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An Overview of Methods for Control of Flexible Resources

Integrated Master’s in Electrical and Computer Engineering
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Integrated Master’s in Electrical and Computers Engineering

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An Overview of Methods for Control of Flexible Resources

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“We have this handy fusion reactor in the sky called the sun, you don’t have to do anything, it just works. It shows up every day.”

Elon Musk

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Abstract

A recurrent subject related with the electrical grids in the last years, is the necessity to adopt sustainable energy policies. Due to massive raises in the greenhouse gas emissions, the planet Earth has suffered serious consequences.

The European Union, trying to reduce this emissions, has played an important role, with the financing of enormous projects with the aim to improve the Power Quality (PQ) and at the same time, reduce the greenhouse gas emissions, for a better ambient and a better service.

Two of those projects are the *Increase* and the *Story*. The principal ambition of these two projects is to study and develop new controls to permit a better penetration and at the same time, a better control of the distributed renewable energy sources (DRES) in the distribution network. In the case of the *Story*, the aim is to use storage technologies to this end.

Distribution networks are recently becoming a target of this intensive research. The increasing penetration of the DRES, such as photovoltaic (PV) and wind generation, as well as flexible load consumption units, have influence the network operation. Normally, the Distribution System Operator (DSO) would strive to reinforce the grid through additional investments to deal with this issues. This investment can cause technical problems in the grid, although, this new development can also provide a potential source of flexibility from the network users and thus a desirable source of solutions for the grid operations.

With appropriate approaches to conjure and to use this flexibility, the DSO can increase hosting capacity with the existing grid infrastructure, deferring grid reinforcement investments.

The ambition of my master thesis is, in collaboration with the Laboratory of Energy Policy from the University of Ljubljana, to study the effects of the different types of controls in distribution network, to allow the injection of power from DRES, keeping all the network parameters inside the regulated levels, allowing this flexibility aforementioned. For that, was used the *Increase* simulation platform to simulate a Rural Network with the parameters and characteristics close to a real one.

This is a first part in this two European projects, with this results, they will be used for further investigation. Is essential to deliver new tools and methods to the DSO to allow a higher increase of DRES in the network, because, with this inclusion will be a big step to a fossil independent networks.

Key words:

- Distributed Renewable Energy Sources;
- Distribution Networks;
- Power Quality;
- Ancillary Services;
- Greenhouse gas emissions.

Resumo

Um assunto recorrente relacionado com as redes elétricas durante os últimos anos, é a necessidade de adotar politicas energeticamente sustentáveis. Devido ao enorme crescimento nas emissões de gases de estufa, o nosso planeta tem vindo a sofrer graves consequências.

A União Europeia tem tido um papel importante no combate a este crescimento das emissões, com o financiamento de vários projetos com o fim de melhorar a qualidade de energia e ao mesmo tempo, reduzir as emissões dos gases de estufa, para um melhor ambiente e um serviço melhorado.

Dois destes projetos são o *Increase* e o *Story*. A principal ambição destes dois projetos, é o estudo e o desenvolvimento de novos tipos de controlo, que permitam uma melhor penetração e ao mesmo tempo, um controlo improvado das *distributed renewable energy sources* (DRES) nas redes de distribuição elétricas. No caso do programa *Story* são usadas unidades de armazenamento para este fim.

As redes de distribuição elétricas têm vindo a ser alvo de uma pesquisa intensiva. A penetração das DRES, como fotovoltaicas (PV) e energia eólica, bem como as cargas com consumo flexível, influenciam a operação das redes. Normalmente, o operador destas redes opta pela via do investimento para lidar com estes problemas, no entanto, este mesmo investimento pode provocar novos problemas técnicos na rede de energia. Com estes recentes desenvolvimentos, os consumidores podem vir a ser uma fonte potencial de flexibilidade para a rede, sendo uma solução desejável para os problemas na operação da rede.

Com um apropriado uso desta flexibilidade, o DSO pode aumentar a capacidade da rede usando apenas a infraestrutura já instalada, evitando assim custos da instalação de novos equipamentos.

Esta dissertação tem como ambição, numa colaboração com o *Laboratory of Energy Policiy* da Universidade de Ljubljana, estudar os efeitos de diferentes tipos de controlos numa rede de distribuição, para assim, permitir uma máxima injeção de energia das fontes renováveis, mantendo todos os parâmetros dentro dos valores regulados. Para isso, foi usada a plataforma de simulação do *Increase* para simular uma rede rural com parâmetros e características baseadas numa rede real.

Este é uma primeira aproximação dos dois projetos acima referidos, sendo que estes resultados irão ser usados em investigações futuras. O desenvolvimento de novas ferramentas e métodos para o DSO permitir uma maior penetração de DRES na rede, é de elevada importância, pois com esta inclusão vai permitir uma maior independência dos combustíveis fósseis.

Palavras chaves:

- Fontes de Energia Renováveis Distribuídas;
- Redes de Distribuição;
- Qualidade de Energia;
- Serviços Auxiliares;
- Gases de Efeito de Estufa.

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Abbreviations and Symbols

Abreviations

AS	Ancillary Services
CDE	Controllable Distributed
DA	Day ahead
DG	Distributed Generation
DN	Distribution Network
DR	Demand Response
DRES	Distributed Renewable Energy Sources
DSO	Distribution System Operator
EB	DR units with Energy Optimization
Econ	DR units with Economic Optimization
EU	European Union
FCR	Frequency Restoration Reserve
FEP	Flexible Energy Product
FRR	Frequency Restoration Reserve
HH	Household
HV	High Voltage
HP	Heat Pump
Int	DR units with Intelligent Schedule
KGC	Key Grid Challenges
LC	Local Control
LV	Low Voltage
MAS	Multi-Agent System
MV	Medium Voltage
NC	No Control
OC	Overlay Control
OTC	Over the Counter
PQ	Power Quality
PV	Photovoltaic
RES	Renewable Energy Source
RN	Rural Network

RR	Replacement Reserve
SiC	Simple Control
SC	Scheduling Control
SCA	Scheduling Control Agent
TLS	Traffic Light System
TN	Transmission Network
TOU	Time of Use of a demand response unit
TSO	Transmission System Operator

Symbols

kV	Kilovolt
kVA	Kilovolt-amps
kWp	Kilowatt peak
m	Meters
mm^2	Square millimetre
MWh	Megawatt hour
p.u.	per unit

Chapter 1

Introduction

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1. Introduction

1.1. Contextualization

Out of the political aims of the European Union, the reduction of greenhouse gas emission and the reduction of the dependency on fossil energy are keys elements and priorities in the agenda for the next years. Is expected an 40% reduction in greenhouse gas emission by 2030 compared with 1990 levels, and at least 27% of all EU energy with origin in renewables sources [1].

The use of Distributed Renewable Energy Sources (DRES) connected to the distribution network can have a significant contribution to reach these objectives by replacing conventional power plants, in power generation and also in the provision of Ancillary Services (AS).

The distribution network, where the majority of DRES units are connected on low and medium voltage levels (LV and MV[1]), are built as meshed but, traditionally operated as a radial network where the flow occurs from the transmission network side towards the distribution grid connected loads. The increase of the intermittent DRES in LV and MV networks can led to a bidirectional power flow. Related with this power flow, new operational and control strategies are urgently needed in order to retain the ability of the system to provide the consumers with reliable supply of electricity at an acceptable power quality level.

Apart from the energy-based electricity markets, Ancillary services (AS) are a core element in the networks for a secure operation of the power system. AS are grid support services essential to the transmission or distribution system operator to maintain the stability and acceptable power quality along all the power grid. Usually, this services include voltage and reactive power control, regulation of frequency, active power reserves, among others.

Traditionally, the AS are provided by conventional generators connected to the HV transmission network, however, the DRES also have the potential to provide AS. With high shares of DRES units in power generation in nowadays power systems, these units need to be able to perform control tasks in a manner similar to conventional power units, in order to keep or even increase the efficiency, quality and security of the power grid system.

The European project *Increase* was created with the aim to help the EU met the European 20-20-20 targets [2], in which by 2020 the share of renewable energy needs to be 20% of the

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[1] International Standard IEC 60038:1983 defines the voltage levels as follow: Low voltage – up to 1kV; Medium voltage – 1 kV up to 33 kV.

electric energy demand. The principal challenge is to develop control strategies, test this controls and assess options to provide AS.

In complement to *Increase*, the European Project *Story* was created with the aim to study and create new technologies to create the future of energy storage. The principal challenge is to find solutions, which are affordable, secure and ensure an increased percentage of self-supply energy. In *Story*, the focus is solutions on storage technologies, applied to the distribution network. project *Increase*, where the challenges of the distribution network have been investigated.

This dissertation will aboard one small part of this project, the study of methods of control to be applied in small scale PV generation units and in Demand Response systems

1.2. Objectives

The main goal of this dissertation is to analyse the performance of a Rural Network, using the increase simulation platform, that is a junction of Matlab and OpenDSS. For this simulation it will be applied different types of control for the management of the PV and DR units, three different types of optimizations and also, and also, five different scenarios, with a different nu,ber of PV and DR connected to the network in each of one, to see how the network react with different number of units connected to this.

First, there will be defined the parameters of the Distribution Network, namely, the characteristics of the transformers, number of feeders, length of the feeders, number of customers connected in each feeder, and other important data. It is noteworthy to say that the rural network used was developed with base in a small portion of a distribution network from *Elektro Gorensjka* in Slovenia [3].

Second, the network was defined using the open source software, *Open DSS*, and the simulation platform was adapted to our necessities. It was necessary to defined the number of scenarios, with the number of units connected to each one, as well as the location of the units that are going to be connected to the network in each scenario.

After running the simulation, the data was analysed using the Microsoft tool, *Excel*, to see the bigger differences between the diverse cases, to revolve in what it is the best control and optimization with the most advantages for the network, users and the various operators.

1.3. Structure

This dissertation it is divided in six chapters, bibliographical references and appendix. In this chapter are presented the reasons that led to the preparation of this dissertation, the intended objectives and a brief description of the document structure.

On the second chapter the ancillary services are presented, being one essential theme to the elaboration of the dissertation. It will be presented the definition and a brief description, and in the end the key ancillary services that will be the bases for this document.

The third chapter is dedicated to the description of the rural network, that is used in the simulation platform and analysed posteriorly. The topology and characteristics of the elements composing this RN will be described in this chapter, to a better understand of the network in question.

The forth chapter is about the simulation platform and its description. There will be described the types of control and assumption used in this platform, as well as other features, such as traffic light system, scenarios used, forecasting and tools used.

Fifth chapter it is dedicated to the presentation and analyse of the results from the simulation platform and in the end a general balance about this results and their implication.

In the end, in the sixth chapter, it is present the principal conclusion that it was taken from this dissertation.

In the appendix there are presented the schematics with the PV and DR connections per scenario and also additional results data.

Chapter 2

Key Grid Challenges

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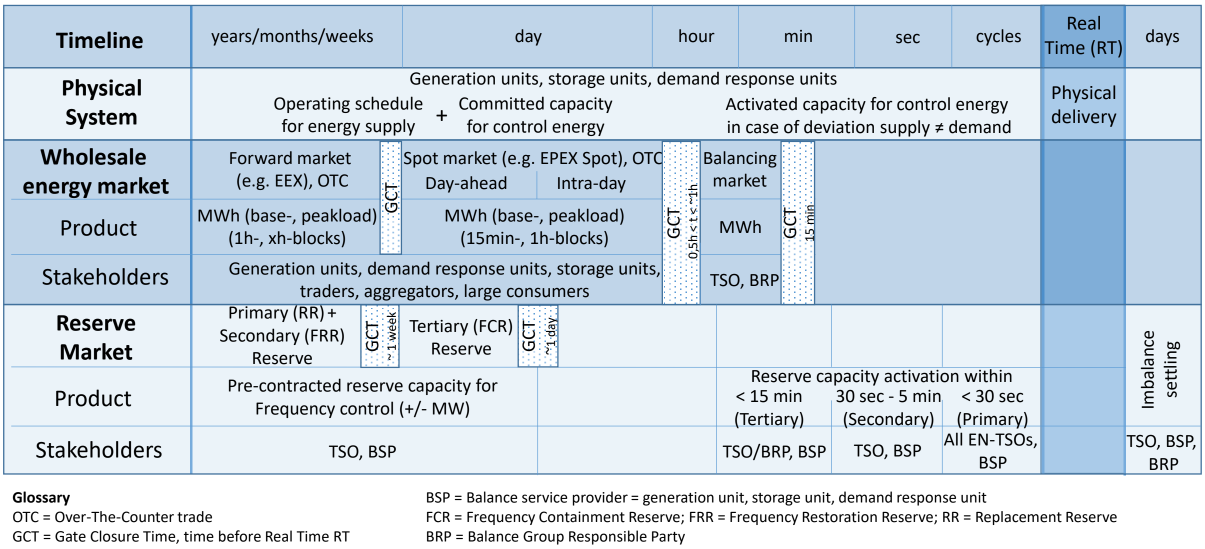
2. Ancillary Services

A starting point to discern the market mechanisms and regulatory frameworks for the AS, this chapter will provide an overview on current energy and AS markets, its stakeholders, terms used in European power systems, current definitions and important key Ancillary Services.

2.1. Energy and Ancillary Service markets

The most fundamental requirement of all the electric power system is that the total electricity injection, on the system, needs to be equal to the total withdraw, and that the stability of the power system is guaranteed in order to maintain the main technical parameters within predefined ranges. For that, different markets, stakeholders and timelines are involved in the system with different responsibilities, as show in Figure 2.1.



Timeline	years/months/weeks	day	hour	min	sec	cycles	Real Time (RT)	days
Physical System	Generation units, storage units, demand response units Operating schedule for energy supply + Committed capacity for control energy			Activated capacity for control energy in case of deviation supply ≠ demand			Physical delivery	
Wholesale energy market	Forward market (e.g. EEX), OTC GCT	Spot market (e.g. EPEX Spot), OTC Day-ahead Intra-day	GCT 0,5h < t < ~1h Balancing market	GCT 15 min				
Product	MWh (base-, peakload) (1h-, xh-blocks)	MWh (base-, peakload) (15min-, 1h-blocks)	MWh					
Stakeholders	Generation units, demand response units, storage units, traders, aggregators, large consumers		TSO, BRP					
Reserve Market	Primary (RR) + Secondary (FRR) Reserve GCT ~ 1 week	Tertiary (FCR) Reserve GCT ~1 day						Imbalance settling
Product	Pre-contracted reserve capacity for Frequency control (+/- MW)			Reserve capacity activation within < 15 min (Tertiary)	30 sec - 5 min (Secondary)	< 30 sec (Primary)		
Stakeholders	TSO, BSP			TSO/BRP, BSP	TSO, BSP	All EN-TSOs, BSP		TSO, BSP, BRP

Glossary
OTC = Over-The-Counter trade
GCT = Gate Closure Time, time before Real Time RT
BSP = Balance service provider = generation unit, storage unit, demand response unit
FCR = Frequency Containment Reserve; FRR = Frequency Restoration Reserve; RR = Replacement Reserve
BRP = Balance Group Responsible Party

Figure 2.1: Overview of energy and reserve markets, products and stakeholders in an European electric power system [4]

The physical aspect of an electric grid, represented in the Figure 2.1, includes the generating units, storage units and flexible loads. Their operating schedules are usually resolved on two separated markets: the wholesale energy markets and the reserve markets.

The wholesale energy markets include all the trades by market participants of standardized energy products (e.g. peak load, base load). Energy is sold via bilateral contracts (OTC) and also via the energy stock markets [5]. Depending on the timeline, the energy markets are divided into forward markets for long term transactions and the spot markets for short-term scheduling of electricity supply.

Following the end of the wholesale energy market, the transmission system operators (TSOs) are the responsible for maintaining the network frequency and to setting measures to control the short-term unbalanced supply and demand. The generation capacities, require to solve the fluctuations in the network parameters, to supply short-term flexible control energy as reserve to the grid are also pre-contracted on the reserve market [6].

The reserves for frequency control are defined according to their activation, following a deviation between supply and demand as:

- Primary reserve: Frequency Containment Reserve (FCR);
- Secondary reserve: Frequency Restoration Reserve (FRR);
- Tertiary Reserve: Replacement Reserve (RR).

In Europe, the overall frequency control scheme is organized on a European level, where all the European TSOs are involved. FCRs are automatically provided by the generating units to stabilize the frequency within seconds. The FRRs are activated in the control area of the TSO from which the disturbance occurs, and restore the frequency to its normal level. The RR are activated to replace the FRR with the aim to have them available again for future deviations.

The provision of this reserves to maintain the system frequency belongs to the Ancillary Services. In the following chapters, definition of AS relevant in the Transmission and the Distribution System, and as follow essential to this document, and description of key AS elements.

2.2. Definition of Ancillary Services

In the UCTE Operation Handbook, the definition of AS is: AS are Interconnected Services identified as necessary to affect a transfer of electricity between purchasing and selling entities and which a provider of transmission services must include in an open access transmission tariff [7].

EURELECTRIC states that: AS are all the services required by the transmission or distribution system operator to enable them to maintain the integrity and stability of the transmission or distribution systems as well as the power quality [8].

The ENTSO-E (European Network of Transmission System Operators for Electricity) also refers to AS as a range of functions which TSOs contract to guarantee the system security. In these are include frequency response, fast reserve, provision of reactive power, black start capability and various other services [9].

Some attributes, for instance remote start-up, automatic voltage regulation, fault rude-through, parallel running, governor control and real time metering were not being features of distributed generation design in the past, although many of those are key to the provision of AS.

