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Control Strategies of Distributed Renewable Energy Sources and Demand Response Scheduling

Dissertação de Mestrado em Engenharia Eletrotécnica e de Computadores

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Control Strategies of Distributed Renewable Energy Sources and Demand Response Scheduling

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“Success is going from failure to failure without losing your enthusiasm”

Winston Churchill

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Resumo

Existe atualmente uma grande preocupação com o ambiente, o que inclui o aumento da energia renovável e a redução da emissão de gases de efeito de estufa associados à geração. Por esse motivo, tem-se verificado o aumento de fontes distribuídas de energia renovável, principalmente painéis fotovoltaicos (PV), na rede de distribuição de baixa tensão. O comportamento dessas fontes tornou-se um fator importante em problemas relacionados com o nível de tensão, qualidade de energia e estabilidade da rede.

O projeto INCREASE tem como objetivo o desenvolvimento de soluções técnicas para problemas nas redes de baixa tensão, de maneira a permitir o aumento da penetração de fontes distribuídas de energia renovável. Foram desenvolvidos novos controlos para fontes distribuídas de energia renovável, que permitem ao Operador do Sistema de Distribuição um melhor controlo sobre o nível de tensão e qualidade de energia da rede. De forma a complementar os novos controlos de inversor, foi concebida uma nova estratégia para permitir a agregação e operação de fontes renováveis e cargas flexíveis (DR).

Esta dissertação tem como objetivo avaliar os novos controlos para os inversores e as estratégias de agendamento para cargas flexíveis numa rede urbana, através de diferentes cenários criados com diferentes níveis de penetração PV e DR, e para o verão e inverno. São avaliados nos resultados das simulações aspetos como a energia injetada pelos PV, receitas, poupança de custos em emissões e adequação de produção.

Foram estudados e avaliados diferentes serviços, começando com o Basic Service onde o Simple Control e Local Control implementam novas estratégias de redução no inversor do PV, aquando a ocorrência de violações na qualidade de energia. O Scheduling Service pretende analisar o efeito da implementação e utilização de unidades de carga flexível no aumento da injeção de energia fotovoltaica na rede. Com o agendamento de unidades DR, é criada uma nova opção com o Balancing Service, que vai permitir uma otimização do agendamento em função de objetivos económicos ou energéticos. Por último, o Traffic Light System Service acrescenta uma verificação da adequação dos agendamentos das cargas flexíveis com as condições da rede.

Com os resultados das simulações verificou-se um impacto positivo provocado pelos novos controlos das unidades PV e estratégias de agendamento de DR, ao nível da média e alta penetração fotovoltaica, demonstrando um aumento considerável de injeção de energia PV na rede. Contudo, o mais importante são os benefícios alcançados por estas estratégias, permitindo um aumento de energia renovável, receitas para os proprietários dos painéis fotovoltaicos e diminuição de emissões e custos associados. As soluções propostas revelam-se efetivas no apoio ao operador da rede, mas mais importante, proporcionam vantagens e benefícios para a sociedade e ambiente.

Palavras-chave:

Fontes distribuídas de energia renovável

Cargas flexíveis

Controlos e estratégias de agendamento

Rede de distribuição urbana

Qualidade de energia

Serviços de Sistema

Abstract

Nowadays, there is a huge concern about the environment, which includes the increase of renewable energy and a reduction of greenhouse gases at generation level. Therefore the distributed renewable energy sources (DRES) share, mainly small-scale photovoltaic (PV) units, on the low voltage (LV) grid is increasing. Their behaviour is becoming an important factor in issues related with voltage level, power quality and network stability.

The INCREASE project has the aim of developing technical solution for problems in low voltage networks, in order to increase the penetration of DRES on distribution networks. The project developed new control mechanisms of DRES, enabling the distribution system operator (DSO) to better control voltage levels and the power quality of the network. In addition to the new inverters controls, a new multi-agent strategy was designed for aggregating and operating DRES and flexible loads.

This dissertation aims to assess the new inverter controls and demand response (DR) scheduling strategies in an urban network environment, through different scenarios created with different PV and DR penetration levels for the summer and winter. The simulations results assess aspects like PV electricity injection, Revenues, Costs of Emissions and Supply Adequacy.

Different services were assessed, starting with a Basic Service where the Simple Control and Local Control with new curtailment strategies implemented on the PV inverter when power quality (PQ) violations occur. Scheduling Service aims to analyse the implementation and utilization of flexible demand response units to increase the injection of PV generation into the grid. With the scheduling of DR units, another option is created with the new Balancing Service, which allow to optimize the demand response scheduling with Energy and Economic objectives. Finally, the Traffic Light System Service checks the suitability of DR schedule with the network power flows.

The simulation results show the positive impact of Simple and Local Controls on DRES and DR scheduling strategies in medium and high PV penetration levels, demonstrating a relevant increase of PV generation injection. However, the most important is the positive results achieved with new controls and DR scheduling, increasing the renewable energy injection and the PV owners' revenues, and decreasing the emissions costs from the traditional power plants. INCREASE solutions are effective to support DSO and most important, they bring overall advantages and benefits for the society and environment.

Keywords:

Distributed renewable energy sources

Demand response

Controls and scheduling strategies

Urban distribution network

Power Quality

Ancillary Services

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Abbreviations

AS – Ancillary Service

CC – Congestion Control

DA – Day Ahead

DCM – Distribution Line Congestion Management

DG – Distribution Grid

DN – Distribution Network

DR – Demand Response

DRES – Distributed Renewable Energy Sources

DSO – Distribution System Operator

GHG – Green House Gases

HV – High Voltage

IEC – Internacional Electrotechnical Commission

LC – Local Control

LV – Low Voltage

MV - Medium Voltage

NC – No Control

OH – Overhead

PQ – Power Quality

PV – Photovoltaics

RES – Renewable Energy Source

RMS – Root Mean Square

RP – Reserve Provision

SAIFI – System Average Index Frequency Interruption

SAIFI – System Average Interruption Frequency Index

SCA – Scheduling Control Agent

SiC – Simple Control

TLS – Traffic Light System

TOU – Time of Use

TSO – Transmission System Operator

V – Volt

VC – Voltage Control

VUM – Voltage Unbalance Mitigation

Symbols

C – Capacitance

CO – Carbon Monoxide

CO_2 – Carbon Dioxide

F – Faraday

Km – kilometre

kWp – kilowatt peak

kWh – kilowatt hour

kV – kilovolt

MWh – Megawatt hour

NH_3 – Ammonia

NMVOC – Non-methane volatile organic compounds

NO_x – Nitrogen Oxides

Ω - Ohm

PM10 – Fine Particles

R – Resistance

SO_2 – Sulfur Dioxide

X – Reactance

1 - Introduction

1.1 - Contextualization and Motivation

Renewable energies are the present and the future of the energy sector. For this reason governments and companies are supporting the development and creation of new software, hardware and technological solutions to improve and expand the renewable energy sector.

Nowadays, it is possible to notice the high increase of Distributed Renewable Energy Sources (DRES) in the electrical grids, being installed in diverse locations, since small villages until cities with high density population and factories. Photovoltaic panels are used to support and replace the traditional power plants, which have high environmental impacts.

Recently, Slovenia reached 195 MW of solar energy installed power, which was a result of energy market incentives proposed by the government. With the suddenly increase of DRES in the distribution grid, some concerns about technical aspects related with the voltage level and power quality on the low voltage distribution network have appeared. The intermittent supply of energy from RES in low and medium voltage networks, can lead to a bidirectional power flow. Therefore it is urgent to develop new operational control strategies to maintain the ability of the system to provide consumers with reliable supply of electricity at an acceptable power quality level and cost.

This dissertation is included in the INCREASE project (www.project-increase.eu), a European project developed by five different countries, Austria, Belgium, Greece, Slovenia and The Netherlands, oriented to delivering tools and solutions to Distribution System Operators (DSO´s). Control strategies and ancillary services are investigated with the objective to increase the penetration of renewable energy sources in the distribution grid.

1.2 - Objectives

The main goal of this work is to developed simulations based on realistic environments, and analyse different control strategies applied in DRES and Demand Response units in a low voltage urban distribution network.

The explanation and assessment of all controls and strategies involved for DRES and the scheduling of DR units realized by INCREASE solutions is also an important objective. With the comparison of different scenarios of PV penetration levels and different services it is possible to obtain results about the new smart controls and realize the differences between them. That comparison will give important information about the improvements provided by the services in aspects related with renewable energy injection, revenues, emissions and supply adequacy. Other aim is to select best scenarios for the new different control solutions and try to understand and explain why they prove to be a better solution for certain circumstances.

1.3 - Structure

In the first part of this dissertation the technical problems on the network caused by the high penetration of distributed renewable resources is explained and each problem is followed by a brief description. Chapter 3 introduces the Ancillary Services concept and what they provide to transmission and distribution system operators. In the same chapter, the ancillary services provided by INCREASE solutions and technologies are explained.

The scheduling strategy of demand response units is presented in chapter 4, where the concept of demand response, scheduling strategies, different optimizations and scheduling control agent (SCA) are exploited. After that, it is introduced the different traffic light systems and the description of operation way of each one.

Chapter 5 presents the considered grid, where the network type and design, and the different grid parameters used on simulations are described. Chapter 6 explains the environment use to data processing, as well as the parameters and assumptions used on performed simulations. The investigated services are also presented in simulations model description. Finally, chapter 7 analyses and explain the simulations results and chapter 8 draws the conclusions.

2 - Technical Problems for distribution systems with high penetration of DRES

The “old” Distribution Grid (DG) is designed to supply power from a single point, usually the substation transformer, to the different loads distributed on the grid. Originally, the DG was not designed and prepared for some recent innovations like DRES and storage systems that can create technical problems.

2.1 – Technical Problems

In this sub-chapter we present an overview of the technical problems in low and medium voltage distribution grids that are of particular interest in INCREASE project [1]:

- Voltage unbalance
- Overvoltages
- Line congestions
- On-off oscillations

2.1.1 - Voltage unbalance

Voltage unbalance according to IEEE “*is the maximum deviation from the average phase voltage, referred to the average of the phase voltage.*” [2].This technical problem is caused by a high number of the single-phase connected DRES and consequently limits the installation and penetration of DRES. It is observable that the voltage in phase 1, which is the connection phase of the PV inverter, is higher when compared with the other two phases. The fact of DSO does not know about the localization of DRES nor the connected phase, makes the central solution impossible.

Unbalance voltages produce an unbalance distribution system which have more losses and overloading effects. It can also have a negative effect on equipment like induction motors, power electronic converters and adjustable speed drivers.

2.1.2 - Overvoltages

It is defined by the IEEE “*as an increase in the AC voltage (RMS), typically to 110% -120% of the nominal voltage, at the power frequency for durations longer than one minute*”[1][3], and is classified as a long-duration voltage phenomenon. Usually, it results from high distribution voltage due the incorrect tap setting on transformers, switching off of large loads, or excessive correction for the voltage drop on the transmission and distribution systems. The principal sources of this problem are inadequate voltage controls or the weakness of the system for voltage regulation. The most common effects are overheating of electronic devices, malfunction and shorter operating life [1].

2.1.3 - Line Congestion

The increasing renewable energy sources (RES) penetration and low-load conditions causes line congestions in distribution lines. Line congestion means that the current flowing through the line is above of maximum allowed by the line loading. This effect makes the cables/lines temperature rise over thermal limit, therefore there are an increase of losses and a decrease of life span of the cables. That’s why it is so important to protect the load limits in the cable. In situations with low-penetration levels of RES, the injected power from these renewable sources decreases the line loading, but as the injected power increases, reverse-power flow may appear and the line load increases. Reverse-power flow is strongly associated with the voltage rise problem in radial distribution lines. The reactive power from DRES can be used to mitigate the voltage rise but the line current will suffer an increment.

One solution to this problem is the line upgrade or limit the penetration of DRES. Currently at distribution level the control of congestion level is done in a static way, the opposite of the proposed on this dissertation and by the INCREASE project.

2.1.4 - On-off oscillations

With a high production from RES and a low consumption, the voltage level will rise and the generation unit is disconnected, decreasing the current injection and finally decreasing the voltage. Oppositely when the consumption is larger than the generation, the voltage level will decrease and the DRES are connected again resulting in a voltage increase. This loop of switch on, switch off results on voltage oscillations, which can lead to resonances in weakly dampened grid. The results are connected to systems damage and losses of energy generated by RES that can be translated in profit losses.

2.2 – Solution Strategy

The solution for these problems can be a control strategy organized hierarchically that consists in two different layers:

- Local control: does not need communication between controlled units, since it works using local information.
- Scheduling Control: responsible for scheduling the DR units. It is necessary communication.

2.2.1 - Local Control strategy

The main objective of this control strategy is the mitigation of voltage unbalance and under/overvoltages by means of a droop control and to provide fault-ride through capabilities. It works without communication among the local controllers and ensures a reliable operation of the distribution grid. The solution for voltage unbalance problem is to add smart control strategies to the three-phase grid-connected inverters, located in every RES, in order to mitigate the voltage unbalance by distributing the active power between the phases. By emulating a resistive behavior towards the negative and zero-sequence component of the grid voltage, it is possible to mitigate the voltage unbalance. Once this problem is mitigated, overvoltages can still exist. Overvoltages are tackled by means of a droop control scheme that adjust the power exchanged with the grid, based on the grid voltage at the terminals. In case of disturbances, local voltage control will be enable and the system stability will be maintained due to the use of frequency response and the provision of fault-ride through capabilities. The voltage unbalance decrease will result in a better voltage profile that allows higher penetration of RES in the low voltage grid.

2.2.2 - Scheduling Control Strategy

Demand Response units are scheduled according to several optimizations criteria. The optimization process is based on additional inputs, such as wholesale energy market prices, forecast of local demand and DRES production, network topology and regulatory limitations [4].It aims the problems related with line congestion and reserve provision. The communication process is essential on this control layer. This subject will be explained in chapter 4, Scheduling of Demand Response.

To achieve stability and reliability on the network it is important to keep the different control layers out of conflicts.

3 - Ancillary Services

With the opening of the electricity markets, the balancing of energy demand and supply in the power system is done by the Transmission System Operator (TSO) based on the generation schedules, coming from the energy markets. The TSO and DSO require various systems support services, called Ancillary Services (AS), to operate the power system securely. AS can, in principle, be provided by generators, prosumers[1] and flexible loads, as well the network equipment. Some AS are procured as needed by TSOs and DSOs to keep the frequency and the voltage of the power system within operation limits or to recover the system in case of disturbance or failure.

The increasing penetration of variable generation is already impacting the system, increasing the variability and uncertainty in power systems. The new variable RES that are replacing the conventional generation in operating schedules can also provide ancillary services.

3.1 - Definition

There is not only one way to define Ancillary Services (AS), and the main sources of definitions for AS come from European Commission, ENTSO-E, EURELECTRIC, Energy Community, and ACER. For the project, the most adequate definition is "*AS are all services required by the transmission or distribution system operator to enable them to maintain the integrity and stability of the transmission or distribution system as well as the power quality* [5]. *AS are those services provided by generation, transmission and control equipment which are necessary to support the transmission of electric power from producer to purchaser. These services are required to ensure that the system operator meets its responsibilities in relation to the safe, secure and reliable operation of the interconnected power system. The services include both mandatory services and services subject to competition.*" [6]

The AS can be grouped into the main categories of voltage support, frequency support and restoration services. Table 1 present such services.

[1] Prosumer – Producer and consumer

Table 1 - Unified structure of AS, REserviceS project

Frequency support	Voltage support	System restoration
-Frequency Containment reserve FCR (<5, 10 or 30 sec) -Frequency Restoration Reserve FRR (<15min) -Replacement Reserve RR (15 min to hours) -Fast frequency response (< 2s) -Ramping margin (1, 3, 8 hours ahead)	-Normal Operation: control of power factor, reactive power or voltage -Fast reactive current injection	-Black start[2] -Islanding[3]

3.2 - Ancillary Services at Transmission and Distribution level

The main objective of this project is to facilitate and increase the integration of DRES in distribution networks and to improve the distribution network operational security. Operating an electric system requires electricity balance between injected and withdrawn energy, in order to keep the voltage and frequency within the predefined parameters range. The physical units present on power system, such as generating units (RES), storage units and demand response units allow the system operator to have the ability to schedule long-term and flexible short-term energy injections into the grid.

In the future due the increase of system needs and the increasing share of decentralized generation and storage units, it is expected a request of AS to TSO and DSO in order to help these systems. Some services available to the transmission level are not used at distribution level, but the opposite happens too. So it is possible to make a division of AS between TSO and DSO.

3.2.1 - AS provided to TSO

- Active Power / Frequency Control: Nowadays frequency control is handled by TSO and provided by generators connected to the transmission networks. Control of the active power of generating sets in response to variations in system frequency. Provision of downward active power reserves, as well as upward active power reserve in cases where DRES were curtailed, operating at lower than rated power output.

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[2] Black start – process of restoring an electric power station or a part of an electric grid to operation without relying on the external transmission network.

[3] Islanding – refers to the condition in which a distributed generator continues to power a location even though electrical grid power from the electric utility is no longer present.

- Reactive Power / Voltage Control: voltage control using adjustment of reactive power generation.
- Active Power / Voltage Control: This control is executed in TSO, but can also be done in DSO. The INCREASE project intends to investigate ways to enable distribution generation to contribute to active power in a way of control voltage on distribution network [9].

3.2.2 - AS provided to DSO

- Congestion Management: occurs when the current exceeds its limit for a certain time period. AS can help to control and re-dispatch of DRES power flows using intelligent control based on real-time line ratings. Other solutions are possible, like network reinforcement and reconfiguration.
- Power Losses Reduction: the main objective is to reduce costs of the power transmission and distribution due the transmission and distribution losses. The losses due to active and reactive power flows can be optimised during the operation by power dispatch strategies.
- Power Quality Improvement: aims to improve some characteristics such voltage, electric current and frequency in electric power system, complementing the action realized by the TSO. The focus of the project is on voltage unbalance and voltage rise mitigation.

3.3 - INCREASE Ancillary Services

Several problems appear in the medium and low voltage networks due the increasing DRES penetration (high number of single-phased connected DRES) and distribution lines with low-load conditions. The INCREASE AS objective is to find solutions for that problems and facilitate the installation and integration of small renewable generation units on the distribution network.

The main problems in distribution low voltage networks are Voltage Control (VC), Voltage Unbalance Mitigation (VUM), Distribution Line Congestion Management (DCM) and Active Power Reserve Provision (RP). Traditionally, there are two solutions that DSOs use to solve these problems. One is performing a line upgrade and the second one is limiting the penetration of DRES on the line. In INCREASE these problems are solved using technological solutions based on different control strategies at different levels and a 3-phase grid-connected inverter. That management and control over the distribution network bring some advantages:

- better exploitation of current low voltage (LV) grid capacity
- better capacity exploitation of already installed DRES
- facilitating higher DRES penetration

- provide AS to DSO/TSO to maintain the reliable supply of electricity at required PQ levels in LV networks
- reduce costs of current power systems

The solutions provided by INCREASE are based on smart control strategies and on the 3-phase inverters. The inverters installed on every single DRES allied with Local Control (LC) strategy are able to mitigate problems like voltage unbalance, line congestion and overvoltage, due the new smooth curtailment control. In addition to LC integrated on the inverters, Scheduling Control is implemented to support the objective of active management and control of LV networks, enabling the aggregation of DR units and offering their energy products on electricity market.

3.3.1 - Voltage Control (VC)

Voltage control aims to keep the grid voltage within pre-defined ranges. By adjusting the active and reactive power injection it is possible to control overvoltages and undervoltages in LV distribution network.

- Inverter + LC enable a dynamic curtailment of active power infeed of DRES, thus overvoltages can be reduced.
- SC contribute to Voltage Control mitigating of under- and over-voltages by balancing DRES production and demand of DR units.

3.3.2 - Voltage Unbalance Mitigation (VUM)

Voltage balance control and flow management are among the key network planning issues, governed by the Quality of Supply standard EN 50160 [10], to help in situations of dynamic unbalancing caused by unbalance loads, outages and switching of loads. The dynamic balance of 3-phase system is enable by:

- Inverter + LC ensure the dynamic balance voltage between the phases as bridge between single-phase DRES units and the 3-phase LV network. This solution provided by an intelligent hierarchical control structure involving local controllers, solve the unbalance voltage problem and improve voltage profiles. It also allows a higher penetration of DRES in the LV network.

3.3.3 - Distribution Line Congestion Management (DCM)

When the network distribution is operating close to the limits, the DRES operation could lead to a line overloading. The mitigation of line congestion is performed by a coordinated control of active and reactive power injection through intelligent controls installed on inverters.

- Inverter + LC enables a dynamic curtailment of active power infeed of DRES units, reducing this way the line congestion.
- SC affects DCM with an energy optimization and balancing DRES production and demand.

