribution of distributed resources to efficient network operation
- ICT tools that support the implementation of the functionalities of the DSM schemes

5.4. Demand-Side Management as an Effective Mechanism for Addressing Supply Shortages in South Africa

5.4.1. DSM Opportunities for South Africa

South Africa faces unique challenges in "keeping the lights on." It has become apparent that relying purely on the supply side of the power system to address the growing grid capacity constraints is very limiting. Eskom, the National grid operator, has signalled the intention to intensify its demand-side management intervention efforts to support the management of electricity supply and demand. Speaking at the inaugural National Demand Management Indaba held in Muldersdrift, West Rand in April 2023, Eskom Board Chairperson Mpho Makwana pointed out that DSM programs enable the effective management of customers' energy consumption, leading to reduced peak demand or overall consumption during specific periods [38]. Eskom has made a number of strides in a range of DSM initiatives, which encompass energy efficiency, demand response, distributed generation and energy storage. The utility operator has been extensively engaged in awareness campaigns aimed at sensitizing consumers to efficient energy use and energy saving. It has also piloted some energy efficiency initiatives, such as the replacement of incandescent light bulbs (ICLs) with the more efficient compact fluorescent lamps (CFLs). In April 2023, the Demand Response and Distribution Demand Management Program (DDMP) was launched [39]. The program has been launched as a mechanism for curbing the growing use of load shedding due to the inability of the electricity grid capacity to adequately meet demand. The DDMP has a number of categories, including:

- Industrial, Commercial and Agricultural Load Management: the program is open to all sectors, excluding the residential sector, and has a minimum size of load shifting or peak clipping of 0.5 MW (megawatt). The targeted demand reduction period is the Eskom-defined evening peak period for both summer and winter
- Residential Load Management (RLM): the program's objective is to shift evening peak demand to standard and off-peak periods, which should help to reduce demand during Eskom-defined evening peak periods in residential households. The RLM scheme targets the shifting of hot water demand during peak periods by remotely switching off residential customers' geysers. The minimum size of the residential load shifting is required to be 1 MW
- Energy Efficiency Program: This is an incentive-based program that offers customers the opportunity to lower their electrical energy costs by reducing their load demand via the use of more energy-efficient technologies. The program is open to all sectors, except the residential sector. It has a minimum requirement of 100 kW average demand reduction of the baseline consumption between 6 a.m. and 8 p.m. during weekdays

5.4.2. Short-Term System Operation Opportunities for DSM

A peculiar characteristic of the electric power system operation is the need to maintain a balance between supply and demand second-by-second. Any imbalance caused by an unexpected loss of generation or sudden demand reduction would lead to anomalous operating conditions that would compromise the integrity of the entire system if not remedied timeously. The system operator has to plan for such probable contingencies, and this is usually achieved by securing short-term operating reserves (STOR). STOR is normally required to manage a situation where the actual demand is greater than the forecast demand, or any other situation that leads to a supply shortfall (e.g., due to unforeseen generation unavailability). It is classified as a balancing service and can be provided either as generation capacity or steady demand reduction of a stipulated magnitude and duration [38]. Since it is a function of the demand profile at any given time,

the requirement for STOR will vary from time to time. As an example, Ref. [40] stipulates the following minimum capability requirements for the service:

- A minimum of three megawatt (MW) generation or steady demand reduction (which can be aggregated)
- Maximum response time for delivery of 240 min following instruction from the system operator to provide the service
- Ability to deliver the contracted MW for a continuous period of not less than 2 h
- A recovery period after providing the service of not more than 1200 min
- Ability to deliver the service at least three times per week

The opportunity for DSM to participate in the provision of this service depends on the capability to meet the requirements stated above. The magnitude requirement alone suggests that the service is more suitable for provision by large industrial or commercial energy users with sufficient demand flexibility. Small energy consumers may also have the opportunity to participate, but this would be most likely by means of an aggregator, since such a possibility exists, as stated in the requirements above.

It is evident from the opportunities discussed above that the potential of demand-side management to contribute materially to addressing the severe electricity supply constraints being faced in South Africa has been well recognized, and efforts are being made to exploit this resource. These efforts need to be extended, however, so that demand-side management is explicitly integrated into long-term network planning, as discussed in Section 5.3, which requires a salient shift in the manner and approach to network planning.

6. Conclusions

A secure and reliable electric energy supply lies at the heart of economic growth and development and has become almost indispensable to modern society. The challenge of meeting the growing energy demand in an economically and environmentally sustainable manner requires a multifaceted approach. This review has presented a study of demand-side management in terms of the role it can play in network planning and network operation. The study has examined the main drivers and benefits of demand-side management, as well as the potential barriers that may hamper progress in the effective implementation of demand-side management. The study has also covered a review of the main demand-side management schemes and programs that are implemented in the industrial, commercial and residential customer segments, the key supporting infrastructure needed for the effective implementation of demand-side management and some examples of demand-side management initiatives in some parts of the world. One of the key objectives of the study has been to closely look into how demand-side management can be more comprehensively integrated into network planning and network operation. The findings from the study reveal that the achievement of this requires a shift from the traditional network planning approach, which leans heavily (and almost exclusively relies) on the supply side to determine the needed resources and infrastructure for present and future load requirements, to one that explicitly considers the various flexibility resources available on the demand side. These resources include distributed generation, energy storage and dispatchable demand. Because these resources are stochastic rather than deterministic, probabilistic and stochastic network planning and analysis tools need to be adopted to be able to properly represent the uncertainty that is inherent in the distributed flexible resources.

South Africa faces significant challenges in meeting electric energy demand, and the grid operator has for some years now had to resort to sustained load shedding in an effort to preserve the integrity of the power system. The National Grid Operator (Eskom) has seen the need to intensify efforts and initiatives to promote demand-side management and demand response as an effective way of easing the supply capacity constraints faced by the electric grid. Future work will further explore the actual impact of these initiatives on the grid's capacity to deliver power more securely, reliably and efficiently.

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