Between all the AS provided to TSO, the provision of reserves for frequency control is the most expensive. As example, in the Figure 2.2 for the year of 2013, the net costs of AS in Germany [10], for the group of primary secondary and tertiary reserve, was 595 million euros, while others AS, such as voltage control, black start capacity and re-dispatch accounted in 154 million euros.

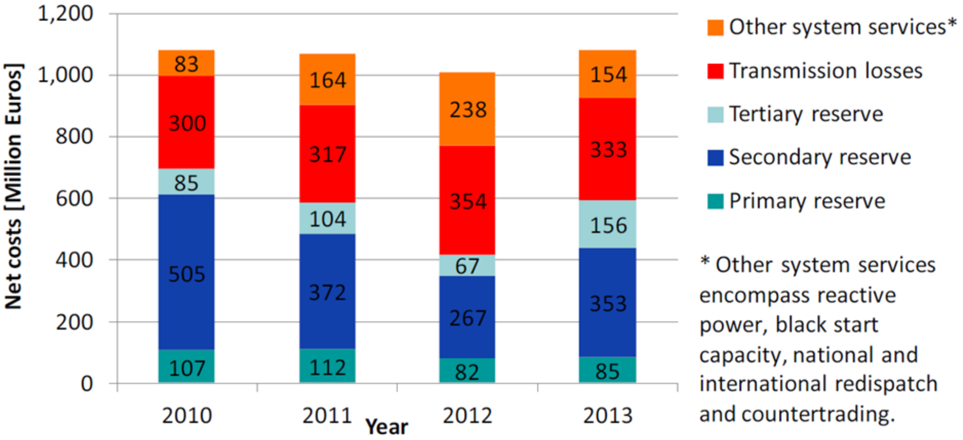


Figure 2.2: Net costs of AS in Germany from 2010 until 2013 [10]

2.3. Key Ancillary Services

The most usual problems in the low voltage networks are voltage unbalance, overvoltages and line congestion, as are likely to appear in distribution lines with increased RES penetration and low-load conditions. To surpass this problems, the DSOs commonly employ one of the following methods: upgrade the line or limit the penetration of the DRES in it.

INCREASE project approach this problem by developing technological solutions, empowering an active management and control of LV networks, hence:

- Exploiting current LV grid capacity;
- Facilitating higher DRES penetration and per consequent a better use of the already installed DRES units;
- Providing AS to DSO/TSO to maintain the reliable supply of electricity;
- Reducing costs of current power systems.

This INCREASE technological solutions are based on smart control strategies on different levels, as shown in the Figure 2.3. The INCREASE 3-phase grid-connected inverters, added to every single DRES installation are able to mitigate the problems expose in the paragraph before. These are based on the smart control strategies of *Local Control (LC)* and on *Overlay Control (OC).* In short description (a more detailed control strategy information is presented in [11] and [12]), the LC is directly integrated in the inverters connected to the DRES units and are capable of mitigate the LV network problems by means of a droop control, using local information for an autonomous off line operation. LC can ensure a stable voltage profile on the power grid. For its part, the OC is a supervisory control strategy at the level of the DSO that resorts on the communication between the LC and the DSO, assuring an optimal operation in the LC voltage control distribution grid without the use of demand response.

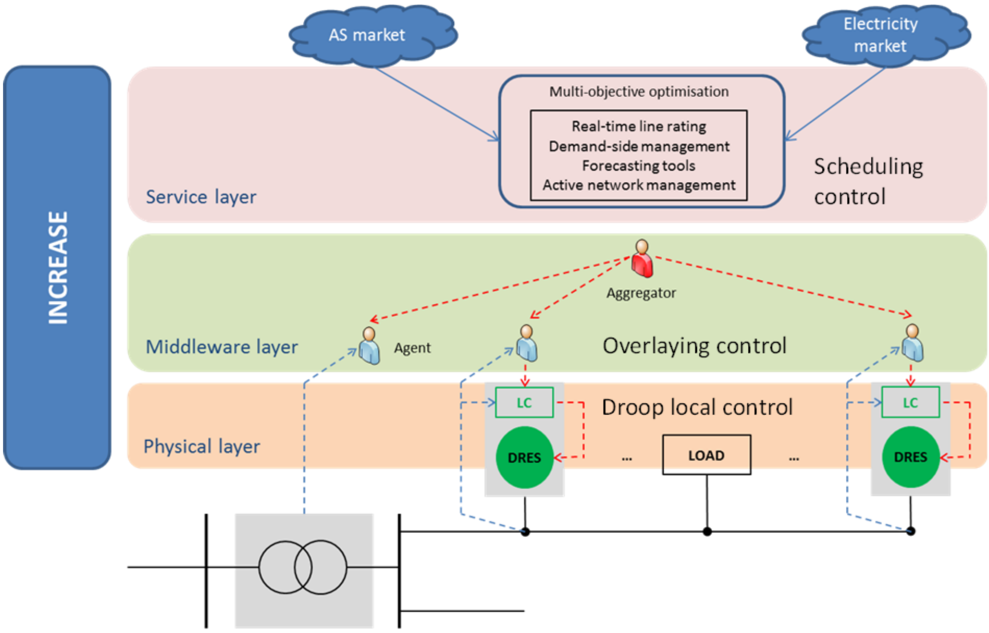


Figure 2.3: INCREASE smart control strategies

Apart from the positive impact on the power quality in the distribution grid, this controls have also an effect on the DRES active power injected to the network. This is a result of the capacity of the LC to enable dynamic curtailment of active power infeed of DRES unit into the grid, hence allowing intermediate levels of electricity generation, instead of a simple on/off control (SiC). The OC will assure that the dynamic curtailment of DRES units is equally distributed, enabling a “fairness” strategy. Consequently, DRES units will be able to generate maximum energy within the margins set by the objectives of LC and OC.

2.3.1. Voltage Control

Usually, the voltage control in the power grid is done by injecting or absorbing reactive power. The needed amounts of reactive power in the typical DN are provided from or to the transmission network. This occurs due to the lack of resources in the DN. All the reactive needs in DN are usually covered by reactive power provided by large generators on the HV side in the TN. In the DN, the voltage control is normally implemented through the tap changer action at the HV/MV transformer in the substations.

Figure 2.4 presents the ranking of reactive resources suitable for reactive balancing, and therefore the voltage control, according to the electrical distance to the HV grid [13]. The growing of controllable distributed energy (CDE) units connected to the DN at MV level, facilitates the reactive power balancing and voltage control in DN.

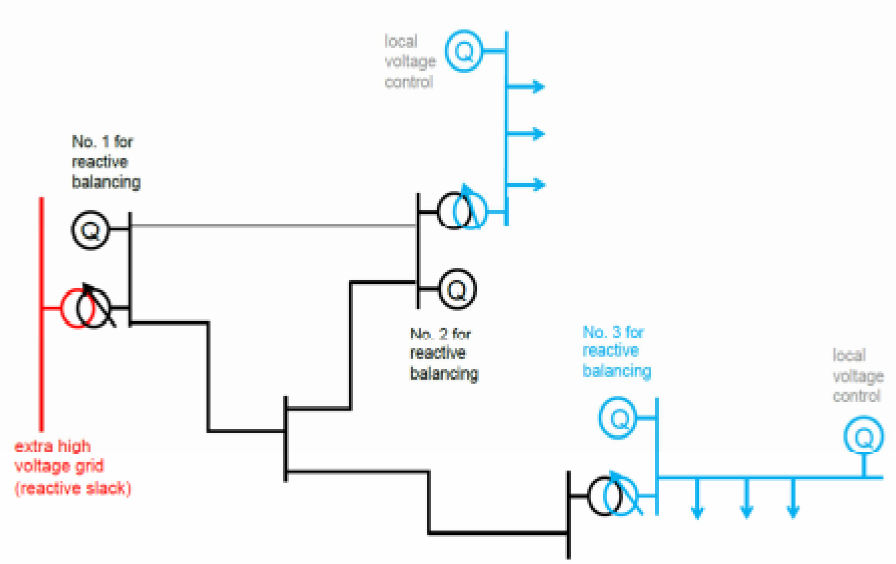


Figure 2.4: Ranking of reactive resources suitable for reactive balancing [13]

Reactive power generated in DRES units connected at distant MV nodes or at LV nodes can be used for local reactive power support and local voltage control [13]. With this, the amount of reactive power required from transmission-connected generation can be reduce due to the DRES units equipped with advanced inverters.

At lower voltages levels, nowadays the proliferation of DG connected to the grid, can make a significant impact on the amount of reactive power exchanged between TSO and DSO system. There are different ways of providing reactive power from DRES units [14]:

- DRES generate only active power, reducing the amount of active power imported from TSO, which means that less reactive power is needed;

- DRES generate active and reactive power, reducing the active power losses in the transmission of power from the HV to the MV and LV levels;
- DRES generate active and absorb reactive power.

2.3.2. Voltage unbalance mitigation

With the crescent number of single-phase connected DRES, the voltage unbalance is also an increasingly problem in LV distribution networks. This problem is related with unequal voltage magnitudes (under and over voltages), phase angle deviation and unequal levels of harmonic distortion between the phases.

Voltage balancing control are among the key planning issues, as is evidenced in the Quality of Supply standard EN 50160 [15]. However, in order to be able to connect to the DN, DRES need to comply with the technical standards embedded in the DN regulation, pay for the connection costs, or its connection can be denied by the DSO.

To mitigate this problem, it is necessary to create an intelligent hierarchical control structure involving local controllers. The advanced three phase inverters of DRES could be controlled with the aim to distribute equally the active power between the phases, diminish voltage unbalance, raising voltage profile and allowing a higher penetration of DRES on LV distribution network.

2.3.3. Line congestion

The CDE units can provided flexible response to mitigate line congestion in the DN. With an adequate intelligent control structure which enables a better mitigation of the primary source variability, the security of supply contribution of CDE units can also be essential to the DSO. This units, connected on LV level close to loads, could extend the transport capacities of existing distribution lines, if a hierarchical control structure is applied to this loads, to coordinated the services of each load.

The security of supply is mainly determined during the planning process of DN. The proposed planning recommendations are being modernized to include the recent advances in DRES. It is expected that in the medium to long term, load growth and asset replacements could increase opportunities for the DRES units to provide network support services, being the mitigation of the congestion in lines one of the most important service. The values of this service could be established from the avoided cost, by the DSO, to the DN reinforcement.

2.3.4. Reserve provision

Frequency support as the AS is an obligation of the TSO to maintain the transmission system integrity. Frequency control is achieved through the real-time matching of supply to demand. This control encompasses the FCR, FRR and RR reserves, as previously explained.

There are two types of reserve that can be provided upon requisition of the TSO:

- **Down reserve:** the generation in the CDE units is reduced or the consumption of active power is increased. In the case of DRES units, this is possible in most cases, but for aggregators of DR, increased consumption is only possible if their capabilities allow it.
- **Up-reserve:** The generation in the CDE units is increased or their consumption is reduced. Since that DRES are upwards constrained with the availability of the energy source, they are able to increase the production only if the energy source (e.g. sun or wind) is available and they are operating below the installed capacity. The reduction of energy consumption the DR aggregator is always possible, since that is within their limits.

Due to the high penetration of DRES in the DN, the CDE can potentially provide these services to TSOs. For this crescent participation of CDE units in future reserve markets on the DSO level, an intelligent hierarchical control algorithm is necessary for unit coordination. This would need to use an appropriate optimization criterion to optimally combine the reserve from DRES and DR units.

2.4. Impact Factors

The impact factors were defined as conditions that determine the success of the provision of solutions, to the key ancillary services discussed in the prior chapter. These factors can influence the normal operation of the network, within the parameters and power quality acceptable.

2.4.1. Balancing of demand profile

In a power system, a load curve or load profile is a diagram illustrating the variation, over a specific time interval, of demand/electrical load. The key feature in the power grid is that consumption and generation must be balanced at all the time. Any significant imbalance could cause frequency discursion, and could lead to grid instability or to voltage fluctuations, as a result the demand profile acquires a fundamental role in the good operation of the grid.

There are two important distinct time intervals for Demand profile:

- **Long-term interval:** this period is related to power generation adequacy. This profiles are used to plan how much electrical generation will be needed to cover demand for a long period of time, usually from several months to years ahead.
- **Short-term interval:** related to power system operation. The operational reserves have to be scheduled since the scale of week ahead, down to seconds ahead of operation.

Small-scale storage connected to the distribution network, when is appropriately connected, can act as a flexible consumption unit or as a schedulable producer, within its operating range. This is the aspect that will be focus on the European project STORY. The smart control of energy that can be applied to these storage units is aboard on INCREASE project, and it is one of the main objectives of this work.

2.4.2. Distributed Generation

Distribution generation is a term affect to the production of electricity near the consumption location. The DG resources are often renewable energy sources and co-generation. However, there are various technical issues that need to be addressed when considering the presence of DG in the distribution network. The effects due to the presence of DG include increased short circuit levels, changed in the network losses, changes in the voltage profile in the DN, appearance of the voltage transients, occurrence of congestions in system branches and affected power quality and reliability.

The following impacts of DG in the DN are of particular interest:

- **Impact on voltage regulation**: the voltage regulation on the radial distribution systems is donned with the aid of load tap changing transformers at the substation, additionally by line regulators on the distribution feeders and shunt capacitors on feeders or along the line. This regulation is usually based on one-way power flow where regulators are equipped with line drop compensation. For that, the connection of DG can result in changes in voltage profile along the feeder by changing the magnitude and direction of real and reactive power flow in the DN.
- **Increased feeder losses**: the location of the DG units is a major point that has to be optimized to improve reliability of the system to reduce the power losses.

- **Source of harmonics**: these units are also a source of harmonics that need to be taken into consideration.

2.4.3. Demand Response

The definition of demand response (DR) is as the change in electric consumption by the end-use customers from their normal consumption patterns, in response to a control signal from the DSO. This signal can be related with changes in price of electricity over time, or to incentive payments delineated to compensate lower electricity use at time of high levels of electricity demand or when the reliability of the DN is jeopardized [16]. Usually, DR is often related with the short-term changes focus on critical hours during a day with high demand profile or when the reserve margin is low.

The most obvious effect of DR in the power systems are the security of supply and voltage control. Nevertheless, there are other three fundamental areas of DR and DN mutual influence which can lead to the power quality violations and demand response loss of effectiveness, such as:

- **Load pickup** after and before demand response event. To compensate, DR unit needs to increase or decrease its consumption in the succeeding time frame to be ready for renewed deployment;
- **Lack of coordination** between demand response and distribution grid volt/var control. The DR unit activation is scheduled with market effects in mind, without taking in consideration local network conditions, which can lead to PQ violations;
- **Asymmetric demand response balancing** between phase in a three phase system. This occurs because the DR units are connected to random phases on the network, without a planning and coordinated activation.

Chapter 3

Rural Network

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  3.1.2. Medium voltage network 16
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3.3. Rural LV network parameters 18

3. Rural Network

For the investigation of the impact of renewable production, advanced inverter controls and the implementation of DR units in the network, it was important that the selected model had to represent a general structure of a network applicable to multiple locations.

To facilitate the selection of a suitable grid model, a questionnaire about the typical network settings and parameters was used to collect information from the partners in the project STORY [17]. The partners are originated from four different countries, Belgium, Finland, Slovenia and Spain. Based on those typical average values of the different network around Europe, a representative case was developed.

3.1. Network information

3.1.1. Low voltage network of rural area

Low voltage networks in rural areas are, usually, operating radially, being supplied by one transformer station. Transformers with a power rating from 50 kVA up to 800 kVA are used in the different countries (Table 3.1).

Table 3.1: Transformer information in LV network

Country	Rated Power [kVA]	Voltage level [kV]	Loading rate [%]
Belgium	160, 250, 400, 800	10/0.4	50 – 60
Finland	100	20/0.4	15 - 25
Slovenia	50 – 630	20/0.4	50 – 60
Spain	50, 100, 160, 250	30–10/0.4	50 - 70

The distribution network is composed by 3 to 10 feeders, that can supply from 5 to 80 loads each, and with a variable length of 90 m up to 800 m (Table 3.2).

Table 3.2: Feeder and nodes information in LV networks

Country	Number of feeders	Load nodes/feeder	Average length [m]
Belgium	4 – 8	1 – 20	200 - 800
Finland	3	5	370
Slovenia	5 - 10	30 – 80	400 – 800
Spain	N/A	N/A	90 – 160

3.1.2. Medium voltage network

The information and difference between countries about the grid structure on MV level are presented in the Table 3.3 and

Table 3.4.

Table 3.3: Transformers on MV levels of rural networks

Country	Rated power [MVA]	Voltage level [kV]	Loading rate [%]
Belgium	20 – 50	(150 – 70)/(15 – 10)	50 – 60
Finland	15	110/20	23
Slovenia	4 – 8	110/20	40 – 60
Spain	N/A	N/A	N/A

Table 3.4: Feeders information in MV úrban network

Country	Number of feeders	Load nodes/feeder	Average length [km]
Belgium	10 – 15	N/A	10
Finland	6	N/A	30
Slovenia	3 – 8	20 – 30	5 – 8
Spain	N/A	N/A	3

3.2. Grid topology

With the information provided, it was defined the parameters for the rural network that will be used for further scrutiny. The general concept of the network is represented in the Figure 3.1.