3.3.4 - Active Power Reserve Provision (RP)

Intelligent control strategies execute the management of reserves performing the scheduling of DR units. When there are DRES in LV networks available to be dispatched in a certain period, the power can be used to provide services to DSO, executing the balance loading with intelligent control.

- SC provide a flexible energy product by aggregating DR units that can be offered on reserve markets.

DRES generation is preferentially dispatched in most European countries.

The influence of DRES on distribution network can be beneficial, however only VC and RP can be characterized as classic AS potentially supplied to the TSO, while Voltage Control, Voltage Unbalance Mitigation and Distribution Line Congestion Management can be classified as AS provided to DSO.

4 - Scheduling of Demand Response

The basic idea of scheduling flexibility is to enable the demand flexibility that can be provided by aggregator[4] to the DSO, in order to solve network operational issues including current congestion and voltage variation. The objective of this control is adapt the DR units in function of the chosen objective. The principal actors are: DSO, PV units, DR units, Aggregator, and Scheduling Control Agent (SCA). The Figure 1 show the interaction between the actors. In this situation, the Aggregator ensures the coordination of the required DR unit flexible energy and interacts with the energy market. The communication between Aggregator, DR units, PV units and DSO is necessary. It is assumed that the scheduling control operation entails the Local Control [11].

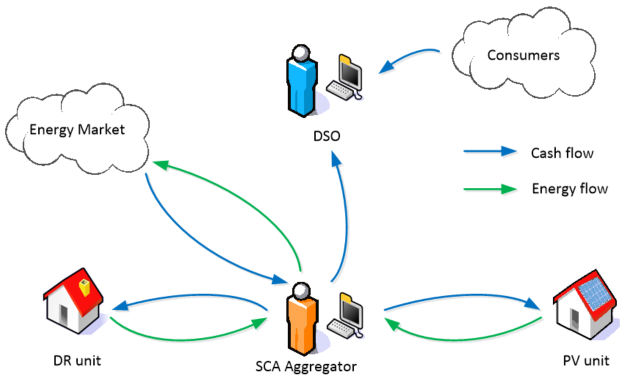

Figure 1 - Interaction with Scheduling Control, [11]

4.1 - Demand Response

Households or large consumers can provide flexibility to the electricity system by voluntarily changing the usual electricity consumption in reaction to electricity market prices or other specific requests, and at the same time receive economic incentives to do it, [12].

Demand response aims the shifting of consumption to a different point, as can be seen in Figure 2.

[4] Aggregator – refers to a web site or computer software that coordinate or aggregates a specific information, in our case demand response, from individual consumers to better meet technical requirements for specific routes to market.

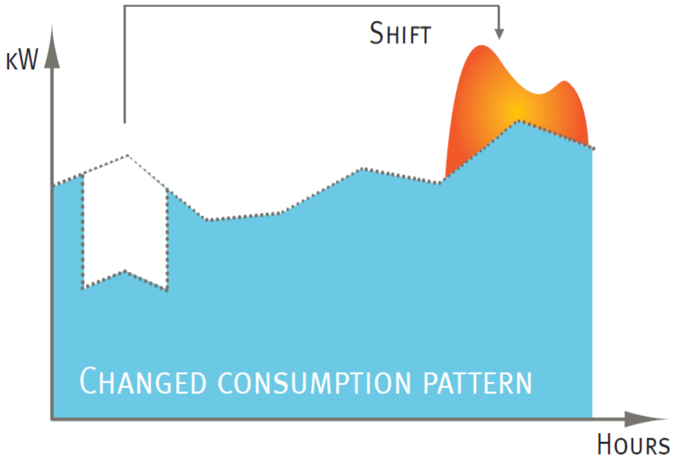

Figure 2 – Demand Response shift, [12]

This changing entails a temporarily increasing or decreasing in the normal consumption patterns that can lead to costs savings. Demand response has already an active role in the electricity systems. However, in the recent years, with the variable and unpredictable renewable generation from DRES, mainly installed on the distribution grid, the matching between supply and demand is becoming more difficult to achieve, due to the need of more flexibility from electricity system.

4.2 - Scheduling Control Agent (SCA)

In this project the SCA uses the flexibility of DR in order to mitigate problems related with overvoltage/undervoltage and current congestion. The two main goals of SCA are:

- Minimize the number of PQ violations and increasing the renewable energy injection.
- Maximize the profit of DR units.

In the scheduling process, the algorithm takes into account different parameters of DR units: Rated power, Energy constraints, Time of use, Internal DR unit energy price.

For real time operation of DR units, a traffic light system approach is used that enables the DSO to approve or block the proposed DR schedules.

4.3 - DR units´ parameters

The parameters of DR units are very important in a scheduling process, since the Schedule Control Agent needs to know the functional characteristics [11]:

- Time of use (TOU): represent the time period (day/night or mixed, and the duration), when the DR unit is available to participate in the scheduling process.

- Energy constraints: defines the amount of energy in a particular time period that can be offered by the DR unit to the SCA for scheduling purposes and is then optimally distributed during TOU.
- Rated power: maximum available power of every DR unit. This information directly affects the power bid on the market.
- Internal DR unit price: is the operation cost of the DR unit and it reflects the cost of DR flexibility.

4.4 -Optimization Scheduling

Schedule Control Agent (SCA) can ensure the schedule of units, selecting between two different options, economic optimization or energy optimization.

4.4.1 - Economic Optimization

SCA uses the DR flexibility to maximize the profit of DR units. This optimization used in the scheduling algorithm, make the observation of daily energy prices and costs for DR unit adjustment, deploying schedules for each DR unit, considering the limit parameters of individual DR unit [11]. The main objective is the profit, and that profit is ensured by maximizing the income of the DR unit energy sold on the day ahead (DA) wholesale market and by minimizing DR unit adjustment costs. In hours where the electricity price is lower, the DR units are scheduled for fully consumption, oppositely, when the electricity price is high, the consumption is decreased.

This optimization includes a mixed integer linear programming approach [13]. The results of the optimization is a daily schedule of DR, based in economical optimization.

4.4.2 - Energy Optimization

The target of energy optimization is to fully support DRES (in this specific case they are PV units) production in the network and enable the maximum injection of renewable energy. It is possible to reach that goal by reducing the difference between the total consumption and PV generation. With the decrease of energy difference in the network, power flows are minimized and voltage fluctuations are lowered, which means less PQ violations. This scenario allow less curtailment of DRES and higher injection of green energy into the grid.

Using a linear programming approach on Matlab, like in economic optimization, it is possible to decrease or increase the consumption of DR units, according to the sign of network energy difference. If the generation is higher than consumption, the DR consumption can be increase, if the consumption is lower than generation, the generation of DR units can be increased. The sign is 0 when the DR units is no active in the corresponding hour [4][11].

4.5 - Issues of LV distribution networks

In scheduling control, it is very important to take into account the geographical dispersion of DRES and DR units, since that scheduling is performed very close to their operation. Wholesale electricity market prices should also be taken into account in the scheduling operation to ensure higher profits.

Short term forecast (15- 30 min ahead) of unmetered demand and DRES generation is necessary in the area covered by the scheduling control. Such forecast is routinely executed on high level transmission networks since the DRES generation and demand units are large enough to execute an accurately forecast. The units connected at lower voltage levels are forecasted as aggregated to predict network congestions and PQ violations.

In the LV and Medium Voltage (MV) distribution networks the following forecast are necessary:

- DRES generation: An accurate forecast of generation is extremely important, due to the quick changes of weather conditions. It has an important impact on the LV networks, since the DRES units are installed in this voltage grid level [14].
- Unmetered demand on LV and MV: Frequent changes in consumer behaviour and network topology make the long-term demand forecast on LV and MV network a problem [15].
- PQ violations: At feeder level the current status of grid topology is necessary to determine any PQ violations arising from the scheduling proposed for DR units.

The low voltage grid configuration can change very fast with the dynamic reconfiguration of the feeders, influenced by the modifications of rural and urban areas. In a single feeder, a relatively large consumer or DRES unit addition can have a large impact. That is why a detailed and updated information about network topology is necessary to perform power flow calculations.

4.6 - Traffic Light System

Traffic Light System (TLS) concept was introduced to give DSOs the ultimate control over DR unit schedules. TLS software is implemented in DSO control mechanisms, uses initial SCA DR schedule together with DRES production forecast to check the suitability of the DR schedule with network power flows. It detects and prevents possible PQ violations in the network.

TLS is used to evaluate network situation, caused by DR unit commitment. The activation of DR units in certain time instances can cause PQ violations or line congestions. When a DR scheduling is executed without TLS, demand response units are deployed and they do not participate in mitigation of PQ violations, even if they are the cause of it. In a way to prevent or reduce PQ violations, the management and scheduling of DR units is done by TLS. Therefore, TLS helps the DSO to operate the grid securely, and increase the renewable electricity injection.

In these simulations, four control levels of traffic light system were implemented:

- TLS0: No traffic light system
- TLS1: Simple traffic light system
- TLS2: Advanced traffic light system
- TLS3: Intelligent traffic light system

The main differences between traffic light systems are explained below and a summarized table can be observed on Appendix B, Table 21.

4.6.1 - No traffic light system (TLS0)

The system does not have control over DR units and cannot check PQ violations. It is used on simulations as baseline to assess the difference between traffic light systems.

4.6.2 - Simple traffic light system (TLS1)

It is the basic and simplest way of DR units` management. The TLS checks for PQ violations based in voltage profiles and power flows, and if the DR unit is active at the moment that a PQ violation occurs, the TLS shuts down the unit. This traffic light system can also be used with PQ violations forecasts for day ahead (DA). Appendix B, figure.24 presents the algorithm scheme of simple TLS.

4.6.3 - Advanced traffic light system (TLS2)

Like in simple TLS, the PQ violations check is performed to assess if some violation occurs. If any violation is detected and a DR unit is active, the TLS assesses how the DR unit affects the situation. If the DR unit helps with the problem, the TLS keep the DR unit active, otherwise the unit is shut down. The decision between keep the unit active or shut down it is taken by TLS logic, Table 2.

Table 2 - Advanced TLS logic, INCREASE project

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

On Appendix B, Figure 25 it is possible to check the algorithm scheme of advanced TLS.

4.6.4 - Intelligent traffic light system (TLS3)

This case of control and management of DR units offers more interactivity and flexibility, providing the option of prescheduling, and also an operation without prescheduling that ensures more adjustability of the demand. The intelligent TLS implements a schedule 15 min ahead (oppositely to simple and advanced which are implemented 60 min ahead) on available DR units which were without predefined scheduling in order to mitigate PQ violations. The main advantage is the fact of DR units are not prescheduled and their entire flexibility can be put on service to mitigate PQ violations. It is fundamentally different from both Simple and Advanced TLS, since his goal is to determine a way to deploy DR units to prevent PQ violations. The DR scheduling is never rejected, but rather adapted. Appendix B, Figure 26 presents the scheme of intelligent TLS algorithm scheme.

5 - Grid description

This chapter presents a description of the type of grid and its implementation on OpenDSS. The most important parameters and grid components are also described.

From high voltage (HV) level, two transformers supply energy to separated networks. One medium voltage (MV) network has urban characteristics and the others represents rural area. In MV networks HV/MV transformers supplies several feeders, which have attached load, generation and distribution MV/LV substations. A small scheme to a better understand can be found on Figure 27, Appendix B. My focus in this dissertation is one of the LV networks that is fully defined and is a matter of investigation.

5.1 - LV Urban network

The objective of the Distribution Network (DN) is to distribute the electric energy to the final consumers. Traditionally, they operate as radial networks with energy flows from the transmission network to the loads, which are connected to the distribution network. Most DRES units are connected on DN at low and medium voltage levels. The International Electrotechnical Commission (IEC) has classified the voltages into the following levels: Low voltage – up to 1 kV and Medium voltage – 1 kV to 35 kV, [16].

As greater the load current and conductor impedance, the larger the voltage drop will be. On MV distribution networks the load current is smaller than in LV networks, resulting in a smaller voltage drop, eliminating the need of oversized conductors and improving the efficiency of the overall system. If a LV network has long feeders, they should be oversized to compensate the conductor impedance. A major advantage of MV- over LV- connected units is a lower current flow for a given output power. Hence, the type of network in terms of voltage will affect the voltage control and security of supply, related to the distribution network. In these simulations, the used distribution network is a LV model [17].

Low voltage networks of urban areas have relatively shorter feeders when compared to rural areas. On INCREASE and STORY projects a research about the feeder information was performed for four different countries from UE. The Table 3 show us the study results.

Table 3 – Feeder information in urban LV networks, [18]

Country	Number of feeders	Average length [m]	Load nodes/feeder
Finland	9	100 – 200	30
Belgium	4 - 8	200 – 600	10 - 35
Slovenia	5 - 10	100 – 200	80 - 100
Spain	N/A	100 - 170	N/A

From the research and for the simulations assumptions, these measures from collected data were taken into account to build the synthetic urban LV grid. The parameters of the transformers used was also a target of the study conducted on STORY project, since each country use transformers with different parameters. In Table 4 those different parameters for the same countries assessed before, can be observed, and also were taken into account in our simulation environment.

Table 4 – Transformer information in urban area, [18]

Country	Rated power [kVA]	Voltage level [kV]	Loading rate [%]
Finland	500	20/0.4	17
Belgium	160, 250, 400	10/0.4	50 – 60
Slovenia	400 - 1250	20/0.4	50 – 60
Spain	250, 400	30-10/0.4	50 – 70

The urban distribution network has a radial configuration, mostly with underground cables, frequently with interconnections and the overall feeder lengths are shorter than in rural networks and the amount of load nodes is higher. These characteristics make the urban network less susceptible to impacts related with voltage control, line congestion and security supply than rural networks, which predominantly have long radial overhead feeders.

Underground cables are usually used in low and medium voltage distribution networks and also to connect power plants to substations, whereas overhead (OH) lines are used to transmit electrical energy in high voltage transmission systems. The use of underground cables is only justified under special circumstances like wide river crossing, densely populated urban areas of major environmental concern, due the high cost and technical problems associated with the capacitive charging current [17].

Due the fact of underground cables are stronger in adverse situations such snow storms, high winds and falling trees, they help to improve the electrical grid´s reliability when compared with OH lines. However, they are not immune to all storms and others extreme weather conditions. The initial cost of underground cables is higher, but the operation costs over its lifetime can be lower. One advantage of OH line is the easy replacement and reparation compared to underground cables. The considered network is of urban type, so the most connection are done by underground cables.

5.2 - Simulation Network description

The network model used in the simulations is a LV [0.4kV] residential urban network and similar to the distribution network of the DSO Elektro Gorenjska in Slovenia. Due some problems related with converging errors on Matlab simulations, the original network with eight feeders had to be reduced to a new network with six feeders. The grid design is present on Figure 3 to a better understand and a global vision of the network used in simulations.

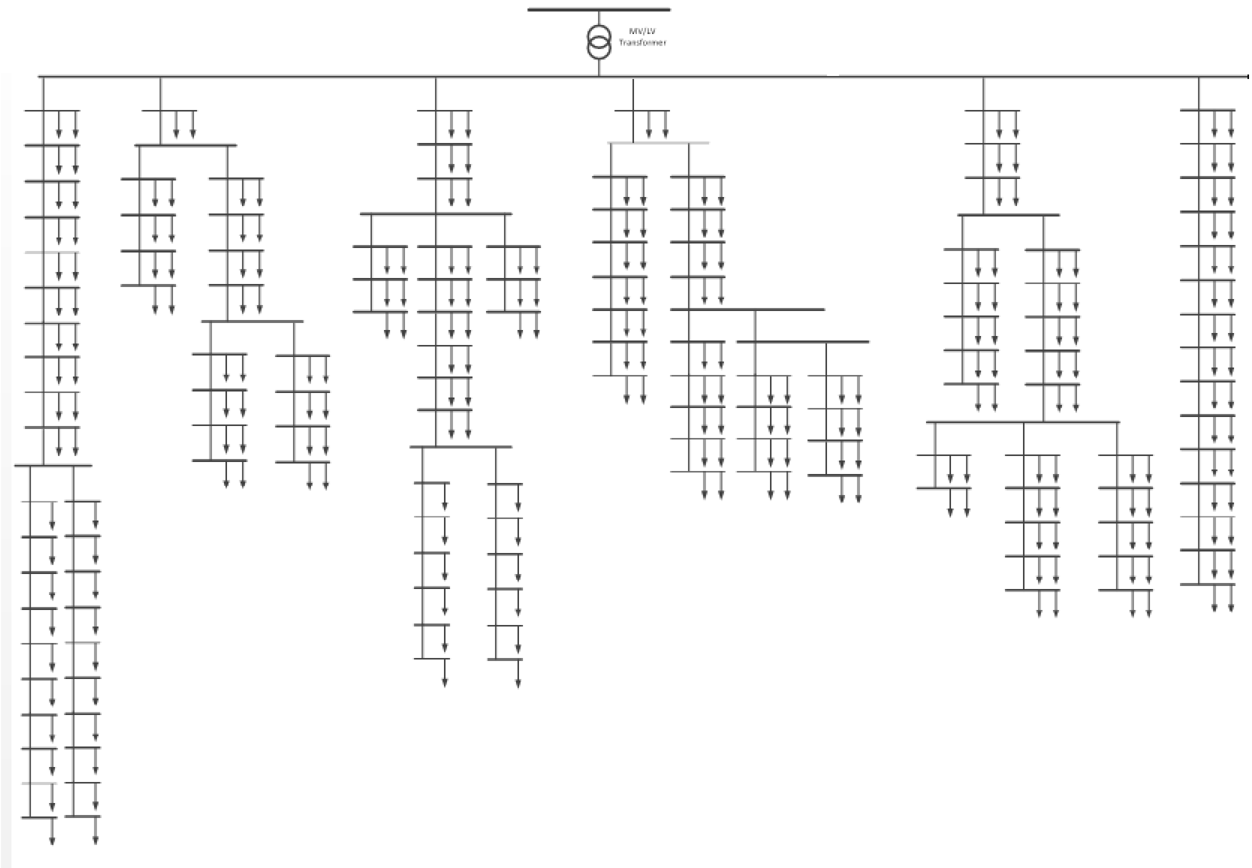

Figure 3 - Synthetic network design

The Figure 3 presents the used LV Urban network that consist of 6 feeders, supplying 30 to 50 loads each one with a total of 139 nodes. Feeders are designed to operate radially and vary in branch structure and length.

Lines: There are three types of lines used in OpenDSS code to build the grid. The first (3x35mm²+50mm², and also 3x50mm²+70mm²) and second (3x25mm²+35mm²) types will be used to the main feeder, and the third type (3x16/25) for lines between point of common coupling (PCC) and load/source. The lines were designed in the code as Feeder+feeder number+section. The entire feeder section length is 400m and the lines have 4 phases.

The parameters are R1=0,44Ω, X1=0.082Ω, R0=1.772Ω, X0=0.246Ω, C1=0.25F, C0=0.25F. The used line lengths are 0.0194km, 0.0364km, 0.0235km, 0.0334km, 0.0265km. Part of the code to build the lines is presented in the Appendix B, Figure 28.

Transformer: It is as Delta-y connection three-phase transformer with 250kVA (21/0.4kV) connected to MV grid and a frequency of 50Hz. More information about the code implemented can be found in Appendix B, Figure 29.

Loads: All the loads connected on the network are 3-phase load with 0.23kV, being Vmin=0.9p.u. and Vmax=1.1p.u. In Appendix B, Figure 30 it is possible to check the OpenDSS code to configure and install the loads.

On the Table 5 it is summarized the number of loads per feeder and the total loads on the network used for simulations:

Table 5 – Number of nodes and loads

Feeder Number	Number of loads per feeder	Number of nodes per feeder
1	40	30
2	34	17
3	42	27
4	50	25
5	50	25
6	30	15
Total	246	139

PV units: The PV units were evenly distributed between the feeders and connected with 3-phase inverter and constant factor Cos φ = 1. Each PV unit installed has 20kWp.

DR units: Demand response units are installed in some loads and they have an available power of 7kW each one, and are implemented in the grid like the PV units.

6 - Simulation Model Description

The grid described in the previous chapter was used on the simulations environment. However, several extremely important assumptions were defined and used. These assumptions are going to be present below. To perform the simulations, first the synthetic network model for power flow calculations had to be built on OpenDSS, where the network topology and transmission elements such power lines, loads, generators and transformers are also implemented in OpenDSS code, like it was mentioned in the grid description.

The power flows calculations are exported to Matlab, where the time series for loads, PV and DR units are included, as well all algorithms of inverter controls, scheduling and traffic light systems. The next flowchart, Figure 4, give a better idea about the simulation process.

