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Reference Electric Distribution Network Modelling and Integration of Electric Vehicle Charging Stations

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Summary

Smart cities, with prosumers at the centre, are at the front line of the energy transition. The national and international policies should encourage then this transition by promoting, among many aspects, energy digitalization, massive penetration of renewable energies and electrification of the transport sector. To embrace all these changes, a holistic view, covering not only the distribution system, is necessary to plan, design and reorganize in particular urban areas. The radical distribution networks transformation is monitored and presented, both considering technical and non-technical aspects, which aims at encouraging potential directions that distribution system operators can pursue.

The thesis work has three main objectives. From the distribution system operator (DSO) perspective, the main objective is to investigate how the technical and non-technical features vary among distribution system networks in Europe. From the modelling perspective, the second main objective is firstly to define a method which incorporates the previous findings to properly design a tool able to reproduce representative urban networks and secondly to validate the results through a statistical methodology. From the electric vehicle's infrastructure perspective, the third main objective is firstly to understand the electric vehicles demand behaviour and develop models capable of reproducing them, and secondly to assess, through a dedicated methodology, the electric vehicles charging infrastructure features and performance.

The results from this thesis indicates that the increasing attention toward the distribution sector should not be underestimated by the main actor, distribution system operator, which appears to have different approaches in smartening and digitalizing their network especially concerning electric mobility, demand response and

data management between distribution and transmission system operators (TSO). It is urgent for policy makers and stakeholders involved to align distribution system operators to a common strategy to tackle the introduction in the distribution network grids of new players. Tools like DiNeMo platform applied in this thesis may be used to perform preliminary research studies concerning the installation of new charging infrastructure, renewable energy generators or network reinforcement analysis. Indeed, it is crucial for regulators to take into account the physical layer of distribution grids when designing new policies and incentives in order to address challenges of tomorrow's cities.

Keywords: distribution network; charging station; modelling; distribution system operators; synthetic grids; optimization; electric vehicles.

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Chiedo scusa a coloro che disegnavano e io non capivo.
Chiedo scusa a coloro che a furia di mettere puntini mi hanno indirizzato sulla retta via, perchè non ho atteso abbastanza prima di giudicare.
Siete tanti, troppi da ringraziare. Non potrò mai farvi capire fino in fondo a ognuno di voi cosa significhi anche solo una sfumatura, una sbavutara per me.
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E infine un pensiero all'Europa..

In times of fear and distrust we should remember that Europe is like love, it may evolve but we should never forget the reason why we fell in love and got married.

A Simone che così
come è entrato se ne è
andato, silenziosamente
in punta di piedi,
lasciando un vuoto
incolmabile, ti voglio
bene..

Nomenclature

BEV	Battery Electric Vehicle
BMM	Beta Mixture Model
CAPEX	Capital Expenditure
CBA	Cost and Benefit Analysis
CDF	Cumulative Distribution Function
CPG	Conventional Power Generators
DER	Distributed Energy Resources
DG	Distributed Generation
DiNeMo	Distribution Network Model
DR	Demand Response
DSM	Demand Side Management
DSO	Distribution System Operator
EC	European Commission
EPDF	Empirical Probability Distribution Function
EU	European Union
EV	Electric Vehicle

EVSE	Electric Vehicle Supply Equipment
FCA	Fiat Chrysler Automobiles
G2V	Grid to Vehicle
GIS	Geographical Information Systems
HV	High Voltage
ICE	Internal Combustion Engine
ICT	Information and Communication Technologies
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
IIT	Instituto de Investigación Tecnológica
IRENA	International Renewable Energy Agency
ISTAT	Istituto Nazionale di Statistica
JRC	Joint Research Centre
KS	Kolmogorov-Smirnov
LV	Low Voltage
MS	Member State
MV	Medium Voltage
NCR	Network Computation Request
NIMBLE	Network Imitating Method Based on Learning
NN	Nearest Neighbor
NRA	National Regulatory Authority
OPEX	Operational Expenditure

OSM	Open Street Map
PDF	Probability Distribution Function
PHEV	Plug-in Electric Vehicle
POI	Point of Interest
PSO	Particle Swarm Optimization
PV	Photovoltaic
RES	Renwable Energy Sources
RNM	Reference Network Models
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
TSO	Transmission System Operator
UX	User Experience
V2G	Vehicle to Grid
V2X	Vehicle to Everything
VAT	Value Added Tax

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Chapter 1

Introduction

The underlining risk of climatic adversities due to increased energy demand and growing consumption of fossil fuel has raised pressure towards alternative solutions. It is imperative to establish global development for creating a secure, affordable and sustainable energy system. Limit the average temperature increase to 1.5°C by the end of the century, as recommended by the Intergovernmental Panel on Climate Change (IPCC), is crucial to stop climate change. To accomplish this goal, energy system are facing new challenges and unprecedented changes which are reshaping society and economy.

This pronounced urgency and immediacy at an international level requires a new link across sectors, such as transport and power system, and to redefine relationship between markets, networks, producers and consumers. The new paradigm sees the coupled advent of energy efficiency and renewable energy to ensure sustainable and economic solutions. If on one hand this decisive energy shift is necessary to guarantee the planet's survival, on the other hand is not an easy task to implement due to the technological, political and economical barriers. Differently from any other issue humanity has faced until now, the energy transition is incorporating basically every sector going from industry, to transport to buildings. Therefore holistic approaches are necessary to face these issues locally while having an eye on the global impact.

The power sector development has drastically modified our way of living and opened to infinite economic and social opportunities which were unthinkable before the electricity was fully exploited. To tackle the new opportunities, the network grid has evolved, especially in the last decades, due to the increase demand, the energy efficiency improvement, the energy security boost, the renewable energy penetration and lastly the electrification of the transport sector. All these elements combined with the increasing consumers awareness is slowly shifting the attention toward the role of prosumers, thus consumers which are also producing electricity, as the leading element of the power system. In the new role prosumers are changing roles and functions of every stakeholders involved. Indeed, due to the fact that the electricity demand moved from inflexible and semi-deterministic to a more variable concept which drastically influence the historically view of the power system. Nowadays generation, transmission, distribution and consumption categories are somehow merging and interacting like never before. The decentralization process has transferred the focus on the distribution grid rather than transmission, due to the arrival of storage devices, smart meters, renewable energies, energy communities and electric vehicles.

The international renewable energy agency (IRENA) and the international energy agency (IEA) forecast, to limit global warming within the next decades, that the major investment will focus on energy efficiency, renewable energy and the power sector. In this latter a considerable amount is oriented in the distribution one. Affected by the unbundling process, the distribution sector is now dealing with new emerging challenges such as designing the reinforcement of the network to host high penetration of renewable energies and electric vehicles, enhancing cyber security and data protection as well as efficiently implementing demand response programs.

Regulators should investigate in new policies to foster stakeholders participants through ad hoc incentives. Industry should conduct research to test smart grid projects in key areas to achieve profitable policy goals.

To support regulators and industries goals, this study aim at indicating an in depth overview of the current status of the distribution level. In this work the similarities and difference across the European networks are presented, in order to provide a

better understanding of a sector which was until now passively supplying electricity and reluctant in sharing data. The radical distribution networks transformation is monitored and presented, both considering technical and non-technical aspects, which aims at encouraging potential directions that distribution system operators can pursue.
The impressive number of distribution system operators across Europe has obliged to perform a more restricted study focusing on those subject to unbundling, thus the ones serving more than 100.000 customers. Huge disparities emerge in designing, managing and operating the network grids supplied by distributor system operators. Moreover, smart meter roll out, electric vehicles charging station installations and smart grids projects are implemented with complete different approaches which clearly require a methodology toward common strategies.
A special focus is made on the role of electric vehicles in the distribution networks due to the increasing potential interaction in balancing load demand and voltage deviations. Differently from main studies find in literature, the attention is oriented from the distributor system operator point of view, therefore understanding where charging stations should be located to minimize adverse impacts while enhancing vehicle to grid services.
On top of these activities, during the thesis a collaboration has been established for the realization of a distribution network modelling platform named DiNeMo, which address researchers and distribution system operators needs. DiNeMo is a solid tool that based on real data is capable to reproduce representative distribution grids of a given urban area of interest. This platform is also bound to become a virtual place where diverse users, with different roles, will collaborate with the aim of building reliable models to be used in order to design and develop the smart cities of tomorrow. The collaboration with several distribution system operators allows to conduct a statistical validation of urban areas in Europe. A common methodology has been designed to compare 10 key indicators which describe distribution networks.
The results from this thesis indicate that it is of significant importance to align, at the European level, strategies concerning the installation of charging stations to guarantee interoperability and cooperation among all stakeholders within the

electricity sector. It is crucial for regulators to take into account the physical layer of distribution grids when designing new policies and incentives in order to address tomorrow challenges.

1.1 Thesis framework structure and research questions

This section discusses the thesis framework structure and where it should fit within the scientific literature and the *Distribution System Operator Observatory project* recently started by the European Commission (EC) which aim to deepen the current status of distribution system operators.
The research project is funded by a Marie Curie scholarship shared between the Joint Research Centre, the European Commission's science and knowledge service which provide independent scientific advice and support to EU policy, and the Electrical, Electronic and Telecommunication department of Politecnico of Torino.
The thesis project is structured as follows: in Chapter 1 a general overview is presented as well as the thesis framework and the research questions which were addressed during the research. It provides a description of the main activities planned during the 3 years in order to achieve the pre-defined research goals. The focus of Chapter 2 is on the state of play of the Distribution System Operators in Europe. A survey has been designed in order to deepen the knowledge of how Distribution System Operators are managing their on network and its results are extensively described. In addition, the key aspects of the European Directives and Regulations defining the role of DSOs are summarized. Chapter 3 discusses the most relevant scientific papers concerning distribution network grids and charging infrastructure interaction. The key findings and the literature *weaknesses* are listed and highlighted. In the second part of this Chapter, the DiNeMo platform is described and its applicability through a network computation example is elaborated and discussed. Chapter 4 is centered on the interaction among network grids and electric vehicles' infrastructures. It analyses an electric vehicle database and evaluates the metrics including the user's behaviour. Furthermore, it illustrates

a new methodology for assessing the electric vehicle charging infrastructures features and performances. It concludes by performing a test case showing the network expansion costs required for the installation of new electric vehicles charging infrastructures. Chapter 5 starts with a literature review on the statistical approaches to validate modelled network. Then it describes the validation methodology built to asses the reliability of DiNeMo platform. A set of indicators are built to compare DiNeMo's results with those from a real distribution network in Croatia. It concludes by performing a power flow analysis of the network with different electric vehicles charging infrastructure penetration. The final Chapter 6 summarizes the main achievement of the research activities and gives an insight of future development and involvement of DiNeMo platform with Distribution System Operators, the electric vehicles interaction with the network grid and on the facing challenges and opportunities that Distribution System Operators may address.

The scientific literature reported in 3.2, proves that inadequate distribution network grids are available for researchers. Moreover, the different needs require ad hoc distribution grids with geo-reference layout and more flexibility in terms of equipment, automation devices, lines and transformers. Therefore this thesis work is trying to provide a powerful tool for the development of real distribution network grids cases. A special focus will be on the EVs role and effects in distribution system. To summarize the following questions have been addressed during the research:

What are the main technical differences across the European distribution system operators?

This aspect is described in Chapter 2. Interesting results pops out from the survey launched to DSOs. The technical data collected indicates that considerable difference among the metrics describing networks are observed at each voltage level. Circuit length, underground ratio, capacity of substation per consumers, reliability index, and the number of consumer per substation are those varying the most based on the data collected. The reasons behind these differences, among many, lie in the city layout, population density, national regulations, investment applied on the network grid, and the level of smartness implemented.

How can reliable distribution network grid models be designed for an urban area of interest?

This aspect is described in Chapter 3. The lesson learnt from literature and from the DSOs's survey highlights the relatively limited number of buses, branches and therefore consumers; the lack of geo-referenced layout; and the fact that the original purpose of the networks were neither for distribution network analysis either for representing European network grids. Therefore a unique platform named DiNeMo has been designed to allow the creation of representative distribution network grids of urban areas of interest. The structure of the network is based on the median values of selected data, within the survey, collected from the 99 DSOs's. The core module is a modified version of the algorithm for the creation of representative networks, developed by Comillas University, who has been originally designed to regulate the revenues and cost for the Spanish power system.

What is the most accurate location of charging stations in the network to avoid congestion management issues?

This aspect is described in Chapter 4 and 5. Based on a EVs dataset of 2900 charging columns installed in the Netherlands a multi-modal probability distribution has been created. This allows to reproduce plug-in, plug-out and charging profile with a time step of 1 minute. The EV's drivers behaviour serve as the base to understand the potential threads occurring in a urban areas especially during peak hours. The new charging stations will be most likely installed closed to point of interests as long as the network reinforcement costs will not exceed DSO's costs or may thread the reliability of the network itself. A first test case has been produced to analyse the network reinforcement costs. A second test case focuses more on the congestion management issues during peak hour with a higher penetration of EVs.

How representative reference models can be statistically validated with real networks?

This aspect is described in Chapter 5. A comprehensive list of criteria selected to validate DiNeMo output with real networks is presented. The validation process is composed of involving expert in the field and on a statistical validation. The fist one has been directly done in collaboration with the Croatian DSOs as well as fruitful collaboration with experts. The statistical one relies on 10 indicators which affect the creation of representative networks on DiNeMo platform.

To answer the above research questions the structure in Figure 1.1 has been defined and divided in 3 main phases. Phase 1, addressed in chapter 2.3, consists in the data collection, which is subdivided in 4 stages: literature review, DSO observatory survey, data clustering and the creation of the indicators from the data elaborated. In literature review stage, the main objective is to understand the technical and non-technical features associated with distribution networks. Furthermore, the available networks in literature were scout and analysed the tests performed on those grids. The second stage of phase 1 is the DSO Observatory survey in which a long lists of question were asked to European DSOs in order to collect the the information necessary to design a network grid based on what discovered in stage 1 and to improve them in terms of size, geo-references, etc. Moreover, the questions posed on the survey were necessary to understand answer the first main objective of the PhD thesis. The consequently stage, is the data clustering which end up in the DSO Observatory report, where a holistic view of the current European DSOs situation is deeply analyzed. The data clustering stage helped understanding the main different approaches in designing the grid at urban level across DSOs. In addition to this, a better knowledge on how the handle new electricity player such as: electric vehicles and storage devices within their are of competence. The final stage of the data collection phase is the creation of the networks indicators. Up to 36 indicators with the aim of describing the metrics adopted to design the structure, the distributed generation, the substation and reliability of distribution network

grids.
With the help and experience of the Institute for Research and Technology of Comillas University in Madrid I worked on the phase 2 (described in Chapter 3): reference network creation. This phase 2 has also been divided in 4 stages: physical and structural attributes, operational attributes, scenario optimization and reference network creation.

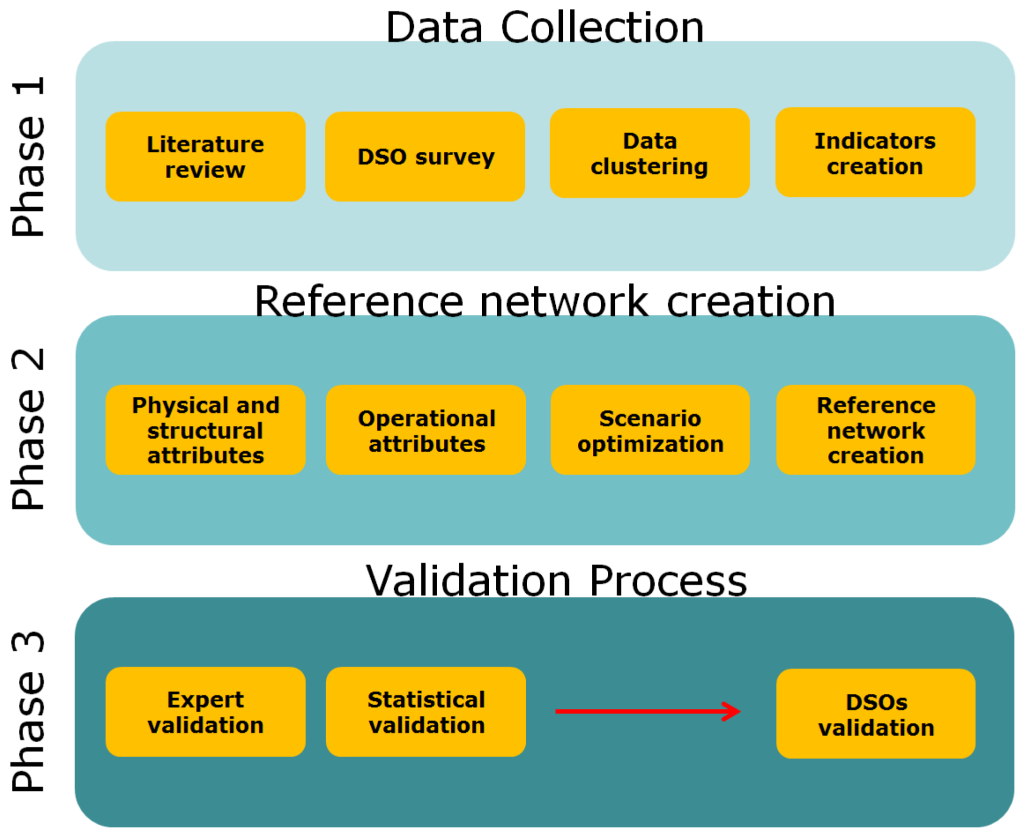


Figure 1.1: PhD thesis structure

In this phase the programming code to design the network is developed while physical, structural, operational attributes are optimized in order to implement power flow analysis within reasonable timing. Beside these activities in the scenario optimization stage the demand profile of electric vehicles charging station in order to understand their impact on the network has been studied (Chapter 4).
The final phase, developed in Chapter 5, is based on the direct consultation of expert for the validation (DSOs, researchers, etc.) and on the statistical validation

of the indicators developed in phase 1. DSOs are also considered for comparing these indicators between their real network and the one developed by the platform.

Chapter 2

Distribution System Operators

This chapter provides an overview on distribution system operators (DSO) and the different configurations available. It describes the main technical features and the smart grid dimension. It also presents the e-Directive and e-Regulation of the Clean Energy Package concerning DSOs. This chapter is based on the DSO Observatory report 2018 [1].

2.1 The future role of the distribution grid

The leading characteristic that makes electricity a unique commodity lies on the complexity in storing it in an efficient and economic way. This peculiarity makes power systems dynamic and highly complex where electricity have to be instantaneously generated, transmitted, distributed and consumed. The generation sector produces electricity in the range of 6-20 kV, which is transformed, for the transmission sector, at extra high voltage levels (over 100 kV), to reduce line losses over reasonable overhead lines and cables costs. Substations at the distribution level reduce voltage at medium voltage levels (around 20 kV), then at low voltage level (400 V) to deliver electricity to the final consumers (at also 220 V) in single phase, as described in Figure 2.1.

Another relevant peculiarity is that electricity flows according to the lines technical characteristics (i.e impedance, etc.). This means that electricity, differently from a product, can not be delivered through specific power lines, within the grid, but depends on Kirchhoff's laws. Consequently, the whole system is completely interdependent and a single variation in any point of the power system will instantaneously reconfigure all flows. For this reason, the dynamic equilibrium lies on permanently maintaining the supply and demand balanced. This is possible by constantly monitoring frequency and voltage values, and keeping them within secure limits. On top of this, the economic aspect, behind the power dispatch, has the objective of minimizing costs which consider also cost associated with ancillary services. The economic decision are threatened by the uncertainty on the demand and supply (i.e. wind, sunlight, failures, etc.) side.

Historically the electric power system has been subject to a traditional regulation scheme where utilities, vertically integrated, were supplying electricity under a monopoly business model. Indeed, the same company was producing electricity through centralized power plants and owning the transmission and distribution sectors. In this context, national regulators were establishing minimum quality of service standards in order to protect consumers from possible market power which may lead to unjustifiably high prices [2].

Since the 90s several business sectors, such as telecommunication, have been opened to competitive markets aiming at the same time to reduce prices and improve quality. Differently from the other sector, the power system has been partially switched to a more *perfect* competitive market. Indeed, the restructuring and liberalization have been applied to the generation and retail sectors, meanwhile transmission and distribution were kept the same as being, by nature, natural monopolies. This unbundling process affects the sector by separating accounts, functions, legal and ownership activities of generation and retail activities [3]. Even though, transmission and distribution sectors were not directly subject to unbundling, due to their monopoly structure, they have seen radical changes in the last decades.

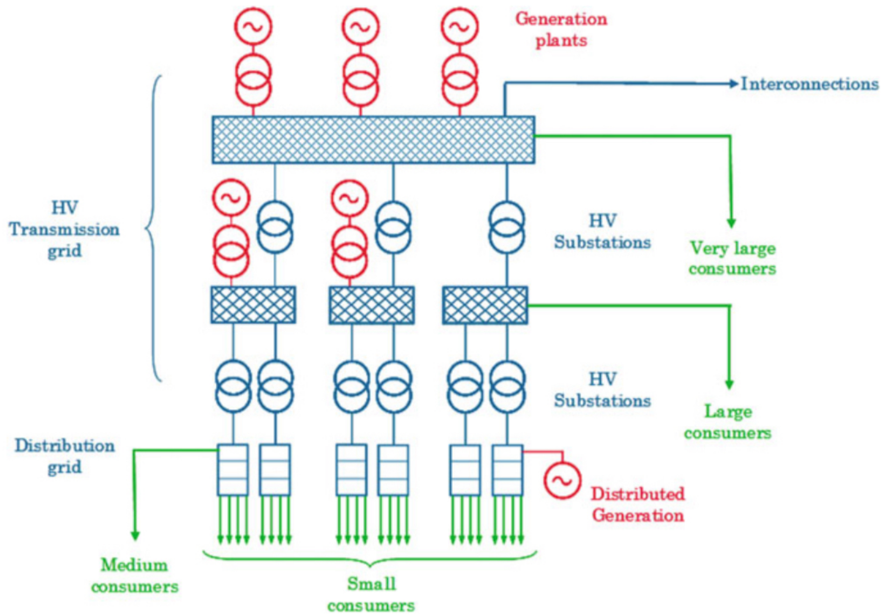


Figure 2.1: Electric power system structure [4]

Focusing on distribution systems, in particular at the European level, after the unbundling process the retail activity, which was previously owned by DSOs, is now managed by retailers. Thus now distribution operators have kept the unique role to ensure grid connection and to carry power through the grids toward final consumers which can be either low voltage (LV), medium voltage level (MV) or very few at high voltage level (HV).
The whole power system sector is undergoing unprecedented changes provoked by several crucial trends such as: the growth of renewable energy sources; the decarbonization actions to mitigate climate change; the deployment of smart meters and demand response programs; the proliferation of distributed generations as well as energy storage systems; the digitalization through the introduction of information and communications technologies [5]. In addition, the electrification of the transport sector is interconnecting two systems which have been completely separate until now. All these changes are creating a paradigm: shifting the top-down power system approach, where energy was produced far from energy hub, to a more bottom-up approach, where distributed generation is rapidly propagating [2]. For this reason, the new bottom-up approach is accentuating the importance of the whole power system chain on the distribution sector, in which all these changes are

occurring. This may lead to threat the reliability and security of the distribution system if no ad hoc actions are going to be adopted and powerful tools developed. Indeed, the distribution system has been considered until now as a passive system simply aiming to deliver electricity to final *naive* consumers.
To summarize three main drivers are disrupting the traditional approach of power system, and reshaping the whole power sector and especially the distribution sector. The first driver is associated to innovations in technologies, which goes from dramatic reduction of wind and photovoltaic costs, light-emitting diodes widespread adoption, to the drop in lithium-ion battery costs for both stationary storage solutions and electric vehicles. Second, ad hoc policies provide incentives (i.e. feed in premium, feed in tariff, green certificates, etc.) that boost investments in renewable energy-based solutions. The third driver is the change in awareness and preferences of consumers. Indeed, consumers through their choices can not be considered anymore as passive agents in the power system sector but rather as new *stakeholders*. Their decisions, in terms of consumption, production and reduction of their environmental impact, place them at the core of the system with a new role: prosumers.
The unprecedented changes appearing right now are shifting the attention toward the distribution system which have been considered, so far, less *attractive* for researchers. These transformations are targeting, directly and indirectly, mainly the distribution grid that until now, compared to the transmission one, lack adequate knowledge to address these challenges. Indeed, to deepen the understanding of the different technical features that characterize the various DSOs operating in Europe is fundamental. For this reason, in this study in order to acquire consolidate knowledge, a first benchmark on European DSOs indicators have been achieved.