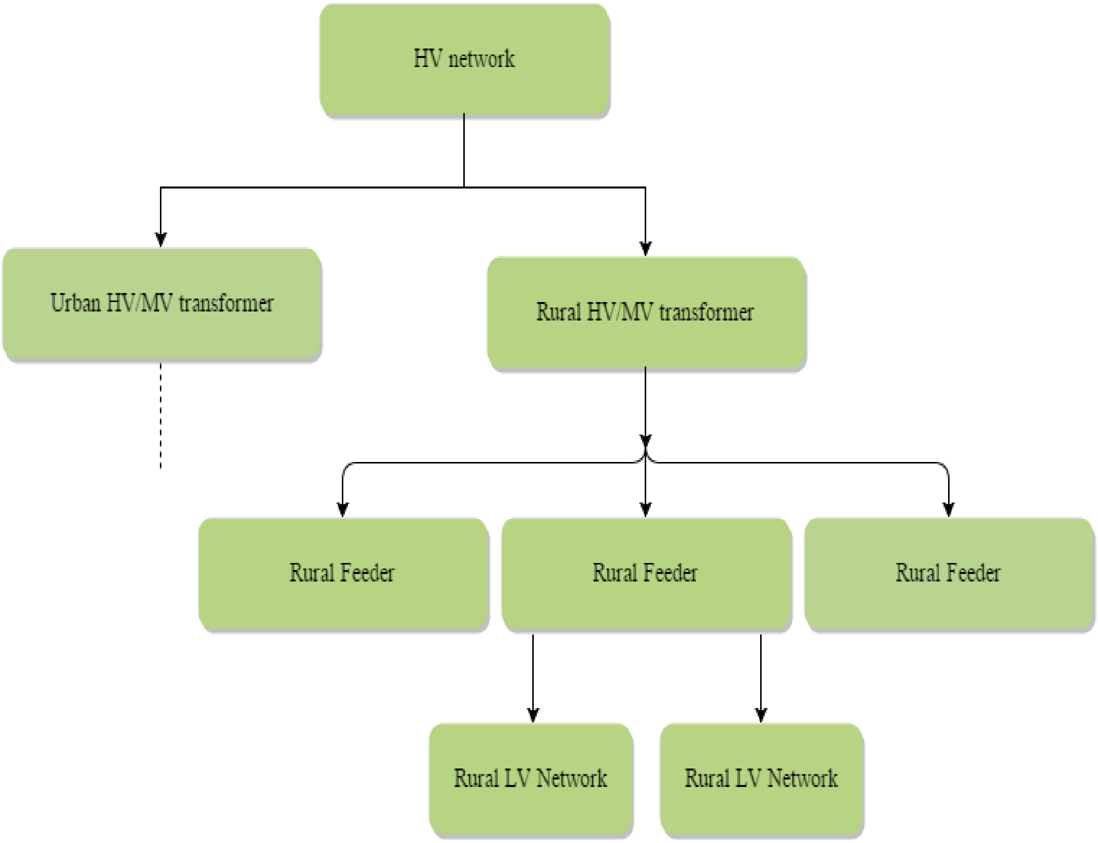

Figure 3.1: Synthetic Network Concept

From the HV level, two transformers supply energy to different networks, one of them with characteristics of a rural network. The Rural HV/MV transformer will supply various feeders, each one having attached loads, generation and distribution MV/LV substations. However, the research in this work will be only focused on the low level of this network, regarding one of this LV networks, that is fully defined.

3.3. Rural LV network parameters

In this network it was used a low load density, with two factors contributing to this: longer average feeder length and unstructured branch topology. 6 radial feeders were defined, each feeder supplies 15 a 25 loads depending on the feeder. Table 3.5 lists the parameters used for the rural network.

Table 3.5: Rural network parameter

Number of feeders	6
Number of loads per feeder	15 – 20
Feeder length [m]	600
Power line properties (Cable/OHL, sections)	OHL, $3\times35\ mm^2 + 35\ mm^2$ $3\times70\ mm^2 + 70\ mm^2$
Rated power of MV/LV transformer [kVA]	250
Loading of MV/LV transformer	55%

The structure designed for this network is depicted in the **Error! Reference source not found.**. In total the grid is composed by 6 feeders and with a total of 120 connected loads, each of them representing one household (HH). The largest feeder has 25 HH connected, while the smallest has only 15 HH.

Each HH is connected to the bus with a $3\times35\ mm^2 + 35\ mm^2$ line with a length of 7 meters.

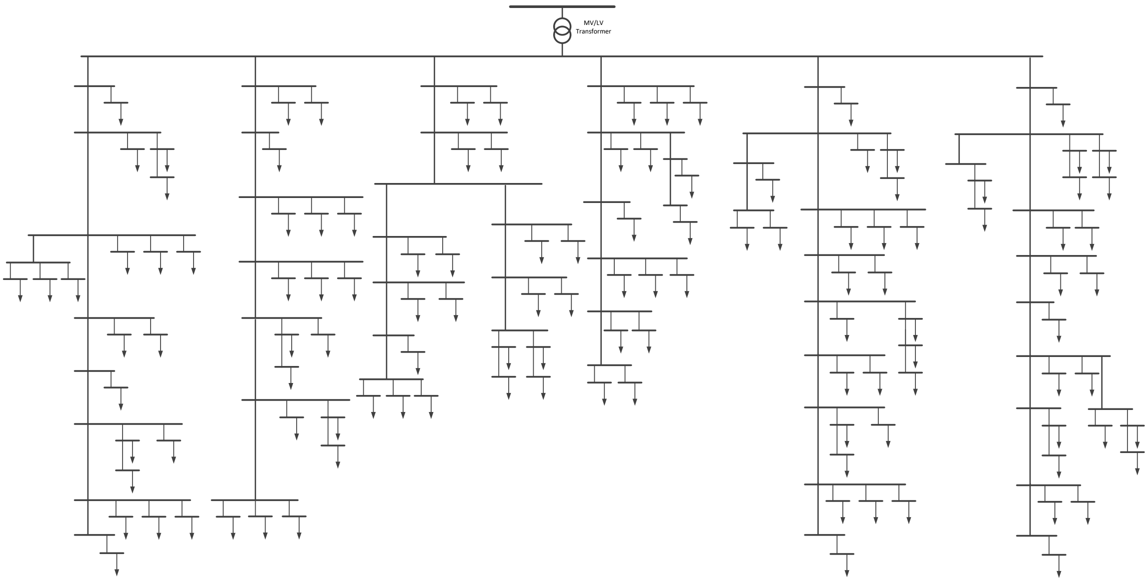

Figure 3.2: Rural network structure

3.4. Household and PV units

In this network, to represent every HH it was designed a load with the following parameters presents in the Table 3.6.

Table 3.6: HH load parameters

Number of phase	1
Nominal rated voltage [kV]	0.23094
Installed PV power [kWp]	20

Connected to every HH it is a PV unit, that is activated during the simulation when is necessary. The general parameters of this generators are presented in the Table 3.7.

Table 3.7. PV unit load parameters

Number of phase	1
Nominal rated[kV]	0.23094
Available power [kW]	7

Power of the PV and DR units was not indicated, because the Increase simulation platform will overwrite the assigned power in each iteration.

3.5. Transformer

Rated power of the transformer was used for scaling up the consumption in order to achieve proper average loading of the transformer of 55%. Due to the later implementation of PV plants, and power peaks of consumption above the rated power, transformer was swapped for 400 kVA in order to avoid convergence issues with power flow calculations and possible higher rate of implementation of the PV's within the DN.

Table 3.8 presents the parameters of the used transformer in this RN.

Table 3.8: Transformer parameters

Rated power [kVA]	6
Voltage levels [kV]	21 / 0.42
Full load losses	1.011%
Idle state losses	0.129%
Rated power of MV/LV transformer [kVA]	250
U_K factor	4%

Chapter 4

Simulation Model Description

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4. Simulation Model Description

In this chapter the simulation environment will be described. All the parameters will be specified, as well as the applied control methods, description of all the services considered in this simulations model and other important aspects for the comprehension of the final results.

4.1. Key Simulation Assumptions

The focus of the multi-agent system (MAS) control strategies is to solve the technical problems associated with the integration of DRES in the distribution network. Due to that, the following key simulation assumption were used:

- Voltage limits: the allowed voltage limits are set to [0.9,1.1] p.u.
    - Inverter control, which activates the curtailment of PV generation in case of overvoltage in the node where is installed. In this case the droop control will be activated on an interval from [1.06, 1.10] p.u.
- Control Strategies:
    - Two control strategies were used: Simple Control (SiC) and the Local Control (LC).
    - The SiC disconnects the PV plant from the grid (in the simulation it set the generation to 0) when the voltage level in the PV node exceeds 1.10 p.u.
    - All the voltage controls are, per default, active before the congestion control, which is activated in case of line congestion, but without PQ violations
- Time data:
    - The base hourly data for a typical daily diagram of PV and load units were acquire from real measurements in the based network. A small noise component of ± 10 % was added to the values as a variation of the typical values around the original profile in each time instance for the whole period.
- Schedule of DR unit:
    - DR unit's time of use (TOU) was set by default for each unit and based on the following points:
        - Time of availability of each unit was randomly assigned.
        - TOU of fully flexible loads was set to 24 hours per day, and for the loads with constrained flexibility it was 12 h per day.
        - To a given hour, the DR can operate at 50% or 100% of the flexible part only.

    - DR units cannot operate in all-hours within the TOU.
- Schedule was optimized according a defined objective function: economic or energy optimization (explained in chapter 4.7).
- Schedule was defined in hourly resolution due to hourly rates of electricity prices.

4.2. Type of Controls

In this simulation three different controls strategies were tested, No Control (NC), Simple Control (SiC) and Local Control (LC). Table 4.1 presents the characteristics of each control strategy.

Table 4.1:Type of controls

Type of Control	Description
NC	• All installed PV units operate with full power; • In case of PQ violations all PV will remain active; • No mitigation of PQ violations.
SiC	• The control of each PV unit is done with simple on-off control; • The control will act if the voltage in PV node is above the pre-defined upper limit. In this case the PV unit is turned off.
LC	• The generation of PV is controlled with an inverter control; • In case of a PQ violation, the PV generation will drop according to a drop curve specific to the unit.

4.3. PV time series and scenarios

The PV generations levels used in this simulations were based on real measured data from a Elektro Gorenjska network. A 4 different PV generation time series in a span of one week for each season were used.

The RES development scenarios new PV units are added in increments of 12 units and randomly distributed throughout the network. In the first scenario there will be presented in the network 12 PV units, in the second scenario 12 PV units will be added to the first 12 units, to a total of 60 PV units in the fifth scenario. The PV generation is equally distributed between the 3 phases.

The total installed PV power per scenario is shown in Table 4.2.

Table 4.2: Implementation of PV units

Scenario	Amount of PV units	Installed PV power [kWp]
1	12	240
2	24	480
3	36	720
4	48	960
5	60	1200

4.4. Demand response scenarios

Loads in the network nodes were composed of two components: non-responsive loads (e.g. uncontrollable house appliances) and an equal sized flexible and controllable load, following an hourly load profile. The participating of the costumers on the DR program is at the level of the variation of the flexible load component schedule, thus, the DR units were only assigned to nodes with installed load and no PV units. Otherwise the production of the PV would be lowered and the observed effect would be less significant.

The model used for DR units was the heat pumps (HP) to ensure a firm flexibility. For each unit the following parameters were defined:

- Installed power: amount for which the DR unit can increase or reduce its energy output;
- Energy constraints: amount of energy that is available for flexibility;
- Time of use: availability of the unit in each hour of the day;
- Comfort loss cost: the units were schedule to work in periods with high probability of the use heat pumps from the part of the costumer;
- Internal price of DR unit: price at which the unit is willing to adjust its output.

DR units per default, have predefined internal prices of their flexibility and penalties for non-compliance with the schedule. In the simulation, those values were set to 0 to ensure the complete and full DR deployment.

In the case of DR, in each increment of scenario 6 more DR units were added, one per feeder. In the first scenario 6 DR units were activated, and in the second more 6 DR units for a total of 12 units. In the last scenario, fifth scenario there were 5 DR units active in the network

Table 4.3 defines the DR unit implementation scenarios, with the available DR power.

Table 4.3: DR unit implementation scenarios

Scenario	Amount of DR units	Available DR power [kW]
1	6	42
2	12	84
3	18	126
4	24	168
5	30	210

4.5. Traffic Light System

One of the main goals for the MAS control concept in INSCREASE is to ensure the control over the grid by the DSO. A Traffic Light System (TLS) concept was implemented to give DSOs the ultimate control over DR unit schedules. The TLS will be used to evaluate the network situation, due to the DR unit schedule. If the activation of a DR unit for a particular period causes PQ violations in the grid, measures are taken to prevent these situations.

The main purpose of TLS is to help managing the DR units and their schedule to prevent or reduce PQ violations. There are three different types of TLSs that will be approached in the next points. A more detailed description can be found in [18].

4.5.1. Simple TLS

This is the simplest form of scheduling control mechanism to manage DR units. Based on voltage profiles in the network and power flows, TLS look for PQ violations. If a DR unit is active in the same instant that a PQ violation occurs, the TLS shuts down the unit. Other feature of this TLS it is that is possible to be used with PQ constraint forecast for day ahead (DA), being able to avoid unsuccessful activation of penalization of DR units. This penalization it is effective depending on the accuracy of the PQ constraint forecast.

A simple diagram of the simple TLS algorithm is presented in Figure 4.1.

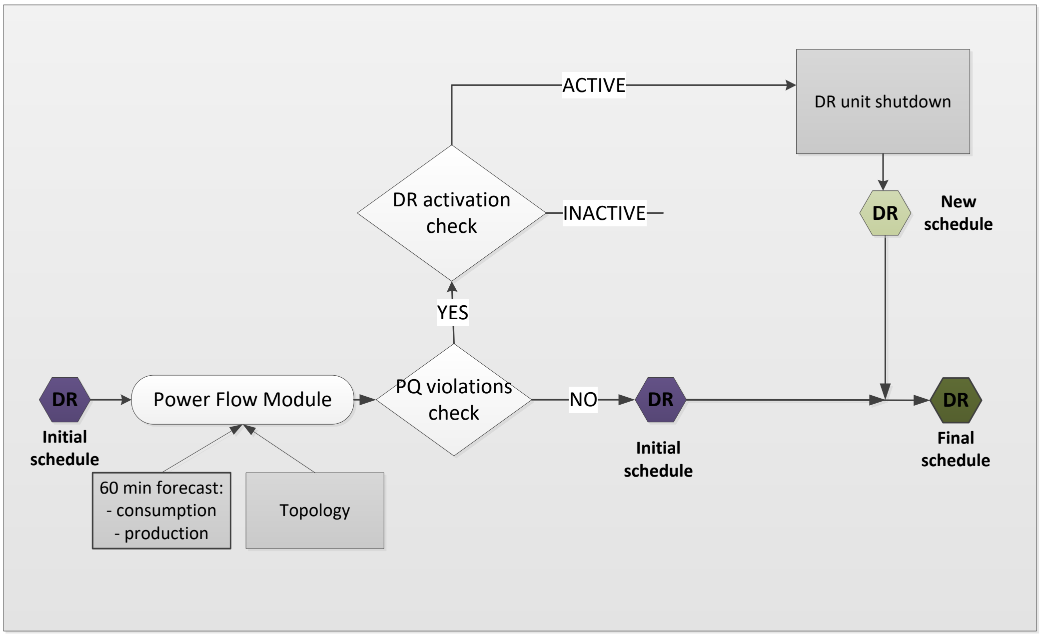

Figure 4.1: Simple TLS algorithm

4.5.2. Advanced TLS

The advanced TLS grant a more effective approach to the control of DR operation. The PQ check is performed by the advanced TLS and if a PQ violation is detected and a DR unit is active at the same time, TLS will check how does the DR unit affects the situation in the network. If the presence of the unit is favourable to the mitigation of the PQ violation, this unit stays active, otherwise, the TLS shuts down the unit.

The decision by the TLS if the DR units it helps the PQ mitigation or not is done through TLS logic, which is evident in Table 4.4. Identical to simple TLS, the advanced TLS can also be used to avoid unsuccessful activation penalization of DR units in advance.

Table 4.4: Advanced TLS logic

PQ type / DR state	**DR up**	**DR down**
Overvoltage	OK	Stop
Undervoltage	Stop	OK
Line congestion	Stop	OK

Figure 4.2 presents a simplified diagram of the algorithm used in the advanced TLS.

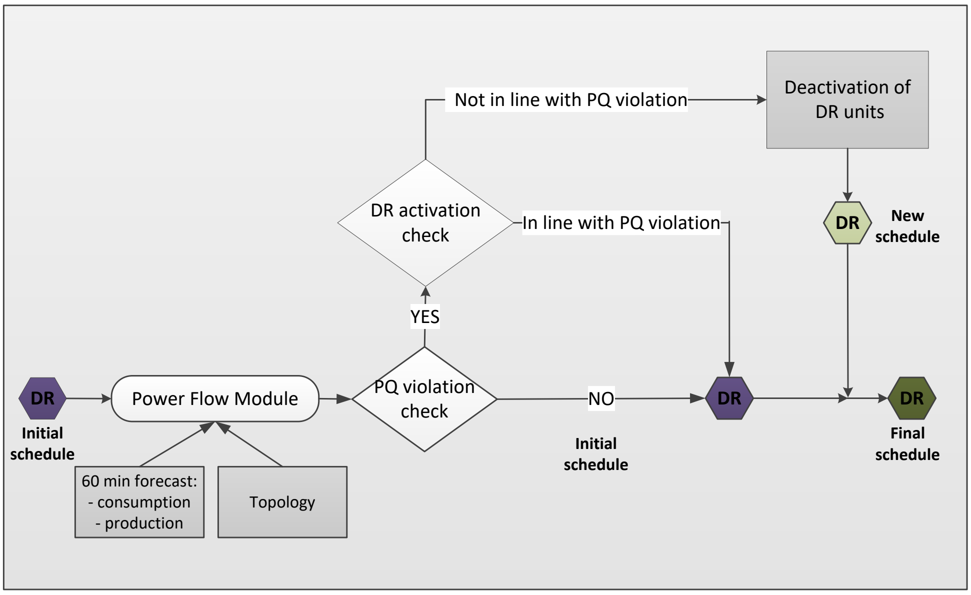

Figure 4.2: Advanced TLS algorithm

4.5.3. Intelligent TLS

Intelligent TLS is a most interactive way of DR management. DR units can be prescheduled for DA, or they can operate without prescheduling, offering more flexibility on demand, acting as a balancing service provider. Intelligent TLS manages available DR units which do not have a predefined schedule and scheduling those 15 min ahead if needed to help in the mitigation of PQ violations on the network, as seen in Figure 4.3. With the DR unit not prescheduled, their whole flexibility can be used for a better mitigation of PQ violations on demand.

