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Stochastic Management Framework of Distribution Network Systems Featuring Large-Scale Variable Renewable Energy Sources and Flexibility Options

Marco Rafael Meneses Cruz

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(3º ciclo de estudos)

Orientador: Doutor João Paulo da Silva Catalão
Co-orientador: Doutor Sílvio José Pinto Simões Mariano
Co-orientador: Doutor Desta Zahlay Fitiwi

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Engineering

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Supervisor: Dr. João Paulo da Silva Catalão

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Co-supervisor: Dr. Desta Zahlay Fitiwi

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Resumo

As mudanças climáticas, a crescente procura por energia e a segurança de abastecimento estão a modificar a operação e o planeamento das redes de distribuição, especialmente pela necessidade de integração em larga escala de fontes de energia renováveis. O aumento desses recursos energéticos sustentáveis gera enormes desafios a nível técnico no sistema, atendendo a que o operador do sistema de distribuição tem o dever de manter a integridade e a estabilidade da rede, bem como a qualidade de energia entregue aos consumidores. Portanto, os sistemas de energia elétrica existentes devem passar por um eminente processo de transformação para que as limitações atuais sejam devidamente atenuadas ou mesmo evitadas, esperando-se assim chegar ao paradigma das redes elétricas inteligentes.

Para as redes de distribuição acomodarem fontes variáveis de energia renovável, novas e emergentes opções de flexibilidade, que dizem respeito à geração, carga e à própria rede, precisam de ser desenvolvidas e consideradas na operação ótima da rede de distribuição. Assim, a gestão das opções de flexibilidade deve ser cuidadosamente efetuada para minimizar os efeitos secundários como o aumento dos custos, agravamento do perfil de tensão e o desempenho geral do sistema. Desta perspetiva, é necessário entender como uma rede de distribuição pode operar de forma ótima quando se expõe a uma integração em larga escala de fontes variáveis de energia renovável. Devido à variabilidade e incerteza associadas a estas tecnologias, novas metodologias e ferramentas computacionais devem ser desenvolvidas para lidar com os desafios subsequentes. Desta forma, as opções de flexibilidade existentes e emergentes devem ser implantadas para gerir a incerteza e variabilidade das fontes de energia renovável, mantendo o necessário balanço entre carga e geração.

Nesta tese é feita uma análise extensiva das principais tecnologias que podem providenciar flexibilidade aos sistemas de energia elétrica, e as suas contribuições para a operação ótima dos sistemas de distribuição, tendo em consideração a natureza estocástica dos recursos energéticos intermitentes e outras fontes de incerteza. Adicionalmente, este trabalho contém investigação detalhada sobre como o sistema pode ser otimamente gerido tendo em conta estas tecnologias de forma a que a uma maior percentagem de carga seja fornecida por fontes variáveis de energia renovável, mantendo a fiabilidade, estabilidade e eficiência do sistema. Por esse motivo, novas metodologias e ferramentas computacionais usando programação estocástica são desenvolvidas para modelizar a variabilidade e incerteza inerente à geração eólica e solar. A convergência para uma solução ótima é garantida usando programação linear inteira-mista para formular o problema.

Palavras Chave

Fontes de energia renováveis; operação da rede; geração distribuída; programação linear inteira-mista estocástica; redes elétricas inteligentes; sistemas de armazenamento de energia; topologia da rede; variabilidade e incerteza.

Abstract

The concerns surrounding climate change, energy supply security and the growing demand are forcing changes in the way distribution network systems are planned and operated, especially considering the need to accommodate large-scale integration of variable renewable energy sources (vRESs). An increased level of vRESs creates technical challenges in the system, bringing a huge concern for distribution system operators who are given the mandate to keep the integrity and stability of the system, as well as the quality of power delivered to end-users. Hence, existing electric energy systems need to go through an eminent transformation process so that current limitations are significantly alleviated or even avoided, leading to the so-called smart grids paradigm.

For distribution networks, new and emerging flexibility options pertaining to the generation, demand and network sides need to be deployed for these systems to accommodate large quantities of variable energy sources, ensuring an optimal operation. Therefore, the management of different flexibility options needs to be carefully handled, minimizing the side-effects such as increasing costs, worsening voltage profile and overall system performance. From this perspective, it is necessary to understand how a distribution network can be optimally operated when featuring large-scale vRESs. Because of the variability and uncertainty pertinent to these technologies, new methodologies and computational tools need to be developed to deal with the ensuing challenges. To this end, it is necessary to explore emerging and existing flexibility options that need to be deployed in distribution networks so that the uncertainty and variability of vRESs are effectively managed, leading to the real-time balancing of demand and supply.

This thesis presents an extensive analysis of the main technologies that can provide flexibility to the electric energy systems. Their individual or collective contributions to the optimal operation of distribution systems featuring large-scale vRESs are thoroughly investigated. This is accomplished by taking into account the stochastic nature of intermittent power sources and other sources of uncertainty. In addition, this work encompasses a detailed operational analysis of distribution systems from the context of creating a sustainable energy future. The roles of different flexibility options are analyzed in such a way that a major percentage of load is met by variable RESs, while maintaining the reliability, stability and efficiency of the system. Therefore, new methodologies and computational tools are developed in a stochastic programming framework so as to model the inherent variability and uncertainty of wind and solar power generation. The developed models are of integer-mixed linear programming type, ensuring tractability and optimality.

Keywords

Distributed generation; Energy storage systems; Network operation; Network topology; Renewable energy sources; Smart grids; Stochastic integer-mixed linear programming; Variability and uncertainty.

Contents

List of Figures

List of Tables

List of Symbols

The main notations used in Chapters 3, 4 and 5 are listed below. Other symbols are defined where they first appear.

Chapter3

Sets and Indices

$h', h/\Omega^h$	Index/set of hourly snapshots
c/Ω^c	Index/set of switchable capacitor banks
es/Ω^{es}	Index/set of Energy Storage Systems (ESSs)
g/Ω^{DG}	Index/set of Renewable Energy Sources (RESs)/Distributed Generators (DGs)
i/Ω^i	Index/set of buses
k/Ω^k	Index/set of branches
s/Ω^s	Index/set of scenarios
$\varsigma\ /\Omega^{\varsigma}$	Index/set of substations

Parameters

$\overline{\lambda_s^{\varsigma}}$	Considered average price of electricity at substation level (€/MWh)
$ER_g, ER_{\varsigma}^{SS}$	Emission rates of DGs, and emissions intensity of purchased energy, respectively (tCO_2e/MWh)
$E_{es,i}^{min}, E_{es,i}^{max}$	ESSs upper and lower bounds (MWh)
MP_k, MQ_k	Big-M parameters related with active and reactive power flows over each branch *k*
N_i, N_{ς}	Number of buses and substations, respectively
$OC_{g,i,s,h}$	Price of unit energy production (€/MWh)
$P_{es,i}^{ch,max}, P_{es,i}^{dch,max}$	Charging and discharging power bounds of ESSs (MW)
P_r	Rated power of RES unit (MW)
$P_{solar,h}$	Hourly solar PV output (MW)
$P_{wind,h}$	Hourly wind power output (MW)
R_h	Hourly solar radiation (W/m^2)
R_c	Certain radian point (usually $150W/m^2$)
$R_k,\ X_k$	Resistance, Reactance (Ω, Ω)
R_{std}	Standard condition of solar radiation (usually $1000W/m^2$)
SC_k	Switching cost of each branch *k* (€ per single switching)
V_{nom}	Rated voltage of the system (kV)
Z_k	Impedance of each branch k (Ω)

g_k, b_k, S_k^{max}	Conductance, susceptance and flow boundaries of each branch *k* (S, S, MVA)
pf_g, pf_{ss}	Power factor of RES and substation, respectively
v_h	Sampled wind speed (m/s)
v_{ci}	Cut-in wind speed (m/s)
v_{co}	Cut-out wind speed (m/s)
$\eta_{es}^{ch}, \eta_{es}^{dch}$	Charging/discharging efficiency (%)
$\lambda_{es,i,s,h}^{dch}$	Variable cost of storing energy in ESSs (€/MWh)
$\lambda_{s,h}^{CO_2e}$	Emissions price (€/tCO_2e)
$\lambda_{s,h}^{\varsigma}$	Electricity price at the substation level (€/MWh)
$\lambda_s^{Off-peak}$	Considered average electricity price in off-peak hours (€/MWh)
λ_s^{Peak}	Considered average electricity price in peak hours (€/MWh)
λ_s^{Valley}	Considered average electricity price in valley hours (€/MWh)
μ_{es}	Scaling factor (%)
$\xi_{h,h'}$	Price elasticity of electricity demand
ρ_s	Probability of hourly scenario *s*
$v_{s,h}$	Unserved power penalty factor (€/MW)
Δh	Time increment (hour)
α	Percentage of demand that can be scheduled

Variables and Functions (Units in M€)

EC_h^{DG}	Expected cost of energy produced by DGs
EC_h^{ES}	Expected cost energy discharged from ESSs
EC_h^{SS}	Expected cost of energy imported through the substation level
$E_{es,i,s,h}$	Energy storage level (MWh)
$EmiC_h^{DG}$	Expected emission cost due to DG power production
$EmiC_h^{SS}$	Expected emission cost of energy imported through the substations
$I_{es,i,s,h}^{dch}, I_{es,i,s,h}^{ch}$	Discharging/charging binary indicator variables
$PD_{s,h}^i, QD_{s,h}^i$	Active and reactive power demand at bus i (MW, MVAr)
PL_k, QL_k	Active and reactive power losses of each branch k (MW, MVAr)
$PL_{\varsigma,s,h}, QL_{\varsigma,s,h}$	Active and reactive power losses at substation ς (MW, MVAr)
$P_{es,i,s,h}^{dch}, P_{es,i,s,h}^{ch}$	Discharged/charged power of ESSs (MW)
$P_{g,i,s,h}, Q_{g,i,s,h}$	Active and reactive power produced by RESs at bus i (MW)
$P_{i,s,h}^{NS}$	Unserved active power at bus i (MW)
P_k, Q_k, θ_k	Active and reactive power flows respectively, and voltage angle difference of branch k (MW, MVAr, radians)
$P_{\varsigma,s,h}^{SS}, Q_{\varsigma,s,h}^{SS}$	Active and reactive power imported from the substation (MW)

$Q^{NS}_{i,s,h}$	Unserved reactive power at bus i (MVAr)
V_i, V_j	Voltage magnitudes at bus i and j (kV)
$u_{k,h}$	Switching (binary) variables of existing branches
$x_{k,h}$	Binary variable to indicate line status
$y^{+}_{k,h}, y^{-}_{k,h}$	Auxiliary variables to indicate the status of a line
θ_i, θ_j	Voltage angle at node i and j (radians)
$\varphi^{RTP}_{s,h}$	Real-time price of electricity (€/MWh)
TEC	Total expected costs of supplied energy
$TENSC$	Total expected costs of energy not supplied
$TEmiC$	Total expected costs of emissions
TSC	Total expected costs of line switching

Chapter 4

Sets and Indices

$g/\Omega^g / \Omega^{DG}$	Index/set of generators/vRES
$hh, h/\Omega^h$	Index/set of hourly snapshots
i/Ω^i	Index/set of buses
k/Ω^k	Index/set of branches
s/Ω^s	Index/set of scenarios
$\varsigma/\Omega^\varsigma$	Index/set of substations

Parameters

ER_g, ER^{SS}_ς	Emission rates of vRES, and energy purchased, respectively (tCO_2e/MWh)
MP_k, MQ_k	Big-M parameters associated to active and reactive power flows through branch k
MP_k, MQ_k	Big-M parameters associated to active and reactive power flows through branch k
N_i, N_ς	Number of buses and substations, respectively
$OC_{g,i,s,h}$	Operation cost of unit energy production by vRES (€/MWh)
$OC_{g,i,s,h}$	Operation cost of unit energy production by vRES (€/MWh)
V_{nom}	Nominal voltage (kV)
Z_{ij}, R_k, X_k	Impedances of branch *i-j* (Ω)
g_k, b_k, S^{max}_k	Conductance, susceptance and flow limit of branch k (Ω, Ω, MVA)
$\lambda^{CO_2e}_{s,h}$	Price of emissions (€/tons of CO_2 equivalent)
$\lambda^{\varsigma}_{s,h}$	Price of electricity purchased upstream (€/MWh)

ρ_s, π_w	Probability of hourly scenario *s* and weight (in hours) of hourly snapshot group h
$\upsilon_{s,h}^{P}, \upsilon_{s,h}^{Q}$	Penalty for active and reactive unserved power, respectively (€/MW, €/MVAr)

Variables and Functions

$PD_{s,h}^{i}, QD_{s,h}^{i}$	Active and reactive power demand at node *i* (MW, MVAr)
$P_{i,s,h}^{NS}$	Unserved power at node *i* (MW)
$P_{g,i,s,h}, Q_{g,i,s,h}$	Active and reactive power produced by vRESs (MW)
${Q^{NS}}_{i,s,h}$	Unserved power at node *i* (MW)
$P_{\varsigma,s,h}^{SS}, Q_{\varsigma,s,h}^{SS}$	Active and reactive power imported from grid (MW)
V_i, V_j	Voltage magnitudes at nodes *i* and *j* (kV)
P_k, Q_k, θ_k	Active and reactive power flows, and voltage angle difference of link k (MW, MVAr, radians)
$u_{k,h}$	Utilization variables of existing lines
PL_k, QL_k	Active and reactive power losses (MW, MVAr)
θ_i, θ_j	Voltage angles at node *i* and *j* (radians)
$PL_{\varsigma,s,h}, QL_{\varsigma,s,h}$	Active and reactive power losses at substation ς (MW, MVAr)
$\lambda_{s,h'}$	Real-time price of electricity (€/MWh)
EC_h^{SS}	Expected cost of energy imported through the substation level (€)
EC_h^{vRES}	Expected cost of energy produced by vRES (€)
$EmiC_h^{vRES}$	Expected emission cost due to vRES power production (€)
$EmiC_h^{SS}$	Expected emission cost of energy imported through the substations (€)
TEC	Total expected costs of supplied energy (€)
$TENSC$	Total expected costs of energy not supplied (€)
$TEmiC$	Total expected costs of emissions (€)

Relevant Acronyms

ACO	Ant Colony Optimization
CCGTs	Combined-Cycle Gas Turbines
CHP	Combined Heat and Power
CPP	Critical Peak Pricing
DAHP	Day-Ahead Hourly Pricing
DG	Distributed Generation
DM	Demand Management
DMS	Demand Management Systems
DNR	Dynamic Network Reconfiguration
DR	Demand Response
DSM	Demand Side Management
DSOs	Distribution System Operators
DSR	Dynamic System Reconfiguration
EMS	Energy Management Systems
ESSs	Energy Storage Systems
EU	European Union
EV	Electric Vehicles
FCLs	Fault Current Limits
GA	Genetic Algorithm
GHGs	Greenhouse Gas Emissions
ICTs	Information and Communication Technologies
IOTs	Internet of Things
LCOE	Levelized Cost Of Electricity

MISOP	Mixed Integer Second Order Program
OPF	Optimal Power Flow
P2G	Power-to-Gas
PQ	Power Quality
PTR	Peak Time Rebate
RLC	Resistor, Inductor and Capacitor
RTP	Real-Time Pricing
SCADA	Supervisory Control And Data Acquisition
SCBs	Switchable Capacitor Banks
SMES	Superconducting Magnetic Energy Storage
S-MILP	Stochastic Mixed Integer Linear Programing
SOPs	Soft Open Points
TCL	Thermostat-Controlled Loads
ToU	Time-of-Use
vRESs	Variable Renewable Energy Sources

Chapter 1

Introduction

1.1 Background

It is now widely accepted that integrating variable renewable energy sources (vRESs) in power systems is inevitable to meet a growing demand for electricity, enhance energy security and reduce the heavy dependence on fossil fuels to produce electricity, which are associated with high carbon footprint. Many states, as in the European Union (EU), are now forging ahead with ambitious vRES integration targets aiming to achieve a substantial reduction of greenhouse gas emissions (GHGs). The integration of vRES technologies is expected to lead to 80% to 95% reduction of GHG emissions by 2050 [1]. One eminent fact about these technologies is that they depend on the availability of primary energy resources such as wind speed and solar irradiation, which are unevenly distributed over a wide geographical area. This means distributed (rather than centralized) development of such resources could be more convenient, efficient and even cost-effective despite the economies-of-scale. The main reason for this is because distributed generations are installed in places closer to demand, which means they are often connected to distribution networks. If this is executed in a well-coordinated manner, vRESs can bring vast benefits to the systems as a whole in terms of improved efficiency, deferred transmission investments, reduced use of fossil fuels for energy production and therefore lower GHG emissions [2]. Hence, distribution networks are expected to accommodate more and more vRESs.

Current trends generally show that the share of vRESs in the overall energy consumption is rapidly increasing in many power systems globally amid a number of barriers. However, the intermittent nature of such resources means a large-scale integration creates technical problems in the systems. Electrical distribution network systems are especially experiencing unprecedented challenges due to the increasing penetration level of distributed power generation sources of variable in nature, particularly, wind and solar. In other words, distributed generations (DGs) are attracting a lot of attention from policy makers and planners to meet the increased demand for electricity in the future. There is nowadays a growing trend of adding more new DG capacities than centralized generation capacities. This brings serious concerns to grid operators, though. The partially unpredictable nature of power generation from the key renewable type DGs may endanger the stability and integrity of power systems as a whole, and distribution systems in particular. This may also deteriorate the quality of power delivered to consumers.

Because of these concerns, future distribution grids should be prepared to handle the ongoing transformation process of power generation from the traditionally centralized to a more distributed and small power productions. Nonetheless, conventional distribution systems are not designed to manage this, and as a result, regulators often impose a maximum penetration limit which does not help further development of distributed vRESs. But distribution network systems are slowly evolving to smart grids, which are adequately equipped with the necessary tools and mechanisms to accommodate large-scale vRESs while minimizing their side-effects mentioned earlier. In this chapter, flexibility options that can support the much-needed integration and efficient utilization of large-scale vRESs in the future distribution systems are explored and discussed. The assessment also includes managing the negative impacts of vRESs, induced by their high variability and uncertainty, by means of various flexibility options.

For this purpose, this thesis performs optimal management of distribution systems via an appropriate mathematical optimization – a stochastic mixed integer linear programing (S-MILP) – for deploying different flexibility options along with vRESs. The work here aims to address the operation issues that can occur in distribution systems due to the high-level variability and uncertainty of vRESs. The analysis is made from the economic and technical point of view. In particular, this thesis makes an extensive analysis on the impacts of vRESs on the overall performance of the system such as voltage profile, losses, costs, system reliability stability and power quality. In addition, the contributions of different flexibility options in enabling high penetration of vRESs and their wide-range benefits are assessed thoroughly.

1.2 The Need for Flexibility Options in Distribution Systems

Because of the reasons mentioned earlier, an increasing level of DGs is being connected to distribution systems. The fact that these are based on erratic power sources (wind and solar, for example) is creating technical problems in such systems. Grid operators are especially concerned as the conventional means of overseeing the network systems are now becoming insufficient to keep a healthy operation of such systems. The main reason for this boils down to the partially unpredictable nature of these energy resources. In such circumstances, proper management mechanisms need to be put in place so as to seamlessly accommodate large-scale vRES type DGs. This is critical to address a multitude of global concerns, partly described in the previous section.

In general, there is an increased need for flexibility in distribution systems to counterbalance the continuous fluctuations in RES power productions and even demand [3], [4]. Traditionally, demand-generation balancing is handled by conventional power plants. However, in the presence of high level vRESs, this approach may be prohibitively expensive or even not sufficient to provide the standard balancing service level.

Increasing levels of vRESs in the system decreases the effectiveness of existing flexibility mechanisms attributed to the traditional system, mainly due to the intermittent nature of renewables. In other words, the system needs a higher level of flexibility to be able to guarantee standard system reliability as the variation increases (both in supply and demand). This is one of the key challenges of integrating vRESs. Therefore, new flexibility options are needed to manage the real-time imbalances in demand and power production. This way, the security of electric supply, stability and power quality can be guaranteed.

Flexibility can be defined as the ability of power systems to efficiently manage its own resources in the event of continuous changes in power supply and demand sides. In this regard, voltage and frequency controls are the primary resources to face uncertainty and variability [5], [6]. In addition, another power system resource useful for handling the imbalances as a result of unpredictable changes in the system (either from supply, demand or both sides) is the network reserve capacity. Nonetheless, power system flexibility can be affected by many factors such as the amount of reserve capacity, the ramp rates of generators, the type of generation, the availability of generation, interconnection with other power systems, capacity of interconnections, etc. [7]. These are traditional mechanisms to deal with imbalances mainly caused by traditional sources of uncertainty and variability. Conventional power plants can add reserve capacity to the system but the inherent variability and uncertainty of vRESs definitively change the operation of distribution networks. Under these circumstances, it may not be economical for conventional power plants to offer spinning reserves. This would be costly because of a possibly increased use of fossil fuels for providing the huge requirement of spinning reserves to a vRES rich systems [8].

The fact that the energy sector is transforming to a new paradigm with improved energy efficiency and environmentally friendly technologies to produce energy at reasonably priced tariffs [9] brings both opportunities and challenges. Flexibility options will be highly needed to address those challenges and reap the benefits. The system-wide reliability, efficiency, reduction of GHGs and affordability of energy can be achieved by deploying and coordinating different flexibility options such as energy storage systems (ESSs), switchable capacitor banks (SCBs), demand response (DR) and others. These technologies substantially enhance the flexibility of the system and its ability to continuously maintain a standard level of service in the face of large fluctuations in the supply and demand [10], [11].

Given the background above, the question of having adequate renewables to meet the electricity demand requires one to have sufficient flexibility technologies to balance forecasting errors and fluctuations [12]. These flexibility options can be provided by energy storage media, network, demand and supply sides as shown in Figure 1.1. For example, from the network side, the network system can dynamically change its topology, and effectively adapt to changing operational situations.

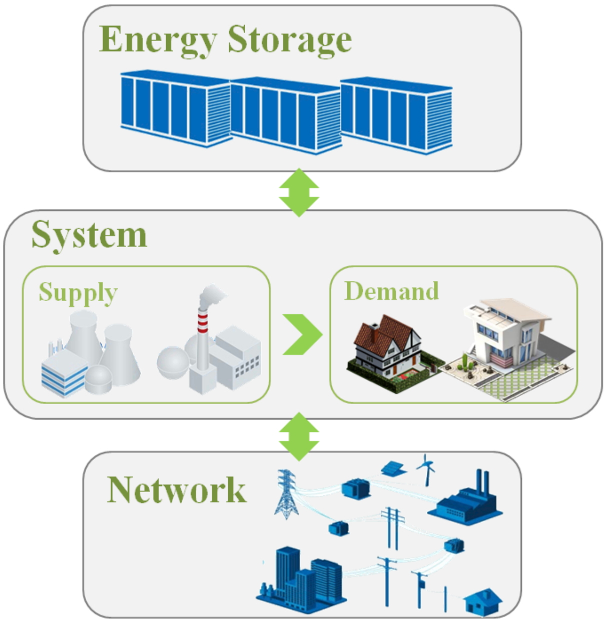


Figure 1.1 - Identifying power system flexibility options.

The more frequent the reconfiguration is, the better the contribution of such a flexibility mechanism will generally be. From the supply side, the traditional flexibility service in the form of spinning reserve provided by conventional generators is one example. Others include curtailment of variable power and reactive power control. On the demand side, some flexibility options are demand response, energy efficiency and electric vehicles.

1.2.1 Challenges in Variable Energy Sources Integration

Traditionally, distribution systems are built to serve the peak demand, and fulfill reliability and quality requirements, in a radial structure [13]. The role of distribution operators has so far been mainly to construct, maintain and manage outages of their distribution network assets [13]. However, with the advent of new technologies and new consumption forms as well as increasing penetration of DGs, there is a growing need to structurally change this conventional business model. Under this circumstance, distribution grids are expected to support bi-directional power flows, which is completely different from the way these are designed to operate. This is increasingly becoming a concern for grid operators as this new role complicates the operation of such grids. As a result, the architecture of distributions systems needs to change to effectively overcome the limitations and address the operators' concerns. The systems need to adopt modern technologies after careful planning and be equipped with necessary tools for their efficient operation. This is important to deal with compounded issues pertaining to the political, social, economic and environmental concerns, as well as meet rising demand for energy and sustainable development goals [14].

Generally, the integration of variable energy sources has several challenges and barriers, which can be categorized as technical, economic, social, political, financial, policy and regulatory aspects [15]–[24]. These are summarized in Figure 1.2. The technical challenges and barriers are already discussed. The financial markets, such as banks, investors or capital firms are the main contributors for economic growth as they define the technological trajectories [15]. Because of this, they can provide a fundamental element to any strategy in the direction of a more sustainable future. Understanding the importance, profile and information that an investor needs is critical to formulate renewable energy source (RES) policies and strategies. In this context, it is expected that the challenges with integration of variable energy sources are related with cost benefit scenario, policies and social acceptance analysis as can be seen in Figure 1.2.

Policies and regulations have unexpected, and sometimes counterproductive, effects on integrating RESs. It is necessary for policy makers to study the system by modeling the interactions between different parts of the system and different policies adopted in order to accommodate a large-scale integration of vRESs [25]. Although there are very supportive contributions from different nations, we face a regulatory framework that comprises laws to overall support RESs but there is no long-term planning because the approaches and framework conditions are always changing [26]. As the network requires to build and operate complex systems involving many corporations, these changing conditions does not permit a system to function effectively [26]. Policies for renewable energy integration are being promoted to diffuse renewable energies within power systems though their effectiveness to accommodate large-scale integration remains subject to uncertainty [27]. For instance, states often try to assist countries that import laws from others and do not adapt the framework to their reality [26]. The lack of planning combined with inappropriate incentives can result in financial problems limiting the progress of companies. Lack of qualified persons combined with the absence of information about markets, operation, planning and potential customers are other barriers to growth of vRESs. The slow rate of decentralized energy systems could be purposely due to fear of losing control with power shifting to new competitors and their pioneering business models [26]. For example, "investment in oil and gas infrastructure and exploration in 2012 was about US$ 650 billion, and on the flip side, investments in vRESs was only US$ 244 billion" [28].

Among the aforementioned challenges, the technical ones present serious problems in the network systems. In the absence of adequate countering mechanisms, the level of vRES power absorbed by such systems could be insignificant, which hardly help to achieve the targets set forth by regulators and policy makers. This thesis explores ways to address these issues by means of deploying different flexibility options.

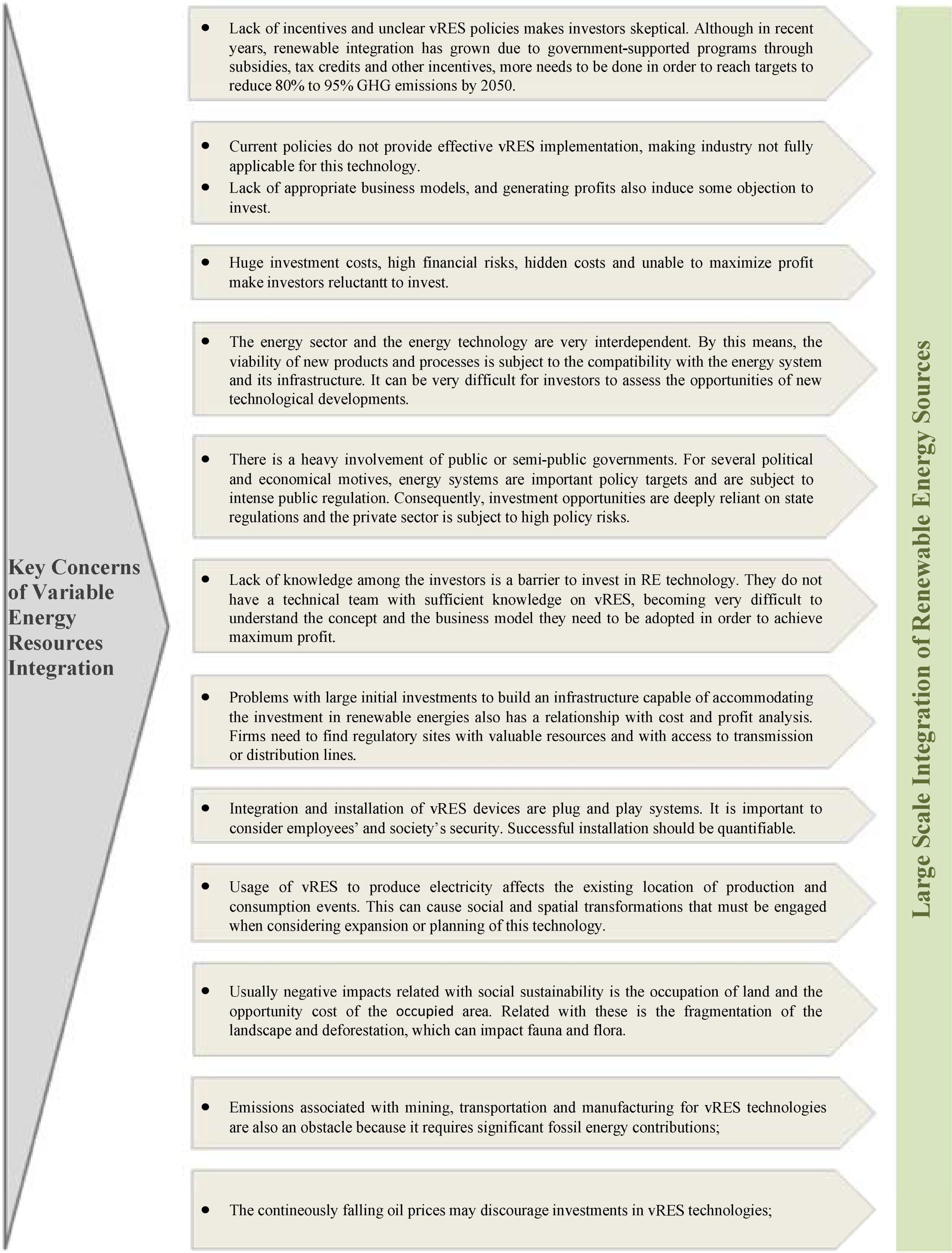


Figure 1.2 - Challenges on integrating vRES.

1.2.2 Emerging Energy Consumption Forms

The electric sector is undergoing rapid changes with a paradigm shift in three fronts: generation, network and demand sides. Much has been said in the previous sections of this chapter about the growing changes on the generation side. The demand side is also experiencing rapid transformations. This means that along with the current evolution of the electric sector and society, new forms of consumptions are emerging and other forms are moving from parallel sectors to the energy sector. For example, new and increasing consumption styles include e-mobility (such as electric vehicles), power-to-X (an initiative to convert electricity to other forms of energy), etc. These can be broadly grouped into three categories: the demand response, electric vehicles and power-to-X, as shown in Figure 1.3. The category of demand response according [29] can be divided into three new sub categories, industry intensive energy demand, demand management in services and households and smart applications. The latter stems from the changes that are being made in the electricity sector by transforming the traditional networks into smart grid, taking advantage of the new communication capabilities that are being integrated into the system. The remaining subcategories arise from the electrification of other sectors such as, the transportation and the heating/cooling sectors [29].

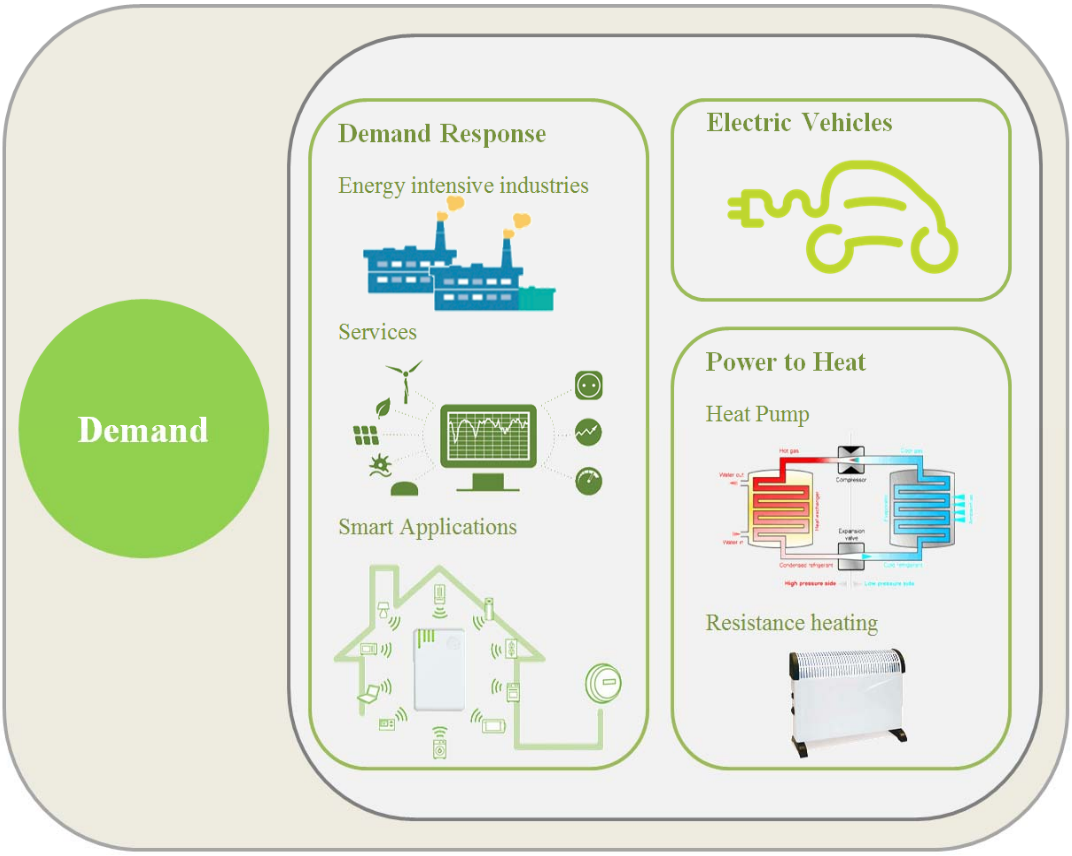


Figure 1.3 - New emerging forms of energy consumption.

1.2.3 Risk Posed by Increasing Uncertainty and Variability

Variable RESs are not always available when needed. They are subject to high level variability and uncertainty. Variability is related to the natural variation, for instance, of wind or sun to produce energy, meaning that the produced energy can fluctuate in certain quantity over regular time intervals. Uncertainty refers to the partially unpredictable nature of the uncertain parameters. As a result, daily and seasonal effects and limited predictability turns vRESs as highly intermittent generation sources [27]. Hence, as they are intermittent, they are not dispatchable as we cannot have control over the power output. Because of these reasons, in the absence of proper strategies, integration of vRESs can pose significant operational risk, making system voltage and frequency controls very difficult. This is because increasing penetration of vRESs increases fluctuations and creates big and uncertain generation-demand imbalances [30]. This leads to power quality and stability concerns. Grid disturbances, for instance, short-circuit faults can cause voltage sags and frequency variations, sending them both off the standard limits. Generally, increased levels of vRESs may cause more complex and uncertain operation situations [30]. Accordingly, there is a need for proper planning and decision making to face uncertainties for achieving optimal vRES integration [31].

Power quality issues when integrating vRES encompass the following important issues: (1) voltage and frequency oscillations triggered by non-controllable vRESs and by power grid disturbances, and (2) harmonics that are introduced by the electronic converters used in vRESs, that are necessary for adapting fluctuating production with grid requirements [30], [32]. Because of the intermittence of vRESs, one way to control power output is simply by curtailing the power production. Nonetheless, it is not an effective way since the curtailed energy could be stored and used on latter moments, not only for demand supply but also for voltage and frequency control of the power output.