2.1.1 State of play of Distribution System Operators in Europe

The Paris climate conference (COP21) held in December 2015 has seen 195 countries declaring a common action plan agreement to set an ambitious goal of limiting global warming to 1.5°C [6].
Subsequently the Paris agreement, the Clean energy for all Europeans package (one

Directive on common rules for the internal market for electricity

Unbundling for Distribution System Operators (DSOs)

The unbundling regime of DSOs laid down in Article 26 Electricity and Gas Directives remains in substance unchanged as compared to the preceding regime. The DSO is part of a vertically integrated undertaking, the basic elements of this unbundling regime are the following:

(a) legal unbundling of the DSO from other activities of the vertically integrated undertaking not related to distribution;

(b) functional unbundling of the DSO in order to ensure its independence from other activities of the vertically integrated undertaking;

(c) accounting unbundling: requirement to keep separate accounts for DSO activities;

(d) possibility of exemptions from the requirement of legal and functional unbundling for certain DSOs.

of the six initiatives of the energy union framework) marks a serious step forward in the implementation of the energy union strategy which sees as a key goals the economy decarbonisation, energy efficiency improvement, energy security boost as well as the creation of a fully integrated internal energy market [7]. It puts emphasis on 5 main domains: energy performance in buildings, renewable energy, energy efficiency, governance regulation, electricity market design. It will enter into force by summer 2019 with 8 legislative acts (directives and regulations). The most two relevant proposals tackling the distribution sector are the Directive on common rules for the internal market in electricity (e-Directive) and the Regulation on the internal market for electricity (e-Regulation).
The directive 2009/72/EC [3] defines the distribution system operator as: *..a natural or legal person responsible for operating, ensuring the maintenance of, and if necessary, developing the distribution system in a given area, and where applicable its interconnections with other systems and for ensuring the long-term ability of the system to meet reasonable demands for the distribution of electricity.*
The articles 26 (shown in the box above) and 32 of the same directive also oblige DSOs that were part of a vertically integrated company to unbundle functional

and legal tasks, thus accounting and ownership, for those DSOs serving more than 100,000 connected customers. The separation of the vertically integrated company may undertake two choices: the company can still keep the shares in the network company, thus allowing it to control the network, but a functional unbundling is required; or it can give up the control over the company (i.e. by selling shares) in order to not be anymore legally bundled.
At the current status not much is known about the European DSOs and the network they manage and operate. This unawareness is mainly attributed to the confidential nature of this information as well as the heterogenity and enormous number of DSOs in Europe [8]. The first point related to confidentiality is linked to the fact that often DSOs are not aware about their network topology and the interaction with the transmission system operator (TSO) can be considered negligible due to the non reciprocal sharing of data. Concerning the second point, there are more than 2,600 electricity distribution companies spread across the 28 European Member State serving 260 million customers with 2,700 TWh of energy per year. Of those 2,600 DSOs the unbundling applies to only 13% based on [9]. Even if this number may seem small, these DSOs serve more than 220 million users and thus keep this industry sector rather concentrated.
The DSOs' situation varies radically for each country, because of historical, geographical, legal, political and economic reasons. This variety is plotted in the radial bar chart visible in Figure 2.2, on a logarithmic scale per geographical area. The numbers are related to all DSOs operating in each country, which it means also those not unbundled. It is clear that the southern countries in Europe, except for Italy that has 151 DSOs, have a relatively limited number of operating DSOs. A common trend in all regions is the fact that there are one or few dominant DSOs for each Member State and many smaller players sharing the remaining market. Germany is a unique case due to the significant number of operators: 885 of which 75 are subject to the unbundling procedure [10]. Indeed in some Member States there is only one DSO (i.e. Cyprus, Lithuania), while in others there are tens (i.e. Belgium, Portugal) or hundreds (i.e. Germany, France) of them operating their networks on a municipal or regional level. A panoramic view of the current status

is summarized in Table 2.2 which highlights the wide difference across countries regardless of the country geographical size, population or economic value [8]. Indeed similar countries, such as Germany and France have rather different granularity in total number of DSOs, and even more accentuated for unbundled DSOs. Further differences are related to the operating voltage levels, DSO-TSO interaction, smart metering deployment, technical features, the level extension of unbundling as well as the activities and scope of DSOs. For the reasons explained above, it becomes crucial to deepen the knowledge of distribution grids and operators.

2.2 e-Directive and e-Regulation for DSOs

The official journal of the European Union agreed upon the e-Directive [3] on the common rules for the international market for electricity and the e-Regulation [4] on the internal market for electricity. From a legislative point of view the main difference is the following: the directive lay down certain results that must be achieved but each Member States (MS) is free to decide how to transpose directives into national laws; the regulation have binding legal force throughout every MS and enter into force on a set date in all the MS.
The chapter 4 of the e-Directive focuses on Distribution system operator and the articles from 30 to 39 covers the following aspects: tasks of distribution system operators, incentives for the use of flexibility in distribution networks, integration of electromobility into the electricity network, tasks of distribution system operators in data management, unbundling of distribution system operators, ownership of energy storage facilities by distribution system operators, confidentiality obligation of distribution system operators, closed distribution systems and combined operator. The DSO's tasks consist in operating, maintaining and developing under economic conditions reliable and efficient electricity distribution system. It should not discriminate between connected users, and when dispatching renewable energy sources and cogeneration should be prioritized. Moreover, the service and products procurement to ensure system security is performed in coordination with transmission system operators and national regulatory authority (NRA).

Article 32 defines the use of flexibility services within distribution systems. Indeed, MS should provide the necessary regulatory framework which allow proper incentives to DSOs for the flexibility procurement including demand response, energy storage to avoid congestion. Moreover, unbundled DSOs should submit to NRA the network development plan as well as the investment one at least every two years with a timescale of 5-10 years.
The electro-mobility topic is addressed in article 33 which remark the growing importance of this thematic within the distribution network. MS should provide, like for flexibility incentives, the regulatory framework to facilitate the connection and accessibility of public recharging points to distribution networks. The key element is the fact that a DSO cannot own, operate, manage and develop charging infrastructure. Exceptions are allowed based on some criteria: no 3rd parties is interested (i.e. not cost effective), the NRA gives the approval after an ex-ante assessment or the DSO operates the charging infrastructures for a 3rd party. The NRA should reassess the potential interest of a 3rd party at least every 5 years.
Concerning data management (article 34), DSO should provide non-discriminatory access to data for eligible parties and MS should verify that those DSOs not subjected to unbundling are not taking advantages of this. The unbundling process explained in article 35 is highlighted in the above box. Energy storage facilities, as for charging infrastructure, can not be own, develop, manage and operate by DSOs.
The e-Regulation focuses on the re-dispatching, network tariffs, development of new network codes and DSO-TSO cooperation. The articles 12 and 13 of the regulation explains that renewable energy sources with a power of maximum 400 kW are prioritized as well as demo projects. Moreover, DSOs are obliged to annual report to the NRA the re-dispatching mechanisms adopted, reasons, volumes and type of generation subject to re-dispatch and the measures taken to reduce downward re-dispatching of renewable energy sources. Regarding network tariff, the charges applied by network operators should be transparent and cost-reflective for the maintenance of network security. This charges should be determined through price signals to customers and producers to support the overall system efficiency. In addition, the tariff methodologies should reflect the fixed costs of operators while

at the same time incentivise them to increase efficiency and market integration. For the new network codes DSOs should be taken into account in the consultation process and all documents should be public. The e-Regulation in the article 37 accentuates the fact that DSO-TSO cooperation on planning and operation should be increased by sharing the necessary information and demand regarding performance of generation assets and demand side response on daily basis.

2.3 DSOs Obsevatory survey

To the best of our knowledge, as explained in paragraph 2.1.1, little information is available in the public domain, and it does not allow in depth analysis of the distribution grids status. To fill this gap, the Joint Research Centre (JRC), launched an initiative named, DSO Observatory project. The project consists of collecting a variety of data directly from the distribution system operators [11]. Given the fact that the number of DSOs exceed 2,600, it was necessary to restrict the survey to a specific target of DSOs, which in this case were the ones complying with the unbundling requirements set in the EU Electricity Directive (thus the ones serving more than 100,000 customers).
The survey was oriented toward DSOs with the help of the four DSOs industry associations, based in Bruxelles, that are: EURELECTRIC gathering large power generator and retailers; GEODE and CEDEC representing the *smaller* local and regional energy distributors; EDSO which aim at fostering the cooperation of DSOs for a common development of smart grids projects, and adequate policies and Member State regulations. The aim of the survey was to provide to researchers and stakeholders, in the energy sector, an in depth overview of DSOs similarities and differences among them. The online survey[1], as previously mentioned poses a series of questions (listed in Appendix A), targeting the 191 DSOs serving more than 100,000 customers. JRC gathered 99 answers from the 191 larger DSOs covering at least one DSO for each country, except for Malta. Although, the survey coverage is

[1] A similar survey was launched in 2014 with a different purpose. For further information please refer to [11]

around 50%, the number of customers supplied is almost 220 million which corresponds to 85% of the total. Furthermore, the data collected from those DSOs who actively participate allow to cover a total area of 3.4 million km^2 and 8.6 million km of power lines [1].
Substantially the survey objective has been divided in two main categories: first understanding the network structure, and how decisions are made to plan and reinforce distribution grids through a series of technical questions; second to figure out how they are dealing with the energy transition which see DSOs and consumers at the core centre of the future upcoming power system. For instance, how are they managing the interaction with TSOs and adjacent DSOs? Which information are they sharing? And how often, hourly, daily or monthly basis? How far are they with the deployment of smart meters? What is the distributed generation penetration at each voltage level (LV, MV, HV)? How many electric vehicle charging stations are installed in their competent area? Do they manage them? To which extend demand side programs have been applied? In which way prosumers have been engaged? How far is the digitalization and smartening process of substations, circuit breaker, etc.? To answer these questions the data collected in the survey were divided in: technical features and smart grid dimension as listed hereby:

1. **Technical Data**:
   - Network structure;
   - Substation design;
   - Reliability and other metrics;
   - Distributed generation per voltage level.
2. **Smart Grid Dimension**:
   - DSO as a user of non-frequency ancillary services;
   - DSO - TSO data management.
   - Meter data management;
   - Remote control of substations;
   - Electric mobility;

Within the 4 categories of the technical data, up to 36 indicators have been obtained to describe the network grid, and they are listed and explained in section 2.4.1. Until

now, the availability of distribution grid structure was extremely limited compared to transmission grids, which have been deeply analyzed for different scenarios and stress test conditions through IEEE case studies. These case studies refer to real or *fictitious* transmissions grid layouts which have been utilized in the powerful tool MATPOWER for power flows and optimal power flows analysis [12].
To fill this gap, among the PhD thesis there has been a cooperation to develop a new platform to provide stakeholders in the electricity sector with a solid tool that based on the network structural indicators is capable to reproduce the representative distribution grid of a given area of interest.

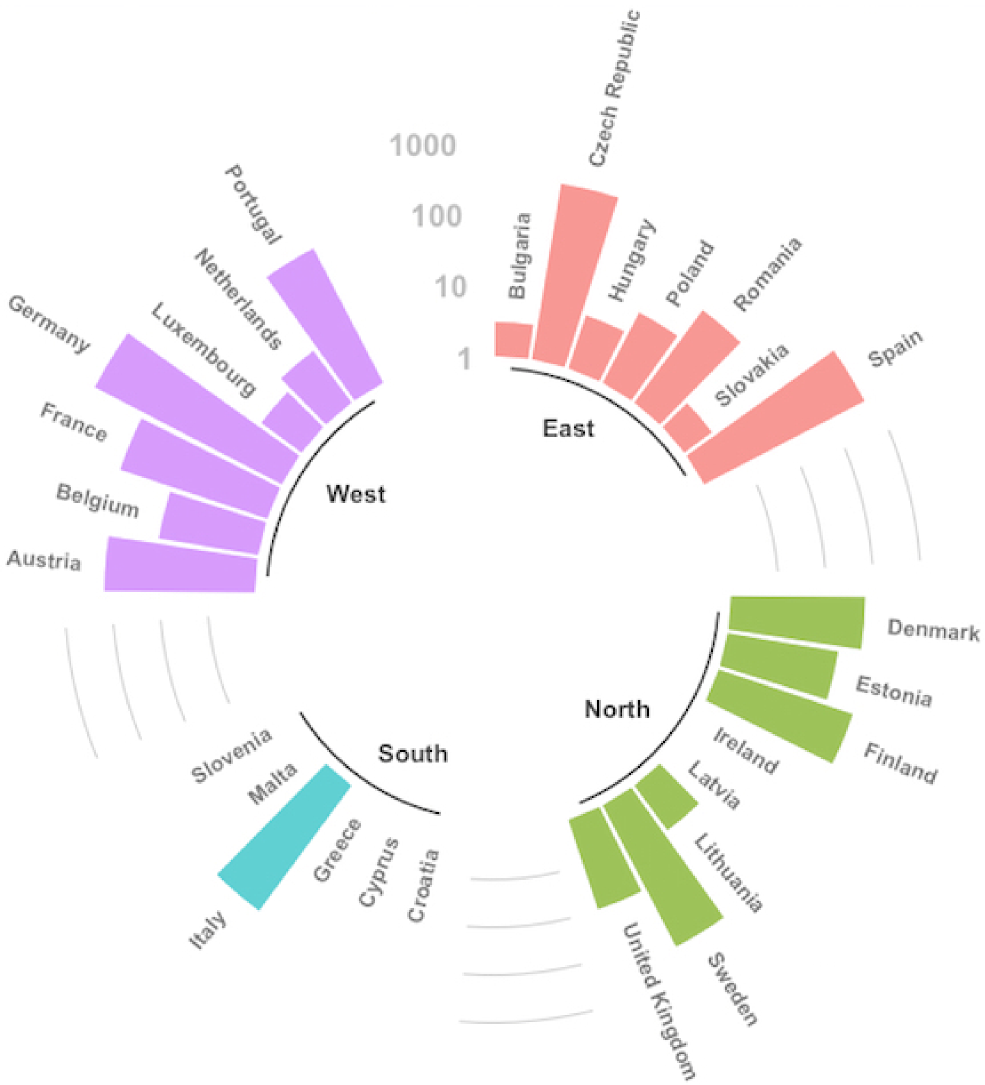


Figure 2.2: DSOs number per country

In order to do so, in the post processing phase, the gathered data are clustered in order to derive a subset of 10 indicators which are the most relevant for designing and planning the network grid structure.
The distribution network model (DiNeMO) is a flexible and impressive tool which is bound to become the virtual place where diverse users, with different roles within the power system sector, will collaborate with the aim of building reliable models to study and shape the smart cities of tomorrow.
The DiNeMo platform intent is to provide different stakeholders with ad hoc instruments to properly understand the rapid changing scene, enabling the identification of developments, opportunities and supporting evidence-based policy making concerning the distribution grid level. Indeed, the decision-making process, in Member States, of distributions network development appears less transparent and structured if compared to the transmission network one (ENTSO-e).
Moreover, the importance in having a joint and coordinated DSO-TSO approach is key to overcome future challenges. For instance, planned reinforcements on the transmission side may oversize the one occurring at the distribution level if no ad hoc communication is taking place. Another important aspect which can be analyzed with DiNeMo is the the increased flexibility required at the DSO level through the emerging roles of storage facilities and charging infrastructure.
Therefore motivated by this goal a second DSOs Observatory survey have been launched to gather data and information which focus more on the technical features plus an overview on the smart grid dimension. Those inputs will be the technical input values of the core module for developing the distribution network model platform (DiNeMo).
DiNeMo aims to provide stakeholders in the electricity sector with a solid tool that based on real data is capable to reproduce the representative distribution grid of a given area of interest as will be further explained in Chapter 3.
For this reason the main project objective is to throw light on the different characteristics of some of the major European distribution networks. Moreover, it will contribute to a better understanding of the challenges that the energy system transition is posing to European distribution system operators and to elaborate sound solutions, also through the use of DiNeMo platform, to address them.

2.4 Survey Results

The DSO data collection exercise provides also a reasonable holistic view of the main difference among DSOs in terms of yearly distributed energy, geographical area covered, power lines length and number of connected customers as shown in Figure 2.3. Regarding the survey out of the 28 Member States about 16 countries reach a 100% coverage of those DSOs serving more than 100,000 customers. Among the 28 Member State, the *outliers* with a high number of larger DSOs are Belgium, Austria and Germany which respectively have 13, 15 and 75 DSOs.
This figure is surprisingly high if we taking into account that the median value equals 3. These different characteristics are even more exacerbate while having a looking at the technical features in section 2.4.1 and the smart grid dimension in section 2.4.3.
In Figure 2.3 a more profound categorization of DSOs is highlighted. The Figure illustrates the distribution of energy in GWh (blue), the distributed area in km^2 (green), the power lines length in km (purple) and the number of connected customers in million (red). The distributed energy chart (blue) reveals that few DSOs (<3%), among the 99 who participate, are very large, and deliver above 180 TWh. This number combined with the figure showing the number of connected customers, indicate that these operators deliver electricity to more than 15 million customers. This is the case for E-Distribuzione in Italy and ENEDIS in France which are by far the leading DSOs in their respective country, covering an area above 100,000 km^2.
These two countries have a lot of similarities in their distribution sector, indeed France has a total number of DSOs of 148 and Italy 151, which, except for ENEDIS and ENEL, are supplying relatively small regions or even municipalities. Among all Member States the case of Germany deserves a special focus due to the fact that it is composed of 4 principal TSOs and up to almost 900 DSOs, of which 75 subject to the unbundling.
The 3 major DSOs are delivering electricity to slightly less than half of the industry sector [10]. This extreme spread of operators require a proper management and demand forecast, thus is surprising that the smart metering roll-out for Germany is still limited to 23% [13]. The opposite cases is found for a series of countries, limited

in terms of geographical area, that are composed by few DSOs such as: Cyprus, Estonia, Latvia, Ireland and Luxembourg. In general the mean and median yearly distributed energy are respectively 23 TWh and 7.9 TWh. Concerning the connected customers (red) almost 95% are LV connected customers with a mean and median values of customers supplied per DSO is 2 and 0.7 millions respectively. It is important to highlight that the LV connected customers within each country may have a complete different connection limit in terms of power, thus affecting also the type and length of power lines.

For instance, single phase contracted power levels in Luxembourg starts from 9.2 kVA and grow up to 18.4 kVA, meanwhile in Italy, Denmark and Slovakia can not exceed 6 kVA. The majority of DSOs (40%) supply electricity to less than 750,000 customers [14].

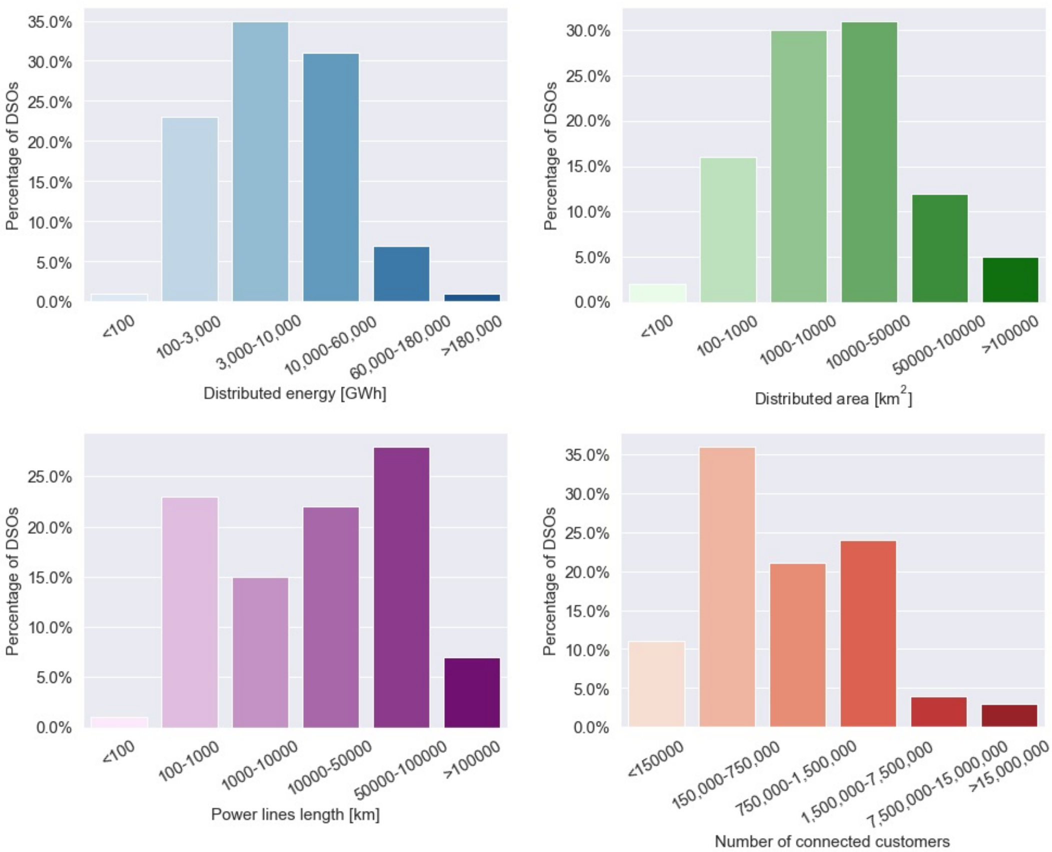


Figure 2.3: DSOs general features overview

The power lines length figure (purple), in line with the distributed one (green) point out a relative high level of cables utilization. This may be attributed partially to the fact that the cities development (i.e. new district, industrial or commercial areas) along the years may have left some constraints (i.e. land use) affecting the distribution grid layout growth.
Furthermore, another reason can be linked to DSOs, which according to the survey, deliver electricity to both urban and rural areas, and consequently increase the average area served as well as power lines.
This latter is also influenced by the use of underground and overhead ratio, as well as the typology of consumers served (LV, MV or HV). By having a general look at the smart grid dimension, the survey reveals that DSOs in compliance with the EU electricity market legislation are effectively unbundled[2].
Indeed, concerning ownership DSOs are classified in 4 main classes: private, public owned by municipality, public and other. The one replying "other" explained that they have a hybrid ownership, which is usually split in 50% private and 50% public. Up to 87% of the DSOs are part of a bigger group operating in the power sector and with respect to the parent company they are all separated from a legal and functional (organization and decision making rights) point of view. Less than 5% have also separate in the accounting from their parent company.

2.4.1 Technical Data

This section focuses more in detail on the technical features that describe a distribution grid network. The technical questions posed to the DSOs allow to collect up to 36 indicators, shown in Table 2.1, 2.2, 2.3 and 2.4. Table 2.1 focuses on the metrics at different voltage levels of the network structures, such as the number of LV, MV and HV customers per supplied area or the length of the power lines utilized.

[2]As stated in the preamble of Directive 2009/72/EC, the reasoning behind the new rules was that *"without effective separation of networks from activities of generation and supply (effective unbundling), there is an inherent risk of discrimination not only in the operation of the network but also in the incentives for vertically integrated undertakings to invest adequately in their networks"*

Table 2.1: Distribution network structure indicators

Network structure
1. Metrics associated to LV network
LV consumers per area of distribution
LV circuit length per LV consumer
LV circuit length per area of distribution
LV underground and overhead lines ratio
2. Metrics associated to MV network
Number of MV consumers per area
MV circuit length per MV supply point
MV circuit length per area of distribution
MV underground and overhead lines ratio
3. Metrics associated to HV network
HV circuit length per HV supply point
HV circuit length per area of distribution
HV underground and overhead lines ratio

Table 2.2 collects the installed distributed generation (photovoltaic, wind, hydro, biomass and waste) breakdown per voltage level for each DSO. Similar to the network structure (Table 2.1) Table 2.3 shows the indicators related to the substation

Table 2.2: Distributed generation indicators

Distributed generation
1. Metrics associated to generation
Total installed capacity of generation connected
Percentage of generation connected to LV per technology
Percentage of generation connected to MV per technology
Percentage of generation connected to HV per technology

design at urban and rural level. These indicators provide planning and operation metrics of HV/MV and MV/LV substations, thus the capacity in kVA, area covered and the number of connected customers supplied by each substation.
Table 2.4 reports indicators regarding urban and rural areas of the feeders. Moreover, the number of electric vehicle charging infrastructure, reliability indexes (SAIDI and SAIFI among many), plus information related to DSO-TSO interconnection points are collected. Furthermore, the automation equipment installed and the degree of automation, which indicate the digitalization of the distribution grid. This later aspect is crucial to manage the massive penetration of renewables which are drastically reducing the inertia of the whole system (for i.e. because photovoltaics produce power in DC rather than AC), therefore threatening the reliability of the system.

Table 2.3: Distribution substation indicators

Substation design
1. Metrics associated to MV/LV substations
Number of LV consumers per MV/LV substation
Area per MV/LV substation
Capacity of MV/LV substation per consumer
Area covered per capacity of MV/LV substation
Typical transformation capacity of MV/LV substations per urban areas
Typical transformation capacity of MV/LV substations per rural areas
2. Metrics associated to HV/MV substation
Number of MV supply points per HV/MV substation
Area per HV/MV substation
Capacity of HV/MV substation per MV supply point
Area covered per capacity of HV/MV substation
Ratio of capacity of MV/LV per capacity of HV/MV
Typical transformation capacity of HV/MV substations

On one hand the input parameters such as the number of connected consumers (LV, MV, HV), the area of supply, distributed annual energy (as well as demand, and peak demand), plus distributed generation data breakdown for voltage level are the information necessary for DSOs in order to plan and operate the grid. On the other hand, the output parameters correspond to the assets planned by the DSO to cope with the given inputs in order to plan and manage, in a safe and reliable way, the development of the grids. More specifically, the data can be related by applying different relations between inputs and outputs as follows: Input/Input, Input/Output, Output/Input and Output/Output ratios.

Table 2.4: Distribution network mixed indicators

Reliability indicators
1. Metrics associated to feeders
Average length per MV feeder in urban areas
Average length per MV feeder in rural areas
2. Reliability indicators
Number of electric vehicles public charging points per consumer
SAIDI for long unplanned interruptions
SAIFI for long unplanned interruptions
3. Other relevant metrics
Voltage level
Automation equipment and degree of automation
TSO-DSO interconnection points

To the best of our knowledge this is the most exhaustive collection of technical features, related to the distribution grid, which were not addressed yet due mainly to confidentiality issues and to the huge varieties among DSOs design approaches. This innovative contribution open an unprecedented branch of studies which can target future scenarios or comparing different distribution system design and plan. For instance, one could study the distribution grid flexibility evolution due to the introduction of massive renewable energies sources. Power flow analysis may be performed on the representative distribution grid produced by the online platform tool DiNeMo based on the distributed generation installation information acquired, for each voltage level, in the survey.

To conclude, these indicators tie the inputs, which are the structure of the demand or the distributed generation that DSOs must connect, with the outputs, which represent the installations (power lines, substations, etc.) that DSO uses to cover that given demand and to connect the distributed renewable sources. All the indicators extrapolated from the survey questions are deeply analysed and explained in the report [1].

2.4.2 Description of the main indicators

This section will describe the subset of main indicators utilized from DiNeMo platform. The subset of the 10 indicators, listed in Table 2.5, have been derived by calculating ratios, among the 36 indicators collected from the survey, as explained before in the following way: Input/Input, Input/Output, Output/Input and Output/Output. This subset represents the key input parameters for the reference network model, a large-scale distribution planning tool, which has been largely explained by Domingo et al. [15] and applied in DiNeMo platform.