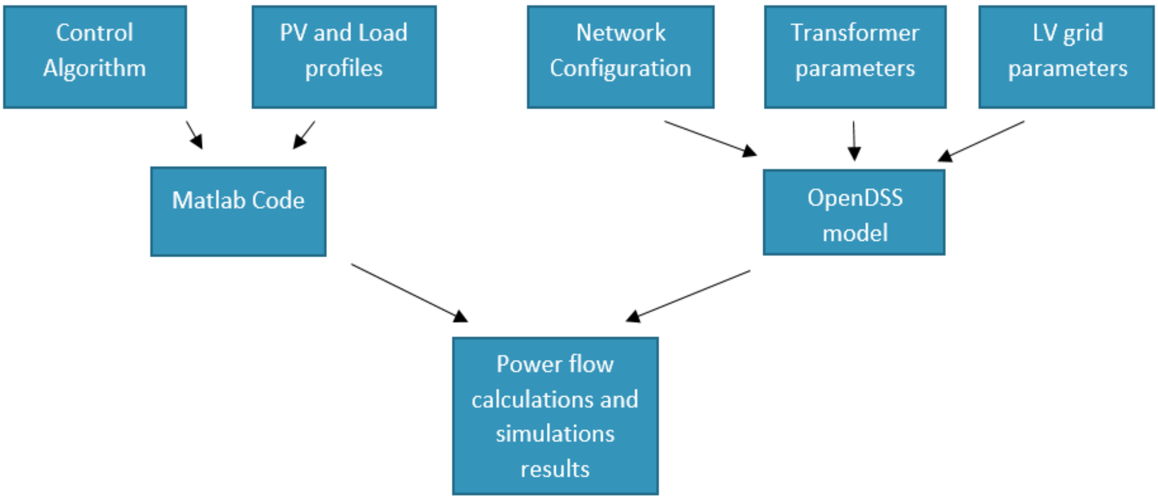

Figure 4 – Simulations flowchart

The simulations take into account:

- Season
- Control type
- Scenario
- DR Scheduling Optimization
- DR Traffic Light System

Season: The simulations were implemented for two different and opposite seasons of the year, summer and winter. This choice was made thinking about the extreme conditions of PV generation and load profiles in a way to give evidence and assess the differences between the control strategies. In the summer the radiation of PV units is higher, thus the PV generation is higher too.

In winter, the PV generation decreases due the lower solar radiation of PV units. Load profiles are different in summer and winter, due to the fluctuation on electricity demand. Typically the electricity demand fluctuates a lot during the day and across the week, but generally is higher in the winter. The PV generation profiles are presented in Appendix B, Figure 31 and 32, summer and winter respectively. Load profiles are presented in Appendix B, Figure 33 for summer and Figure 34 for winter.

<u>Scenario</u>: The scenarios are useful to assess which is the best option regarding the ratio of PV units and DR units. The total number of scenarios is five, the fist scenario has 12 PV units and 6 DR units, and in each next scenario more 12 PV units and 6 DR units, which are aleatory distributed by the feeders on the grid, are incremented. In the Figure 5 it is possible to see the local where the PV units and DR units were installed.

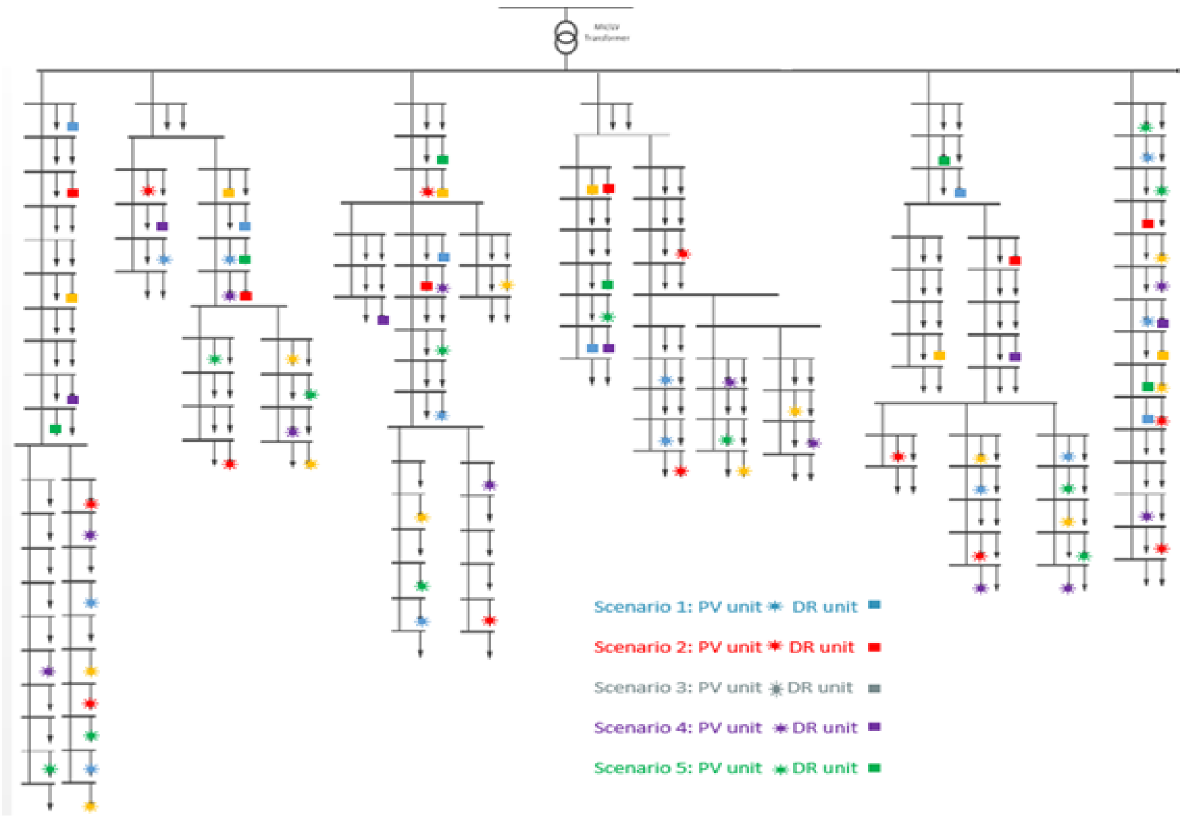

Figure 5 – Localization of PV and DR units

The percentage of DRES penetration is calculated by dividing the number of network nodes with PV units installed by the total number of network nodes, which is 139. In the same way, the percentage of DR penetration was defined. In the Table 6 it is summarized all the differences for each scenario.

Table 6 – Installed power and penetration levels of PV and DR units.

Scenario	Nr of PV installed	Installed PV Power [kWp]	DRES (PV) penetration [%]	Nr of DR units	Available DR power [kW]	DR penetration [%]
1	12	240	8,63	6	42	4,31
2	24	480	17,27	12	84	8,63
3	36	720	25,89	18	126	12,95
4	48	960	35,53	24	168	17,27
5	60	1200	43,17	30	210	21,58

Each run of the simulation platform includes the results about the generation of each PV unit (already curtailed), voltages per each node and losses in the network, for each 5 minute instance for the whole typical week of the selected season. For simulations of DR, in addition to all above information, the results also include the final DR schedule. That data are going to be use in Matlab scripts developed to analyse the results, for all possible technical simulations described above. Matlab files developed and implement to analyse and process the data collected are presented in Appendix B, Figures 35 and 36. Those Matlab scripts have the objective to compare the different control strategies for the different evaluated scenarios.

6.1 - Simulation assumptions

The following assumptions were taken into account in our simulations [19]:

- *"Voltage limits: standard limits are set to [0.9, 1.1] p.u.*
    - *Inverter control, which activates curtailment of PV generation in case of overvoltage, activates droop control on interval from [1.06, 1.10] p.u.*
- *Control strategies:*
    - *Simple control disconnects PV plant from the grid (setting its generation to 0) when voltage level in PV node exceeds 1.10 p.u.*
    - *All of the voltage controls are activated before congestion control, which is activated in case there is line congestion but no PQ violations.*
- *Data for the time series:*
    - *The modelled network was a segment urban LV network with six feeders, based in a grid from Slovenia*, [20].
    - *The base hourly values for a typical daily diagram of PV and load units were obtained from the real measurements of the modelled LV network. To obtain the load diagrams for the rest of the PV units and loads the typical daily diagrams were scaled*

according to its installed power and assigned to units of the same type. A small noise component was added as a variation of the typical values in a range of ±10 % around the original profile in each time instance.

- *DR unit scheduling:*
  - *DR unit's TOU was predefined for each unit and based on the following options:*
    - *Time of availability of each unit was randomly assigned. TOU of fully flexible loads was set to 24 h per day, and TOU of loads with constrained flexibility to 12 h per day.*
    - *DR unit in a given hour could only operate at maximum power or not at all.*
    - *Energy and power constraints of DR units were set so that the DR unit was unable to operate in all hours within the TOU.*
  - *Schedule was optimized using a chosen objective function: economic or energy optimization.*
  - *Initial schedule was hourly based, due to fact that DR units participate in day-ahead market.*
  - *When using intelligent TLS, DR units don't have initial schedule.*
    - *SCA was able to fully commit DR unit to mitigation of PQ violations.*
    - *In this case DR units schedule was defined for 15 minute intervals, which is the interval of voltage control and congestion control."*

This assumptions for simulations were used in INCREASE project.

<u>6.1.1 - Loads</u>

Loads are defined as 3-phase and the consumption is equally distributed by the 3-phases. The time series for unmetered loads were generate using real measure data of Slovenia, like it was said before. For every season, five base load profiles for different installed capacities were created, differing in average consumption, Table 7.

Table 7 – Base load profiles

Base load profile	Average hourly consumption (kWh)	Assigned installed power (kW)
1	0.33	6
2	0.5197	11
3	0.7639	14
4	0.935	17
5	1.065	24

For generating additional loads profiles of the same type, these base load profiles were scaled like pervious described in assumptions of *Data for time series*. After that, the loads profiles are assign to the distributed loads in the grid based on their installed power. Total sum of loads less the PV generation in the same slot time must fit in the measured load value of the transformer (Elektro Gorenjska) on LV side. Figure 6 show the method used to ensure the loads scale.

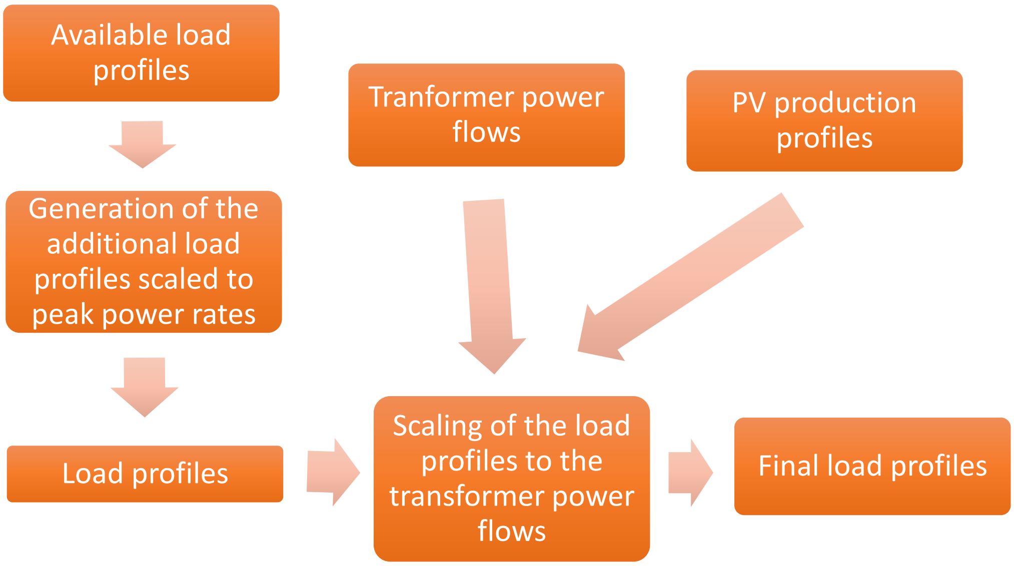

Figure 6 – Scaling of loads profiles

6.1.2 - PV time series

The PV generation was also taken from real measurements data of installed PV from Elektro Gorenjska network. Two different PV production time series in a time span of one week for both seasons were taken. The PV generation of unit is shown in Appendix B, Figure 31 and 32. The data was standardized on 1kW and then scaled accordingly to PV unit installed power. For the next scenarios, the addition PV units were generated with 10% variation from base generating profile, and PV units were randomly distributed throughout the network. In the simulations the PV generation is equally distributed between the 3 phases.

6.1.3 - DR scenarios

To simulate the DR units it was used loads which have two components: non-responsive load, the case of house appliances that is impossible to control, and a controllable load, following a typical hourly load profile. The role of the consumers in the DR program is to participate by variating the flexible load component. Each unit has also defined the DR parameters (Time of Use, Energy constraints, Installed power and Internal price) like was explained on sub-chapter 4.3, DR units´ parameters. For every single DR unit, SCA creates a schedule based on units´ TOU, generation and consumption, market prices and optimization function. Since SCA has the control over the DR unit, it was assumed an instantaneous and an activation failure rate of 0. These assumptions are sufficiently realistic for the purpose of these simulations.

6.1.4 - Inverter Control types

In the simulations three different inverter control types were tested with the following characteristics [19]:

- No Control (NC): The network do not have any type of control and the PV units operate at full production without any kind of regulation or control. In case of PQ violations, all PV units are not curtailed, which means, no PQ violations mitigation. Appendix B, Figure 37 presents the voltage (p.u.) graph, revealing the absence of voltage control.
- Simple Control (SiC): When voltage in the point of connection of the PV rises above the voltage limitation in the network, the inverter curtails active power output of power plant to zero. It can be summarized as a simple On/Off control. The threshold for the SiC activation is 1.1 p.u, how can be visible on Appendix B, Figure 38.
- Local Control (LC): The PV generation is managed by the installed inverter control. When PQ violations occurs, the inverter execute a partial curtailment of the PV generation, according to the specific droop curve of the unit. The reduction of curtailment leads to an increased on the renewable electricity injection, when compared with the Simple Control. The partial curtailment of LC is activated at 1.06 p.u, and it is visible on Appendix B, Figure 39.

  With the installation of a new 3-phase inverter, this control also tackle the voltage unbalance, distributing the active power between the phases and decreasing the voltage unbalance.

6.1.5 - Forecasting

The forecasting has an important role in these simulations, since it is essential for DR scheduling and schedule optimizations. In the project a 100% accurate forecasting was used. DSO performs the PQ violations check based on that forecast, including TLS control. Traffic light system control will check the DR schedule compliance. If the schedule is optimized in a proper way, PQ violations will be mitigated or profits maximized, depending on the selected optimization type. On the other hand if a non-compliance is detected, the information is sent to the SCA that adjusts the DR deployment schedules if necessary.

6.2 - Services Investigated

The Ancillary Services that will be investigated were developed to facilitate the integration of DRES in distribution networks, to improve the DN operational security and to provide solutions to the grid challenges. The main aspects used in AS assessment are:

- PV electricity injection
- Revenue
- Costs of Emissions
- Local Supply Adequacy

6.2.1 - Basic Service

It provide voltage control, voltage unbalance mitigation and current congestion (CC) with the installation of advanced inverters or upgrading the existing old ones. VC and CC provision requires the software update of conventional converters, but for provision of VUM is necessary the installation of new advances inverters (VC and CC also provided by advanced inverters).The addition of the Local Control already described, allow a smoothly reduction of PV electricity injection in case of PQ violations, instead of a simple “on/off” provided by fully curtailment of Simple Control.

6.2.2 - Scheduling Service

Scheduling Service is an upgrade of the Basic Service by including scheduling control to Demand Response units. This service assesses the effects of SC application of DR unit schedules on the provision aspects of VC, VUM, CC and active power reserve. The provision of the scheduling service dependent on the type of inverters installed on PV units, like in basic service case.

The next assumptions were used [20]:

- *“Summer and winter seasons (extremes)*
- *Simple TLS is used to exclude the TLS influence on the results*
- *SC with an economic optimization is used “*

6.2.3 - Balancing Service

With the Scheduling Service already implemented, the Balancing Service bring the option to choose between two optimization objective functions:

- Economic optimization: DR unit are scheduled to maximize the profit.
- Energy optimization: DR units are scheduled to maximize the PV electricity injected.

The following assumptions were made [20]:

- *“Summer and winter seasons (extremes)*
- *Simple TLS is used to exclude influence on the results*
- *Scheduling optimizations are compared between each other*
- *100% forecast accuracy was assumed for economic and energy optimization”*

6.2.4 - TLS Service

The TLS is added to the scheduling control in order to ensure that the additional PQ violations do not arise due the DR schedule. In this way, it is possible to maintain a secure operation in the grid. TLS types enable DSO to steer the scheduling of DR units in order to minimize the PV generation curtailment. This service assess the effect of using different TLS systems, Simple, Advanced and Intelligent.

The following assumptions were used [20]:

- *“ Summer and winter seasons (extremes)*
- *Assumed forecast of 100%*
- *TLS options were compared to No TLS option as the base case.”*

7 - Results

This chapter presents an analysis of the simulations results, followed by an assessment of the different control strategies and the impact of the new services.

7.1 - PV Electricity Injection

Due the smart control strategies to reduce the curtailment of PV units, they are able to inject more electricity into the grid. Through power flow simulations it is possible to calculate the different amounts of PV electricity injection, by the different control strategies.

Actually, to keep the voltage levels in the LV network within the limits, the active power is fully curtailed when the voltage is above the limit. If this situation happens, the PV unit owner loses its income during the curtailment period and a significant amount of energy is lost. In order to avoid that loss of energy the advanced inverter installed on the PV unit runs the LC control that execute the partially curtailment in case of PQ violations. The Scheduling Control can be used to schedule the DR units and reduce their electricity demand in case of undervoltages and by increasing the electricity demand in overvoltage cases.

7.1.1 - Basic Service

In this service there is no DR units, which means none of Scheduling Service or TLS system is implemented. It is about upgrading the inverter and show the results for PV electricity injection in different scenarios. With this comparison it is pretended to evidence the main differences between the two control strategies, SiC and LC in comparison with the absence of control strategy scenario, No Control (NC).

Figure 7 presents the results of PV Electricity Injection during one week in summer and winter. It is also possible to observe the results with more detail in the Appendix B, Table 22. It is possible to check the amount of energy injected with the different control strategies and in different and progressive PV penetration scenarios.

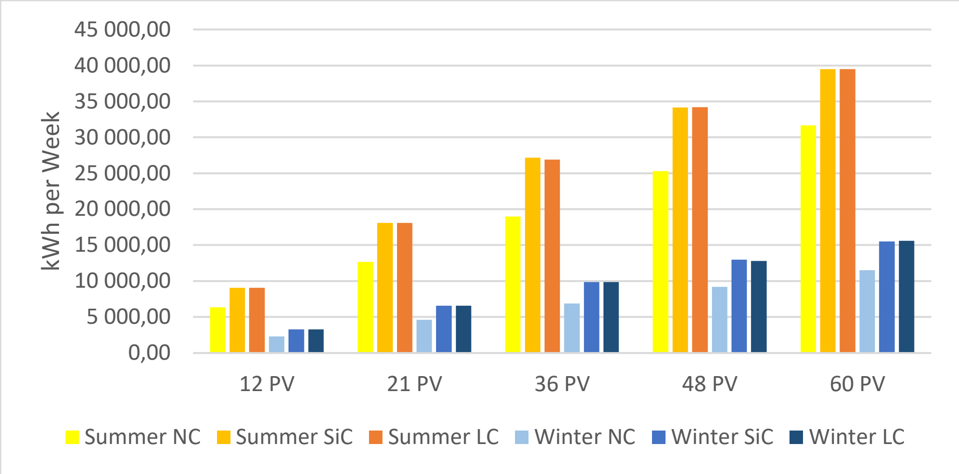

Figure 7 - PV electricity injection comparing SiC and LC to NC, summer and winter

Evaluating the results from Figure 7 it is evident the difference of renewable energy injected into the grid with the different control types. The results without control strategy (NC) for all PV scenarios and both seasons, show a lower amount of electricity in comparison to the results with SiC and LC control, for the same correspondent time period, scenarios and season. This situation happens due the curtailment strategies implemented (SiC and LC controls) on the PV inverter, increasing the renewable energy injection. In No Control the PV units operate at full production without any control or regulation, even in case of PQ violations occurs the PV units are still active without curtailment, which means a lot of energy lost, that is not injected on the grid due the grid limitations. In Figure 8 it is possible to observe with more detail the higher amount of renewable energy injected into the grid using SiC and LC controls, in comparison with my base case, No Control situation.