In order to face voltage and frequency problems, utilities have introduced various grid codes for connecting vRESs to power systems. The regulatory framework of the grid codes are defined by the system operators to outline the duties and rights of all loads and power generation connected to the transmission and distribution systems [33]. Previously, the large-scale integration of vRESs, grid codes did not include regulations for wind and solar systems because the installed generation was very insignificant compared to the traditional generation systems. This situation has been changing in recent years as the level of vRESs integrated in distribution grids is on the rise. Such a massive integration of vRESs creates genuine stability concerns in the system due to the negative impacts of large solar and wind power plants. These concerns are related with voltage and frequency drops in the presence of a fault or high winds, making wind turbines stall, that can lead to outages [33].

Accordingly, rigorous technical requirements are enforced to protect networks to contrast to these threats. As an example, wind power plants are required to withstand various grid disturbances and contribute to the stability of the system and provide ancillary services. The technical challenges that vRES introduces to electrical power systems increases the need for high level flexibility from other parts of the systems and flexibility through interaction with other energy sectors, like heating sector, natural gas and interaction between transportation and distribution systems [25].

1.2.4 The Path Towards More Flexible and Smarter Grids

Given the new developments from the demand and supply sides, distribution network systems need to undergo the necessary transition to more flexible and smarter grids. Future grids will be equipped with different types of flexibility options such as energy storage systems (ESSs), reactive power sources such as switchable capacitor banks (SCBs), demand response (DR) and dynamic network reconfiguration (DNR). Moreover, a coordinated deployment and scheduling of flexibility options are needed to optimally manage an increased penetration of vRES in distribution systems. For example, energy storage systems can be added onsite for frequency control and add quick reserve capacity to the system. ESSs can also provide other services. Their fast response means that they can be part of the ancillary services (frequency control) and suited to black-out restart of the system. The operation principle of ESSs is to store excessive energy during the low demand period that will be utilized in periods of high demand.

Load flexibility options like demand response (DR) can also enhance the integration of vRESs, giving the control of operation of contracted services to a new competitor, named aggregator. From the network side, one example of potential flexibility option is dynamic reconfiguration of the distribution network system. Dynamic reconfiguration can play substantial role in improving reliability, increasing RES penetration and minimizing power losses. Switchable capacitor banks can also provide adequate flexibility to the system, enhancing stability and RES integration level.

Flexibility options form important components of power systems and play important roles in the transformation of current electric power systems to smarter grids in the future. Most current systems are based on fossil fuels. Yet, the recent trend of system evolution shows that future grid systems will be based on the efficient accommodation of large scale variable renewable energy sources [34]. The existence of sufficient operational flexibility is a necessary prerequisite for the efficient large-scale integration RES energy in such network systems. Flexibility is not only necessary to mitigate supply variations due to increased uncertainties but also the variations in from demand side due to new and relatively unpredictable energy consumption forms. This is graphically illustrated in Figure 1.4.

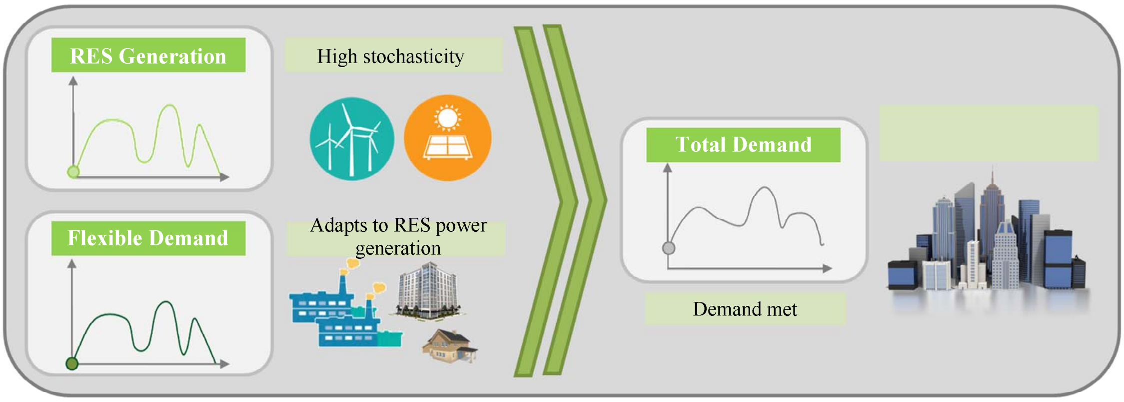


Figure 1.4. - Flexibility options and smart grids.

Therefore, future power grids need to become smarter, allowing multi-directional power flows, and allowing consumers to no longer have a passive role instead to play an active role in the electricity markets [11], [35], [36, p. 21]. Intelligent infrastructures are being developed both at the distribution and transmission levels. Intelligent network projects are being generalized around the world, where budgets have kept on increasing almost exponentially from 2006 [12].

However, the development of smart grids faces a significant set of challenges. In particular, standardization of communication and operational protocols, which will play a key role in future networks, is yet an ongoing process. Energy consumption optimization should be based on near-real time, which requires well-developed communication framework to facilitate the active interactions between producers and consumers. In order to select these communications individually, standardized protocols already exist. However, these are limited to a single domain [37]. With regard to the introduction of smart grids, one of the key tasks in the near future is the establishment of an interactive bidirectional communication system from the generation to the final consumer.

Having smart grids in perspective, the main ways to introduce flexibility into the electrical system are through the introduction of fast markets, flexible generation (e.g. gas and water), demand side management, energy storage systems and interconnections. The smart grids in combination with all other forms of flexibility options mentioned previously will considerably increase the flexibility of the system, overcome congestion in the network systems, either by changing flexible loads from peak periods to periods with less congestion, or through the control of the network power flow due to the integration of large-scale renewables in the near future, among others. This leads to the creation of a more flexible and manageable network. However, the costs and benefits associated with the development of smart grids and network flexibility have direct and indirect effects, as can be seen in the scheme of Figure 1.5.

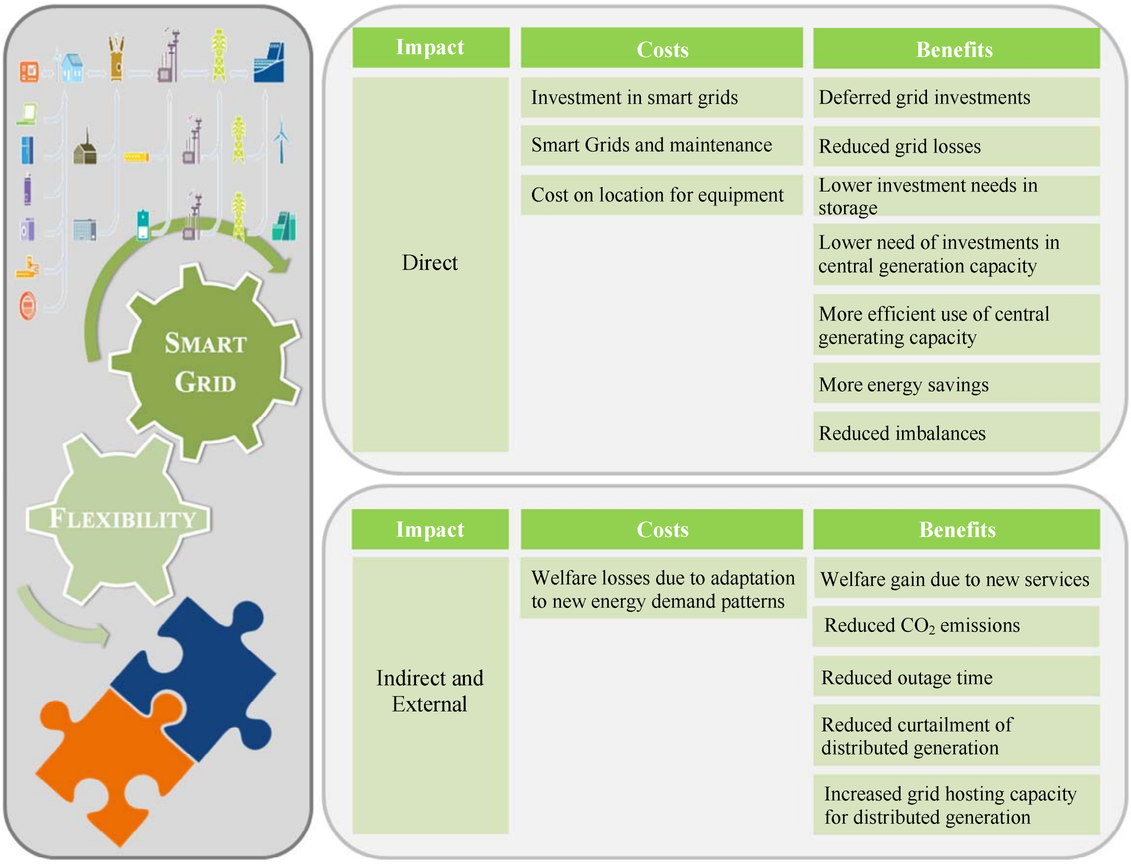


Figure 1.5 - Comparison of potential costs and benefits of developing smart grids and flexibility.

With regard to integrated solutions for low carbon emissions, Smart Grids will be a key element in the implementation of modern technologies. The need for flexibility resulting from the integration of renewable energies, demand and contingencies can be met in different ways, including through flexible generation, response to demand, energy storage and interconnections of the electrical networks. All this makes it a key component for the emergence of Smart Grids.

1.3 Research Motivation and Problem Definition

Existing electrical distribution network systems may become unsustainable in the future if nothing is done. This is because they are not capable of managing the growing need of integrating variable energy sources to address a multitude of global as well as local concerns. The concerns surrounding climate change, energy security and growing demand for electricity, are forcing dramatic changes to the way distribution networks are planned and operated. This is a result of large-scale integration of variable renewable energy sources at distribution levels.

An increased level of such energy sources creates technical challenges in the system, a huge concern for distribution system operators (DSOs) who are given the mandate to keep the integrity and stability of the system as well as the quality of power delivered to the end-users. Hence, existing network systems need to go through a series of eminent transformation processes so that current limitations are significantly alleviated or even avoided. This is expected to slowly but surely lead to the so-called smart grids. Some advantages related to smart-grids are reduction of greenhouse gas (GHG) emissions, demand side management, encouraging energy efficiency, improving reliability and power delivery as well as creating the necessary platform to easily integrate distributed generations (DGs) [38], [39].

For distribution networks to accommodate large quantities of variable energy sources, new and emerging flexibility options pertaining to the generation, demand and network sides need to be deployed in the entire grid to ensure its seamless and optimal operation. Clearly, the management and coordination of various flexibility options needs to be carefully handled by minimizing the side-effects such as increasing costs, worsening voltage profile and overall system performance, etc. This research work mainly focuses on flexibility options that can be provided by the network itself but with some coordination with those provided by the remaining two. Such analysis is supported by optimization models formulated here in a stochastic framework. It can be understood that the whole approach in this thesis emulates the so-called smart grids concept.

Smart grids are systems that incorporate dynamic optimization of the grid operation. This can involve, for example, dynamic reconfiguration processes and demand-side management, with digital communication and smart meters facilitating these processes [38]. From this context, the work here develops an optimization model that ensures an optimal operation of distribution networks with large quantities of vRESs and taking into consideration the stochastic behavior of the system. This can be regarded as the first step to understand the major considerations to evolve from the traditional distribution network to a smarter distribution network.

A key factor to evolve to a smart-grid can be the transformation from a radial network to a meshed one. This is deemed to increase network-related flexibility in the system, leading to higher integration of distributed generations of vRES type. As the source of energy is not limited to the traditional power generations, with the operation of wind, solar or biomass power technology, optimal allocation of distributed renewable generation can effectively relieve the energy crisis mainly in terms meeting increasing energy demand and reducing the GHG emissions [40]. One of the major concerns associated with variable energy sources is their intermittent nature, which endangers the quality and stability of power grids.

However, an optimal deployment of flexibility options such as Energy Storage Systems (ESSs), Dynamic Reconfiguration (DR) and Demand-Side Management (DSM) can positively influence the operational requirements in such grids. The challenges with demand coordination complexity, diversification and stability of power supply, efficiency and economic problems are stated in [41].

From this perspective, it is necessary to understand how a distribution network system can be optimally operated when featuring large-scale variable RESs. Because of the variability and uncertainty pertinent to these technologies, new methods and tools need to be developed to deal with the ensuing challenges. To this end, emerging and existing flexibility options need to be deployed to manage the uncertainty and the variability of variable RESs and keep the balance between demand and supply in real-time [7].

For example, integrating ESSs can help to smooth power output from variable RESs and, at the same time, reduce marginal costs of the system because cheap energy is stored when energy production is higher than actual demand. Another way to provide system-wide flexibility is via demand side management, one of which is to shift certain percentages of non-critical demand to a period with low tariffs, bringing economic benefits to end users and operational benefits to the network system. In line with this, the thesis work carries out an extensive analysis of the main technologies that can provide flexibility, and their contributions to the optimal operation of distribution network systems. This is accomplished by taking into account the stochastic nature of intermittent power sources and other traditional sources of uncertainty. In addition, the work encompasses detailed investigation of the system featuring these technologies in such a way that a major percentage of demand is met by variable RESs while the reliability, stability, efficient and economic operation of the grid is maintained at standard levels.

1.4 Research Questions, Objectives and Contributions of the Thesis

This thesis comes up with the intention of analyzing flexibility options in order to achieve maximum vRES power utilization in a short term operation scheme of distribution networks. Such an analysis is made taking into consideration the operational variability and uncertainty associated with vRES power generation.

The objective of this thesis is to increase the utilization level of vRES power (wind and solar) deployed in distribution networks with the support of various flexibility options. This is done by maintaining the standard levels of power quality and stability of the distribution network, and minimizing operation related costs.

The following research questions are addressed in this thesis:

- *What are the main existing and emerging flexibility options that can be deployed in power systems to support the integration of "carbon-free" and variable power production technologies? What are the main challenges and opportunities associated with various flexibility options provided by different technologies?*

- *From the existing and emerging flexibility options that can facilitate the integration of large-scale vRESs in the next-gen distribution systems, what are the best combinations of flexibility options that maximize the utilization level of vRES power?*

    - *From a quantitative and qualitative viewpoint, what are the impacts of deploying flexibility options such as Demand Response, Energy Storage Systems and Dynamic Reconfiguration on the overall operational performance of the system?*

    - *What is the level of flexibility that a dynamically changing network can provide and what is its impact on vRES utilization level?*

The main objectives of the PhD thesis are highlighted below:

1) To carry out state-of-the-art literature review on the technological advances of flexibility options to transform current distribution network systems into standalone smart systems, capable of accommodating large-scale distributed variable energy sources (wind and solar, in particular).

2) To develop appropriate stochastic optimization models for optimally managing next-gen distribution network systems featuring large-scale intermittent power and other distributed energy resources.

3) To explore new distribution network flexibility options for maximizing the utilization of variable renewable energy sources.

4) To carry out an extensive analysis regarding the costs and the benefits of meshed operation of distribution network systems on the penetration level of variable energy resources.

The contributions of this thesis are summarized as follows:

- A comprehensive survey of flexibility options, pertaining to demand-side, supply-side, network-side and other sources, for large-scale integration of low carbon technologies. This contribution is published in ***Renewable and Sustainable Energy Reviews - ELSEVIER*** [43].
- The development of an operational model featuring large-scale intermittent power sources with the help of various flexibility mechanisms. This contribution is published in a ***Book Chapter*** in ***SPRINGER*** [44].
- The development of a stochastic MILP operational model considering Demand Response, Energy Storage Systems, and Dynamic Reconfiguration to support more integration of vRESs. This contribution is accepted for publication in the ***IEEE Transactions on Sustainable Energy***.
- The presentation of a stochastic MILP operational model to increase the use of renewable energy in daily use, taking advantage of the new technologies, where, distribution systems can be operated in a meshed manner considering several levels of complexity. This contribution is accepted for publication in ***Energies (Open Access Journal)***.

1.5 Methodology

In this thesis, the mathematical models developed are based on well-established methods, specifically, mixed-integer linear programming (MILP) and multi-objective optimization. To achieve the objectives set in this thesis, appropriate optimization tools, methods and solution strategies are developed to evaluate the operation of distribution networks under uncertainty, variability and a variety of flexibility options over a 24-hour time-period. The optimization models are implemented and coded in GAMS™ and solved using CPLEX™ mostly by invoking default parameters.

1.6 Notation

The present thesis uses the notation commonly used in the scientific literature, harmonizing the common aspects in all sections, wherever possible. However, whenever necessary, in each section, a suitable notation may be used. The mathematical formulas will be identified with reference to the subsection in which they appear and not in a sequential manner throughout the thesis, restarting them whenever a new section or subsection is created.

Moreover, figures and tables will be identified with reference to the section in which they are inserted and not in a sequential manner throughout the thesis. Mathematical formulas are identified by parentheses (x.x.x) and called "Equation (x.x.x)" and references are identified by square brackets [xx]. The acronyms used in this thesis are structured under synthesis of names and technical information coming from both the Portuguese or English languages, as accepted in the technical and scientific community.

1.7 Organization of the Thesis

This thesis encompasses five chapters, organized as follows:

Chapter 1 introduces this thesis. The content in this chapter starts with a background. This is then followed by brief descriptions of research motivations and problem definition. Then, the research questions, objectives and contributions are provided. The methodology in this thesis is subsequently presented, followed by notation assumed in this thesis. This first chapter is concluded by delineating the organization of the thesis.

In Chapter 2, a wide-range summary of flexibility options is presented. At first, flexibility options are framed in the context of integration and utilization of vRES power generation at distribution network level. Then, a full characterization of different flexibility options in different sides of a power system is presented.

In Chapter 3, the operation model developed in this thesis is introduced, describing the stochastic framework in which the model is formulated. The methods used for handling uncertainty and variability are fully presented in this chapter. This is followed by case studies intended for understanding the impacts of flexibility mechanisms in terms of operating distribution system with large-scale vRESs. The case studies involve two standard IEEE test systems, the 41-bus and the 119-bus distribution networks.

A meshed network operation as a way of flexibility is introduced in Chapter 4. The problem is formulated also as a multi-scenario optimization problem, accounting for uncertainty and variability in the model. To demonstrate the benefits, the same 119-bus distribution network is used in the analysis.

Chapter 5 provides some concluding remarks drawn from the analysis made in this thesis. The scientific contributions from this research work are summarized in this chapter, supported by the publications in journals with high impact factor (first quartile), and book chapters or in conference proceedings of high standard. Indications for future works in this field of research are also presented in this chapter.

Chapter 2

Flexibility options for supporting the low-carbon energy future

This chapter presents an extensive and critical review of the main existing and emerging flexibility options that can be deployed in power systems to support the integration of "carbon-free" and variable power production technologies. Starting from a broader definition of flexibility, this chapter highlights the growing importance of such flexibility in renewable-rich energy systems and provide insights into the challenges and opportunities associated with various flexibility options provided by different technologies. The chapter also summarizes the main barriers to the deployment of more flexibility options.

2.1 Introduction

Driven by several factors such as favorable RES integration policies and growing environmental concerns, investments in variable RESs such as wind and solar have been recently outpacing investments in conventional ones. And, this trend is largely expected to continue even in a more pronounced manner amid the ambitious emission reduction targets put in place by many states across the world. The European Union (EU), for example, has a target to reduce greenhouse gas (GHG) emissions in 2050 by 80 to 95% compared to the 1990 levels. This can only be achieved by integrating "clean" energy technologies, mainly, wind and solar [45]. In particular, wind and solar power sources are expected to provide half of the electricity consumption in the EU by 2050 [45]. This indicates that the installed capacities of wind and solar technologies will have to dramatically increase in the near future both at transmission and distribution levels [46], [47]. Increased quantities of such resources creates enormous technical challenges especially in distribution systems [48]. This is because conventional distribution networks are simply not designed to accommodate generation sources. The presence of generation sources means distribution systems will face bidirectional power flows, making control, safety and flexibility more relevant issues [48]. Under these circumstances, maintaining the standard levels of reliability, security and power quality is not an easy task [46], [49]. To effectively integrate wind and solar power, additional reserve capacity is needed [50], [51]. It is known that conventional power plants often provide majority of the reserve capacity needed in power systems. But this may not be sufficient in the future because of the inherent variability and uncertainty of wind and solar which dramatically increase the amount of reserve required to maintain a healthy operation of the system.

Moreover, under such circumstances, the traditional way of firming reserves may not be economical in the first place, and environmentally friendly in the second place [50], [51], [52]. However, the use of various flexibility options can substantially reduce the negative effects of integrating RESs such as this one. Note that flexibility should be understood as the ability of a power system to cope with the imbalances in generation and demand created as a result of abrupt changes in system conditions (which are triggered by unpredictable nature of some renewable power generation sources, contingency situations, etc.). Traditionally, such flexibility is largely provided by conventional power sources. However, due to the advent of new technologies and concepts such as demand response, this role has been changing especially in recent years. There are various emerging technologies that can provide efficient flexibility options (which are the subject of this chapter). Therefore, the future energy sector is expected to provide secure, reliable and affordable energy services to end-users. For this, the sector needs to be highly efficient and possess environmentally-friendly energy sources [53]. In this context, flexibility options play a crucial role in achieving the required efficiency, reliability, cost effective tariffs for end-users and simultaneously reducing GHG emissions worldwide.

The unique feature of power systems is the need to match demand and supply in real time. Power systems require flexibility to continuously match demand with supply both of which are subject to high level variation and uncertainty [54], [55]. When the penetration level of renewables gets higher and higher, traditional flexibility mechanisms (mostly provided by conventional power plants) are not simply sufficient. New flexibility options are required to ensure a proper balance between supply and demand [42], [54]. Another issue is that sustainable energy management endeavors are being affected by an increased demand, ineffective production practices and insufficient power supply [56]. The flexibility options can take part in efficient strategies to integrate variable RESs in power grids [49]. Flexibility options are resources that help the system to effectively deal with imminent changes in operational conditions [42], [49], [57] . Such flexibility is also associated with frequency and voltage control, a useful tool in handling uncertainty and variability of power systems and ramping rates [51], [52], [54], [57]. Flexibility options can also be used to defer investments in certain components of power systems, which implies that such systems operate optimally [57], [58]. Correspondingly, an increased usage of carbon-free technologies requires greater flexibility, and enhances the “active management and better use of existing network-related resources” [59], [60]. Flexibility options can be provided by technologies deployed at the supply, network and/or demand sides. The present work largely structures the flexibility options based on such hierarchical classifications. The flexibility options from the supply side, which will be shortly discussed in this chapter, include enhanced ramping capabilities of conventional power plants, flexible generation, diversification of power generation, wide-area generation expansion, RES power curtailment, etc.

Flexibility mechanisms on the demand side such as demand response, energy efficiency, electric vehicles, etc. are also broadly described in the following section. Electricity networks can also provide some flexibility options via optimal network reconfiguration, smartification of the grids, dynamic line rating, wide-area interconnections, meshing, etc. Apart from all these, energy systems integration, energy storage systems, effectively designed regulation and energy markets can also provide essential flexibility in power systems and enable large-scale integration of intermittent resources. Figure 2.1 schematically summarizes the increasing need for flexibility options and their main sources.

2.2 Review of Flexibility Options

As stated earlier, flexibility can be provided by different components of power systems placed at the supply, network and/or demand side. The flexibility options reviewed in this thesis are mostly structured into these main pillars. However, the review also encompasses flexibility options provided by emerging technologies such as energy storage systems which can be optimally placed at either side of power systems. In addition, the main institutional mechanisms such as energy systems integration that have proven or foreseen capabilities to enhance power system flexibility are broadly reviewed.

2.2.1 Demand-side Flexibility Options

In power systems, it is widely known that the demand side has huge potential for flexibility provisions. Such flexibility options mostly come as a result of changes in the consumption patterns of end-users in response to financial and non-financial incentives and/or dynamic price signals. The resulting changes could be permanent (such as energy efficiency) and/or temporary (demand response such as shifting energy consumption from peak to off-peak hours).

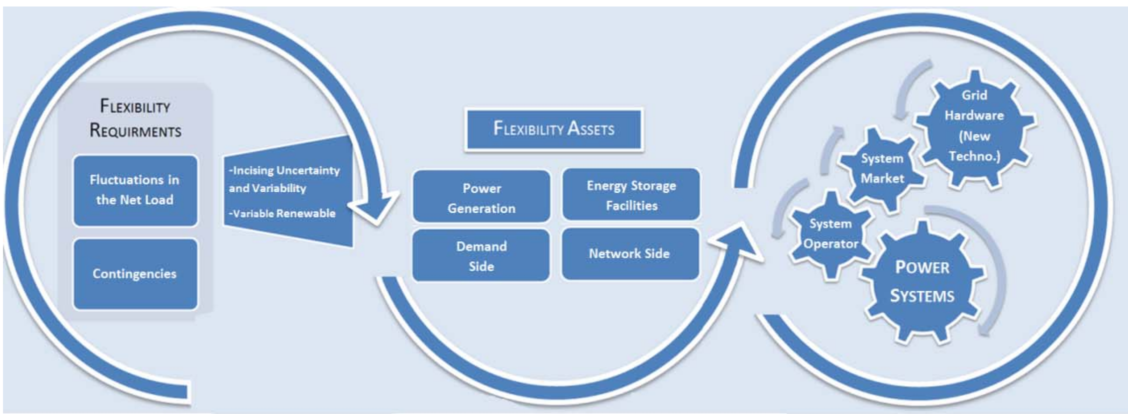


Figure 2.1 - Flexibility needs in power systems.

Demand side flexibility mechanisms are emerging as the most viable and "least cost" means of enhancing power system flexibility, and thereby increasing the integration of intermittent power sources. Among the most prominent sources of flexibility options reviewed here are demand response, energy efficiency and new forms of electricity consumption.

2.2.1.1 Demand Response

Demand Response (DR) is one of the flexibility options obtained from the consumers' side, and involves alterations of energy consumption levels and/or patterns of end-users in response to dynamically changing prices and incentives (for example, see in Figures 2.2 and 2.3). In other words, properly designed DR programs make electricity demand more flexible, responsive and adaptable to economic signals [46], [61]. As shown in Figure 2.3, the alterations could be in the form of reduction, shift in energy consumptions or both depending on the consumers' price elasticities of electricity demand. Note that an elasticity index quantifies the relative change in consumption as a result of marginal changes in an electricity price. When the values of such indices are high, more dramatic changes will be observed in consumption patterns. As illustrated in Figure 2.3, higher self-elasticity values lead to higher peak shaving and valley fillings, and hence, a flatter demand profile along the day.

Demand response can be either incentive-based or price-based. The former category is characterized by changes in the consumers' electricity consumption in response to non-price signals (often, financial or non-financial incentives). Whereas, the second one relies on price signals to change consumption patterns. Incentive-based DR include demand side programs such as direct load control, curtailable load services, demand bidding or buyback programs and emergency DR among others. Price-based DR on the other hand mainly includes time-of-use (ToU), critical peak pricing (CPP), peak time rebate (PTR) and real-time pricing (RTP) programs. The example shown in Figure 2.3 falls in the second category, RTP program.

Apart from the flexibility perspective, demand response has wide-range benefits, which can be found in the extensive body of literature in this subject area. Even if the benefits of DR are widely recognized, its penetration level is not significant in many power systems due to several limitations such as lack of appropriate market framework, effective forecasting tools, and communication and control strategies. However, the interest in DR has been growing in recent years because of many factors such as increasing level of variable power generation which in turn builds up the flexibility requirements in such systems, significant advances in IT and continuously improving forecasting tools, etc. Generally, there is a strong body of evidence on the potential of DR in reducing costs for end-users and improving the integration of variable RESs [46], [62]. There is no cloud of doubt that DR will be part of the solution to the endeavors in creating a sustainable energy future, and addressing a multitude of global as well as local concerns such as climate change and energy security.

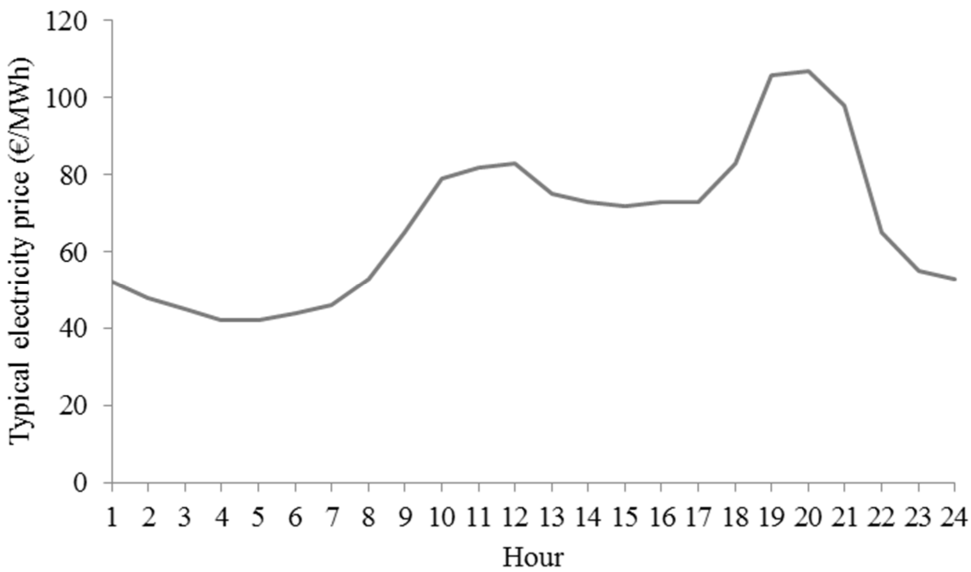


Figure 2.2 - Real-time electricity prices.

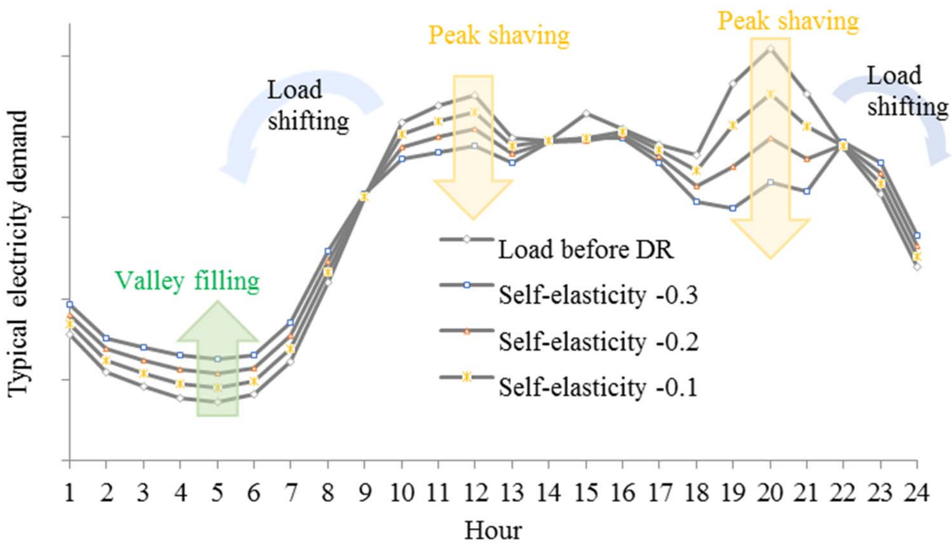


Figure 2.3 - Flexibility via demand response programs – an illustrative example

Demand response is normally achieved by introducing a new competitor in the market, called aggregator, to control the operation of contracted services, but also sell flexibility services to system operators or directly to an electricity market [57], [61], [62]. DR can be based on a direct control and an indirect control mechanism [63]. Under a direct control setup, the aggregator has direct communication with individual utilizations and comprehensive information on their relations with the neighboring environment [63]. Computationally, this may be very exhaustive, but it is characterized by an exact response, with controllable set-points that can be directed to each individual purpose, this enables demand control at the highest possible resolution [63].

Under an indirect control scheme, the aggregator has limited information about the actual demand. However, it must evaluate the price response of the collected demand, with prices being geographically fluctuating depending on the resolution of the information available to the aggregator [63].

The literature on DR is vast; the current work aims to complement earlier reviews by other researchers. Tulabing *et al.* [51] propose a methodology for DR that aggregates electrical loads, electric vehicles (EV) and storage. Del Granado *et al.* [55] formulate a dynamic optimization model for systems composed of a co-generation unit, gas boilers, electric heaters and wind turbines with storage units. The main purpose is to analyze storage policy strategies to satisfy heat and electricity demand and discover operational mechanisms for a more efficient utilization of distributed generations (DGs) under DR programs. Similarly, Agnetis *et al.* [62] use a mixed integer linear programming (MILP) model to optimize the profits of an aggregator who manages aggregated consumers, gather flexibility and generate bids for electricity market. Alcaraz *et al.* [64] resort to an analytical approach to illustrate the effects of DR on the efficiency of the network's operation. In their work, dynamic pricing has been used with critical peak shaving tariffs and hourly pricing schemes. Haque *et al.* [65] present an extensive discussion on a decentralized method to empower DR for managing congestions in a better manner. Despite its wide-range benefits, DR faces many challenges, which needs to be overcome. Eid *et al.* [66] have attempted to identify the main obstacles for DR aggregators in Europe and provide a policy review for European market designs to support aggregation processes. In relation to this, Zhang *et al.* [67] propose a flexible market aggregator, called FLECH to promote small scale distributed generation to participate in flexibility services such as ancillary services. Heussen *et al.* [68] also propose a similar FLECH aggregator. More works on DR mechanisms can be found in [69]-[155].

As mentioned earlier, demand response can in principle provide ancillary services, which are largely accepted to be more competitive and economically viable. As such, DR programs providing ancillary services are trivial players in the grid. Yet, it is necessary to evaluate the economic and regulatory frameworks to achieve the DR's maximum potential in providing such services. In reality, current regulations and rules are hardly adapted to reap the DR's full potential in providing ancillary services [96]. However, there are several studies that demonstrate the feasibility of DR as a key source of ancillary services. For example, Ryan [156] presents a method to optimally schedule ancillary service provisions by DR accounting for "the risk of consumer response fatigue". Backing with some numerical results, the author concludes that residential DR can solely provide between 50% and 75% of the total ancillary services needed in the considered system. In [157], authors further highlight the potential of DR in ancillary service provision. Their work extensively provides a quantitative analysis of demand response resources that can provide auxiliary services. The economic value and the impact of these resources on the entire energy system are clearly demonstrated in [157].

Generally, some of the wide-range benefits of DR (also contained in [51], [55], [63]–[155]) are summarized as follows:

- DR can be used to support the integration of RESs, and address the fluctuations of RES power outputs by means of load curtailment and shifting;
- Power consumption can be adjusted instantaneously with DR, permitting a more effective ramping rate from the aggregated demand than larger power plants;
- Cost reduction of the system capacity requirements can be achieved with DR.
- DR can balance fluctuations of power productions, reducing peak demand with demand shifting, resulting in big savings by avoiding or deferring investments in peaking plants which are often among the "dirtiest" means of power productions that cause immense environmental pollutions. In this way, existing plants can be better utilized, maintaining constant power output, and allowing a better management of the fluctuations in the generation-demand balances;
- Markets incorporating DR mechanisms may dramatically reduce the frequency of utilizing the most expensive peaking units, effectively lowering the system's marginal costs;
- Reduction in power generation using fossil fuels significantly abates GHG emissions;
- Allowing DR to participate in power markets may lead to an overall reduction in supply and locational market power because DR responds to time varying prices, limiting producers to manipulate wholesale price of electricity. This consequently leads to reductions of average wholesale price and volatility of peak prices;

Although demand response is not new, its implementation has been really slow due to a number of barriers. Despite the wide-range benefits, DR faces enormous challenges mostly related to the control and its optimal usage [63]. Some of the main barriers of DR are summarized as follows:

- *Unsuitable market*: Most of the current energy markets are designed in a centralized manner, and they are not suited for the natural demand diversity and distribution. However, emerging technologies such as blockchain technology and distributed market designs are expected to unlock the immense potential of DR.
- *Non-transparent regulatory and tariff schemes*: In most cases, regulatory and tariff structures are not setup to be visible for end-users. Addressing this issue allows consumers to respond to price signals.