In order to maintain the confidentiality of the results, which is still a key element for DSOs, these indicators have been kept anonymous and sorted in the following figures of this chapter based on the indicator's value. This means that the DSO in position #1 for one figure may not necessarily be the same DSO in position #1 for another indicator's figure.

The first indicator: **Number of LV consumers per MV consumers**, plotted in Figure 2.4, provides a measure of the percentage of LV consumers (mainly residential) versus MV ones (commercial and small industries) supplied by the DSO in that specific region. Figure 2.4 highlights a wide disparity among DSOs, indeed the minimum and maximum values are respectively 22 and 3,700 LV consumers per MV consumers. The average and median value are 614 and 402.

This difference can be attributed to the fact that certain DSOs serve more urban or industrial areas, therefore with a much lower LV consumer per MV consumers ratio, compared to the rural networks.

Table 2.5: Indicators subset to build the large-scale representative distribution networks

ID	DSOs indicators
1	Number of LV consumers per MV consumers
2	LV circuit length per LV consumer
3	LV underground ratio
4	Number of LV consumer per MV/LV substation
5	MV/LV substation capacity per LV consumer
6	MV circuit length per MV supply point
7	MV underground ratio
8	Number of MV supply points per HV/MV substation
9	Transformation capacity of MV/LV secondary substations in urban areas
10	Transformation capacity of MV/LV secondary substations in rural areas

Furthermore, DSOs supplying very large areas (visible in 2.3), therefore also rural ares, have inevitably lower values. This is proven by the fact that for instance DSO operating in Cologne, Luxembourg city, and other main German cities have

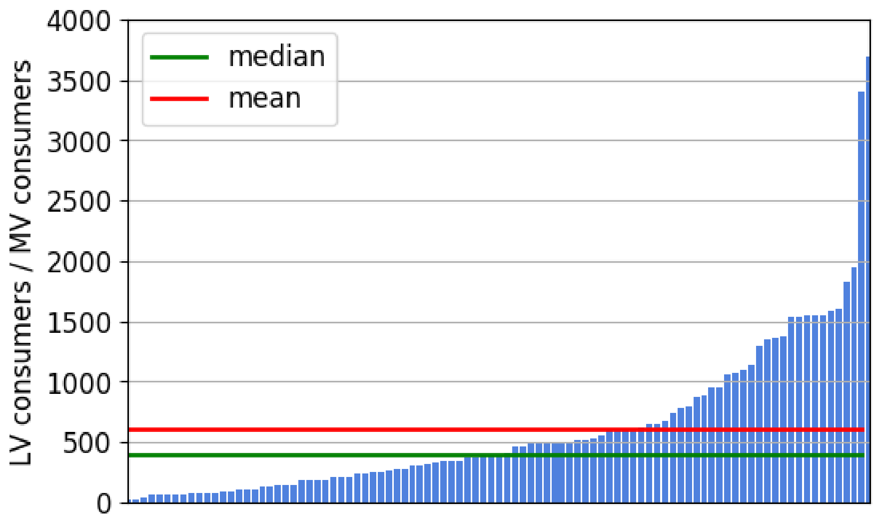


Figure 2.4: LV consumers per MV consumers

the highest values, meanwhile Hungarian and Polish DSOs have a way lower ratio. The second indicator, **LV circuit length per LV consumer** plotted in Figure 2.5, provides interesting results and thoughts for discussion.

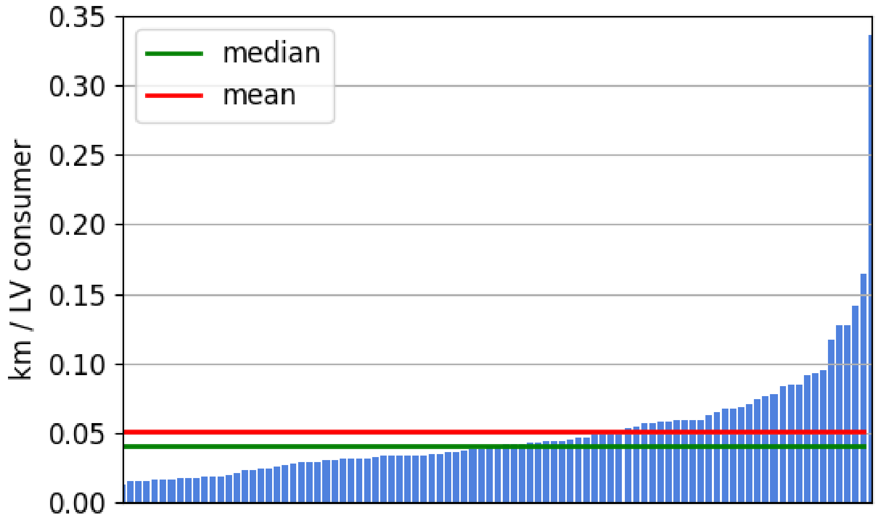


Figure 2.5: LV circuit length per LV consumer

This ratio mainly depends on the geographical distribution of consumers and the distance among them. Moreover, it depends also on the type of consumer, thus the voltage level (LV, MV, HV).

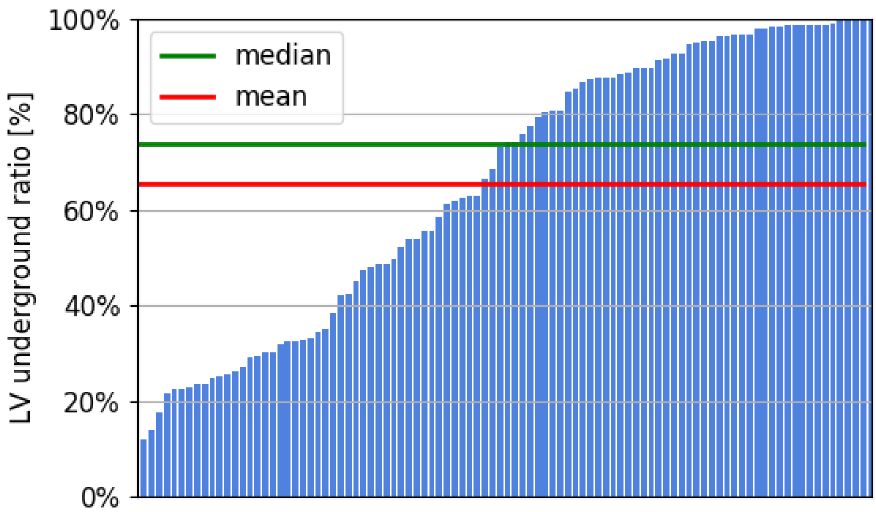


Figure 2.6: LV underground ratio

Except for few cases, this indicator has a tight gap with an almost identical average and median values of 0.05 km/LV consumer and 0.04 km/LV consumer. Higher values are expected for those DSO who address rural areas where electricity density is lower and feeders are longer due to the more scattered distribution of consumers. Indeed the maximum value corresponding to 0.33 km/LV consumer relates to a Finnish DSO supplying a relatively small amount of electricity across a huge area (southeastern area) of about 25 municipalities. On the other hand, the minimum value is achieved by a German DSO serving a city and its surrounding with a total population of 2.2 million. This indicator provides some insights also about the capital expenditure (CAPEX) and operation expenditure (OPEX) related to power lines installations and maintenance. In fact a DSO is obliged by law to guarantee electricity connections and to distribute electricity even in those areas where it is not cost-effective.

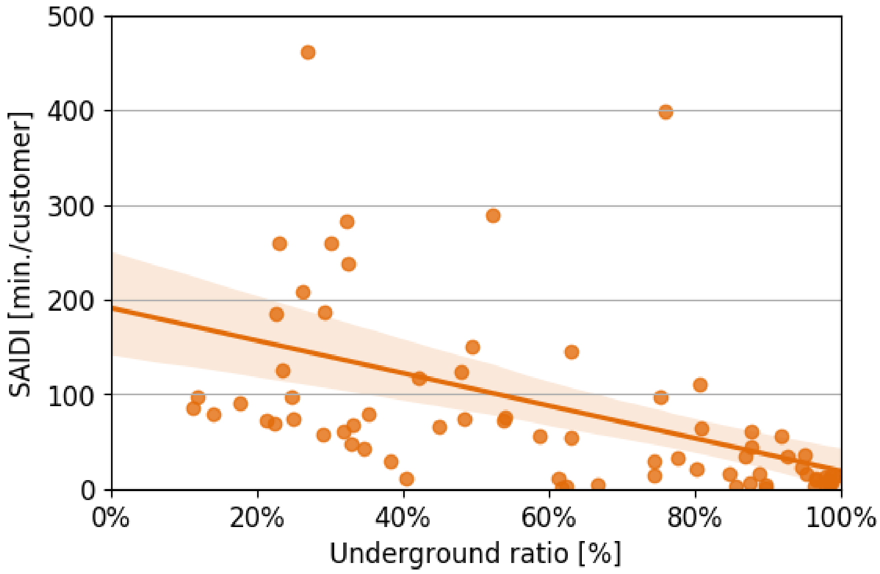


Figure 2.7: SAIDI correlation with LV underground ratio

Figure 2.6 illustrates the **LV underground ratio**, which is defined as the ratio between length (measured in km) of the LV underground circuits over the total length (sum of underground and overhead LV circuits). In green the median value is shown and corresponds to about 75%, this value reaches a maximum of 100% and a minimum of 11.2%. The average value, in red, is 66%. Figure 2.6 suggests that

DSOs with a LV underground ratio above 80% may corresponds to urban areas, between 80% to 30% to semi-urban, and below 30% to rural areas. Indeed, underground installations are often more desirable for *space* reason for highly populated areas, and also because they provide a reduced number of interruptions, as visible in Figure 2.7 concerning SAIDI performance index.
It is clear from the linear regression, plotted in Figure 2.7, that with higher ratios of underground power lines installations the SAIDI index decreases. There are few cases in which this statement is not true, and this might be attributed to exceptional weather events, as stated by DSOs in the survey, or particular maintenance operations done by DSOs.

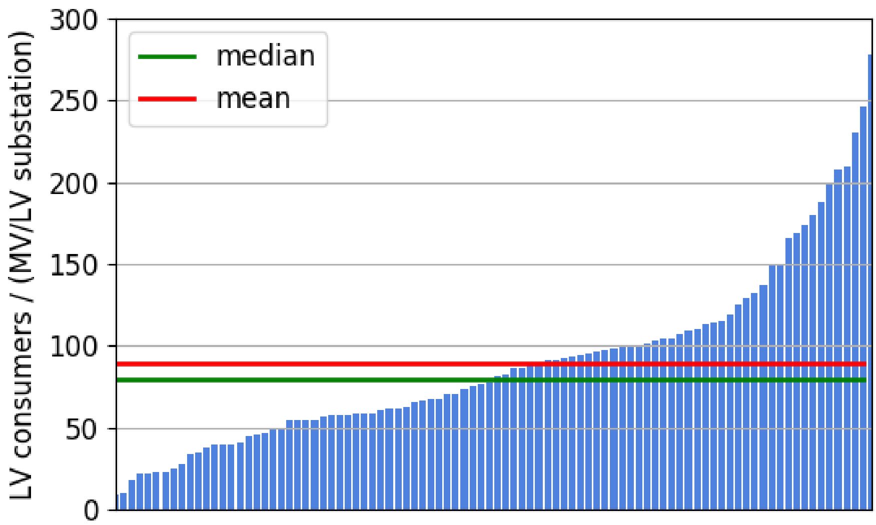


Figure 2.8: Number of LV consumers per MV/LV substation

Furthermore, the underground installations are less oriented to failure rate because less subject to adverse conditions as well as impact with moving objects, such as: birds, drones, small planes. On the other, underground power lines are more expensive to install and maintain. The fourth indicator, listed in Table 2.5, shows the **number of LV consumers connected to a MV/LV substation**, which is plotted in Figure 2.8. It points out the wide range of situations occurring across European DSOs. The minimum values are achieved by a Finnish DSO, and DSOs supplying small islands. On the other hand, high values are obtained for a German DSO serving Berlin and another one in Hamburg region, and others supplying

Prague and more capital cities in Europe.

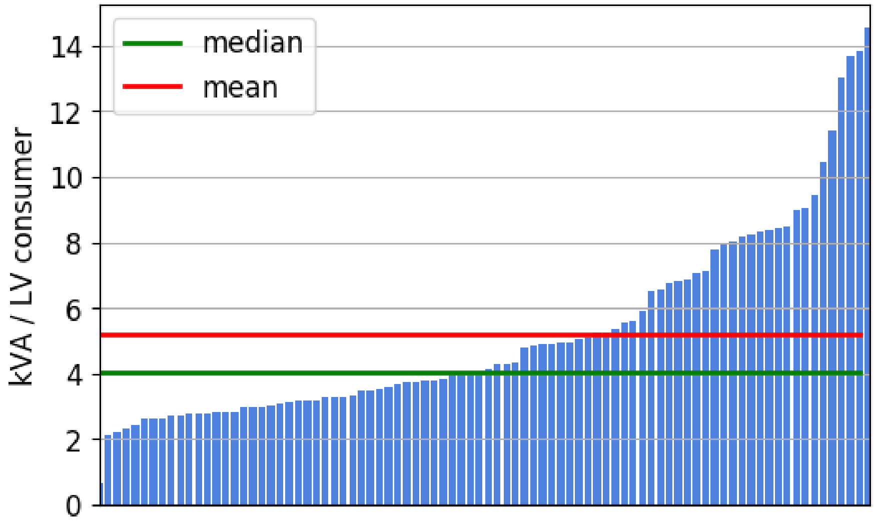


Figure 2.9: Transformers capacity per LV consumer

This ratio is useful because it provides an idea of the amount of low voltage network installed below each The average and median values are respectively 89 and 79. MV/LV substation. Of course, this ratio also depends on the granularity

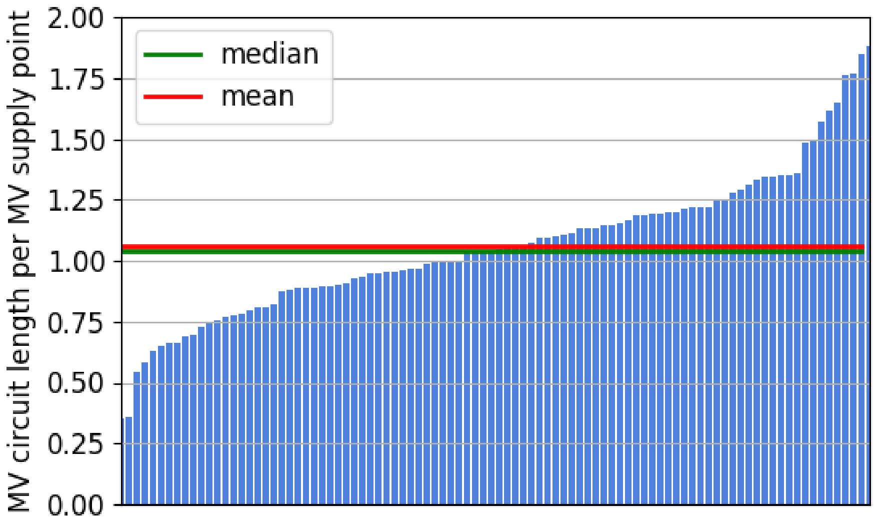


Figure 2.10: MV circuit length per MV supply point

and dispersion of the consumers, which are very different in rural, semi-urban and urban areas. To add on the just mentioned point the fifth indicator is reported in Figure 2.9. It shows the **capacity of MV/LV substation per LV consumers** giving an indication of how much power distributed generation is installed below the MV/LV substation.

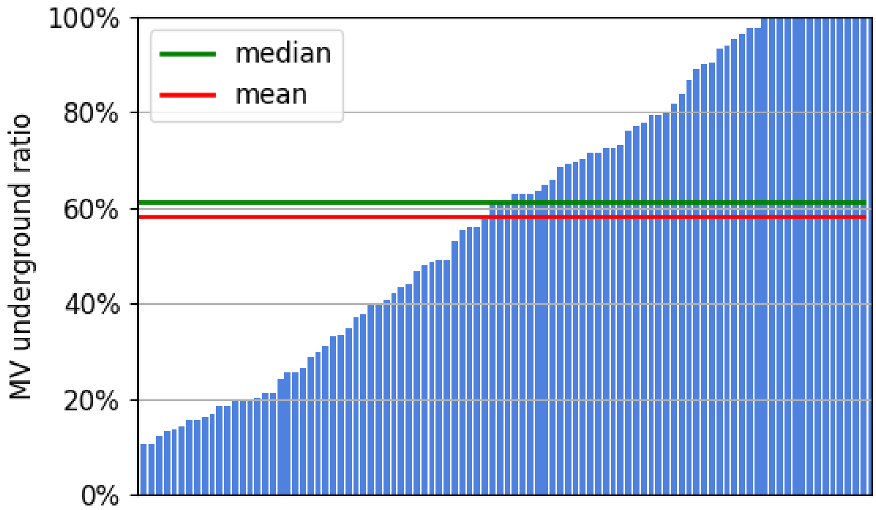


Figure 2.11: MV underground ratio

Thus, it may reflect the number and ratio of residential, commercial and industrial consumers. This is a critical value, because in certain distribution areas, for

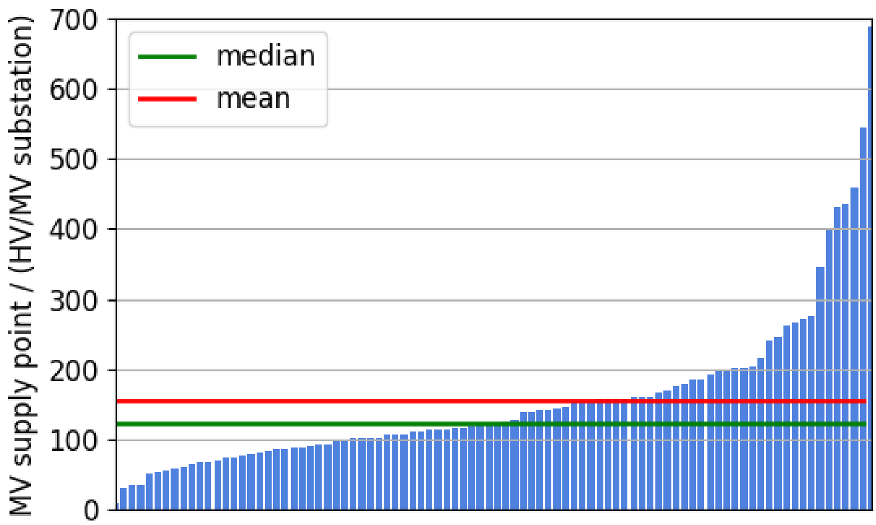


Figure 2.12: Number of MV supply point per HV/MV substation

safety reason, MV/LV substation have been oversized, and MV/LV values are much higher than expected. It highly depends on the average typical peak power of residential consumers. This latter value, is different for each country according to the study [14], and several ranges of contracted capacity are even possible within the same country. To understand the MV circuit, the **MV circuit length per MV supply point** ratio was selected and plotted in Figure 2.11. The MV supply points are the MV consumers and MV/LV substations, which are the key elements of interest for sizing and operating the MV network grid. The median and mean values are almost equivalent, and in the order of 1.06 km per MV supply point.

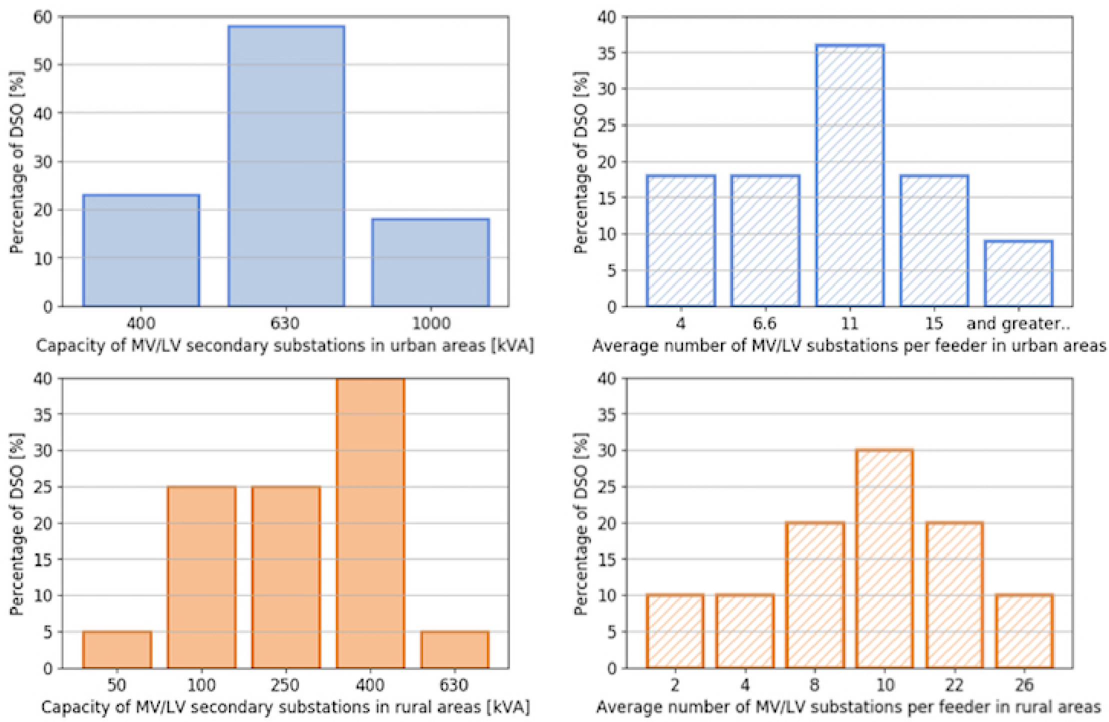


Figure 2.13: Typical transformation capacity level, and average number of HV/LV substations per feeder at Urban (blue) and Rural (orange)

Despite the fact that there is so much variability in the number of MV consumers per area, the MV circuit length per MV supply point does not differ so much among different regions, meaning that the DSO can have some control on this variable, but the range is not so wide. The bar chart in Figure 2.11 represents the **MV underground ratio** that is defined as the length of MV underground circuits divided by the total length of MV circuits (overhead and underground cables).

Usually the MV underground ratio is higher in urban areas rather than semi-urban and rural ones. This parameter affects also the reliability indexes, such as SAIDI and SAIFI (Figure 2.7), due to the fact that the chances of failure are reduced. Although, underground power lines are more expensive, the decision of installing underground or overhead cables could be based on aesthetic reasons. The median MV underground ratio is about 60%, with a maximum of 100% and a minimum of 9.8%. The chart also highlights the large diversity between the maximum and the minimum values, and this could suggest that the DSOs have the freedom to choose this ratio. Figure 2.12 describes the **number of MV supply point per HV/MV substation**, which is very different among DSOs. The HV/MV substation supply electricity to connected MV distributed generation (which are rapidly increasing in the recent years) and to the MV consumers. The median number of MV supply points per HV/MV substation is 125, with a maximum of 700. The MV consumers and MV/LV substations are distributed along feeders, and therefore the number of MV supply points per HV/MV substation can be calculated as the product of the number of feeders of the substations and the average number of MV supply points per feeder. Both of them are ratios which depend on the structure of the distribution networks, giving the DSOs some control on them. The typical transformation capacity of MV/LV substation at urban and rural level are reported in Figure 2.13. The chart 2.13 indicates, on the left side, the urban (blue) and rural (orange) capacity level. As expected, in rural areas there are more options due to the fact that different layout and consumers distribution may arise. On the other hand, at urban levels the MV/LV substation capacity is considerably higher and up to 1000 kVA compared to the maximum rural areas which is limited to 630 kVA. This occurs because of the increased electricity density per area served by the DSO, as well as the higher number of industries and commercial customers settled in cities. In line with the previous explanation, at the rural level there is a higher number of feeders below the substation due to the dispersion of consumers.

2.4.3 DSO Smart Grid Dimension

The unprecedented changes transforming the distribution system are opening new challenges and business opportunities. Beside the more technical aspects arose from the survey, the smart grid dimension section elucidates the initiatives and projects ongoing concerning the smartening and digitalization of the grid. The digitalization process, possible through the introduction of ICT instruments, enables to end the passive network management paradigm toward a more active one. Indeed, the digitalization and data related to the grid can be considered as the basic ingredients of the network of the future. It will allow DSOs to improve customers flexibility by promoting them demand response (DR) and demand side management (DSM); enhance the collaboration and data sharing with TSOs for a better congestion management and voltage support (in addition a common planning decision making would avoid over-sizing substations and power lines); smart metering implementation enable improved monitoring of outages, power quality and customers profiling; raise grid reliability through more automated remote control of substations; unlock the potential flexible contribution of resources, such as electric vehicles and storage devices.

The survey results concerning the smart grid dimension provide insights for future scenarios which can be tested on distribution grids produced by DiNeMo. For instance, the economic impact of price-responsive initiatives in an urban area may be analyzed through optimal power flow analysis. Another interesting approach would be to optimally localize electric vehicles charging infrastructure and storage facilities to contain voltage unbalances within a specific urban neighborhood as studied in the chapter 4.

Differently from other stakeholders in the power sector, DSOs are one of the key investors in smart grid solutions according to [16]. This arises because, as previously mentioned, the main changes are occurring at the distribution level. The report by Gangale et al. [16] collected 950 smart grid projects which can be categorized and clustered in five main domains:

1. Smart Network Management
2. Demand Side Management
3. Integration of Distributed Generation & Storage
4. Electric Vehicles
5. Integration of Large RES

The combined results of the Smart Grid Projects Outlook 2017, shown in Figure 2.14, and the DSO Observatory report of 2018 shed lights on which aspects DSOs are more prone to work on in the near future. Furthermore, Figure 2.14 highlights that the private investment (corresponding only to DSOs) are the most consistent, meanwhile the one related to national and European Commission (EC) financing is still limited which is indicated by the difference between the total and private one. It is clear that the investment in smart network management is by far the most extended achieving almost 400 million € in the period from 2004 till 2016.
These investment focus on projects to boost the use of advanced sensors to identify anomalies; tools for grid self-controlling as well as self-healing; frequency, reactive and power-flow control; finally smart devices such as controllable distribution substations, inverters, relays, capacitors, etc. Even if, until now investment on EV projects are still contained and the EC directive does not allow DSO to own charging infrastructures, in future business models this may be possible. For example, some DSOs are considering to offer services directly to the operators of charging infrastructures, thus indirectly to EV users.