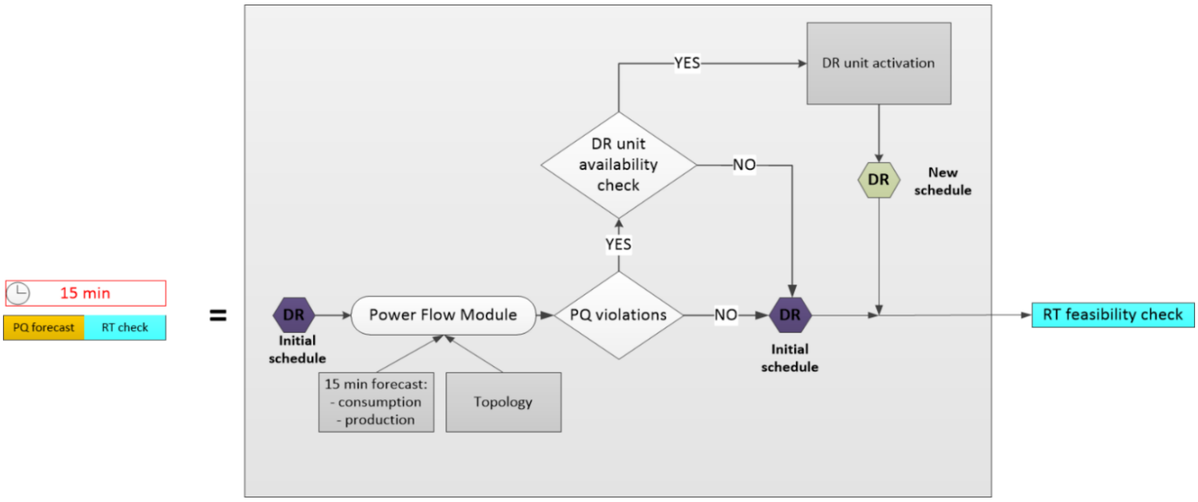

Figure 4.3: Intelligent TLS algorithm

4.5.4. Day Ahead PQ check

The day ahead PQ check can be used to avoid unsuccessful activation of DR and penalizations. By accepting or rejecting the initial DR schedule, the TLS determines if the unit can operate in a given time slot, usually 60 min. If, for this time slot, the initial scheduling is rejected and the unit is not allowed to operate, the overall DA DR unit schedule it is no longer optimised.

Figure 4.4 shows all the connections of the scheduling process with DA, for PQ check and TLS.

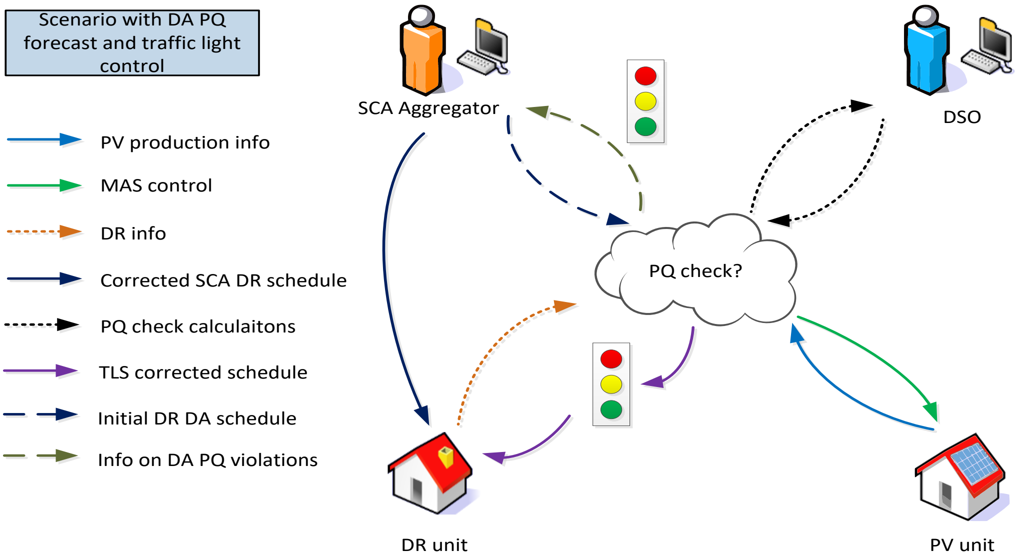

Figure 4.4: Diagram of scheduling process with DA PQ check and TLS

The SCA can define a new schedule, for this DR unit for the next time slot, optimizing the engagement of the remaining DR units and accounting for acceptable operating time and the units predefined time of use. The DR schedule optimization is active after the first evaluation of PQ violations on the network. Whit the updated joint schedule, PQ violations are checked again and send through the TLS. Flow chart for simulations with a new schedule is shown in Figure 4.5.

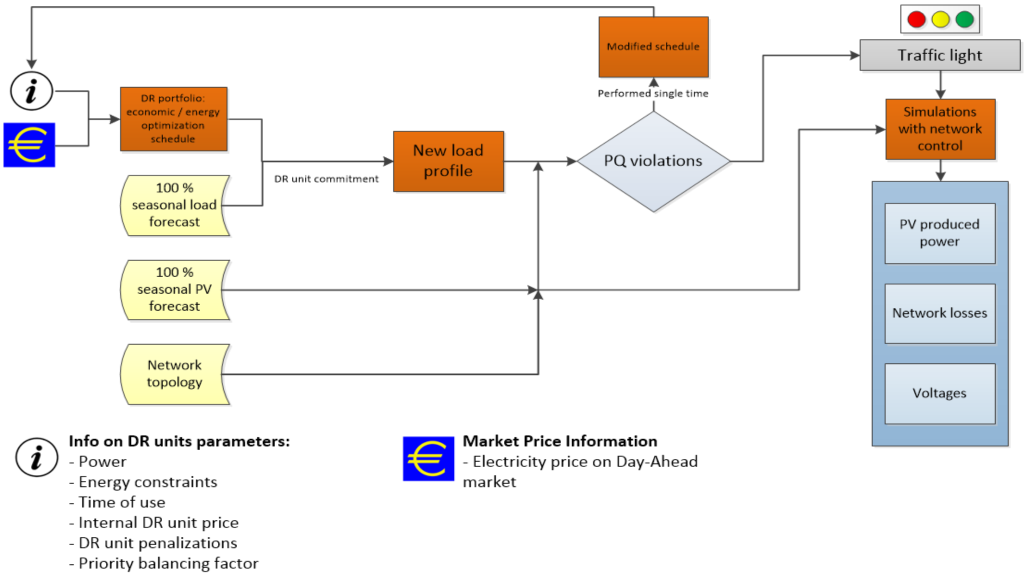

Figure 4.5: Simulation diagram with new DR schedule

4.6. Forecasting

For this simulation model a 100% accurate forecasting was used to approximate the simulations values to the real one. The data is related with the real place where the based network (Elektro Gorenjska grid) is installed.

4.7. Scheduling Optimization

The SCA can use an optimization algorithm. This optimization algorithm has two objectives functions: the economic optimization and the energy optimization. A brief description of each one of the optimizations will be presented next. A more detailed information is presented in [18].

4.7.1. Economic optimization of DR units

This economic optimization (Econ) has the objective of observing the daily energy prices and the costs for DR unit adjustment. The objective function in (4.1) intent to maximize the income of the DR unit energy sold to the DA wholesale market, minimizing at the same time the cost of the DR unit adjustment, thereby maximizing the profit of the DR schedule.

$$\min \sum_{t=1}^{N_T} \left(\sum_{i=1}^{N_{DR}} W_{DR,i,t} \cdot S_{M,t} + \sum_{i=1}^{N_{DR}} \left| W_{DR,i,t} \right| \cdot S_{DR,i,t} \right) \tag{4.1}$$

where:

N_{DR}	number of DR units
N_T	number of time steps
$W_{DR,i,t}$	energy of *i-th* DR unit in hour *t*
$S_{M,t}$	wholesale market price in hour *t* (energy price)
$S_{DR,i,t}$	internal DR unit output adjustment price in hour *t*

The consumption of the DR unit can either increase $(W_{DR,i,t+})$ or decrease $(W_{DR,i,t-})$ or remain the same at a determined hour *t* (4.2):

$$W_{DR,i,t} = \begin{cases} W_{DR,i,t+} \\ W_{DR,i,t-} \\ 0 \end{cases} \tag{4.2}$$

With the consumption increase in the hours with lower energy prices and consumption reducing during the high price periods, the SCA ensures profit with its FEP portfolio.

4.7.2. Energy optimization

The Energy optimization (EB) scheduling goal is to maximize the injection of green energy generated by the DRES, in this case PV. This is reached by reducing the difference between the total consumption and the PV production in the network. The objective function can be composed as in (4.3).

$$\min \sum_{t=1}^{N_T} \left(\left(W_{load,t} - W_{PV,t} \right) - \sum_{i=1}^{N_{DR}} W_{DR,i,t} \right) \tag{4.3}$$

where:

N_{DR}	number of DR units
N_T	number of time steps
$W_{DR,i,t}$	energy of *i-th* DR unit in hour *t*
$W_{load,t}$	wholesale market price in hour *t* (energy price)
$W_{PV,t}$	internal DR unit output adjustment price in hour *t*

The difference in the energy between $W_{load,t}$ and $W_{PV,t}$ is decreased by the activation of the DR units. Their consumption will increase in case of net network production and decrease otherwise, in case of net network consumption.

4.8. Tools

For the analysis of the simulated network, and control algorithms a combination of Matlab and OpenDSS software environment was used. OpenDSS software is used for the definition of the network topology, in this, the transmission elements such power lines and transformers are described together with the information about the MV side of the network. Connection of the loads and PV units is also done in this software. Power flows are calculated and exported to Matlab environment.

Input information about load and PV time series is stored, together with all control mechanisms in the network. Consumption and production is from within Matlab used for values of the elements in the OpenDSS calculations. After an initial power flow analysis and calculation, the network data, such as voltage levels, losses, power and currents flows are imported to the Matlab, being the input for the control mechanism implemented.

The final power flow calculations determine the status of the network and are stored together with the information about the storage system as a result.

4.9. Final Scheduling Control applications

In the simulations of the rural network the following characteristics were applied. The simulations were run for two different seasons, winter and summer. Spring and autumn were not simulated because of the similarity with the summer and winter, respectively.

The PV only SC optimization type was added to serve as a basis for comparison, for a better analysis of the final data from the simulations. In this, all the PV units are activated and the DR units will not be activated.

The number of PV and DR units, as well as the number of type of control of the MAS is the same for each SC optimization type. However, the TLS used is different for the no optimization and PV only SC. Table 4.5: Evaluation Scenario matrix presents the evaluation scenario matrix used in the simulations.

Table 4.5: Evaluation Scenario matrix

SC optimization type	TLS	PV + DR penetration level	MAS	Seasons
Economic	No-TLS Simple TLS Advanced TLS	12 PV (10%) – 6 DR (5%) 24 PV (20%) – 12 DR (10%) 36 PV (30%) – 18 DR (15%) 48 PV (40%) – 24 DR (20%) 60 PV (50%) – 30 DR (30%)	No control Simple control Local control	Winter Summer
Energy				
Intelligent schedule	Intelligent TLS			
PV_only	No TLS			

All the TLS are combined with 100% forecast accuracy. All the optimizations are assuming full energy payback, meaning that the optimization function observes the constraint of balancing all the increased and reduced DR consumption to zero at the end of the day. With this it is assumed that the comfort of all the costumers is not affected with DR actions, allowing the assumption of the internal price of DR units to be 0 for flexibility.

4.10. Evaluation Scenarios Summary

To simulate all the Evaluations Scenarios, 240 simulations were run in the simulation platform using Matlab and OpenDSS.

Each run of the simulation platform for MAS control scenarios included the results about actual generation of each PV unit (already curtailed), voltages of each node and losses in the network, in 5 minutes’ instance for the one week for each season.

To determine the curtailment and the unsuccessful DR activations, each of the simulation results also includes an input file with the information of the maximum generation point for each PV units, as well as the initial DR schedule.

Chapter 5

Simulation Results and Assessment

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5. Simulation Results and Assessment

In this all the results from the simulations will be presented. It will be investigated the impact of the diverse types of control, AS and level of penetration.

5.1. PV generation

The PV electricity injection into the grid will be the first parameter to be analysed.

5.1.1. Smart inverter control implementation

Figure 5.1 presents the PV generation for a case where all the PV units in the network per scenario are active, for the summer season. In this graph the generation with SiC and LC was divided with the generation with no control active. In this case the best scenario is the fourth with 48 PV units in the rural network, where the highest value of green energy generation is achieved.

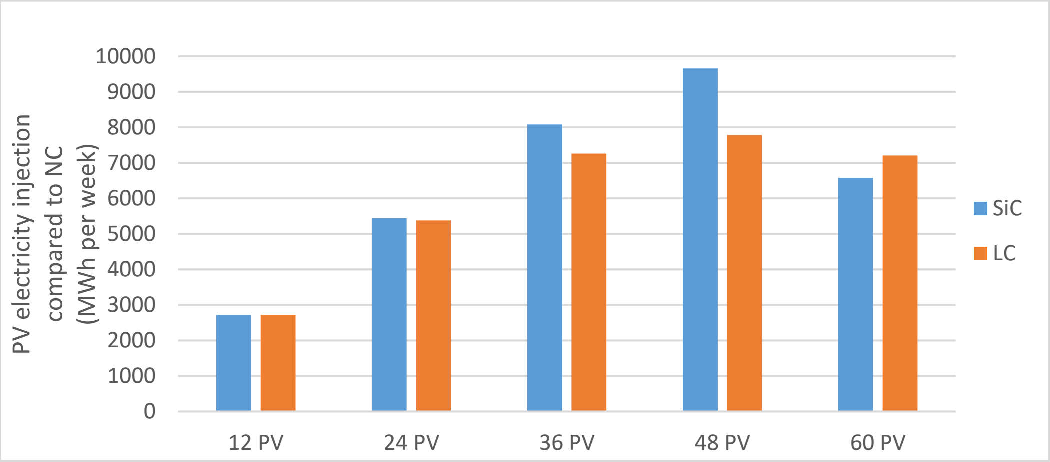

Figure 5.1: PV electricity injection by control, compared to NC (summer season)

For the winter season, as can be seen in Figure 5.2, the PV generation will be lower due to the smaller solar radiation in the winter season.

The effect of the SiC is more beneficial to the network that the LC, if it is only considered the contribution of this control, without any AS effect. In Figure 5.1, it is noticeable that scenario the last scenario presents the turning point of the penetration level for this network. Voltage rise is high enough to trigger SiC as well, as opposed to lower scenarios where only LC partial curtailment is activated. It is visible that for higher level, LC is beneficial from all points of view.

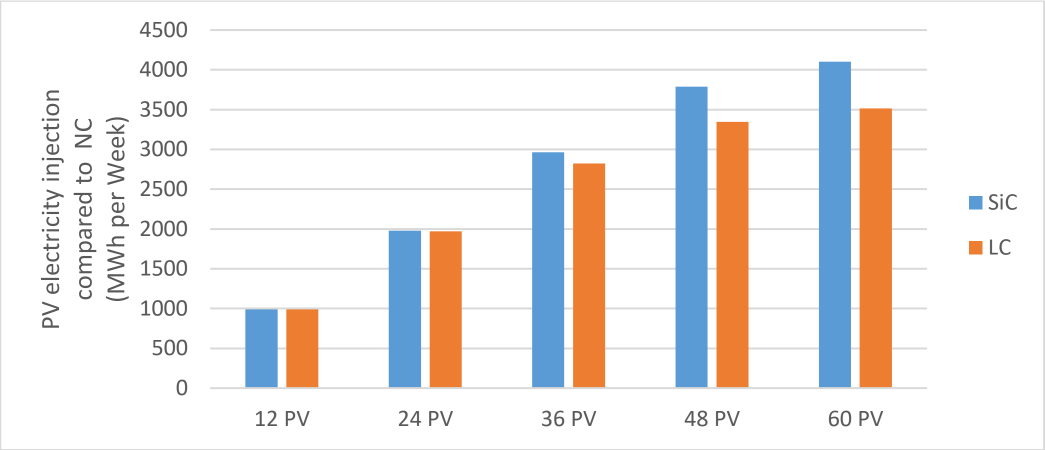

Figure 5.2: PV electricity injection by control, compared to NC (winter season)

5.1.2. Scheduling control implementation

5.1.2.1. DR units with Energy optimization

The aim of the Energy optimization is to maximize the PV injection into the grid. Table 5.1 presents the PV injection for all the scenarios and TLS types for the summer season. In this case, the injection of power is larger than the power generation in PV only evaluation, as seen before.