- *Inadequate business environment*: Nowadays, there is an overwhelming difficulty in creating a business case for DR. It is recognized that incorporating demand in electricity markets increases social welfare. Welfare is distributed among different corporations, and can be difficult to create a business model that gather sufficient social welfare with satisfactory certainty to make the business feasible and justify investments in infrastructures.

- *Potential conflicts of interest*: A higher penetration level of DR can lead to potential conflicts of interest. For example, some power plants that participate in reserve capacity markets may be against the implementation of DR because of possible losses in their incomes. If the capacity value and the availability in times of the need for DR is very significant, DR will take over the responsibility for regulation and ramping, decreasing income for peaking power plants.

- *Complex end-users' behavior*: DR heavily involves customers' behavior, which is often difficult to predict. End-users can have different priorities. For example, some consumers may not give priority to reducing their electricity bills at all; others may be interested to participate in DR programs but concerned on privacy issues. The demand curve is affected by different and time varying external factors, like weather or any other factor. Because of all this, demand behavior may not be suitable for conventional economical models.

- *Forecasting, communication, control and modeling limitations*: In order to optimally reap the benefits of DR and maintain healthy operations of systems, reasonably accurate forecasting tools, appropriate communication and control infrastructures need to be put in place. In addition, the nature of DR necessitates accurate modeling of consumers' energy consumption behavior, which is often a challenging task. In many power systems, all these issues have been partly limiting the penetration levels of DR programs. However, over the past few years, there have been significant advances in forecasting capabilities and information and communication technologies (ICTs) as well as continuous improvements in the modeling strand, which can be rolled out to support the full integration of DR programs.

- *Massive investment needs*: Most power systems are not suitable for the DR programs to seamlessly flourish. Hence, effective integration of DR programs in power systems requires at least partly automating existing infrastructures, which means hefty investment needs. This is considered to be one of the biggest hurdles to the demand response penetration.

- *Inadequate incentives*: The savings consumers get from participating in DR programs may be oftentimes small, which may not be attractive enough not only for new consumers to join in but also existing ones to continue in such programs.
- *Privacy and data security issues*: The key factor to DR's success is ICT. But problems arise regarding privacy and security of users' data as well as the entire automated system. This is becoming one of the key challenges for the growth of DR amid increased cyberattacks in recent years.
- *Energy security*: One of the major obstacles to the wide implementation of these resources in the network comes from the fact of schemes that can be applied transversally, in different jurisdictions. As such, one way to assess the influence of these technologies on the level of security of supply is through the use of metrics [158]. For example, one of the metrics that can be used is the ratio between flexible demand and total demand, among others. The use of such metrics will level the use of different technologies which in parallel have the potential to accelerate the integration of these technologies, allowing the transition from the conventional network to an intelligent one.

2.2.1.2 Energy Efficiency

Demand Side Management (DSM) is the ability to influence the use of electricity by end-users or alter the pattern and magnitude of demand [159]–[161]. Some strategies of DSM are peak clipping, load shifting, valley filling, strategic conservation and even strategic load growth [159]. Load shifting requires intermediate storage, and involves a mechanism for rescheduling energy demand. Some examples of load shifting are heat and cold storages. Normally, DSM strategies are employed by utilities when they predict unusual demand patterns [159]. Some of these DSM facets are illustrated in Figure 2.3 and are largely discussed in the previous section under the auspices of demand response. The review in this section is devoted to energy efficiency (also known as energy conservation), which is one of the demand side management programs that are largely anticipated to partly provide some solutions to the energy crisis that may unfold over the coming decades. As graphically illustrated in Figure 2.4, energy efficiency involves voluntary reductions of consumers' energy usage by investing in energy efficient technologies or responding to incentives designed to entice consumers to participate in energy conservation initiatives. Such initiatives heavily depend on the goodwill of end-users. Therefore, one of the key aspects to the successes of such initiatives is empowering consumers so that they voluntarily participate in energy efficiency programs (or, DSM programs in general). The most effective strategies are via appropriately designed incentive mechanisms, which could be financial or non-financial types. For example, consumers can be enticed by offering them contracts with low rates of electricity or giving them certain credits on the maximum demand charge.

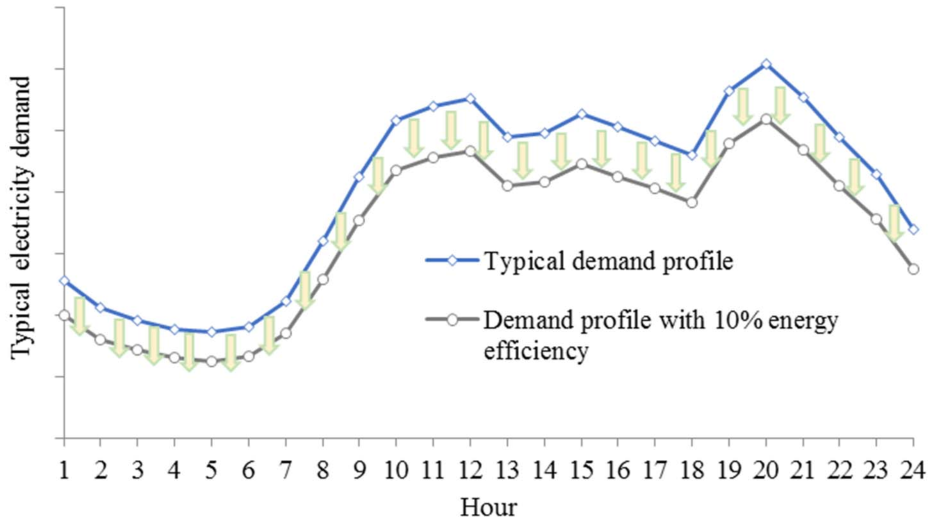


Figure 2.4 - Flexibility via energy efficiency measures – An illustrative example.

Energy efficiency schemes also share some of the advantages of demand response programs discussed earlier. Some of the benefits of such schemes are as follows [54], [160]:

- Balancing energy and capacity;
- Response in various time scales;
- Reducing price spikes and average spot price volatilities;
- Balanced market power i.e. roles shared between generators and consumers;
- Reduced investments in infrastructure expansion;
- Reduced system-wide costs as a result of reduced usage of peaking power plants;
- Reduced transmission and distribution losses;

Some of the barriers for energy efficiency measures are [54]:

- Lack of information and communications technology (ICT);
- Inadequate technology financing;
- Inadequate incentive mechanisms (often small savings for participating in energy efficiency programs);
- Lack of key stakeholders' strong involvements;
- Lack of adequate structural and market designs;
- Lack of appropriate regulatory and policies to promote energy efficiency programs.

2.2.1.3 Unconventional Energy Consumption Forms

Currently, the energy consumption throughout the world heavily depends on fossil fuels. Fossil fuels are largely used among others in transportation, industry, commercial and residential sectors and even to generate electricity. In fact, on a global scale, nearly 80% of the energy consumption by mankind comes from burning these non-renewable fuels. This is however gradually changing amid growing concerns in several intertwined issues such as climate change and energy security. As a result, over the past years, a lot of countries have been gearing up efforts to decarbonize their energy industries by embarking on ambitious targets to increase the penetration levels of renewables. Apart from the conventional forms of final electricity consumption, new ones are taking shape across various energy intensive sectors. Among these "unconventional" energy consumptions is electric mobility (also known as e-mobility). Across this line, the numbers of electric vehicles (EVs) are growing rapidly in many countries. EVs can be considered as mobile energy storage devices, with relatively regular charging and discharging cycles. They are connected at the distribution level of power systems. Such vehicles can be plugged in to the grids during night at places where the end-users reside, and/or daytime close by commercial places. This makes EVs such good candidates for providing the much-needed flexibility in electricity grids. Generally, it can be said that EVs have relatively good availability, predictability and easy controllability [162]. This means they can offer a broad flexibility bundle including services like energy scheduling, reserve capacity, regulation, emergency load curtailment, energy balancing, power quality enhancement and supporting RES integration and utilization [54], [163]. However, all this requires the provision of appropriate technologies such as smart counters, telemetry and two-way communications. It is worth mentioning here that DR mechanisms could be employed here to aggregate EVs to accomplish the required scale of flexibility. In this respect, Knezović *et al.* [162] deduce that the technical requirements and the organizational framework of the flexibility that EVs can provide to DSOs, with market design recommendations.

2.2.2 Supply-side Flexibility Options

There are a number of flexibility options that can be delivered by the supply side. The most important ones come from conventional power sources in the form of flexible generation and enhanced ramping capability, from diversified and complementary energy resources, strategic curtailment of RES power, as well as from wide-area variable power generation planning. These are discussed in the following subsections.

2.2.2.1 Conventional Power Plants

For a proper operation of power systems, demand and supply should be instantaneously balanced in every split second. In other words, flexibility is required to manage the unavoidable variations in demand, generation or both due to unforeseen operational situations. Such a balancing service (or flexibility) is traditionally provided by conventional power plants. The flexibilities given by such power plants are measures that can modify the output of power supply to achieve balance in the grid. Depending on their levels of flexibility, power plants are classified into baseload, peaking and load following regimes [54].

Baseload power plants such as coal and nuclear run at constant power outputs, and they hardly have ramping or shut-down mechanisms put in place due to technical and economic reasons. In other words, their power production regimes are often inflexible; hence, they are often intended to run as a baseload. However, this is expected to change in the future. Due to the increasing flexibility needs in power systems, such power plants will be required to put in place mechanisms that increase their ramping capabilities and provide considerable flexibility in power productions. Peaking power plants enter into action in high demand situations; so, they have very irregular utilization.

The third category, i.e. load following power plants, includes gas and hydropower plants. These power plants traditionally serve as instant balancing units mainly due to their fast responses, start-up and ramping capabilities. For example, combined-cycle gas turbines (CCGTs) are characterized by high ramping rates (often in the order of 10 MW per minute) and reasonably higher efficiencies (often above 60%); hence, they are often attractive options to increase flexibility in power systems [54]. The fuel costs of CCGTS can however be prohibitively high. And, this may hamper their wide usage as flexibility mechanisms i.e. their use in balancing markets may be limited due to economic reasons [54], [163].

Another example under this category is a combined heat and power (CHP) plant. CHPs are becoming as suitable technologies to enhance the flexibility of power systems, and increase RES integrations. The main flexibility of CHPs is underpinned in the emerging and existing technologies such as heat pumps, thermal storage, electric boilers, etc. They produce heat and power simultaneously with a conversion efficiency of more than 80% [54]. One of the main advantages of coordinating CHPs with RES integrations is the increased rate of load shifting due to thermal storage—an important source of flexibility, leading to a more efficient RES utilization [54].

2.2.2.2 Strategic RES Power Curtailment

The power outputs from variable energy sources such as wind and solar are subject to high level uncertainty as these sources heavily depend on weather conditions which are partially unpredictable. Sometimes, the actual power potential could be substantially lower than the forecasted value. Other times, the actual power productions by RESs could largely exceed predictions or even the actual demand. Either case leads to large unforeseen demand-supply unbalances in the system. Under such situations, the balancing process may be very expensive and/or technically impossible. One may argue here that situations with low RES power productions could be relatively easier to manage than those with excess RES power, especially in the absence of any energy storage medium. In the latter case, regulating RES power injection in to power systems could be economically feasible [54]. In other words, a strategic curtailment of RES power could be justified under the following situations: over-generations, oversupply of RES power outputs, congestions and widespread use of inflexible baseload generators. Strategic curtailment can also be done to dampen quick changes in power productions or in the provision of reserve power capacity by a ramp-up margin [54]. All this could increase flexibility in power systems.

2.2.3 Network-side Flexibility Options

Transmission and distribution networks are the backbones of power systems. These power system components can also provide important flexibility options by means of network reconfiguration (switching), smartification (both at transmission and distribution levels), dynamic line ratings, wide-area interconnections, meshed operations, etc. The following subsections present discussions of some of these flexibility mechanisms.

2.2.3.1 Smart-Grids

Although the term smart grid is widely used in the literature, there is generally no agreed definition of this term. There is however a general consensus on its concept and technologies adopted for its adoption [164], [165]. For example, according to the Strategic Deployment Document for Europe's Electricity Networks of the Future, a smart grid is defined as “an electricity network that can intelligently integrate the actions of all users connected to it”, generators, consumers and prosumers, “in order to efficiently deliver sustainable, economic and secure electricity supplies”. The Korean Smart Grid Roadmap 2030 states that, a smart grid refers to a next-generation network that integrates information technology into the existing power grid to optimize energy efficiency through a two-way exchange of electricity information between suppliers and consumers in a real time.

It is important to note that the term “smart” refers to the integration of a set of technologies and software in the electrical networks, allowing such networks to function autonomously (or at least partly). This leads to a more optimal network operation in the short and long term time horizons. Smart grids are generally characterized by some sort of intelligence. And, such intelligence can come from different sources, such as through the automation accompanied by supervisory control and data acquisition (SCADA), state-of-the-art energy management systems (EMS), and demand management systems (DMS) among others. An example of this is demand-side intelligence, which, with the integration of smart meters and advanced metering infrastructure, enables sharing information not only with an aggregator but also with a network operator, so that the entire grid can be operated more efficiently.

The focus on electric networks in terms of flexibility provision has been dramatically increasing over the last decade or so. In particular, the issue of network smartification has been gaining more attention in the last few years. As mentioned earlier, the smartification process involves gradual transformation of existing passive electric networks into smarter grids which are equipped with state-of-the-art information and communication technologies (ICTs). This makes control, protection and energy management relatively easier [65], [166].

In terms of flexibility, smart grids for example make it possible to know end-users’ demand patterns in real-time thanks to a well-developed two-way information communication, smart metering facilities and immense automation [54], [55]. The communication among energy producers, end-users and network operators is made easier in a smart-grids arena, leading to more efficient operations of power systems [54]. In addition, due to the communication and metering technologies, the use of RESs to balance grid services can be achieved. In particular, smart grids have been touted as one of the key ways for abating the negative effects of the increasing penetration level of variable RESs in power systems. For example, in smart grids, any shortfall in electricity supply can be easily counter-balanced by optimally changing demand in the form of an active demand response [55]. Smart-grids can be equipped with advanced technologies such as soft open points (SOPs), power electronic devices, replacing open points in active distribution systems, providing active and reactive power flow control and voltage regulation under normal operations, and fast fault isolation and restoration under abnormal situations [167]. González and Myrzik [168] estimate the degree of flexibility of an active distribution network which has RESs interfaced via full-power converters. Their results show the capability of the active distribution networks in providing ancillary services for a short period of time considering the availability and uncertainty of RESs.

In general, smart-grids are largely expected to play a key role in creating a sustainable, affordable and reliable energy future. In other words, smart grids will help to resolve a multitude of concerns related to energy supply worldwide; particularly, in increasing the reliability of power supply while reducing GHG emissions and other ecological impacts as well as savings in operation and investment costs. Smart grids are also expected to create a level playing field for all types of producers and consumers which is very crucial for having more optimal and efficient energy systems [54].

However, the gradual transformation of passive networks into smart grids comes with a number of challenges [169]. One of these challenges is security of supply. In the network transition process, a significant set of technologies will have to be integrated. In addition, conventional power generation regimes will be changed in order for power systems to become increasingly renewable. Consequently, the integration of large quantities of vRESs considerably reduces the amount of energy generated by conventional power plants. All this, along with the decommissioning of older thermal and nuclear power plants [158], [170], may have strong influence on the security of power supply. This remains to be one of the key concerns in many jurisdictions. However, such concerns may be alleviated by deploying a set of smart grid enabling technologies such as ESSs and demand response.

2.2.3.2 Dynamic Network Reconfiguration

It is known that electrical power systems have several interacting components such as renewable and conventional power generators, energy storage media, large and small consumers, different network components, etc. Of a paramount importance in the day to day operation of such systems is keeping the interaction among these components at a standard level. In fact, the target of such interactions should be to create more reliable and efficient systems that can cope with any operational event that may unfold over time. Lack of proper coordination in such interactions may result in large-scale interruptions of supply, and even a complete collapse of the overall system. To ensure an optimal operation of such systems, it is very important to build mechanisms that take their dynamic nature into special account [171]. For example, the increasing penetration of renewables in distribution systems may complicate the control and energy management in these systems, especially considering the static and passive nature of electrical distribution networks. Basically, distribution systems may be built as meshed networks but they are normally operated in a radial manner, which is often kept static regardless of the operational situation in the system [171]. Such a network setup does not provide enough flexibility to the continuously changing and unpredictable conditions that may happen in current and future power systems. However, a dynamically changing network system can partly cope with this dynamism. An optimal configuration of the system can be achieved by maneuvering closed or opened branches [171], [172]. The aim of a dynamic reconfiguration is therefore to automatically adapt the network to varying operational situations, which may be caused by variable RES integration or any unforeseen system condition [166], [173].

Generally, network reconfiguration can be classified in two categories: static and dynamic. In a static reconfiguration, a single configuration is determined at a specific time, and considered to be optimal regardless of the changing operational conditions; hence, this topology is kept the same over an extended period of time [172]. On the other hand, a dynamic reconfiguration method considers different time intervals, and hence, new configurations are obtained that are fit enough to cope with different types of operational situations [172]. In fact, the optimal time intervals to perform dynamic network reconfigurations are subject to further studies [172]. But the major difference between static and dynamic reconfigurations is that, unlike the static one, dynamic reconfiguration considers varying operational situations [174]. In real systems, dynamic reconfiguration can be considered as a viable flexibility option that can provide a safe and more efficient power system operation because of the consideration of continuously changing operational conditions along a specified period of time. Apart from the flexibility provision, dynamic reconfiguration can play an important role in power losses minimization in smart systems [175]. Furthermore, it is important for restoration of supply after faulty events and to perform maintenance operations in power plants [176].

In the literature, Alcaraz *et al.* [56] propose a two-phase approach for a short-term operational scheduling of RESs in distribution systems. The first phase determines the power purchased from an electricity market and a number of DGs integrated in the system, while the second phase is a real-time scheduling coordination with an hourly reconfiguration. Novoselnik and Baotic [171] present a mixed integer second order program (MISOP) predictive control strategy for a dynamic reconfiguration of distribution system with DGs and ESSs. Milani and Haghifam [172] propose a genetic algorithm (GA) approach which aims to determine optimal time intervals for carrying out reconfigurations. Similarly, Huang *et al.* [173] present an optimal reconfiguration model based on dynamic tariffs for congestion management and losses reduction considering EVs. Li *et al.* [174] develop a multi agent system to perform dynamic reconfigurations of distribution systems by dividing each day into several time intervals managed by the agent. Ameli *et al.* [177] use ant colony optimization (ACO) algorithm to dynamically schedule feeder reconfiguration and capacitor banks along with DGs, dividing the planning period into several intervals to determine the optimal topology of the network which matches different operational situations. Tu and Guo [178] present a conceptual model of median current moment for dynamic reconfigurations. Yang *et al.* [179] employ a gradual approach that deals with dynamic reconfigurations of distribution networks. Canzhi *et al.* [180] present a new method of dynamic reconfiguration that is based on credibility theory, and considers day-ahead prediction of PV generation and forecast uncertainty. Meng *et al.* [181] consider large scale integrations of DGs with scheduling of active power outputs and dynamic reconfigurations.

2.2.3.3 Meshed Operation of Distribution Networks

Electrical distribution networks are experiencing new challenges amid the growing changes in power generation from centralized to distributed paradigms. The level of DG integration in such systems is unprecedented. But such networks are not especially designed to support power generation sources. Their sole purpose so far has in fact been to direct power flows from upstream grid (transmission where the centralized generators are connected) to the end-users. This is however slowly changing with the advent of several enabling technologies. A lot of policy makers in the world seem to favor distributed power generation, to the dismal of conventionally centralized power generators. In order this to happen, distribution grids need to undergo a huge transformation process including dramatic changes in the operational scheme. One example from the operational perspective is the topologies of such grids, which are radial in nature. In order to support DG integrations (variable RESs in particular), new operational strategies should be put in place, which enhance the flexibility of the system as a whole, paving the way to more RES integrations. One of these strategies is meshed operation. This goes against the normal operation strategy in conventional distribution grids (i.e. radial) [171] but it can be an important source of flexibility in future electric power systems. Technology-wise, this is already feasible. It has in fact been shown in recent studies [166], [182] that adopting meshed configurations of distribution networks increases DG integration and fulfils reliability requirements. Other previous works in this subject area include that of Ivic *et al.* [182] which present detailed comparisons of optimal power flow outcomes of radial and meshed distribution networks with DGs and compensating devices. Chalapathi *et al.* [183] perform studies on the allocations of DGs in weakly meshed distribution networks and evaluate the contributions of DGs in the meshed network. Yang *et al.* [184] model a method to approximate a large meshed structure of distribution networks to a simple load model consisting of two RLC elements. Yu *et al.* [185] have developed a time sequence load-flow method for steady-state analysis in a heavy meshed distribution system with DG integrations. Generally, previous studies show that a well-adapted distribution network (meshed one, in particular) is expected to play an essential role in future power systems, particularly, in terms of flexibility provisions.

2.2.3.4 Micro-Grid and Islanding Control

Micro-grids can be described as local grids that supply energy to local consumers. Micro-grids are slated as one of the flexible systems that are expected to be part of the solution to integrate more RESs in power systems by properly balancing demand and supply [54], [186]. A micro-grid can include small RESs, CHPs, ESSs, controllable loads and connection to a main grid [54], [186]. Therefore, a micro-grid can be a component of a large distribution network system that can be islanded with a proper islanding control mechanism.

In the event of unavoidable disturbances, micro-grids can be isolated from distribution systems, and continue to operate in an island mode supplying energy locally. However, challenges exist during the transition to the island mode. For example, power balance issues while islanding can lead to frequency instability, and such instability can cause a blackout in the islanded system because of lack of adequate reserve capacity from the main grid [187]. However, if we are talking about an island system that has installed DGs, they are used to re-stablish power balance and prevent blackouts in the islanded zone. In this manner, islanding operation and micro-grids can enhance reliability of the system [186]. Another possible problem that immediately arises is the coordination of feeder protection schemes when changing the topology of the grid. This must be well coordinated to avoid incorrect operation of protection devices.

Cheng [186] highlights the principles of a seamless grid islanding. Results show that DGs can be applied for grid control purposes. Chen *et al.* [187] have developed an Islanding Control Architecture based on the Islanding Security Region. With their method, system operators could effectively know in advance if an island operation a system would be successful given its current operating state. Majzoobi and Khodaei [188] have analyzed the application of micro-grids in effectively capturing load variability in distribution systems. In their work, an optimal scheduling of a micro-grid is proposed and coordinated in order to meet the micro-grid's net load with the aggregated net load consumed in the distribution system, focusing on ramping issues.

2.2.3.5 Network Interconnections

It is widely recognized that interconnections of different electric network systems through enhanced transmission networks facilitate cross-border power flows, and hence access to neighboring energy markets. It is important to note that cross-border flows enable geographical smoothing both at the demand and generation levels, which is very important for scaling up RES integrations. For example, aggregated RES power outputs change softer and slower. And, this decreases flexibility requirements such as balancing services. In addition, interconnections create large balancing areas and a much improved energy management in the resulting systems. It is also worth mentioning that larger balancing areas provide greater access to varieties of load and power generation regimes as well as a larger pool of reserves. All these result in huge flexibility and operational efficiency in the interconnected systems. Despite all these benefits, in most cases, investments in cross-border electricity networks are overlooked due to various reasons such as geopolitical, technical and economic issues. As a result, bottlenecks are created at border areas among different countries. Realizing the wide-range benefits of strengthening cross-border interconnections, many countries are now forging forward towards enhancing and interconnecting their electricity grids. And, this will undoubtedly be an important source of flexibility in creating a sustainable energy future.

2.2.3.6 Network Expansion Planning

Network expansion planning, which is often overlooked, is a very important means to improve power system flexibility. Such an expansion planning process includes reinforcement of existing transmission and distribution corridors, building alternative paths and installing power flow controllers, reactive power sources such as smart-inverters and other advanced technologies. All this helps to meet multiple objectives such as enhancing market efficiency, motivating new market players, proper and optimal management of congestions, and supporting more RES integrations among others.

2.2.4 Other Sources of Flexibility

This section is devoted to other sources of flexibility that mainly fall into the three pillars already mentioned earlier. For example, the flexibility provided by energy storage systems, properly designed market and regulatory aspects are reviewed in this section.

2.2.4.1 Energy Storage Systems

Energy storage is a mechanism that enables one to store energy produced at some time (usually when the demand is low or when there is over-supply) and use it later (often when the demand is high). The use of energy storage systems (ESSs) for enhancing the flexibility of power systems is nowadays at the forefront of many policy makers and planners. Until recently, storing electrical energy in bulk quantities has not been feasible because of economic and/or technological reasons. However, significant advances in storage technologies and their continuously falling capital costs are proving the viability of ESSs in providing flexibility at this important period of time, in which more integration of variable RESs is highly needed to address a multitude of global as well as local concerns. ESSs have multitudes of technical and economic benefits, and can be integrated at the supply, demand and/or network side. In addition, they can be incorporated into wholesale electricity markets and provide support in terms of ancillary services. During periods of low electricity demand, excess energy produced by such sources can be stored and utilized during periods of high electricity demand, reducing or even avoiding the utilizations of peaking power plants which are often expensive and among the “dirtiest” means of power generation [189]. In addition, ESSs can provide grid support. They have fast response, making them suitable to be part of ancillary services, providing frequency and voltage control services [190]. When ESSs are not providing (discharging) power to the grid, they can be utilized as capacity reserves with literally low costs, and are well-suited to restart system operation after black-outs [190]. Figure 2.5 schematically illustrates the benefits and operational schemes of ESSs.

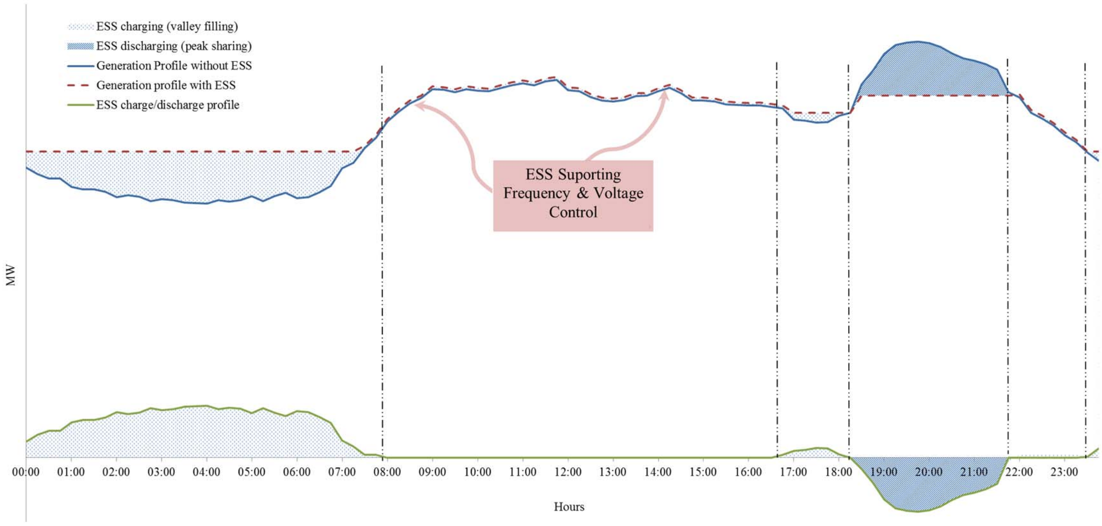


Figure 2.5 - Illustration of the possible roles of energy storage systems.

Generally, ESS technologies can be divided into five groups: 1) physical storages – e.g. compressed air and pumped hydro; 2) electro-mechanical storages – e.g. flywheels; 3) electrochemical storages – e.g. fuel cells and batteries; 4) electrostatic storages- e.g. capacitors and supercapacitors; and 5) electromagnetic storages – e.g. superconducting magnets [191], [192]. Each technology has its own advantages and disadvantages, making them suitable for different applications. Table 1 summarizes the pros and cons of different ESS technologies [191]-[197].

Table 2.1 - Advantages and disadvantages of each ESS technology.

TECHNOLOGY	TYPE	ADVANTAGES	DISADVANTAGES
Lead-Acid	Electrochemical	-Easy installation; -Low self-discharge	-Short lifetime; -Maintenance costs; -Low power; -Partial discharging; -Premature failure; -Needs temperature management;
Lithium-Ion	Electrochemical	-Efficiency (almost 100%); -Improved lifecycle; -Improved energy efficiency;	-Inflammable; -Fragile; -Lifetime dependent on temperature; -Charge/discharge current limitations

Table 2.1 - Advantages and disadvantages of each ESS technology (continuation).

TECHNOLOGY	TYPE	ADVANTAGES	DISADVANTAGES
Nickel-Cadmium	Electrochemical	-Lifecycle; -Low maintenance requirements; -Wide range of sizes; -Economic in cost per cycle; -Long term storage capacity; -Low temperature performance;	-Toxicity of cadmium; -Costs ten times higher than Lead--Acid storage technologies; -Low efficiency; -High self-discharge rate; -Suffer from memory effect; -Continuous maintenance due to high self-discharge;
Sodium-Sulphur	Electrochemical	-Energy Efficiency; -Not dependent on ambient temperature; -Lifecycle; -Energy capacity; -Power density	-Safety conditions for thermal management, seal and freeze-thaw durability.
Flow Battery	Electrochemical	-High power; -Longer duration of operation; -Scalable; -Safe to replace electrolytes; -Decoupling between power rating and energy rating; -Fast response; -No self-discharge.	-Low efficiency; -High operation costs; -Low energy density; -Thermal management; -Contamination can occur from mixing used and fresh electrolytes
Fuel Cells	Electrochemical	-Continuous operation; no need for recharging the cells	-Very expensive

Table 2.1 - Advantages and disadvantages of each ESS technology (continuation).

TECHNOLOGY	TYPE	ADVANTAGES	DISADVANTAGES
Supercondu-cting Magnetic Energy Storage (SMES)	Electrical	-Capable of very quick discharge making it suitable for short term applications; -Easy to increase energy storage capacity by increasing the current flowing through the coil.	-Very expensive; -Dependent on the temperature of the coil.
Supercapacitors/ Capacitors	Electrical	-Fast response operations; -High energy density; -Long term storage; -Low losses	Very expensive
Flywheel	Mechanical	-High efficiency; -Durability; -Low maintenance; -Minimal environmental impacts; -High capacity.	Very expensive
Compressed Air	Mechanical	Long term energy storage.	Toxicity
Pumped-Hydro	Mechanical	Efficiency about 70%; Reserve capacity provision; -Frequency control, -Load balancing and energy management.	-Costly; -Requires building a hydroelectric dam.

Details of each of these ESS technologies and their applications can be found in the literature [189], [191]–[193], [196], [197]. Among the much-anticipated contributions of ESSs is the reduction in the effects of fluctuations caused by RESs. In the absence of appropriate management mechanisms such as ESSs, these fluctuations can cause several problems in terms of power system stability, security and quality of power delivered to consumers. Moreover, power outages may be common phenomena [193], [196]. However, ESSs can help to prevent outages and enhance the overall stability of power systems. In addition, ESSs have the necessary flexibility capabilities to contain the intermittency of RESs and support an increasing penetration of these technologies in power systems. As mentioned earlier, ESSs store excess energy generated during off-peak periods that can be injected back to the grid whenever it is needed. This makes ESSs one of the most cost effective ways to alleviate the problems that may arise as a result of variability and uncertainty in system conditions. As shown in Figure 2.5, ESSs also counter the possible fluctuations in voltage and frequency especially in systems where there is high penetration of intermittent energy sources.

ESS technologies with high lifetime cycles and shorter response times are especially suitable for regulating voltage and frequency [189], [192], [193], [196]. Likewise, ESSs are able to add reserve capacity to power systems [189], [191], and can further provide wide-range ancillary services [189], [191], [196]. Another interesting feature of ESSs is time and spatial shifting of energy consumptions and generations. Energy stored from a remote power generation source is shifted in time and geographical location [189], [191], [192], [196]. Time and spatial shifting operations are related to load shifting, time of use and variable energy generation shift [189], [191], [192], [196]. Load shifting allows the delivery of renewable energy from off-peak times to peak times, increasing the value of RESs [189], [191], [192], [196]. A shift in variable energy generation reduces peak reverse power flows through power system components, respecting operational limits [189], [191], [192], [196]. The process of suppling and discharging is related to time of use. If ESSs charge and discharge in specific time periods, such an operation can be defined when time-of-use tariffs for charging are economic while tariffs for discharging are more expensive [189], [191], [192], [196]. Finally, ESSs can avoid, postpone or reschedule investments in transmission and distribution systems. Installing permanent or temporary ESSs in overloaded nodes can avoid or reduce congestion and hence investments to relieve such congestion, eventually saving funds for critical areas and reducing cost to the end-users. Further literature on ESSs include the work by Farrokhifar [58] which investigates the positive impacts of adding ESSs to distribution grids. Vandoorn *et al.* [60] presents a voltage-based droop control for controlling loads, DG units and storage equipment in islanded distribution network systems. Skarvelis-kazaos *et al.* [198] have proposed an agent-based model to control multiple energy carrier systems. Khasawneh and Illindala [199] consider a micro-grid consisting of fuel cell batteries to supply crusher-conveyor load when power from the main grid is not available.

Moreno *et al.* [200] have developed a MILP model to schedule the optimal operation of ESSs by coordinating the delivery of various system services which are rewarded at different market prices. Mousavizadeh and Haghifam [201] have studied power flow analysis on AC/DC distribution networks, including weakly meshed ones, in the presence of DGs and ESSs. Palmintier *et al.* [202] explore design solutions that may never emerge when distributed energy resources are treated in a deterministic approach. Riaz *et al.* [203] present detailed analysis concerning the integration of RESs and ESSs in future grid scenarios. Other works in areas of ESSs and related subjects are compiled in [204]-[278].

The integration of smart grid enabling technologies such as ESSs raises a number of concerns, mainly in the security of electricity supply, beginning with the fact that the established security requirements in different jurisdictions are defined almost exclusively for conventional assets, this is also one reason integration of ESSs is being delayed. In this perspective, and to speed up the integration of ESSs in the different networks, different jurisdictions, one of the main points that has to be made is leveling the field of action of this and all the others smart grids enabling technologies [158]. Regarding the ESSs, this technology has the ability to cope with the supply variation and uncertainty (mostly from RESs). However, the effect that comes from the integration of this technology has to be quantified. A good practice is the use of metrics, for example, see in [158]. These metrics could be regarded differently in different jurisdictions. For the ESSs case, one metric that could be used is the ratio between the flexibility of the load that can be delivered in an hour and the maximum load that can be suppressed by the ESSs in the previous year. This ratio can be adapted to all sources of supply. This would make it possible to achieve greater security of supply, eliminating one of the major obstacles to the integration of ESSs in the network. In general, the key pros and cons of ESSs can be summarized using the following bullet points:

Pros of ESSs:

- ESSs facilitate effective utilization of intermittent renewable sources;
- ESSs can be key components of a smarter and integrated energy system;
- ESSs can reduce the need for increased peak generation capacity;
- ESSs can enhance both grid reliability and stability;
- ESSs have their performance and costs continually improving.