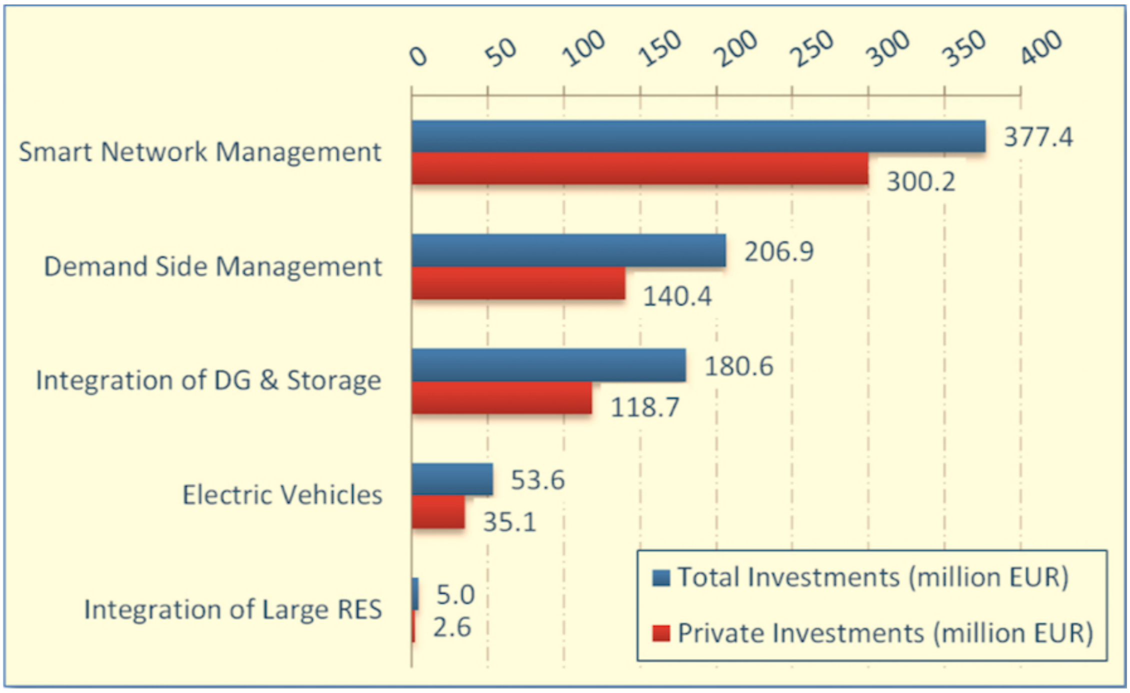


Figure 2.14: Smart Grid investments by category made by the DSOs in recent years

2.4.3.1 DSO as a user of non-frequency ancillary services

Concerning non-ancillary services, considered in the survey, the DSO participation in demand response (DR) and demand side management (DSM) has been analyzed. The first one focuses on short-term demand reduction, such as turning off lighting or shutting down manufacturing process, which can be done by actively involving participants. This occur if economic incentives, or price signals are promoted. Meanwhile, DSM is more oriented on improving consumer flexibility through autonomous and efficient energy systems.

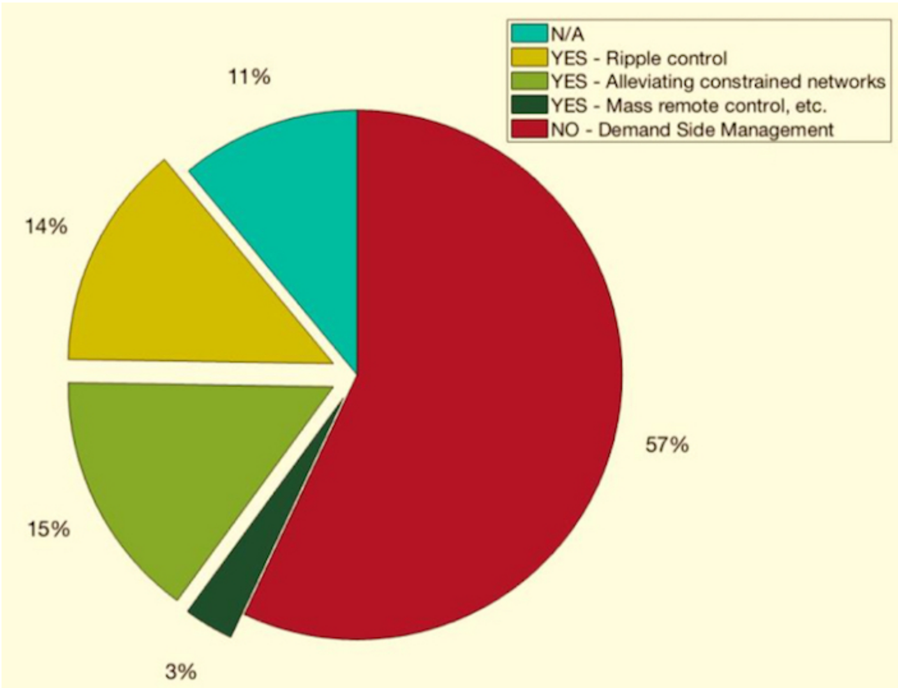


Figure 2.15: Participation in Demand Side Management programs

Surprisingly the survey illustrates, in Figure 2.15, that almost 57% of DSOs affirms that no Demand Response or Demand Side Management programmes are currently applied, although a small percentage of them mentioned that they have participated in some pilot projects in the past. Except the one who didn't reply, the remaining 32% replied positively to the question: *Is your company managing Demand Response and/or Demand Side Management or Flexibility programmes?*. Out of those DSOs who are applying DR and DSM programmes, 15% use consumer

flexibility to alleviate constrained networks, which appear as the most relevant issue for distribution grid operators. For 14% of DSOs the DSM is controlled by triggering circuit breakers with the use of ripple control. Few DSOs (3%) utilize different circuit breakers such as mass remote control.
More in detail, 5 DSOs specify that the ripple control mechanism is utilized to control hot water boilers and heat pumps. Only 1 DSO mention the participation in DSM programs in the past related to storage system. This limited number may be linked to the new regulation avoiding the ownership, operation and management of storage for facilities for DSOs.
By having a look at those who replied no, it is worth noticing that 19% of them commented on their indirect involvement in DR or DSM projects, such as coordinated participation with the TSO. Few also declared that they will start by beginning of 2020.

2.4.3.2 DSO - TSO data management

DSOs and TSOs have responsibilities and roles which may slightly vary across countries as being both network operators and neutral market facilitators. In general, TSOs are responsible for the system security by keeping the frequency within safety margins, and managing load congestion and voltage deviations. DSOs and TSOs have both key role in providing information as well as support to electricity market participants. They also provide different services to diverse market participants: connection of users and grid access; supplier switching, when applicable; activation of flexible resources; communication of public data and public authorities, etc. All these tasks need to be performed in a transparent and non-discriminatory way, but mostly important data needs to be shared in a structured and continuous way between these two fundamental actors and other parties. With the increasing growth of renewable energy sources (RES) and with the advent of demand response, coordination between TSOs and DSOs has become of utmost importance in order to avoid disturbances in the power system. To this aim, data exchanges between TSOs, DSOs and market parties are fundamental to enhance the value that customers flexibility can bring to the markets. Regarding data on network conditions shared with the TSO, a relatively small percentage of the questioned DSOs gave feedback on this, namely 19%. With respect to the granularity of data exchange, a very diverse picture has emerged. Indeed there are cases in which no communication is exchanged at all between them and on the opposite, situation where active and reactive power measurements are shared in real-time for relevant agreed nodal areas.

With respect to the demand and generation forecasts data exchange between the two parties, 40% of the questioned DSOs have given some relevant feedback. Cases in which no communication at all is shared between them are seen throughout the questionnaires. Others, in which generation forecasts are sent from TSO to DSO and demand forecasts from DSO to TSO on an hourly basis even though not through a common digital platform. In general, the frequency with which the parties exchange data varies a lot; specifically, 7 DSOs have stated hourly communication with TSO for this specific category of data, 2 stated daily communication, 4 monthly and 7 yearly, respectively. In addition, there have been two DSOs that have declared communication every two years, whereas another one stated communication twice per year. Another DSO stated that they plan to have hourly communication for future purposes.

With respect to the scheduled data of each power-generating facility connected to the grid, 34% of the questioned DSOs gave feedback. The granularity of data exchange varies from hourly to daily to weekly to monthly. In few cases, once a year DSO gives information about the connected distributed energy resources (DER) amount. Also for this kind of data, there are many DSOs which stated that no data are exchanged about this. There is one DSO that indicated that hourly communication is foreseen for future purposes, whereas two more state that it is not their responsibility to send such data; instead the generators directly communicate with the TSO. Regarding real-time measurements, 55% of the questioned DSOs have mentioned some activity. The majority of these DSOs provides real-time data (39% of the DSOs which have positive replied) through an online connection. One DSO stated that real-time data is provided according to an agreement between the DSO and TSO, whereas another one stated that such data is sent every half an hour. Real time measurements are provided in a few cases for HV substations and, when TSO demands it, for PV production. Active power measurement of PV-facilities in medium voltage from DSO to TSO and active power measurement of feeders in high voltage from DSO to TSO are also shared in certain cases. In Germany there is no legal obligation to have real time measurements and PVs infeed (in absolute terms and as a percentage of total installed capacity) per network area are provided by the network control centre. Regarding ex-post data (metered data), the major part of the questioned DSOs has given positive feedback.

2.4.3.3 Meter data management

As previously mentioned the potential use of big data related to electricity consumption (and not only) is daily produced. It is crucial for stakeholders and customers to have access to them even though for different aims. For instance, consumer awareness is increasing and therefore more transparent data sharing is needed to allow them to switch retailer. At the same time, for DSOs, they are also necessary for the planning of energy services and to engage customers more and more into an active participation in the electricity market. The data collected in this edition of the DSO Observatory are useful to understand the current smart metering status but also shed some light on future planning and implementations in Europe. To provide a clearer picture of the current status Memeber States have been clustered in 3 categories, according to the cost and benefit analysis (CBA):

- CBA conducted with positive outcome;
- CBA conducted with negative outcome;
- CBA not available.

The countries who had a positive CBA were 13, and only 3 already complete the smart metering installations, meanwhile countries like Ireland, Poland and Romania are still below 10%. For those with a negative CBA (7 countries) two alternatives have been found: no actions (i.e. Belgium, Czech Republic), and a selective installation of smart meters (i.e Germany). Particular is the case for Latvia and Slovakia, because even with a negative CBA they decided for a complete smart metering roll-out.

2.4.3.4 Remote control of substations

At the HV/MV network level the DSOs who replied to the survey provided information concerning the degree of automation and with which equipment the substation are monitored or automated. It emerge from the survey that only 3% of the DSOs, among the 62% of the total that replied positively, deal with a large number of automated HV/MV substations (over 1200). All the remaining ones manage a much fewer automated HV/MV substations (lower than 450). Furthermore, the majority of them deals with a tiny portion of almost 100 substations. The extreme situation, is the fact that in one case 18% of the DSOs have no automated HV/MV substations at all, meanwhile on the other hand, 22% of them stated that all of the substations they handle are automated.

2.4.3.5 Electric mobility

The electrification of the transport sector is happening and it will introduce a massive penetration of loads in the distribution grid.

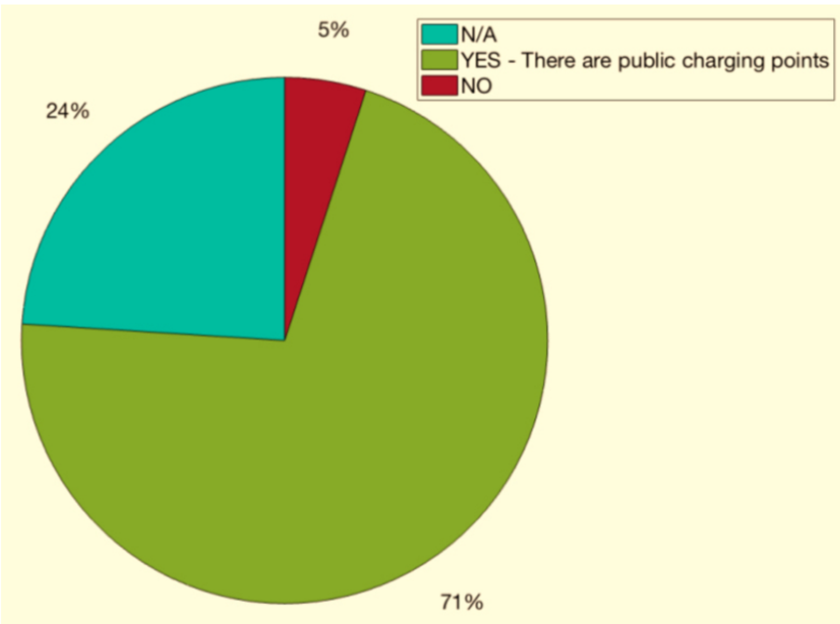


Figure 2.16: Electric mobility infrastructure status

If not properly managed, the charging of electric vehicles may lead to a faster deterioration of substation and stress on the power lines, as well as increase peak demand and thus electricity prices. Investment to reinforce the current infrastructure and ad hoc tariffs or incentives for EV users are necessary to shift the consumption, which will avoid an accelerated aging of the grid (substations, etc.). Interesting results have been pointed out from the survey: a lack of data and information exchange among the utilities installing charging infrastructure and the DSOs. Thus, DSOs are not always aware about where and how many charging infrastructure have been installed in their region of competence.

Directive on common rules for the internal market for electricity

Article 33 - Integration of electromobility into the electricity network

1. Without prejudice to Directive 2014/94/EU of the European Parliament and of the Council, Member States shall provide the necessary regulatory framework to facilitate the connection of publicly accessible and private recharging points to the distribution networks. Member States shall ensure that distribution system operators cooperate on a non-discriminatory basis with any undertaking that owns, develops, operates or manages recharging points for electric vehicles, including with regard to connection to the grid

2. Distribution system operators shall not own, develop, manage or operate recharging points for electric vehicles, except where distribution system operators own private recharging points solely for their own use.

This could be explained by the fact that certain countries have a relatively high residential power installation (e.g. up to 8.8 kW peak), which is enough for an EV home charging infrastructure. This may inevitably lead to higher balancing costs, wrong demand forecast and consequently a higher costs for final consumers. Remarkably, only 5% of the DSOs questioned stated that in their managed area there are no charging infrastructure (or they are not aware about it).

2.5 Chapter summary and main contribution

This chapter has highlighted the main transformations that DSOs are going to face in the next decades. These changes will be subject to three main drivers: innovation in technologies, policies, and consumer awareness. To understand how DSOs are reacting to the external solicitations coming mainly from stakeholders a survey has been designed focusing on those DSOs subject to unbundling. The main goal of the survey was to give an overview of the technical features describing the network at each voltage level; to provide information concerning their smart grid dimension; and finally to observe their implementation of the e-Directive and e-Regulation. The technical data collected indicates that several differences have been observed, especially in terms of LV consumers per MV consumers, LV underground ratio and transformers capacity per LV consumer. The survey points out that the mere reason of a different number of consumers supplied may be too approximative to cluster DSOs in two categories (below and above 100'000 consumers) as attempted by the unbundling process. Indeed, within this category very wide parameters intervals are detected, which are caused by several elements such as the number of MV consumers, the geographical area, the topography of the area, the distributed generation capacity installed to cite a few.

The smart grid dimension emphasizes even more the differences observed at the technical level especially concerning the DSO-TSO interaction and electro-mobility. The first point shows that there are cases in which no communication is exchanged at all to cases where active and reactive power measurements are shared in real time at the point of intersection even under the same national regulations. The second point indicates that almost a quarter of DSOs are not aware about the presence of charging infrastructures in their network of competence.

These findings reflect the fact that, at the current status, the national implementation of the European e-Directive and e-Regulation from DSOs is creating discrepancies across countries and even within the same one. The survey's results may indicate that clustering in only two groups the whole set of DSOs is insufficient. Furthermore, DSO-TSO management and electro-mobility actions should be more strictly defined at law level in order to design DSOs investment toward a common approach.

My contribution to the DSO Observatory report has been spread across all the phases required to drawing up the document: the construction of the questions pose to DSOs; the data collection, cleaning, analysis, clustering and charts calculation through the use of Python and Matlab programming languages; the description of the main indicators, DSO-TSO data management, meter data management and electro-mobility sections in the DSO Observatory report; and the revisions of the whole document.

Chapter 3

Creation of reference electric distribution networks

This chapter presents a general context for the thesis work, a review regarding the previous research in the field, the overall motivation, objectives, methods and an outline of the thesis. This chapter is based on the development of the distribution network modelling platform [17].

3.1 State of the art on Distribution Networks

Smart cities, with prosumers at the centre, are at the front line of the energy transition. The national and international policies should encourage then this transition by promoting, among many aspects, energy digitalization, massive penetration of renewable energies and electrification of the transport sector. To embrace all these changes, a holistic view, covering not only the distribution system, is necessary to plan, design and reorganize in particular urban areas. Therefore, to meet these targets, detailed network maps at the local levels are needed. Indeed, compared to former studies, especially in the last decades, which were focusing more on the transmission level, now more in depth analysis of the distribution network are key

to understand how to redesign future districts [18].
To this aim, representative network models (RNM), and in particular feeder-type networks, are utilized as alternative to actual grids [19]. The first use of RNM, based on an optimization algorithm aiming at minimizing cost, was applied to transmission grids for network pricing. Until now, based on literature review, the application toward the distribution system has been limited to small number of buses, branches and few geo-reference network were found. The confidential nature of DSOs data and the inadequate tools have limited the studies, among many scenarios, to assess the capacity of the district to host distributed generation and/or electric vehicle charging station infrastructures.
The integration of electric vehicles and charging stations in power system cover an extremely large range of scientific contributions, therefore it has been identified the knowledge gap that the thesis aims to fill within a complex and broad topic. The topic of the thesis can be defined, in a general way, as designing distribution network grids, from a point of view of DSOs managing the grid, the validation of those networks and the role of charging stations within them. In literature research the interest is in the following query applied in ScienceDirect and IEEXplore[1]:

```
TITLE-ABS-KEY(
"charging infrastructure" OR "charging station" ) AND
TITLE-ABS-KEY(
"grid" OR "system" OR "network" ) AND ("distribution" ))
AND (LIMIT-TO(DOCTYPE ( "ar" )))
```

First some macro-level aspects concerning the literature list are discussed, and then a deeper analysis on the most relevant papers per sub-field. Finally, the work of this thesis is positioned based on the literature of this topic. The query outcome counts 265 articles, and Figure 3.1 represents the number of articles published per year according to the above query until June 2019. The dashed blue line indicates the projected number of articles expected by the end of year.

[1]It is assumed that the query results of these two database are enough complete as a basis for this literature research.

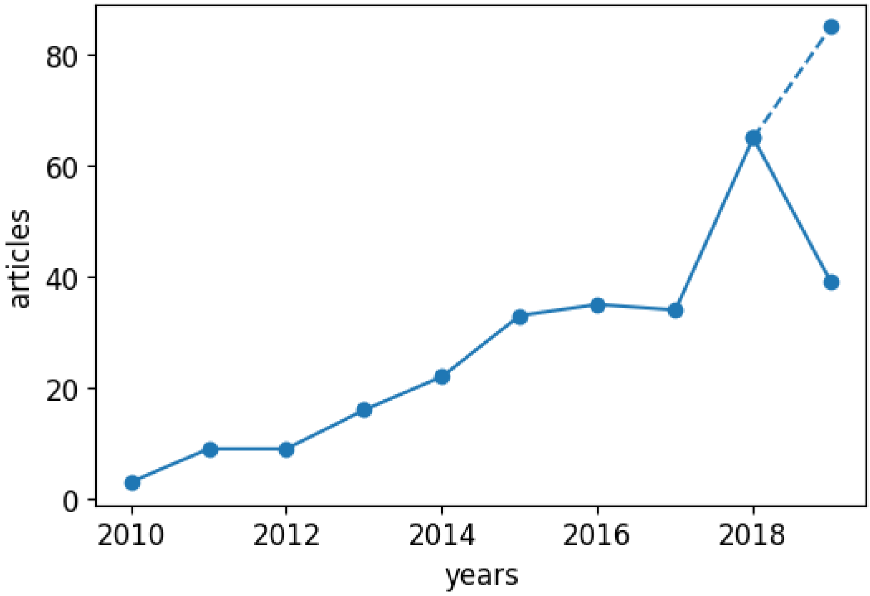


Figure 3.1: Research trend in the number of articles concerning charging infrastructure and distribution grid management

Although the records concerning EVs integration in the power system have seen a drastic increase since 2005 according to [20], the research has seen them mainly from an aggregated point of view.
Indeed, the attention toward the role of charging stations with the distribution grid, the network design, and the coordination of two system, transport and power system, is clearly a new trend in this research domain. This trend is emphasized in Figure 3.1 especially starting from 2017.

3.2 Discussion of some relevant papers based on network type

In this section some significant articles extracted from the literature research based on the query described above are discussed. Furthermore, some more research works were added and described in the following sections because considered pertinent. The scientific research has been divided in three sub-fields: synthetic network based on IEEE layout, synthetic network grid not based on IEEE layout and real network grids. In addition, in each sub-section papers are described from the smallest network, in terms of buses, to the biggest one.

3.2.1 Synthetic network grid based on IEEE layout

The study conducted by Turan et al. [21], analyzes how an EV parking lot (capacity 100 spots) with PV installation can stabilize voltage regulation as well as reduce line power losses. Randomized arrival and departure of EVs in a parking lot equipped with a MV/LV substation are simulated on a IEEE 13 distribution bus test system. The operation strategy proposed ends up with no adverse effects to regulate voltage and a reduction in lines losses. This is possible due to a lower purchase of electricity from the grid, thanks to the optimized combination of PV panels and EVs parked.

The IEEE 15 distribution synthetic network has been utilized for different purposes, for instance Sadati et al. [22, 23] propose a bi-level optimization model to maximize DSO revenues and minimize the cost of purchasing electricity from the grid by properly scheduling and managing a EVs parking lot and RES; meanwhile, Anastasiadis et al. [24] investigate merely on large penetration of EVs and how they could enlarge voltage deviations in each bus.

The most utilized network found in the literature is the IEEE 34 distribution bus system which was designed in 1992 and has been modified in literature mainly into 3 variants: 32, 33 and 34 nodes, with different branches length, transformer ratio and layout structure. The network is a reduced-order model of an actual feeder located in Arizona, where the initial aim was to evaluate and benchmark different algorithms in solving unbalanced three-phase radial systems.

The minimization of network loss index, voltage deviation and voltage stability margin index has been performed by Cheng et al. [25] on a IEEE network system with 32 nodes. They state that EVs, especially in V2G mode, can play a key role in the network reconfiguration in order to improve economy and reliability of the network. Another study by Tabatabaee et al. [26] on the same distribution grid (derived from [27]) aims at investigating how optimal scheduling of EVs and RES can minimize the total cost of the network, which includes also reliability cost, energy not supplied and power supplied for loads.

The second variant of the IEEE 34 is the 33-node distribution network which is adopted, in research projects, with different objectives, for instance by Sedighizadeh et al. [28] in order to minimize the overall costs. Indeed, they formulate several controlled and uncontrolled electric vehicle pattern to study their voltage deviations on each bus. These simulations conclude that V2G capability and controlled charging behaviour may lead to reduce costs of purchasing power from the upstream grid. With the same aim, but considering also the role of aggregators, Mohiti et al. [29] propose a novel model with deep sensitivity analysis performed. A second approach is carried out by [30, 31] to evaluate voltage deviations and reliability index of the network due to fast chargers installation in one case, and advanced V2G operations in the second one. They conclude that charging pricing strategies may lead to significant improvement to the network thanks to the shifting of demand to off-peak hours. Further interesting studies [32, 33] are oriented toward the optimal positioning and sizing of EVs parking lot, with the objective of minimizing the system operation costs.
In the different approaches, the maintenance of reliable operation condition in the IEEE 34 distribution bus network is the core objective of the models developed in [34, 35, 36, 37]. Within reliable operation condition Clement-Nyns et al. [37] proposed a coordinated charging strategy to minimize power losses and maximize grid load factor, Bharati et al. [36] researched how V2G allows the distribution grid operator to minimize the power losses as well as energy cost of EVs charging. The delay in grid reinforcement, even under high EVs penetration, is analyzed by [35] while keeping the voltage within the limits.
The IEEE 37 distribution bus network is another common network utilized by researchers. It is based on an actual feeder in California, with a 4.8 kV operating voltage, characterized by delta configuration with underground cables, and the original design is very unbalanced due to few spot loads spread in the grid. Similarly to the IEEE 33 network, also the IEEE 37 has been modified by the different authors for their specific purposes. Indeed [38, 39] minimize the operational costs, the time of outage and the power loss in the network respectively by using vehicle-to-building (V2B) and a predictive control model. The maximization of EV users profit by scheduling charging and discharging for each node is performed by Cabrera et al.