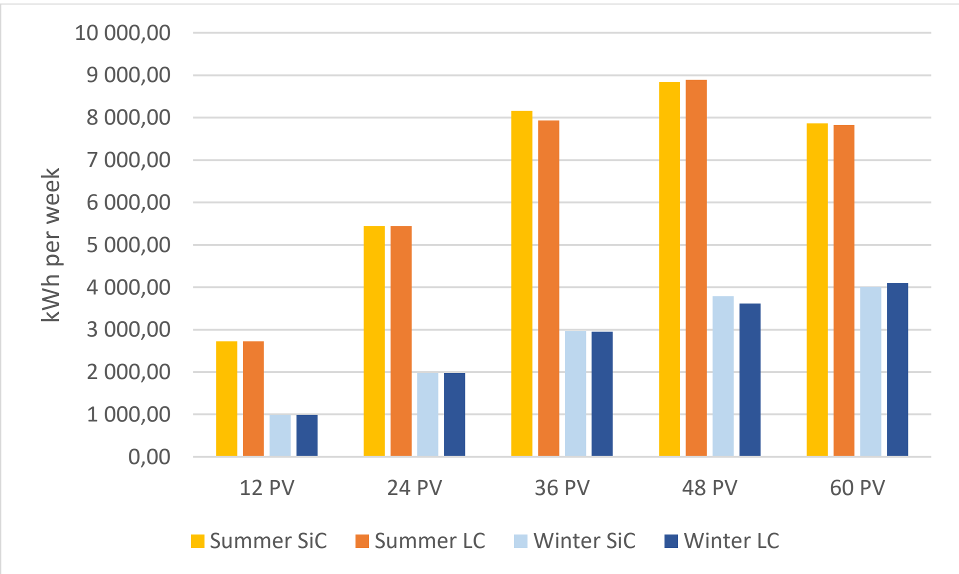

Figure 8 – The difference of PV Electricity injection with SiC and LC, compared do NC

It is visible the increase of electricity injected in the grid compared to NC situation through the progressive PV penetration, simultaneously during summer and winter. However, in the summer scenario with 60 PV units it is possible to see a decrease of electricity injection from SiC and LC in comparison to NC. This happens because the production get curtailed due the high voltage and grid limitations, translated in more frequent PQ violations, which are not problematic on the previous scenarios. This fact means higher levels of lost energy, and a good solution for this problem can be a small-scale storage system connected to the PV unit. Appendix A presents some solutions and advantages that storage systems can offer when implemented on the distribution grid.

The highest difference to No control situation is achieved in summer season at the scenario with 48 PV installed, with an increase of 8 842 kWh for SiC and 8 890 kWh for LC during one week.

The differences between SiC and LC are not so evident, as expected but in some scenarios it is visible less green energy injection from LC compared to SiC (scenarios with 36 PV and 60 PV), due to the different strategies implemented. LC starts a partial curtailment when the voltage reaches 1.06 p.u., while SiC control shuts down the PV generation when the voltage level reaches 1.1 p.u.

7.1.2 - Scheduling Service

In this case the demand response units are added to the distribution network. The Scheduling Service using an Economic optimization and Simple traffic light system (TLS1) is going to be compared with Basic Service, for the same scenarios and seasons (summer and winter), to demonstrate the impact of demand response implementation in PV electricity injection into the network. Table 8 presents such comparison for a period of one week. The DR units´ implementation decrease the voltage level, and therefore an increase on PV injection is expected.

Table 8 – Difference of the PV injection (kWh) between the scenarios with and without DR units, summer and winter

Scenario	Summer			Winter		
	NC	SiC	LC	NC	SiC	LC
12PV/6DR	0,00	0,00	0,00	0,00	0,00	0,00
24PV/12DR	0,00	0,00	0,00	0,00	0,00	0,00
36PV/18DR	0,00	0,00	73,00	0,00	0,00	13,70
48PV/24DR	4,00	540,00	461,00	0,00	133,00	196,00
60PV/30DR	-1 582,00	-143,00	875,00	0,00	591,00	432,00

With No Control and 48 PV/24 DR scenario during summer it is visible an electricity injection increase of 4 kWh/week compared to Figure 7 (Basic Service) caused by DR implementation effect over the voltage level. However, in the last scenario there is a huge waste of PV energy (-1582 kWh/week) due to the rise of PQ violations and the absence of curtailment strategy with NC.

In the 36PV/18DR scenario it is already visible the enable of Local Control curtailment strategy and the lower voltage profile due the DR implementation, which allow an increase of 73 kWh per week during summer and 13,4 kWh per week on winter season. In the follows scenarios the increase of renewable energy continues for higher values of PV generation and DR.

With scenario 4 (48PV/24DR) on summer season the SiC has an increase in electricity injection (540 kWh) due the impact of DR on the voltage decrease, so the curtailment "on/off" will occur later. However, in the next scenario (60 PV/30DR) there is a decrease of electricity injection, that is justified by the fully curtailment of SiC due the increase of PQ violations. On the same scenarios (4 and 5) but during winter, the curtailment of SiC has a later first curtailment due to the lower voltage level profile, which allow an increase on electricity injection in the last 2 scenarios.

In the last scenario, the higher injection of SiC compared with LC control is caused by the later curtailment and lower voltage profile during winter, allowing a better performance of SiC control in this case, as explained on Basic Service.

The observations for Local Control show global better results of injection in medium and high PV penetration scenarios, starting at scenario 3, in both seasons. The reason behind this observation is the effect of DR unit schedule that results in a lower voltage profile and a later and less partial PV curtailment, which allow more energy injection.

7.1.3 - Balancing Service

In this service an evaluation of the two different optimizations, Economic and Energy, is performed by simulations. With the economic optimization, all DR units are scheduled to maximize the profit, oppositely in the energy optimization, where the DR units are scheduled to maximize the PV electricity injection and avoid PQ violations.

Figure 9 show the difference of electricity injected with energy optimization schedule and the economic optimization, both with Simple TLS and 100% forecast accuracy, to observe the increase of injection when the energy optimization is selected.

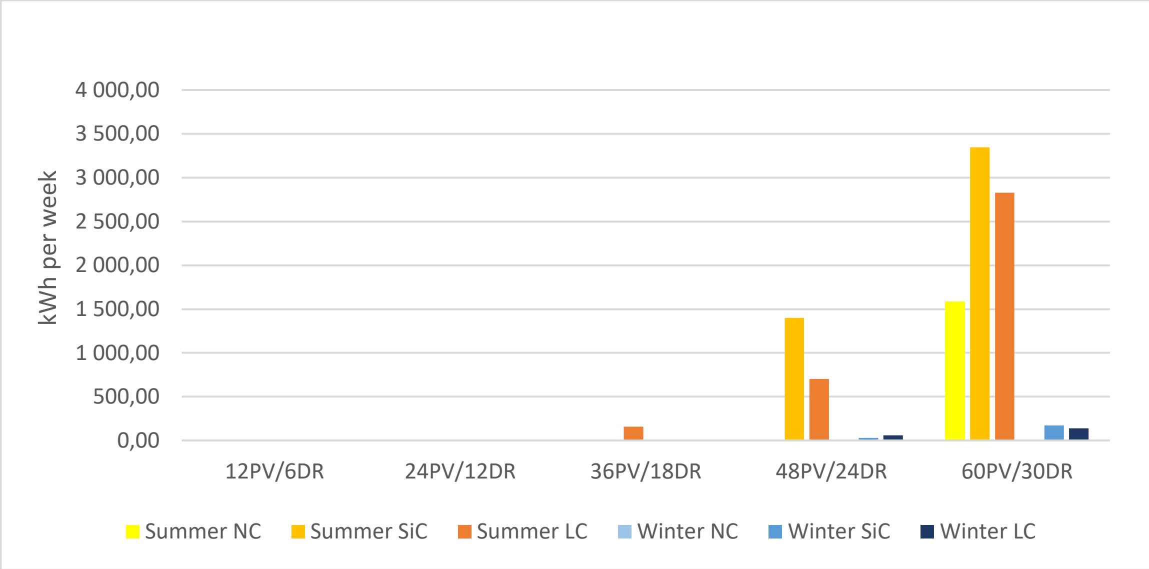

Figure 9 – Difference between Energy and Economic optimizations in terms of PV injection, summer and winter

With Energy optimization there is always more PV injected energy than with Economic optimization for medium and high PV penetration scenarios. This is due lower energy differences between production and consumption and also the reduction of PQ violations (target of energy optimization algorithm) that allow a higher injection of energy, since less production is curtailed.

In this comparison it is also important mention that economic optimization aims the profit, and sometimes the profit is not achieved with more PV injection, due the impact of the energy market prices on consumption.

In the two first scenarios, in both seasons, the electricity injection with energy and economic schedule is the same, indicating no PQ violations occurred in those simulations, so no curtailment was enable for both control strategies.

On scenario 3 (36PV/18DR) for both seasons it is already visible the benefits of energy optimization allied with partial curtailment from Local Control, allowing an increase of energy injection. In winter season it is also perceptible an increase caused by energy optimization, however the values in winter are lower, due to the reduced solar radiation on PV units.

In the last scenarios for summer season, SiC show better results than LC due to the later curtailment at 1.1 p.u. instead of 1.06 p.u. of LC. The partial curtailment cannot provide so much energy to compensate the “on/off” curtailment of SiC with energy optimization associated.

7.1.4 - TLS Service

TLS aims the comparison of the effectiveness between different traffic light systems. The results of simulations are compared with the results of economic scheduling optimization without TLS (TLS0), where DR schedules are simply accepted and any resulting PQ violations are resolved by the control strategies through PV curtailment. First, on Figure 10 the results for summer season are presented.

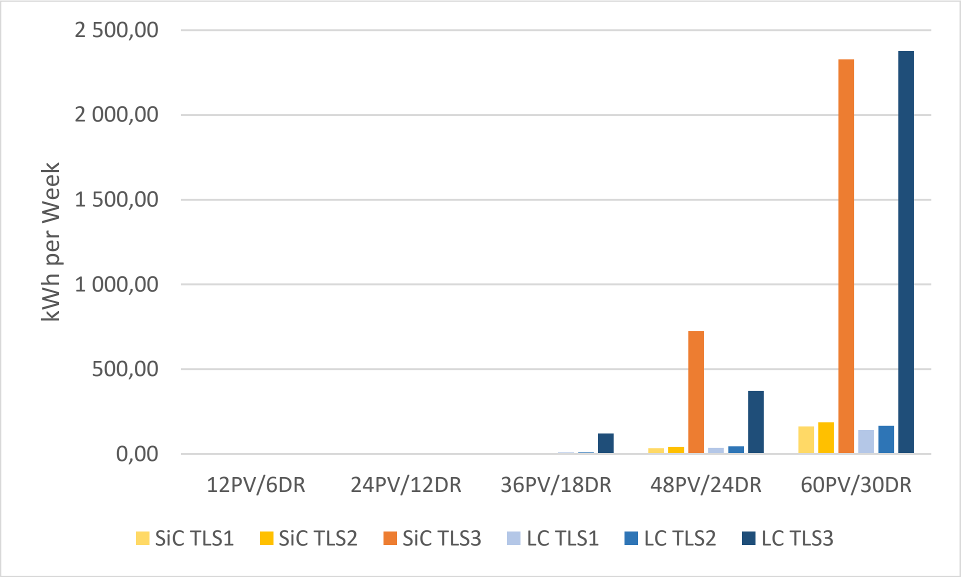

Figure 10 - PV injection comparison on SC Economic using different TLS, summer

In Figure 10, in general, it is patent that the injected energy increase with the new traffic light systems when compared with No TLS (TLS0). It is evident the benefit of Intelligent Traffic Light System (TLS3) for medium/high PV penetration, translated in more injected energy, due the intelligent scheduling and algorithm. In the last scenario, the differences between TLS3 and TLS1 and TLS2 are very drastic, around 2 200 kWh using either SiC or either LC.

On the last scenario (48PV/24DR) the TLS3 with SiC reveals to be more efficient, so it can be concluded, that for this level of PV and DR penetration, the SiC allied with TLS3 is more efficient than the LC. However, in the last scenario the LC control shows a better performance with TLS3.

As expected the Intelligent TLS bring more PV energy injection due the flexibility on demand scheduling to mitigate PQ violations.

Figure 11 presents the TLS effect for winter season.

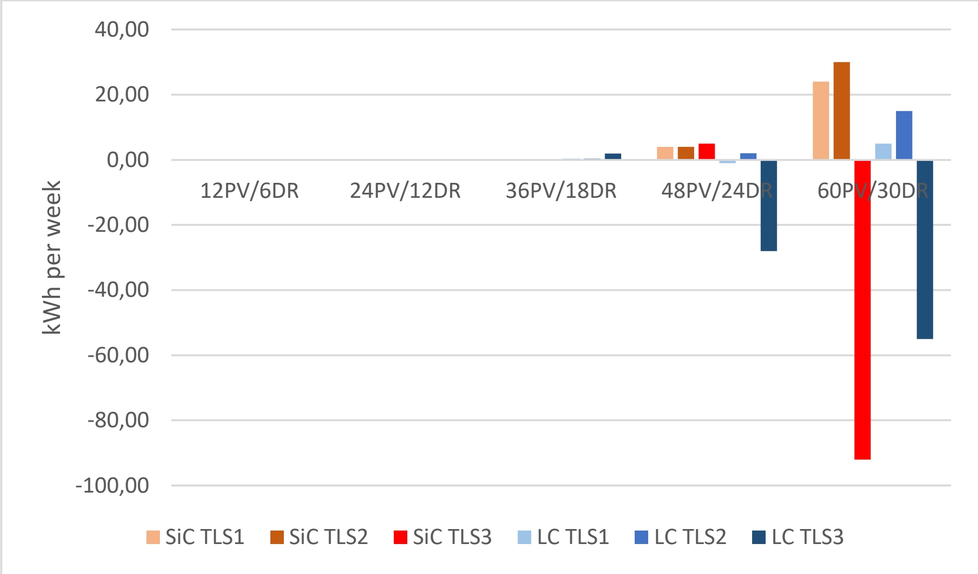

Figure 11 - PV injection comparison on SC Economic optimization using different TLS, winter

The results show an increase of injection on high PV penetration scenarios with TL1 and TLS2 using SiC and LC controls due to the demand scheduling strategy.

However, the intelligent TLS results are worse in winter in winter, when compared with the impact in summer. Due to the lower production rates, consequence of the seasonality conditions, the voltage level rise is overall smaller. Since the TLS3 does not have predefined schedule, which would increase the load consumption, and the fact that TLS3 mechanism is activated when voltage levels are on 1.1 p.u., it does not react effectively compared to simple and advanced TLS.

7.2 - Revenue

In the section PV Electricity Injection, the amount of energy injected by the new control strategies was measured. The section Revenue is going to quantify that energy in euros. For such assessment, a table with the real time energy prices in €/kWh, Appendix B, Table 23 (from the Slovenia Market) and a Matlab script, (Appendix B, Figure 40) was implemented to analyse the simulations and achieve the potential income with PV energy injection and demand response scheduling.

7.2.1 - Basic Service

Figure 12 presents the revenue in € per week in the 3 different situations of control, NC, SiC and LC, for the different PV penetration levels and the extreme seasons of the year, summer and winter.

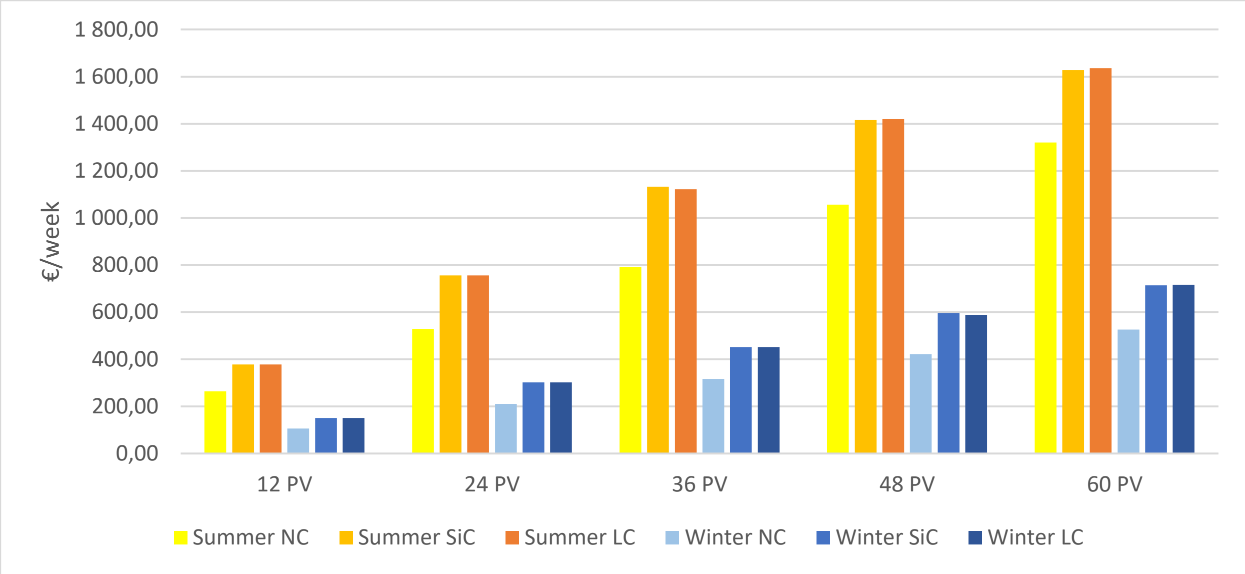

Figure 12 - PV energy revenue for three control types, summer and winter

It is possible to observe the different revenue in €/week with the different controls for all scenarios and seasons. Simple Control and Local Control show a higher income due to the higher PV energy injection caused by the better curtailment strategy. Figure 13 presents the results from the difference of SiC and LC with NC, respectively.

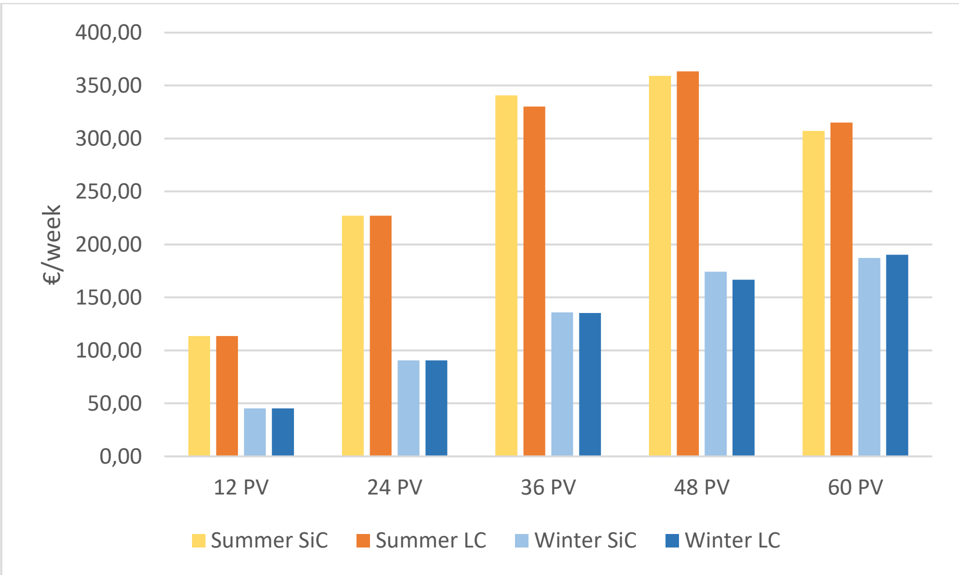

Figure 13 - SiC and LC profits compared to NC, summer and winter

It is easy to notice the improvement and income with SiC and LC control compared to NC. This values are linearly related with the results from Basic Service for PV Electricity Injection. The values from SiC and LC are very similar and in the last scenario of summer it is visible a decrease of revenue that follows the trend of renewable energy injection lost due the grid limitations and higher level of curtailment.

7.2.2 - Scheduling Service

Table 9 show the revenue difference with DR units already installed in comparison with a scenario without DR units (Basic Service).

Table 9 – Income in €/week with SC Service compared to Basic Service, summer and winter

Scenario	Summer			Winter		
	NC	SiC	LC	NC	SiC	LC
12PV/6DR	0,00	0,00	0,00	0,00	0,00	0,00
24PV/12DR	0,00	0,00	0,00	0,00	0,00	0,00
36PV/18DR	0,00	0,00	2,91	0,00	0,00	0,55
48PV/24DR	0,00	20,34	17,93	0,00	5,40	8,25
60PV/30DR	-66,02	-8,03	34,15	0,00	24,53	18,25

With No Control strategy it is not noticed any income, because the amount of electricity injected is the same, except on the last scenario where due to higher voltage levels and the absence of curtailment strategy it is visible a waste of energy and consequently a money loss. SiC and LC in a scenario with SC reveal a higher income compared with Basic Service due to the decrease of voltage caused by the implementation of DR units and, consequently later curtailment. It is also possible to observe the gains with LC on 36PV/18DR scenario for summer and winter seasons.

In the last scenario of summer, it is visible the revenue difference between SiC (-8.03 €/week) compared to LC (+ 34.15 €/week) caused by the different curtailment strategies and DR effect.

7.2.3 - Balancing Service

In the balancing service, the two schedule optimizations are compared. Before of analyse the simulations results it is necessary to remember, that as it is explained in the Scheduling Optimization, chapter 4, the Economic optimization (sub-chapter 4.4) aims the consumption reduction in high prices energy hours and increasing the consumption in lower price hours. In the next results is necessary take into account the fact such income is related only with the PV electricity injection and demand response scheduling effect.