Table 5.1: PV injection using Energy optimization for summer (MWh per week)

Scenario		NC	SiC	SiC/NC	LC	LC/NC
12 PV - 6 DR	TLS0	6328.622	9049.929	**1.430**	9049.929	**1.430**
	TLS1	6328.622	9049.929	**1.430**	9049.929	**1.430**
	TLS2	6328.622	9049.929	**1.430**	9049.929	**1.430**
24 PV - 12 DR	TLS0	12657.244	18099.859	**1.430**	18090.456	**1.429**
	TLS1	12657.244	18099.859	**1.430**	18080.948	**1.429**
	TLS2	12657.244	18099.859	**1.430**	18092.501	**1.429**
36 PV - 18 DR	TLS0	18985.866	27149.788	**1.430**	26953.210	**1.420**
	TLS1	18985.866	27149.788	**1.430**	26888.005	**1.416**
	TLS2	18985.866	27149.788	**1.430**	26959.634	**1.420**
48 PV - 24 DR	TLS0	25314.488	36171.400	**1.429**	35494.188	**1.402**
	TLS1	25314.488	35953.183	**1.420**	35342.837	**1.396**
	TLS2	25314.488	36198.377	**1.430**	35523.901	**1.403**
60 PV - 30 DR	TLS0	31643.110	44427.322	**1.404**	43002.546	**1.359**
	TLS1	31643.110	43968.393	**1.390**	42739.317	**1.351**
	TLS2	31643.110	44504.423	**1.406**	43046.222	**1.360**

For the winter season, the results are presented in Table 5.2. As happened with the summer season, the value of the PV injection has increase compared to the PV only optimization. This increase in the PV generation are related with the traffic lights used. With the simple TLS (TLS1) the total generation of green energy is lower that when a TLS is not used in the control of the rural network. However, the advanced TLS (TLS2) improves the generation of energy in some scenarios, maximizing the PV generation.

Table 5.2: PV injection using Energy optimization for winter (MWh per week)

Scenario		NC	SiC	SiC/NC	LC	LC/NC
12 PV - 6 DR	TLS0	2300.184	3289.264	**1.430**	3289.264	**1.430**
	TLS1	2300.184	3289.264	**1.430**	3289.264	**1.430**
	TLS2	2300.184	3289.264	**1.430**	3289.264	**1.430**
24 PV - 12 DR	TLS0	4600.369	6578.528	**1.430**	6578.297	**1.430**
	TLS1	4600.369	6578.528	**1.430**	6577.297	**1.430**
	TLS2	4600.369	6578.528	**1.430**	6578.297	**1.430**
36 PV - 18 DR	TLS0	6900.553	9867.791	**1.430**	9842.183	**1.426**
	TLS1	6900.553	9867.791	**1.430**	9828.957	**1.424**
	TLS2	6900.553	9867.791	**1.430**	9844.466	**1.427**
48 PV - 24 DR	TLS0	9200.738	13157.055	**1.430**	13090.024	**1.423**
	TLS1	9200.738	13150.634	**1.429**	13054.304	**1.419**
	TLS2	9200.738	13157.055	**1.430**	13092.820	**1.423**
60 PV - 30 DR	TLS0	11500.922	16421.365	**1.428**	16244.932	**1.412**
	TLS1	11500.922	16279.018	**1.415**	16151.211	**1.404**
	TLS2	11500.922	16421.365	**1.428**	16244.932	**1.412**

For the EB evaluation, the difference of PV injection, taking into account the different controls, is small. However, considering the different TLS, the simple TLS is the one with lower energy generation from the PV units, due to the fact the advanced TLS before shutting down the unit, analyses the network to see if this action will be prejudicial or favourable to the network.

5.1.2.2. DR units with Economic optimization

Table 5.3 presents the PV injection for the RN when the Economic optimization (Econ) is used. The main objective of this optimization is to maximize the income of the DR unit energy sold to the DA wholesale market. With the Econ, the PV generation is going to have a slight decrease when compared to the EB case. This difference is more noticeable in the last scenarios (fourth and fifth).

Table 5.3: PV injection using Economic optimization for summer (MWh per week)

Scenario		NC	SiC	SiC/NC	LC	LC/NC
12 PV - 6 DR	TLS0	6328.622	9049.929	**1.430**	9049.929	**1.430**
	TLS1	6328.622	9049.929	**1.430**	9049.929	**1.430**
	TLS2	6328.622	9049.929	**1.430**	9049.929	**1.430**
24 PV - 12 DR	TLS0	12657.244	18099.859	**1.430**	18057.957	**1.427**
	TLS1	12657.244	18099.859	**1.430**	18068.804	**1.428**
	TLS2	12657.244	18099.859	**1.430**	18073.448	**1.428**
36 PV - 18 DR	TLS0	18985.866	27145.834	**1.430**	26522.192	**1.397**
	TLS1	18985.866	27149.788	**1.430**	26533.949	**1.398**

	TLS2	18985.866	27149.788	**1.430**	26573.406	**1.400**
48 PV - 24 DR	TLS0	25314.488	35508.529	**1.403**	34083.300	**1.346**
	TLS1	25314.488	35644.655	**1.408**	34164.587	**1.350**
	TLS2	25314.488	35774.490	**1.413**	34241.818	**1.353**
60 PV - 30 DR	TLS0	31643.110	41139.957	**1.300**	40601.792	**1.283**
	TLS1	31643.110	41684.072	**1.317**	40784.922	**1.289**
	TLS2	31643.110	41925.800	**1.325**	40919.698	**1.293**

For the winter season, the data is presented in the Table 5.4.

Table 5.4: PV injection using Economic optimization for winter (MWh per week)

Scenario		NC	SiC	SiC/NC	LC	LC/NC
12 PV - 6 DR	TLS0	2300.184	3289.264	**1.430**	3289.264	**1.430**
	TLS1	2300.184	3289.264	**1.430**	3289.264	**1.430**
	TLS2	2300.184	3289.264	**1.430**	3289.264	**1.430**
24 PV - 12 DR	TLS0	4600.369	6578.528	**1.430**	6576.247	**1.430**
	TLS1	4600.369	6578.528	**1.430**	6576.722	**1.430**
	TLS2	4600.369	6578.528	**1.430**	6577.347	**1.430**
36 PV - 18 DR	TLS0	6900.553	9867.791	**1.430**	9817.493	**1.423**
	TLS1	6900.553	9867.791	**1.430**	9810.179	**1.422**
	TLS2	6900.553	9867.791	**1.430**	9821.750	**1.423**
48 PV - 24 DR	TLS0	9200.738	13138.430	**1.428**	12971.543	**1.410**
	TLS1	9200.738	13135.754	**1.428**	12958.140	**1.408**
	TLS2	9200.738	13148.087	**1.429**	12982.590	**1.411**
60 PV - 30 DR	TLS0	11500.922	16227.392	**1.411**	15928.044	**1.385**
	TLS1	11500.922	16168.604	**1.406**	15901.981	**1.383**
	TLS2	11500.922	16271.095	**1.415**	15960.160	**1.388**

5.1.2.3. DR units with Intelligent schedule

Intelligent schedule is a most interactive way of DR management. In this, the DR units can be prescheduled for DA, or if need, they can operate without any scheduling, offering more flexibility on demand in the grid. With this type of optimization, as seen in the Table 5.5, the PV injection for all the controls is higher than the PV injection achieve by the previous optimization. For example, the maximum PV injection in this case is 44583.777 MWh/week for the higher penetration in the network using the SiC, while for the EB, to the same type of control and scenario, the maximum is 44504.423 MWh/week.

Table 5.5: PV injection using Intelligent Schedule for summer (MWh per week)

Scenario		NC	SiC	SiC/NC	LC	LC/NC
12 PV - 6 DR	TLS3	6328.622	9049.929	**1.430**	9049.929	**1.430**
24 PV - 12 DR	TLS3	12657.244	18099.859	**1.430**	18079.995	**1.428**
36 PV - 18 DR	TLS3	18985.866	27149.788	**1.430**	26854.582	**1.414**

48 PV - 24 DR	TLS3	25314.488	36197.030	**1.430**	35001.892	**1.383**
60 PV - 30 DR	TLS3	31643.110	44583.777	**1.409**	42287.709	**1.336**

Regarding the winter season, the values are presented in the Table 5.6. Where, the difference in the PV injection is non-existent.

Table 5.6: PV injection using Intelligent Schedule for winter (MWh per week)

Scenario		**NC**	**SiC**	**SiC/NC**	**LC**	**LC/NC**
12 PV - 6 DR	TLS3	2300.184	3289.264	**1.430**	3289.264	**1.430**
24 PV - 12 DR	TLS3	4600.369	6578.528	**1.430**	6576.729	**1.430**
36 PV - 18 DR	TLS3	6900.553	9867.791	**1.430**	9825.696	**1.424**
48 PV - 24 DR	TLS3	9200.738	13157.055	**1.430**	12987.720	**1.412**
60 PV - 30 DR	TLS3	11500.922	16411.417	**1.427**	15930.343	**1.385**

5.2. Losses in the network

Other important factor for the DSO is the losses in the network. Table 5.7 presents the network loss for the PV only scenario, of the LC when compared to the SC. The negative values indicate a reduction of losses, while the positive represent an increase of losses.

It is visible that if the effect of the PV units in the network is considered, and with the LC active, the network will have lower losses that when the SC is used. This effect is also visible for the Energy optimization (

Table 5.8), Economic optimization (

Table 5.9) and for the intelligent scheduling (Table 5.10).

Table 5.7: Losses in RN for PV only of the LC compare to the SC (% per week)

Scenario		**Summer**		**Winter**	
		P	**Q**	**P**	**Q**
12 PV	TLS0	-0.004	-0.004	-0.007	-0.007
24 PV	TLS0	-0.890	-0.705	-0.263	-0.246
36 PV	TLS0	-7.511	-6.335	-3.515	-3.279
48 PV	TLS0	-12.542	-11.126	-8.057	-7.850
60 PV	TLS0	1.017	2.999	-9.554	-8.608

Table 5.8: Losses in RN for the Energy optimization only of the LC compare to the SC (% per week)

Scenario		**Summer**		**Winter**	
		P	**Q**	**P**	**Q**
12 PV - 6 DR	TLS0	-0.007	-0.008	-0.006	-0.005
	TLS1	-0.007	-0.008	-0.006	-0.005
	TLS2	-0.007	-0.008	-0.006	-0.005
24 PV - 12 DR	TLS0	-0.171	-0.131	-0.014	-0.010

	TLS1	-0.348	-0.265	-0.052	-0.048
	TLS2	-0.132	-0.102	-0.014	-0.010
36 PV - 18 DR	TLS0	-2.652	-2.040	-0.822	-0.750
	TLS1	-3.540	-2.681	-1.265	-1.135
	TLS2	-2.569	-1.979	-0.749	-0.689
48 PV - 24 DR	TLS0	-6.281	-5.280	-1.556	-1.431
	TLS1	-5.586	-4.682	-2.256	-2.008
	TLS2	-6.280	-5.289	-1.487	-1.372
60 PV - 30 DR	TLS0	-10.136	-8.801	-3.060	-2.938
	TLS1	-8.911	-7.577	-2.195	-2.015
	TLS2	-10.345	-9.022	-3.060	-2.938

Table 5.9: Losses in RN for the Economic optimization only of the LC compare to the SC (% per week)

Scenario		**Summer**		**Winter**	
		P	**Q**	**P**	**Q**
12 PV - 6 DR	TLS0	-0.004	-0.005	-0.006	-0.006
	TLS1	-0.004	-0.005	-0.006	-0.006
	TLS2	-0.004	-0.005	-0.006	-0.006
24 PV - 12 DR	TLS0	-0.654	-0.531	-0.088	-0.087
	TLS1	-0.481	-0.388	-0.070	-0.067
	TLS2	-0.408	-0.333	-0.047	-0.045
36 PV - 18 DR	TLS0	-6.387	-5.419	-1.394	-1.314
	TLS1	-6.315	-5.343	-1.604	-1.475
	TLS2	-5.926	-5.050	-1.271	-1.202
48 PV - 24 DR	TLS0	-10.439	-9.299	-3.296	-3.164
	TLS1	-10.856	-9.661	-3.518	-3.318
	TLS2	-11.291	-10.050	-3.277	-3.161
60 PV - 30 DR	TLS0	-4.983	-3.215	-4.487	-4.195
	TLS1	-6.627	-5.074	-3.990	-3.745
	TLS2	-7.192	-5.685	-4.652	-4.407

In general, the Econ brings more power losses into the system with lower penetration level. However, for higher penetration levels, the losses for the Econ are lower that for the EB. For the DSO, the choice between the EB or Econ to acquire the lower losses in all the RN will depend on the number of PV and DR installed in the network. In the **Error! Reference source not found.** this relation is more noticeable. In this case, for the active power, in low penetration, the EB introduce lower losses in the grid. Still, for the higher penetration scenario, the Econ is the optimization with lower losses.

Intelligent TLS is the most advanced form of DR control, since the energy infeed is highest. High energy flows, will result in a higher network, as shown in Table 5.10.

Table 5.10Intelligent TLS is the most advanced form of DR control, since the energy infeed is highest. High energy flows, will result in a higher network, as shown in Table 5.10.

Table 5.10: Losses in RN for the Intelligent scheduling only of the LC compare to the SC (% per week)

Scenario		**Summer**		**Winter**	
		P	**Q**	**P**	**Q**
12 PV - 6 DR	TLS3	-0.005	-0.006	-0.006	-0.007
24 PV - 12 DR	TLS3	-0.326	-0.254	-0.066	-0.061
36 PV - 18 DR	TLS3	-3.374	-2.704	-1.116	-1.008
48 PV - 24 DR	TLS3	-9.489	-8.293	-3.322	-3.190
60 PV - 30 DR	TLS3	-14.561	-12.870	-7.750	-7.562

If only the losses in the system are considered, it is hard to choose the ideal optimization, because this choice will depend on the number of PV and DR in the network, as well as the type of TLS and the control used.

5.3. Reliability indicators

The reliability indicators analysed in this study are the SAIDI (System Average Interruption Duration Index), equation (5.1) and the SAIFI (System Average Interruption Frequency Index), equation (5.2). While SAIFI is express without units, SAIDI is expressed in curtailed PV unit hours per week.

$$SAIDI = \frac{\sum U_i \, N_i}{N_T} \tag{5.1}$$

$$SAIFI = \frac{\sum \lambda_i \, N_i}{N_T} \tag{5.2}$$

where:

N_i	number of customers for the location *i*
N_T	total number of customers served
U_i	annual outage time for location *i*
λ_i	failure rate

The data in Table 5.11 presents the lower values of the SAIDI for the RN in summer season are during the simulations with the EB. This is a result of an energy balance preoccupation of this optimization, where for all the scenarios the SAIDI average is less than 1. However, with the Int scenario the SAIDI index for the SiC are also the lowest in all the simulation, but, for the LC for the last scenario the index is bigger than 2.

Table 5.11: SAIDI indicator for summer season

	PV only		EB		Econ		Int	
	SiC	LC	SiC	LC	SiC	LC	SiC	LC
12 PV - 6 DR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
			0.000	0.000	0.000	0.000		
			0.000	0.000	0.000	0.000		
24 PV - 12 DR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
			0.000	0.000	0.000	0.000		
			0.000	0.000	0.000	0.000		
36 PV - 18 DR	0.063	1.160	0.000	0.014	0.000	0.625	0.000	0.049
			0.000	0.278	0.000	0.646		
			0.000	0.007	0.000	0.431		
48 PV - 24 DR	1.333	4.156	0.010	0.495	0.766	2.542	0.000	0.557
			0.229	0.786	0.578	2.323		
			0.000	0.443	0.406	2.208		
60 PV - 30 DR	6.238	10.075	0.675	1.275	3.575	6.550	0.533	2.096
			1.158	1.771	3.104	6.171		
			0.604	1.208	2.858	5.950		

Figure 5.3 presents the relation between the SAIDI indicator of SiC and LC for the EB and Econ optimization. It is noticeable that the in general the EB has the lower values, presenting higher benefits.

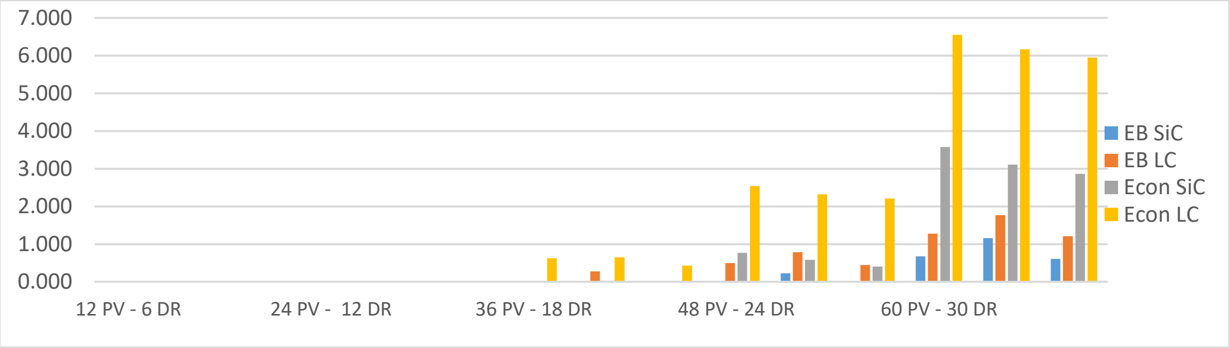

Figure 5.3: SAIDI indicator for SiC and LC with EB and Econ optimization (Summer)

For the SAIFI indicator, the conclusions are the same that for the SAIDI indicator. The comportment of this index along all the scenarios is similar.