[40]. Two prices, for charging (11.54 c€/kWh) and discharging (18.64 c€/kWh) have been adopted for the maximization problem. In addition, the optimization model considered battery lifetime. Finally, like for the smaller network (IEEE 33) the optimal placement of V2G charging stations is conducted by Alijanad et al. [41]. To do so line loading and bus voltage limits are simulated to optimally locate charging infrastructure. On the same page, a mixed-integer nonlinear programming done by Mortaz et al. [42] is utilized as an investment planning for charging station in the network. In this latter case, a sensitivity analysis concerning uncertainties related to payback time, market price, and electric vehicle arrival and departure is also performed. They both conclude that V2G charging stations installation should be carefully decided because it should be seen also as an alternative source to the grid to reduce voltage distortions.
The biggest synthetic distribution network found in literature is the IEEE 123[2]. As described in [44] the IEEE 32 node test feeder, in the way it has been designed, is subjected to voltage drop problems solved with the application of shunt capacitors or voltage regulators. Furthermore is composed of both overhead and underground cable lines, multiple switches and shunt capacitor banks. It is mainly utilized in research to find the best size and location of EV aggregator like the work conducted by Gao et al. [45]. The model goal is to minimize the cost, by taking into account expenditure on supplying electricity, power losses and EVs charging. Moreover, in this work for each node load pattern and voltage deviation are calculated in order to evaluate the efficiency of the model proposed.

3.2.2 Synthetic network not based on IEEE layout

The second relevant category of distribution networks are those developed by researchers but not strictly related to the IEEE standard structure described in 3.2.1. In this group unique layout and size are developed, going from microgrids to urban ones, depending on the study required. Wang et al. [46] propose a control method

[2]The largest IEEE network is actually the 8500 bus one. It represents an unbalanced radial system with a large number of line segments which include secondary systems. In literature few articles were found probably due to the challenges explained in [43, 44]

to ensure limited voltage deviations within a LV residential distribution network with 17 bus. The contribution of this work is summarized in describing the battery degradation behaviour, utilizing real PV and load profiles and monitoring the voltages of the critical buses. The control method and the communication within the 10 buses equipped with charging station allow to maintain voltage ranges while avoiding effect on users charging demand.

A double optimization method to minimize the daily total cost incurred for EVs and simultaneously minimizing the system power loss utilizing the reactive power from EVs is designed by Mehta et al. [47]. The innovative aspect lies in the utilization of reactive power in a V2G context applied on a 12.66 kV 33 bus distribution system modified from [48]. For each node no more than 50 EVs have been assigned. This study suggests that the utilization of reactive power enables an even higher penetration of EVs in the grid, and the simulations show that battery degradation is negligible.

A 33 bus 22.6 kV radial distribution system based on [49] is modified by Zakariazadeh et al. [50] to test a multi-objective approach for electric vehicle scheduling in which EVs driving pattern, economic and environmental issues are taken into account. A Benders decomposition method to solve the large-scale multi period problem was used. The results show that the inclusion of emission objective function modify charging and discharging EVs programs in order to contain the total air pollution.

A cooperative game model has been proposed by Aghajani et al. [51] to determine charging and discharging price adaptively. The main contributions are: the interaction of stochastic game model related to EVs with the upstream grid; considering the degradation of EVs batteries; the cooperative interaction between utilities and parking lots; the minimization of operating cost for parking lots and maximization profit for utilities. The model is tested on a 34 bus distribution network with the nominal voltage of 11 kV and 300 EVs within the area based on [52]. The results evidence the fact that proper management of charging and discharging reduce operating costs of parking lots.

The study of Khanekehdani et al. [53] investigate the reliability of distribution grid based on a stochastic behaviour of EVs and renewable energy sources. The

model is tested on a Roy Billinton test system with 36 node points described in [54]. Within this grid there are 4 microgrids composed of diverse percentage of residential, commercial and industrial customers. Based on the method proposed the grid health status is increased if EVs penetration is increased, due to the fact that the battery capacity is also enhanced. Thus power injecting from the vehicles to the grid is helpful for the reliability of the grid itself. The island mode adoption by the microgrid in certain cases may lead to an improved network health status.
The paper of Tan et al. [55] propose a multi-control V2G charger with reactive power compensation, power factor correction and grid voltage regulation capability. The design of the bi-directional active and reactive power charge is the innovative aspect of the paper. This charger has been implemented on a residential-commercial township with a total of 42 substations across 6 feeders. They claim that this multi-control selection algorithm, to assist V2G charger, may be implemented in any charger to support voltage deviations.
The optimal number of EVs charging without reinforcing the grid is studied in a 107 bus distribution grid with 75 households by Sachan et al. [56]. In doing so, charging plans are scheduled in order to flatten the voltage profile within the nodes. In addition, customers and aggregators benefit are optimized by reducing grid losses and charging costs. The results show that once again dumb charging demand would exceed the limit capacity of the grids and consequently reinforcement would be necessary, especially when combined with uncertainties related to wind energy.

3.2.3 Real network grids

In this section studies on real distribution network grids are listed. Differently from the previous paragraph, DSOs provide data, of restricted real grid areas, to universities or researchers centers in order to test algorithm and models. A LV semi-urban distribution system in Dublin with 10 buses, 134 customers and a 10 kV /0.4 kV transformer is utilized to test the controlled charging of EVs aiming at minimizing energy losses [57]. Four different charging scenarios were adopted: uniform, random, conditional-random and valley-filling with this latter being the most successful one for reducing energy losses.

A particle swarm optimization (PSO) model is proposed by Yang et al. [58] to optimize EVs charging and discharging including power grid cost, EV owners' satisfaction, statistic characteristics of EVs and optimal power flow. PSO is performed on a 10-bus distribution system of Kaili city in China. The power system has 10 EVs per node, a base capacity of 1 MVA and a base voltage of 10 kV. The simulation outcome shows that uncoordinated EVs charging enlarge peak-to-valley difference and power loss in the grid.

A voltage dependent EVs reactive power control is developed by Knezovic et al. [59] on a real Danish distribution grid to observe EVs charging may lead to unbalanced three-phase network. The semi-urban network is composed by 10 buses, a substation of 10.5/0.42 kV and 42 residential loads. Therefore only home charging is considered in this study. The research highlights the fact that if EVs are not providing support to the grid, then DSO are forced to reinforce the network in order to ensure power quality in case of high penetration of EVs.

The coordinated operational method (multi-agent based) of self-interests and operational constraints of respectively, EVs owner and DSOs, is proposed by Hu et al. [60]. Differently from the typical hierarchical control system, the authors apply market based control at both levels. A 10 kV radial network modified from a Danish network [61], has a transformer of 60 kV and is composed of 11 buses, 9 distribution lines, 7 load buses, 1400 households and 280 EVs. The methodology applied is able to mitigate adverse impact of price control where all EVs are trying to recharge during low period price and efficiently allocates power resources of the transformer while considering EV user's price behavior.

The paper of Garcia-Villalobos et al. [62] developed a smart charging agent-based algorithm with 3 objectives: improve load factor, reduce cost for EVs users and enhance voltage quality. The methodology is analyzed on a 14 nodes distribution grid in the city of Borup (Denmark). The grid is composed of 43 houses, 13 lines, a total length of 681 m and a transformer 10.5 kV /0.42 kV.

A step wise congestion management scheme has been developed by O' Connell et al. [63] in order to optimize EVs charging with respect to day-ahead electricity prices. A real Danish distribution grid, from the Island of Bornholm, has been tested for assessing EV impacts with non-homogenous state of charge starting values and driving pattern. The network comprises 72 household customers with two 10 kV /0.4 kV transformers, 33 cables and 33 buses.

The distribution system considered by Fathabadi in [64] comprises distributed generation, V2G capability and conventional power generators (CPG). These elements are tested in 4 different combinations. Furthermore, in this work the objective is to minimize the total cost of electric energy production, the bus voltages deviations and the active power loss during the 24h considered. It has been simulated on an urban network of Manjil city in Iran with 33-bus, 10 DGs, 3 PVs, 4 wind turbines and 60 EVs. They conclude that the lowest power loss is achieved by using DGs and conventional power generators, meanwhile the best voltage profile and minimum cost of production is reached by using DGs, EVs and CPG.

The article of Leemput et al. [65] discussed in an innovative way the support that reactive power from EVs' chargers can induce, while recharging, in a LV residential distribution grid. This study is performed on a real urban feeder topology, with a MV/LV transformer of 400 kVA and 42 buses, of a Flemish DSO. The results of this research show that an increased EVs hosting capacity even in cases of uncoordinated charging can occur if, while recharging, there is a higher percentage of reactive power injection. This reactive power injection produces benefits for the grid by avoiding extreme voltage deviations. Furthermore, no increased transformer aging occurred.

A novel study of Karakitsios et al. [66] analyses the impact of fast inductive technologies (up to 20 kW) on the electric grid. The proposed methodology assesses the line loading, network losses and voltage profile of EVs recharged through contactless technology. The method is tested on a radial feeder of a primary substation (HV/MV of 25 MVA) in the area of Katerini in Greece with 73 buses. Up to 35 MV/LV substations and 1000 EVs are present in the network. The analysis outcome can be utilized to study the grid adequacy to host charging stations, prior to any premature grid reinforcement, through a smart charging strategy.

3.3 What can be extracted from literature?

Although not all the distribution networks available in literature have been taken into account, the previous review is considered as a coherent and sufficient picture of the current status. Several models have been developed to analyze the electric distribution grid behaviour under different scenarios. These studies are subject to many assumptions, either simple, or more complex in modelling buses, branches and loads. The desired goals of each research activities is different and goes from: control algorithm for electric vehicles charging, extreme distributed renewable generation, voltage and transformer stress monitoring, demand response programs to network reinforcement cost.
Historically, in order to perform those analysis representative reference network models were developed for both transmission and distribution with standardized structure and known parameters. These developed networks are reasonable as a benchmark, and therefore researches have used them for decades to test different scenarios and algorithms.
Two major distribution grid networks classes pop out from the scientific works: real network grids and synthetic ones (IEEE and not-IEEE). The real network grids are less common in academic community due to their intrinsic confidential nature, in fact are often subjected to non disclosure agreement signed with the DSO. Furthermore, depending on the agreement often these network are incomplete and therefore manually designed. The second category of networks, thus the synthetic ones built upon real network data, are the most known and used in the research community. For this reason, they are more suitable for testing algorithm or operation scenarios. This category are represented mainly by IEEE, EPRI, TAMU and CIGRE networks. Among them, for the IEEE networks there are already made files in Matlab (MATPOWER) with all the information concerning the network features which made them, for this reason, the most adopted in research projects [67].
More in detail, the literature indicates, excluding those networks related to transmission, that there are 8 IEEE grids with respectively 13, 15, 32, 33, 34, 37, 69, 123 buses. Moreover, the literature shows that IEEE networks are modified, based on user's knowledge, in terms of transformer capacity, power lines lengths and automation devices, to perform the specific analysis. This clearly indicates that more

flexible solutions are required in both layout and network characteristics. This occurs because different goals are applied to the networks and in particular the most frequent optimization are: minimizing overall costs, minimize transformer degradation and maximize electric vehicles penetration. In addition, all these optimization algorithms are then subjected to very different initial assumptions, like households load balanced between phases, aggregators revenues, loading capacity of distribution lines (thus no overloading), EVs number per node, V2G constraints, EVs initial state of charge, EVs charging power, which are often based on the information available by researchers. Moreover, some of these assumptions are manually implemented and applied on the identified feeders, according merely to users knowledge, by aggregating or clustering different loads, modifying lines capacity, networks layout, etc. [68].

Besides the IEEE there are some examples of actual distribution grids, which are directly provided from the local DSOs, such as: the Island of Bornholm in Denmark [63], a semi-urban system in Dublin [57], a fraction of the city of Borup in Denmark [62], a distribution system of Kaili city in China [58], a small neighbourhood in China has been used by [30], the urban distribution network of Manjil city in Iran [64], a real Danish distribution grid in [59], a small area of Katerini in Greece [66], a realistic Flemish distribution grid [65]. These actual distribution grids are case specific, and among them they greatly differ in terms of geographical area, number of consumers, transformer capacity and many more aspects.

However, a well defined picture arises from literature which sees, as a common element, the relatively limited number of available distribution network layouts. Moreover, another clear outcome has emerged, indeed network parameters are not well documented or even known in certain cases, therefore calculations of several operation scenarios are complicated and often time consuming. To summarize and provide a better view of the current situation, among all the articles analyzed, some common *weaknesses* concerning network grids and EVs charging profile have been detected and listed hereby:

- The relatively limited number of buses, branches and therefore consumers;

- The distribution network layout is rarely geo-referenced to real city areas;

- The electric vehicle impact is analyzed almost only at the substation level, and few times at buses level;

- The electricity network is the only layer used in the studies leaving several open questions.

Another criticism that arises is if these networks, developed in the 90's, are still valid for the current distribution grid due to the drastic changes occurred (and still occurring) at power system level. Nevertheless, none of those networks were originally designed neither for distribution network analysis either for large-scale representative network for European cases. To complete this aspect, the IEEE networks, which are the most utilized in the scientific community, were designed for United States distribution network grids which have significant differences compared to European ones especially in terms of unbalances and three-phase MV/LV transformers [19]. More specific regarding unbalances, if in Europe they occur due to the existence of single-phase loads which may be unevenly distributed, in US it happens because of how the grid is designed (three-phase feeders with single-phase laterals). On top of all this, another relevant element observed is the lack of real electric vehicles demand profile that can be partially attributed to the fact that monitoring system are not yet standardized and big data is still missing.
In order to overcome this lack of knowledge on distribution networks, part of the activity of this thesis has been carried out to assist the development of a distribution network platform named DiNeMo aiming at reproducing the representative distribution grid of a given area of interest. The networks characteristics, gathered through the DSO survey and described in Chapter 2.3, serve as input for the design of synthetic networks. This platform combined with the work carried on EVs and charging columns dataset (Chapter 4), acquired from ElaadNL[3] for the Netherlands pave a new frontier for the real case studies on the impacts of EVs on distribution networks.

[3] As stated in their website *"...Through their mutual involvement via ElaadNL, the grid operators prepare for a future with electric mobility and sustainable charging. It is our mission to make sure that everyone can charge smart. We monitor the EV-charging infrastructure and coordinate the connections between public charging stations and the electricity grid..."*

3.4 DiNeMo platform

Based on the technical features collected through the DSO Observatory survey explained in Chapter 2 at JRC developed a platform named DiNeMo to face the lack of available synthetic distribution networks. DiNeMo is the new platform thus aims to provide stakeholders in the electricity sector with a solid tool that based on real data is capable to reproduce the representative distribution grid of a given area of interest.

The platform is also bound to become the virtual place where diverse users, with different roles, will collaborate with the aim of building reliable models to be used in order to design and develop the smart cities of tomorrow. For this reason, beside the network computation request of a single user to construct the representative network of a urban zone, it will be introduced in the near future the collaborative project named city project. It aims at joining forces between users for designing a greater network area of adjacent neighbourhoods in which few information need to be shared among users.

3.4.1 DiNeMo structure overview

Before proceeding to present the structure of DiNeMo, it is fundamental to understand the meaning of reference network models and their purpose within the scientific community. Reference network models were initially designed as a regulatory tool for energy regulators in order to assist them in establishing distribution system operator remuneration.

Indeed, traditionally, because of their natural monopoly, these firms were subject to low risk and high financial stability thanks to their cost-of-service remuneration. The key idea, behind the new regulation mechanism, was to endeavor to increase the efficiency for these firms by adding a price or revenue cap. To do so, RNM were developed aiming at building a quasi-optimal and realistic reference network. Within this network it was possible to derive key parameters as a sort of indicator of maintenance costs, energy losses level, efficient investment and quality-of-service levels.

A RNM is able to link the transmission network with a three-level hierarchical distribution network structure: high, medium and low voltage, which are constructed with a branch-exchange algorithm technique described in [69]. It is possible, through this tool, to simultaneously optimize either rural or urban zones by minimizing the total length of cables while keeping voltage drop and a minimum level of supply quality into account. In addition to these constraints, the algorithm considers geographical constraints, which are associated with street topology (especially in urban areas) and environmental aspects, are taken also into account. More in detail, natural reserves, mountains and big avenue roads are among some of the geographical constraints that the RNM tool can take into consideration in the designing process of the distribution grid.

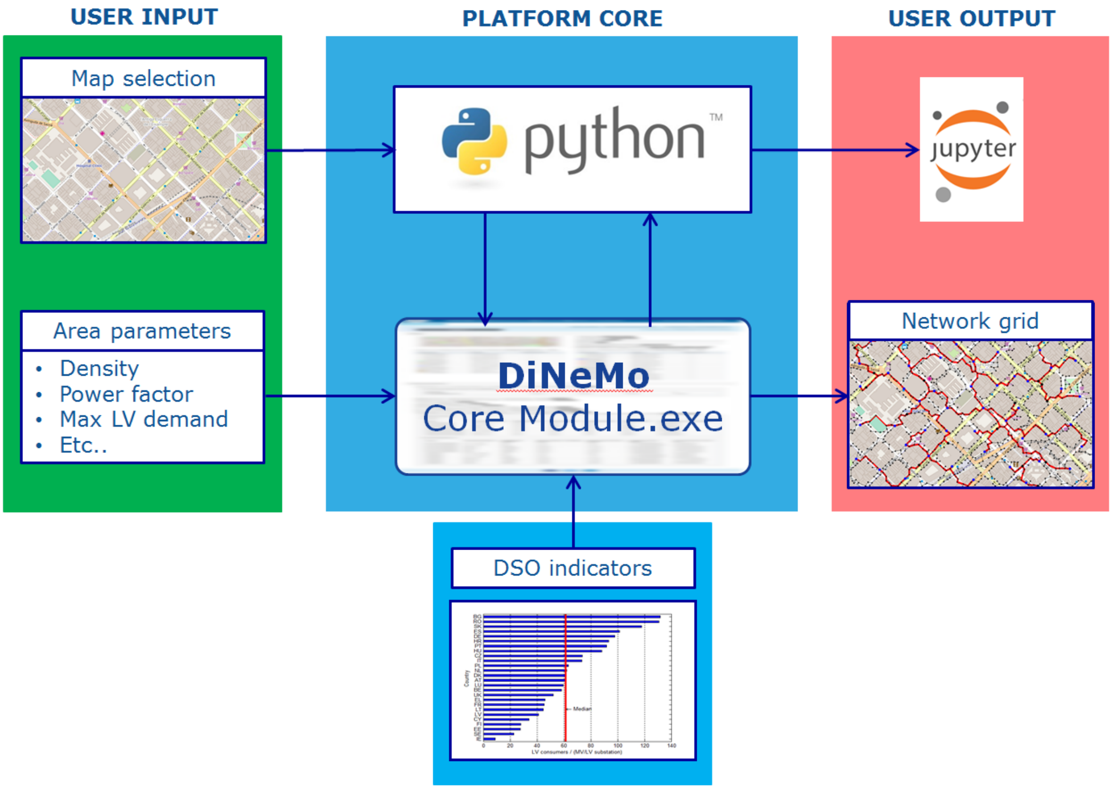


Figure 3.2: DiNeMo platform structure

In general, two main approaches are possible when we talk about reference network models:

- **green-field** model which designs from scratch the whole distribution grid, including power lines, substations and consumption points;

- **brown-field** model which starting from an already existing distribution network aims at designs the expansion of this latter, thus it provides the reinforcement for the addition of new loads or distributed generation.

DiNeMo platform is based on the green-field model, and by doing so it aims at providing a useful tool to construct the whole distribution grid of, for instance, an urban area in Milano, or a semi-urban or rural area in Almeria. Therefore, DiNeMo gives the adequate flexibility to researchers to test their algorithm or scenario in the specific area of interest rather than applying it in a standard IEEE network.
Figure 3.2 gives an overview of the DiNeMo platform structure which is accessible, prior to an ECAS account registration, at `https://ses.jrc.ec.europa.eu/dinemo`.
The platform is composed of 3 main blocks: the user input, the platform core and the user output. Differently, from the distribution network grids available in literature, the input parameters set by the user in DiNeMo can be easily found in internet, as the platform itself is already based on the technical results collected in the DSO Observatory report of Chapter 2.3. Therefore, it is not required a deep knowledge in order to pursue a network computation request of a given area of interest.
The platform core is composed by a python program, which re-elaborates the image, and the DiNeMo core module developed by Comillas university, which designs the network. The 10 DSO indicators explained in section 2.4.2 serve as the basic input values for the core module, and as it is designed the confidentiality of DSO's parameters is kept. The RNM core module designs the network aiming at minimize the investment cost, therefore on cable lengths, selection of transformer, etc.
Concerning the output, two main results are observable: the network plotted in the interactive tool known as jupyter notebook, and the network grid results composed of a set of files.

3.4.1.1 User Input

This paragraph focuses on the list of input parameters which are inserted by DiNeMo user. Moreover, a suggestion on where to find the required parameter is provided, as well as how they are relevant for the construction of the network.

The input block shown in Figure 3.2 is composed of two main items: map selection and area parameters. The map selection represents the urban, semi-urban or rural neighbourhood of interest that is selected by the user.

The user navigating through the platform is able to capture the area which has been restricted, in size, to around 1.5 km^2. This limitation has been applied due to the construction methodology of the RNM, which builds the network starting from a HV/MV substation towards LV final consumers.

For this reason, the HV/MV capacity is the limiting factor that determines the maximum number of connected customers supplied. Even if aware that a low consumer density may play a role in the area extension thus having a larger area, the square of interest has been fixed to around 1.5 km^2. Moreover, as smart cities are becoming more and more important it is key to focus DiNeMo attention on this category, thus on urban areas.

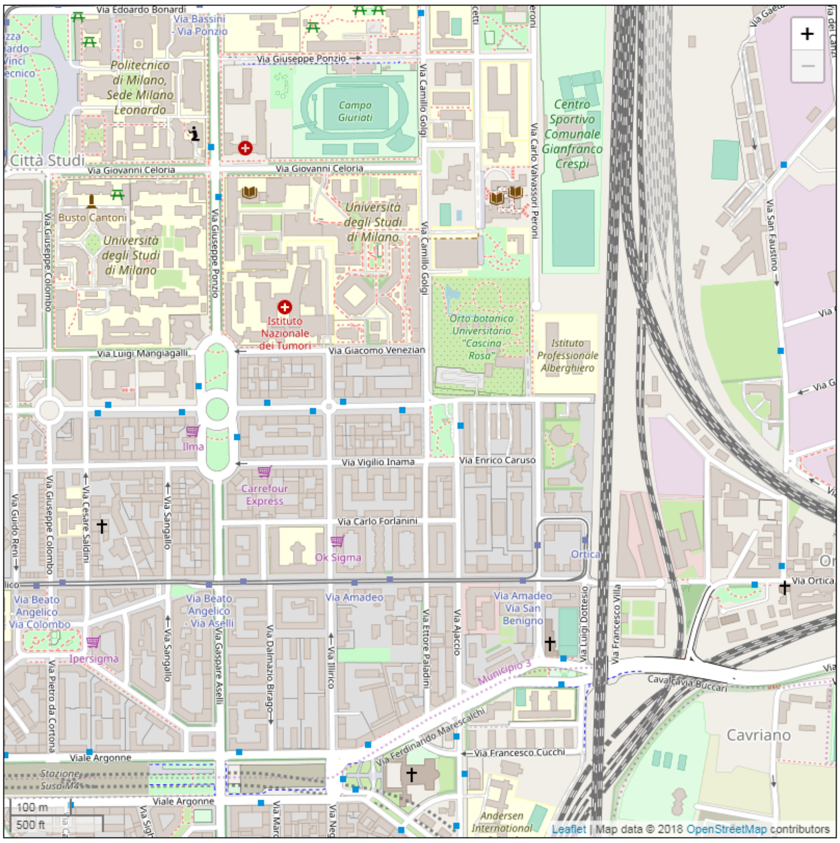


Figure 3.3: Observed urban area of interest

Figure 3.3 provides an example of a capture image in a neighbourhood of Milano. Differently from networks found in literature, the unique feature of the distribution grids produced by DiNeMo lies on the geo-reference of buses, lines and substations. Moreover, the utilization of OpenStreetMap layers provides several useful information such as the transport system which is recently merging with the electric one. The original module for detecting buildings designed by Comillas University was merely based on colors. Therefore, the potential use of extra layers through OpenStreetMap was somehow forbidden and buildings detection did not have an adequate resolution in certain cases. In addition to this, the size of the network was limited due to the resolution of the map[4]
More in detail, roads and parking spots are identified and give the opportunity, for instance, to simulate EVs traffic or EVs aggregated in a parking spot providing V2G service. In addition, with DiNeMo, a charging infrastructure may be located close to specific point of interest, such as parks, shopping mall, universities, etc. Each charging point can be considered as a bus within the network, its impact on the whole grid and the electricity network congestion can be analyzed.
Another important aspect of DiNeMo is related to the land use layer, indeed point of interest such as residential, commercial and industrial areas can be detected and utilized to assign MV consumer profile. Therefore, more accurate demand profiles can be included in the analysis.
For a complete list of available points of interest and land use description please refer to `https://wiki.openstreetmap.org/wiki/Main_Page`. Regarding the area parameters, of the input section the list of values that can be implemented is the following:

- **power factor** defined as the ratio of the real power absorbed by the load to the apparent power flowing in the circuit. Lower is the value, less efficient is the system, less reliable, and more expensive equipment (cables) are necessary. This value is usually close to 1;

- **low, medium and high voltage level (kV)** represents the nominal voltage

[4] If a user zoom out the map, the buildings becomes too small to be capture by the module when based on colors detection.

level. Usually in Europe LV residential is at 0.4 kV, and for MV it is at 10 kV, 20 kV or 35 kV which might be affected according to the commercial/residential concentration in the area of interest. For HV it usually ranges from 110 kV to 135 kV;

- **consumer density** indicates the number of connected consumers per area. It is relatively high in urban areas, for instance in the zone of Milano selected in Figure 3.3 is 9.924 per km^2 as stated in [70]. This value can be obtained in statistical demographic studies which are usually available per province or city in each country;

- **maximum demand of LV and MV consumers** is utilized to set a threshold in the maximum demand of every low and medium voltage consumer. These values are combined with the simultaneity factor[5] to determine the peak flow, therefore which cables to select in order to design and keep the system reliable while minimizing costs;

- **lower and upper limit of transformer capacity of MV/LV substations (kVA)** indicate the thresholds for the substations capacity, and thus restrict or enlarge substation choice from the available equipment catalogue. Users should be aware that some exceptions may occur because the core module is designed also based on the investment costs of each item;

- **number and probability of consumers per building (%)** is applied in order to distributed customers around the area of interest. This detailed information are provided by each national census. For instance, for the Italian case the responsible is ISTAT, and data concerning the family cluster is available at [71].