Figure 14 presents the difference of revenue between energy and economic optimizations.

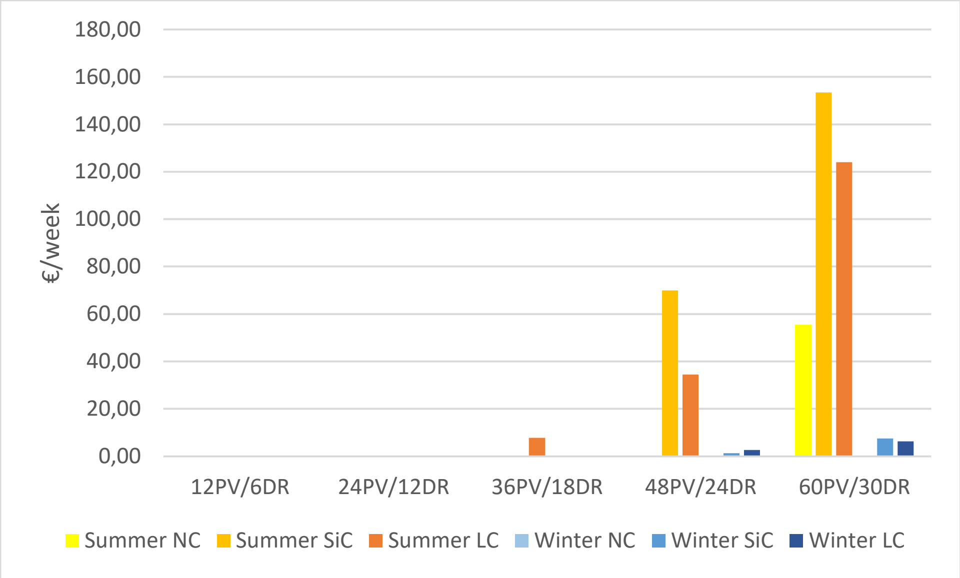

Figure 14 – Revenue difference with Energy Scheduling less Economic Scheduling, summer and winter

According to the expectation, the Energy Optimization reveals better results in comparison with Economic Scheduling. This fact happens due the aim of Energy Optimization that in this case, overrides the Economic, showing a higher income. Since the third scenario on summer season is visible a small income using Local Control. On the following scenarios the revenue becomes higher with the increase of PV penetration and consequently more green energy injection. Looking for summer season and last scenario, about more 153.45 € and 124.01 € per week are reached with SiC and LC respectively. Winter season show lower values, as expected. However on the last scenario almost more 6.20 € per week is reached by the smart controls and energy scheduling.

7.2.4 - TLS Service

Once again, the evaluation from the benefits given by the different traffic light systems is going to be done and presented on Figure 15.

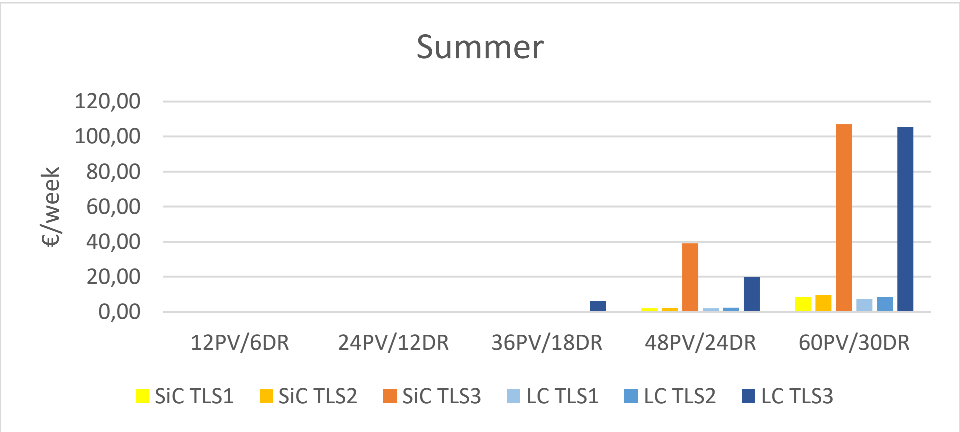

Figure 15 – TLS impact on revenue, summer

As can been seen in Figure 15, once again and following the trend, it is visible the flexibility and adjustability on demand response scheduling performed by Intelligent traffic light system, always allied to the smart PV controls, in this way increasing the income, mainly in the last two scenarios when the PV penetration levels are larger. Compared to TLS0 (no traffic light system) it is observable a high increase, of about more 105 €/week, on 60PV/30DR scenario with SiC and LC controls.

Figure 16 presents the impact of the traffic light system during winter season.

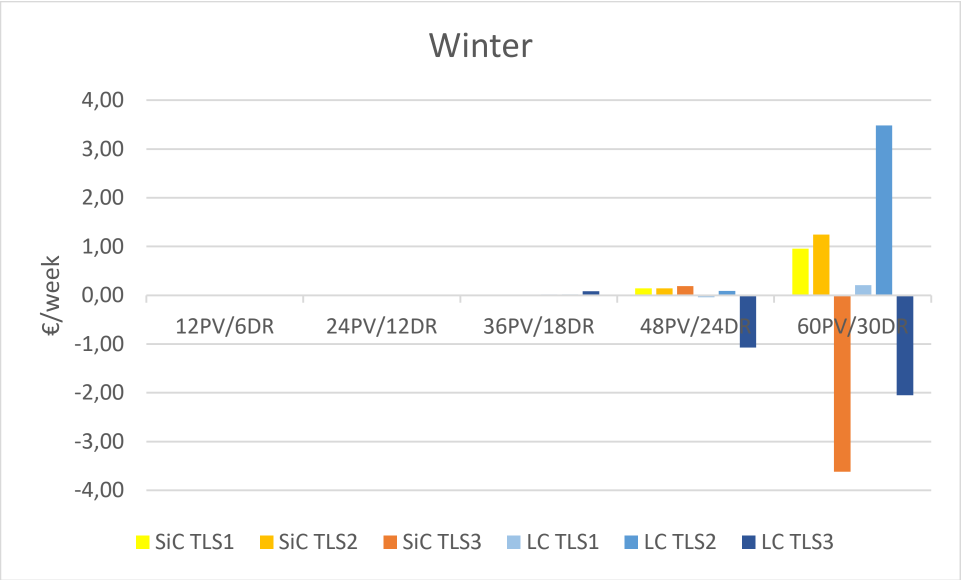

Figure 16 - Impact of TL Systems on green energy injection revenue, winter

For the same reasons, explained on PV electricity Injection and TLS Service, the intelligent TLS show a negative results when allied to SiC and LC for the higher PV penetration scenarios.

The income increase by simple and advanced TLS is still visible. Therefore, it can be concluded that for low voltage profiles like happen in winter days, the prescheduling is also more beneficial for revenue objectives.

7.3 - Emissions Cost

New strategies to improve the efficiency of DRES and reduce Green House Gases (GHG) are required by the governments and society, to combat climate changes, especially in urban areas.

By decreasing the curtailment time of DRES and increasing the renewable energy injection there is a replacement of the energy from conventional power plants, which means less costs associated to emissions of air pollutants. That costs are calculated from avoided GHG emissions. Emissions costs are expressed from a change in emissions due the application of strategies at PV electricity injection level and through the different PV penetration scenarios. The air pollutants taken into consideration are:

- CO_2
- CO
- Fine Particles (PM10)
- NH_3
- NMVOC
- SO_2
- NOx

All these pollutants are differently harmful to the society, so it was necessary to ensure a weighting of importance. Therefore, an Excel Input file (Appendix B, Table 24) on Matlab code was used to calculate the cost saving associated with the reduction of emissions by the PV electricity production and injection.

Figure 17 presents the considered costs for which considered air pollutants. NH_3 is the most expensive pollutant, followed by SO_2 and NOx with almost the same cost per tonne. CO_2 and CO have the lowest costs.

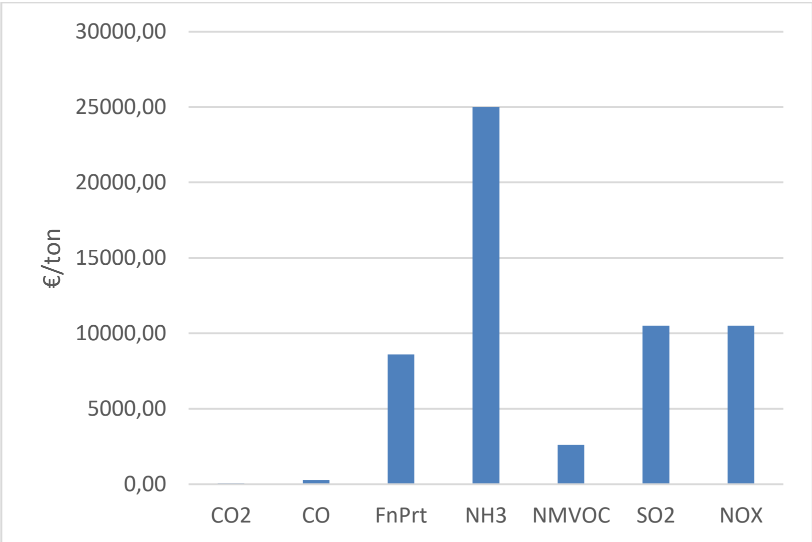

Figure 17 - Different costs associated to the different kinds of air pollutants, INCREASE project, Slovenia market

The simulations results are going to be globally evaluated, including all different kinds of air pollutants that are going to be designed by "emissions". Emissions Costs are the sum of all different gases costs. In this case, it is important to think in the Emissions Costs as costs savings, since the impact to be evaluated is the reduction of costs due to the emissions decrease.

7.3.1 - Basic Service

The costs of the different air pollutant achieved with the different control strategies are presented in Appendix B, for summer in Figure 41 and for winter in Figure 42.

Figure 18 presents the costs saving in emissions using the three different inverter control strategies, NC, SiC and LC.

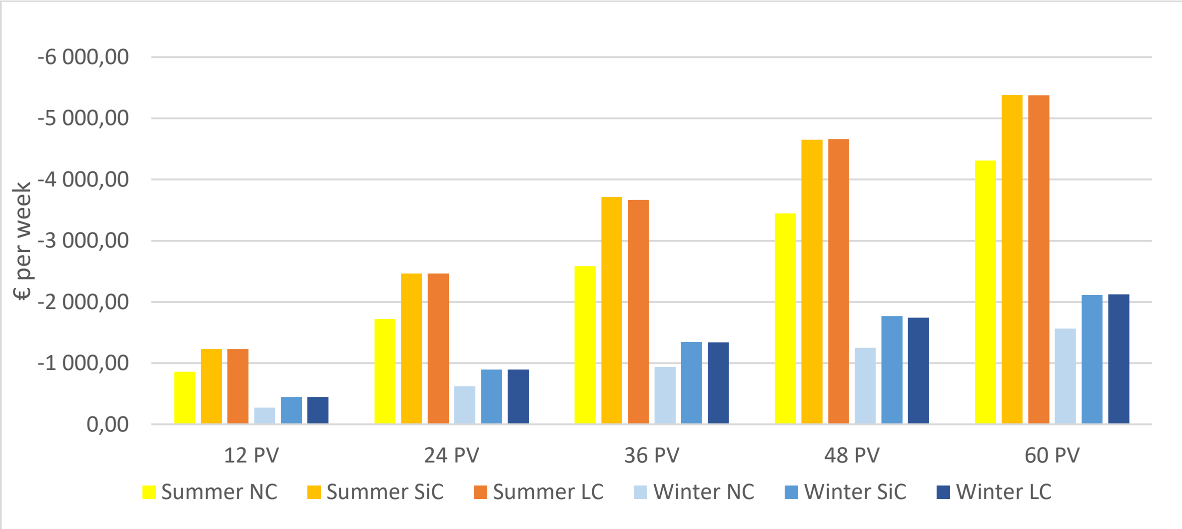

Figure 18 - Emissions cost reduction using the 3 different control strategies, summer and winter

As can be seen there is a reduction of costs associated with GHG emissions, due the higher level of PV penetration and consequently higher renewable energy injected into the grid. It is also observable the difference on cost savings between NC, SiC and LC scenarios, where the last two exhibit a higher reduction of emissions costs. On the last scenario (60 PV) for summer season a reduction of 5 380 €/week is accomplish by SiC and LC, compared to the 4 309 €/week of NC. Of course in summer, due to the higher solar radiation there are better results than in winter, as can be seen in Figure 19 with more detail.

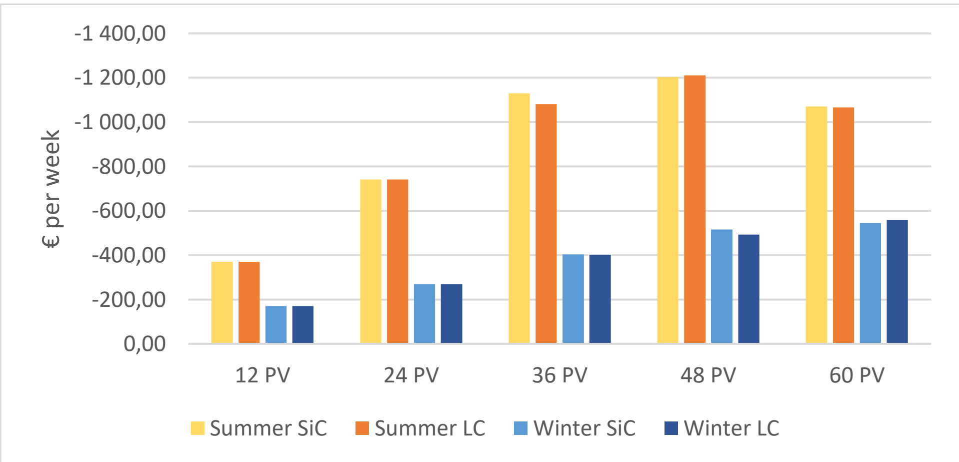

Figure 19 - Emissions Cost Reduction with SiC and LC compared to NC, summer and winter

Compared with NC, the new control strategies (SiC and LC) have higher savings in emissions cost. The maximum occurs in scenario 4, with 48 PV units installed during summer, exhibiting a reduction of 1 210.13 € for LC and 1 203.63 € for SiC. For winter, the higher savings occur in the last scenario, with 545.54 € for SiC and 558.42 € for LC. The emissions saved by both controls in the last scenario show a reduction of emission costs due to the increasing PQ violations and therefore more curtailment and less energy injected, when we compared the SiC and LC with NC.

It is evident the impact of the control strategies (SiC and LC) compared to NC, because there is a strong and linear relation with the increase of PV energy injected that replace the energy from conventional power plants and decrease the emissions and consequently the costs of emissions. So, the analysis for the PV Electricity Injection, Basic Service about control strategies and curtailment can be adopted. As higher is the renewable energy generation injected into the grid, lower are the costs associated with the emissions.

7.3.2 - Scheduling Service

Table 10 presents the results when the DR units are installed in the grid and its impact on emissions associated costs, comparing an Economic Optimization with a Simple traffic light system. The positive values (also green colour) identify the costs savings on emissions.

Table 10 – The difference of cost savings in emissions by Scheduling Service when compared to Basic Service, summer and winter

Scenario	Summer			Winter		
	NC	SiC	LC	NC	SiC	LC
12PV/6DR	0,00	0,00	0,00	0,00	0,00	0,00
24PV/12DR	0,00	0,00	0,00	0,00	0,00	0,00
36PV/18DR	0,00	-17,70	9,75	0,00	0,00	1,86
48PV/24DR	0,00	73,54	62,85	0,00	18,11	26,71
60PV/30DR	-233,18	-19,46	119,16	0,00	80,48	58,86

As can be seen for medium and high PV penetration scenarios, there is a relevant amount of costs savings related with emissions, due to the DR implementation. For Local Control there is a reduction since the third scenario for both seasons. Looking for the results, scheduling service can increase the cost savings from basic service, especially on the last scenario, where there is more 119.16 €/week on summer and 58.86 €/week on winter.

Using SiC control for the last scenario and summer season, there is an increase in emissions costs (-19.46 €/week), due to the decrease of renewable energy injection, as it was already explained on chapter PV Electricity Injection, Scheduling Service.

7.3.3 - Balancing Service

Figure 20 presents the cost savings between Energy and Economic optimizations, for the Balancing Service. As expected, the Energy optimization reveals better values of cost savings related with emissions than Economic Optimization.

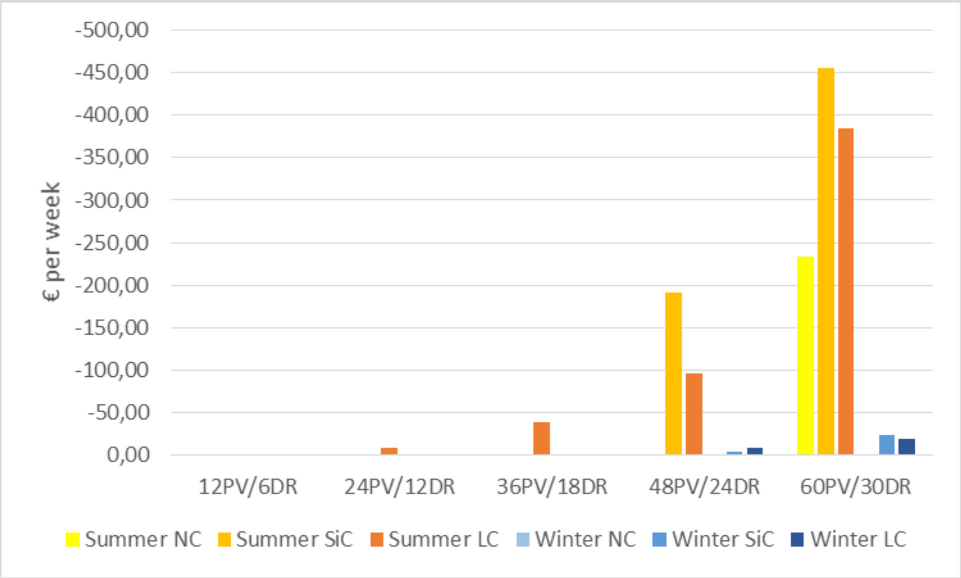

Figure 20 – The difference of money saved on emissions with Energy optimization when compared to Economic optimization, summer and winter

For the analysis of results and comparisons between optimizations, it is used the Energy optimization less the Economic optimization. It is visible the beneficial effect of Energy optimization regarding the Economical scheduling, allowing a higher decrease on emissions costs.

From comparisons, the effect of LC since the low/medium PV penetrations levels until the highest one can be observed, with an increase of the reduction of emissions costs. A reduction about more 455 €/week on emissions costs using SiC and 384.93 €/week with LC control, both with Energy optimization, is obtained when compared with Economic.

In the winter scenarios, the results are not so significant, due to the lower solar radiation during winter days. The maximum reduction on emissions cost was more 18.79 €/week with LC and 23.38 €/week using the simple control, when compared with economic schedule.

7.3.4 - TLS Service

On this evaluation, it is intended to assess the effect of different traffic light systems over emissions and costs. Figure 21 presents the achieved results.

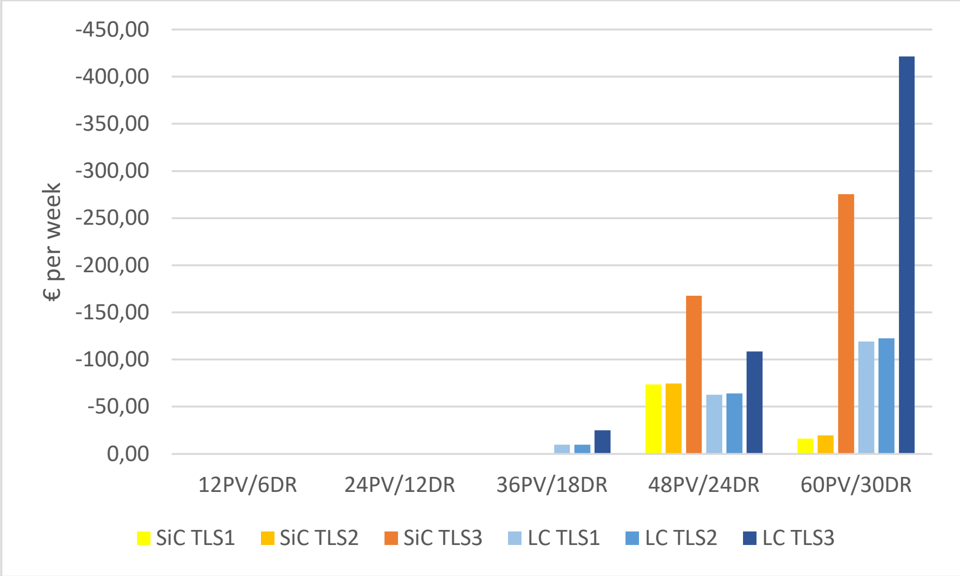

Figure 21 - Reduction of emissions costs for Economic Optimization, comparing the different TLS system with No TLS, summer

In the two first scenarios, the condition without benefits is maintained due to the non-occurrence of PQ violations. With the implementation of simple, advanced and intelligent traffic light systems, with the new control strategies associated, it is observable the reduction on emissions costs for the higher penetration scenarios when compared to scenarios without TLS (TLS0).