Cons of ESSs:

- Energy losses as a result of round trip inefficiencies;
- Additional cost and complexity;
- Additional infrastructure and space requirements.

2.2.4.2 Energy Systems Integration

The integration of multi-sectoral energy systems (for example, power-to-gas initiatives, electrification of the transport sector, etc.) is believed to add more dimensions to the flexibility needed to pursue a sustainable energy future. The advent of new technologies and emerging business models are expected to make such integration possible. The energy required by the heating and cooling as well as transport sectors is largely met by conventional energy sources (which are often non-sustainable). However, advances in technologies and growing concerns in energy security and environmental changes among others are already resulting in a paradigm shift in many countries. It is now widely accepted that electrification of such sectors shall be one of the solutions for the energy "poverty" and severe effects of global climate change that may unfold over the coming decades. Technologies such as internet of things (IOTs) are expected to facilitate further integration of the energy systems. IOT technologies "*consist of the internet, global network based on communication protocols and things, which are the physical or virtual objects, devices, information and used interfaces*" [279]. The performance of energy systems can be substantially improved via automated responses of IOT controlled systems of various sectors [279].

In many countries, the transport sector is responsible for a significant portion of emissions. This is because of the heavy dependence of the sector on fossil fuels for mobility. Hence, this sector is identified as the main target for partly achieving the massive decarbonization process needed worldwide to address global climate change and mitigate its ensuing consequences. The flexibility potential that this sector possesses is immense, and this is vital to increase the level of RES integration in power systems.

Another promising initiative closely related to energy systems integration is the power-to-X program, which involves converting electrical to any other form of energy. Power-to-gas (P2G) is one example that is widely accepted nowadays in many countries. P2G transforms power to hydrogen by means of electrolysis or to methane by a process called methanation [54], [280]. Hydrogen or methane can be stored in nominated pipe storage or in an underground reservoir. The conversion process to hydrogen can have an efficiency of about 75-80%; whereas, the conversion to methane is reported to have an efficiency of about 60-65% [280]. However, the reverse process (i.e. P2G-to-power) leads to a round-trip efficiency of about 36%, which can be the main source of controversy of such initiatives [280]. Hydrogen production from RESs can be understood as one type of ESS because this gas can be converted back to electricity using fuel cells or combustion power plants [54]. Methane could be absorbed by the gas distribution systems that have a large storage facility [54], [281]. Hydrogen requires large storage capacities, making investment costs very high and possibly reducing revenues from such an option [280]. On the contrary, methane requires a lower amount of storage (4-5 times less than hydrogen), making it economically attractive [280].

It has been reported that P2G provides an important flexibility mechanism, and deals well with the variability of RESs with the seasonal demand of gas, storing the gas in special facilities to stream it with no interruption in winter seasons [280]. This way, the energy produced from RESs can be better utilized, avoiding or minimizing curtailments. In addition, P2G can be used for ancillary services accessible by TSOs and can be integrated in spot markets for temporal arbitrage [280].

In the future, P2G is largely expected to become one of the most competitive long term storage options, which at this moment is dominated by pumped hydro [281]. One advantage of P2G over a pumped hydro storage is that P2G can have dramatically larger energy storage potential [281]. The financial risk of P2G systems is the price risks originating from the gas sales [280]. However, suitable storage choices will help to alleviate price risks, and can enable P2G applications in the coming years [280]. Voluntarily or imposed by regulation, improvements in transparency and quality of accessible information on electricity prices and time series have been effectuated by many organizations [282]. The price uncertainty has appeared in most recent studies in the literature, for example in [283], where the operation and planning of systems with multiple assets are evaluated in terms of flexibility which incorporated in the steps of operation and investment, subject to long term uncertainties. However, majority of the models do not consider realistic time series of prices, turning into imprecise predictions of hourly electricity prices [282].

In general, energy systems integration has enormous potential in terms of flexibility. In other words, multi-energy systems can optimize different energy vectors such as gas, electricity and heat simultaneously, proving to be important sources of flexibility (for example, see [283]-[285]). In particular, the study in [286] discusses in detail the flexibility potential and economic aspects of energy systems integration for renewable-rich systems. In addition, the effectiveness and viability of energy systems integration in terms of ancillary services provision has been demonstrated in the same study, i.e. [286].

However, it should be noted that the integration of multiple energy systems brings more flexibility to power systems if holistically optimized using holistic approaches that deal with different system trajectories. This is because of the fact that holistic approaches help to better quantify the strategic value of such an integration, as reported in [283], [287]-[291]. In [287], a stochastic decision support model is proposed for scheduling flexibility services in the next day, in which flexible consumers are exposed to dynamic prices in the retail electricity market. The problem has been modeled using a stochastic programming approach where uncertain parameters are represented through a scenario tree resulting in significant savings in terms of cost. In [288], Good and Mancarella present a multi-energy communities approach incorporating electrical and thermal storages. The approach covers all relevant energy vectors, allowing a more comprehensive modeling of the different flexibility options.

In [283], a multi-energy system with different vectors is modeled, namely, electricity and heat simultaneously optimized, proving to be a valuable source of flexibility on the demand side. Planning these resources is done in the presence of price uncertainty of the energy vectors in the long term. However, the planning process of integrated energy systems is extremely challenging, particularly in the presence of long-term price uncertainty in the underlying energy vectors. The implementation of advanced tools to access the risk in the planning stages are encouraged to reach the potential of multi-energy systems, reducing risks from unfavorable realizations of uncertain parameters and capitalizing on the benefits of favorable realizations [283].

2.2.4.3 Energy Markets

Physical or technological means are not the only ones that can provide flexibility. For example, properly designed energy markets can also increase the flexibility of systems [54], [163]. Electricity markets are normally designed to meet the following purposes among others [292], [293]:

- Balance demand and supply in real-times;
- Optimally use RES power outputs when congestion or any unforeseen condition occurs;
- Effectively manage transmission and distribution constraints, congestions and bottlenecks;
- Optimize sets for market agents taking into consideration grid requirements at specific times and locations;
- Reduce grid investments especially if flexibility is used effectively incorporated in the TSO's and DSO's planning processes.

A number of researchers have reported assessments in relation to the impacts of having flexible markets on various metrics. Eid *et al.* [163] provide a review of existing distributed energy sources acting as flexibility providers and trading platforms for distributed energy sources flexibility in electricity markets. In [294], authors have analyzed three projects in the Netherlands and Germany to understand if organizational models for flexibility management guarantee retail competition and feasibility of upscaling in Europe. Saá *et al.* [166] propose congestion management mechanisms in smart-grids which rely on the wholesale electricity market. Ramos *et al.* [292] have proposed a market design that enable access to flexibility contracts to solve network problems and balance the grid at a specific location. The designed market is dimensioned in time, space, contractual and price-clearing perspectives. Torbaghan *et al.* [293] propose a framework of two mechanisms.

The first one is related to a pre planning process via markets and real-time dispatching, which includes day-ahead and intra-day mechanisms. This framework is operated by a local flexibility market operator. The second one is related to establishing a strategy for DSOs to seek the flexibility they need from the day-ahead and intra-day markets, as well as from the real-time dispatching at the lowest possible cost. Kornrumpf *et al.* [286] have modelled a framework for a local flexibility market based on Optimal Power Flow (OPF) calculations.

Generally, earlier works by researchers have clearly demonstrated that properly designed electricity markets can substantially enhance the flexibility of power systems, and create conducive environment for flexibility market players to provide services that ultimately lead to more efficient systems. In particular, integrated energy markets facilitate access to neighboring markets. In recent years, such an integration process has been touted as the main mechanism for addressing the long-standing energy problems. For example, market integration can substantially minimize the frequency and the amount of curtailments of intermittent power sources, increasing their values. The flexibility requirements of larger and integrated power systems are in fact lower than that of local grids, mainly due to the geographical smoothing effects. Moreover, designing and implementing faster electricity markets (i.e. with markets shorter temporal resolutions) help to follow actual system conditions, avoiding unrealistically high pricing of forecasted system conditions. Instead, faster markets result in better pricing of real-time operational situations. Such markets also create an institutional flexibility mechanism that can support large-scale integration and utilization of variable energy sources.

2.2.4.4 Regulatory Policies

To abate global warming and meet climate change goals, a dramatically high reduction of GHG emissions is required worldwide. These targets are strongly dependent on renewable energy technologies [209],[294]. And, this requires appropriate regulatory policy interventions to be put in place on a state-wide and global scale, which speeds up the integration of such “clean” energy technologies and ensures their efficient utilization. For example, it has been some years since the European Union embraced ambitious targets for sustainable energy developments. By 2050, all electricity consumption in the EU is expected to come from renewables [209]. EU countries have already drafted a number of regulatory policies designed to support these developments. Yet, there remain a lot of regulatory gaps in many countries (including the EU) that need to be addressed. For instance, investments in distribution networks are not being effectively stimulated by the present regulatory frameworks in many countries [209]. In particular, distribution systems can be at greater risks of outages, network congestions, inadequate RES integration and quality deterioration of energy delivered to end-users. Properly designed incentives for investments in distribution networks can scale up the integration of vRESs as well as their efficient utilization [209].

Regulatory revision of the financing model administered to DSOs by national energy regulators is essential for encouraging technological changes [209]. Regulators have leading responsibilities to encourage DSOs to invest and develop distribution grids in the best way possible. Nevertheless, the problem is that many regulators do not consider innovation in their regulatory frameworks, resulting in negligence to spend capital in innovative solutions and do not make the cost benefit analysis on their reports [209].

There are some exceptions, but most regulators seem to only seek for short-term optimization while largely overlooking long-term requirements. For example, current regulatory frameworks in many countries hardly provide conducive environments for emerging market players such as flexibility service providers and multi-energy carriers to flourish and become competitive [295].

Generally, new regulatory policies are highly needed to shape the long-term evolution of energy systems. Such policies play a critical role in creating flexible systems that are capable of efficiently handling all sorts of dynamics in the systems. It is important to note that effective regulatory frameworks clearly reflects market players' roles and responsibilities for managing flexibility options provided by different resources in the future energy market.

2.3 Chapter Conclusions

This chapter has presented an extensive review of various flexibility options, rigorously discussing the prospects, challenges, advantages and disadvantages of each flexibility option. The flexibility options reviewed in this chapter are structured into different categories that are not only easy to follow and understand but also sensible enough from structural and technical standpoints. The work in this chapter complements existing review works by other researchers in related subjects, highlighting the importance of flexibility mechanisms in power systems that are experiencing unprecedented transformations from the supply side to the end-users. In addition, we provide insights into the challenges and opportunities associated with various flexibility options provided by different technologies. The growing need to integrate more "carbon-free" energy resources dramatically increases the flexibility requirements. Traditional flexibility mechanisms are not simply sufficient to meet the flexibility gaps created as a result of increasing variable renewables. Fortunately, there are a number of emerging and promising technologies that can be deployed at the supply-, network- and/or demand-sides and fill in these gaps in close coordination with existing flexibility mechanisms. These flexibility mechanisms are extensively discussed in this thesis.

Chapter 3

Multi Flexibility Options Integration to Cope with Large-Scale Integration of Renewables

This chapter focuses on the operation of an electrical distribution system with large-scale integration of solar and wind power. In order to cope with the intermittency inherent to such power sources, it is necessary to introduce more flexibility into the system. In this context, Demand Response, Energy Storage Systems and Dynamic Reconfiguration of the system are introduced, and the operational performance of the resulting system is thoroughly analyzed. To perform this analysis, two standard IEEE test systems are used: the IEEE 41-bus test system and the IEEE 119-bus in order to validate its scalability.

3.1 Introduction

The decarbonization of our electrical system brings new challenges for the electrical network. From the European perspective, for example, in a short period of time, European countries are facing the closure of significant parts of their generation mix in response to the Large Combustion Plant directive [296]. This can reduce the margins of capacity of generation to unsafe levels. In addition, the issues surrounding climate change have exacerbated the problem of fossil fuel shortages [297],[298].

Similarly, given the fact that electrical networks are old infrastructures, conventional management methods of such networks are becoming obsolete [299]. The growth of demand, concerns with CO_2 emissions and varied consumption profiles raise new reasons for investigating new solutions.

In the topic of Smart Grids, several solutions have been studied to operate electrical networks more efficiently, more environmentally friendly and with better reliability indices. A recent phenomenon is that the share of distributed Renewable Energy Sources (RESs) in the overall power production mix has been increasing in many countries.

One of the benefits of such integration is to reduce network losses because generation is placed closer to demand. However, its inherent intermittence and lack of competitive storage mechanism are currently raising one of the greatest issues on the continued development of these clean energy technologies.

When a large number of these energy sources are integrated into network systems, several problems may arise. One of the problems has to do with the rapid changes in the solar and wind power generation during the operation time. And, this is due to the variability and uncertainty such power sources. Other problems that come with the integration of renewables are of a technical nature such as the adjustment of network security and protection, quality of service, and bi-directional power flows among others.

Despite several benefits, it is sometimes argued that an upgraded dispatch of these technologies may increase energy costs and reduce the overall efficiency of the system [300]. For example, in the countries of northern Europe, where there is already a lot of renewable power generation, there often appears a problem of excess electricity production. Although excess energy production can be exported to other countries, interconnection capability may not be sufficient. When renewable power production is high, excess production may force the system operator to dispatch down wind turbines until demand and supply are balanced.

As conventional methods have been limited to being based on the use of High Cost/Low Efficiency peaking plants or curtailment of renewable power generation, the system operator needs to have more flexibility options that are economical and rapidly acting resources [54].

In relation to all this, the focus so far has mainly been on Demand Response (DR), Dynamic System Reconfiguration (DSR) and deployment of Energy Storage Systems (ESSs). A system reconfiguration aims to obtain the power network topology that best suits conditions in the system at a particular moment (which can be on an hourly, daily or seasonal basis). DR and ESSs can achieve the same goals, not needing a market structure during emergency situations. The objectives of these two technologies can be load shifting, peak clipping, valley filling, strategic conservation and flexible load shaping [301].

In the medium term, large-scale integration of RESs brings new challenges that evoke wider system flexibility needs. And, in the long term, the electrification of heating and transportation can put more pressure on system integration. So, the flexibility on the demand side can partly fill in the needs described above. If well incentivized, demand can be more responsive to system requirements. It can also cope with the stochastic behavior of RESs in the absence of proper energy storage media.

The economic effects of the introduction of large-scale RESs on energy systems are related to the profile, balances and network-related costs that can come as a reduction in revenue for the provision of RESs or as additional costs, such as the cost of integration for market-specific participants.

From the perspective of the overall energy system, the levelized cost of electricity (LCOE) of the RES power generation compromises the LCOE of the technology itself and the cost of integration. The current magnitude of RES integration costs depends on the flexibility of each system, i.e. to what extent demand-side and supply-side can accompany the inherent variability of wind and solar systems. It should be noted here that flexibility is the ability to balance rapid changes in the renewable production and forecasting errors of the energy system or can be described as a general characteristic of the ability of a specific aggregation of generators to respond to the variation and uncertainty of the network load [302].

In general, flexibility in the traditional electrical system has been dominated by conventional thermal units. On the other hand, the current electricity system has incorporated a flexible set of resources, namely DR, market, ESSs and DSR among others, to help mitigate the impact of RESs integration (namely the variability and uncertainty), in addition to the uncertainty associated with demand itself. The different types of flexibility sources mentioned, i.e. DR, market, ESS and DSR, have been explored by different approaches in the literature and in different configurations. From these resources, the first three are the most commonly used in the literature; while the last one is rarely exploited as a source of flexibility for the system.

Among the approaches present in the literature, there is a set of works that explore DR's flexibility [288], [303]-[315]. In [315], a description of the flexibility resources by the DR to balance the system at the planning level is presented, not considering any other source of flexibility other than DR. Another set of approaches (more embracing) is the flexibility that comes from the junction of DR and ESSs. Within this set of works, there are different configurations in the approaches. A very significant set explores the flexibility of the DR in the form of demand side management, for residential heating and also cooling considering thermal energy storage systems [303], [305], [313], [314].

A new active control form of heating/cooling systems in the smart grid context is explored in [303], with the aim of promoting the integration of RESs. Mubbashir *et al.* [305] present a work to increase the system's operational flexibility focusing on scaling up the integration of wind power generation together with DRs, but in the absence of intelligent network management using real-time thermal rating to support hourly wind power production. A similar work is presented in [304] whose focus is on mitigating the wind power output fluctuations by means of demand response.

In addition to these approaches, there is still a set of works that use the core of the previous approaches, but adding/replacing some aspects or entities in the optimization process, namely, electric vehicles, ancillary services, market scheme or dynamic prices [51], [304], [306], [307], [309]-[312], [316].

Table 3.1 - Literature review from related works.

Ref.	Year	Methodology	Planning	Operation	Wind	Solar	DR/EMS	ESS	Switching	Stochastic	Flexibility	Analysis
[317]	2018	Multiagent based MILP		✓			✓	✓				Multi-microgrid operation
[318]	2017	MILP		✓	✓		✓	✓		✓	✓	Day-ahead scheduling microgrid
[319]	2017	Lagrange duality method and distributed finite-time consensus algorithm		✓	✓		✓	✓				Economic dispatch of a microgrid
[320]	2016	MILP		✓	✓	✓	✓	✓		✓		Short-term operation
[321]	2018	Monte Carlo Simulation	✓		✓		✓				✓	Assessment of the capacity credit of RESs
[322]	2016	Non-dominated Sorting Genetic Algorithm	✓		✓	✓		✓	✓			DG siting and sizing in the presence of ESSs
[323]	2018	MILP	✓				✓	✓			✓	Evaluation of the impact of wind curtailment
[324]	2018	Sequential Monte Carlo		✓	✓	✓		✓	✓	✓		Analysis after a fault with formation of microgrids
[325]	2017	MILP		✓	✓	✓	✓	✓		✓		Analysis of the bidding strategy for grid-connected microgrids
This thesis	-	SMILP		✓	✓	✓	✓	✓	✓	✓	✓	Short-term operation analysis of a distributed system

In [316], the potential of flexible demand resources such as heat pumps and thermal storage in local industries is studied. The optimization process of this thesis also considers the presence of electric vehicles (EVs) and RESs. In [309], some business models in the electrical sector are explored to evaluate the flexibility mechanisms over time. The works in [310] and [51] focus on the flexibility generated from ancillary services. In [310], a demand side management methodology is presented based on the aggregation/ disaggregation of residential thermal storage for different time intervals, ensuring the thermal comfort of the individual dwellings. In [51], a load aggregation methodology is presented based on the prioritization of loads according to their flexibility. Different types of flexible loads are categorized as thermostat-controlled loads (TCL), non-TCL and battery-based non-TCL and non-urgent loads.

The works in [306], [312] have taken market in to consideration. In [306], a day-ahead hourly pricing (DAHP) mechanism is proposed for distributed DR in uncertain and dynamic environments considering electricity price in the retail market, in order to be applied in later works with DR, ESSs, and renewable integration. In [312], an Optimal Bidding Strategy for a DR aggregator is presented in the Day-Ahead Market in the presence of demand flexibility. Good and Mancarella in [288] have presented a multi-energy work in order to ensure that thermal comfort cannot be degraded beyond agreed limits in the event of a call. The approach is demonstrated through a case study that illustrates how the different flexibility options can be used to integrate more electric heat pumps into a capacity constrained smart district that is managed as a community energy system, while maximizing its revenues from multiple markets/services. There are also approaches that seek only the flexibility on the generation side, as is the case of [322], [326]–[328]. These works investigate the flexibility of a system featuring RESs and ESSs. In [326], the flexibility resulting from the joint integration of RESs and ESSs is investigated. Steffen and Weber in [327] investigate the effect of pumping storage as a means of system flexibility to accommodate a higher level of RES in the considered system. In [328], a case study of China for RES expansion is presented, analyzing the flexibility constraints in the low-carbon policy.

It should be pointed out that majority of the existing approaches reviewed here focus on the planning level [303], [305], [309], [315], [316], [321], [323], [327]-[331] and not in terms of system operation. Moreover, Table I provides a summary of existing works that are closely related to the present work. From this table, it is possible to verify that there are very few works that consider DSR as a flexibility source, and those which consider this resource do not approach it from a flexibility analysis perspective, as it is the case in [322] and [323].

Therefore, despite the existence of several works in the area of power systems flexibility, most of the works in the literature focus on the flexibility that can be obtained from the demand side, in heating and cooling schemes of residential houses, or in conjugation with EV in the presence of RESs.

It should be noted that, with the exception of the works that consider EV, the ESSs considered throughout the vast majority of the remaining works are of the thermal storage type (by the process described above) or combined with industrial thermal storage through aggregation that aim supply the residential sector. In the presence of large-scale integration of RESs, this thesis differs from the previous ones because it considers the existence of DSR, ESSs (battery-type) and DR, analyzing the impacts of such a mix from the flexibility perspective. The current work (in this chapter) aims to further assess the level of RES integration in the energy mix with this approach.

In addition to the flexibility analysis perspective, this thesis also presents a new optimization model that considers the uncertainty and variability of the renewables, which is one of the salient contributions of our work.

3.2 Handling Uncertainty and Variability

3.2.1 Description

Uncertainty in this thesis refers to the degree of precision that each parameter is measured. As for variability, it is referred to as “the natural variation in time of a specific uncertain parameter” [332]. These terminologies are employed and followed in this thesis when referring to operational variability and uncertainty. For example, demand can be characterized by its hourly variability that has associated some degree of uncertainty, associated to the error that can be introduced by predicting the demand.

In this thesis, scenarios are used for the operation period. A scenario represents a sequence of events of an uncertain parameter. For example, the RES power output uncertainty is translated by a possible number of story lines. The operation period is the time window where the operation variables are being analyzed. In this work, an operation period of 24 hours is defined.

In the current work, the uncertainty and variability associated to the considered problem are taken into account through a stochastic process. For a given stochastic parameter, instead of being considered as only a single evolution mode, different possible realizations are considered, each with associated probability.

3.2.2 Uncertainty and Variability Generation

Variability and uncertainty are non-exclusive characteristics of renewable power generation. There are other parameters in the optimization process that are also characterized by these variables [333]. In this thesis, three sources of uncertainty and variability are identified, namely wind, solar and demand.

To account for demand uncertainties, two demand profile scenarios are taken, considering a ±5% prediction error margin from real-life short-term demand profile (i.e. 24 hours) [334]. This then leads to three demand scenarios, which are used in the analysis. Wind speed and solar radiation are generated following the methodology in [332]. The average wind speed and solar radiation profiles are obtained based on real data. These values are plugged in equations (1) and (2) to obtain the respective power outputs. The power outputs cannot be used straightforward because they may not directly maintain the proper correlation with the average demand profile. Therefore, the power outputs should be readjusted to replicate the time-based correlations that happen between demand, solar radiation and wind speed. The correlation between wind and solar, wind and demand, and solar and demand are respectively -0.3, 0.28, 0.5, being obtained from [332].

After obtaining the correlation matrix, the wind and solar power outputs can be transformed into new ones, given the correlation between them. Cholesky factorization is used to adjust the data series. The method consists of having a correlation matrix R, uncorrelated data D, so that a new data C, whose correlation matrix is R, is generated by multiplying the Cholesky decomposition of R by D. The power output profiles are determined by using these readjusted values. Note that the following power curve is used in converting the wind speed into power:

$$P_{wind,h} = \begin{cases} 0; & 0 \leq v_h \leq v_{ci} \\ P_r\left(A + Bv_h^3\right); & v_{ci} \leq v_h \leq v_r \\ P_r; & v_r \leq v_h \leq v_{co} \\ 0; & v_h \geq v_{co} \end{cases} \tag{3.1}$$

In equation (3.1), parameters A and B are given by the expressions in [335] and [336]. In the same way, the solar power output are determined using the following expression [337]:

$$P_{solar,h} = \begin{cases} \dfrac{P_r R_h^2}{R_{std} R_c}; & 0 \leq R_h \leq R_c \\ \dfrac{P_r R_h}{R_{std}}; & R_c \leq R_h \leq R_{std} \\ P_r; & R_h \geq R_{std} \end{cases} \tag{3.2}$$

Uncertainty pertaining to wind and solar power productions is assumed to have ±15% deviation from the average power output profiles. This translates approximately to a ±5% forecasting error in wind speed or solar radiation. The hourly profiles of wind and solar power outputs are constructed based on the considered deviations. This is transformed into three wind and solar power outputs profiles (namely, high, low and average).

The individual scenarios of demand, wind and solar power outputs are combined to form a set of 27 scenarios (i.e. 3*3*3). All of these scenarios are expected to be equally probable with ρ_s equal to 1/27.

3.3 Model Formulation

3.3.1 Objective Function

To carry out the required analysis and account for the variability and uncertainty inherent to the problem at hand, a stochastic MILP optimization model is formulated. Model accuracy is guaranteed because the subsequent optimization model employs a linearized AC-OPF based network model, which has the right balance between accuracy and computational requirements.

The resulting optimization model minimizes the algebraic sum of four relevant cost terms while fulfilling a number of technical and economic constraints. These cost terms are related to network switching, operation, unserved power and emissions in the system:

$$Minimize\ TC = TSC + TEC + TENSC + TEmiC \tag{3.3}$$

The first term in (3.3) is related to the total switching costs that is a result of the distribution network reconfiguration (DNR). Note that a switching cost occurs when the status of a given feeder changes from open (0) to closed (1) or vice-versa. This gives the absolute difference between sequential switching operations in time. The absolute difference in (3.4) is represented by a module, and it can be linearly represented by introducing two non-negative variables: $y_{l,h}^{+}$ and $y_{l,h}^{-}$. TSC is therefore expressed by the following equation:

$$TSC = \sum_{k\in\Omega^k} \sum_{h\in\Omega^h} SC_k * \Delta h * \left(y_{k,h}^{+} + y_{k,h}^{-}\right) \tag{3.4}$$

where:

$$x_{k,h} - x_{k,h-1} = y_{k,h}^{+} - y_{k,h}^{-};\ y_{k,h}^{+} \geq 0;\ y_{k,h}^{-} \geq 0 \tag{3.5}$$

$$x_{k,0} = 1;\ \forall k \in \Omega^1\ and\ x_{k,0} = 0;\ \forall k \in \Omega^0 \tag{3.6}$$

The sets Ω^1 and Ω^0 refer to the normally closed feeders and tie lines, respectively. The statuses of the feeders and tie lines can change during the optimization period i.e. depending on the optimal topology obtained following the dynamic network reconfiguration. *TEC*, the second term in (3.3), characterizes the expected production costs of energy by distributed generations, ESSs and by importing power from the transmission system:

$$TEC = EC^{DG} + EC^{ES} + EC^{SS} \tag{3.7}$$

Each term in (7) can be defined as:

$$EC^{DG} = \sum_{s\in\Omega^s} \rho_s \sum_{h\in\Omega^h} \Delta h \sum_{g\in\Omega^g} OC_{g,i,s,h} P_{g,i,s,h} \tag{3.8}$$

$$EC^{ES} = \sum_{s\in\Omega^s} \rho_s \sum_{h\in\Omega^h} \Delta h \sum_{es\in\Omega^{es}} \lambda^{dch}_{es,i,s,h} P^{dch}_{es,i,s,h} \tag{3.9}$$

$$EC^{SS} = \sum_{s\in\Omega^s} \rho_s \sum_{h\in\Omega^h} \Delta h \sum_{\varsigma\in\Omega^\varsigma} \lambda^{\varsigma}_{s,h} P^{SS}_{\varsigma,s,h} \tag{3.10}$$

The expected cost of energy not supplied is formulated in *TENSC*; that is, the third term in (3). The load not supplied can be in the form of active and reactive power. Hence, this is computed the following expression:

$$TENSC = \sum_{s\in\Omega^s} \rho_s \sum_{h\in\Omega^h} \Delta h \sum_{i\in\Omega^i} \left(\upsilon^P_{s,h} P^{NS}_{i,s,h} + \upsilon^Q_{s,h} Q^{NS}_{i,s,h}\right) \tag{3.11}$$

Here, $\upsilon^P_{s,h}$ and $\upsilon^Q_{s,h}$ define penalty parameters for active and reactive power that is not supplied. These two parameters are each set to a sufficiently high value, which roughly quantifies the value of lost load. The fourth and the last term in (3.3), *TEmiC*, is related to the expected costs of emissions in the system. These costs are a result of producing power using local DG resources and by importing power from the transmission system:

$$TEmiC = EmiC^{DG} + EmiC^{SS} \quad (3.12)$$

The terms in (3.12) are calculated by the following expressions:

$$EmiC^{DG} = \sum_{s\in\Omega^s} \rho_s \sum_{h\in\Omega^h} \Delta h \sum_{g\in\Omega^g} \sum_{i\in\Omega^i} \lambda^{CO_2} ER_g P_{g,i,s,h} \quad (3.13)$$

$$EmiC^{SS} = \sum_{s\in\Omega^s} \rho_s \sum_{h\in\Omega^h} \Delta h \sum_{\varsigma\in\Omega^\varsigma} \sum_{i\in\Omega^i} \lambda^{CO_2} ER_\varsigma^{SS} P_{\varsigma,s,h}^{SS} \quad (3.14)$$

3.3.2 Constraints

The healthy operation of the distribution system is guaranteed by the technical and economic constraints that are respected during all operational times. One of the major technical constraints is the Kirchhoff's current law [332], which states that the sum of all flows arriving at a bus must be always equal to the sum of all flows leaving that bus at any time.

Therefore, the active power flows (3.15) and reactive power flows (3.16) should be respected. Equation (3.15) includes in the incoming flows the active power produced by distributed generators, the power flows associated to the feeder (incoming), the power that is being discharged from ESSs and the power that is being imported from the transmission system (P^{SS}) if the considered bus has a substation. On the other hand, the outgoing flows consider the demand, losses and power flows associated to the feeders.

$$\sum_{g\in\Omega^g} P_{g,i,s,h} + \sum_{es\in\Omega^{es}} \left(P_{es,i,s,h}^{dch} - P_{es,i,s,h}^{ch}\right) + P_{\varsigma,s,h}^{SS} + P_{i,s,h}^{NS} + \sum_{in,k\in\Omega^k} P_{k,s,h} - \sum_{out,k\in\Omega^k} P_{k,s,h} = PD_{s,h}^{i} + \sum_{in,k\in\Omega^k} \frac{1}{2} PL_{k,s,h} + \sum_{out,k\in\Omega^k} \frac{1}{2} PL_{k,s,h} \ ; \forall\varsigma\epsilon\Omega^\varsigma;\ \forall\varsigma\epsilon i; k\epsilon i \quad (3.15)$$

$$\sum_{g\in\Omega^g} Q_{g,i,s,h} + Q_{c,i,s,h}^{c} + Q_{\varsigma,s,h}^{SS} + Q_{i,s,h}^{NS} + \sum_{in,k\in\Omega^k} Q_{k,s,h} - \sum_{out,k\in\Omega^k} Q_{k,s,h} = QD_{s,h}^{i} + \sum_{in,k\in\Omega^k} \frac{1}{2} QL_{k,s,h} + \sum_{out,k\in\Omega^k} \frac{1}{2} QL_{k,s,h} \ ; \forall\varsigma\epsilon\Omega^\varsigma;\ \forall\varsigma\epsilon i; k\epsilon i \quad (3.16)$$

The power flow in any feeder must respect the Kirchhoff's voltage law. This is considered by including linearized power flow equations. This linearization follows two assumptions. First, the voltage angle difference θ_k is normally very small in distribution networks. In trigonometric approximations, this results in $\sin\theta_k \approx \theta_k$ and $\cos\theta_k \approx 1$. Second, the bus voltage magnitudes are expected to be close to the rated value V_{nom} in distribution systems. By using these simplifying assumptions, the complex nonlinear and nonconvex flow equations can be linearized as in [40]:

$$\left|P_{k,s,h} - \left(V_{nom}\left(\Delta V_{i,s,h} - \Delta V_{j,s,h}\right)g_k - V_{nom}^2 b_k \theta_{k,s,h}\right)\right| \le MP_k\left(1 - u_{k,h}\right) \tag{3.17}$$

$$\left|Q_{k,s,h} - \left(- V_{nom}\left(\Delta V_{i,s,h} - \Delta V_{j,s,h}\right)b_k - V_{nom}^2 g_k \theta_{k,s,h}\right)\right| \le MQ_k\left(1 - u_{k,h}\right) \tag{3.18}$$

where $\Delta V^{min} \le \Delta V_{i,s,h} \le \Delta V^{max}$ and $\theta_{l,s,h}$ is defined as $\theta_{k,s,h} = \theta_{i,s,h} - \theta_{j,s,h}$, *i* and *j* resemble to the same line *k*. Note that $\Delta V_{i,s,h}$ corresponds to the voltage deviation at node *i* (from the nominal value) in a given scenario and hour. The transfer capacity of each line should respect the maximum power flow limits, given by:

$$P_{k,s,h}^2 + Q_{k,s,h}^2 \le (S_k^{max})^2 \tag{3.19}$$

In addition, active and reactive power losses in each feeder are given by:

$$PL_{k,s,h} = \frac{R_k\left(P_{k,s,h}^2 + Q_{k,s,h}^2\right)}{V_{nom}^2} \tag{3.20}$$

$$QL_{k,s,h} = \frac{X_k\left(P_{k,s,h}^2 + Q_{k,s,h}^2\right)}{V_{nom}^2} \tag{3.21}$$

To model ESSs, the following constraints are added [332]:

$$0 \le P_{es,i,s,h}^{ch} \le I_{es,i,s,h}^{ch} P_{es,i,h}^{ch,max} \tag{3.22}$$

$$0 \leq P_{es,i,s,h}^{dch} \leq I_{es,i,s,h}^{dch} P_{es,i}^{ch,max} \tag{3.23}$$

$$I_{es,i,s,h}^{ch} + I_{es,i,s,h}^{dch} \leq 1 \tag{3.24}$$

$$E_{es,i,s,h} = E_{es,i,s,h-1} + \left(\eta_{es}^{ch} P_{es,i,s,h}^{ch} - \frac{P_{es,i,s,h}^{dch}}{\eta_{es}^{dch}} \right) \Delta h \tag{3.25}$$

$$E_{es,i}^{min} \leq E_{es,i,s,h} \leq E_{es,i}^{max} \tag{3.26}$$

$$E_{es,i,s,h0} = \mu_{es} E_{es,i}^{max}; \; E_{es,i,s,h24} = \mu_{es} E_{e.s,i}^{max} \tag{3.27}$$

Equation (3.22) and (3.23) set the limits of power charged and discharged, respectively. In (3.24), it is ensured that the operation of charging and discharging of ESSs does not occur at the same time. Equation (3.25) denotes the state of charge. Equation (3.26) ensures that the storage level is within the permissible range. Eq. (3.27) ensures that the storage level at final time period is the same as the initial storage level.

The active and reactive power limits of power generators are generally enforced by adding the following constraints:

$$P_{g,i,s,h}^{min} \leq P_{g,i,s,h} \leq P_{g,i,s,h}^{max} \tag{3.28}$$

$$Q_{g,i,s,h}^{min} \leq Q_{g,i,s,h} \leq Q_{g,i,s,h}^{max} \tag{3.29}$$

In the case of wind and solar PV power generators, $P_{g,i,s,h}^{min}$ is often set to zero; whereas, $P_{g,i,s,h}^{max}$ is determined by the strength of primary energy resources (wind speed and solar radiation). Hence, it is set to the actual power production, $P_{g,i,s,h}$.