Table 5.12: SAIFI indicator for summer season

	PV only		EB		Econ		Int	
	SiC	LC	SiC	LC	SiC	LC	SiC	LC
12 PV - 6 DR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
			0.000	0.000	0.000	0.000		
			0.000	0.000	0.000	0.000		
24 PV - 12 DR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
			0.000	0.000	0.000	0.000		
			0.000	0.000	0.000	0.000		
36 PV - 18 DR	0.167	0.917	0.000	0.056	0.000	0.583	0.000	0.167
			0.000	0.417	0.000	0.611		
			0.000	0.028	0.000	0.417		
48 PV - 24 DR	1.104	3.417	0.042	0.458	0.563	2.354	0.000	0.646
			0.354	0.583	0.542	2.125		
			0.000	0.458	0.396	2.104		
60 PV - 30 DR	5.200	7.267	0.667	1.450	3.267	4.983	0.550	1.967
			1.158	1.771	3.104	6.171		
			0.604	1.208	2.858	5.950		

For the winter results, as shown in Table 5.13 and Table 5.14, both indicators are always lower than 1 for all the scenarios and optimizations. Only for the LC in Econ for the higher penetration in the network, the SAIFI indicator reaches almost 1.

The intelligent schedule, present again the lowest values of SAIDI and SAIFI, being this the most reliable optimization.

Table 5.13: SAIDI indicator for winter season

	PV only		EB		Econ		Int	
	SiC	LC	SiC	LC	SiC	LC	SiC	LC
12 PV - 6 DR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
			0.000	0.000	0.000	0.000		
			0.000	0.000	0.000	0.000		
24 PV - 12 DR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
			0.000	0.000	0.000	0.000		
			0.000	0.000	0.000	0.000		
36 PV - 18 DR	0.000	0.188	0.000	0.000	0.000	0.014	0.000	0.000
			0.000	0.000	0.000	0.007		
			0.000	0.000	0.000	0.007		
48 PV - 24 DR	0.172	0.646	0.000	0.010	0.010	0.146	0.000	0.021
			0.000	0.125	0.010	0.188		
			0.000	0.005	0.005	0.125		
60 PV - 30 DR	0.725	2.154	0.004	0.050	0.154	0.496	0.008	0.129
			0.138	0.300	0.208	0.571		
			0.004	0.050	0.108	0.429		

Table 5.14: SAIFI indicator for winter season

	PV only		EB		Econ		Int	
	SiC	LC	SiC	LC	SiC	LC	SiC	LC
12 PV - 6 DR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
			0.000	0.000	0.000	0.000		
			0.000	0.000	0.000	0.000		
24 PV - 12 DR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
			0.000	0.000	0.000	0.000		
			0.000	0.000	0.000	0.000		
36 PV - 18 DR	0.000	0.306	0.000	0.000	0.000	0.056	0.000	0.000
			0.000	0.000	0.000	0.028		
			0.000	0.000	0.000	0.028		
48 PV - 24 DR	0.313	0.750	0.000	0.021	0.042	0.333	0.000	0.063
			0.000	0.250	0.042	0.396		
			0.000	0.021	0.021	0.333		
60 PV - 30 DR	0.917	1.867	0.017	0.133	0.383	0.883	0.033	0.333
			0.283	0.283	0.400	0.950		
			0.017	0.133	0.317	0.917		

As seen before for the summer results, in winter season, the EB presents better indicators that the Econ (Figure 5.4).

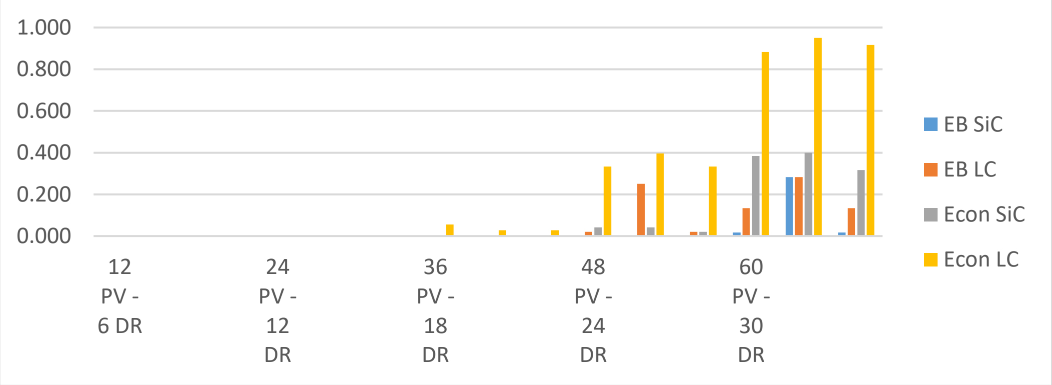

Figure 5.4: SAIFI indicator for SiC and LC with EB and Econ optimization (Winter)

5.4. Emissions

The main aim leading to a higher penetration of DRES in the network is to decrease the greenhouse gases emissions from the large thermal power plants used nowadays to produce electricity. For that, it is fundamental to understand how this optimizations methods can influence the emissions.

For this assessment, the following emissions gases were considered:

- Carbon dioxide (CO_2);
- Carbon monoxide (CO);
- (FnPrt);
- Ammonia (NH_3);
- Non-methane volatile organic compounds (NMVOC);
- Nitrogen oxides (NOx);
- Sulphur dioxide (SO_2).

The prices used for the determination of the reduction in the emission cost are represented in the Table 5.15.

Table 5.15: Cost in Euros/ton of the emission gases

CO2Costs	50
COCosts	262
FnPrtCosts	8600
NH3Costs	25000
NMVOCCosts	2600
SO2Costs	10500
NOXCosts	10500

Figure 5.5 presents the costs reduction for the Energy balanced optimization during the summer season and Figure 5.6 presents the same data, but for the Economic optimization. The SiC control allows a higher savings for the grid operators, however this difference is not relevant.

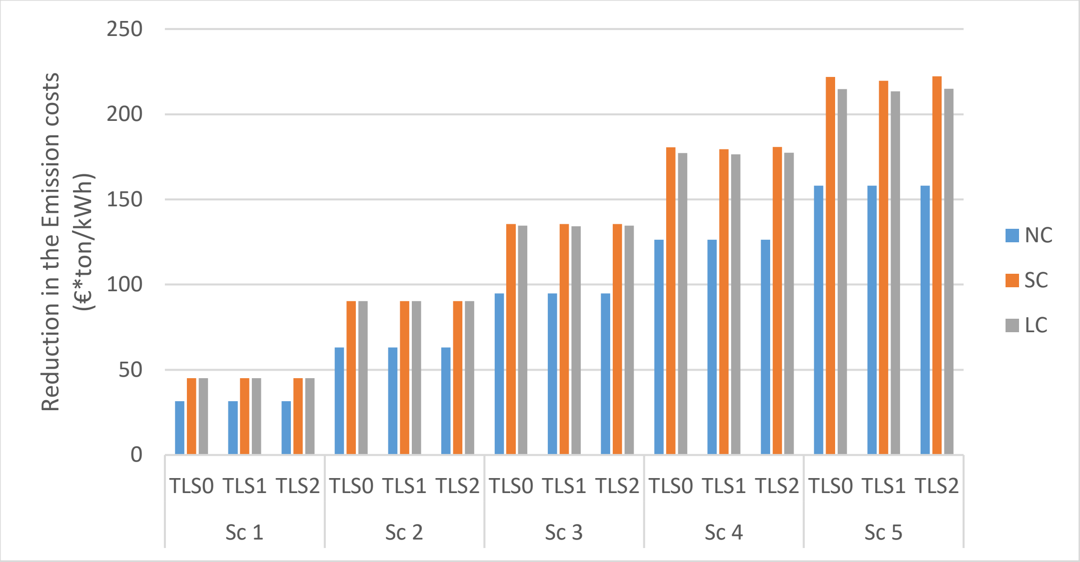

Figure 5.5: Costs reduction for the EB during summer (€ ton/kWh)

Between the EB and Econ optimization, the EB is the one with higher saving, but the difference is only visible in the scenarios with higher penetration of the DRES.

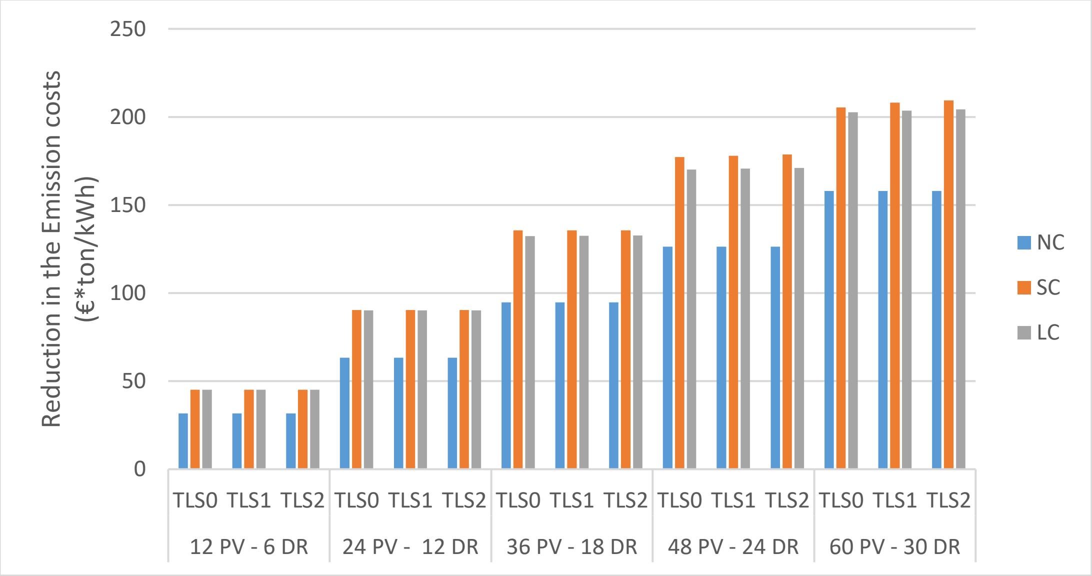

Figure 5.6: Costs reduction for the Econ during summer (€ ton/kWh)

In the case of the Int, the reduction is lower than EB and Econ.

For the winter season, the reduction in the emission costs is similar for the SiC and LC, and also for the EB and Econ optimization, as can be seen in Figure 5.7 and Figure 5.8.

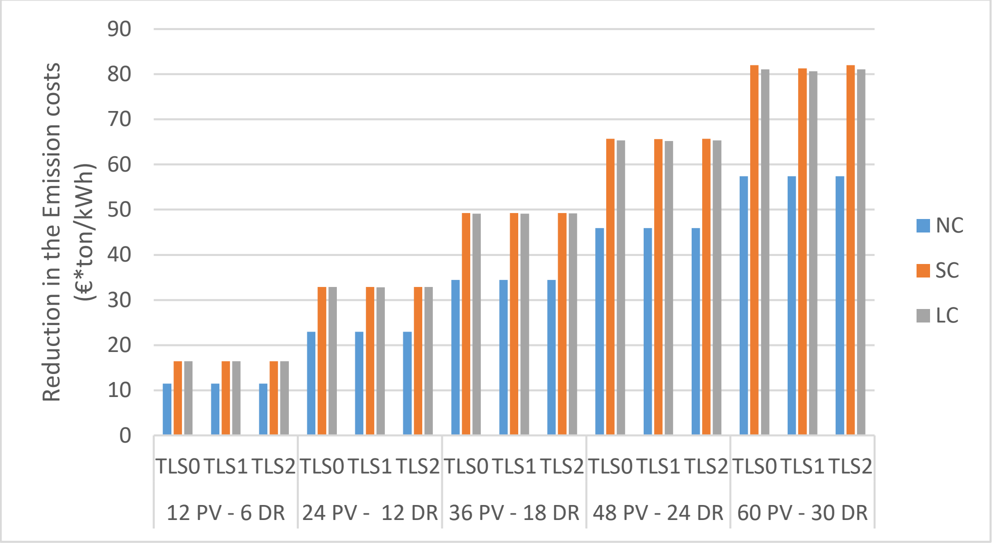

Figure 5.7: Costs reduction for the EB during winter (€ ton/kWh)

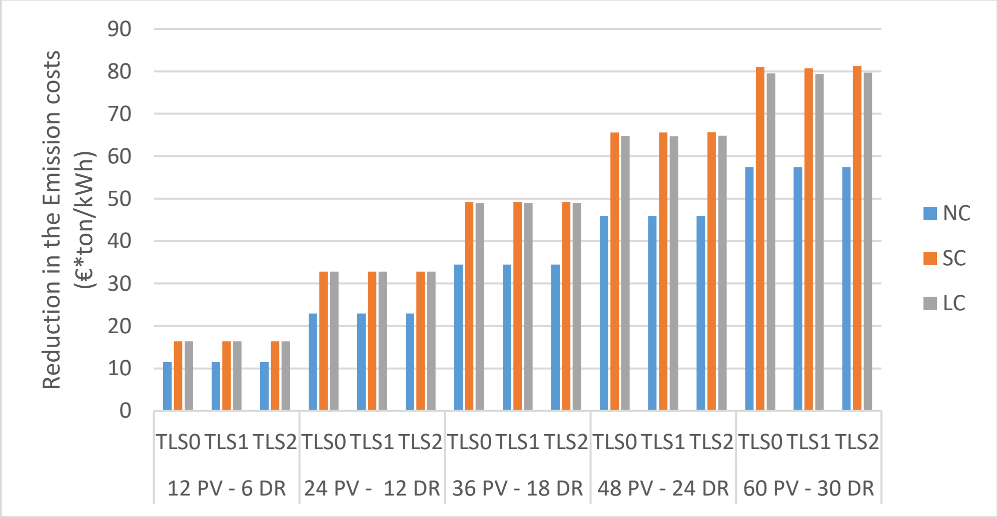

Figure 5.8: Costs reduction for the Econ during winter (€ ton/kWh)

5.5. SWOT analyses

In this subchapter a SWOT analysis will be developed to facilitate the understanding of the best optimization and control for the rural network. A SWOT analysis allows to compare different solutions based on their strengths, weaknesses, opportunities and threats.

5.5.1. Energy optimization

Table 5.16: SWOT table for EB

O	Strengths	Weaknesses	Opportunities	Threats
EB with SiC	Higher PV injection; Higher emissions savings.	Higher losses in the network	In overall the SiC is more profitable and safe for the network.	
EB with LC	Lower losses in the grid	More interruptions (SAIFI); Larger outage duration for each customer served.		More interruptions and therefore more outage duration for each customer served.

5.5.2. Economic optimization

Table 5.17: SWOT table for Econ

	Strengths	Weaknesses	Opportunities	Threats
Econ with SiC	Higher PV injection; Higher emissions savings.	Higher energy losses in the grid.	In overall the SiC is more profitable and safe for the network.	
Econ with LC		Higher reliability index (SAIDI and SAIFI)		More interruptions and therefore more outage duration for each customer served.

5.5.3. Intelligent Scheduling

Table 5.18: SWOT table for Int

	Strengths	Weaknesses	Opportunities	Threats
Econ with SiC	Higher PV generation. Higher emissions savings.	Higher energy losses in the grid.	More profitable and better reliability index.	
Econ with LC		Higher power losses level in the grid; Higher reliability index (SAIFI and SAIDI)		More interruptions and more outage time for each customer.

5.6. Balance

The advantages and disadvantages of the SiC and LC are similar for all optimization strategies. In all, the SiC allows a higher PV generation, and consequently, presents more energy losses in the network. However, the reliability index, are lower for this type of the control, being this indicator one of the most important, due to his relation to the power quality index. The reliability index, SAIFI and SAIDI, must be the lowest possible in the DN, because this mean that the costumers connected to this networks have less interruptions and a lower time without energy.

The principal aim of the *Story* and *Increase* project is to study types of control to allow a higher penetration of DRES in the network and, consequently to achieve a higher energy generation from renewable source and less gasses emissions. Due to that, the use of the SiC is more adequate.

The optimization with the best results, is the energy balance. With it, the PV generation was higher with the lowest reliability index, and the losses, for a higher PV injection in the network, are low in this optimization. But, is important to say, that all of this control and optimizations are possibilities to improve the penetration of the DRES in network, due to the fact that the results are better that when we don’t have these improvements active in the network.

Chapter 6

Conclusions

6. Conclusions

Solar and other renewables have been a key piece in the effort to a fossil fuel free electrical systems. One of the ways to achieve this fossil fuel independence is to allow a higher penetration of DRES on the distribution networks, since units installed on the consumer part to small renewable sources connected on the low voltage grid.

Due to this needs, is vital to have better and more controllable distribution network, without the need for elevated investment, being the control of the DRES an important part in this system.

The simulations done in this dissertation was fundamental to understand the benefits to the network of the controls addressed in this work. Not forgetting the importance of the delivering the energy with the power quality inside the regulation parameters.

The simple control, used in the simulations, allows a higher penetration of DRES in the study network, being one potential tool for the DSO to installed in the existent networks. The use of the DR units with the energy balance presented satisfactory results, allowing more PV injection from the units connected to the RN, which is one of the most important requirements in this study.