The intelligent TLS allows more flexibility on the demand scheduling, which is going to decrease the PQ violations and ensure more PV electricity injection and consequently less emissions from conventional power plants, what imply costs savings related with emissions. In the last scenario, there is the higher difference in traffic light systems. With TLS3 the reduction can be increased to almost 421.51 €/week with LC and 275.39 €/week with SiC, when compared with TLS0.

Figure 22 presents the simulations results for the Traffic Light System during winter.

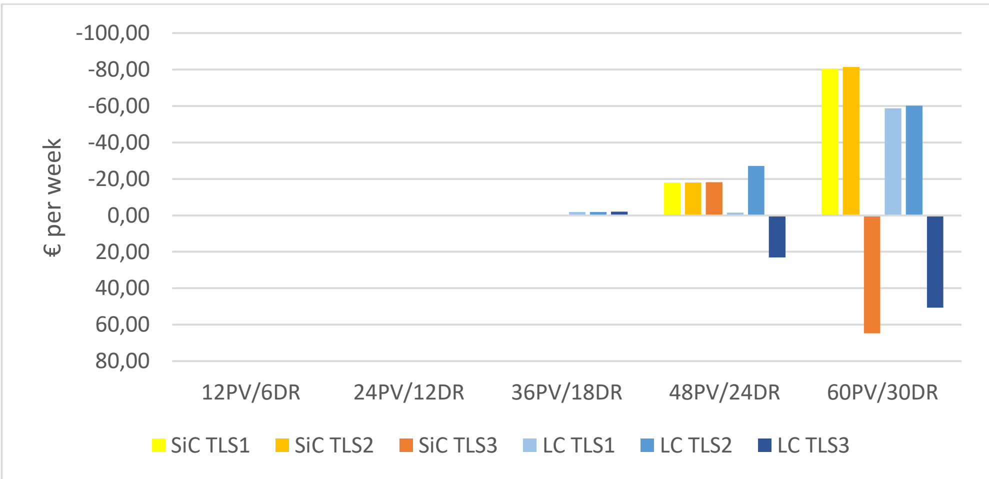

Figure 22 - Reduction of emissions costs for Economic Optimization, comparing the TLS systems with No TLS, winter

With the scenario 36PV/18DR it is already possible to observe the TLS effect, when compared with the No TLS scenario. For the following scenarios, and with the PV penetration level increasing, the amount of cost savings becomes higher. On the fourth and fifth scenarios the save cost savings trend continues, excepting when the intelligent traffic light system is used. Such effect lead to the conclusion that the predefined schedule is a better option in low voltage profiles (winter case), because when TLS3 is not fully utilized becomes less effective than simple and advanced systems.

7.4 - Supply Adequacy

Supply adequacy is the ability of a system to meet the current and future demand. In this section the control strategies are evaluated using SAIFI[5] and a modified SAIDI[6] indexes. The new control strategies reduce the risk of curtailment when they are injecting energy or participating in the energy market during the solar radiation hours. In our case let´s call to the local supply adequacy by PV plant electricity injection reliability in times with enough solar radiation. The SAIDI index has been adapted to measure the duration of curtailment instances of the PV units. Even when the PV unit is partially curtailed, the unit is marked as curtailed. In this section there is not No Control since SAIFI and SAIDI are for curtailment, and with NC the PV units are not curtailed. The equation 1 explain how is calculated the SAIFI index:

$$SAIFI = \frac{\sum_{i=1}^{Npv} \lambda i Ni}{Npv}$$

Equation 1 - SAIFI

Where:

λi = failure rate

Ni = number of PV units curtailed

Npv = number of PV units

[5] SAIFI – System Average Interruption Frequency Index, is the average number of interruptions that the PV unit is curtailed.
[6] SAIDI – System Average Interruption Duration Index.

The equation 2 explain how is calculated the SAIDI index:

$$SAIDI = \frac{\sum_{i=1}^{Npv} Tint,i}{Npv}$$

Equation 2 – SAIDI

Where:

$Tint,i$ = duration of the interval in which i-th PV unit is curtailed

Npv = number of PV units.

7.4.1 - Basic Service

The SAIFI and SAIDI indexes are going to assess the performance of Simple Control and Local Control without DR units implemented or traffic light systems, like is present on Table 11. Therefore, this is just the inverter control implemented on PV units.

Table 11 - SAIFI and SAIFI for different controls, summer and winter

	SAIFI				SAIDI - hours per week			
Scenario	Summer		Winter		Summer		Winter	
	SiC	LC	SiC	LC	SiC	LC	SiC	LC
12PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
24PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
36PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
48PV	2,23	2,92	0,31	0,71	2,22	3,15	0,12	0,34
60PV	4,62	5,53	1,08	1,28	5,19	6,46	0,88	1,23

With the results from Table 11, it can be seen the indexes increasing proportionally with the PV penetration levels, demonstrating more curtailment occurrences in with higher voltage level. Simple Control shows lower index values. However, it is important to remember that LC executes a partial curtailment, but for SAIFI and SAIDI indexes that curtailment is counted as total (unit shuts down). So it can be concluded that LC curtailment increases the indexes, but the cumulative curtailed PV energy is reduced. During winter these indexes are always lower because less PQ violations occur due the lower PV solar radiation.

7.4.2 - Scheduling Service

The influence of the Demand Response implementation on the index values was assessed, using Simple Traffic Light (TSL1) and Economic Optimization, as presented on Table 12.

Table 12 - SAIFI and SAIDI with DR implementation

Scenario	SAIFI				SAIDI - hours per week			
	Summer		Winter		Summer		Winter	
	SiC	LC	SiC	LC	SiC	LC	SiC	LC
12PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
24PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
36PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
48PV	1,25	2,08	0,13	0,27	1,57	2,35	0,03	0,08
60PV	3,02	3,65	0,70	0,82	3,37	4,07	0,28	0,45

Comparing it with the previous results from Table 11, it is visible a large decrease on the index values for both controls, SiC and LC, due to the lower voltage level caused by DR implementation and therefore less PV units curtailed. In the higher PV penetration scenarios some reductions in curtailed time are very sharp, with almost 50% of the hours per week.

7.4.3 - Balancing Service

Table 13 presents the assessment of the SAIFI and SAIDI indexes for the different scheduling optimizations, Energy and Economic.

Table 13 - SAIFI and SAIDI for Economic and Energy optimizations, summer and winter

Scenario	SAIFI							
	Summer				Winter			
	Energy Optimization		Economic Optimization		Energy Optimization		Economic Optimization	
	SiC	LC	SiC	LC	SiC	LC	SiC	LC
12PV/6DR	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
24PV/12DR	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
36PV/18DR	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
48PV/24DR	0,17	0,94	1,25	2,08	0,00	0,00	0,13	0,27
60PV/30DR	2,25	2,65	3,02	3,65	0,28	0,32	0,70	0,82
	SAIDI - hours per week							
Scenario	SiC	LC	SiC	LC	SiC	LC	SiC	LC
12PV/6DR	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
24PV/12DR	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
36PV/18DR	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
48PV/24DR	0,05	0,71	1,57	2,35	0,00	0,00	0,03	0,08
60PV/30DR	2,13	2,54	3,37	4,07	0,11	0,20	0,28	0,45

The indexes presents lower values using SC Energy Optimization since energy optimization aims minimize PQ violations and maximize the renewable energy injection, which means less curtailment occurrences and time of curtailment. The main difference between optimizations is reached on the last scenario, where for example with SiC and Energy optimization there is a SAIDI of 2.13 h/week and with SC Economic the index increases to 3.37 h/week.

The indexes values for LC are still higher than for SiC, for the same reasons as for the Basic Service. Economic optimization does not inject so much energy like Energy optimization, and pays more attention to the energy market prices, so the number of curtailment instances will be higher.

7.4.4 - TLS Service

The different SAIFI and SAIDI indexes values are presented to exhibit how traffic light system can affect the supply adequacy. Table 14 presents the simulations results for SAIFI and SAIDI.

Table 14 - SAIFI and SAIDI for different traffic light systems, summer

Scenario	SUMMER							
	SAIFI							
	SiC				LC			
	TLS0	TLS1	TLS2	TLS3	TLS0	TLS1	TLS2	TLS3
12PV/6DR	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
24PV/12DR	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
36PV/18DR	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
48PV/24DR	1,40	1,25	1,25	1,00	2,23	0,92	0,92	1,52
60PV/30DR	3,10	3,02	2,98	3,05	3,75	2,63	2,55	3,45
Scenario	SAIDI - hours per week							
12PV/6DR	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
24PV/12DR	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
36PV/18DR	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
48PV/24DR	1,63	1,57	1,57	0,70	2,44	0,73	0,73	1,49
60PV/30DR	3,57	3,37	3,35	3,28	4,30	2,66	2,51	3,64

From the results it is visible a decrease on SAIFI and SAIDI indexes, when the Simple and Advanced traffic light systems are used, in comparison with the scenarios without TLS (TLS0). The scheduling check by TLS1 and TLS2 reduces the number of curtailment occurrences and the duration of PV curtailment, injecting in this way more renewable energy into the grid and decreasing the indexes values. The Intelligent TLS with SiC presents the best indexes results, proving the effectiveness of intelligent algorithm. The Local Control indexes is still higher than SiC, like expected. However, the TLS3 allied with LC does not seems so beneficial like SiC, due to the often occurrences of partial curtailment, avoiding PQ violations and injecting more PV electricity.

Table 15 presents the SAIFI and SAIDI indexes for winter, showing the TLS effect.

Table 15 - SAIFI and SAIDI for different traffic light systems, winter

Scenario	WINTER							
	SAIFI							
	SiC				LC			
	TLS0	TLS1	TLS2	TLS3	TLS0	TLS1	TLS2	TLS3
12PV/6DR	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
24PV/12DR	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
36PV/18DR	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
48PV/24DR	0,13	0,13	0,13	0,00	0,29	0,00	0,00	0,23
60PV/30DR	0,67	0,70	0,67	0,63	0,85	0,35	0,32	0,68
Scenario	SAIDI - hours per week							
12PV/6DR	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
24PV/12DR	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
36PV/18DR	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
48PV/24DR	0,03	0,03	0,03	0,00	0,08	0,00	0,00	0,08
60PV/30DR	0,30	0,28	0,28	1,00	0,49	0,22	0,20	0,53

Winter season follow the same trend of summer, but with lower values due to the lower solar radiation that does not increases the voltage levels so frequently. Checking the SAIFI and SAIDI values, becomes obviously that TLS1 and TLS2 have the same positive impact over the indexes values. Again, the Intelligent traffic light systems show the worse indexes for summer due to the same reasons explained already on TLS Service from PV Electricity Injection.

8 - Conclusions

This chapter presents the conclusions based on simulation results analysis. It was possible to draw for each service assessed service an individual conclusion and an overall conclusion.

8.1 - Basic Service

From the normal PV units without control like, such in the No Control case, the Simple Control and Local Control bring an upgrade, increasing the PV electricity injection into the distribution grid. The inverter upgrade from SiC to LC results in a smooth curtailment compared to the simple On/Off implemented in Simple control. To provide VUM is necessary a new inverter installation. Theoretically, the LC should ensure better injection levels on the grid than SiC, but this fact does not happened so frequently like we can check in the Basic Service simulations results. The levels of injection are very similar in all PV/DR penetration scenarios and seasons. However, when comparing NC with SiC and LC, the last two control strategies present better results. It is easy to conclude that Basic Service can be a good upgrade, but other services can provide better improvements. A conclusion resume is presented on Table 16.

Table 16 – Basic Service conclusions for the different assessed aspects

PV Electicity Injection	Revenue	Emissions Cost	Supply Adequacy
•SiC and LC show better results than NC for both seasons and all PV penetrations scenarios	•Both allow more income than NC •LC becomes more profitable in high PV penetration scenarios than SiC	•A significant decrease on emissions compares do NC •LC is better in winter season •SiC is better in the last scenario	•SiC has better indexes values, however LC is more efficient due to the partial curtailment

8.2 - Scheduling Service

This second service provides VC + VUM as like Basic Service and also DCM and RP, but for VUM provision it is necessary the installation of 3-phase inverter. The effects of DR integration reveal an increase in all assessed aspects, since the DR unit schedules result in lower voltage profiles that allow a higher injection of renewable energy. Comparing the results with the Basic Service it is visible the improvement in all aspects for both new controls. However, Local Control is the control that shows better results and seems to be the best option. Local Control included on

Scheduling Service can provide better results than with the simple Basic Service. Table 17 show a summarized conclusion.

Table 17 – Scheduling Service conclusions for the different assessed aspects

PV Electricity Injection	Revenue	Emissions Cost	Supply Adequacy
• DR Scheduling show an increase of green energy injection due to DR implementation	• Local control with Schedulling Service becomes more profitable	• LC with SC Service is better in summer • SiC allied to SC Service is better on winter	• SC service decrease the indexes values for SiC and LC • SiC has still beter values

8.3 - Balancing Service

Adding Energy optimization on Scheduling Service, has better results in all assessed aspects for both seasons.

With energy optimization, Simple Control has better results than Local Control, so it can be concluded that choosing SiC and energy scheduling, it is a good and profitable choice. When compared with Scheduling service with Economic scheduling, the results justify the change to Energy optimization option. Conclusions are summarized on Table 18.

Table 18 . Balancing Service conclusions for the different assessed aspects

PV Electicity Injection	Revenue	Emissions Cost	Supply Adequacy
• Energy optimization injects more energy than economic opt • SiC with Energy balance show better results than LC	• Energy optimization show higher revenue	• Due to the higher injection of renewable energy, the Energy opt. has better results in avoided emissions costs	• Energy optimization reveals better SAIFI and SAIDI indexes

8.4 - TLS Service

The previous services assumed only Simple traffic light system (TLS1) and with TLS it is intended to offer Advanced and Intelligent TLS, as an option for the consumers. During summer it is clear the superiority of TLS2 over TLS1 and even more evident the TLS3 benefits over all previous TLS systems, since medium/high PV penetration levels. During winter, the Advanced TLS becomes the best choice, since it offers better benefits in all assessed aspects. So TLS3, in an environment with high solar radiation and high voltage levels becomes more beneficial than in winter days, where Advances TLS is a better option. A resume of the benefits it is shown on Table 19.

Table 19 – TLS Service conclusions for the different assessed aspects

PV Electricity Injection	Revenue	Emissions Cost	Supply Adequacy
• Summer: TLS3 is far away the best option • Winter: TLS2 reveals better option with lower PV generation	• TLS3 ensures more profit in summer • TLS2 is more profitable during winter	• TLS3 is the best during summer • TLS2 allows more savings in winter	• Summer: TLS3 +SiC reveal the best indexes. LC is better with TLS2 • Winter: TLS2 has better performances

In overall, TLS service offers higher benefits in all aspects. The Advanced and Intelligent traffic light systems provide the mitigation of PQ violations and increase electricity injection and all the associated revenues.

In Table 20 it is evidenced the improvement in all assessed aspects of Local Control with Scheduling Service and Intelligent Traffic Light System, when compared with our base case, No Control of DRES and without Scheduling Service of DR units.

Table 20 - Intelligent TLS with LC compared to NC without SC, summer

Scenario	PV Electricity Injection [kWh/week]	Revenue [€/week]	Emissions Costs [€/week]
12 PV	2 721	113.56 €	370.62 €
21 PV	5 443	227.12€	741.25 €
36 PV	8 119	338.59 €	1105.75 €
48 PV	9 686	399.13 €	1318.62 €
60 PV	10 937	447.06€	1487.40 €

Some considerable values of renewable energy injection, associated costs and environmental benefits can be achieved with the ancillary services proposed in INCREASE project.

8.5 - Global Conclusion

In all simulations the best results were achieved during the summer with TLS Service, Local Control with Intelligent traffic light system, demonstrating for medium and high PV penetration scenarios, a huge increase on the PV electricity injection when compared to the base case. In winter the best choice is TLS Service with Advanced TLS, Energy optimization and Local Control.

From all options and services for the new control of DRES and scheduling for DR units, it becomes evident the economic and technical benefits for the distribution grid and final consumers. This dissertation and INCREASE Project aims to assess solutions to demonstrate that it is possible to install PV units in the distribution grid, no matter how many PVs are already installed on the grid, without being necessary an extra grid reinforcement. It is also important the decrease of curtailment time, which increases the renewable energy injection into the grid and provides higher revenues for the PV owners. Increasing the renewable energy leads to the reduction of emissions and the associated costs, saving in this way money and the most important thing, our planet and our life quality.

These solutions are a good option to allow the connection of new DRES in actual congested grids while the storage technology cannot offer attractive solutions and prices.

9 – Literature

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10 - Appendices A

10.1 - Storage Systems

Following the development of INCREASE project and the demand for electricity, new and improved energy storage solutions are needed in order to ensure the matching between electricity generated when the renewable sources are available and the electricity demand.

10.2 - Grid challenges

With the installation of medium and small scale storage units on residential LV network, three grid challenges [21] will be tackle, voltage control, current congestion mitigation and electricity supply. Control strategies implemented in storage systems (as it was done to DRES and DR units) allow flexibility and robustness. Since a large number of PV plants are installed in the network, one of the mains control goals is to maximize the green energy output, through the reduction of PV curtailment due to the storage systems activation. The energy which will be lost due to the network limitations will be stored in that storage systems and used in more favourable periods. The combination of storage systems with DRES provide energy for local consumption and makes the system less grid dependent, more reliable in case of unpredicted situations and reduce the impact on black-out situations [22].

The STORY project considers the following grid challenges:

- Security of electricity supply (SoES): it is defined as an ability of the power system to provide electricity to the final consumers with a specific lever of continuity and quality in a sustainable manner.
- Voltage control: in the distribution system operation the voltage control function is to keep the steady state voltage in a system within an acceptable range all the time. The desired voltages can be obtained by either directly controlling the voltage or by controlling the reactive power flow, that in turn, will affect the voltage drop.
- Current congestion mitigation: occurs when in the distribution network the current flowing through a line or a transformer is higher than the maximum allowable loading.

10.2.1 - Security of electricity supply

The new storage systems technologies could contribute into an additional reserve and primary regulation in weak and isolated grids. Therefore they would contribute in reinforcing the reliability and reducing the risk of unforeseen supply cuts. Acting as backup system, storage technologies allow the user to operate the load in normal condition when a supply cut occurs. The storage systems are limited, and for that reasons the system must be dimensioned according with the time and service power required [23].

10.2.2 - Voltage Control

Voltage control procedures are conducted by supercapacitor banks or inductances synchronous compensators and generators. However, electronic power systems associated to the storage could be a good solution in order to implement voltage control and to help to keep the grid voltage within the prescribed limits, especially in distribution networks [24].

10.2.3 - Current congestion mitigation

Current congestion could be mitigated by introducing storage systems into the grid congested nodes or feeders, in order to supply or consume energy when it is required. Energy will be stored when there is no congestion, and it will be discharged during peak demand or DRES production periods to reduce the peak transmission capacity requirements.

10.3 - Storage technology solutions

The storage systems can act as stabilizes for the energy network, ensuring optimal quality, supply and electricity reliability, providing at the same time support to the operation of the network. They may also prevent current congestion problems and compensate the variability of renewable resources and their integration into the network.

Actually the energy systems devices for distributed generation application can be divide in [25], [26]:

- Mechanical systems: Flywheels.
- Thermal systems: Water or oil heaters
- Pneumatic systems: Air compressors
- Magnetic systems: Superconducting Magnetic Energy Storage (SMES)
- Electric systems: Supercapacitors
- Electromechanical systems: Batteries and flow cells.

There is two methods of storage electricity, direct and indirect. The direct method are the SMES and capacitators. Classified as indirect method there is mechanical, thermal and chemical methods.

The choose between the storage technology to implemented in each case depends on various parameters, capacity and power, durability, time of response, price investment and maintenance costs [26].

Small scale storage systems technologies can be used in various services or grid applications. The most promising applications include voltage support, power quality services, uninterruptable power supply, time shifting and load levelling and peak shaving. Figure 22 presents the classification of the services provided by energy storage.