In the case of variable power generators such as wind and solar PV, the expressions related to reactive power production constraints are derived based on the assumption that each of the variable power generators are operated at a constant power factor, pf_g. In addition, conventional wind and solar PV sources do not often have the capability to provide reactive power support; hence, they are operated at a constant and lagging or unity power factor. Under such an operation, the following constraints should be used:

$$Q_{g,i,s,h} = \tan\left(\cos^{-1}(pf_g)\right) * \; P_{g,i,s,h} \tag{3.30}$$

Whereas, for wind and solar PV type DGs with reactive power support capabilities such as doubly fed induction generator based wind turbine and voltage source inverter based PV, the following constraints are used:

$$-\,tan\left(cos^{-1}(pf_g)\right)\; P_{g,i,s,h} \;\leq\; Q_{g,i,s,h} \leq tan\left(cos^{-1}(pf_g)\right)\; P_{g,i,s,h} \tag{3.31}$$

The above two inequalities, i.e. (3.31), show that the wind and solar type DGs are capable of operating between pf_g leading power factor (capacitive) and pf_g lagging power factor (reactive). This means such DGs are capable of “producing” and “consuming” reactive power depending on the operational situations in the system. Note that the upper and lower bounds in (3.31) are determined by assuming a constant power factor operation. But the reactive power production or consumption can assume any optimal value between these bounds, depending on the operational situation of the system.

Also, the reactive power at the substation bus should be subject to reactive power limits (again under the assumption of constant power factor operation):

$$-\tan\left(cos^{-1}(pf_{ss})\right)\; P^{SS}_{\varsigma,s,h} \;\leq\; Q^{SS}_{\varsigma,s,h} \leq \tan\left(cos^{-1}(pf_{ss})\right)\; P^{SS}_{\varsigma,s,h} \tag{3.32}$$

The reactive power supplied by switchable capacitor banks (SCBs) is limited by inequality (3.33):

$$0 \;\leq\; \mathrm{Q}^{\mathrm{c}}_{\mathrm{c,i,s,h}} \leq \mathrm{x}_{\mathrm{c,i,h}}\, \mathrm{Q}^{0}_{\mathrm{c}} \tag{3.33}$$

where $\mathrm{Q}^{0}_{\mathrm{c}}$ is the minimum deployable unit of a capacitor bank.

To account for DR, the following equations are introduced. Note that it is accounted for responsive active and reactive demand [338]:

$$PD_{s,h}^{i} = PD_{s,h}^{i,0}\left(1 + \alpha \sum_{h'} \xi_{h,h'} \left(\frac{\varphi_{s,h}^{RTP} - \lambda_{s}^{flat}}{\lambda_{s}^{flat}}\right)\right) \quad (3.34)$$

$$QD_{s,h}^{i} = QD_{s,h}^{i,0}\left(1 + \alpha \sum_{h'} \xi_{h,h'} \left(\frac{\varphi_{s,h}^{RTP} - \lambda_{s}^{flat}}{\lambda_{s}^{flat}}\right)\right) \quad (3.35)$$

$$\lambda_{s}^{flat} = \frac{\sum_{h} \lambda_{s,h}^{\varsigma}}{24} \quad (3.36)$$

$$\varphi_{s,h}^{RTP} = \begin{cases} \lambda_{s}^{Valley} = \frac{\sum_{h} \lambda_{s,h}^{\varsigma}}{8}, & h \in [1-8] \\ \lambda_{s}^{Off-Peak} = \frac{\sum_{h} \lambda_{s,h}^{\varsigma}}{10}, & h \in [9-18] \\ \lambda_{s}^{Peak} = \frac{\sum_{h} \lambda_{s,h}^{\varsigma}}{6}, & h \in [19-24] \end{cases} \quad (3.37)$$

The parameters $PD_{s,h}^{i,0}$ and $QD_{s,h}^{i,0}$ reflect active and reactive power before DR implementation. The average electricity price of the day (3.32) is assumed to be the flat price. The Real Time Pricing $\varphi_{s,h}^{RTP}$ is divided into three categories corresponding to valley, off-peak and peak times of demand profile (3.36). Each one is the average of the price in that time.

Table 3.2 contains the elasticities $\xi_{h,h'}$, considered in the simulations (used only for the second case study). In addition to the above constraints, it must be ensured that the distribution system operates radially. For this, the radiality constraints in [339] are included in our model.

Table 3.2 - Elasticity Matrix

	Valley	Off-Peak	Peak
Valley	-0.2	0.008	0.008
Off-Peak	0.01	-0.2	0.008
Peak	0.012	0.008	-0.2

3.3.3 Methodology

The present methodology is explained in the flowchart presented in Figure 3.1. This model is composed by a multiobjective approach in the perspective of minimizing the total costs considering the stochastic nature of RESs (solar and wind) as well as the demand. Therefore, the total costs are minimized considering four cost terms: the cost of switching, the cost of energy, the cost of energy not supplied, and the cost of emissions. The aim of the optimization is to obtain a coordinated model where the benefits of flexibility found through the use of DSR, DR ESS modeling along with an AC OPF model are verified, for example, in terms of allowing for greater integration of RESs.

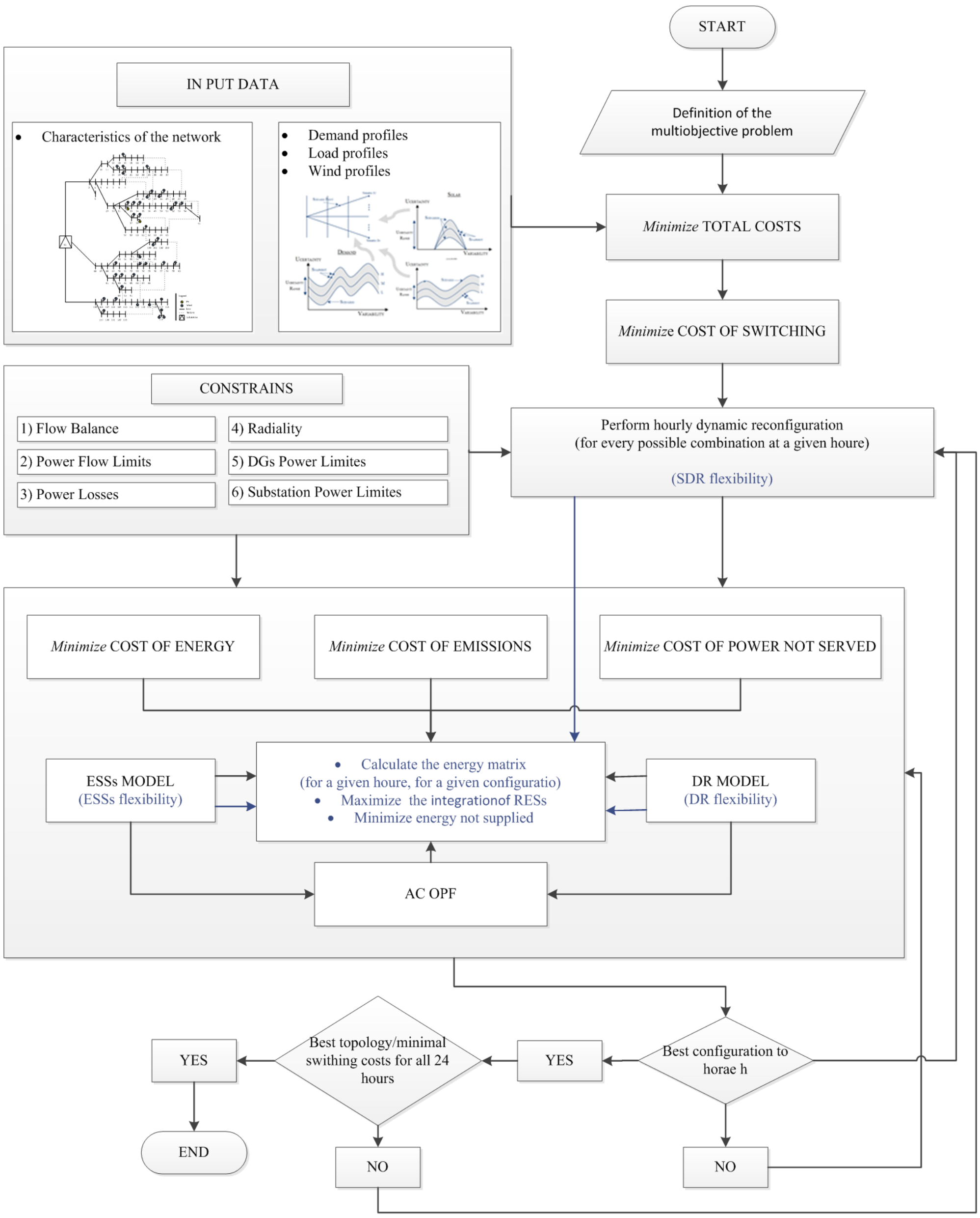


Figure 3.1 - Methodology flowchart.

3.4 Case Study, Numerical Results and Discussions

In this chapter, two IEEE test system are used to validate the new proposed methodology. One small system the IEEE 41-bus test system, and a large test system, the IEEE 119-bus test system in order to validate its scalability. The numerical results and respective discussion for the two test systems are presented in the following sections.

3.4.1 Case Study 1 (IEEE 41-bus test system)

3.4.1.1 - Input Data and Assumptions

A standard IEEE 41-bus test system, whose single-line diagram is shown in Figure 3.2, is employed here to perform the required technical and economic analysis. The total active and reactive power demand of this system are 4.635 MW and 3.25 MVAr, respectively. The nominal voltage of the system is 12.66 kV. Further details and information of this test system can be found in [340], [341].

The optimal locations and sizes of various distributed energy resources such as wind and solar type DGs, ESSs and SCBs in [341] are considered in this work. The only exception is at bus 14, where, instead of the optimal DG size (3 MW) reported in [341], a 2 MW DG is considered throughout this analysis. To make this chapter self-contained, the input data with regards to reactive power sources, DGs and ESSs are presented in Tables 3.3, 3.4 and 3.5 [341]. Figure 3.2 also clearly shows the locations of the considered DGs and ESSs. In addition, the following considerations are made when carrying out the simulations:

- The operational analysis spans over a 24-hour period, with the possibility of hourly network reconfiguration.
- The maximum allowable deviation of the nodal voltage at each node is set to ±5% of the nominal value (12.66 kV).
- For all simulations, the substation serves as the reference node, whose voltage magnitude and angle are set equal to the nominal value and 0, respectively.
- The power factor at the substation is set equal to 0.8, and this is held constant throughout the analysis. The power factor of all DG types is considered to be 0.95.
- The emission rate at the substation is arbitrarily set to 0.4 tCO_2e/MWh while those of solar and wind type DGs are assumed to be 0.0584 and 0.0276 tCO_2e/MWh, respectively.
- The price of emissions is considered to be 7 $€/tCO_2e$.

- The tariffs of solar and wind power generation are set equal to 40 and 20 €/MWh, respectively.
- Both charging and discharging efficiency of ESSs is 90%.
- The variable cost of operating ESSs is considered as 5 €/MWh.
- The cost of load shedding is 3000 €/MW, and any unserved reactive power is also penalized by the same amount.
- All feeders (including tie-lines) have a maximum transfer capacity of 6.986 MVA, which needs to be respected.
- All big-M parameters are set equal to 20, which is sufficiently large for the considered system.
- The number of partitions considered for linearizing quadratic terms in (3.17)—(3.19) is 5, which is set according to the findings in [342].
- The switching cost parameter is set to 10 €/switching.
- All self-elasticity parameters are set equal to -0.2 while the effect of cross-elasticities is not accounted for in this work. This means that cross-elasticity parameters are all considered to be zero.

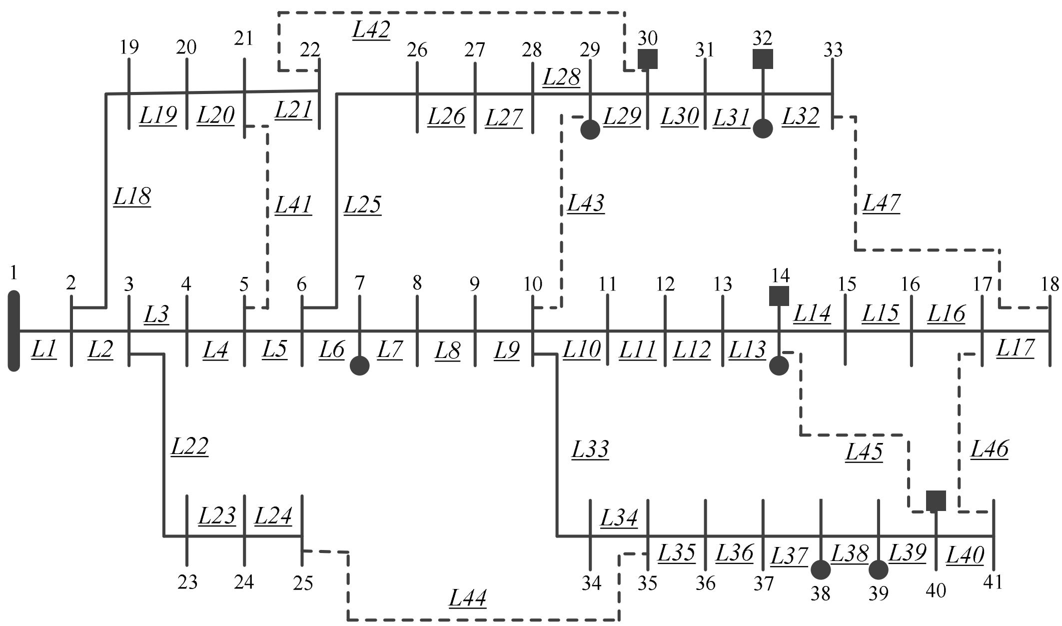


Figure 3.2 - IEEE 41-bus distribution system with new tie-lines (square and circle dots represent the locations of ESSs and DGs, respectively).

Table 3.3 - Placement and Size of Capacitor Banks

Location (Bus)	Size [MVAr]
7	0.9
14	1.3
24	0.1
25	0.3
29	0.3
30	1
31	0.2
32	0.5
37	0.1
38	2
39	0.1
40	0.6

Table 3.4 - Location and Size of DGs

vRES Type	Location (Bus)	Size [MW]
PV	32	1
PV	38	1
Wind	7	1
Wind	14	2
Wind	29	1
Wind	32	1
Wind	38	1
Wind	39	1

Table 3.5 - Location and Size of ESSs

Location (Bus)	Size [MW]
14	2
30	1
32	1
40	1

In addition, for the sake of brevity, the energy intensities of solar and wind power sources is considered to be uniform throughout the system nodes. This means that the power generation profiles of solar and wind type DGs are the same in all the nodes where these resources are connected to. Moreover, it is assumed that the energy consumption patterns at all load nodes follow the same trend.

In order to account for the uncertainty pertaining to demand, wind and solar power outputs, six different scenarios are considered for each uncertain parameter, as shown in Figures 3.3 through 3.5. As can be seen in these figures, each scenario represents possible hourly realizations of the uncertain parameter over the 24-hour period. The individual scenarios are obtained by clustering a larger number of scenarios (30 in this case). These scenarios are then combined to form a new set of 216 (6^3) scenarios that are considered in the analysis.

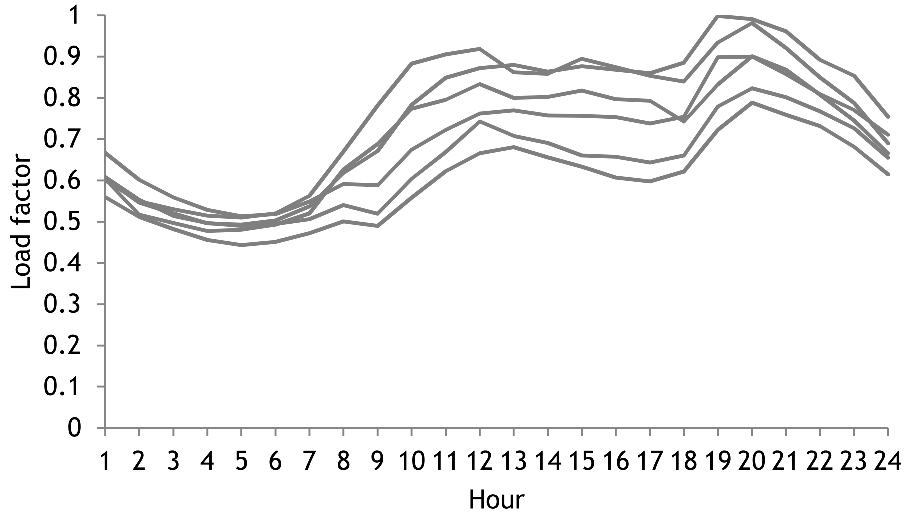


Figure 3.3 - Considered demand scenarios.

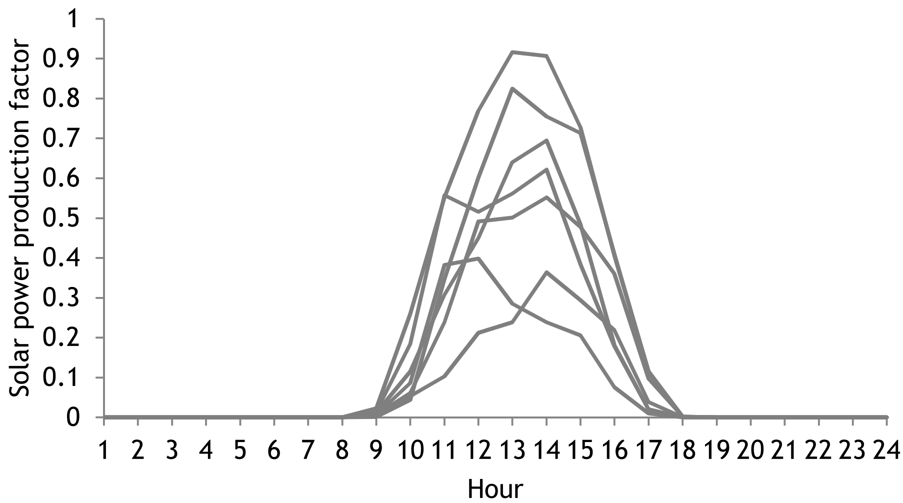


Figure 3.4 - Considered solar PV power output scenarios.

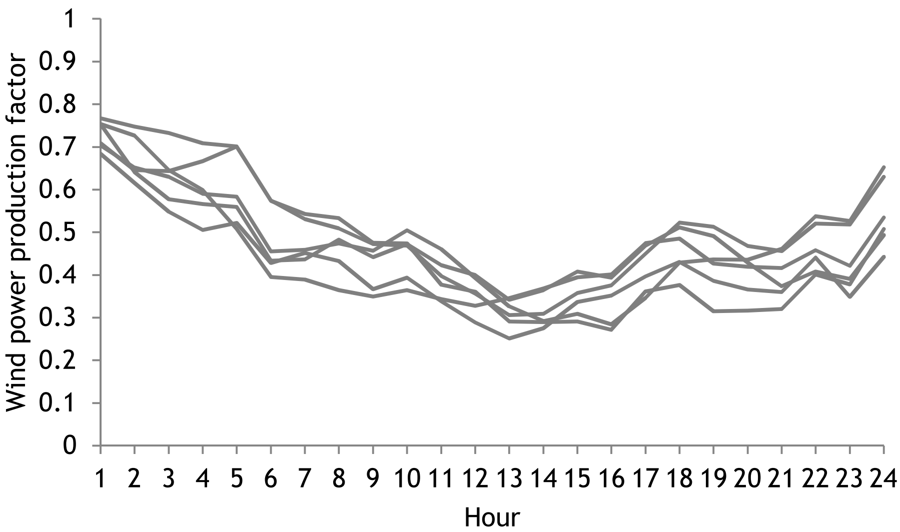


Figure 3.5 - Considered wind power output scenarios.

Electricity prices are assumed to follow a similar trend as demand, varying between 107 €/MWh during peak and 30 €/MWh during shallow hours. This is depicted in Figure 3.6. The potential of DR in the provision of flexibility for integrating vRESs is assessed by considering different self-elasticity values. Figure 3.7 demonstrates the impact of DR in the hourly consumption profile. In the results section, we shall present analysis results for a self-elasticity of -0.2.

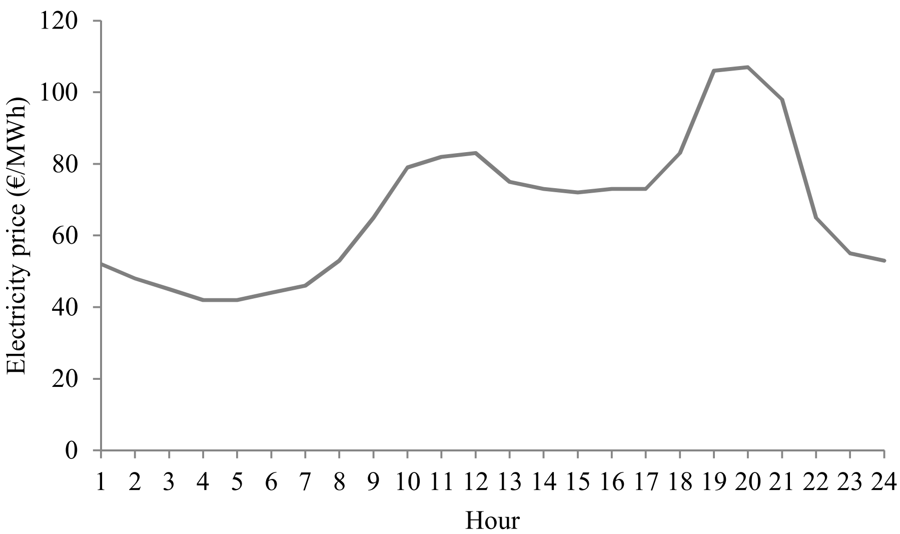


Figure 3.6 - Dynamic electricity price.

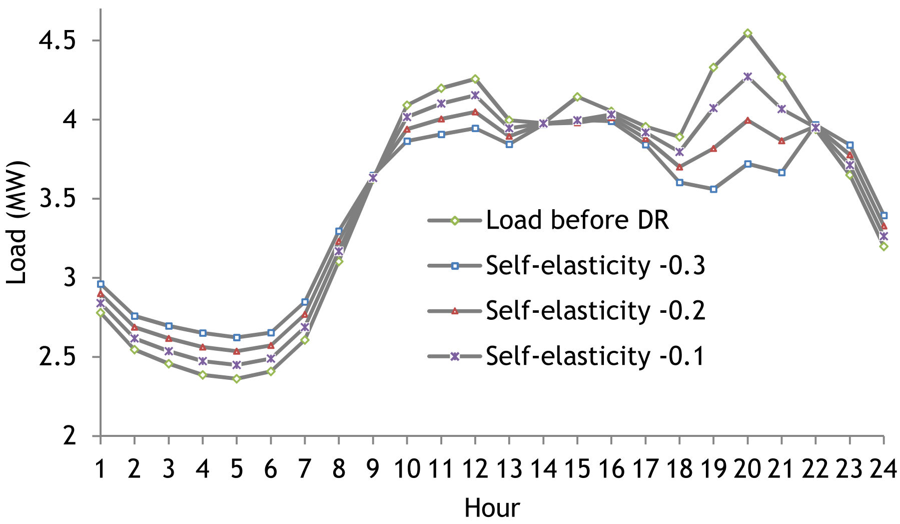


Figure 3.7 - Flexibility via demand response.

3.4.1.2 - Numerical Results and Discussions

To ease the aforementioned analysis work, a total of six cases are considered here. Table 3.6 summarizes the distinctive features of each case. As can be observed in this table, all cases except the first case have two things in common – dynamic network reconfiguration (DNR) and DG integration but differ in other aspects as clearly shown in Table 3.6.

The first case is related to the "do-nothing" scenario, where no distributed energy resource is connected and the entire load is met by importing power via the substation at bus 1. And, this is referred to as the "Base case". The second one considers DG integration with dynamic network reconfiguration, and is hereinafter referred to as "Only DNR". Note that DNR deals with the possibility of optimally changing the statuses of feeders (on an hourly basis) depending on the operational situation in the system. This case helps to understand the possible contribution of DNR in terms of enhancing system flexibility, and thereby increasing vRES utilization level. In addition to DNR, the third case considers switchable capacitor banks as a means of flexibility option. From now onwards, we shall refer this as the "Plus SCBs" case. The fourth and the fifth cases are similar in that both consider the flexibility options provided by DNR, SCBs and ESSs. The only difference between these two cases is that the former does not have DR integrated as an additional flexibility mechanism. These cases are denoted as "Plus SCBs & ESSs" and "Full flex", respectively. The last case only considers the flexibility options: DNR, SCBs and DR, and we shall denote this by "Plus SCBs & DR". Note that lower bound of nodal voltage is relaxed in the base case to avoid infeasibility. This is due to the fact that the original system is poorly compensated. And, under this circumstance, it is not technically possible to meet the high reactive power requirement in this system while simultaneously imposing the voltage limits.

For comparison purposes, the average voltage deviation at each bus is presented in Figure 3.8. This also displays the minimum and maximum average values corresponding to different operational situations. We can observe that most of the voltages fall outside the permissible range, particularly at the nodes located far away from the substation. The lowest voltage deviation occurs at bus 41, which can reach 18% in some operational situations.

Table 3.6 - Details of the cases considered in the analysis

Cases	Features					
	DNR	DGs	SCBs	ESSs	DR	Voltage limits
Base case	No	No	No	No	No	Not imposed
Only DNR	Yes	Yes	No	No	No	Imposed
Plus SCBs	Yes	Yes	Yes	No	No	Imposed
Plus SCBs & ESSs	Yes	Yes	Yes	Yes	No	Imposed
Full flex	Yes	Yes	Yes	Yes	Yes	Imposed
Plus SCBs & DR	Yes	Yes	Yes	No	Yes	Imposed

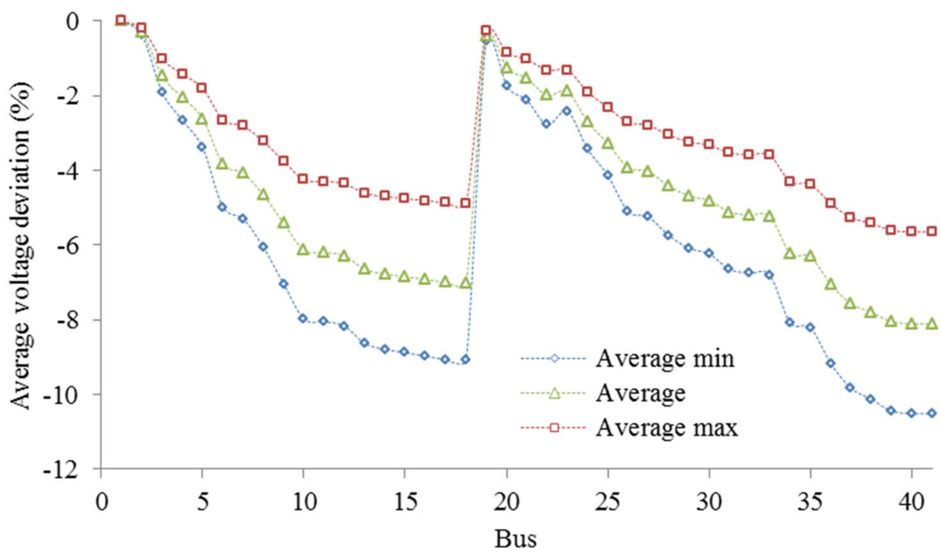


Figure 3.8 - Average voltage deviation profiles with no flexibility options (base case).

Table 3.7 compares the objective function values and average losses corresponding to the different cases considered in the analysis. Compared to the base case, we can see that there are substantial improvements in the values of the designated function and variables. In the "Only DNR" case, for example, the total cost is reduced by about 9% and average losses by 24%. However, the vRES penetration level in this particular case (which stands at 12.2%) is not significant; solar PV and wind type DG utilization levels are only 0.4% and 11.8%, respectively.

The wind and solar PV power sources are not being utilized because of technical constraints mainly related to the voltage limits. Since the system is not well-compensated, more power needs to be imported to support the high reactive power requirement in the system. Injecting more active power from the DGs, without proper compensation, would otherwise lead to voltage hikes which is not acceptable.

Figure 3.9 shows the energy mix in the "Only DNR" case. Based on these results, it seems DNR alone may not contribute enough to enhance vRES penetration level in distribution systems. However, this may be case-dependent. Moreover, some of the assumptions made in this work may not reflect the real potential of DNR as a key flexibility option. For example, the assumptions on the uniform patterns of electricity consumptions and vRES power outputs may not encourage more frequent reconfigurations of the network so as to adapt to varying operational situations.

Table 3.7 - Total expected costs and average losses for the considered cases

Cases	Total cost (€)	Average losses		Voltage limits
		Active (MW)	Reactive (MVAr)	
Base case	6036.281	0.275	0.201	Not imposed
Only DNR	5512.385	0.208	0.158	Imposed
Plus SCBs	2677.782	0.073	0.058	Imposed
Plus SCBs & ESSs	2229.248	0.096	0.075	Imposed
Full flex	2151.926	0.093	0.073	Imposed
Plus SCBs & DR	2522.484	0.072	0.057	Imposed

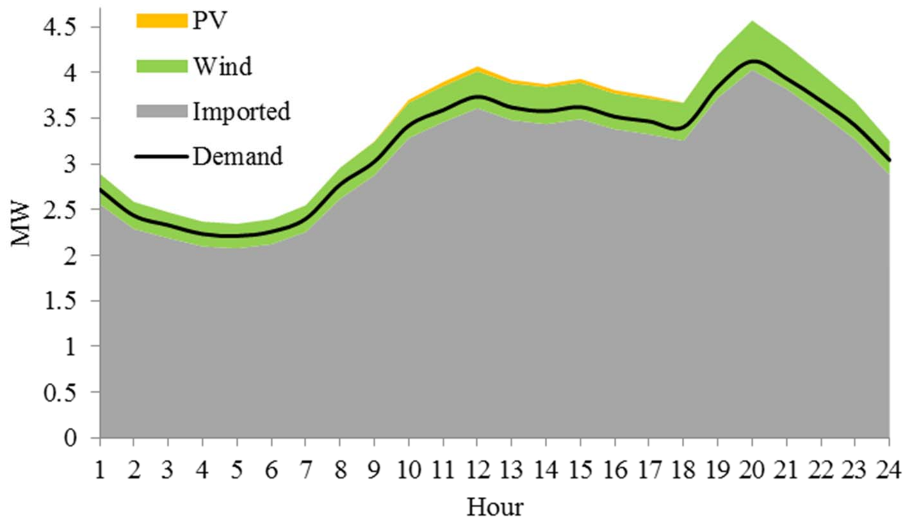


Figure 3.9 - Aggregate energy mix in the system in the "Only DNR" case.

In the case of "Plus SCBs", the results in Table 3.7 show that the reduction in total cost and losses is simply dramatic, and so is the level of vRES penetration. Compared to the base case, costs are slashed by about 56% while the reduction of losses amounts to more than 73%. In this case, solar PV and wind cover about 12.6% and 66.8% of the aggregate demand in the system over the whole day. The energy-mix corresponding to this case is depicted in Figure 3.10. As we can see, there are hours where the system operates in island mode (see the first four hours). This mean the demand in these hours is fully met by locally produced renewable power. Generally, the results here reveal the substantial benefits of SCBs in enabling a large-scale penetration of variable energy resources. In other words, a properly compensated distribution system can manage the technical risk posed by the intermittent nature of such resources.

As can be observed in Table 3.7, the overall cost is further reduced in the "Plus SCBs & ESSs" case by 63% in comparison to that of the base case. However, losses are slightly higher in this case than in the "Plus SCBs" one. This is mainly because of the fact that some feeders carry more power to charge/discharge the ESSs as opposed to the "Plus SCBs" case. It should be noted that the losses are yet substantially lower than that of the base case by 65%. The presence of ESSs in the "Plus SCBs & ESSs" case further increases the flexibility of the system, and allows a more efficient utilization of the "cleaner" DG power. This is can be seen in Figure 3.11. One interesting observation in this figure is that the system operates autonomously during peak hours by releasing the cheaper energy stored in the ESSs during valley and off-peak hours. Here, solar and wind power contribute 14.3% and 72.2% to the total energy consumption during the whole period. This means the total penetration level of vRESs reaches 86.5%, which is very high by any standard.

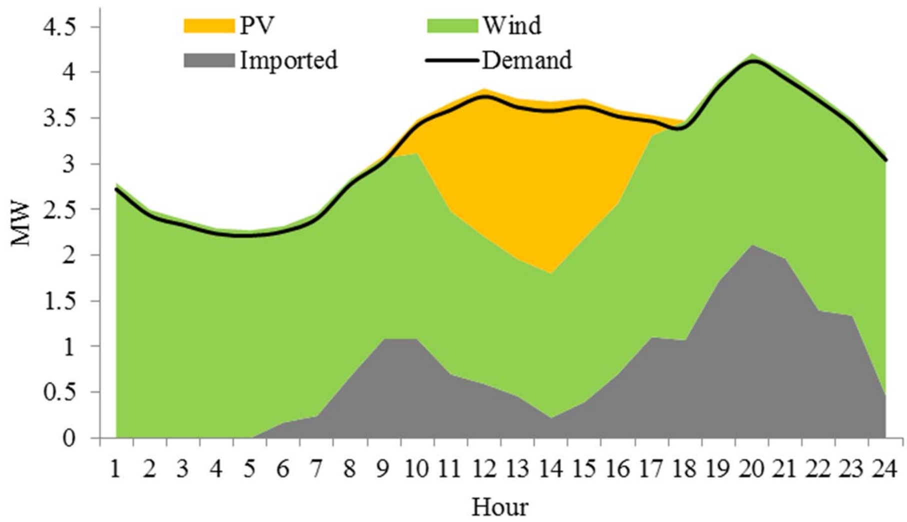


Figure 3.10 - Aggregate energy mix in the system corresponding to the “Plus SCBs” case.

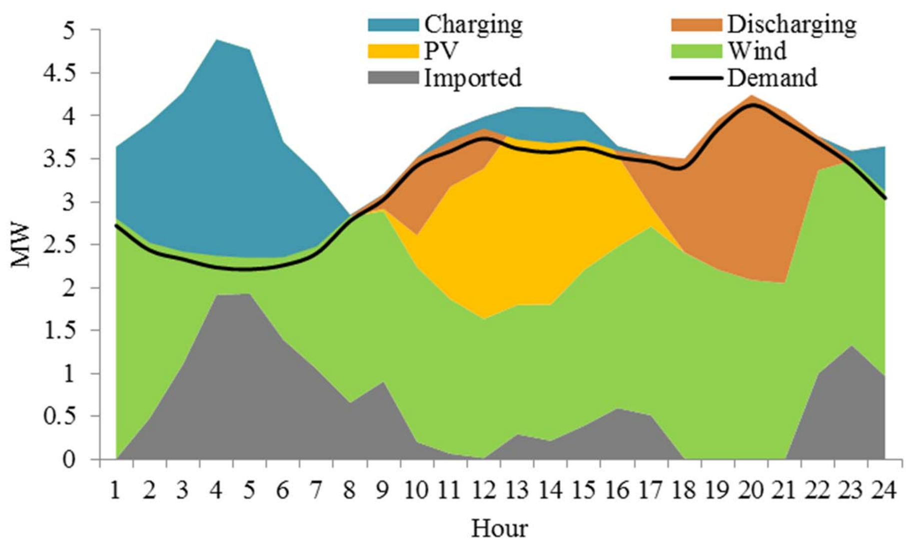


Figure 3.11 - Aggregate energy mix corresponding to the “Plus SCBs & ESSs” case.