After the image has been captured, the user needs to position the HV/MV substation in case the location is known; otherwise, the positioning occurring either

[5]The simultaneity factor utilized are 0.2-0.4 for LV customers, 0.8 for LV feeders, MV/LV transformer and MV customers, 0.85 for MV feeders, and 1 for HV/MV substations and HV customers based on [19]

by extracting the data from OSM (Substation code visible in Appendix C), or by default it will be placed in the center of the network area.

3.4.1.2 Platform Core

The description of the platform core is based on the methodology deeply explained in [15, 72], which is developed by Comillas university. This methodology combined with the precious data collected in the DSO Observatory survey described in chapter 2.3, gives the scheme of platform core presented in Figure 3.4.

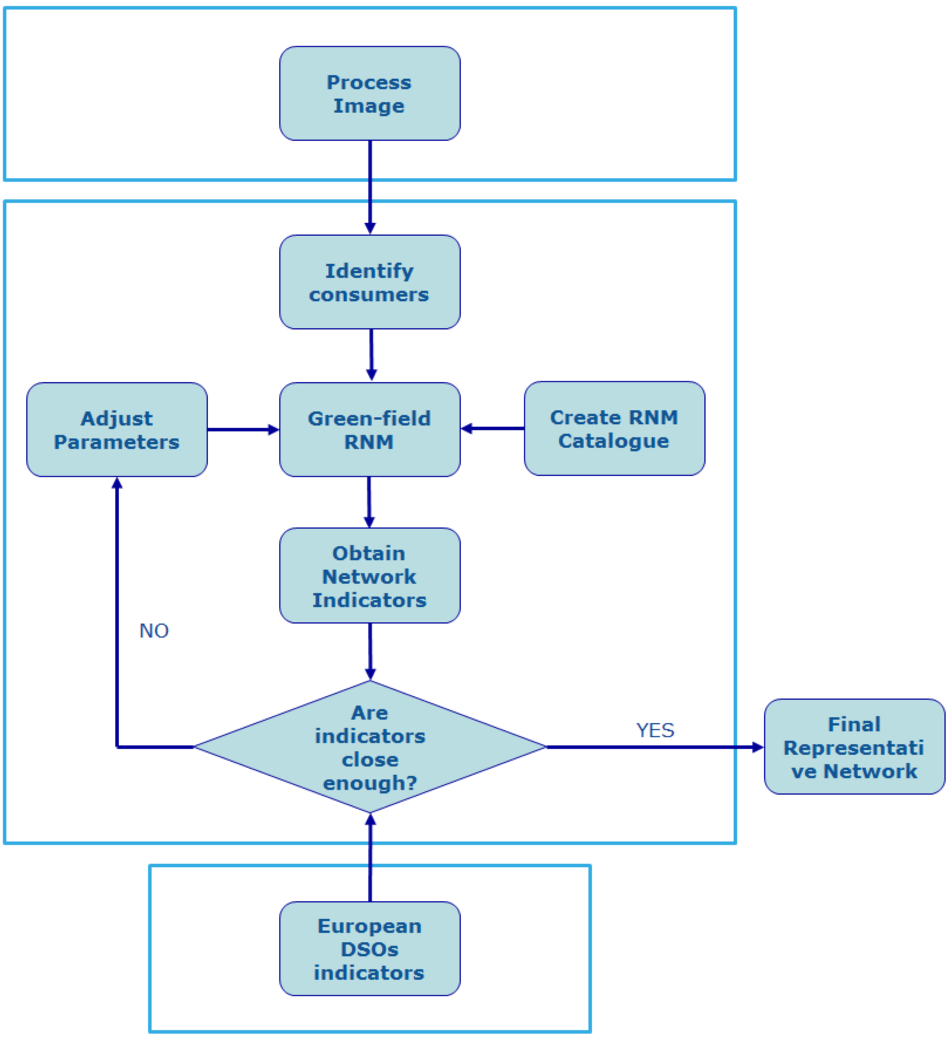


Figure 3.4: Schematic overview of the methodology used to build the representative distribution network

The first step is the image processing which is done through a Python program that automatically detects buildings in the area under study. The code is available in Appendix C. To minimize the power lines crossing streets and buildings, multipolygon buildings where transformed to a simple polygon through a convex procedure. This allows to reduce the erroneous presence of cables in the courtyard of squared or rectangular buildings. By doing so, a slightly higher number of connected customers are assumed, because a bigger surface is estimated. Once the image processing is completed it is sent to the core module box.

The second step is the identification of consumers, which is done by the core module developed by the Instituto de Investigación Tecnológica (IIT) of Comillas University in Madrid. At this stage connected customers are assigned to the buildings, and the geo-reference position of the bus name/number is recorded. The distribution of customers is based on the input parameter *number and probability of consumers per building %* set by the user in the user input phase.

Then, there are two more "*boxes*" of information converging toward the green-field RNM step phase as visible in Figure 3.4, and in particular: the RNM catalogue parameter and adjust parameters.

Table 3.1: RNM catalogue for power lines

Type	R [Ohms/km]	X [Ohms/km]	Ampacity [A]	Voltage [kV]
overhead	0.65	0.1	150	0.4
overhead	0.42	0.39	250	20
underground	0.14	0.08	420	0.4
underground	0.21	0.11	300	20

First, the RNM catalogue provides the simultaneity factors, the settlement underground ratio of both LV and MV lines of the specific area and the network installations. In this latter technical data of LV lines, MV lines, and transformer are extracted. A sample of the RNM catalogue is provided hereby in Tables 3.1 and 3.2 showing power lines and transformer characteristics. For confidential reasons the investment costs of overhead and underground lines, as well as for transformers are not provided.

The power lines and transformer characteristics were not addressed in the DSO Observatory Survey, but they have been implemented in a second phase through a direct collaboration with DSOs. Therefore, not all countries have specific information concerning these two elements. In this latter case, default values are utilized.

Table 3.2: RNM catalogue for transformer

Type	Capacity [kVA]	Secondary voltage [kV]	No load losses [kW]
interurban	400	0.4	0.92
interurban	80000	20	47
urban	630	0.4	1
urban	120000	20	71

The Figure 3.5 shown in Mateo et al. [15] pictures the step to identify LV customers (figure on the left), the planning of MV/LV transformer (figure in the centre) and the planning of LV feeders (figure on the right). The same process is then applied for MV customers, which are indicated with bigger black dots, and for the planning of MV feeders coloured in red in Figure 3.12.
It can be observed from Figure 3.5 that the dots, therefore customers, are located at the border of each building. This mechanism has been applied to limit the possibility for power lines to cross edifices. Indeed, cable will follow the dots. The number of dots around each building is mainly defined by the density parameter set by the user in the input procedure. Each dot, is a bus of the network and it has a specific number of "virtual" connected customer and peak demand which is based on the % of consumer per building.
Downstream to the placement of customers, is the planning of the MV/LV transformers, indicated as red dots in the centre of the same figure. The substations capacity (kVA) is interlinked to the peak demand and the layout composition of the urban area. More in detail, if an area is more dense of customer more substation will be applied. The core module will select the proper substation from the RNM catalogue, of the DSO operating in that area, based on capacity and cost optimization. Then, LV feeders are constructed to associate LV customers and MV/LV substations.

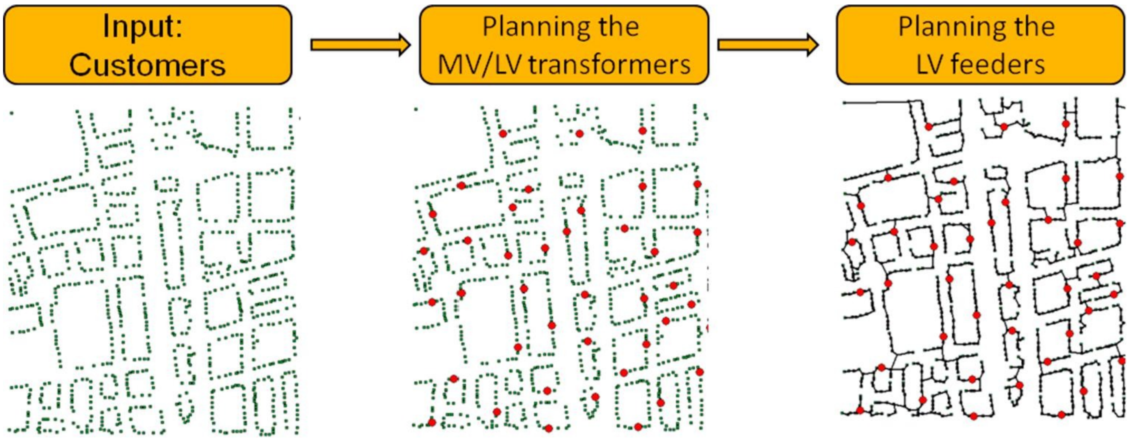


Figure 3.5: Identification of customer and MV/LV substation positioning

The most popular algorithm to develop large-scale distribution networks is the heuristic branch-exchange algorithm. The feeders are constructed based on this algorithm. In our specific case, it is an Euclidean minimum spanning tree problem. Indeed, the network graph is composed by Euclidean straight edges. Starting from the only known data, the geographical coordinates (x,y) of customers and substations, a minimum spanning tree network is developed. The optimization problem minimize the following cost function, which takes into account fixed (MV network) and variable costs (power losses and reliability):

$$\psi = \sum_{i,j \in E} (K_I + K_L I_{i\,j}^2) L_{ij} + \sum_{i,j \in E} K_n I_{ij} L_j \tag{3.1}$$

where K_I is the coefficient of investment costs, K_L and K_n are respectively the cost of power losses and reliability, I_{ij} the current through the branch and L_{ij} the length of the branch.

By having a closer look at the branch-exchange, we start from an initial tree subject to voltage drop and reliability constraints. Then the algorithm through an iterative process select a branch *(i,j)* and substitutes it with a branch *(m,n)* that produces a lower value of the cost function written above.

Once the synthetic network is constructed the module recalculates the 10 network indicators[6].

[6]DiNeMo automatically detects the geographical area under study and consequently the operating DSO. Each country has different indicators according the data provided by the DSO. In a

The Eucledian Minimum Spanning Tree Problem

Branch-exchange technique

A Euclidean spanning tree is a spanning tree of a Euclidean graph, hence it is a circuit-free graph connecting n points in the Euclidean plane. The minimum spanning tree problem becomes the Euclidean minimum spanning tree problem and is: Find the Euclidean spanning tree for which the sum of the Euclidean distances between n points is a minimum [73].

Whether the calculated indicators differ too much from the one provided by the DSO, a new green-field process is run in order to reduce this difference. This control process is also visible in the schematic overview presented in Figure 3.4. The representative network is then developed and provided to the user to be downloaded from DiNeMo output page (visible in Appendix B). All the relevant outputs provided to the user are explained in the next paragraph.

3.4.1.3 User Output

The DiNeMo platform provides to the final user static and *dynamic* outputs. The static ones are several output files grouped in 9 different categories which have different format such as Excel, Matpower, images and shapefile listed hereby:

- **Consumers** contains information regarding low voltage and medium voltage consumers. An image file where consumers are superimposed in the distribution area, and in particular are located around the blocks of building is constructed. Moreover, the excel and shapefile (dbf, shx and shp) files that provide information regarding the consumer identifier, electrical node identifier, nominal voltage (kV) and demand in kVA are provided;

- **Distribution Lines** represents the resistance, reactance and length of conductors. The electrical lines contain several values namely the code of the electrical line, the nominal voltage (kV), the technical features of the lines, as

future release these information will be breakdown to a regional level.

well as information on the status: opened loop or normal operation. Information are provided both in excel and shapefile formats;

- **Network Image** gives the results of DiNeMo elaboration;
- **HV/MV Substation** indicates the data on the HV/MV transformer ratio and capacity utilized in the network;
- **MV/LV Substation** indicates the data on the MV/LV transformer ratio and capacity utilized in the network;
- **Mat power** file collects the branches and buses of the distribution lines. These files provide the bus, branch, protection equipment file with switching devices as well as the main file describing the network. This latter can be used in Matlab[7] for power flow analysis;
- **Switching Devices** contains the switching devices adopted in the distribution network, for instance fuses, breakers and switchers;
- **Summary** highlights the key finding of the distribution network for consumers, electrical lines and substation. Moreover, it gives the input and output image size in terms of width and height. This parameter is useful to understand if the HV/MV substation had enough capacity to supply all the demand, otherwise the distribution network (thus the image) is cut.

The dynamic results are presented in Jupyter Notebook [74], which is an interactive tool containing live code and narrative text. It allows to visualize directly the results of the NCR[8]. The image 3.6 shows an example of a possible interactive visualization through Jupyter Notebook. In this specific case, the voltage level on the nodes and the current levels on branches in per unit are shown, after have run a power flow.
In the platform it is possible to move the cursor on top of nodes and branches to visualize the result. This is an interesting way to have a preliminary understanding

[7] A conversion to Python format is possible in order to compute the power flow in PandaPower

[8] At the moment 22.09.2019 this section has not been implemented yet in the online version

of the result. For instance, the bus 77 has a value of 0.398 kV and a voltage angle of -1.636°.

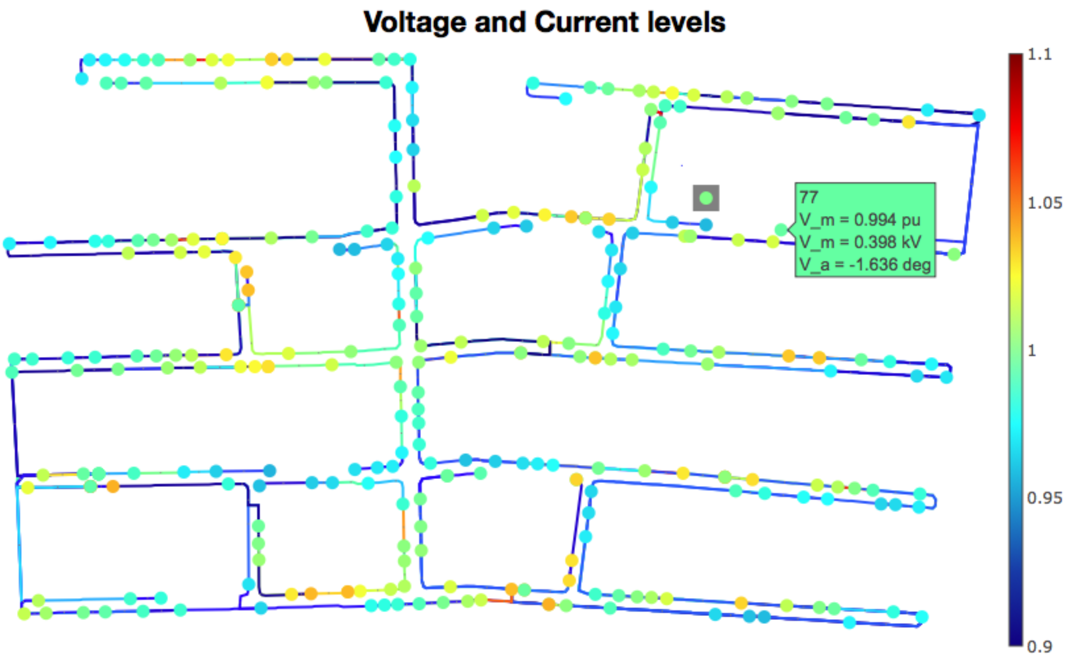


Figure 3.6: Jupyter Notebook Voltage levels

3.5 Network Computation Request example

In this section a concrete example of a network computation request of the neighbourhood *Stadera* in the south zone of Milano is provided. Hereby step by step the illustration of how DiNeMo should be utilized is provided, and images of the platform will be also provided in such a way to serve as a sort of guidelines for users (the guidelines is also provided to users as soon as he/she registers to the platform). A guideline video has been realized and available at https://ses.jrc.ec.europa.eu/distribution-system-operators-observatory.
The dashboard page of DiNeMo is presented in Figure 3.7, and it is composed of 3 main blocks: the network computation request (NCR), the city project and the information area located on the right. The information section shows the last 5 queued requests and the pending notification to participate in a city project.

The first step is to click on *Add New Network Computation Request*, and a new page will appear in which it is necessary to enter a NCR title to the project, which for instance in this case could be named *Milano - Stadera*. Then, once the name has been save is time to type and search for the interested area: Milano.
In the new screen, after selecting between the multiple Milano option provided by OpenStreetMap, we can move through the map to select the specific neighbourhood that we are willing to study. For simplicity the zoom level is blocked to 16 which corresponds to an area of 1.5 km^2.

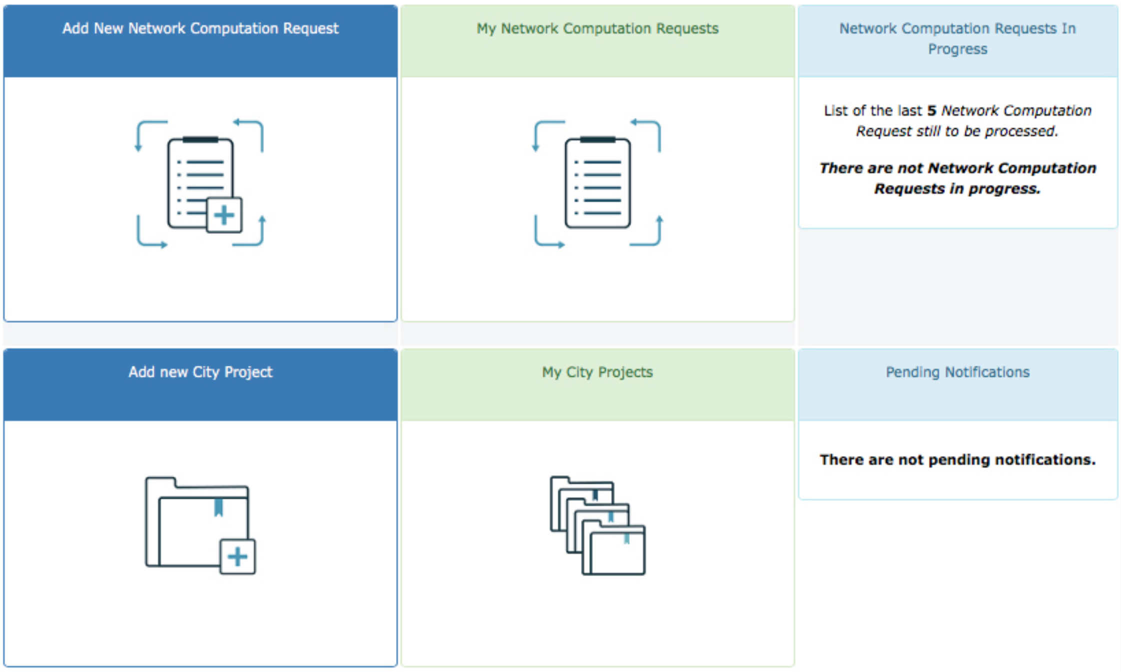


Figure 3.7: DiNeMo homepage website

The zoom area has been selected considering the ratio of the supplied area to the number of HV/MV substations and the total supplied customers to the geographical area. This latter, basically indicates the density of the area analyzed.
The DSO survey shows that the mean value of the ratio supplied area in km^2 to the HV/MV substations number is around 150, which is far from the one adopted in DiNeMo (1.5 km^2). This is because the HV/MV substation data collected in the DSO Observatory survey considers also rural areas. Indeed, to support this concept it is clear from Figure 3.8 that the increasing density is associated with

a lower number of HV/MV substations. Even if may seem misleading, this result certainly indicates that in urban areas, where the density is extremely high, area supplied by few HV/MV substations.

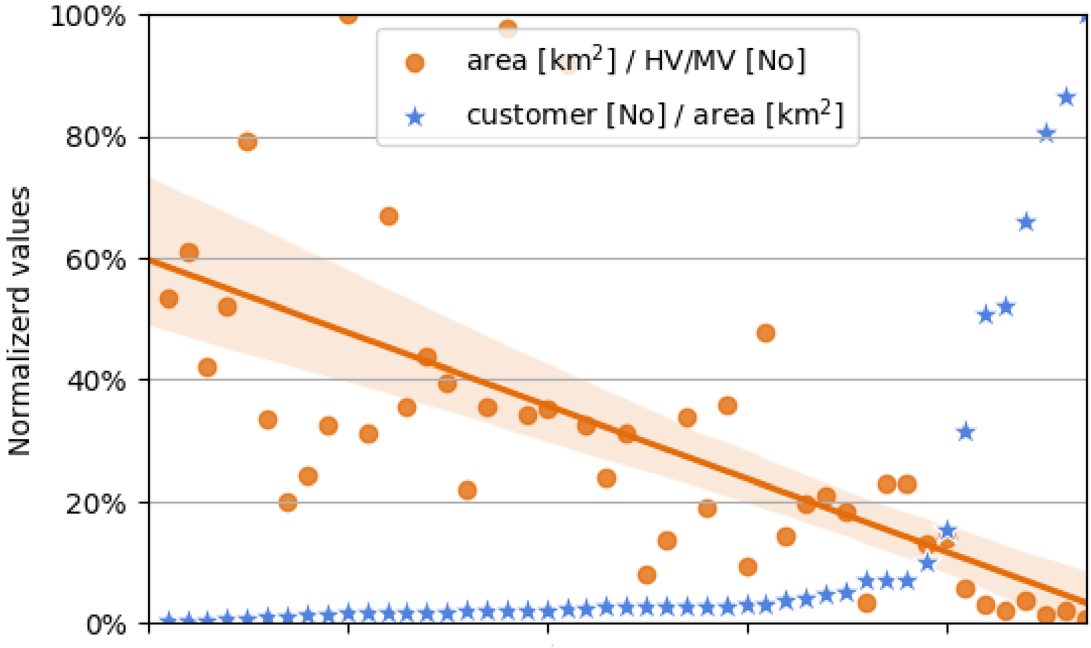


Figure 3.8: Ratios explaining the zoom level choice

Therefore, the average value for the DSO serving merely urban areas is reduced to 1.5 km^2. Although, they serve mainly urban, some semi-urban and rural areas are still covered by them, and for this reason the assumption of 1.5 km^2 is a good representative value of a real situation.

The following step is the location choice of the substation. In the case study considered, the image is captured in proximity to the HV/MV substation named Ricevitrice Sud Milano located in the south part of Milano and operated by the multiutility A2A.

The Ricevitrice Sud Milano is an historical substation built in 1934 by ABB, and upgraded from 65 kV to 130 kV. The transformer ratio set the voltage level of the medium lines to 23 kV [75]. The transformer substation is visible in Figure 3.9 in the bottom left part of the picture highlighted in purple (few transmission power lines are also visible heading down). The geographical area is composed of few main streets and few commercial/industrial areas which are colored (the landuse) in OpenStreetMap in yellow and purple.

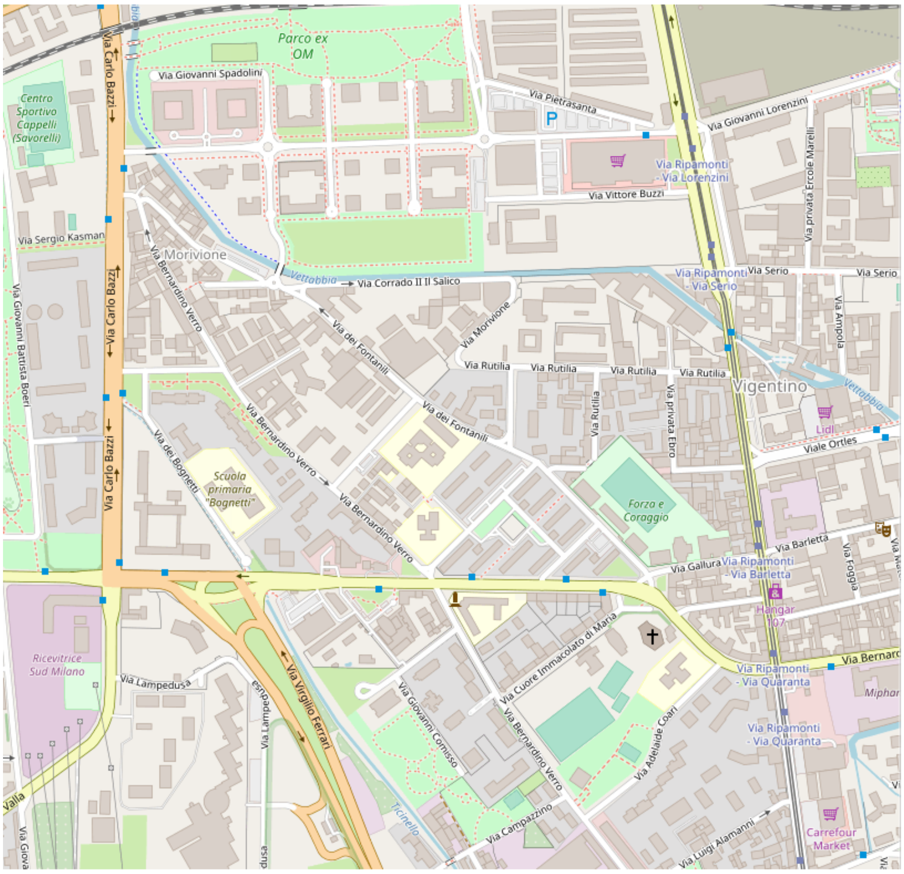


Figure 3.9: OpenStreetMap image and building detection

The input dashboard requires the parameters defined in paragraph 3.4.1.1. The demographic information have been acquired in [71] which indicate the family composition as well as the population density per area. The consumers density is 4669 per km^2 and it is composed as follows: 32% of 1 person, 29% of 2 person, 20% of 3 person per building and 19% for more than 4 people in a building. The LV, MV and HV parameters are respectively 0.4 kV, 23 kV and 130 kV. The LV value is standardized to 0.4 kV, at least across Europe, meanwhile the MV and HV depend on the urbanization level of the city under study. The power factor chosen is the default value, therefore 0.95.