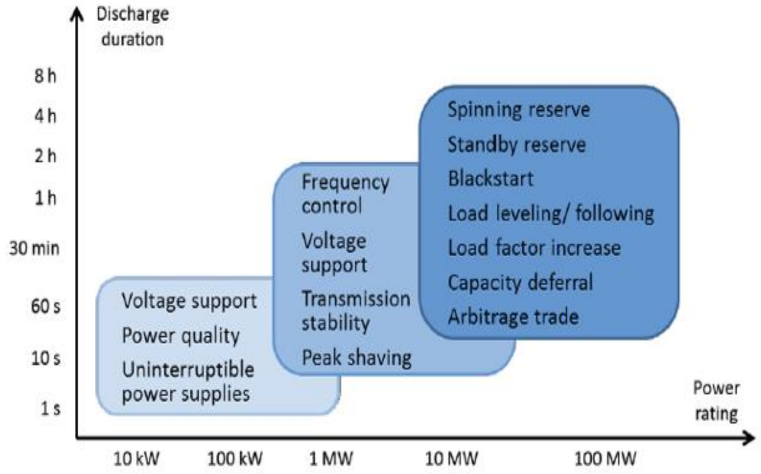

Figure 23 - Classification of the services provided by energy storage, STORY project [22]

For the integration of renewable energy the most appropriated technologies are:

- Batteries (Lead Acid, Ni-Cd, Li-Ion)
- High power supercapacitors
- Flywheels
- SMES

The variations caused by the non-dispatchable renewable generation power plants can be mitigate with the use of storage systems. These variations have a negative effect on grid stability. The energy storage systems can supply more flexibility and balancing to the grid, providing a back-up to variable generation from DRES and uncertain demand. Locally, it can improve the management of distribution networks, reducing costs and improving efficiency [27].

11 - Appendices B

Table 21 – Traffic Light System Operation

Action	Does joint Schedule causes PQ violations?		Direction: Does DR schedule help reduce PQ violations?	
TLS Type	No	Yes	No	Yes
Simple	Accept DR schedule	Reject DR schedule		
Advanced	Accept DR schedule	Check direction	Reject DR schedule	Accept DR schedule
Intelligent	Use 15 min forecasting to optimally schedule DR units			

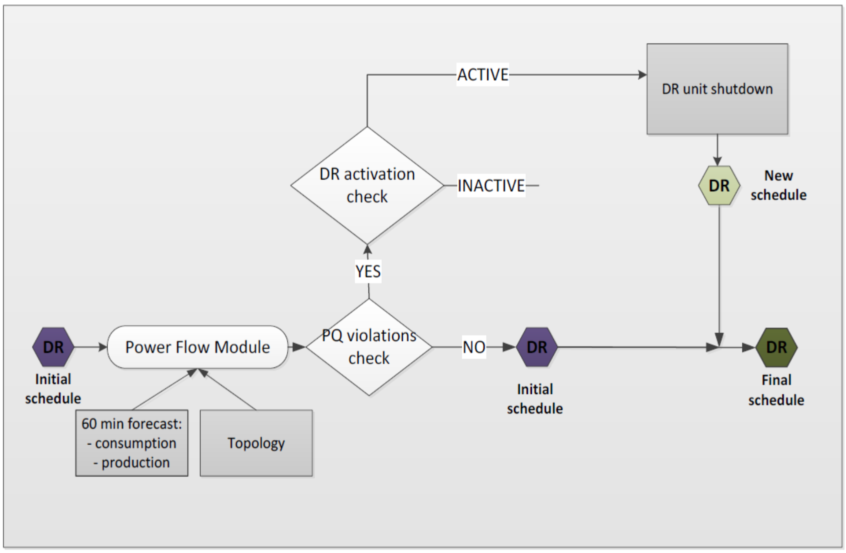

Figure 24 – Simple TLS algorithm

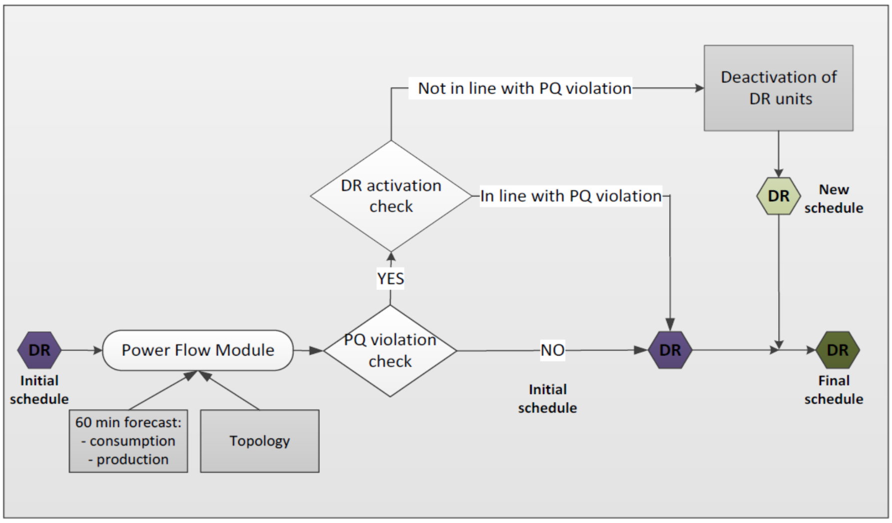

Figure 25 – Advanced Traffic Light System algorithm

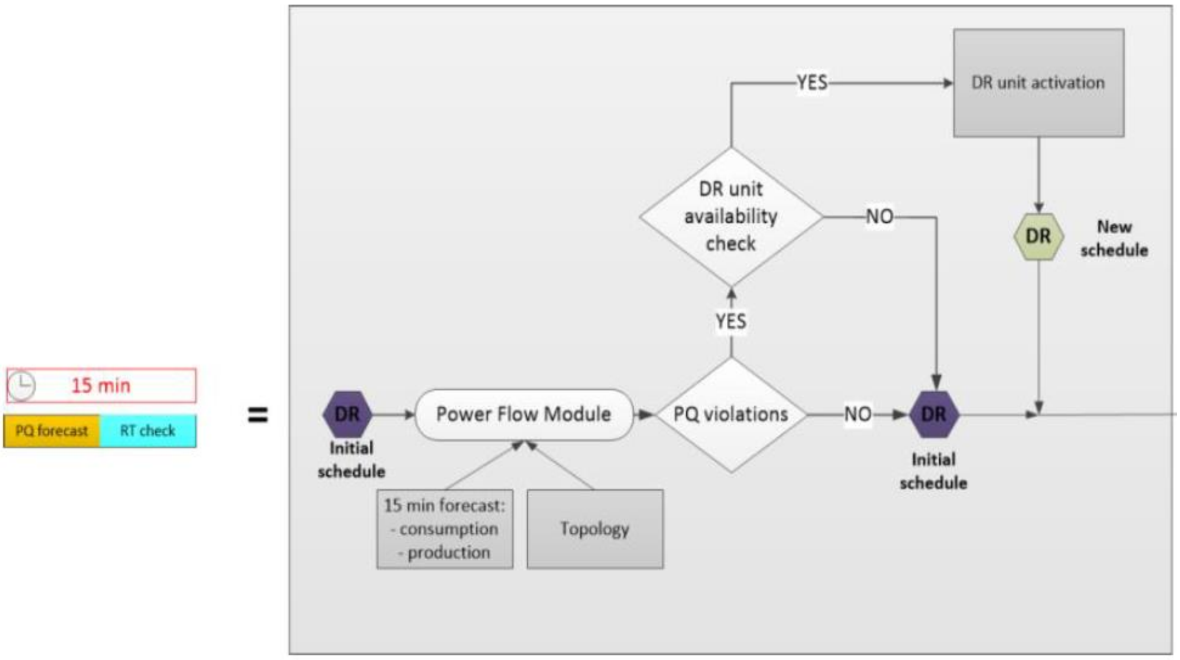

Figure 26 – Intelligent Traffic Light System algorithm

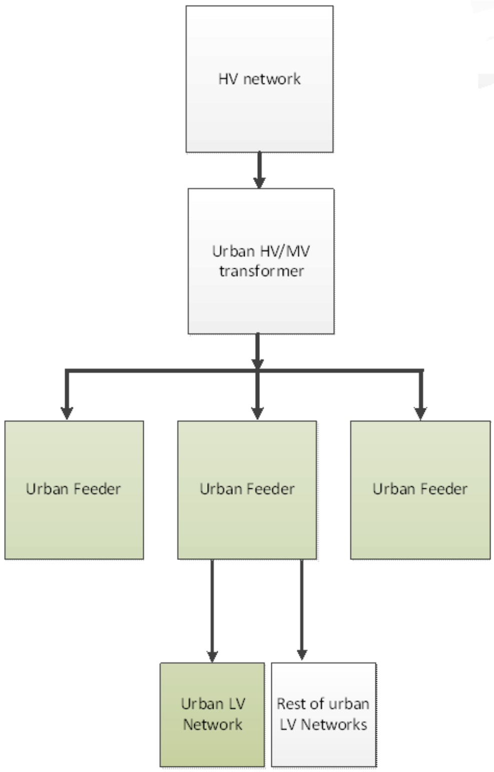

Figure 27 – Synthetic network concept

```
New Line.F1sS19  Bus1=F1sB18.1.2.3.4    Bus2=F1sB19.1.2.3.4   Linecode=PP00A_4X70    Units=km   Length=0.0194
New Line.F1sS20  Bus1=F1sB19.1.2.3.4    Bus2=F1sB20.1.2.3.4   Linecode=PP00A_4X70    Units=km   Length=0.0194

!Feeder2

New Line.F2S1   Bus1=TR1_LV_Bus.1.2.3.4   Bus2=F2B1.1.2.3.4    Linecode=PP00A_4X150   Units=km   Length=0.0364
New Line.F2S2   Bus1=F2B1.1.2.3.4         Bus2=F2B2.1.2.3.4    Linecode=PP00A_4X150   Units=km   Length=0.0364

!Sections

!Left Side

New Line.F2sS1  Bus1=F2B2.1.2.3.4    Bus2=F2sB1.1.2.3.4    Linecode=PP00A_4X70   Units=km   Length=0.0364
New Line.F2sS2  Bus1=F2sB1.1.2.3.4   Bus2=F2sB2.1.2.3.4    Linecode=PP00A_4X70   Units=km   Length=0.0364
New Line.F2sS3  Bus1=F2sB2.1.2.3.4   Bus2=F2sB3.1.2.3.4    Linecode=PP00A_4X70   Units=km   Length=0.0364
New Line.F2sS4  Bus1=F2sB3.1.2.3.4   Bus2=F2sB4.1.2.3.4    Linecode=PP00A_4X70   Units=km   Length=0.0364

!Right Side

New Line.F2sS5  Bus1=F2B2.1.2.3.4    Bus2=F2sB5.1.2.3.4    Linecode=PP00A_4X70   Units=km   Length=0.0364
```

Figure 28 – Lines code, OpenDSS

```
Clear
New Circuit.NE_Urban_LVv1
set defaultbasefreq=50
!vir (SN)

Edit Vsource.Source BasekV=20 pu=1.00 MVASC3=10000 MVASC1=8000 ISC3=577350.3 ISC1=461880.2

!!transformer Dyn5

!!phase 1

new transformer.TP_Suha_ph1 phases=1 windings=2
~ Xhl = 3.87 %loadloss=1.011 %noloadloss=0.129
~ buses=[Sourcebus.1.2 TR1_LV_Bus.4.1  ]
~ kVs=[21 0.242487]
~ conns=[delta wye]
~ kVas=[133.333,133.333]

!!phase 2

new transformer.TP_Suha_ph2 phases=1 windings=2
~ Xhl = 3.87 %loadloss=1.011 %noloadloss=0.129
~ buses=[Sourcebus.2.3 TR1_LV_Bus.4.2]
~ kVs=[21 0.242487]
~ conns=[delta wye]
~ kVas=[133.333,133.333]

!!phase 3

new transformer.TP_Suha_ph3 phases=1 windings=2
~ Xhl = 3.87 %loadloss=1.011 %noloadloss=0.129
~ buses=[Sourcebus.3.1 TR1_LV_Bus.4.3]
~ kVs=[21 0.242487]
~ conns=[delta wye]
~ kVas=[133.333,133.333]
```

Figure 29 – Transformer, OpenDSS code

```
!Load16
New Load.L_F1HH16_A        Bus1=F1B8.1.4    kV=0.230 kW=0 kvar=0 phases=1 Model=8 Vminpu=0.9 Vmaxpu=1.1 ZIPV=[0 1 0 0 1 0 0.5]
New Load.L_F1HH16_B        Bus1=F1B8.2.4    kV=0.230 kW=0 kvar=0 phases=1 Model=8 Vminpu=0.9 Vmaxpu=1.1 ZIPV=[0 1 0 0 1 0 0.5]
New Load.L_F1HH16_C        Bus1=F1B8.3.4    kV=0.230 kW=0 kvar=0 phases=1 Model=8 Vminpu=0.9 Vmaxpu=1.1 ZIPV=[0 1 0 0 1 0 0.5]

!Load17
New Load.L_F1HH17_A        Bus1=F1B9.1.4    kV=0.230 kW=0 kvar=0 phases=1 Model=8 Vminpu=0.9 Vmaxpu=1.1 ZIPV=[0 1 0 0 1 0 0.5]
New Load.L_F1HH17_B        Bus1=F1B9.2.4    kV=0.230 kW=0 kvar=0 phases=1 Model=8 Vminpu=0.9 Vmaxpu=1.1 ZIPV=[0 1 0 0 1 0 0.5]
New Load.L_F1HH17_C        Bus1=F1B9.3.4    kV=0.230 kW=0 kvar=0 phases=1 Model=8 Vminpu=0.9 Vmaxpu=1.1 ZIPV=[0 1 0 0 1 0 0.5]
```

Figure 30 – Loads, OpenDSS code

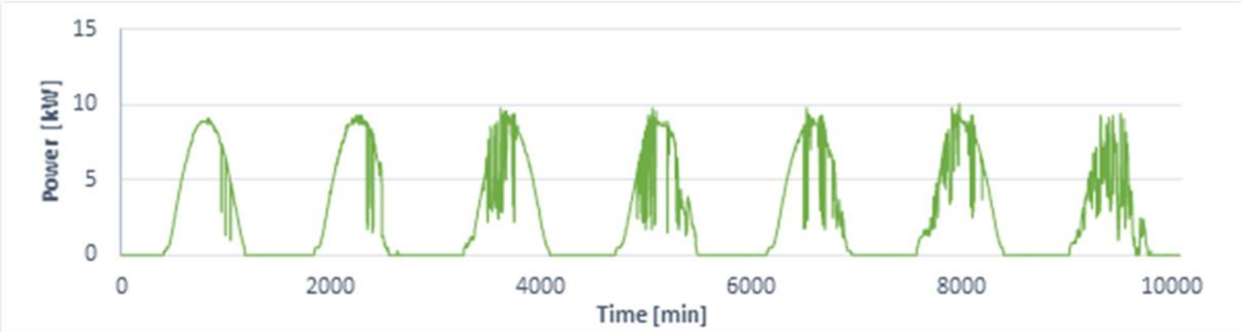

Figure 31 - PV generation from one week, summer

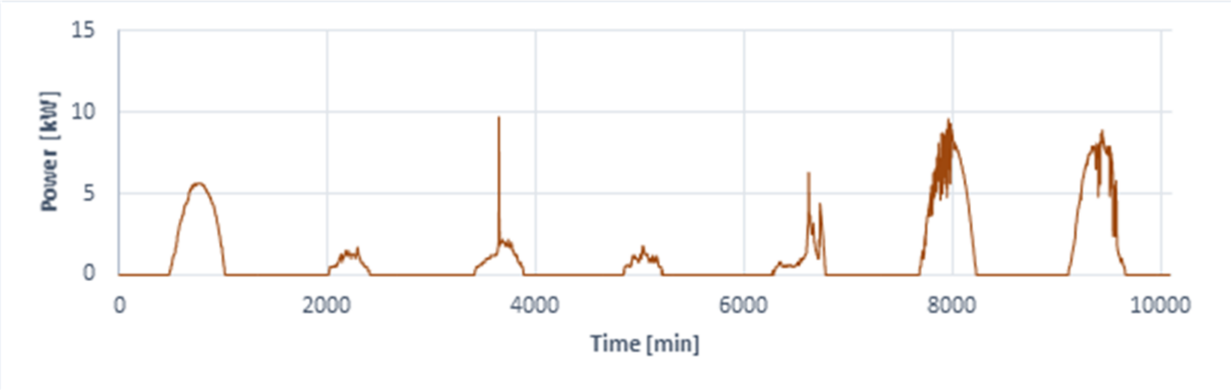

Figure 32 – PV generation from one week, winter

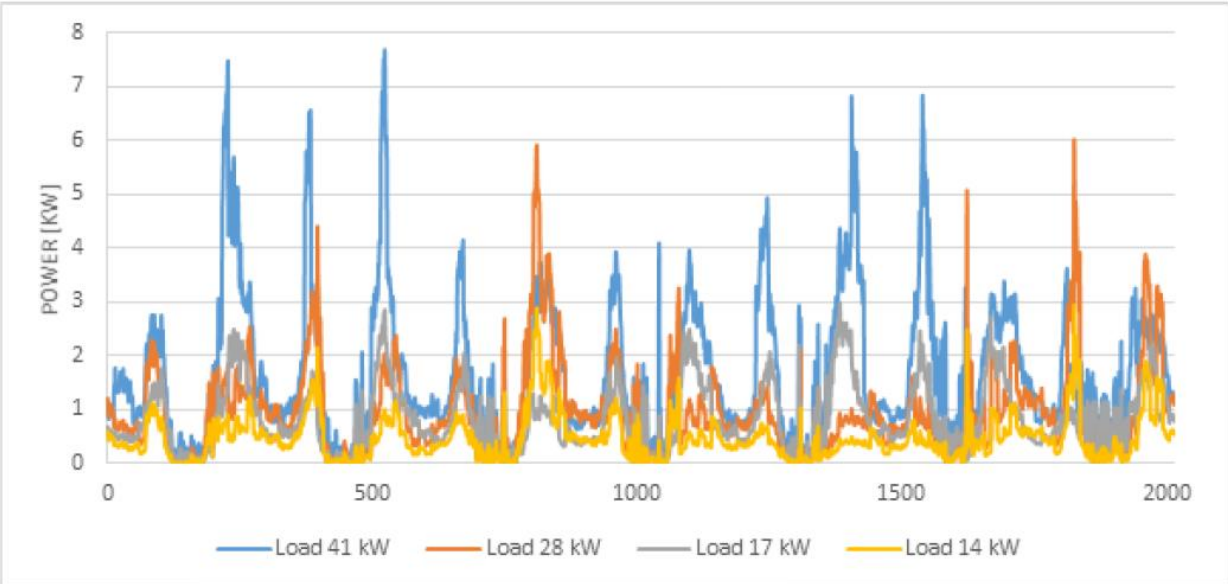

Figure 33 – Weekly summer load profiles

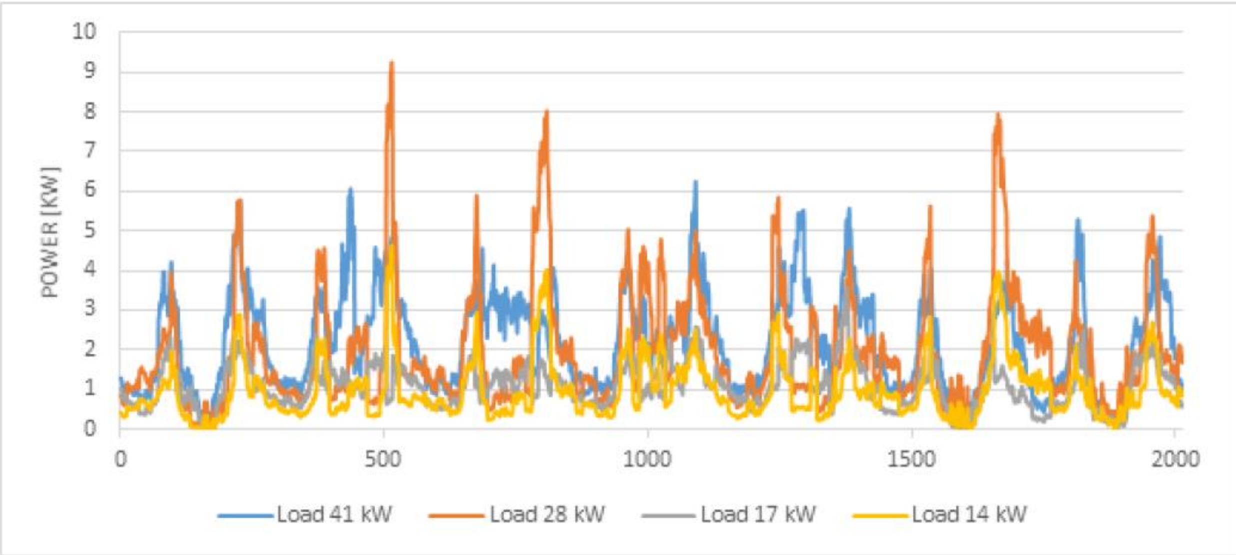

Figure 34 – Weekly winter load profiles

```
%winter
clearvars;
numscenarios=5;
numTLS=2
%LC
for i=1:numscenarios
    for n=0:numTLS
        filename= sprintf('Results_Econ_winter_%i_TLS%i_LC.mat',i,n);
        load(filename);
        %Production sum
        var1=sum(eval(['P_Econ_winter_' num2str(i) '_TLS' num2str(n) '_LC']),1);

        %Production
        var2=var1/12;

        %Total Production
        var3=sum(var2,2);
        %min
        minimun=min(eval(['P_Econ_winter_' num2str(i) '_TLS' num2str(n) '_LC']));
        minimun=min(minimun);

        %max
        maximun=max(eval(['P_Econ_winter_' num2str(i) '_TLS' num2str(n) '_LC']));
        maximun=max(maximun);

        P_name=sprintf('Production_Econ_winter_%i_TLS%i_LC',i,n);
        Ph_name=sprintf('Production_MWh_Econ_winter_%i_TLS%i_LC',i,n);
        TP_name=sprintf('Total_Production_Econ_winter_%i_TLS%i_LC',i,n);
        Max_name=sprintf('Max_Production_Econ_winter_%i_TLS%i_LC',i,n);
        Min_name=sprintf('Min_Production_Econ_winter_%i_TLS%i_LC',i,n);


        assignin('caller', P_name, var1);
        assignin('caller', Ph_name, var2);
        assignin('caller', TP_name, var3);
        assignin('caller', Max_name, maximun);
```