The results in Table 3.7 also demonstrate that the introduction of DR, as in the “SCBs & DR” case, improves the flexibility of the system, and leads to the lowest losses (with an approximately 74% reduction in comparison to the base case). This is because of the relatively reduced amount of flows in the feeders especially during peak hours. Likewise, the total cost here is reduced by about 58%. This is higher by 2% than that of the “Plus SCBs” case. The aggregate energy mix corresponding to the “SCBs & DR” case is shown in Figure 3.12. The shares of wind and solar PV power production over the whole period are 12.4% and 67.9%, respectively, which brings the total vRES penetration level to 80.3%. Because of the absence of a storage medium, this value is lower than the 86.5% share in the “Plus SCBs & ESSs” case.

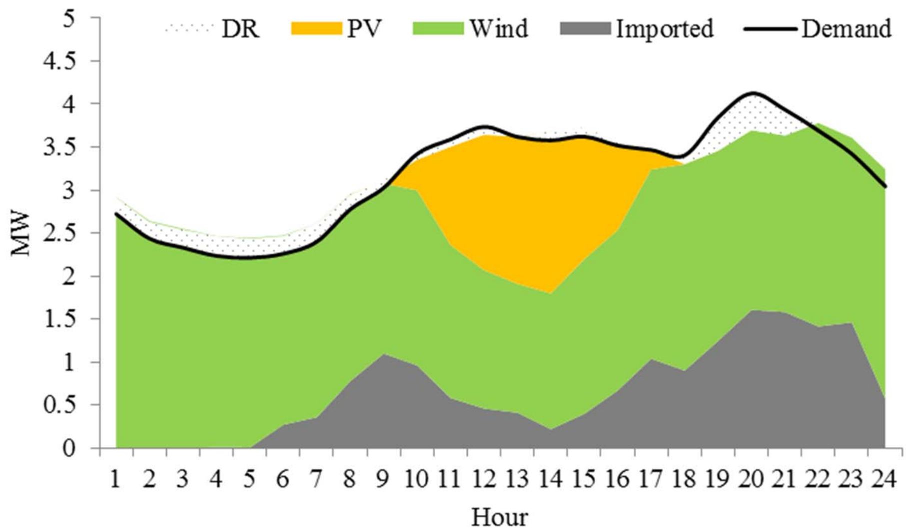


Figure 3.12 - Aggregate energy mix corresponding to the "SCBs & DR" case.

As mentioned earlier, the "Full flex" case jointly deploys all four technologies that are capable of providing flexibility to the system: DNR, SCBs, ESSs and DR. As expected, this case leads to the lowest overall cost in the system (i.e. about 64% lower than that of the base case). As can be seen in Table 3.7, the benefit in terms of losses reduction is also evident even though this is slightly higher than that of the "Plus SCBs & DR" due to the same reasons as before. Because of the increased system flexibility in the "Full flex" case, the amount of imported energy is significantly lower than that of any other case. The total share of vRES power production reaches 86.6% (see Figure 3.13). Wind and solar PV type DGs each contribute 14.4 and 72.2%, respectively.

So far, the analysis has been in terms of cost, energy mix and losses. Obviously, these are all relevant factors. However, it is also important to analyze the performance of the system from the technical point of view. To this end, the voltage profile is a good indicator. Ideally, voltage deviations in all nodes are desired to be close to the nominal value. But the nodal voltages often vary within certain permissible range (which in our case is 1 ± 5% of the nominal voltage).

Figure 3.14 shows average deviations of voltages at every node in the system for all the cases considered in this work. This figure clearly shows that the introduction of flexibility mechanisms dramatically improve the voltage profile within the system. This is very critical to maintain the healthy operation of such a system. The "Only DNR" case alone keeps the voltages within the allowable range. For the remaining cases, the average voltage deviations for most of the nodes are practically insignificant, averaging at about 1%.

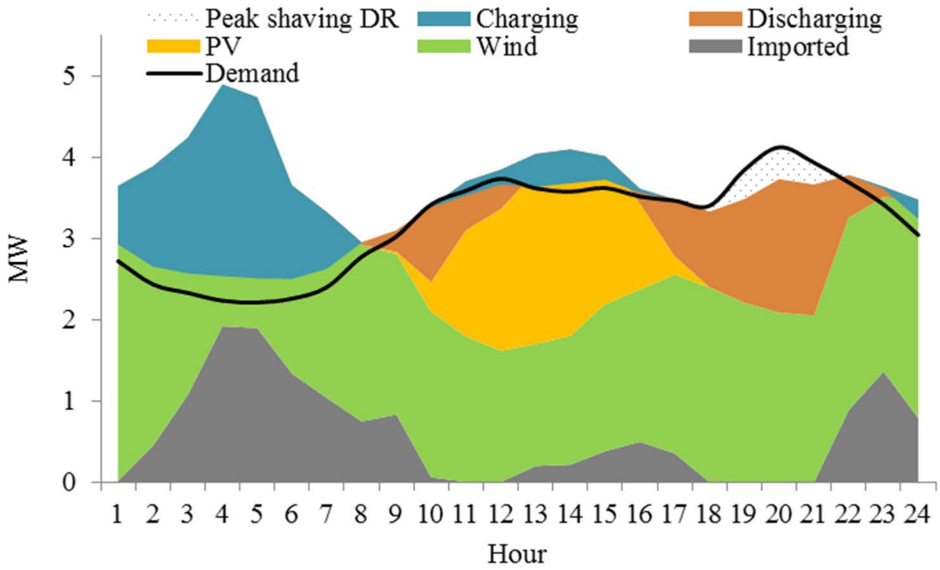


Figure 3.13 - Aggregate energy mix corresponding to the “Full flex” case.

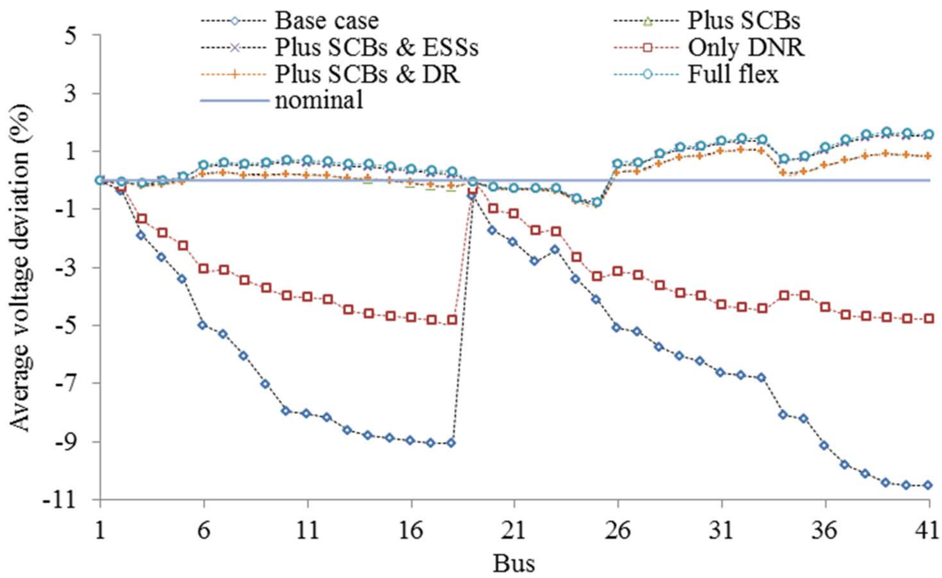


Figure 3.14 - Comparison of average voltage profiles for the different cases.

The benefits of all flexibility options considered in this work are evident with significant impact in achieving minimization of total costs of operation in the distribution system. Analysis of jointly or separated operation of ESSs, capacitor banks, vRES and switching substantially improved voltage profiles. Operation of distribution system with DR show the capability that this technology can have in the utilization of ESSs, making it a more valuable solution during operation, with less impact on total costs, increasing its utilization.

3.4.2 Case Study 2 (IEEE 119-bus test system)

3.4.2.1 - Input Data and Assumptions

In this thesis, the 119-bus test system (whose schematic diagram is shown in Figure 3.15) is used to perform the numerical analysis.

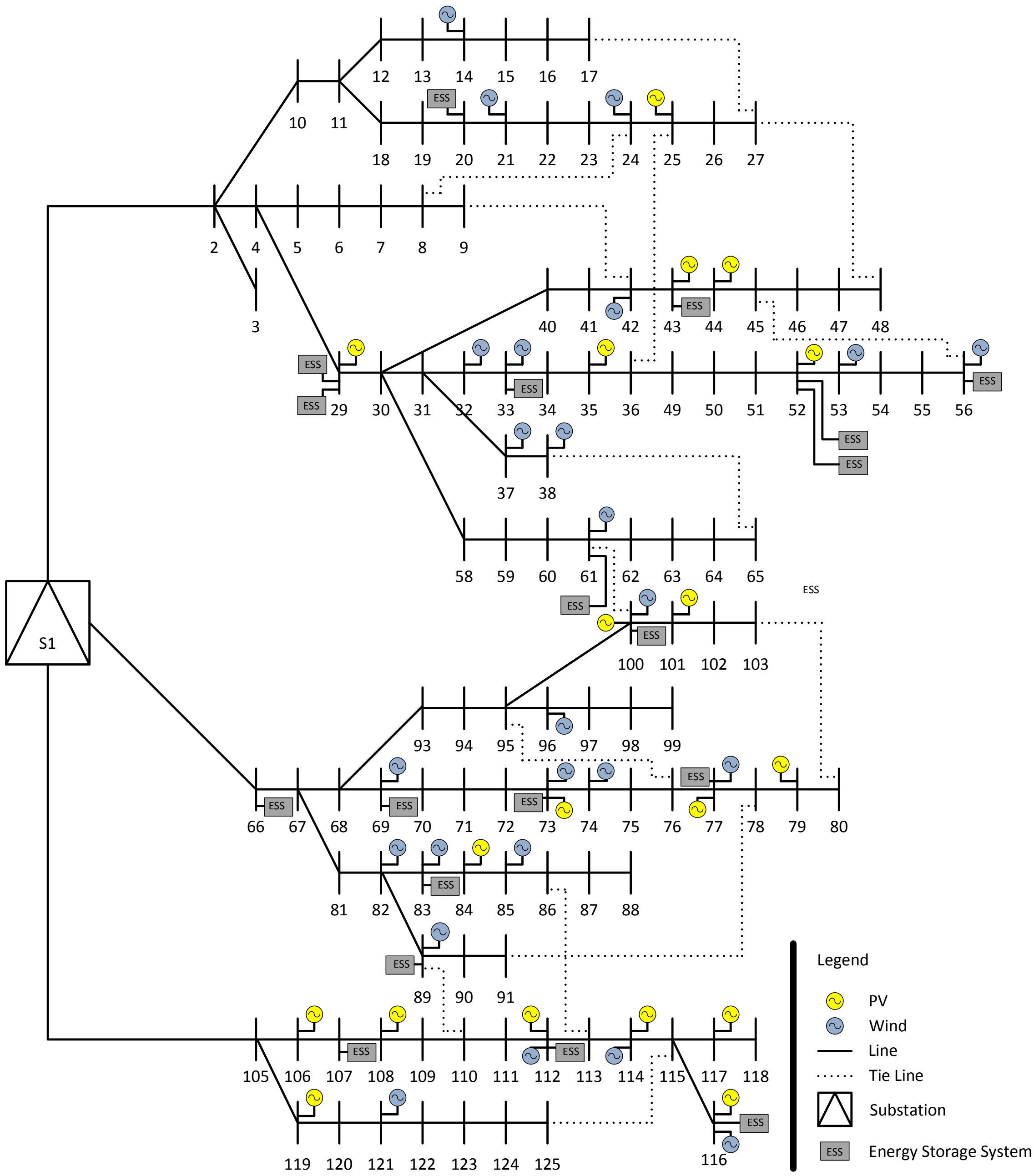


Figure 3.15 - A schematic diagram of the 119-bus test system.

The system has a nominal voltage of 11 kV and demand of 22709.72 kW and 17041.068 kVAr. More information about this test system can be found in [343]. Also, according to [343], active power losses of the system are 1298.09 kW, and the minimum voltage in the system is 0.8783 p.u., occurring at bus 116.

The size and location of RESs and ESSs, and also the power factor of RESs and assumed variable costs of ESSs, are all taken from [343]. The following further assumptions are made in the simulations. The analysis is made for a 24-hour period. The voltage deviation at any node is constrained to fall within ±5% of the nominal value (including boundaries). The reference node is the only substation, whose voltage magnitude and its angle are set to 1 p.u. and 0, respectively. The power factor at the substation is considered to be 0.8, adapted from [339]; the power factor of RESs is 0.95. Both values are held constant for all simulations.

The emission rate at the substation is set to 0.4 $\mathrm{tCO_2e/MWh}$, and that of solar and wind power generation technologies are set to 0.0584 $\mathrm{tCO_2e/MWh}$ and 0.0276 $\mathrm{tCO_2e/MWh}$, respectively. The emissions price is set to 6 $€/\mathrm{tCO_2e}$. These data are in accordance with [344]. The variable operation and maintenance costs for generating power from wind and solar technologies are set to 20 €/MWh and 40 €/MWh, respectively, according to [344].

The charging and discharging efficiencies of ESSs are considered the same and have a value of 90%, adapted from [345], [346]. Discharging power from ESSs have a unit price of 5 $€/\mathrm{MWh}$, which represents the variable operation and maintenance cost of the storage system.

Unserved active and reactive power was adapted from [339] and have a fixed penalty of 3000 $€/\mathrm{MWh}$. Feeders have a maximum capacity of 400A, except the feeders {(1, 2); (2, 4); (1,66); (66,67)} whose respective maximum capacity is set to 1200A and feeders {(4, 5); (5, 6); (6, 7); (4,29); (29,30); (30,31); (67,68); (67,81); (81,82); (1,105); (105,106); (106,107)} each having a maximum capacity of 800A.

The percentage of demand that can be responsive (α) was set to 20%. The losses linearization process consider 5 partitions, which is in line with the findings in [342].

3.4.2.2 - Numerical Results and Discussions

The analysis in this thesis considers four case studies whose results are discussed and analyzed. Case one refers to the Base Case where no RESs and flexibility options are considered. In this case, the lower voltage bound is removed to avoid an unacceptably huge amount of unserved power because of the lack of adequate reactive power compensation mechanism in the original system.

The second case jointly integrates DNR with large scale integration of RESs (and, this is designated as “Without ESSs”). The third case considers ESS deployments in addition to the conditions in the second case (This is hereinafter referred to as the “Plus ESSs” case). The last case is similar to the third case but including DR. Since this case considers all available flexibility options with RESs, it is hereinafter referred to as “Full Flex” case. Table 3.8 summarizes the distinctive features of each case.

The relevant costs of the objective function of each case are presented in Table 3.9. Analyzing the results, the Base Case has the highest expected total costs compared to the other cases due to only importing energy from upstream. Also, because DGs and ESSs are not considered, it has the highest emission costs.

Table 3.8 - Distinguishing the Cases Considered in the Analysis

	DSR	DGs	ESSs	DR	Voltage Limits
Base Case	No	No	No	No	Not imposed
Without ESSs	Yes	Yes	No	No	Imposed
Plus ESSs	Yes	Yes	Yes	No	Imposed
Full Flex	Yes	Yes	Yes	Yes	Imposed

Table 3.9 - Terms of objective function and power losses.

	Base Case	Without ESSs	Plus ESSs	Full Flex
Total Cost (€)	33408.66	19151.81	15657.50	15257.59
TSC (€)	0.00	1050.00	1020.00	1010.00
TEC (€)	31355.50	17442.59	14281.01	13901.64
TEmiC (€)	1255.31	516.20	356.50	345.96
TENSC (€)	797.85	143.02	0.00	0.00
Active Power Losses (MW)	20.25	7.45	6.35	6.29
Reactive Power Losses (MVAr)	14.11	4.95	4.19	4.13

In Case 2, where DNR and DGs are considered, the expected total costs are reduced by 42.7% since there is a reduction in terms of purchased energy from the upstream grid, which is more expensive than the one locally produced by the DGs, allowing the costs to drop. Moreover, since wind and PV power sources have lower emission rates, the expected cost related to emissions is also lower than that of the Base Case. Similarly, active power losses are reduced by 63% and reactive power losses by 65%. As expected, the deployment of DGs in the system lowers power losses because part of the overall energy consumed is met by the locally placed DGs. The expected cost related to the power not supplied also sees a reduction of 82%. In Figure 3.16, the energy mix for this case is depicted, where DGs are added to the system and represent a large part of the energy mix. In this case, the utilization of wind is about 57% and that of PV is about 4%, which brings the total demand covered by RES-based DGs to 61% of the total energy produced.

Concerning the case with ESSs, i.e. Case 3, it is possible to see a further reduction in the total expected costs by 53%. In this case, it is also clear that adding different energy sources in the mix will have a positive impact in the expected energy costs, since discharging the energy stored in the ESSs is cheaper than importing energy from upstream. This is due to the fact that the stored energy is mainly sourced from wind and PV generations. Also, ESSs do not have emission costs; therefore, the expected costs of emissions are reduced by 30% and 72% compared to that of the “Without ESSs” case and “Base Case”, respectively. In the “Plus ESSs” case, there are no instances of load shedding; and hence, no associated costs. This is because adding ESSs into the system along with joint operation with DGs will use the excessive energy produced by DGs to be stored, leading to a better fulfillment of demand in peak hours with more valuable and cheaper energy. In this context, ESSs increase the flexibility of the system, allowing a more efficient use of power produced by “variable type” DGs. Comparing with the “Without ESSs” case, the power losses are not affected very much; yet, a small reduction is achieved between the cases with DGs.

The last case, “Full Flex”, where all available flexibility options are considered, a 2.6% reduction in expected total costs is attained compared with “Plus ESSs”. The aggregated energy mix for the case with full flex is shown in Figure 3.17. Compared with the Base Case, the expected total costs are reduced by 54%. In addition, the expected energy costs are reduced by 56%, expected emissions cost drops by 72%, active power losses are reduced by 69% and reactive power losses by 71%. The case with full flexibility has the best outcome in terms of expected costs and in terms of power losses among all cases considered. It can be seen that, as far as adding more flexibility in the system is concerned, the costs with DNR are being reduced from the case “Without ESSs” to the case “Full Flex”. This shows that the system needs less dynamic switching between time periods when more flexibility options are considered. The dynamic reconfiguration of the system for the "Full Flex" case can be seen in Table 3.10 for the 24 hours of the operating period.

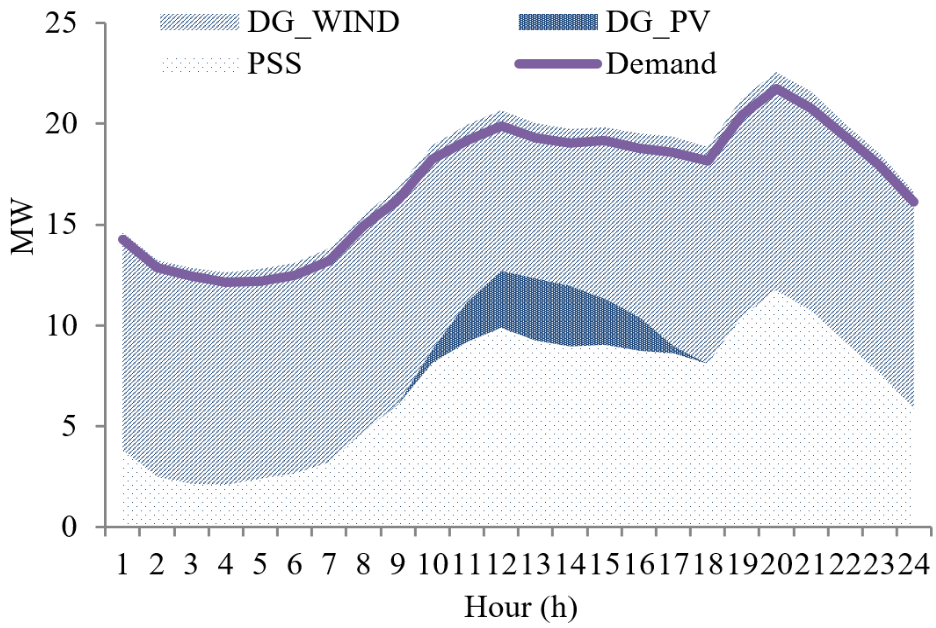


Figure 3.16 - Aggregated energy mix in the “Without ESSs” case.

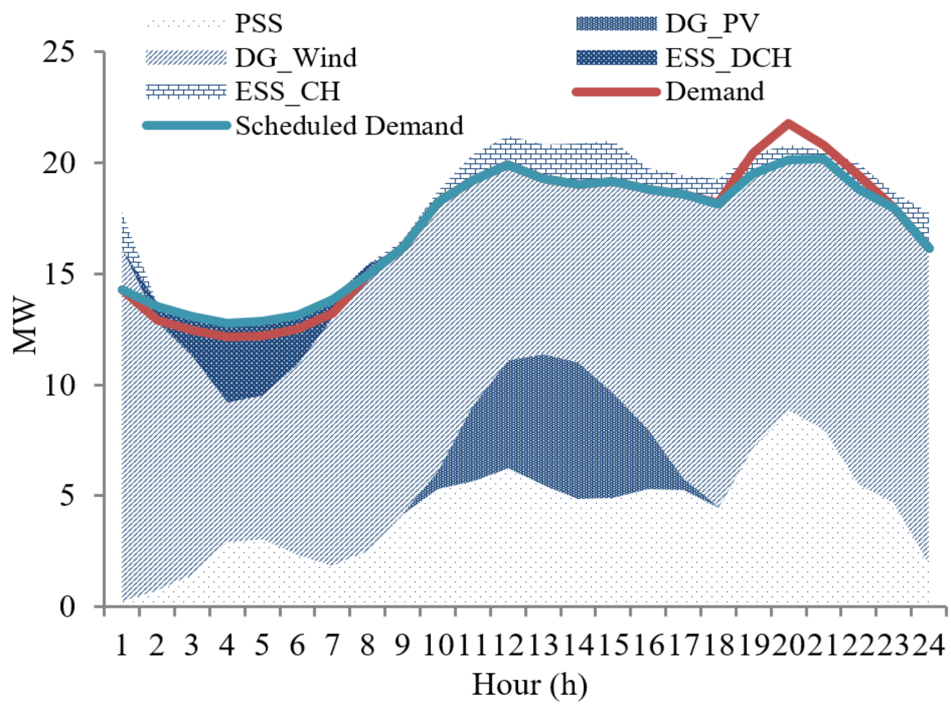


Figure 3.17 - Aggregated energy mix in the “Full Flex” case.

Table 3.10 - Hourly Reconfiguration Outcome in the “Full Flex” Case

Hour	Open Lines $x_{k,h} = 0$	Hour	Open Lines $x_{k,h} = 0$
1	{23, 26, 34, 61, 82, 90, 95, 117, 119, 121, 122, 124, 127, 128, 130}	13	{23, 26, 34, 53, 61, 90, 95, 119, 121, 124, 127, 128-130, 131}
2	{23, 26, 34, 42, 61, 76, 82, 85, 90, 95, 119, 122, 124, 127, 131}	14	{23, 34, 61, 74, 82, 85, 118, 119, 121, 122, 124-126, 131}
3	{23, 26, 34, 61, 74, 76, 82, 85, 90, 95, 119, 121, 122, 124, 131}	15	{23, 34, 61, 74, 82, 85, 117-119, 124-126, 128}
4	{23, 26, 34, 53, 61, 74, 76, 82, 85, 90, 95, 118, 121, 124, 131}	16	{23, 34, 39, 53, 61, 85, 118, 119, 121, 125-129, 131}
5	{23, 26, 34, 42, 53, 61, 74, 76, 82, 90, 95, 118, 124, 130, 131}	17	{23, 26, 34, 53, 61, 74, 90, 95, 117, 118, 121, 124, 128-130}
6	{23, 26, 34, 53, 61, 74, 76, 82, 90, 95, 118, 121, 124, 130, 131}	18	{23, 26, 34, 53, 61, 90, 95, 119, 121, 124, 127-131}
7	{23, 26, 34, 42, 61, 74, 76, 90, 95, 119, 122, 124, 129-131}	19	{26, 34, 39, 53, 61, 85, 118, 120, 121, 125, 126-128, 129, 131}
8	{23, 26, 34, 53, 61, 82, 85, 90, 95, 119, 121, 124, 127, 128, 131}	20	{26, 34, 39, 61, 74, 119-122, 125, 126, 128-130, 131}
9	{23, 26, 34, 61, 82, 85, 90, 95, 119, 121, 122, 124, 126-128, 131}	21	{26, 39, 61, 74, 85, 118, 120-122, 125, 126, 128, 129, 131, 132}
10	{23, 26, 34, 39, 53, 61, 90, 95, 119, 121, 127-130, 131}	22	{23, 34, 39, 53, 61, 76, 82, 85, 118, 119, 121, 125-127, 131}
11	{23, 26, 34, 39, 53, 61, 74, 118, 121, 125, 128-130, 131}	23	{23, 26, 34, 53, 61, 74, 82, 85, 119, 121, 124-126, 131}
12	{23, 26, 34, 39, 61, 85, 90, 119, 121, 122, 125, 116-129, 131}	24	{23, 26, 34, 42, 53, 74, 82, 85, 90, 95, 117, 119, 123, 124, 128}

The aggregated energy mix in the “Full Flex” case (presented in Figure 3.17) shows very interesting results. The integration of DGs and ESSs dramatically decreases the usage of energy imported from upstream. The percentage of PV and wind usage in the mix is 7% and 65%, respectively while ESSs account for 3% of the energy demand. This leads to a total of 76% of demand fulfilled by DGs and ESSs. Local demand is largely supplied by these technologies. The ESSs are being charged during the day, benefiting from the presence of solar starting at 9h and still charging during peak hours, where there is a lot of wind power production. ESSs are discharged between the second and the seventh hour during the course of the day because there is no energy production from PV, and energy from wind production is at its lowest compared to the rest of the time period. In this manner, power import is kept at low level, benefiting the system with integration of ESSs by reducing costs. The profile of demand scheduled is also presented in Figure 3.17.

Another important factor to analyze is the average voltage profile in the system. In Figure 3.18, the average voltage profile for all considered cases is shown. To be in a healthy operation, the voltage magnitude at each bus should be close to the rated (nominal) value. Nevertheless, the voltage will vary within a range in the nodes of the system. In Figure 3.18, it is clear that, with increasing flexibility options in the system, the voltage deviation will get flatter, improving the voltage profile and keeping each node’s voltage close to the nominal value (i.e. with 0% deviation). Figure 3.18 clearly shows that the “Full Flex” case has the best voltage profile in the resulting system. In the “Full Flex” case, the system has a mean voltage deviation value of nearly -0.4%. Obviously, implementing only DNR in the system can also lead to a better average voltage profile, as clearly observed in this figure.

In Figure 3.19, it is possible to observe the ESSs’ charge and discharge at each node for the "Full Flex" case as well as the respective contribution of each ESS, which on average has increased 2% compared with the "Plus ESSs" case. Demand in peak hours is being reduced and is scheduled to valley hours. This leads to lower losses in the system, and an improved voltage profile due to lower stresses in the feeder’s power flows. Correspondingly, the usage of DGs and ESSs are optimized because there is less demand to be fulfilled in peak hours, leading to a less congested network during that period. This is also reflected in the reduction of power losses.

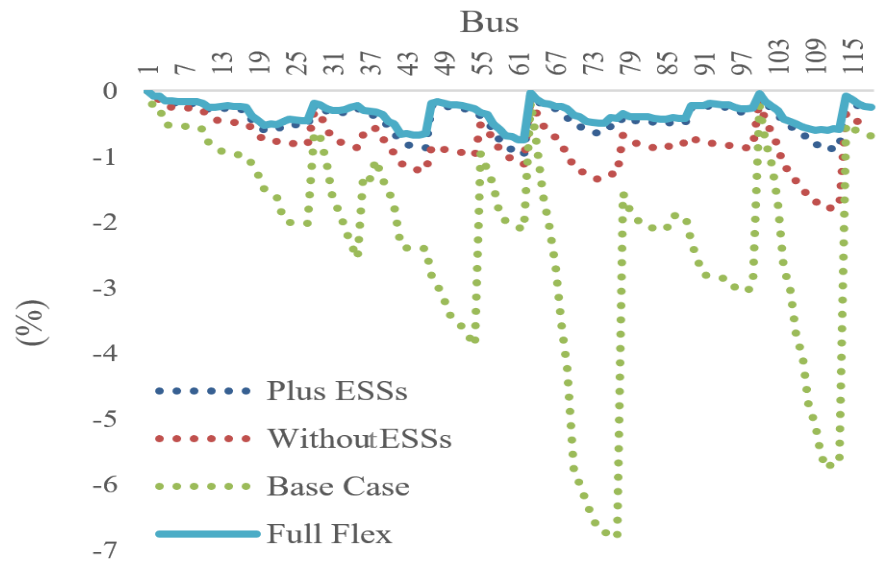


Figure 3.18 - Average system voltage deviation comparison between the considered cases.

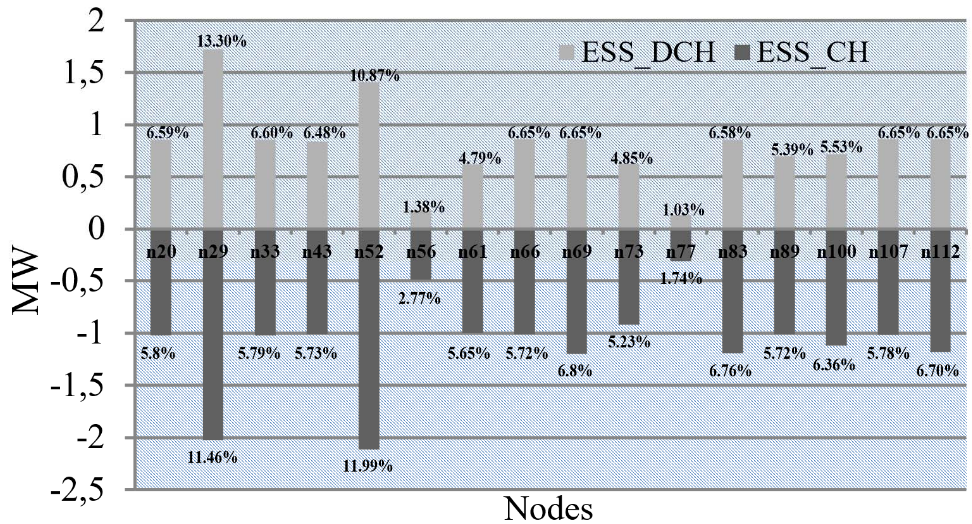


Figure 3.19 - Percentage of ESSs charge and discharge cycle by node in the “Full Flex Case”.

3.5 Chapter Conclusions

This chapter has presented an extensive analysis in relation to the joint integration of flexibility options as a way to cope with the intermittent nature of DG power productions (mainly wind and solar PV) and their efficient usage. To perform the analysis, a stochastic MILP optimization model has been developed. The resulting model is of an operational nature, and aims to operate the distribution systems featuring large scale integration of DGs while fulfilling a number of technical and economic constraints. The constrained optimization is based on a linearized AC-OPF model, and has an objective function encompassing the sum of expected costs related with the operation of distribution systems that is minimized subject to a range of operational and economic constraints. Two test systems were used in the analysis, the IEEE 41-bus test system and the IEEE 119-bus test system. In both test systems, the numerical results show that large scale integration of renewable type DGs can be achieved if this is coordinated with optimal deployment of ESSs and DR. In particular, a more efficient utilization of wind and solar power resources can be achieved as a result of optimally deploying such flexibility options. According to the simulation results in the second test system, as high as 76% of the demand can be covered by energy coming from wind, PV and ESSs, and most importantly without having dramatic impacts on the considered system in terms of its healthy operation. In addition, the expected operation costs are considerably reduced in both test systems, while the voltage profile in the system is also improved. Generally, as the level of flexibility in the system increases, managing the intermittent nature of wind and solar power is made easier.

Chapter 4

Analysis of a Meshed Electrical Distribution System to Accommodate Large-Scale Integration of vRES

Taking the findings in Chapter 3 as references, a new operational strategy is introduced in this chapter that is capable of increasing further the flexibility of electrical distribution systems. The new flexibility mechanism is the operation of distribution systems in a meshed topology with prospects of gradually adopting of such strategy. The analysis made in this chapter includes the additional level of flexibility that can be provided by operating distribution grids in a meshed manner, and the utilization level of variable renewable power. The operational problem is formulated as a mixed integer linear programming in a stochastic framework.

4.1 Introduction

4.1.1 Framework

Distribution power systems are experiencing massive transformations buoyed by the increasing need to integrate more variable renewable type distributed generations (DGs). This means distribution grids will be equipped with necessary tools to enable bidirectional power flows which is contrary to their traditional setup [343], [347]-[352]. Also, such a massive transformation needs to be accompanied by new operational schemes. In other words, new operational strategies should be crafted and widely used in order to increase flexibility in the distribution systems, and hence the penetration of renewables such as solar PV and wind. This is due to the fact that the traditionally radial network operation strategy may not be sufficient to accommodate the increasing penetration of renewables and their efficient utilization.

In this context, smart grids are one of the most promising solutions that enable large-scale integration of variable renewable energy sources (vRESs) at a distribution level [38], [39], [47], [353], [354]. However, the scale of transformation required to “smartify” existing grids means the whole process may be costly and most importantly slow. In other words, the smartification process will not happen overnight; it will rather involve a series of time-consuming and expensive upgrades to existing network infrastructures. Hence, the impact of smart grids would only be felt in the long-run when they are fully materialized.

Most of traditional distribution networks are meshed by design, but they are operated radially only due to technical limitations mainly related to system protection. These limitations are discussed in [13]. This means some tie-lines (also known as switches) are kept open so that the grid topology remains radial. Thus far, the operation and protection of a radial topology has been relatively easier [355]-[358].

The lines that are normally open in radial network systems are only used in emergency situations during situations of fault or power supply failure. The main purpose of this is to enhance the reliability of power delivery, i.e. some of the normally open tie-lines are closed to re-route power flows so that the amount of load shed is minimized. But the radiality of the network system is maintained at all times, regardless of the operational situations that happen in the system. The good news is that, in well-planned distribution networks, contingencies or emergency situations are rare phenomena.

As previously mentioned, one strategy worth considering is the operation of distribution networks in a meshed topology. This type of topology goes contrary to what is established, that is radially operating distribution systems. However, with the technological advances that are seen now, and expected to happen in the near future even in a more accelerated manner, it is possible to deal with all the inherent limitations of meshed operation of distribution networks. Given its multi-faceted benefits, the so-called meshed topology is expected to be a normal operation scheme for distribution grids in the future. But this does not mean that a radial topology would be completely abolished; there may be cases where this would make more sense from an economic and a technical standpoint.

The advantages related to meshed distribution systems are the reduction of power losses, improved voltage profiles, more flexibility and capability to deal with high electricity demand growth, enhancement of power quality (PQ) [359]. Furthermore, in meshed distribution systems where there are no DGs integrated, the distribution of power flows among parallel paths can potentially decrease stress on the entire network system, and possibly defer grid-related investments. This can be achieved only by optimizing the loops in tie lines in the distribution system. When DGs are appropriately allocated in such systems, they can bring in several benefits such as reduction of power losses, better voltage profile and also the investment deferral as a result of reduced congestion in the network components (feeders and transformers) [359].