For future research there will be important to conciliate these technologies with storage units connected to the distribution network, being this the main theme of the project *Story* .The use of electric cars as a DR unit can also be a theme with elevated importance for the achievement of a free fuel system, because with this, there will be possible to increase the use of the renewable source in periods with less energy consumption (e.g. night).

7. References

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Appendix A

Location of the PV and DR units by scenario

Appendix A. Location of the PV and DR units by scenario

The follow images shows the location of all PV and DR units actives in each scenario used in the simulations platform. The square represents a PV unit and the triangle represent a DR unit connected to the network.

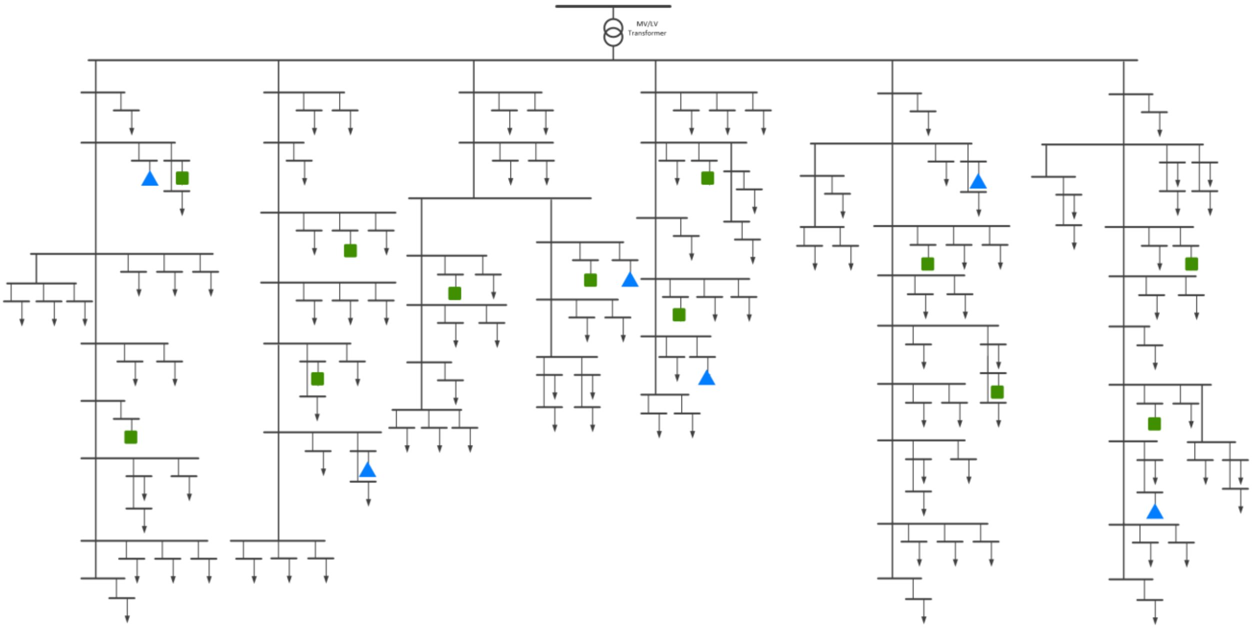

Figure A.1. Location of the PV and DR units for the first scenario

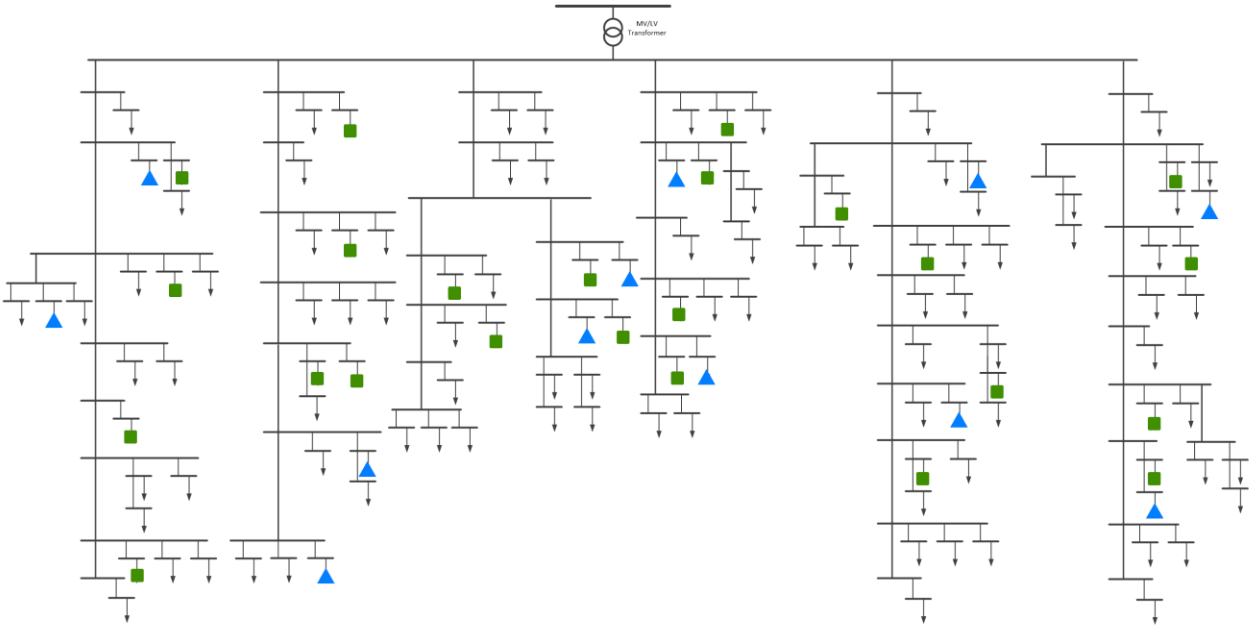

Figure A.2. Location of the PV and DR units for the second scenario

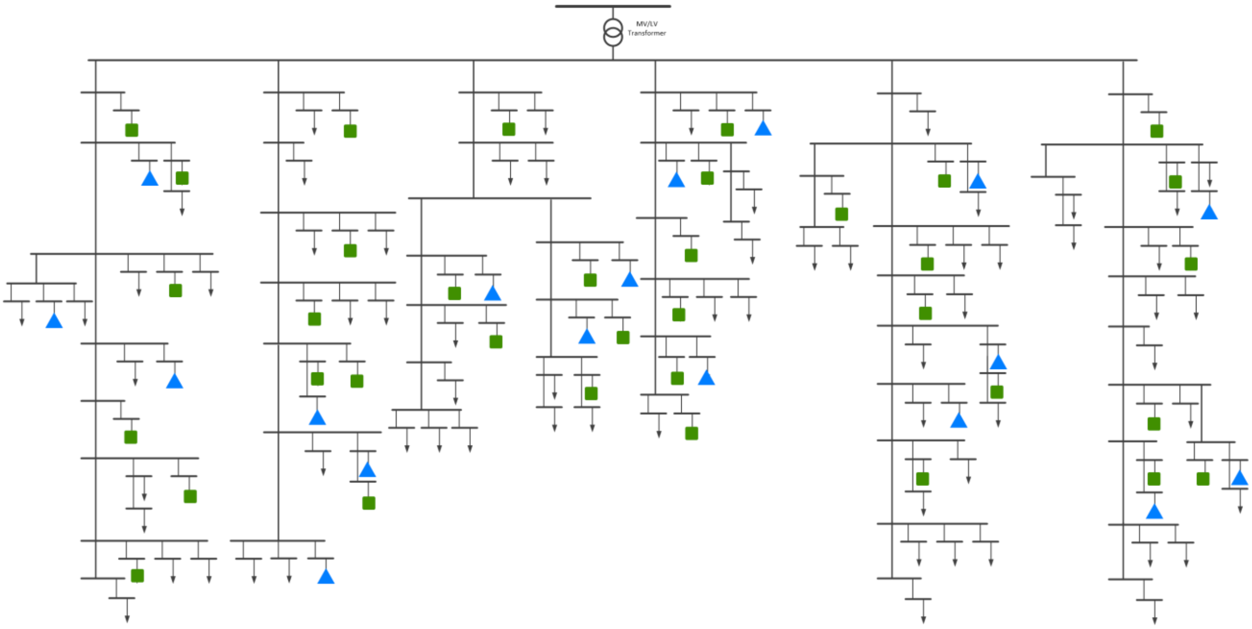

Figure A.3. Location of the PV and DR units for the third scenario

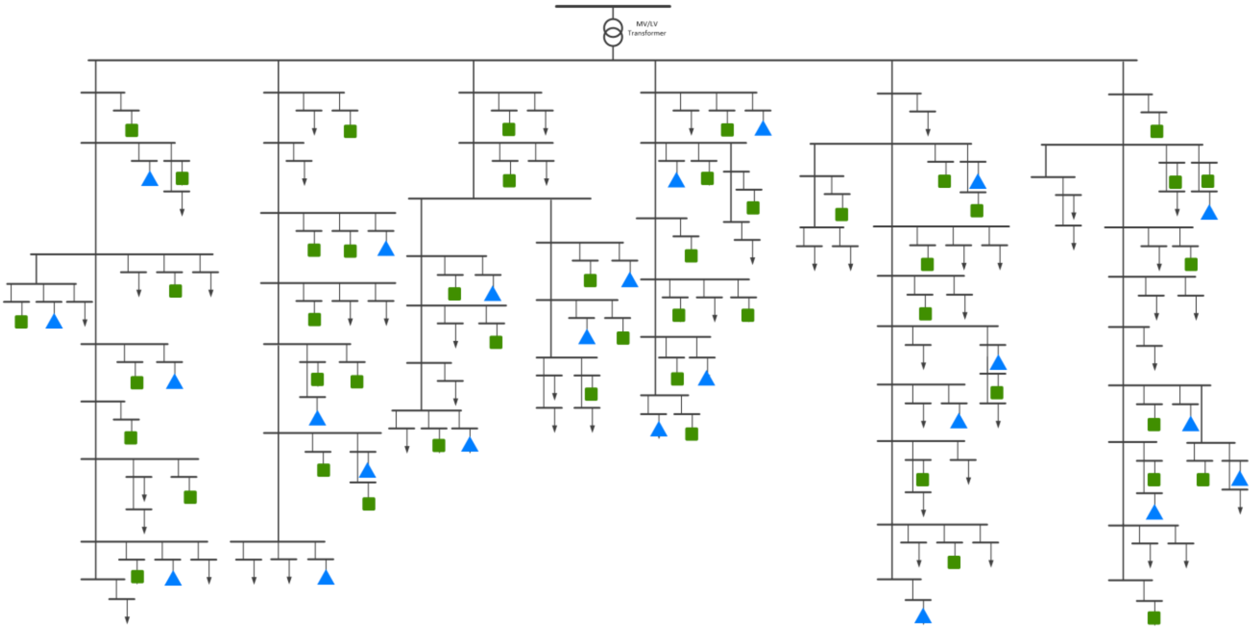

Figure A.4. Location of the PV and DR units for the fourth scenario

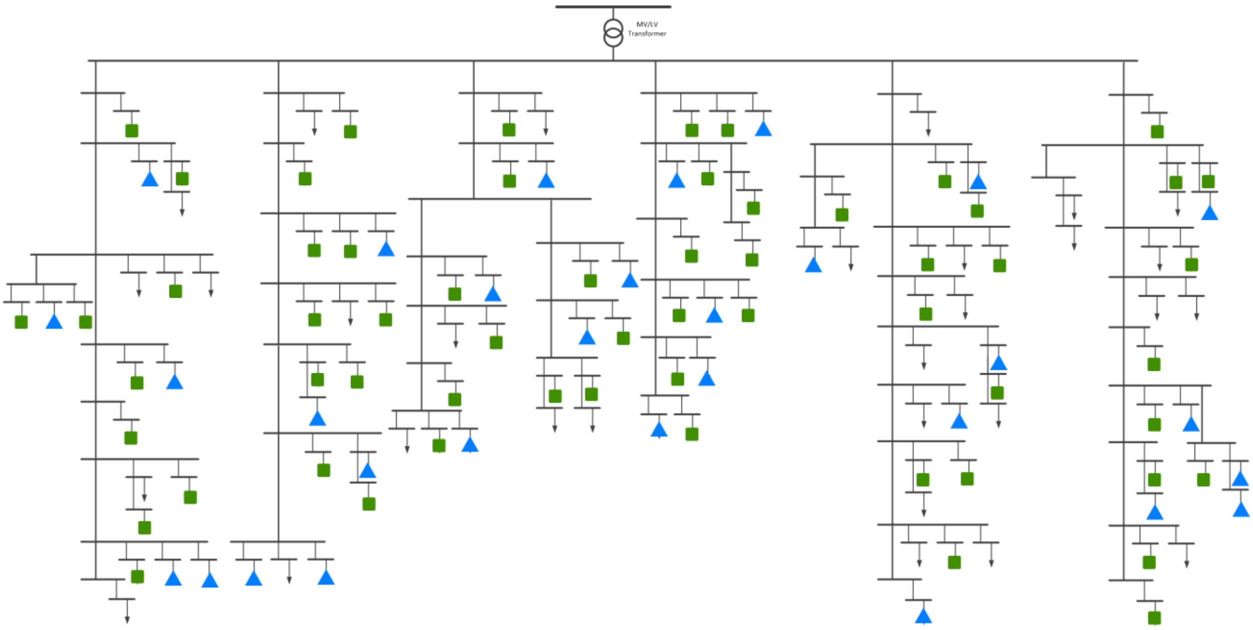

Figure A.5. Location of the PV and DR units for the second scenario

Appendix B

Additional results

Appendix B. Additional results

PV generation

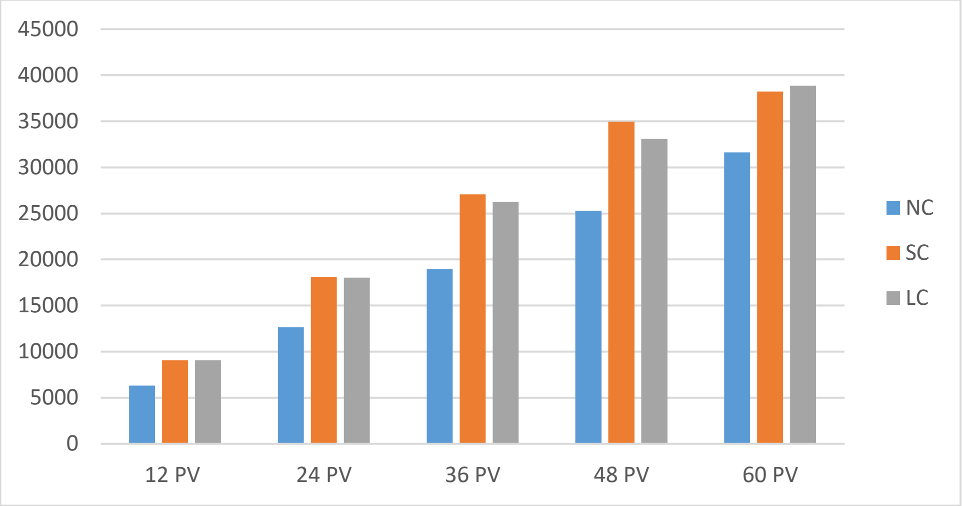

Figure B.1: PV generation using PV only for summer season(MWh per week)

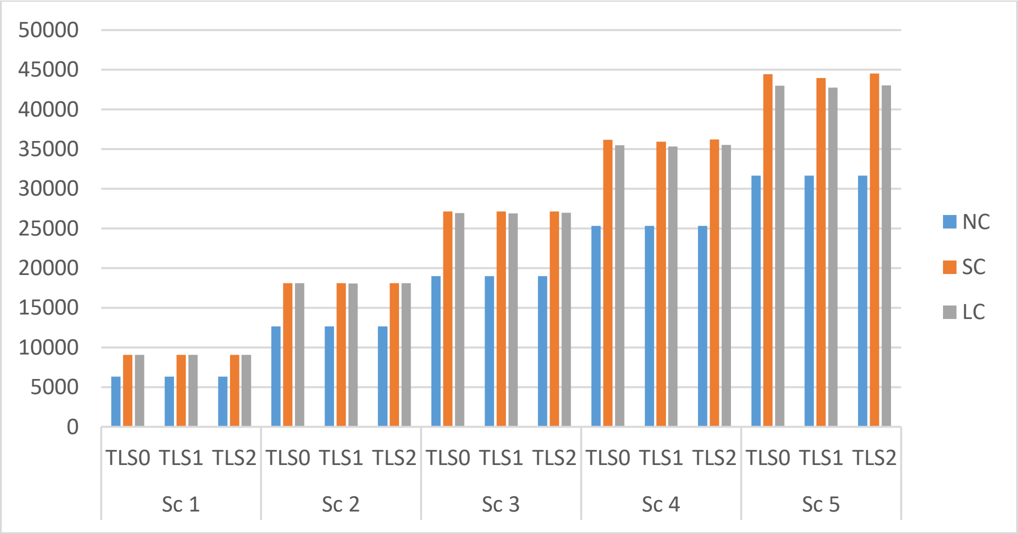

Figure B.2: PV generation using EB for summer season (MWh per week)