Figure 35 – Example of Matlab script used to analyse the results

```
[V_lim_droop,V_lim_down,V_lim_up_DR,V_bus_up]=import_excel_values();


%% scenario definition
DR_num_data=[ 6 12 18 24 30 ]; % number of DR units in network per sc
pv_data=[ 12 24 36 48 60 ];    % number of PV units in network per sce


%% loading of data needed for simulation
load('Data1.mat');% general data:prices, load, production, grid info,

Vcpb_inv(:,1:60)= 1.06;


% Vcpb_inv(:,:) = V_lim_droop;% adjustment of original startin voltag
 load ('Schedule_Int_Eu'); % schedule of DR units where all are deplo
% load ('Schedule_Base');% naive schedule
% load('Schedule_EB.mat')% energy balance optimised schedule
% load('Schedule_Econ.mat')% economicaly optimised schedule


%% Main  technical simulation loop parameters
Simulation ={'Int'}; %{} (PV only, Basic schedule of DR, Economic opt
% Simulation = {'PV_only'};% (PV only, Basic schedule of DR, Economic
% Season = {'spring','summer','fall','winter'};
Season = {'summer','winter'};%
% Control = {'NC','SC','LC','OC','OC_CC'};% NC=no control, SC=simple
Control = {'NC','SC','LC'};% NC=no control, SC=simple control, LC=loc


% TLS used in each simulation type, no TLS = TLS0, simple TLS=TLS1,
% Advanced TLS=TLS2, Intelligent TLS= TLS3
TLS1 ={'TLS3'};              % Intelligent scheduling
        %{'TLS0','','';...           % PV_only
        %'TLS0','TLS1','TLS2';...   % Base schedule
```

Figure 36 – Simulations Matlab script

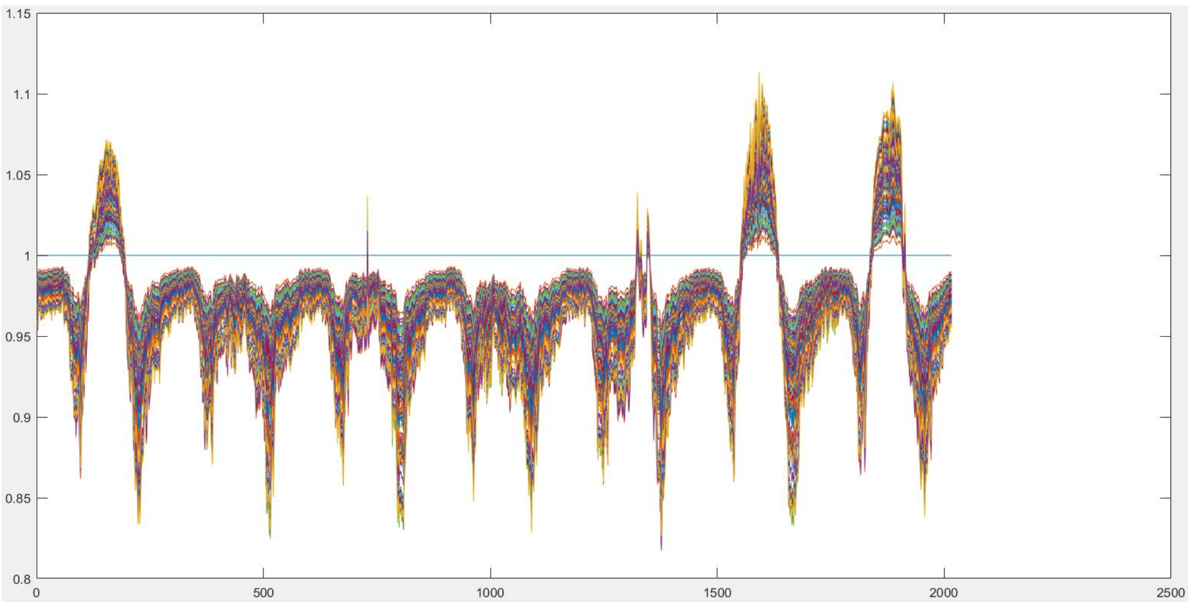

Figure 37 – No Control voltage profile (p.u.)

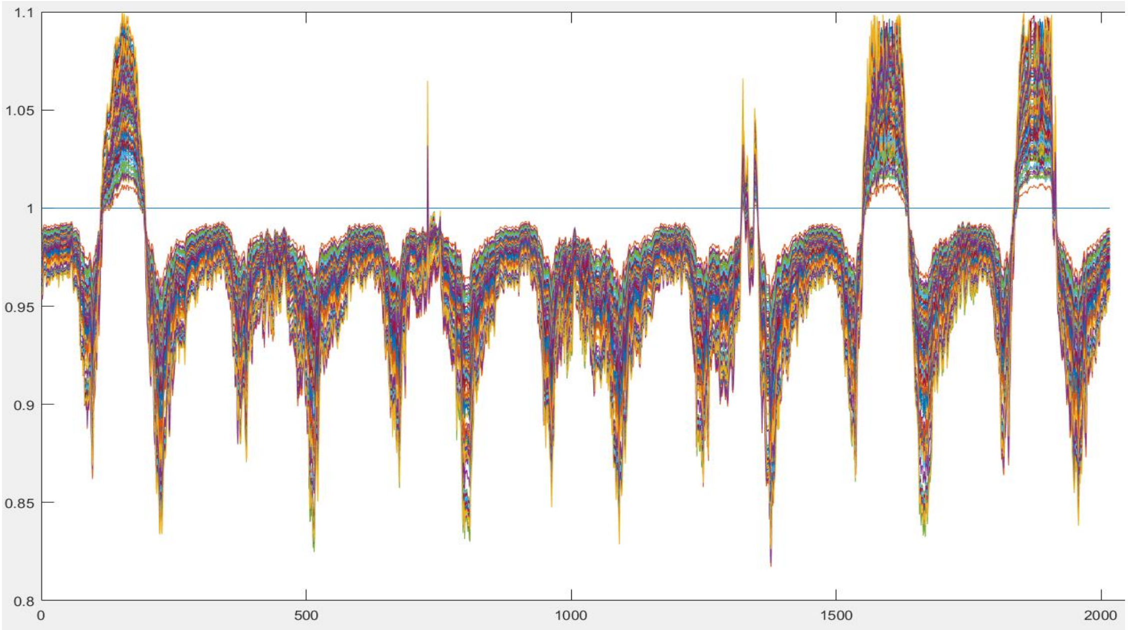

Figure 38 – Simple Control curtailment strategy at 1.1p.u.

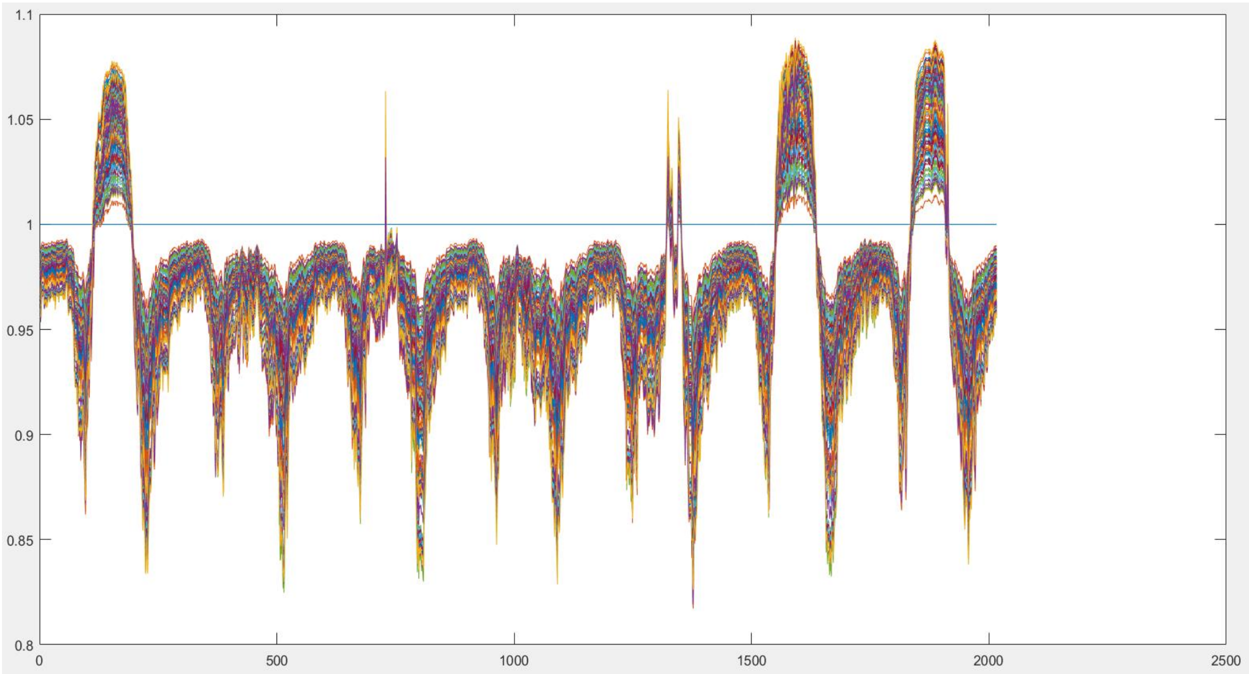

Figure 39 – Local Control partial curtailment strategy at 1,06 p.u.

Table 22 - PV electricity injection (kWh) into the grid by NC, SiC and LC, summer and winter seasons

Scenario	Summer			Winter		
	NC	SiC	LC	NC	SiC	LC
12 PV	6 328,60	9 049,90	9 049,90	2 300,20	3 289,30	3 289,30
21 PV	12 657,00	18 100,00	18 100,00	4 600,40	6 578,50	6 578,50
36 PV	18 986,00	27 150,00	26 920,00	6 900,60	9 867,80	9 850,60
48 PV	25 310,00	34 152,00	34 200,00	9 200,70	12 990,00	12 817,00
60 PV	31 643,00	39 509,00	39 469,00	11 501,00	15 507,00	15 601,00

Table 23 - Energy Market Prices, time interval one week and 1h of resolution

Energy Price - €/kWh							
Summer				Winter			
0,02151	0,02485	0,0368	0,0321	0,03145	0,02717	0,06099	0,05874
0,02138	0,02565	0,02911	0,0284	0,03307	0,04145	0,05495	0,03366
0,01811	0,02195	0,03199	0,02273	0,03138	0,03704	0,0325	0,0245
0,01664	0,02005	0,03036	0,01443	0,026	0,03721	0,02657	0,02665
0,018	0,01946	0,02999	0,012	0,03254	0,03725	0,02149	0,0266
0,02217	0,02278	0,02806	0,01146	0,0293	0,03752	0,02026	0,02415
0,03372	0,026	0,02827	0,0095	0,03789	0,04467	0,01902	0,02425
0,04343	0,04	0,02938	0,00738	0,05948	0,05524	0,01924	0,025
0,04436	0,04134	0,035	0,00444	0,05314	0,05906	0,01772	0,02832
0,04428	0,0491	0,041	0,00493	0,05105	0,06401	0,02279	0,04049
0,04022	0,0491	0,0451	0,00712	0,0492	0,0646	0,04197	0,05298
0,054462	0,0491	0,04441	0,01	0,04899	0,0519	0,0277	0,05688
0,051	0,05161	0,0451	0,013	0,0455	0,05626	0,02809	0,05148
0,050652	0,0491	0,051	0,014	0,043	0,05154	0,03225	0,0465
0,05291	0,05	0,05501	0,02175	0,0388	0,05267	0,02645	0,0448
0,05841	0,051	0,05501	0,019625	0,03897	0,04143	0,02446	0,04276
0,06099	0,05378	0,064	0,01742	0,04254	0,03776	0,05287	0,04141
0,0425	0,05571	0,069101	0,01566	0,0681	0,0483	0,05665	0,0415
0,05734	0,05218	0,051	0,01574	0,08323	0,06214	0,02559	0,04343
0,0455	0,05218	0,05	0,0116	0,074083	0,065	0,06102	0,04633
0,06099	0,0521	0,0451	0,014	0,06719	0,0651	0,0679	0,052
0,06566	0,05	0,0451	0,02208	0,06395	0,058	0,06899	0,06089
0,05724	0,05	0,0401	0,0275	0,06137	0,05819	0,06149	0,05807
0,03874	0,03549	0,0451	0,0275	0,02747	0,05462	0,056	0,04783
0,023805	0,0331	0,0419	0,03244	0,03508	0,0529	0,03133	0,04206
0,02073	0,03135	0,03488	0,037	0,034	0,06214	0,037	0,03797
0,01763	0,0295	0,02516	0,02462	0,03	0,06027	0,02287	0,02759
0,01572	0,02717	0,0224		0,0309	0,05365	0,02232	
0,01671	0,02505	0,02041		0,03499	0,041	0,0216	
0,01973	0,02661	0,01899		0,03903	0,05033	0,02238	
0,02759	0,0266	0,01857		0,04876	0,05431	0,02277	
0,03975	0,03009	0,01797		0,0626	0,02668	0,02487	
0,04421	0,0411	0,01813		0,05518	0,0584	0,05301	
0,04179	0,0411	0,02184		0,0493	0,06093	0,05885	

0,041	0,05119	0,02587	0,0437	0,06397	0,0447
0,04104	0,05025	0,02498	0,04085	0,05964	0,04306
0,0421	0,05057	0,02349	0,0388	0,05623	0,03928
0,0421	0,04618	0,0225	0,04029	0,05448	0,03679
0,0421	0,0449	0,02085	0,03969	0,05296	0,03694
0,0421	0,05057	0,01865	0,04254	0,05402	0,03408
0,0351	0,052	0,01748	0,04429	0,05534	0,03125
0,0351	0,05429	0,0168	0,0536	0,06037	0,03363
0,03582	0,05	0,01667	0,082	0,06422	0,0361
0,0384	0,04042	0,02014	0,06059	0,0716	0,0418
0,03741	0,0421	0,02518	0,04583	0,072	0,04776
0,0421	0,041	0,02645	0,03736	0,06483	0,065
0,03262	0,0411	0,02648	0,0345	0,06102	0,06099

```
%Cycle for reshape the Production on 168( per hour ) KWh

kounter=1;
u=1;
P_sum=0;
for l = 1:168

    for k= kounter:1:kounter+11
        P_sum=P_sum+Production_sum(k)
        %Production_sum_KWh(u,1)=Production_sum(k,1);
    end

    Production_sum_KWh(u,1)=P_sum;
    kounter=kounter+12;
    u=u+1;
    P_sum=0;
end

Prices_winter=Ener_Prices_short(:,4); %KWh (168 table)
Production_cost= Production_sum_KWh.*Prices_winter; % table costs with 1h resolution KWh
sum_Production_cost=sum(Production_cost); %total sum of production cost

% Emissions
Total_Production = sum(Production_sum_KWh); % total of production (one value) gramas


CO2_Emiss=CO2Emiss*Total_Production; % g/KWh
CO_Emiss=COEmiss*Total_Production;
FnPrt_Emiss=FnPrtEmiss*Total_Production;
NH3_Emiss=NH3Emiss*Total_Production;
NMVOC_Emiss=NMVOCEmiss*Total_Production;
SO2_Emiss=SO2Emiss*Total_Production;
NOX_Emiss=NOXEmiss*Total_Production;
```

Figure 40 – Matlab script to revenue calculation

Table 24 - Emissions production and associated costs

Gas	g/kWh	€/tonne
CO2	270	50
CO	0,15	262
FnPrt	0,64	8600
NH3	3,687	25000
NMVOC	0,01	2600
SO2	3,17	10500
NOX	0,718	10500

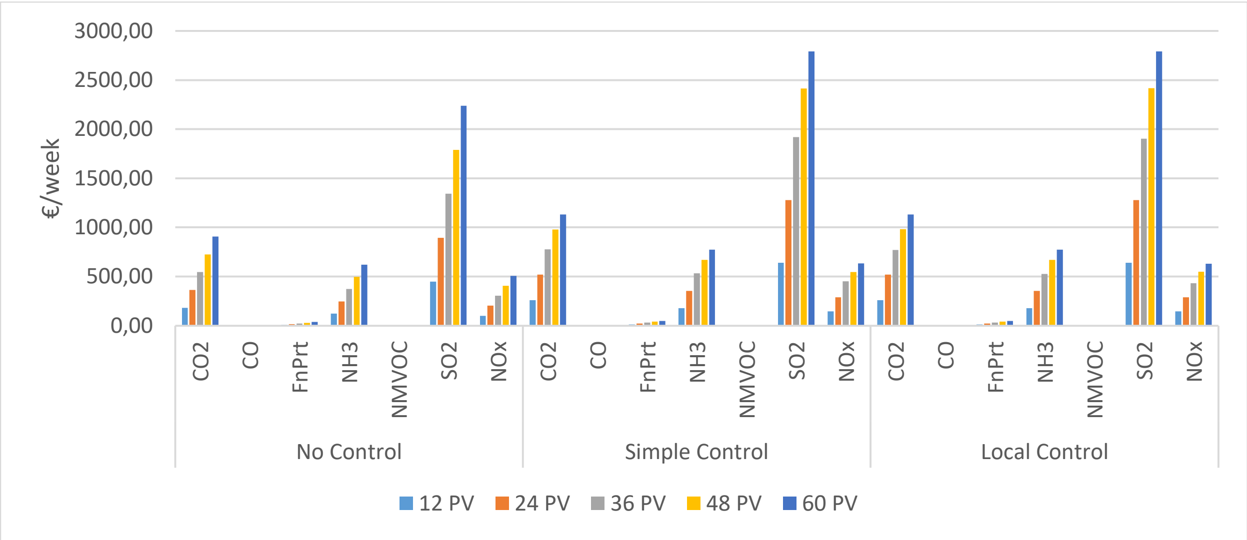

Figure 41 - Emission cost for different gases and control strategies, summer

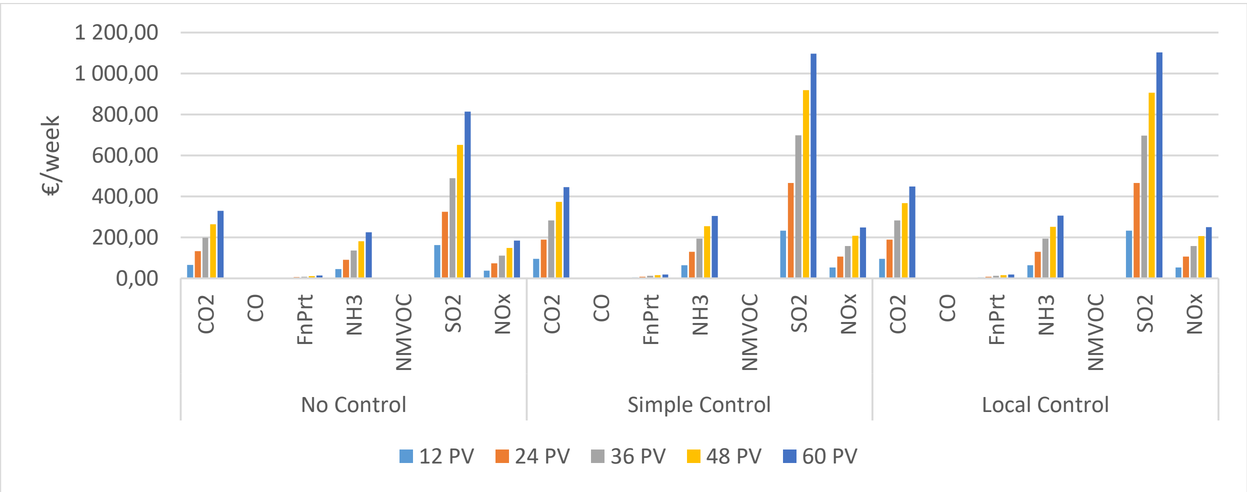

Figure 42 - Emission cost for different gases and control strategies, winter