Likewise, a meshed topology can have similar benefits as DGs. The combination of both can potentially enhance distribution system reliability and the quality of power delivered to end-users. The negative aspects associated with DG integration are the possible increase in short circuit currents, and hence the need for possible modification of protection devices' settings [359].

Because of this, international standards determine the immediate disconnection of DGs from the distribution system in case of faults so that conventional protection devices can act properly. Similarly, a meshed topology also shares this issue. But technological advances make it easier to switch from meshed to a radial topology in case of fault or vice versa, allowing to reap the benefits of the former. For example, a locally generated renewable power can be efficiently utilized under a meshed topology, which would have otherwise been curtailed in the traditional network setup.

There are a set of technologies that could be used to exploit the meshed network topology and minimize the concerns of such a topology. For instance, when a fault occurs in the system, fast de-loopers can be deployed to quickly switch from a meshed to a radial topology so that conventional protection devices can properly act. Another enabling technology with regards to the meshed operation is Fault Current Limits (FCLs) [360]. Generally, the operation of distribution networks in a meshed manner can become a norm in the near future.

4.1.2 Literature Review

Large-scale integration of vRESs has brought about a set of challenges which requires necessary attention and action. The main challenges revolve around protection schemes, voltage regulation as a result of fluctuations induced by vRESs, voltage sags and/or rises, and network congestion among others [361]. Such issues are exacerbated with increasing integration of vRESs in distribution networks because these are designed for unidirectional power flows. However, operating distribution grids in a meshed manner can alleviate some of these issues, and bring in a number of benefits, for example, in terms accommodating more vRES power, an important aspect given the growing global concerns surrounding climate change. However, the prospects of a meshed operational scheme have not been adequately explored in the literature.

A comparative study between a meshed operation and reinforcement of distribution networks has been performed in [362]. The study involves the comparison of results from using enumeration, constraints and loops analysis methods. Authors in [363] develop a model that estimates the maximum penetration of DGs based on a steady state analysis. The approach uses some elements of an optimal power flow analysis, bus voltage and current flow limits to estimate the maximum allowable DG penetration at each node of the considered system. Authors conclude that a meshed topology may be a good alternative to host a large-scale DG power. Furthermore, authors in [183] propose a methodology for allocating conventional DGs in a distribution system, and evaluate their impacts on the distribution system For the analysis, they have considered a meshed operational scheme, and a voltage sensitivity index to quantify the operability of the system.

However, their analysis is based on the integration of conventional sources of energy into distribution systems. In [182], authors provide an extensive analysis of optimum power flows when operating distribution networks in a radial and a meshed manner. The analysis is carried out considering reactive power compensation devices and DGs. In [184], authors develop an operational model for analyzing the prospects of a meshed distribution network topology, which is based on circuits composed of a resistor, inductor and capacitor (RLC). Reference [185] provides a steady state analysis of a meshed distribution system featuring DGs, and is based on iterative load-flow calculations.

However, the analysis of the existing literature, reviewed here, is based on conventional type DGs under a meshed operational scheme. To the best knowledge of the authors, the scope of integrating vRESs in tandem with meshed operation of distribution systems has not been addressed in the literature. Hence, this is the main focus of the current work. The argument provided here is that electrical distribution systems can be operated in a meshed topology under normal situations. Also, they can be equipped with advanced and even currently available technologies that temporarily enable a smooth automated transition to a radial topology in case of contingency, and back to the preferred topology when the fault is cleared. This way, one can take full advantage of the meshed operation of the distribution network, which eventually leads to reduced losses, improved voltage profiles and a more efficient management of locally produced vRES power.

The meshed operational scheme can also have benefits in terms of network-related investments. A more distributed nature of power flows in the meshed topology would mean lower stress (congestion) in the whole system, reducing the need for network upgrades. Note that existing switches and loops in distribution systems can be effectively used to develop an optimal meshed topology.

However, none of the aforementioned references focus on analyzing distribution systems' meshed grid topology in tandem with integrating variable renewable energy. Taking advantage of the new technologies, this work argues that distribution systems can be operated in a meshed way in normal system operation and automatically switch to a radial configuration in case of failure. Therefore, the benefits of a meshed operational scheme can be reaped in full capacity, which includes the reduction of losses, the improvement of the voltage profile and better management renewable energy sources in the distribution system. In practice, switching from radial to mesh operation does not require a large investment in distribution systems. The method makes use of existing switches (loops and tie lines).

4.2 Mathematical Model

4.2.1 Objective Function

The main objective is to minimize the total costs of operating the considered distribution system. These costs are associated with operating costs in the system, namely the cost of energy not supplied, the costs of emissions and the cost of power generation using conventional and renewable power sources.

$$Minimize\ TOC = TEC + TENSC + TEmiC \tag{4.1}$$

Equation (4.1) minimizes the TOC, which represents the total expected cost in the system.

The first term in (4.1) represents the expected costs of producing energy using renewable technologies (solar and wind in this case), and purchasing energy from the upstream network as in (4.2). The two terms in (4.2) are calculated by (4.3) and (4.4), respectively.

$$TEC = EC^{vRES} + EC^{SS} \tag{4.2}$$

$$EC^{vRES} = \sum_{s\in\Omega^s} \rho_s \sum_{h\in\Omega^h} \sum_{g\in\Omega^g} OC_g P^{vRES}_{g,i,s,h} \tag{4.3}$$

$$EC^{SS} = \sum_{s\in\Omega^s} \rho_s \sum_{h\in\Omega^h} \sum_{\varsigma\in\Omega^\varsigma} \lambda^{\varsigma}_h P^{SS}_{\varsigma,s,h} \tag{4.4}$$

Regarding the second term of (4.1), $TENSC$ represents the cost of energy not supplied. This term is based on the calculation of active and reactive power that was not supplied and is given by equation (4.5).

$$TENSC = \sum_{s\in\Omega^s} \rho_s \sum_{h\in\Omega^h} \sum_{i\in\Omega^i} (\upsilon^P_{s,h} P^{NS}_{i,s,h} + \upsilon^Q_{s,h} Q^{NS}_{i,s,h}) \tag{4.5}$$

The terms $\upsilon^P_{s,h}$ and $\upsilon^Q_{s,h}$are defined as penalty factors. They correspond to penalty terms associated with any active and reactive power shed. These must be set to sufficiently high values to avoid unnecessary load shedding. Finally, the term $TEmiC^{vRES}$ represents the expected cost of emissions. These emissions are related to energy production from renewable sources as well as conventional ones and that of energy purchased from the upstream network. This term is defined by:

$$TEmiC = TEmiC^{vRES} + EmiC^{SS} \tag{4.6}$$

The corresponding terms in (4.6) are expressed by:

$$TEmiC^{vRES} = \sum_{s\in\Omega^s} \rho_s \sum_{h\in\Omega^h} \sum_{g\in\Omega^g} \sum_{i\in\Omega^i} \lambda^{CO_2} ER^{vRES}_g P^{vRES}_{g,i,s,h} \tag{4.7}$$

$$EmiC^{SS} = \sum_{s\in\Omega^s} \rho_s \sum_{h\in\Omega^h} \sum_{\varsigma\in\Omega^\varsigma} \sum_{i\in\Omega^i} \lambda^{CO_2} ER_\varsigma^{SS} P_{\varsigma,s,h}^{SS} \tag{4.8}$$

4.2.2 Constraints

Kirchhoff's current law must be enforced for active (4.9) and reactive (4.10) power flows. These ensure that the sum of incoming flows must be equal to outgoing ones. These conditions must be respected at all times for safe operation of the system.

$$\sum_{g\in\Omega^g} P_{g,i,s,h}^{vRES} + P_{\varsigma,s,h}^{SS} + P_{i,s,h}^{NS} + \sum_{in,k\in\Omega^k} P_{k,s,h} - \sum_{out,k\in\Omega^k} P_{k,s,h} = PD_{s,h}^{i} + \sum_{in,k\in\Omega^k} \frac{1}{2} PL_{k,s,h} + \sum_{out,k\in\Omega^k} \frac{1}{2} PL_{k,s,h} \; ; \forall \varsigma\epsilon\Omega^\varsigma; \; \forall\varsigma\epsilon i; k\epsilon i \tag{4.9}$$

$$\sum_{g\in\Omega^g} Q_{g,i,s,h}^{vRES} + Q_{\varsigma,s,h}^{SS} + Q_{i,s,h}^{NS} + \sum_{in,k\in\Omega^k} Q_{k,s,h} - \sum_{out,k\in\Omega^k} Q_{k,s,h} = QD_{s,h}^{i} + \sum_{in,k\in\Omega^k} \frac{1}{2} QL_{k,s,h} + \sum_{out,k\in\Omega^k} \frac{1}{2} QL_{k,s,h} \; ; \forall \varsigma\epsilon\Omega^\varsigma; \; \forall\varsigma\epsilon i; k\epsilon i \tag{4.10}$$

In the left-hand side of equation (4.9), we can see the active power flows from the renewable power generation as well as the power injected at the substation. On the other side of the equation, we have the power flow associated with the demand and the losses (treated here as fictitious loads). The same principles apply to the reactive power flow shown in (4.10).

Kirchhoff's voltage law must also be considered. This restriction governs the power flow in the feeders, which are represented by linearized power flow equations considering two practical assumptions. The first one states that the voltage magnitude are essentially close to the nominal value V_{nom}. The second one is related to the difference of voltage angles θ_k. For security systems, this difference has to be as small as possible, which leads to a trigonometric approximation $\sin\theta_k \approx \theta_k$ and $\cos\theta_k \approx 1$. Considering these two simplifying assumptions, the active and reactive AC power flow equations can be linearized, and represented as in:

$$\left|P_{k,s,h} - \left(V_{nom}\left(\Delta V_{i,s,h} - \Delta V_{j,s,h}\right)g_k - V_{nom}^2 b_k \theta_{k,s,h}\right)\right| \leq MP_k\left(1 - u_{k,h}\right) \tag{4.11}$$

$$\left|Q_{k,s,h} - \left(- V_{nom}\left(\Delta V_{i,s,h} - \Delta V_{j,s,h}\right)b_k - V_{nom}^2 g_k \theta_{k,s,h}\right)\right| \leq MQ_k(1 - u_{k,h}) \tag{4.12}$$

where (4.13)

$$\Delta V^{min} \leq \Delta V_{i,s,h} \ \leq \ \Delta V^{max}$$

In relation to the power flows in each branch, these cannot exceed the maximum transfer capacity:

$$P_{k,s,h}^2 \ + \ Q_{k,s,h}^2 \ \leq u_{k,h}(S_k^{max})^2 \tag{4.14}$$

The active and reactive power losses in each branch are algebraically represented by:

$$PL_{k,s,h} \ = \ R_k \left(P_{k,s,h}^2 \ + \ Q_{k,s,h}^2\right) / \ V_{nom}^2 \tag{4.15}$$

$$QL_{k,s,h} \ = \ X_k \left(P_{k,s,h}^2 \ + \ Q_{k,s,h}^2\right) / \ V_{nom}^2 \tag{4.16}$$

Note that equations (14) - (16) are easily linearized using a piecewise linearization approach, which is common in the literature. Further explanation about the piecewise linearization can be found in Appendix B.

The active and reactive power limits of conventional as well as vRESs are also considered as constraints. Such constraints related to vRESs are given by (4.17) and (4.18):

$$P_{g,i,s,h}^{vRES,min} \ \leq \ P_{g,i,s,h}^{vRES} \leq \ P_{g,i,s,h}^{vRES,max} \tag{4.17}$$

$$-\,tan\left(cos^{-1}(pf_g)\right) \ P_{g,i,s,h}^{vRES} \ \leq \ Q_{g,i,s,h}^{vRES} \leq tan\left(cos^{-1}(pf_g)\right) \ P_{g,i,s,h}^{vRES} \tag{4.18}$$

where pf_g is the power factor of generator g.

The reactive power injected or withdrawn at a substation (4.19) in the system is subject to minimum and maximum level as in (4.18). This is motivated by security concerns.

$$-\tan\left(cos^{-1}(pf_{ss})\right) \ P_{\varsigma,s,h}^{SS} \ \leq \ Q_{\varsigma,s,h}^{SS} \leq \tan\left(cos^{-1}(pf_{ss})\right) \ P_{\varsigma,s,h}^{SS} \tag{4.19}$$

Note that the voltage angle difference $\theta_{k,s,h}$ is defined as $\theta_{k,s,h} = \theta_{i,s,h} - \theta_{j,s,h}$. In this case, i and j belong to the same branch k.

4.3 Results

4.3.1 Data and Assumptions

In this work, we use a standard 119-bus distribution system to perform the required analysis. The schematic diagram of this system is shown in Figure 1. The main data of the considered system are summarized in Table 4.1. Further information about the test system and data can be found in [343]. The size and location of vRESs are adapted from [343], as can be seen in Table 2. More data-related assumptions made in this analysis are presented in Tables 4.3, 4.4 and 4.5. Further assumptions are summarized as follows:

- The operational analysis is based on a 24-hour period, subdivided on an hourly basis.
- Maximum voltage deviation at each bus is set to ±5% of the nominal value (which in this case is 11 kV).
- In all simulations, the substation is treated as the reference node, in which both the voltage deviation and the angle are set to zero.
- The number of partitions considered for linearizing quadratic terms is 5, which is in line with the findings in [342].

Table 4.1 - General system data.

Parameter Description	Parameter Setting
Nominal voltage	11 kV
Active power demand	22709.720 kW
Reactive power demand	17041.068 kVAr
Base case system losses	1298.090 kW
Minimum voltage of the base case system (which occurs at bus 116)	0.8783 p.u.

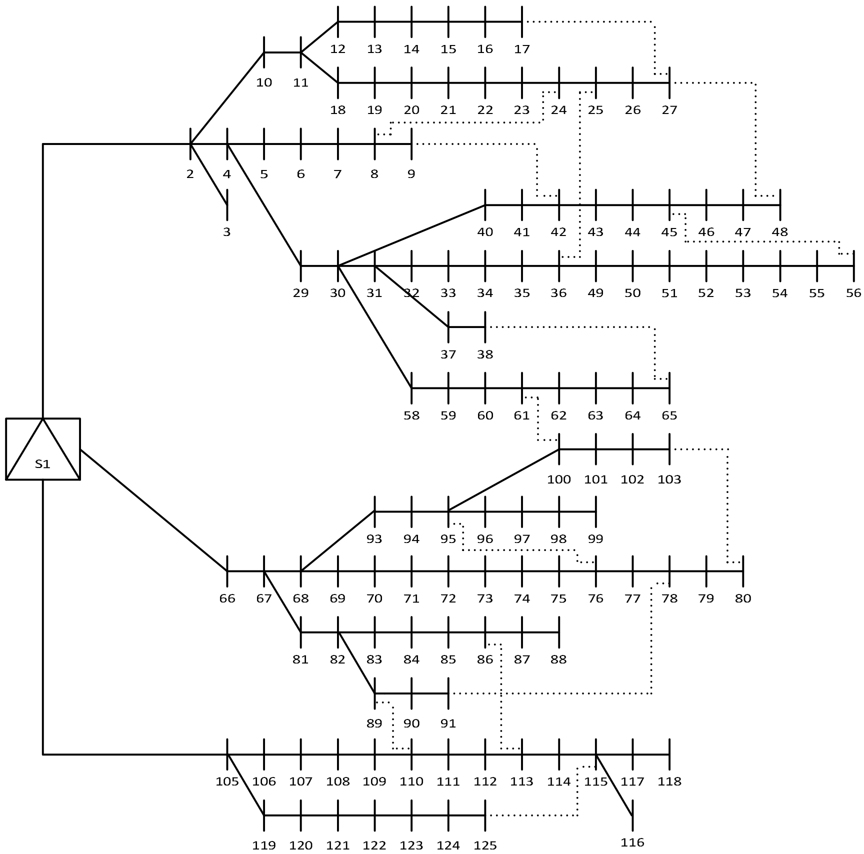


Figure 4.1 - A schematic diagram of the 119-bus test system.

Our work involves power productions using variable renewable sources such as wind and solar. The power outputs from these resources are subject to high level uncertainty and variability. Demand is also variable (say throughout the course of the day), even if it can be fairly predicted more accurately than a variable renewable power output. The stochastic nature in our work arises as a result of these issues. Therefore, we have handled such stochastic parameters via a stochastic programming framework: accounting for the most plausible states of these parameters at a given future time each associated with a probability. Over the considered operational period (which in our case is 24 hours long), such states collectively form storylines (or scenarios) which are jointly considered in the optimization process.

In other words, the stochastic nature of RES power outputs and demand are accounted for by considering adequate number of scenarios for each. Therefore, the power production profiles of wind and solar PV type DGs, as well as the demand profile, are assumed to be uniform throughout the system. The uncertainty associated with solar and wind power generations are taken into account by considering three different scenarios for each uncertain parameter. Demand uncertainty is also taken into account by considering six different scenarios each for residential and industrial type consumers. It should be noted that each scenario represents an hourly profile. The combination of these individual scenarios (which in this case is 81) results in the creation of the final set of scenarios used in our studies.

Table 4.2 - Size and location of wind and solar PV type distributed generations

Bus	Wind [MW]	PV [MW]
14	1	0
21	1	0
24	1	0
25	0	1
29	0	1
32	1	0
33	1	0
35	0	1
37	1	0
38	1	0
42	1	0
43	0	1
44	1	1
52	1	1
53	1	0
56	1	0
61	1	0
69	1	0
73	1	1
74	1	0
77	1	1
79	0	1
82	1	0
83	1	0
84	0	1
85	1	0
89	1	0
96	1	0
100	1	1
101	0	1
106	0	1
108	1	0
112	1	1
114	1	1
116	1	1
117	0	1
119	0	1
121	1	0

Table 4.3 - Further data-related assumptions

Parameter	Setting
pf^{ss}	0.8
pf^{vRES}	0.95
ER^{ss}	0.4 $\mathrm{tCO_2e/MWh}$
λ^{CO_2}	15 $€/\mathrm{tCO_2e}$
$\upsilon^{P}_{s,h}, \upsilon^{Q}_{s,h}$	3000 €/MW, 3000 €/MVAr
MP_k, MQ_k	20

Table 4.4 - Cost of electricity generation from renewable sources and emission rates.

	Variable cost [€/MWh]	Emission rates of DGs [$\mathrm{tCO_2e/MWh}$]
Solar	40	0.0584
Wind	20	0.0276

Table 4.5 - Maximum transfer capacity in feeders.

Feeders	Maximum transfer capacity [A]
{(1, 2); (2, 4); (1,66); (66,67)}	1200
{(4, 5); (5, 6); (6, 7); (4,29); (29,30); (30,31); (67,68); (67,81); (81,82); (1,105); (105,106); (106,107)}	800
Remaining feeders	400

4.3.2. Numerical Results

As stated above, the analysis is carried out to study the operational flexibility that can be provided by operating vRES rich distribution grids in a meshed manner. In addition, the analysis includes the impact of such a scheme on the use and integration of vRESs.

A total of six case studies are considered, designated as Case A to F. Case A is the Base Case which does neither consider network reconfiguration nor a meshed operation. In Case B, network reconfiguration is allowed but always maintaining a radial topology. Cases C to F all consider a meshed operational scheme, but with different levels meshing from 30% in Case C, 60% in case D, 80% in Case E and 100% in Case F. The network configurations for the last four cases are presented in Figure 4.2. Note that meshing the distribution network makes use of existing tie lines. For cases B to F, the upper and lower voltage boundaries have been enforced. Table 6 shows the total expected cost, along with a breakdown of this cost and the total expected power losses in the system.4.6 shows the total expected cost, along with a breakdown of this cost and the total expected power losses in the system.

Among the considered cases, the total costs that has the highest value is the Base Case, as expected. This is because all energy required in the system is imported through the substation. The energy mix associated with the Base Case can be seen in Figure 4.3 (a). Apart from the costs, power losses in the system are also the highest among those computed in the remaining cases.

Table 4.6 - Total expected costs of objective function and power losses

	Case A	Case B	Case C	Case D	Case E	Case F
Total Cost [€]	32217,38	27215,55	24634,12	18458,99	16937,63	15664,99
Energy Cost [€]	30349,82	26629,07	24103,04	17979,25	16501,48	15265,23
Emission Cost [€]	1219,56	557,47	513,63	472,96	436,15	399,76
PNS Cost [€]	647,99	29,01	17,45	6,78	0,00	0,00
Power Loss [MW]	20,25	9,39	8,01	7,21	6,47	5,73
Power Loss [MVar]	14,11	6,13	4,67	3,97	3,24	2,49

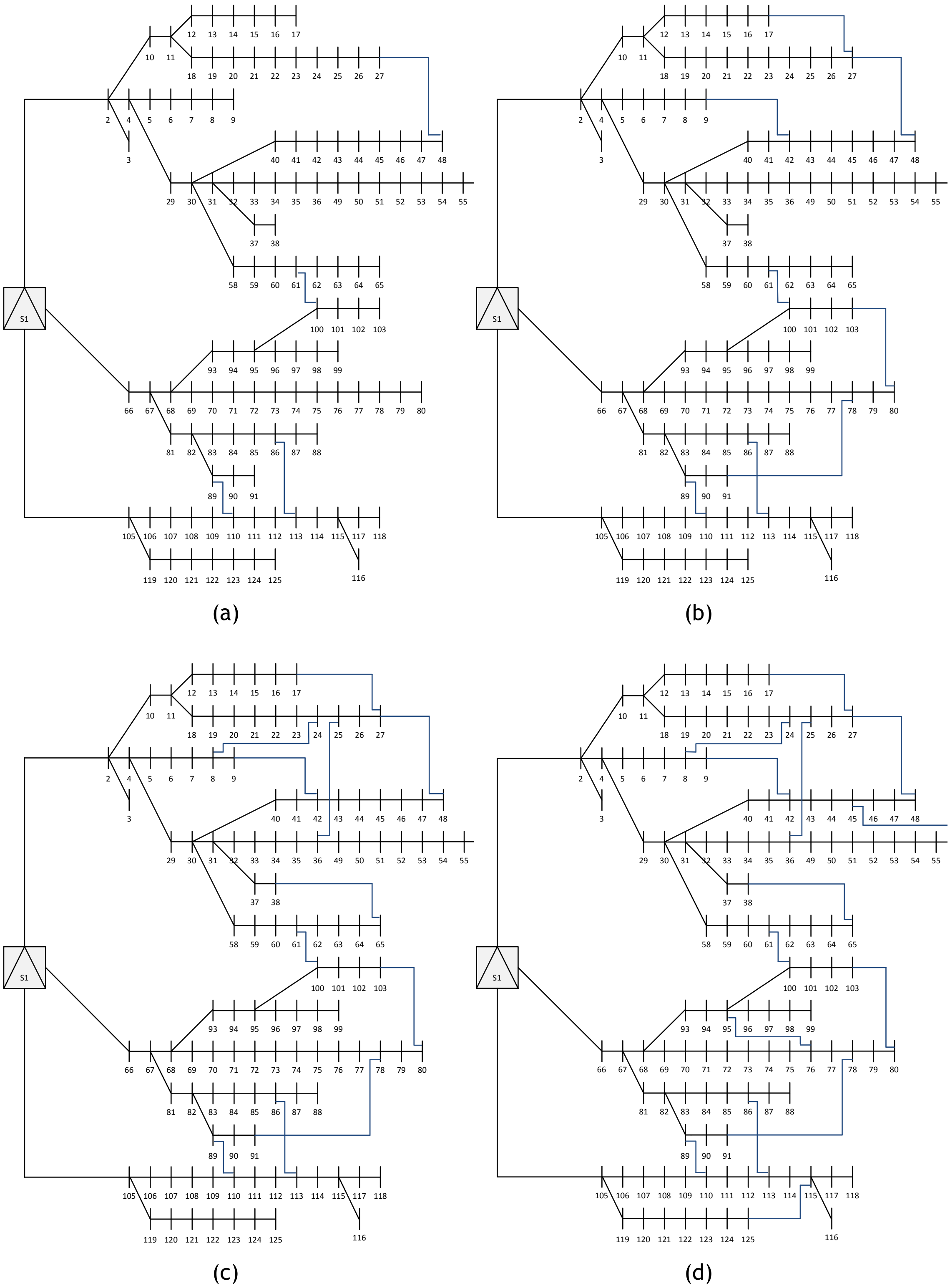
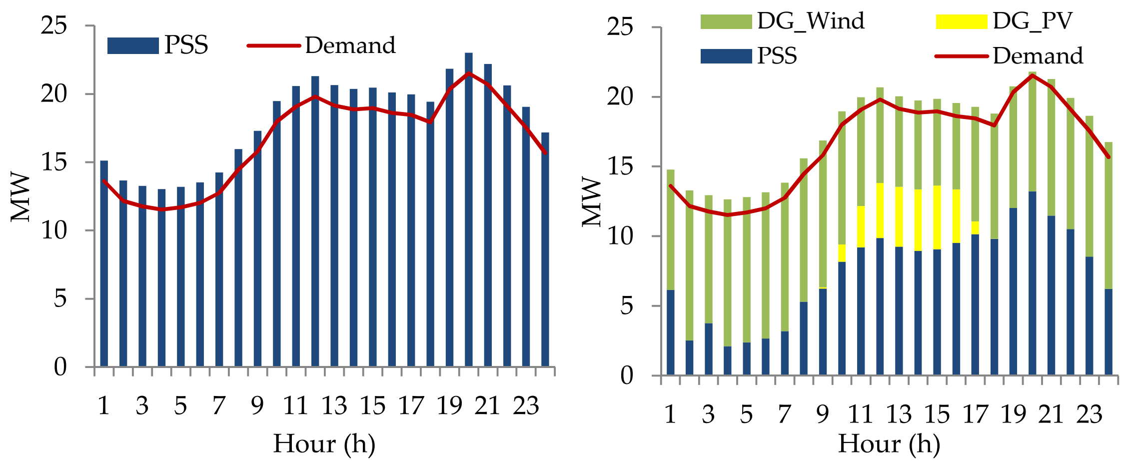


Figure 4.2 - A schematic diagram of the meshed systems associated with Case C to F. (a) 30% meshed network topology for Case C; (b) 60% meshed network topology for Case D; (c) 80% meshed network topology for Case E; and (d) 100% meshed network topology for case F.

In Case B, the expected energy costs are reduced by 12%, expected emissions costs by 54% and expected PNS costs by 96%. This overall translates into a reduction of 16% in expected total cost in the system. The decreases registered in the expected energy and emission costs are mainly due to the locally produced vRES power that is cheaper and “cleaner”. The active and reactive power losses in the system are reduced on average by 54% and 70%, respectively. This is as a result of the combined effect of the DG integration and optimal network reconfiguration. Most of the demand is met by locally generated power, which does not require heavy utilizations of existing feeders, and hence resulting in reduced losses. It is widely proven that an optimal reconfiguration also reduces losses in the system. Figure 4.3 (b) shows the energy mix related to Case B. In this figure, it can be seen that this case has 60,4% of the demand met by vRES power (of which 6,6% comes from solar PV and 53,9% from wind type DGs).

Cases C through F are the ones that represent a system operated in a meshed network topology, but with increasing levels of “meshedness”. In Case C, a 24% more reduction in the expected total cost is observed, as a result of reductions in the individual cost terms: energy, emission and PNS costs, in comparison with that of the Base Case. Active and reactive power losses also see reductions on average by 60% and 77%, respectively. With the increase in the “meshedness” level of the network, the reductions get more pronounced. In Case C, the percentage of demand covered by vRES power is 69,7% (of which 7,3% comes from solar PV and 62,4% from wind). In comparison to the radial topology in the Base Case, even the less meshed topology sees further improvement in the utilization level of vRES power production. Further observation is the fact that even a weakly meshed distribution network (with a 30% connectedness index) shows an improvement of 9,3% in terms of vRES power generation compared to that of an optimally reconfigured radial topology.



(a) (b)

Figure 4.3 - Energy mixes in the (a) Base Case; (b) Case B.

In Cases D and E, where the “meshedness” levels are respectively 60% and 80%, one can observe 43% and 47% overall cost reductions, respectively. In comparison to that of the base case, these can be regarded as significant improvements, and these generally show the favorable impact of a meshed system operation. In Case E, the PNS costs are reduced by 100%. This can be explained by the fact that meshing the grid routes vRES power to where it is consumed. This would otherwise be shed in the radial (or weakly meshed) topology. As a result, the share of renewables in the total consumption in the above two cases (i.e. Cases D and E) amount to 73,6% and 75,1%, respectively.

The last case—Case F—(where all branches are connected, creating a completely meshed network) yields the best operational results among the considered cases. Compared to the Base Case, a 51% reduction in overall cost can be seen. In terms of individual cost terms, the reductions are 50% in expected energy costs, 67% in emission costs, and a 100% in expected PNS costs. System-wide average losses are slashed down by 72% (active) and 88% (reactive). Regarding the energy mix, the fully meshed network, i.e. Case F, has a total of 75,8% of the total energy demand met by vRES energy (out of which 10,7% come from solar PV and 65,1% from wind type DGs). From Case A to Case F, one can easily notice the reductions in terms of energy imported from upstream (see in Table 4.6). In Case F, the entire system operates in near island mode (see hours 4 and 5 in which only 3% of demand in these hours is covered by importing power from the upstream). Also, numerical results highlight that a fully meshed topology increases the utilization level of vRESs power generation by 15,4% compared to that of an optimally reconfigured radial topology. This translates into an about 42% decrease in the overall system cost, 44% and 99% reductions in terms of expected energy and emission costs, respectively, as compared to that of a reconfigured radial topology, which is significant. The share of renewable power in the final energy consumption is as high as 75,8% in the case which incorporates a strongly meshed network, which is again noteworthy.

Figure 4.4 (a), (b), (c) and (d) show the energy mixes corresponding to the meshed cases, from low to a more complex meshed topology, respectively. The results in these figures reveal interesting variations in the utilization levels of vRES power productions during the 24-hour period. It is also possible to see a decrease in the energy purchased from the upstream network ($P^{SS}_{ç,s,h}$) throughout the various case studies.

With regard to energy losses, the average profile of active power losses during the considered 24-hour period of each case is shown in Figure 4.5. The results are in accordance with Table 4.6, dropping from Case B to Case F, as already mentioned before. In cases C to F, losses decrease within an interval since in addition to the DGs being near the loads, there are also now in some sections of the network smaller paths to be “traveled”, resulting in a losses decrease.

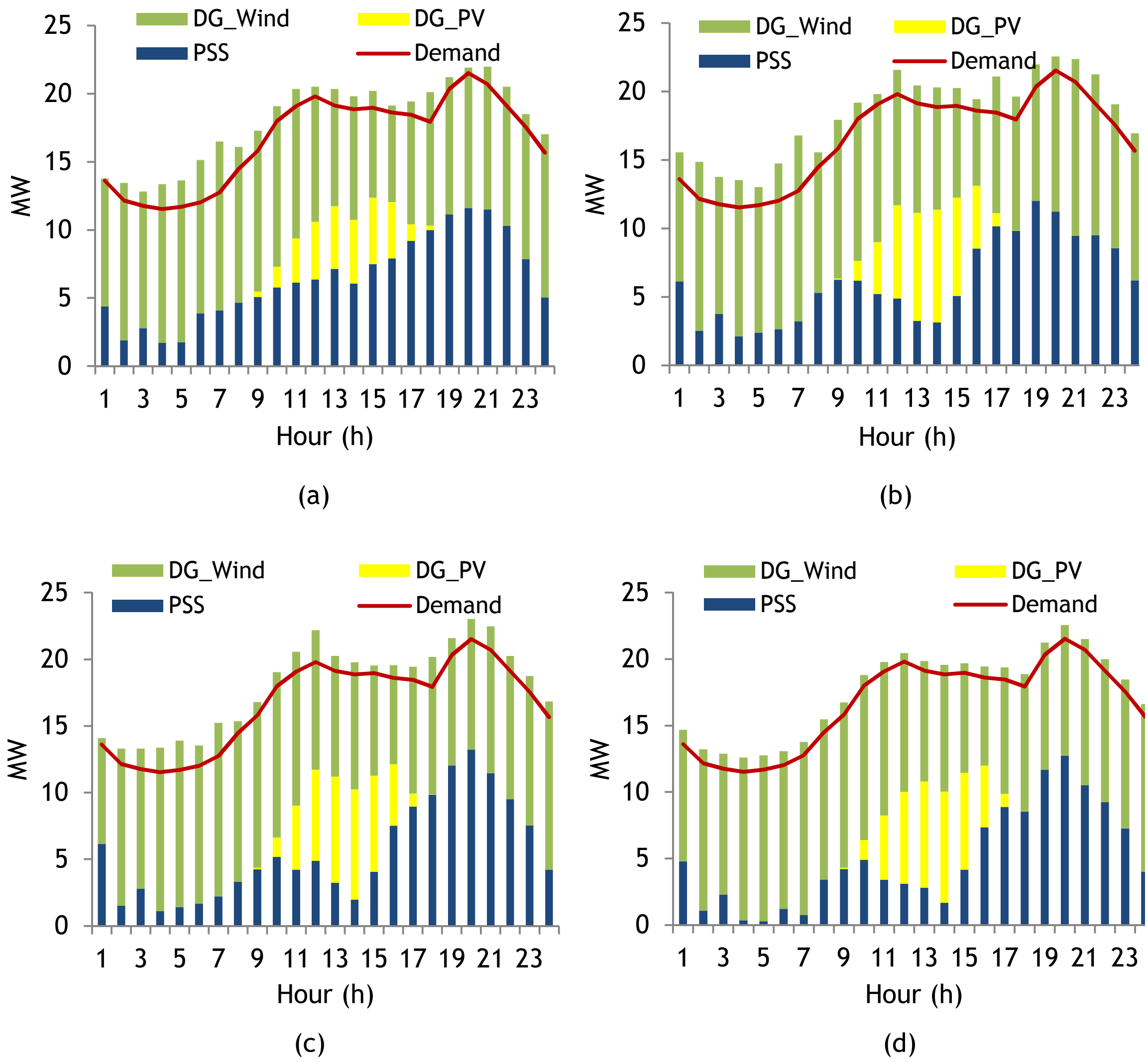


Figure 4.4 - (a) Case C energy mix (30% meshed network); (b) Case D energy mix (60% meshed network); (c) Case E energy mix (80% meshed network); (d) Case F energy mix (100% meshed network).

Figure 4.6 shows the average voltage profile corresponding to each case. The voltage deviation profile in Case A is the only one in which the deviations in some nodes surpasses the lower bound. The remaining cases where DGs are already integrated, all voltage deviations are significantly improved, and largely remain within the permissible range. In Case B as well as in the cases which involve network meshing (i.e. Cases C through F), voltage deviations do not show significant differences. In the figure, detailed voltage deviations for the nodes from 41 to 53 can be seen in the section which is zoomed out. In this particular section, we can see minor improvements in the voltage deviation especially from Cases C through F. Generally, the case that has the most meshed network (i.e. Case F) has the best voltage deviation portfolio among other cases.