Besides the parameters inserted by the user, there are those, taken from the DSO observatory survey explained in Chapter 2.3, that as described in paragraph 3.4.1.2

are utilized, in an iterative process, for the network design validation. For confidentiality reason the 10 Italian indicators are not reported hereby, but all the aggregated values, collected in the survey, are visible in the plots of Chapter 2.3.

Figure 3.10: User Input Parameter Dashboard

The next step is represented by running the python program (automatically performed by clicking on submitting the request), within DiNeMo platform, that will produce from the Input Image the building map. Figure 3.10 shows the results of the building detection in Milano area. The building detection program can generate error, because strictly dependent on the data inserted by the OpenStreetMap user editor of the specific zone. Few buildings are also removed during the image processing, such as kiosks or ruins, because considered not relevant for the electricity distribution system.

By having a deep look through the image some buildings are plotted alone meanwhile some others are deduced from the image analysis due to the tag land use, adopted in OpenStreetMap, and to the size of the buildings and are therefore aggregated. The land use tag gives information on the type of land, such as: residential, commercial, agriculture, industrial etc. and it is not always present on the map. Therefore, in those building a block (aggregated buildings) is detected rather than multiple tiny ones (or buildings with courtyard). This is an added value for DiNeMo when designing the grid, indeed more *holes* within buildings induce more possibility for cables to cross roads or even undesired buildings in some cases.

Figure 3.11: OpenStreetMap building detection

When considering tiny buildings alone is clear that it can be a source of error because of the relatively small size of the buildings. Indeed it is highlighted in few households where no black dots are visible, thus no contour of buildings is drawn. This will incur in an area of buildings of not connected customers because the software was not able to identify and assign clients to those small houses. Finally in Figure 3.11 customers are applied to the buildings. As previously mentioned, the small buildings are not captured by the algorithm[9].

3.5.1 Network computation request result

This section covers some of the outcomes obtained with the DiNeMo platform. The main result of the NCR, thus the design of the distribution network grid, is reported in Figure 3.12. The HV/MV substation is indicated by the green triangle shape in the bottom-left side of the image exactly where the A2A substation is located. The substation reduces the voltage level from 130 kV to 23 kV. Within the network there are 54 MV/LV substations that are pictured as blue dots of which 7.4% have a capacity limit of 1000 kVA, and the remaining are split in 400 kVA and 630 kVA. The MV connected customers are highlighted with a big black dots, and in this case accounts for only 1% (in absolute value 37), due to the fact that the area is not highly populated of commercial or industrial activities.

The LV connected customers are indicated with a smaller black dot, and are linked through the LV feeders (black lines). The total amount of consumers defined by DiNeMo is 5020 with a total length cable of 102.4 km, of which 36% is medium voltage and accounts for 39 lines. The unique feature of this new tool lies in the high number of georeferenced buses, and therefore the realistic network representation provided.

Indeed, it is now possible to *play* with each bus and define if each consumers can install an EV charging column or is already equipped with PV panels, and how this is affecting the whole system. Moreover, the geo-reference positioning of these buses make DiNeMo a powerful tool to test real case situations. In addition to this, the platform provides information on the switching devices installed in the network, which in this case is equipped with a 5.8% of consumers having fuses, 3 fault detectors, 4 breakers, plus 86 switchers.

[9] The sequence of images 3.9, 3.10 and 3.11 is the the methodology explained in 3.5

Figure 3.12: Milano Network Design Result

On top of this, also some aggregated result are provided, such as: the total installed power at LV and MV level which is respectively 45.2 MW and 3.7 MW distributed across 5020 supply points.

3.5.2 Future extra layers on DiNeMo platform

This section provides the future elements that are going to be implemented in the next DiNeMo version. Most of them will apply extra constraints to the branch-exchange algorithm. Some of these new elements have been acquired from the DSO observatory report and some from studying the available layers in OpenStreetMap.

- **Point of interests (POI)** in order to better associate the demand profile (LV or MV) to the corresponding buses in particular by using the georeferenced information of openStreetMap;

- **Street Map Network** which can be helpful to understand the most congested areas, and thus were to locate extra charging columns;
- **Charging stations** to pre-allocate charging columns within the network also considering the power level;
- **MV/MV substations** implemented because some countries have two levels of MV lines depending which customer they are supplying;
- **Building height** will be considered in order to have a better approximation of the number customer per building, thus the peak demand.

Some more images are reported hereby to show how extra layers can be an added value to the already powerful tool. Let us have a look to see how this will influence the already calculated distribution network of Figure 3.12. Indeed, this extra layer of information extracted from OpenStreetMap, listed in Table 3.3, allows the construction of an even more realistic network[10].

Table 3.3: Point of interest found in the network

Type	Quantiy	Voltage Level
Parking	33	LV/MV
Restaurant	17	MV
Cafe	10	MV
School	3	MV/HV
Fuel station	4	MV
Theatre	1	MV

In fact, different demand profiles (restaurant, banks, households) can be applied among the grid buses after the grid network has been designed to perform a power flow analysis. In addition, charging columns could be installed, as well as PV panels. A power flow analysis could help to understand how these elements

[10]This Table reports only the most relevant POI, a way longer list is available in the OpenStreetMap image

affect for instance transformer degradation, voltage and current deviations. It is possible through the Python code listed in Appendix A to extract the POI in the area under study, and the network can be re-plotted according to it.

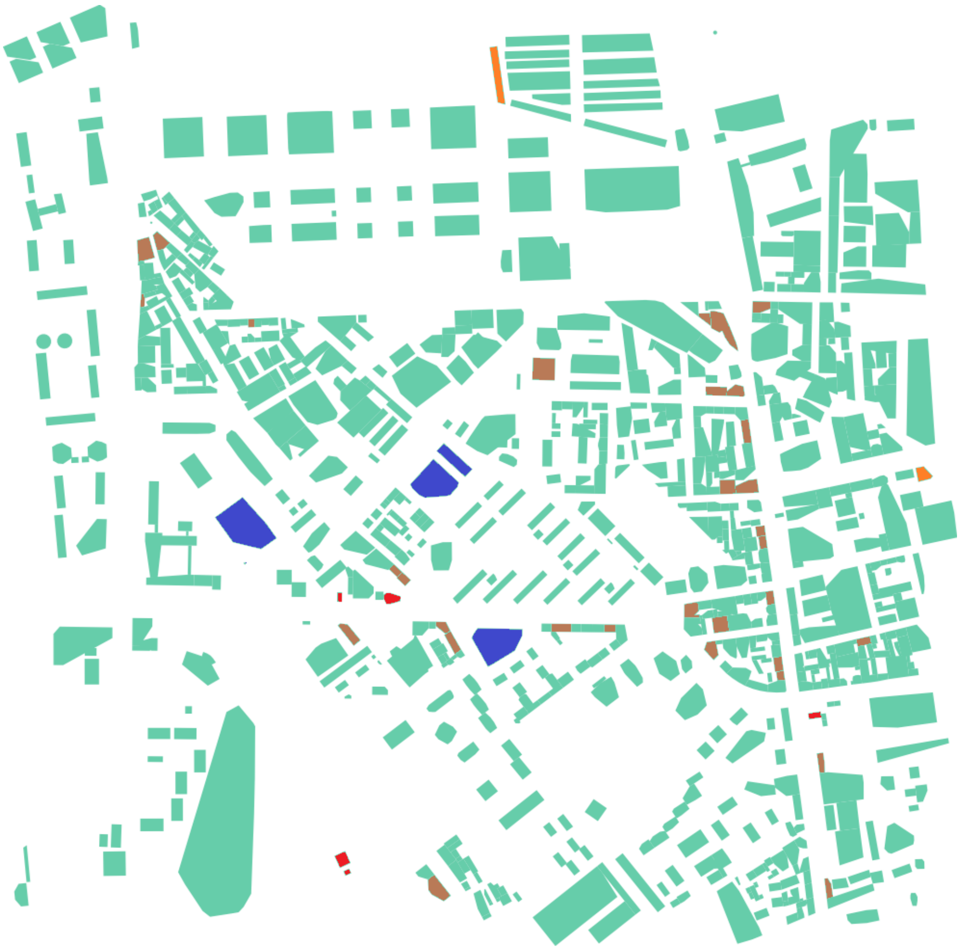


Figure 3.13: Point of interests in the observed area

The POIs, listed in Table 3.3, can then be pictured in Figure 3.13. Restaurants are coloured in brown, schools in blue, fuel station in red and theatre in orange. This extra layer can be useful to understand where EVs may park or be more present in the network.

These few suggestions are showing the potentiality of the tools and its modularity in integrating several information layers in order to reproduce more and more realistic. Even more examples of information layer that could be extracted from OpenStreetMap are available in the package OSMNx and in its documentation [76].

3.6 Chapter summary and main contribution

An in depth literature research has been applied on a query combining charging infrastructure and distribution network grids words, which remarked a peak trend of publication especially after 2017. The papers collected were cluster in three macro categories: the synthetic network based on IEEE layout, synthetic network not based on IEEE layout and real network grids. The most innovative articles were summarized, and a well defined picture arises indicating some common lack across the literature: the limited number of buses, branches and consumers; regularly the absence of geo-referenced layout networks; the electric vehicles analysis often considered at the substation level rather than buses level. On top of this, the fact the most utilized networks (IEEE) in research were originally designed on the technical features describing US distribution networks which have significant difference compared to European ones.

The creation of a unique platform, named DiNeMo, for the construction of geo-referenced and large scale representative networks fills the gap with the current weaknesses found in literature. The platform allows to design from scratch the distribution network grid below a HV/MV substation. The DiNeMo structure is presented in its 3 main components user input, platform core and user output. The input data are based on the data collected from the DSOs's survey and the topographic parameters of the urban area under analysis. The algorithm utilized to develop the large-scale distribution network is described and as well as the schematic overview of the whole methodology. The output data are listed and explained. Finally, an example of a network computation request is illustrated step by step as a sort of guideline for the user.

My original contribution has been to convert a model thought to design transmission network grids tariffs to design distribution networks grids. This innovative approach allows users to developed scenarios on specific real case of urban areas of interest which has been now limited only to those ones where network grids were shared by DSOs. In addition, I have created three codes, in Python, which radically change the module performance. First, the code to detects buildings is no more done according to the RGB of google maps but on OpenStreetMap layer's information, thus building's shape and height is collected. Second, the substation

already present in the area are utilized as a constraint in the module. Third, point of interests are extracted and may be considered for the user's analysis.
On top of this, my contribution to the platform creation can be summarized in: design the functionality of each page; improving the user experience (UX); design platform architecture[11]; define the content such as writing the guidelines and the tutorial video; testing and debugging the development, test and production working environment; and customer interaction management.

[11]The back-end and front end coding was performed by the IT department.

Chapter 4

Electric Vehicles, Charging infrastructure and Network Grids

This chapter presents the interaction among electric vehicles' infrastructure and network grids. Firstly, it analyses an electric vehicle database and evaluates the metrics including the users' behaviour. Secondly, it describes a methodology for assessing the electric vehicle charging infrastructures features and performances. Finally, it presents a test case of the impact of electric vehicles on the distribution network grids. It is based on the two articles [77, 78].

4.1 State of the art of on power-transport sectors interaction

In Europe the road transport sector contributes for 21% of total CO_2 emissions according to [79]. Differently from other sectors, such as industry, agriculture, residential and services, the transport emissions has started to decrease only after 2007 due to the more stringent EURO IV policy. Moreover, within the transport sector, the road one is the leading emitter and account for nearly 70% of the total. More specific, heavy-duty vehicles, trucks and buses, account for almost 5% of the total

CO_2 emissions, thus about a quarter of the road transport sector.
To overcome the harmful emissions produced from internal combustion engines (ICEs), several countries are promoting ad hoc policies and incentives to introduce EVs in their national fleet. The higher engine efficiency and the independence from fossil fuel make them a suitable alternative solution to mitigate CO_2 from road transport.
However, still some barriers are limiting the exponential growth of EVs which can be categorized in two main components, related to the vehicle and to its effects on the network. Concerning the vehicle ones, CAPEX cost and the low number of life cycles of batteries are the key factors; conversely, the effects on the networks are manifold: the lack of fast charging installations, the harmonics introduction in power lines, and low input power factor which degrades quality of supply while increasing losses, as well as peak load generation [80].
Beside these aspects, the benefits that a massive EVs penetration can provide are multiple. The interface with renewable energy can lead to a reduced curtailment of this latter, smart charging can avoid peak demand, extend transformer lifetime, avert costly network reinforcement.
Furthermore, Vehicle-to-Everything (V2X) mode can support grid stability in terms of voltage, power and demand supplied. The curtailment of renewable energies is also playing a key role in the global wheel-to-wheel analysis of EVs. The generation mix of the country is heavily affecting the CO_2 emissions of EVs as highlighted in Figure 4.1. For instance, Norway, Denmark and Sweden have a generation mix which induce a low CO_2 emissions of EVs, thanks to the high shares of renewable energy. Differently, from other countries, for Norway the generation mix is mainly (98%) from hydropower plants, thus it guarantees a high flexibility, which is necessary in case of a high simultaneity of EVs recharging. In countries where the renewable energy production is attributed mainly to wind and solar, EVs can play a key role as storage devices to hold, when necessary, the surplus production of renewable energies [81].

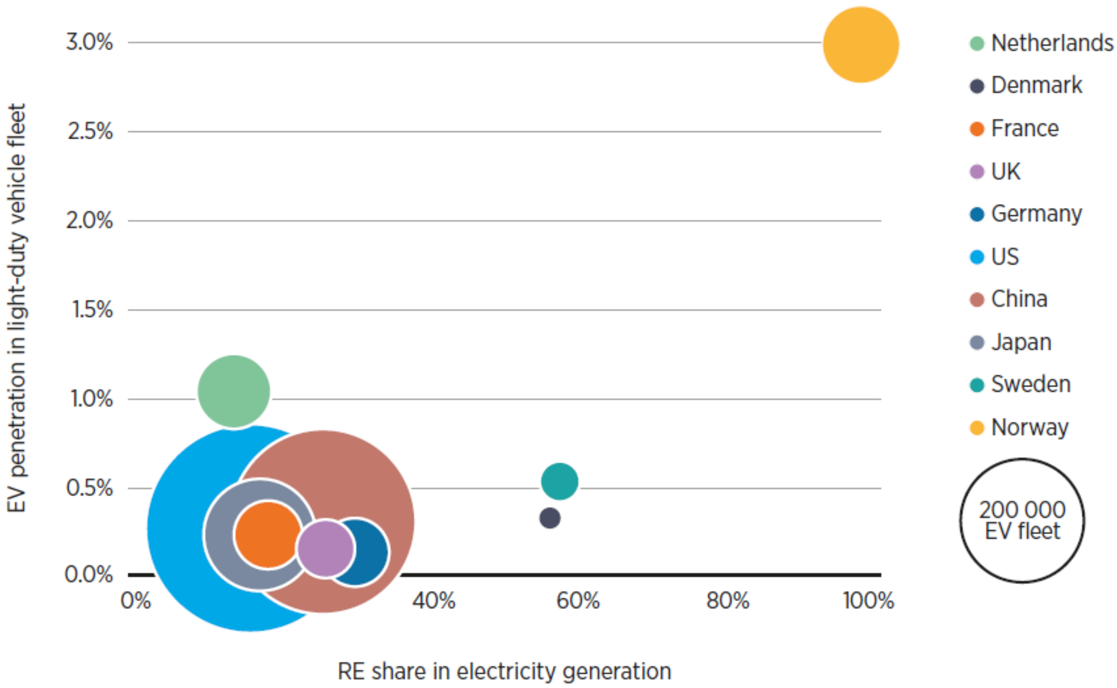


Figure 4.1: Indicators of clean electric mobility penetration in 2016 [81]

4.1.1 Electric vehicles status

Electric mobility has reached by the end of 2018 a global fleet of 5.1 million, of which 64% are battery electric vehicles (BEV), which sees an increment of 2 million vehicles compared to the previous year [82]. This growth is not surprising, if we have a look at the previous rates, of 60% and 57% for the year 2016 and 2017, respectively.

The vast majority is distributed among China, Europe and United States, where China hosts around 45% of all the fleet, meanwhile for Europe and US the situation is similar having 24% and 22%. In China 1.1 million electric cars were sold last year, meanwhile in Europe up to 385'000 units. The only *mature* market that had a fell in sales is Japan (-8%). Starting from 2012 until 2018 the share of BEVs sold has steadily increased up to 68%, indicating that manufacturers and consumers prefer instead of hybrid vehicles a full electric one. The top ten countries per share of EVs are plotted in Figure 4.2. The dark shade indicates BEVs, meanwhile PHEVs are represented with a light shade. Focusing on Europe, we can observe that Norway is by far the most mature market having a 10% of the car fleet being electrical, thanks in particular to the economic incentives. Indeed in 2018, almost 50% of the new cars sold were either hybrid or full electric, achieving a unique result. Plug-in hybrid vehicles (PHEV) are more widely available for large size vehicles, such as SUV and large car. On the other hand, BEVs are more evenly distributed among markets segments.

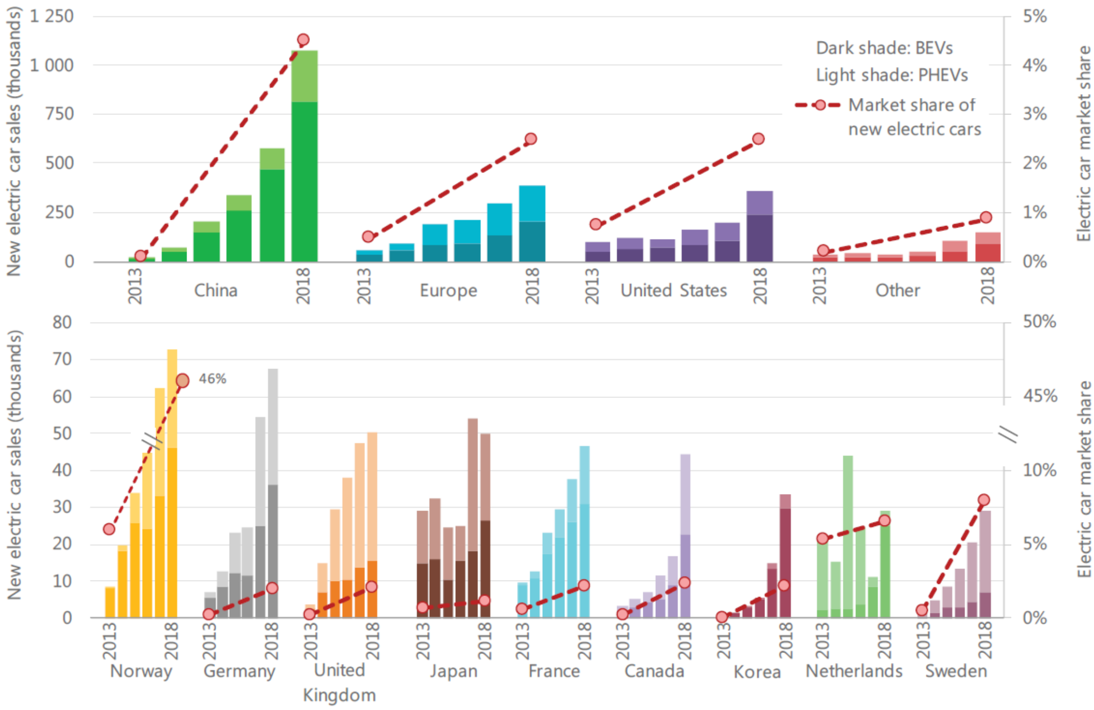


Figure 4.2: EVs sales trend 2013-2018 [82]

The key driver to switch to an electric vehicle lies on the national policies, and their economic incentives which can be in acquisition discount, tax benefits ownership and company cars benefits. Among countries, a wide variety of benefits are applied, for instance in Italy there is no discount in the acquisition neither benefits for company cars [83]. On the other hand, the predominant position of Norway is because the following incentives[1] are applied: No charges on toll roads or ferries, free municipal parking, exemption from 25% VAT on leasing, exemption

[1]The first law dates back to the 1996, in which EVs were exempt from annual road tax [84]

from 25% VAT on purchase. On top of this, several country announcements to reach 100% EVs sales (ICE vehicles sales banned), have been released by Denmark, Iceland, Ireland, Netherlands, Slovenia for 2030, plus France, Portugal, Spain and United Kingdom for 2040. In parallel, car manufactures are increasing their EVs options and have also announced their own target. FCA announced 28 new models by 2022, Volkswagen target for 2030 is a cumulative sales of 22 million and Volvo want to reach a sales of 50% by 2025. Another raising sector, which will probably not impact the network grid due to the limited battery capacity are the electric foot scooter (shared micro-mobility) for the urban transport [82].

4.1.2 Charging Infrastructure status

The charging infrastructure development follows the EVs spread, indeed it reached by the end of 2018 an estimated number of 5.2 million charging points. The 90% are private chargers (mainly Mode 1), therefore the publicly accessible charger represents a small fraction.

IEC 62196 – Conductive charging of electric vehicles

Plugs, socket-outlets, vehicle connectors and vehicle inlets [85]

1. Mode 1 - It is a residential charging with 3-7 kW power and Shuko as connector;
2. Mode 2 - It is both residential and industrial charging with 3-7 kW power, and a current of 16 A or 32 A. The connectors are type 1: YAZAKI, type 2: MENNEKES, type 3A and 3C: SCAME;
3. Mode 3 - It is characterized by a communication between the car and the charging station. IT has a max current of 63 A, and a power ranging from 2 to 22 kW. It utilized the same connectors of the type 2;
4. Mode 4 - It represents the fast charging mode, differently from the other mode is mainly a public or industrial charging point. The current reaches high level up to 200 A, and the power supplied is above 22 kW. The connectors are CHAdeMO (no longer complaint), and Combo CSS which allow both DC and AC charging.

Moreover, of this latter category only 144'000 are fast chargers (2.7% of all charging points). In terms of publicly accessible chargers per EVs, the global ratio decreased to 0.11, but it is still above the recommended value of 0.1 proposed by the European Union Alternative Fuels Infrastructure Directive. The ratio between EVs and EVSE according to [86] has evolved during the last 10 years. At the European level in 2010, the ratio was 11 EVs per EVSE, dropping to 4 in 2016, and now in the last 2 years is stable at 8. Another interesting value is the number of fast chargers (> 22 kW) per 100 km in highway which is 32 for the 2019, and it has linearly increased since 2014.

Concerning charging infrastructure demand profile is challenging to gather those data, especially for private charging points, because metering is often not separate for EVs charging and households. For public charging the lack of data is mainly attributed to the low number of EVSE and data confidentiality. It is key to acquire detailed information to study EVSE impact.

4.1.3 Smart Charging and its role on network grids

One of the precursor of the smart interaction between power and transport sector has been published by Kempton et al. in 2005 [87]. In the study they introduce the concept of vehicle-to-grid[2] and the opportunities to sell electricity of EV's battery in the different markets. It requires three main aspects: a connection to the grid, a communication devices among EV and EVSE, plus a control metering on the vehicle.

This interaction, which see EVs as the bridging component, have several adverse effects on the distribution network if EVs are not properly managed. These impacts can be categorized in 5 groups according to [88]: voltage instability, increased peak demand, power quality problems, increased power losses, transformer heating and overloading. More in detail, power quality studies focus on harmonics distortion issues, voltage imbalances, thus variation between magnitudes and phase angles, voltage sag (which is a short incomplete interruption of power), and power losses. To overcome these potential adverse effects, we have to understand what flexibility

[2]Nowadays some pilot projects have been launched such as the Danish project named Parker

EVs can provide to the network system and what we mean with smart charging. This operational flexibility can be defined by [89] as: "*the technical ability of a power system unit to modulate electrical power feed-in to the grid and/or power output from the grid over time.*" Based on the IRENA innovation outlook on smart charging for electric vehicles [81] the potential flexibility is grouped in system and local. This situation is plotted in Figure 4.3. In this thesis focus is mainly on the local EVs's flexibility and in particular at the distribution system operator level.
The exploiting of flexibility at the system level, thus for TSO, has been already widely used if we think at hydro power plants. Therefore the consolidated knowledge at TSO level can be easily implement to exploit also EVs flexibility. Indeed, TSOs are already equipped with instruments for support real-time balancing by adjusting EVs demand. On the other hand, at DSOs level, despite several pilot projects, DSOs are not yet mature to fully take advantage of EVs capacity.
Smart charging studies has seen in the last decade a special attention. The dumb charging, named uncontrolled charging, has multiple drawbacks well known in literature: voltage deviations, peak power increase, electricity cost increase, needs to reinforce the grid, transformer and lines overload. The smart charging approaches tested, sorted by implementation complexity, are off-peak charging, valley filling and peak shaving [90].

SYSTEM FLEXIBILITY		LOCAL FLEXIBILITY	
Wholesale market	**Transmission System Operator**	**Distribution System Operator**	**Behind-the-meter**
• Peak-shaving • Portfolio balancing	• Frequency control • (primary, secondary and tertiary reserve) • Other ancillary services (*e.g.*, voltage management, emergency power during outages)	• Voltage control • Local congestion and capacity management	• Increasing the rate of Renewable Energy self-consumption • Arbitrage between locally produced electricity and electricity from the grid • Back-up power

Figure 4.3: Potential EVs flexibility

All smart charging techniques rely on the V2X concept, which can be subdivided in 4 main groups:

- **V1G** is the unidirectional controlled charging, in which EVs or EVSE adjust their charging rate according to the battery or grid constraints;

- **V2H** stands for vehicle-to-home and it is an extra source of power supplier for households, as a sort of back power;
- **V2B** is vehicle-to-building and it is not directly affecting the distribution network grid reliability;
- **V2G** initially proposed by Kempton et al. [87] refers mainly to the capacity of partially discharging the EVs to provide support to the grid.