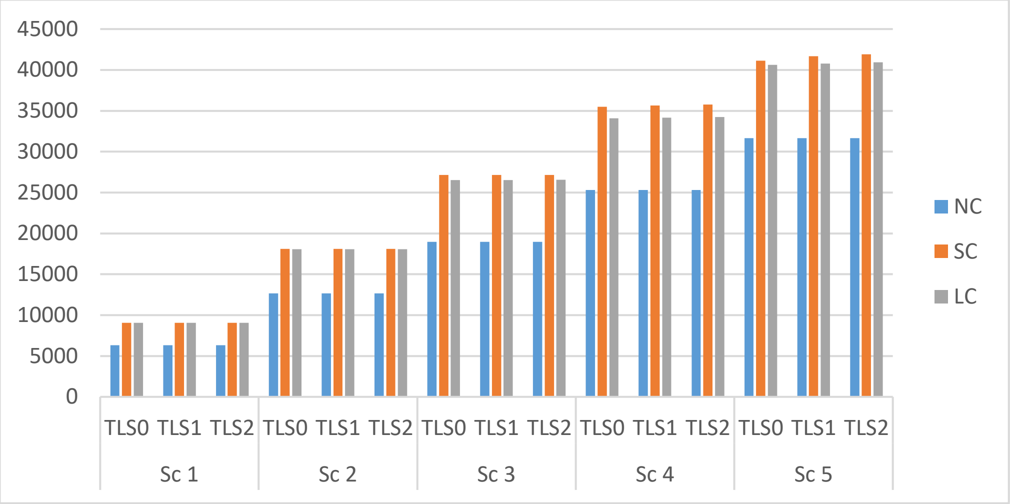

Figure B.3: PV generation using Econ for summer season (MWh per week)

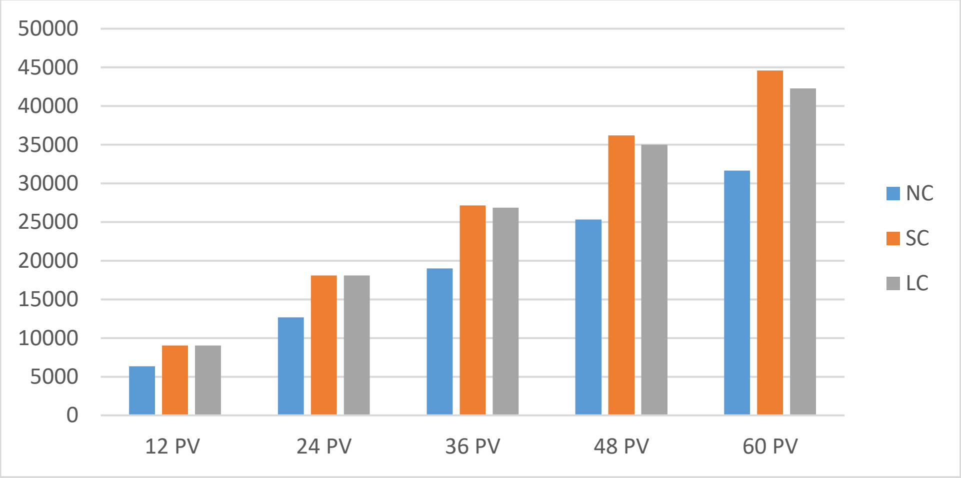

Figure B.4: PV generation using Int for summer season (MWh per week)

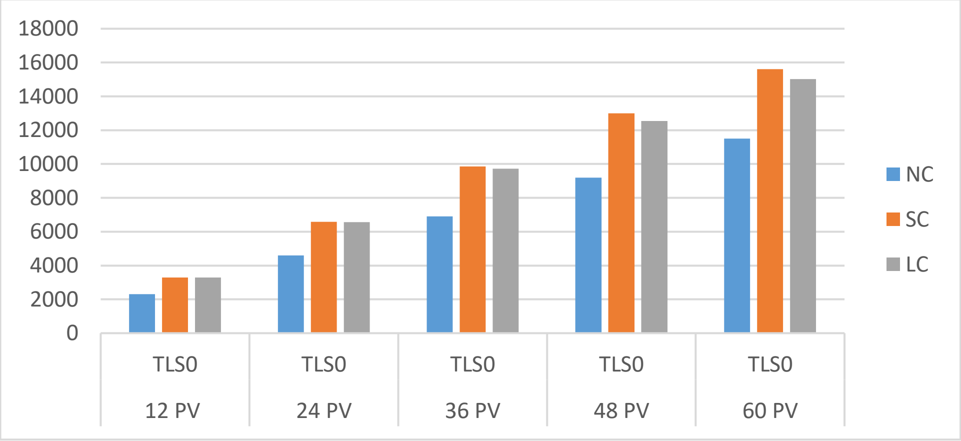

Figure B.5: PV generation using PV only for winter season (MWh per week)

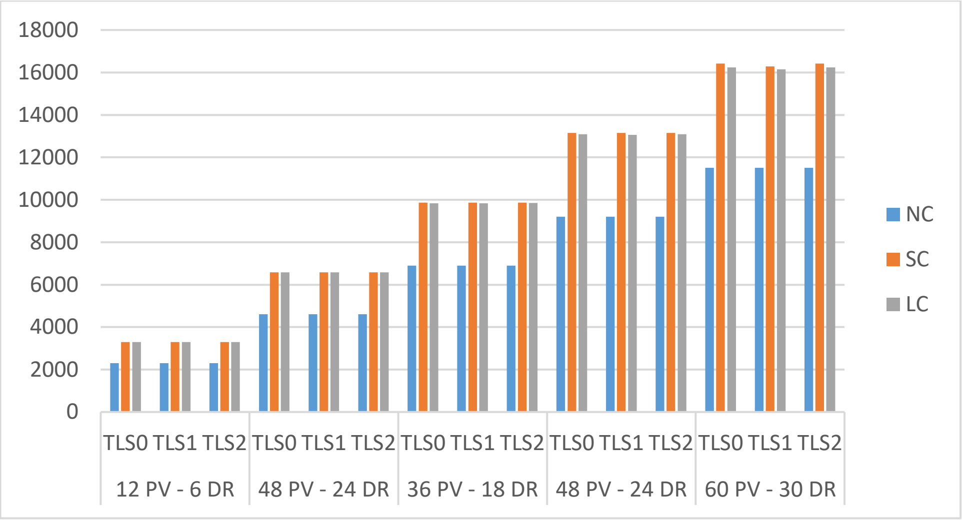

Figure B.6: PV generation using EB for winter season (MWh per week)

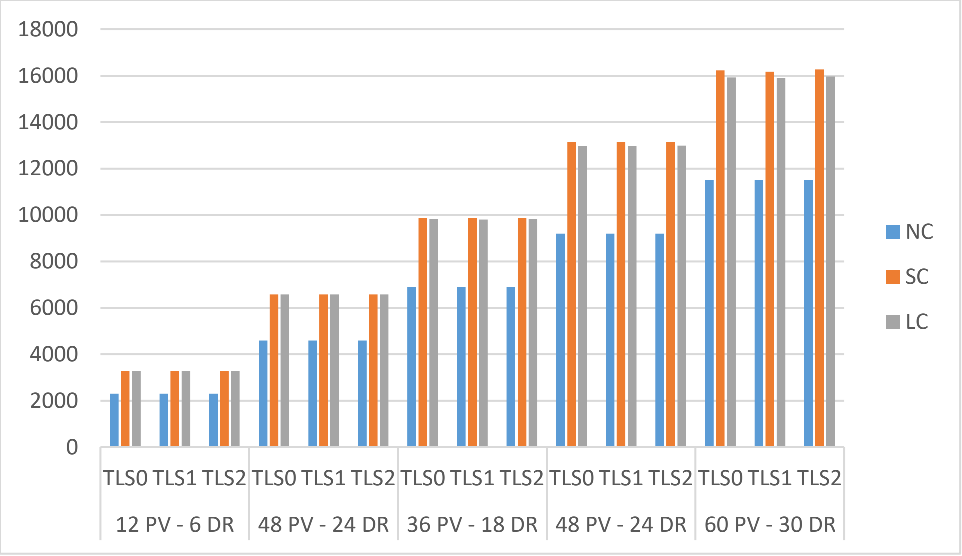

Figure B.7: PV generation using Econ for winter season (MWh per week)

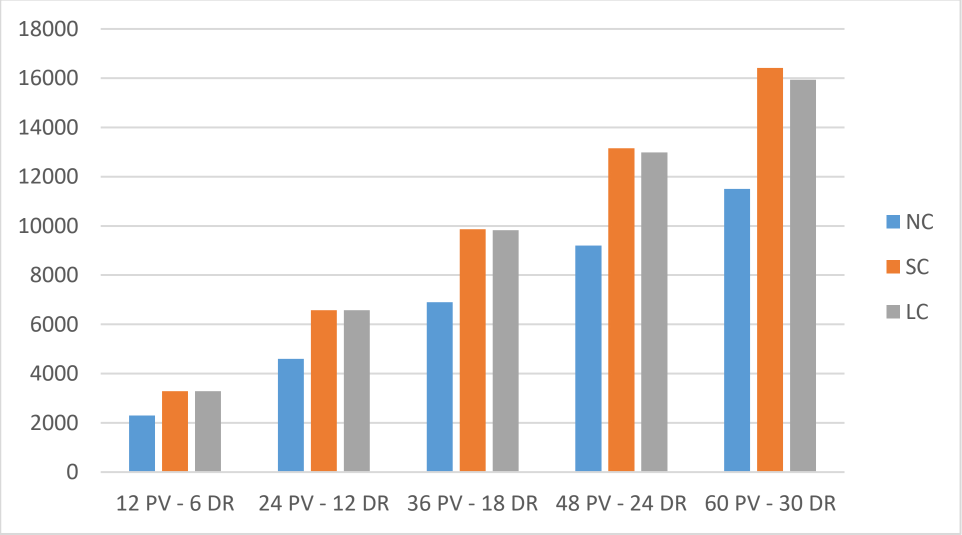

Figure B.8: PV generation using winter for winter season (MWh per week)

SAIDI Indicator

Table B.1: SAIDI indicator using PV only for summer season

		SC	LC
12 PV	TLS0	0	0
24 PV	TLS0	0	0
36 PV	TLS0	0.0625	1.159722
48 PV	TLS0	1.333333	4.15625
60 PV	TLS0	6.2375	10.075

Table B.2: SAIDI indicator using EB for summer season

		SC	LC
12 PV – 6 DR	TLS0	0	0
	TLS1	0	0
	TLS2	0	0
24 PV – 12 DR	TLS0	0	0
	TLS1	0	0
	TLS2	0	0
36 PV – 18 DR	TLS0	0	0.013889
	TLS1	0	0.277778
	TLS2	0	0.006944
48 PV – 24 DR	TLS0	0.010417	0.494792
	TLS1	0.229167	0.786458
	TLS2	0	0.442708
60 PV – 30 DR	TLS0	0.675	1.275
	TLS1	1.158333	1.770833
	TLS2	0.604167	1.208333

Table B.3: SAIDI indicator using Econ for summer season

		SC	LC
12 PV – 6 DR	TLS0	0	0
	TLS1	0	0
	TLS2	0	0
24 PV – 12 DR	TLS0	0	0

	TLS1	0	0
	TLS2	0	0
36 PV – 18 DR	TLS0	0	0.625
	TLS1	0	0.645833
	TLS2	0	0.430556
48 PV – 24 DR	TLS0	0.765625	2.541667
	TLS1	0.578125	2.322917
	TLS2	0.40625	2.208333
60 PV – 30 DR	TLS0	3.575	6.55
	TLS1	3.104167	6.170833
	TLS2	2.858333	5.95

Table B.4: SAIDI indicator using Int for summer season

		SC	**LC**
12 PV – 6 DR	TLS3	0	0
24 PV 12 DR	TLS3	0	0
36 PV – 18 DR	TLS3	0	0.048611
48 PV – 24 DR	TLS3	0	0.557292
60 PV – 30 DR	TLS3	0.533333	2.095833

Table B.5: SAIDI indicator using PV only for winter season

		SC	**LC**
12 PV	TLS0	0	0
24 PV	TLS0	0	0
36 PV	TLS0	0	0.1875
48 PV	TLS0	0.171875	0.645833333
60 PV	TLS0	0.725	2.154166667

Table B.6: SAIDI indicator using EB for winter season

		SC	**LC**
12 PV – 6 DR	TLS0	0	0
	TLS1	0	0
	TLS2	0	0
24 PV – 12 DR	TLS0	0	0

	TLS1	0	0
	TLS2	0	0
36 PV – 18 DR	TLS0	0	0
	TLS1	0	0
	TLS2	0	0
48 PV – 24 DR	TLS0	0	0.010416667
	TLS1	0	0.125
	TLS2	0	0.005208333
60 PV – 30 DR	TLS0	0.004166667	0.05
	TLS1	0.1375	0.3
	TLS2	0.004166667	0.05

Table B.7: SAIDI indicator using Econ for winter season

		SC	**LC**
12 PV – 6 DR	TLS0	0	0
	TLS1	0	0
	TLS2	0	0
24 PV – 12 DR	TLS0	0	0
	TLS1	0	0
	TLS2	0	0
36 PV – 18 DR	TLS0	0	0.013889
	TLS1	0	0.006944
	TLS2	0	0.006944
48 PV – 24 DR	TLS0	0.010417	0.145833
	TLS1	0.010417	0.1875
	TLS2	0.005208	0.125
60 PV – 30 DR	TLS0	0.154167	0.495833
	TLS1	0.208333	0.570833
	TLS2	0.108333	0.429167

Table B.8: SAIDI indicator using Int for winter season

		SC	**LC**
12 PV – 6 DR	TLS3	0	0
24 PV 12 DR	TLS3	0	0

36 PV – 18 DR	TLS3	0	0
48 PV – 24 DR	TLS3	0	0.020833
60 PV – 30 DR	TLS3	0.008333	0.129167

SAIFI Indicator

Table B.9: SAIFI indicator using PV only for summer season

		SC	**LC**
12 PV	TLS0	0	0
24 PV	TLS0	0	0
36 PV	TLS0	0.166666667	0.916666667
48 PV	TLS0	1.104166667	3.416666667
60 PV	TLS0	5.2	7.266666667

Table B.10: SAIFI indicator using EB for summer season

		SC	**LC**
12 PV – 6 DR	TLS0	0	0
	TLS1	0	0
	TLS2	0	0
24 PV – 12 DR	TLS0	0	0
	TLS1	0	0
	TLS2	0	0
36 PV – 18 DR	TLS0	0	0.055555556
	TLS1	0	0.416666667
	TLS2	0	0.027777778
48 PV – 24 DR	TLS0	0.041666667	0.458333333
	TLS1	0.354166667	0.583333333
	TLS2	0	0.458333333
60 PV – 30 DR	TLS0	0.666666667	1.45
	TLS1	0.95	1.666666667
	TLS2	0.6	1.366666667

Table B.11: SAIFI indicator using Econ for summer season

		SC	LC
12 PV – 6 DR	TLS0	0	0
	TLS1	0	0
	TLS2	0	0
24 PV – 12 DR	TLS0	0	0
	TLS1	0	0
	TLS2	0	0
36 PV – 18 DR	TLS0	0	0.583333333
	TLS1	0	0.611111111
	TLS2	0	0.416666667
48 PV – 24 DR	TLS0	0.5625	2.354166667
	TLS1	0.541666667	2.125
	TLS2	0.395833333	2.104166667
60 PV – 30 DR	TLS0	3.266666667	4.983333333
	TLS1	2.833333333	4.683333333
	TLS2	2.716666667	4.633333333

Table B.12: SAIFI indicator using Int for summer season

		SC	LC
12 PV – 6 DR	TLS3	0	0
24 PV 12 DR	TLS3	0	0
36 PV – 18 DR	TLS3	0	0.166666667
48 PV – 24 DR	TLS3	0	0.645833333
60 PV – 30 DR	TLS3	0.55	1.966666667

Table B.13: SAIFI indicator using PV only for winter season

		SC	LC
12 PV	TLS0	0	0
24 PV	TLS0	0	0
36 PV	TLS0	0	0.305555556
48 PV	TLS0	0.3125	0.75
60 PV	TLS0	0.916666667	1.866666667

Table B.14: SAIFI indicator using EB for winter season

		SC	**LC**
12 PV – 6 DR	TLS0	0	0
	TLS1	0	0
	TLS2	0	0
24 PV – 12 DR	TLS0	0	0
	TLS1	0	0
	TLS2	0	0
36 PV – 18 DR	TLS0	0	0
	TLS1	0	0
	TLS2	0	0
48 PV – 24 DR	TLS0	0	0.020833333
	TLS1	0	0.25
	TLS2	0	0.020833333
60 PV – 30 DR	TLS0	0.016666667	0.133333333
	TLS1	0.283333333	0.283333333
	TLS2	0.016666667	0.133333333

Table B.15: SAIFI indicator using Econ for winter season

		SC	**LC**
12 PV – 6 DR	TLS0	0	0
	TLS1	0	0
	TLS2	0	0
24 PV – 12 DR	TLS0	0	0
	TLS1	0	0
	TLS2	0	0
36 PV – 18 DR	TLS0	0	0.055555556
	TLS1	0	0.027777778
	TLS2	0	0.027777778
48 PV – 24 DR	TLS0	0.041666667	0.333333333
	TLS1	0.041666667	0.395833333
	TLS2	0.020833333	0.333333333
60 PV – 30 DR	TLS0	0.383333333	0.883333333
	TLS1	0.4	0.95

	TLS2	0.316666667	0.916666667

Table B.16: SAIFI indicator using Int for winter season

		SC	**LC**
12 PV – 6 DR	TLS3	0	0
24 PV 12 DR	TLS3	0	0
36 PV – 18 DR	TLS3	0	0
48 PV – 24 DR	TLS3	0	0.0625
60 PV – 30 DR	TLS3	0.033333333	0.333333333