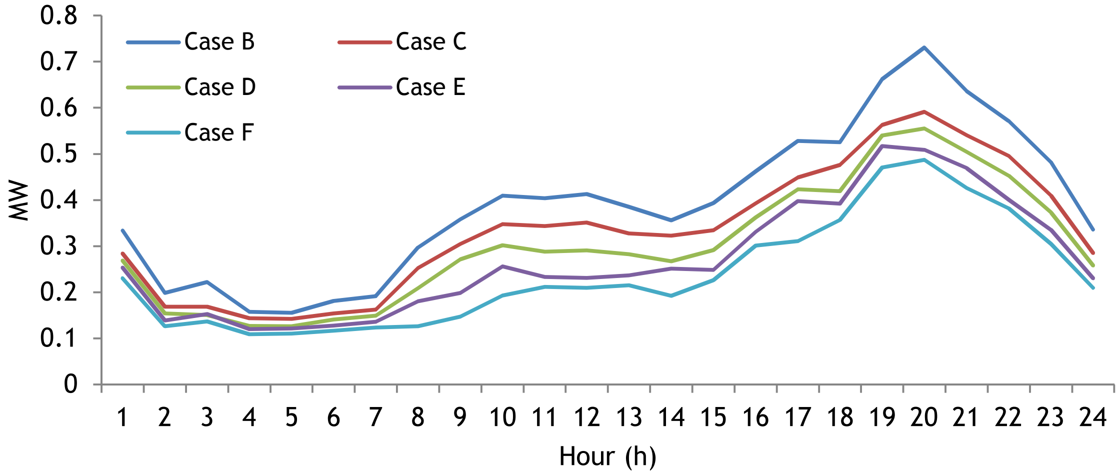


Figure 4.5 - Power losses in the network associated with each case.

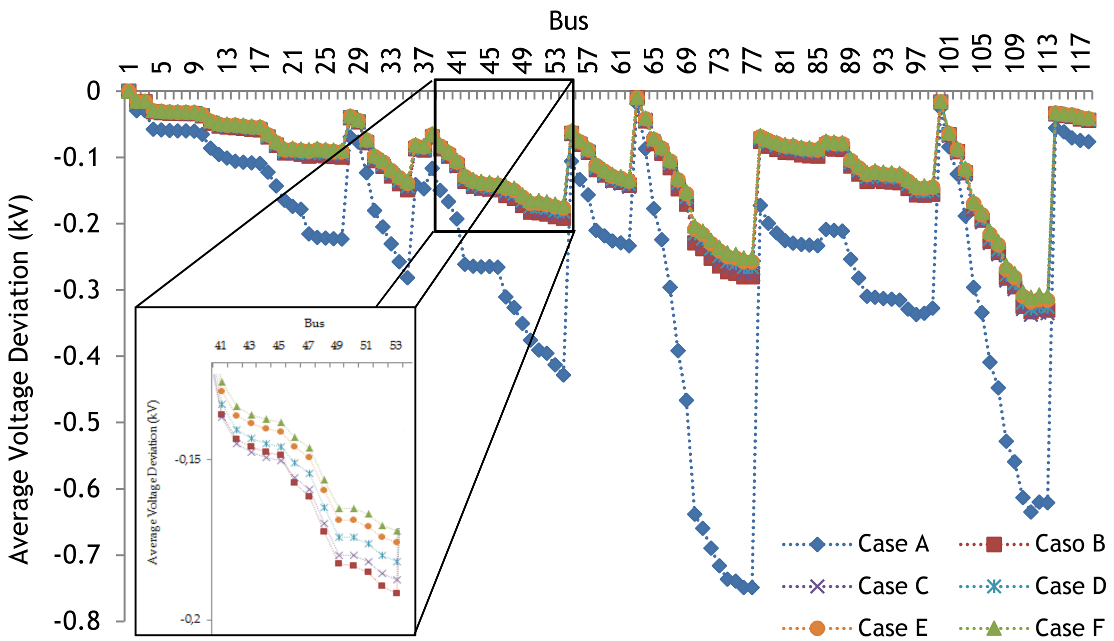
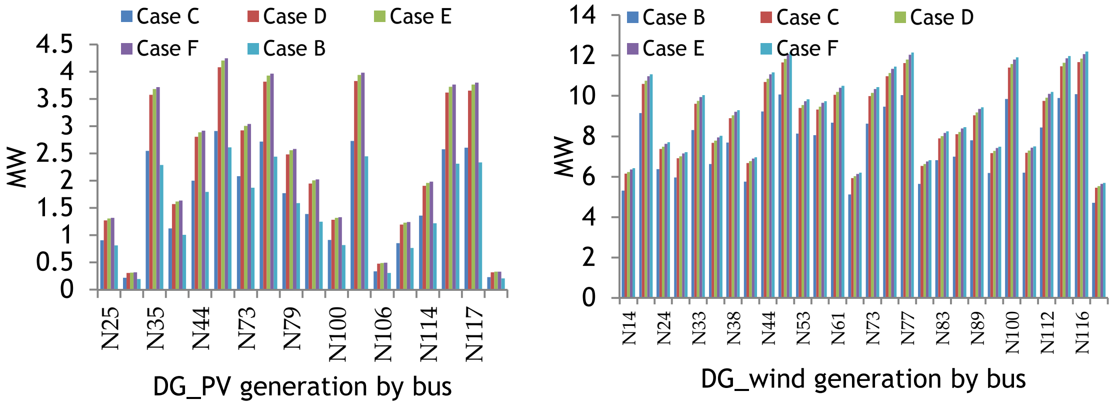


Figure 4.6 - Average voltage deviation to all cases.

Total solar and wind power productions by node are shown in Figure 4.7 (a) and (b), respectively. In these figures, it is possible to observe the increased vRES power generation as one moves from Case B to Case F at each node. The results from these figures along with those in Figure 4.2, we can see the complementarity of meshed operation and renewable integration, in which a higher network meshing leads to a higher network flexibility and hence a more increase in renewable integration. Largely, the results obtained in the case studies, but especially in Case F, point out the immense contributions of the meshed operational scheme in terms of increasing system flexibility and efficient utilization of vRESs in the system.



(a) (b)

Figure 4.7 - Solar PV (a) and wind (b) power outputs by node.

4.5 Chapter Conclusions

The work in this chapter has explored the prospects of operating distribution network systems in a meshed topology, as opposed to the conventionally (radial) operation. Furthermore, the contributions of meshed network topology in terms of enhancing system flexibility and its potential in increasing the integration and efficient utilization of vRES power generation were presented. To accomplish this, a stochastic MILP optimization model has been developed with a reasonably larger scale distribution network as a test system. Numerical results from the cases considered show that adopting a meshed network topology as a mainstream operational strategy for distribution systems has considerable benefits. For the fully meshed topology case, the increase in the utilization level of vRES power amounts to 15,4% compared to that of an optimally reconfigured radial topology. The share of renewable power in the final energy consumption is as high as 75,8% in the case which incorporates a strongly meshed network, which is again noteworthy.

The results generally reveal the multi-faceted contributions and viability of a meshed operational strategy. It has been verified that this strategy adds valuable flexibility to distribution systems that are rich in vRES-based distribution generations. Such an added system flexibility is an important asset to have for ensuring a more efficient utilization of variable renewable power generation in the system.

Chapter 5

Conclusions, Directions for Future Work and Contributions

In this chapter, the main conclusions of the thesis are highlighted on the basis of answering the research questions that constituted the main motivation of this research. The limitations of the work in this thesis, and some directions of future work are also discussed. Finally, the contributions of this work are highlighted by presenting the set of publications in journals, book chapters and conference proceedings of high standard (IEEE), leading to this thesis work.

5.1 Main Conclusions

The main conclusions drawn from the thesis work, pertaining to the research questions presented in Section 1.4, are summarized as follows. For the sake of clarity, the research questions are reproduced here.

- ***What are the main existing and emerging flexibility options that can be deployed in power systems to support the integration of "carbon-free" and variable power production technologies? What are the main challenges and opportunities associated with various flexibility options provided by different technologies?***

  As a result of the increased awareness of the dangers posed by global climate changes (mainly caused by growing global energy consumption needs), the quest for clean and sustainable energy future is becoming of paramount importance. This can be largely realized via a large-scale integration of variable RESs such as wind and solar, which have relatively low carbon footprints. In many power systems, the level of integration of such resources is dramatically increasing. However, their intermittent nature poses significant challenges in the predominantly conventional power systems that currently exist. Among others, frequency and voltage regulation issues can, for example, arise because of improperly balanced and largely uncoordinated RES supply and demand. Generally, the higher the integration level of intermittent power sources is, the higher the flexibility needs are in the system under consideration. Flexibility, in a power systems context, refers to the ability of such a system to effectively cope with unforeseen changes in operational situations, which are mainly induced by the inherent uncertainty and variability arising from the supply side, demand side or any other external factors.

In the absence of appropriate flexibility mechanisms, it is increasingly difficult to manage the real-time imbalances between generation and demand in distribution systems with large quantiles of vRESs as a result of their natural variations. The growing need to integrate more "carbon-free" energy resources dramatically increases the flexibility requirements. Traditional flexibility mechanisms are not simply sufficient to meet the flexibility gaps created as a result of increasing variable renewables. Fortunately, there are a number of emerging and promising technologies that can be deployed at the supply-, network- and/or demand-sides and fill in these gaps in close coordination with existing flexibility mechanisms.

Therefore, in Chapter 2, a critical review of the main existing and emerging flexibility options that can be deployed in power systems to support the integration of "carbon-free" and variable power production technologies has been presented. The main flexibility mechanisms can be divided in three major categories, demand-side flexibility options, supply-side flexibility options and other sources of flexibility. The main mechanisms within the demand-side flexibility options are the demand response, energy efficiency and unconventional energy consumption forms. Within the supply-side flexibility options mechanisms there is a vast set of tools, namely, conventional power plants, strategic RES power curtailment, smart-grids, dynamic network reconfiguration, meshed operation of distribution networks, micro-grid and islanding control, network interconnections. The other sources of flexibility mechanisms are the energy storage systems, energy systems integration, energy markets, and regulatory policies. The wide-range benefits of emerging flexibility options are widely recognized. Their future prospects seem promising. However, there are certain barriers that may hinder their developments in the short to medium terms. The most relevant ones that require attention are:

1. **Lack of suitable market**: Most of the current energy markets are not designed to take into consideration new market players such as flexibility operators, requiring significant changes or even overhauls in order such players to succeed.
2. **Lack of transparent regulatory and tariff schemes**: For most flexibility mechanisms to flourish and work efficiently, the transparency of regulatory and tariff structures is mandatory.
3. **Inadequate business environment**: A conducive business environment is necessary not only for investments in emerging flexibility options to materialize, but also to ensure that existing flexibility mechanisms work efficiently. This seems to be one of the biggest barriers in the developments of various flexibility options, which needs to be addressed.

4. **Potential conflicts of interest**: The integration of emerging flexibility mechanisms (e.g. energy storage systems) may decrease incomes for established flexibility providers (e.g. peaking power plants). This may lead to potential conflicts of interest. New mechanisms for resolving such issues should be put in place.
5. **Huge investment needs**: In order to reap the benefits of most of the flexibility options, hefty investments in automating existing infrastructures may be required. This may also hinder the development of some flexibility mechanisms.
6. **Inadequate incentives**: The savings for consumers from participating in DR programs may be sometimes small, which may not be attractive enough not only for new consumers to join in, but also existing to continue in such programs.
7. **Privacy and data security issues**: The key factor to DR's success is ICT. But problems arise regarding privacy and security of users' data as well as the entire automated system. This is becoming one of the key challenges for the growth of DR amid increased cyberattacks in recent years.

- ***From the existing and emerging flexibility options that can facilitate the integration of large-scale vRESs in next-gen distribution systems, what are the best combinations of flexibility options that maximize the utilization level of vRES power?***

  Future distribution grids should be prepared to handle the ongoing transformation process of power generation from the traditionally centralized to a more distributed and small power productions. Nonetheless, conventional distribution systems are not designed to manage this, and as a result, regulators often impose a maximum penetration limit which does not help further development of distributed vRESs.

  However, distribution network systems are slowly evolving to smart grids, which are adequately equipped with the necessary tools and mechanisms to accommodate large-scale vRESs while minimizing their side-effects. To this end, in Chapter 3 and Chapter 4, different flexibility options have been explored and discussed in detail from the context of supporting the much-needed integration and efficient utilization of large-scale vRESs in future distribution systems. The assessment also includes managing the negative impacts of vRESs, induced by their high variability and uncertainty, by means of various flexibility options.

  Due the complexity of the issue, this one has been analyzed according to several aspects, giving rise to the following sub-questions.

- ***From a quantitative and qualitative standpoint, what are the impacts of deploying flexibility mechanisms such as Demand Response, Energy Storage Systems and Dynamic Reconfiguration on the overall operational performance of the system?***

  Conventional electrical networks are slowly changing. A strong sense of policy urge as well as commitments have recently been surfacing in many countries to integrate more environmentally friendly energy sources into electrical systems. In particular, stern efforts have been made to integrate more and more solar and wind energy sources.

  One of the major setbacks of such resources arises as a result of their intermittent nature, creating several problems in the electrical systems from a technical, market, operation and planning perspectives. In order to cope with the intermittency inherent to such power sources, it is necessary to introduce more flexibility into the system.

  In this context, Demand Response, Energy Storage Systems and Dynamic Reconfiguration of the system are introduced and the operational performance of the resulting system is thoroughly analyzed.

  Accordingly, in Chapter 3, various flexibility options such as demand response, switchable reactive power sources and energy storage systems have been explored to ensure effective utilization of large quantities of wind and solar power.

  To support this analysis, a stochastic MILP operational model was proposed in this chapter. The stochastic model has been formulated based on a linearized AC network model, which captures the physical characteristics of the system in a reasonably accurate manner. Based on the numerical studies, the following conclusions can be drawn:

  1. Jointly integration of DR along with ESSs and DSR into the electrical system to cope with efficient utilization of RES energy production;
  2. Quantitative and qualitative analysis, discussions and comparison of results that are obtained for various case studies related to the level of flexibility options as a way of dealing with intermittency and variability of RESs. The results show that large scale integration of DGs can be achieved by way of using ESSs and DR. A more efficient utilization of wind and solar can be achieved as a result;

3. According to the simulation results, as high as 76% of the demand can be easily covered by energy coming from wind, PV and ESSs, and most importantly without having dramatic impacts on the considered system in terms of its healthy operation. In addition, the expected operation costs are considerably reduced, while voltage profile in the system is also improved;
4. Generally, as the level of flexibility in the system increases, managing the intermittent nature of wind and solar power is made easier.

- ***What is the level of flexibility that a dynamically changing network can provide and what is its impact on vRES utilization level?***

  DSOs are facing increasingly many challenges, mainly as a result of the growing integration of DERs such as solar PV and wind power. Amid the global climate change and other energy-related concerns, the transformation process of EDSs will most likely go ahead by modernizing distribution grids so that more DERs can be accommodated. Therefore, new operational strategies that aim to increase the flexibility of EDSs must be thought and developed.

  This action is indispensable so that EDSs can seamlessly accommodate large amounts of intermittent renewable power. To this end, one plausible strategy that is worth considering was a new operational strategy to operate the distribution systems in a meshed topology with a gradually adopting of this strategy. The new operational strategy is intended to provide additional level of flexibility, which works by operating distribution grids in a meshed manner, and the impact of doing this on the utilization level of variable renewable power is analyzed. Therefore, in Chapter 4, a new stochastic MILP optimization model has been developed with a reasonably large scale distribution network as a test system. A linearized AC power flow is used, and the operational problem is formulated as a least-cost optimization while satisfying a number of technical, economic and environmental constraints. The results have showed that:

1. Adopting a meshed network topology as a mainstream operation strategy for distribution systems has considerable benefits.
2. Generally, a more meshed network leads to better utilization of locally produced vRES power, and hence a higher share of renewable power. In fact, even a weakly meshed distribution network (with a 30% connectedness index) shows an improvement of 9,3% in terms of vRESs power generation compared to that of an optimally reconfigured radial topology.

3. A fully meshed topology increases utilization of vRESs power generation by 15,4% compared to that of a reconfigured radial topology. This translates into an about 42% decrease in the overall system cost, 44% and 99% reductions in terms of expected energy and emission costs, respectively, as compared to that of a reconfigured radial topology, which is significant. The share of renewable power in the final energy consumption is as high as 75,8% in the case which incorporates a strongly meshed network, which is again noteworthy.
4. Most importantly, all these improvements come without creating any undesirable effect on the operation of the considered distribution system. Instead, the average voltage profile is further enhanced, and average power losses are significantly lowered.
5. The results generally reveal the multi-faceted contributions and viability of a meshed operation strategy. It has been verified that this strategy adds valuable flexibility to the system, ensuring a more efficient utilization of variable renewable power generation in the system.

5.2 Directions for Future Works

The following points may be further studied in order to broaden the understanding of the topics covered in this thesis:

- Perform a comparison between price-based and incentive-based demand response programs can be incorporated in the model further analysis;
- An analysis of long-term operation can be made in order to understand how to adapt the different flexibility options in different seasons and to perceive which ones could do better;
- The meshed operation can be studied in terms of protection schemes. The set up and placement of protection devices should be in line with the meshed topology and operation strategy;
- Investigate the possibility of near island operation of meshed distribution network systems under high penetration of renewable energy sources.

5.3 Contributions of the Thesis

5.3.1 Book Chapters

1. **M.R.M. Cruz**, D.Z. Fitiwi, S.F. Santos, M. Shafie-khah, J.P.S. Catalão, "Managing risk in electric distribution networks", in: Electric Distribution Network Management and Control, Eds. A. Arefi, F. Shahnia, G. Ledwich, **SPRINGER**, Singapore, ISBN: 978-981-10-7000-6, pp. 1-36, April 2018.

   https://doi.org/10.1007/978-981-10-7001-3_1

2. **M.R.M. Cruz**, D.Z. Fitiwi, S.F. Santos, J.P.S. Catalão, "Flexibilizing distribution network systems via dynamic reconfiguration to support large-scale integration of variable energy sources using a genetic algorithm", in: Technological Innovation for Smart Systems, Eds. L.M. Camarinha-Matos, M. Parreira-Rocha, J. Ramezani, DoCEIS 2017, IFIP AICT 499, **SPRINGER**, Heidelberg, Germany, ISBN: 978-3-319-56076-2, pp. 72-80, May 2017.

   http://dx.doi.org/10.1007/978-3-319-56077-9_6

5.3.2 Publications in Peer-Reviewed Journals

1. **M.R.M. Cruz**, D.Z. Fitiwi, S.F. Santos, S.J.P.S. Mariano, J.P.S. Catalão, "Multi flexibility options integration to cope with large-scale integration of renewables", **IEEE Transactions on Sustainable Energy** (accepted).

   https://doi.org/10.1109/TSTE.2018.2883515

2. **M.R.M. Cruz**, D.Z. Fitiwi, S. Santos, S.J.P.S. Mariano, J.P.S. Catalão, "Prospects of a meshed electrical distribution system featuring large-scale variable renewable power", **Energies**, Vol. 11, No. 12, pp. 1-17, December 2018.

   https://doi.org/TBD

3. **M.R.M. Cruz**, D.Z. Fitiwi, S.F. Santos, J.P.S. Catalão, "A comprehensive survey of flexibility options for supporting the low-carbon energy future", **Renewable and Sustainable Energy Reviews (ELSEVIER)**, Vol. 97, pp. 338-353, December 2018.

   https://doi.org/10.1016/j.rser.2018.08.028

5.3.3 Publications in International Conference Proceedings

1. **M.R.M. Cruz**, D.Z. Fitiwi, S.F. Santos, J.P.S. Catalão, "Meshed operation of distribution network systems: enabling increased utilization of variable RES power", in: Proceedings of the **IEEE** 18th International Conference on Environment and Electrical Engineering — EEEIC 2018, Palermo, Italy, USB flash drive, 12-15 June, 2018.

   https://doi.org/10.1109/EEEIC.2018.8494512

2. **M.R.M. Cruz**, S.F. Santos, D.Z. Fitiwi, J.P.S. Catalão, "Coordinated distribution network reconfiguration and distributed generation allocation via genetic algorithm", in: Proceedings of the 17th **IEEE** International Conference on Environment and Electrical Engineering — EEEIC 2017, Milan, Italy, USB flash drive, 6-9 June, 2017.

   https://doi.org/10.1109/EEEIC.2017.7977748

3. **M.R.M. Cruz**, D.Z. Fitiwi, S.F. Santos, J.P.S. Catalão, "Influence of distributed storage systems and network switching/reinforcement on RES-based DG integration level", in Proceedings of the 13th International Conference on the European Energy Market — EEM 2016 (technically co-sponsored by **IEEE**), Porto, Portugal, USB flash drive, 6-9 June, 2016.

   http://dx.doi.org/10.1109/EEM.2016.7521337

Appendices

Appendix A

Piecewise Linearization

As mentioned earlier, the quadratic terms in (4.14) through (4.16) are linearized via a piecewise linearization method [342]. For the sake of brevity, here, we only show the piecewise representation of $\mathrm{P}_{\mathrm{k,s,h}}^2$ and $\mathrm{Q}_{\mathrm{k,s,h}}^2$. Others follow the same procedure and similar sets of constraints.

The quadratic expressions of active and reactive power flows can be easily linearized using piecewise linearization, considering a sufficiently large number of linear segments, L .There are a number of ways of linearizing such functions such as incremental, multiple choice, convex combination and other approaches in the literature. Here, the first approach (which is based on first-order approximation of the nonlinear curve) is used because of its relatively simple formulation. To this end, two non-negative auxiliary variables are introduced for each of the flows $\mathrm{P_k}$ and $\mathrm{Q_k}$ such that $\mathrm{P_k} = \mathrm{P_k^+} - \mathrm{P_k^-}$ and $\mathrm{Q_k} = \mathrm{Q_k^+} - \mathrm{Q_k^-}$

Note that these auxiliary variables (i.e., $\mathrm{P_k^+}$, $\mathrm{P_k^-}$, $\mathrm{Q_k^+}$, $\mathrm{Q_k^-}$) represent the positive and negative flows of $\mathrm{P_k}$ and $\mathrm{Q_k}$, respectively. This helps one to consider only the positive quadrant of the nonlinear curve, resulting in a significant reduction in the mathematical complexity, and by implication the computational burden. In this case, the associated linear constraints are:

$$P_{k,s,h}^2 \approx \sum_{l=1}^{L} \alpha_{k,l} p_{k,s,h,l} \tag{B.1}$$

$$Q_{k,s,h}^2 \approx \sum_{l=1}^{L} \beta_{k,l} q_{k,s,h,l} \tag{B.2}$$

$$P_{k,s,h}^+ + P_{k,s,h}^- = \sum_{l=1}^{L} \alpha_{k,l} p_{k,s,h,l} \tag{B.3}$$

$$Q_{k,s,h}^+ + Q_{k,s,h}^- = \beta_{k,l} q_{k,s,h,l} \tag{B.4}$$

were $p_{k,s,h,l} \leq P_k^{max}/L$ and $q_{k,s,h,l} \leq Q_k^{max}/L$.

Appendix B

The derivations related to the losses equations in (3.17), (3.18), (4.11) and (4.12) are provided here. Squaring both sides of the flow equations in in (3.17), (3.18), (4.11) and (4.12) and dividing each by V_{nom}^2, we get:

$$\frac{(P_k)^2}{V_{nom}^2} \approx \underbrace{\left[\left(\Delta V_i - \Delta V_j\right) g_k\right]^2}_{I} - \underbrace{2 * g_k V_{nom} b_k \theta_k * \left(\Delta V_i - \Delta V_j\right)}_{II} + (V_{nom} b_k \theta_k)^2 \quad \text{(B.1)}$$

$$\frac{(Q_k)^2}{V_{nom}^2} \approx \underbrace{\left[\left(\Delta V_i - \Delta V_j\right) b_k\right]^2}_{I} + \underbrace{2 * b_k V_{nom} g_k \theta_k * \left(\Delta V_i - \Delta V_j\right)}_{II} + (V_{nom} g_k \theta_k)^2 \quad \text{(B.2)}$$

Since the variables θ_k, ΔV_i and ΔV_j are very small, the second order terms (i.e. products of these variables) are close to zero. Hence, the first and the second terms in (B.1) and (B.2) can be neglected, leading to the following expressions, respectively.

$$\frac{(P_k)^2}{V_{nom}^2} \approx (V_{nom} b_k \theta_k)^2 \quad \text{(B.3)}$$

$$\frac{(Q_k)^2}{V_{nom}^2} \approx (V_{nom} g_k \theta_k)^2 \quad \text{(D.4)}$$

Multiplying both sides of (B.3) and (B.4) by r_k and summing gives:

$$r_k \left(\frac{P_k}{V_{nom}}\right)^2 + r_k \left(\frac{Q_k}{V_{nom}}\right)^2 \approx r_k (V_{nom} b_k \theta_k)^2 + r_k (V_{nom} g_k \theta_k)^2 \quad \text{(B.5)}$$

After rearranging Eq. (B.5), we get:

$$r_k(P_k^2 + Q_k^2)/V_{nom}^2 \approx g_k(V_{nom}\theta_k)^2 r_k\left(\frac{(b_k)^2}{g_k} + g_k\right) \tag{B.6}$$

One can easily verify that $\mathrm{r_k}\left(\frac{(\mathrm{b_k})^2}{\mathrm{g_k}} + \mathrm{g_k}\right) = 1$, reducing Eq. (B.5) to:

$$r_k(P_k^2 + Q_k^2)/V_{nom}^2 \approx g_k(V_{nom}\theta_k)^2 \tag{B.7}$$

Recall that the right hand side of (B.7) corresponds to the active power losses expression, which proves the derivation. The flow-based reactive power losses are derived in a similar way. Multiplying both sides of (B.3) and (B.4) by $\mathrm{x_k}$ instead of $\mathrm{r_k}$, adding both and rearranging the resulting equation leads to:

$$r_k(P_k^2 + Q_k^2)/V_{nom}^2 \approx -b_k V_{nom}^2 \theta_k^2 x_k[-b_k + (g_k)^2/(-b_k)] \tag{B.8}$$

Note that, in Eq. (B.8), $\mathrm{x_k}[-\mathrm{b_k} + (\mathrm{g_k})^2/(-\mathrm{b_k})] = 1$. Hence, the equation reduces to:

$$r_k(P_k^2 + Q_k^2)/V_{nom}^2 \approx -b_k V_{nom}^2 \theta_k^2 \tag{B.9}$$

Notice that the right hand side of Eq. (B.8) is equal to the reactive losses expression in (3.21) and (4.16).

Appendix C

Test Systems

IEEE 119 BUS DISTRIBUTION SYSTEM

Line Index	From Bus Index	To Bus Index	Line Resistance R [Ω]	Line Reactance X [Ω]	From bus Load Active Power P [kW]	From bus Load Active Power Q [kvar]
1	1	2	0.036	0.01296	0	0
2	2	3	0.033	0.01188	133.84	101.14
3	2	4	0.045	0.0162	1	11.292
4	4	5	0.015	0.054	34.315	21.845
5	5	6	0.015	0.054	73.016	63.602
6	6	7	0.015	0.0125	144.2	68.604
7	7	8	0.018	0.014	104.47	61.725
8	8	9	0.021	0.063	28.547	11.503
9	2	10	0.166	0.01344	87.56	51.073
10	10	11	0.112	0.0789	198.2	106.77
11	11	12	0.187	0.313	146.8	75.995
12	12	13	0.142	0.1512	26.04	18.687
13	13	14	0.18	0.118	52.1	23.22
14	14	15	0.15	0.045	141.9	117.5
15	15	16	0.16	0.18	21.87	28.79
16	16	17	0.157	0.171	33.37	26.45
17	11	18	0.218	0.285	32.43	25.23
18	18	19	0.118	0.185	20.234	11.906
19	19	20	0.16	0.196	156.94	78.523
20	20	21	0.12	0.189	546.29	351.4
21	21	22	0.12	0.0789	93.167	54.594
22	22	23	1.41	0.723	85.18	39.65
23	23	24	0.293	0.1348	168.1	95.178
24	24	25	0.133	0.104	125.11	150.22
25	25	26	0.178	0.134	16.03	24.62
26	26	27	0.178	0.134	26.03	24.62
27	4	28	0.015	0.0296	594.56	522.62
28	28	29	0.012	0.0276	120.62	59.117
29	29	30	0.12	0.2766	102.38	99.554
30	30	31	0.21	0.243	513.4	318.5
31	31	32	0.12	0.054	475.25	456.14
32	32	33	0.178	0.234	151.43	136.79
33	33	34	0.178	0.234	205.38	83.302
34	34	35	0.154	0.162	131.6	93.082
35	30	36	0.187	0.261	448.4	369.79
36	36	37	0.133	0.099	440.52	321.64
37	29	38	0.33	0.194	112.54	55.134
38	38	39	0.31	0.194	53.963	38.998
39	39	40	0.13	0.194	26.04	18.687

(Continuation of the previous table)

Line Index	From Bus Index	To Bus Index	Line Resistance R [Ω]	Line Reactance X [Ω]	From bus Load Active Power P [kW]	From bus Load Active Power Q [kvar]
40	40	41	0.28	0.15	393.05	342.6
41	41	42	1.18	0.85	326.74	278.56
42	42	43	0.42	0.2436	536.26	240.24
43	43	44	0.27	0.0972	76.247	66.562
44	44	45	0.339	0.1221	53.52	39.76
45	45	46	0.27	0.1779	40.328	31.964
46	35	47	0.21	0.1383	39.653	20.758
47	47	48	0.12	0.0789	66.195	42.361
48	48	49	0.15	0.0987	73.904	51.653
49	49	50	0.15	0.0987	114.77	57.965
50	50	51	0.24	0.1581	918.37	1205.1
51	51	52	0.12	0.0789	210.3	146.66
52	52	53	0.405	0.1458	66.68	56.608
53	53	54	0.405	0.1458	42.207	40.184
54	29	55	0.391	0.141	433.74	283.41
55	55	56	0.406	0.1461	62.1	26.86
56	56	57	0.406	0.1461	92.46	88.38
57	57	58	0.706	0.5461	85.188	55.436
58	58	59	0.338	0.1218	345.3	332.4
59	59	60	0.338	0.1218	22.5	16.83
60	60	61	0.207	0.0747	467.5	395.14
61	61	62	0.247	0.8922	95.86	90.758
62	1	63	0.028	0.0418	62.92	47.7
63	63	64	0.117	0.2016	478.8	463.74
64	64	65	0.255	0.0918	120.94	52.006
65	65	66	0.21	0.0759	139.11	100.34
66	66	67	0.383	0.138	391.78	193.5
67	67	68	0.504	0.3303	27.741	26.713
68	68	69	0.406	0.1461	52.814	25.257
69	69	70	0.962	0.761	66.89	38.713
70	70	71	0.165	0.06	467.5	395.14
71	71	72	0.303	0.1092	594.85	239.74
72	72	73	0.303	0.1092	132.5	84.363
73	73	74	0.206	0.144	52.699	22.482
74	74	75	0.233	0.084	869.79	614.775
75	75	76	0.591	0.1773	31.349	29.817
76	76	77	0.126	0.0453	192.39	122.43
77	64	78	0.559	0.3687	65.75	45.37
78	78	79	0.186	0.1227	238.15	223.22
79	79	80	0.186	0.1227	294.55	162.47

(Continuation of the previous table)

Line Index	From Bus Index	To Bus Index	Line Resistance R [Ω]	Line Reactance X [Ω]	From bus Load Active Power P [kW]	From bus Load Active Power Q [kvar]
80	80	81	0.26	0.139	485.57	437.92
81	81	82	0.154	0.148	243.53	183.03
82	82	83	0.23	0.128	243.53	183.03
83	83	84	0.252	0.106	134.25	119.29
84	84	85	0.18	0.148	22.71	27.96
85	79	86	0.16	0.182	49.513	26.515
86	86	87	0.2	0.23	383.78	257.16
87	87	88	0.16	0.393	49.64	20.6
88	65	89	0.669	0.2412	22.473	11.806
89	89	90	0.266	0.1227	62.93	42.96
90	90	91	0.266	0.1227	30.67	34.93
91	91	92	0.266	0.1227	62.53	66.79
92	92	93	0.226	0.1227	114.57	81.748
93	93	94	0.233	0.115	81.292	66.526
94	94	95	0.496	0.138	31.733	15.96
95	91	96	0.196	0.18	33.32	60.48
96	96	97	0.196	0.18	531.28	224.85
97	97	98	0.1866	0.122	507.03	367.42
98	98	99	0.0746	0.318	26.39	11.7
99	1	100	0.0625	0.0265	96.793	83.647
100	100	101	0.1501	0.234	100.66	47.572
101	101	102	0.1347	0.0888	456.48	350.3
102	102	103	0.2307	0.1203	522.56	449.29
103	103	104	0.447	0.1608	408.43	168.46
104	104	105	0.1632	0.0588	141.48	134.25
105	105	106	0.33	0.099	104.43	66.024
106	106	107	0.156	0.0561	96.793	83.647
107	107	108	0.3819	0.1374	493.92	419.34
108	108	109	0.1626	0.0585	225.38	135.88
109	109	110	0.3819	0.1374	509.21	387.21
110	110	111	0.2445	0.0879	188.5	173.46
111	109	112	0.2088	0.0753	918.03	898.55
112	112	113	0.2301	0.0828	305.08	215.37
113	100	114	0.6102	0.2196	54.38	40.97
114	114	115	0.1866	0.127	211.14	192.9
115	115	116	0.3732	0.246	67.009	53.336
116	116	117	0.405	0.367	162.07	90.321
117	117	118	0.489	0.438	48.785	29.156
		118			33.9	18.98

IEEE 41 BUS DISTRIBUTION SYSTEM

Line Index	To Bus Index	From Bus Index	Line Resistance R [Ω]	Line Reactance X [Ω]	From bus Load Active Power P [kW]	From bus Load Active Power Q [kvar]
1	1	2	0.0992	0.0470	100	60
2	2	3	0.4930	0.2511	90	40
3	3	4	0.3660	0.1864	120	80
4	4	5	0.3811	1.1941	60	30
5	5	6	0.8190	0.7070	60	20
6	6	7	0.1872	0.6188	200	100
7	7	8	0.7114	0.2351	200	100
8	8	9	1.0300	0.7400	60	20
9	9	10	1.0440	0.7400	60	20
10	10	11	0.1966	0.0650	45	30
11	11	12	0.3744	0.1238	60	35
12	12	13	1.4680	1.1550	60	35
13	13	14	0.5416	0.7129	120	80
14	14	15	0.5910	0.5260	60	10
15	15	16	0.7463	0.5450	60	20
16	16	17	1.2890	1.7210	60	20
17	17	18	0.7320	0.5470	90	40
18	2	19	0.1640	0.1565	90	40
19	19	20	1.5042	1.3554	90	40
20	20	21	0.4095	0.4784	90	40
21	21	22	0.7089	0.9373	90	40
22	3	23	0.4512	0.3083	90	50
23	23	24	0.8980	0.7091	420	200
24	24	25	0.8960	0.7011	420	200
25	6	26	0.2030	0.1034	60	25
26	26	27	0.2842	0.1447	60	25
27	27	28	1.0590	0.9337	60	20
28	28	29	0.8042	0.7006	120	70
29	29	30	0.5075	0.2585	200	600
30	30	31	0.9744	0.9630	150	70
31	31	32	0.3105	0.3619	210	100
32	32	33	0.3410	0.5302	60	40
33	10	34	0.2030	0.1034	60	25
34	34	35	0.2842	0.1447	60	25
35	35	36	1.0590	0.9337	60	20
36	36	37	0.8042	0.7006	120	70
37	37	38	0.5075	0.2585	200	600
38	38	39	0.9744	0.9630	150	70
39	39	40	0.3105	0.3619	210	100
40	40	41	0.3410	0.5302	60	40

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