In this chapter the study is oriented on the disturbances provoked by different level of EVs penetration in a urban network area in the Hague in the Netherlands, and in chapter 5 on a Croatian city after having validated the network grid. No smart charging approaches will be implemented but a discussion on the idle time, thus the capacity unused of EVs within the network, will be done. The idle time refers to those vehicles still plugged into charging columns which are already completely recharged.
Before analyzing the voltage deviations that EVs may induce into the network it was necessary to understand and learn the EVs demand profile. In order to do so, in collaboration with the Dutch company ElaadNL [91], a dataset of EVs transactions of 2900 public charging columns in the whole Netherlands has been collected. Firstly a statistical analysis of EVSE behaviour is conducted in the article [77]: "*Statistical characterisation of the real transaction data gathered from electric vehicle charging stations*" (section 4.2.1). In a second step a methodology is developed in the article: "*Indicator-Based Methodology for Assessing EV Charging Infrastructure Using Exploratory Data Analysis*" [78] which allows a comparison among EV public charging infrastructures with the use of 8 indicators (section 4.2.2).

4.2 Elaad database analysis

In this section the two articles, based on the ElaadNL database, will be briefly summarized and the main outcome discussed.

4.2.1 Statistical characterisation of the real transaction data gathered from electric vehicle charging stations

As it emerges from the literature, due to the lack of available data, a variety of assumptions and approaches have been produced in studying EV mobility, which include drivers' behaviour, the charging mode adopted, number of charges per day, as well as plug-in and plug-out time. All these differences provide diverse outcomes when testing the EV demand effect on the grid.

Therefore, in order to fill this gap, in the article [77] the following main contributions are provided: real figures of drivers behaviour in terms of connected, charge and idle time; the development of a Beta Mixture Model to show the multi-modal probability distributions of the most relevant parameters; finally, a discussion on the potential use of EVs to provide V2G services.

The objective of this function is to create a BMM for those users who do not have real data to reproduce plug in and plug out per weekday and sunday as well as energy demand profiles.

4.2.1.1 Electric vehicle database overview

To accomplish these contributions, an in depth study of a dataset of 1750 public charging stations (2900 charging points) installed in the Netherlands is done. This dataset is obtained by ElaadNL, a Dutch research centre, who was owning the charging stations, expert in the interoperability and in the smart charging infrastructure. It is composed of more than 1 million transactions (thus recharges) in 4 years (2013-2016) distributed among the estimated 30'000 EV drivers using these charging points. They are all 3-phase chargers with a maximum output power of 12 kW. The year selected in this study was the 2015 as it is the most recent full year available[3].

Concerning the year 2015 the number of transactions is almost 400'000, which is 38.5% of the whole database. From this number have been already removed those

[3]In 2015 the ElaadNL database represents 16% of all charging points in the Netherlands, therefore is assumed to be a good representative of the charging points profile.

recharges lasting less than 10 minutes (0.5% of the 400'000), considered not relevant for this study. The parameters are updated every 15 seconds, but in this analysis a time resolution of 1 minute is utilized. Each transaction records the following information:

1. **Charge time**: Measured in seconds, indicates the duration time in which the EVSE was supplying electricity;

2. **Idle time**: Measured in seconds, it represents the time between the end of the recharge and the plug-out of the EV from the charging point (during this period no effective energy transfer occurs);

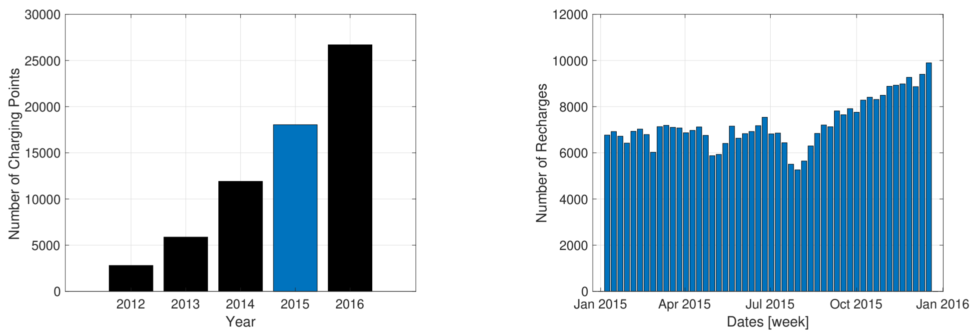
3. **Connected time**: It is the sum of the charge and idle time;

4. **Energy metered**: It is measured in Wh, and is the energy charged to the vehicle during the whole transaction (charge time);

5. **Power metered**: It provides the average power in W every 15 seconds;

6. **Geographical coordinates**: It indicates the latitude and longitude of each charging stations.

The first interesting figure obtained from the dataset is the number of recharges per week in 2015 which is plotted in Figure 4.4 (b).



(a) Accessible public charging points

(b) Recharges per week

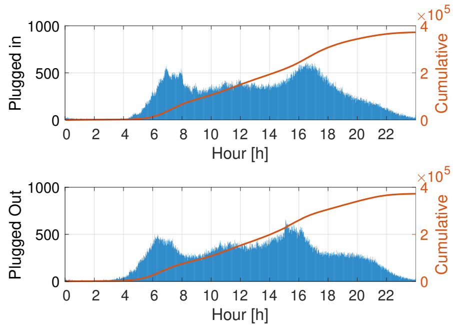
Figure 4.4: Database general overview

The increased number of recharges across the year reflects the increasing penetration of EVs sold in the Netherlands, like for the charging points plotted in Figure

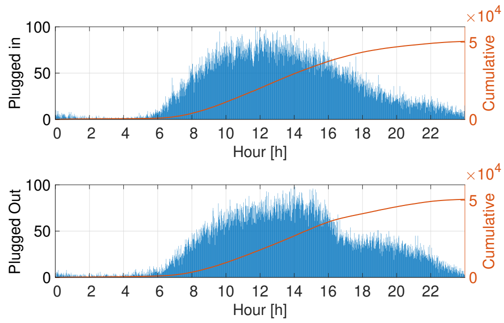
4.4 (a). The average energy supplied to EVs per week is 62 MWh that corresponds to an average recharge per week per vehicle of 8 kWh. It is intriguing to observe few drops in the chart that identified national holidays as well as Christmas and summer break in Figure 4.4 in (b).

4.2.1.2 Multi modal probability distributions

By looking at the plug-in and plug-out in Figure 4.5 during weekdays (a) and Saturday (b) relevant information can be deducted. The time step resolution utilized is 1 minute. The vertical axis highlighted in red show the cumulative results for EVs plugging in. It immediately pops out that there is a different order of magnitude between weekday and Saturday.
Furthermore, the shape profile during weekdays have a double peak for both plug-in and plug-out, one in the early morning between 6:00 a.m. and 8:00 a.m. (reasonably when people are going to work) and the other one between 4:00 p.m. and 6:00 p.m.



(a) Weekday



(b) Saturday

Figure 4.5: Average weekday plug-in and plug-out of EVs

The analysis of cumulative curve shows that 85% of the activities happen before 7:00 p.m. Saturday activities are limited, therefore most likely they will not produce any adverse impact on the distribution network grid. Starting from the results of Figure 4.5 a probabilistic representation through a Beta Mixture Model (BMM) is developed in order to provide a useful outcome which can be used by researchers when testing EV mobility effects. To determine the probability distribution functions (PDFs) the data is considered with an histogram for each minute

(1440 points). According to [92], the most suitable algorithm to approximate the PDF found in the analysis of the EV dataset is the BMM. It is a mixture of M multivariate normal distributions, where each one is composed by a mean, variance and relative mass. Therefore M Beta distribution developed represents the probability distributions functions of the EV-related data as follows:

$$BMM(X) = \sum_{m=1}^{M} (w_m Beta(x|a_m, b_m)) \tag{4.1}$$

where w is the weight[4] of each the Beta distribution, a_m and b_m the shape parameters[5], and where Beta probability distribution is defined as:

$$Beta(x|a, b) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} x^{a-1}(1-x)^{b-1} \tag{4.2}$$

where $\Gamma(.)$ is the Gamma function, and the Beta function is suitable to represent variables which are in a closed interval (x_{min} and x_{max}). The minimum and maximum value are re-scaled in the range [0,1].

Our aim is the identification of the BMM distribution which minimizes the distance between d(BMM,EPDF), where the EPDF represents the empirical probability distribution function composed of N points (1440 in our case). The distance is calculated as:

$$d(BMM, EPDF) = \sqrt{\frac{1}{N} \sum_{n=1}^{N} (BMM(x_n) - EPDF(x_n))^2} \tag{4.3}$$

In line with the above equations the optimization problem is the minimization of $\min_{\mathbf{y}}[d(\mathrm{BMM,EPDF})]$ which is subject to $b_{\mathrm{m}} > 1$, for m=1 to M; $0 < w_{\mathrm{m}} < 1$, for m=1 to M-1; and $0 < \xi_{\mathrm{m}} < 1$, for m=1 to M. The unknowns parameters are included in the vector y which is initialized[6] by satisfying the inequality constraints for b_{m}, w_{m} and ξ_{m}. Based on these initial guess we can calculate a_{m} has follows:

$$a = \frac{1-2\xi}{1-\xi} + \frac{\xi}{1-\xi} b \tag{4.4}$$

[4] The sum of all the weights equals 1

[5] It is defined that $a_{\mathrm{m}} > 0$ and $b_{\mathrm{m}} > 0$

[6] b_{m} has a higher value if there are sharper peaks

To solve this optimization a *fmincon* from Matlab is utilized, which finds the minimum of a constrained nonlinear multivariable function. To verify if the BMM fits properly the EPDF a goodness-of-fit through the Kolmogorov-Smirnov (KS) test is carried out.
Basically it is verified that the maximum vertical difference between the cumulative distribution function built from the BMM and the empirical cumulative distribution function obtained from EPDF is within a certain critical value. This optimization process is applied on the PDF of weekday, Saturday and Sunday plug-in and plug-out profile.
These results allow researchers to reproduce real EV demand profile for testing EV mobility and their impact on the network grid without requiring real dataset. Due to the more complex profile in weekdays the number of modes is 4, compared to the cases of non-weekdays. The results for weekdays are plotted in Figure 4.6.

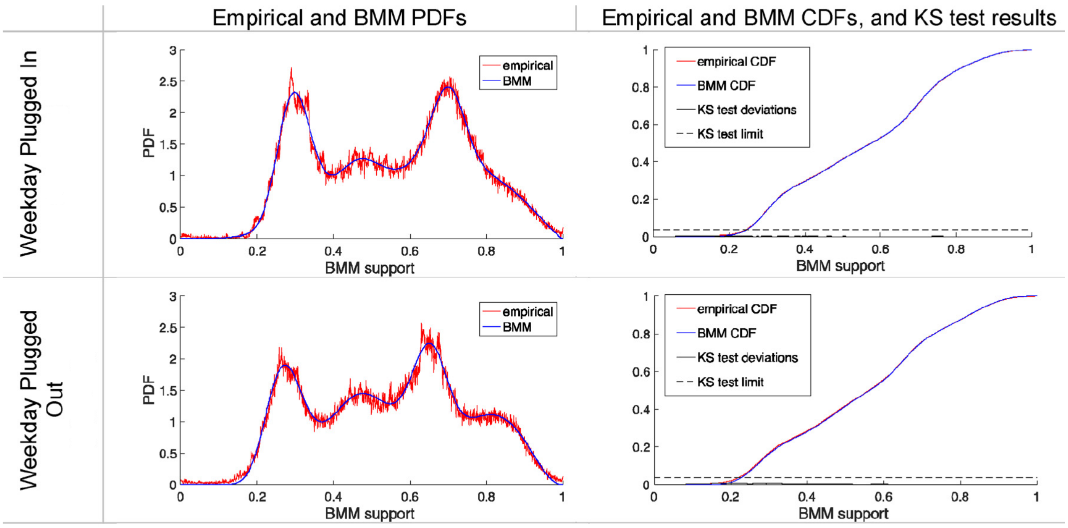


Figure 4.6: BMM and EPDF results for weekdays

The multi-modal probability distribution with the BMM clearly shows a good fit of the real EVs plugging in and out during weekdays, thus the empirical curve colored in red.
The results are also validated with the KS test which indicates a good performance of the BMM. Starting from equation 4.2 and with few values, more specifically the ones of modes, weights, a and b we were able to reproduce the EVs profile.

4.2.1.3 Idle, charge and connected times

The electric vehicle's transactions provide further interesting data which deserve attention: charge, idle and connected time. Moreover, the idle time provides an idea of the potential flexibility of V2G service. The charging points database has been merged with the geographical information systems (GIS), of the applied by OpenStreetMap project[7] [93]. As expected, the primary roads, thus the ones connecting to larger cities, show the smallest idle time for the installed charging points. On the other hand, the residential roads are characterized with the highest average connected time of 7 h. It pops out from the dataset that nearly 75% of EVs connected to charging columns, at any time, are already fully recharged. This clearly indicates that there is room for potential use of V2G services. Furthermore, 50% of the recharges are within 4 h (it does not mean that the vehicle is completely recharged).

The same BMM approach has been applied on charge and idle time to provide researchers a representative function describing charge and idle patterns behaviour of charging columns across the different road classification. Similarly to the multi modal probability distributions applied for plug-in and plug-out, the CDFs for charge and idle time have been constructed (for more detailed result please refer to [77]).

4.2.1.4 Latitude and longitude analysis

In this section is emphasized on the geo-location importance of charging stations. Indeed, it helps to understand where further installation of charging stations may be placed according to users needs in the Netherlands. Figure 4.7 plots the charging stations based on the road classification. By analysing the utilization of each charging stations, the results reveal that users use less those installed in primary roads. This occurs mainly because the power is up to 12 kW, which may indicate that EV users would prefer fast chargers in those type of location. On the other hand, at residential level the utilization is higher, showing that drivers tend to recharge close to their households.

[7]The road classification utilized are primary, secondary, tertiary, residential and motorway

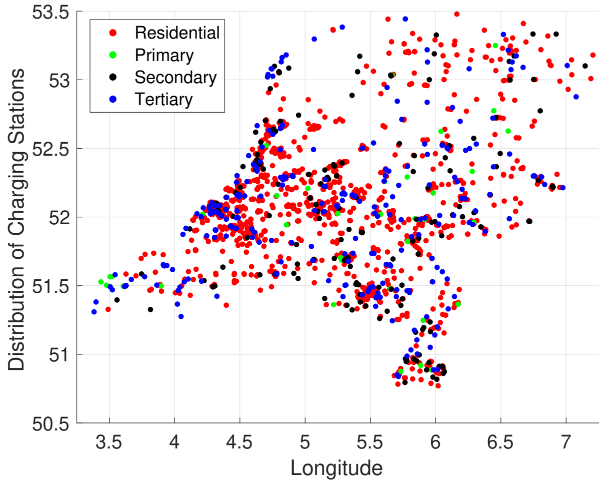


Figure 4.7: Distribution of charging stations across the Netherlands

4.2.1.5 Energy and power analysis

The final section of the article [77] focuses on the energy supplied by the grid to the charging stations. The average profile for Wednesday, Saturday and Sunday is reported in Figure 4.8.

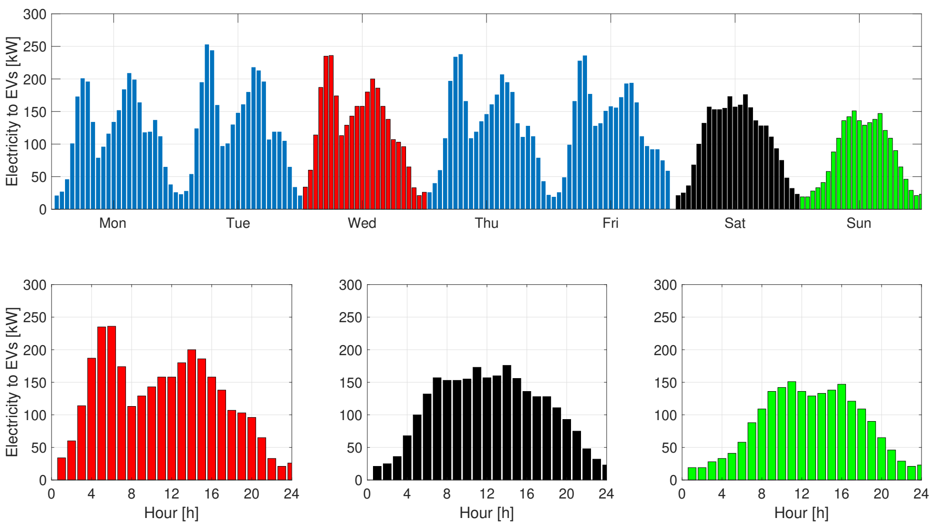


Figure 4.8: Average EVs demand during the week

This outcome emphasizes that night recharge is almost negligible, thus not producing either any adverse accelerated aging on transformer nor on the network grid.

During weekdays the profile is similar independently of the day, with an average daily electricity demand of 950 kWh. The morning peak is present at 6:00 a.m. with a peak power demand of 150 kW. If energy and power are analysed from a geographical point of view, the majority of the demand is concentrated in the biggest cities, such as Utrecht, Rotterdam and Den Haag, as visible in Figure 4.7. This information is useful to understand whether or not a geographical area will need reinforcement to the grid, and moreover at which time the network is mostly affected by EVs recharging.

4.2.2 Indicator based methodology for assessing EVSE

The article [78] aimed at developing a methodology, based upon eight indicators, to analyse EV charging infrastructure performances and features. In addition, it allows the comparison among EV public charging infrastructure which help to understand the different approaches per region and country level.
The eight suggested indicators are extracted based on the EV dataset (previously explained in 4.2.1) provided by ElaadNL and they cover the following aspects: Energy demand from EVs; Energy use intensity; Charger's intensity distribution; The nearest neighbour distance between chargers and availability; The use time ratios; Energy use ratios; The total service ratio and Carbon intensity.

4.2.2.1 Energy demand from EVs

This indicator stresses the fact that it is ambiguous to compare the number of EVs per chargers if they use differently the network. Therefore, the ratio public charger per vehicle is not accurate enough to describe the network use, and for this reason the focus is on an energy usage indicator. From the dataset an average energy demand of 4040 MJ_{year} per connector is derived.
Figure 4.9 reveals that more than 83% of the EV rechargers, among the year in the ElaadNL's infrastructure, are less than 200 kWh. If considering the reference vehicle efficiency of 0.15 kWh/km, this entails that the mileage driven by each EV is around 1300 km per year, which is 10% of the average annual distance in the Netherlands.
Therefore, we can conclude that charging needs are mainly satisfied at home or at

work rather than around the city. In addition, Figure 4.9 (b) emphasizes the fact that users tends to limit the use to a restricted number of charging points.

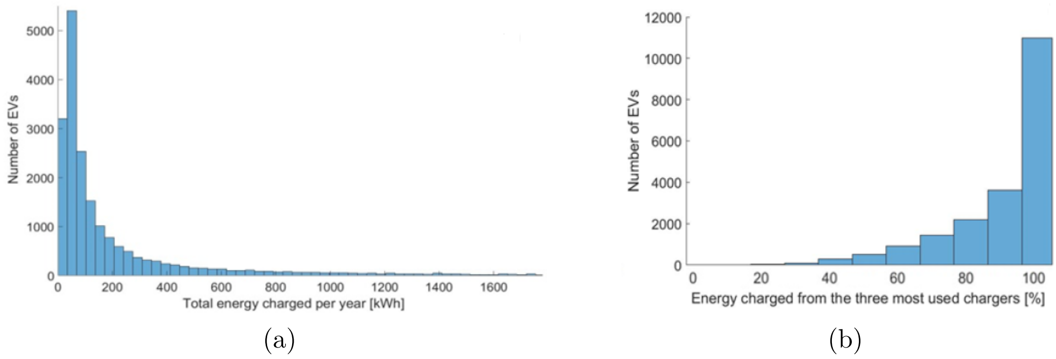


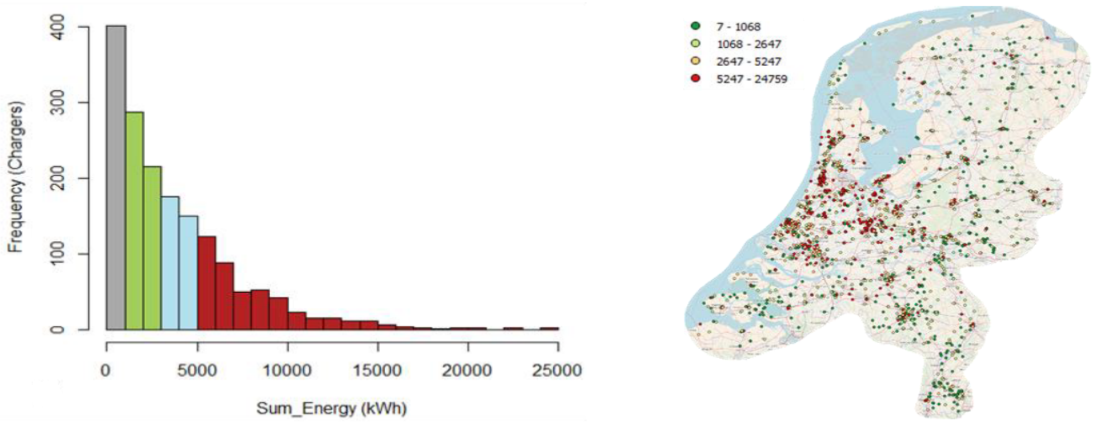
Figure 4.9: Yearly energy charged per EV [kWh] in (a), and energy supplied by the three most used charger [%] in (b)

4.2.2.2 Energy use intensity

In designing the charging network across a city, two main aspects should be taken into account: the distribution of them and the density of chargers. These elements should be carefully utilized to avoid potential accelerated degradation of transformers and cables. For this reason, the energy use intensity indicator with the charger's intensity distribution one are proposed. They have been derived by performing a geospatial analysis.

The energy use intensity provides information concerning the homogeneous energy use across the network and the second one evaluates its density distribution according to fuel station and parking lots. The indicator shows that a higher energy density is observed mainly in six areas where the chargers density is also higher. This situation is visible in Figure 4.10.

The histogram in Figure 4.10 (b) presents quantile breaks, where each colour represents 25% of the energy supplied by the chargers. The corresponding geospatial situation is reported in Figure 4.10 (b). It can be observed that 25% (grey colour) of the chargers supply less than 1000 kWh in the two years, meanwhile the red quantile indicates that 25% of the charging points provide almost 50% of the total energy under study. This is a good indicator of the concentration of the energy demand across the Netherlands infrastructure.



(a) (b)

Figure 4.10: Histogram of energy demand per charger in (a) and geospatial distribution of quantiles in (b)

4.2.2.3 Charger's intensity distribution

This indicator tries to look at any correlations with existing infrastructures such as fuel station, parking lots and population density[8]. Indeed, the deployment of chargers aim at minimizing costs, social impacts and resources by making use of the existing structure. Parking lots are studied by area, meanwhile fuel stations by points, because the different size and number may impact the outcome.
Starting with fuel station, by using Q-GIS and counting running script, then return the number of points in each grid. The results showed 75% of correlation between fuel stations and charging points, therefore a strong one. The same approach with parking lots indicate a moderate to strong correlation of 63%. The population density grid has a 5 km scale and refers to 2015 data. The population density raster with the number of charging points show a correlation of 62%.
Even though, there are several factors influencing on whether and how to deploy charging infrastructure across a country, a moderate positive correlation considering fuel station, parking lots, and population density is obtained.

[8]For population density the Eurostat database has been utilized [94]

4.2.2.4 The nearest neighbour distance between chargers and availability

The fourth indicator is the nearest neighbour distance and availability[9] as it can represent the distance between points on the network or between each other. Indeed, it is important that charging points are located within an acceptable distance which secure vehicles the necessary recharge. In this case, the nearest neighbour (NN) distance analysis has been implemented, in which only the dataset network has been utilized and not the whole country.
This analysis is done per road segment, according to OpenStreetMap classification, as listed in Table 4.1. It gives the NN mean charger and connector distance in respectively column 2 and 3. As expected is higher for primary roads and lower for residential ones. The NN distance is considered to be zero for 2 connectors of the same charging points.

Table 4.1: Average nearest neighbor distances to connector and to column

Road Segment	Mean NN Charg. Dist. (m)	Mean NN Conn. Dist. (m)	Min. (m) Distance	Max (m) Distance	N. of Charg.-Conn.	Availability (%)
Primary	15,565	9462	3.1	52.9	40-67	94.3
Residential	1838	1101	1.78	21.9	1203-1974	87.8
Secondary	6359	3985	1.73	30.6	175-279	91.3
Tertiary	4872	2850	6.99	27.4	258-451	90.5
Total	1603	968	1.73	12.1	1683-2785	88.8

Consequently the same trend is observable for minimum and maximum distance. The availability ratio among the whole set of charging points is almost 90%. By combining these results with those obtained from the idle time of 4.2.1, this "wasted" time should be treated carefully in order to avoid the over installation of charging points and increase the availability parameter.

4.2.2.5 The use time ratio

The use time ratio represents the ratio between the total time in which charging stations are occupied by a vehicle (connected time) and the number of hours of the

[9] It is defined as 1 minus the use time ratio which is expressed in equation 4.5

observation period multiplied by the number of connectors, thus as follows:

$$UsetimeRatio = \frac{ChargeTime + IdleTime}{T_{observation} \times connectors} \tag{4.5}$$

This indicator shows that those charging stations installed in primary and secondary roads are less exploited. Indeed, for residential this indicator is 12.14%, meanwhile for primary reaches only 5.7%. By analysing this indicator between weekdays and weekend there is a slightly lower utilization during weekends.

4.2.2.6 Energy use ratio

The energy use ratio is the sum of all the energy supplied by each charger divided by the energy that it could have been provided at its nominal power rate (max 12 kW in our dataset) over the same period of time $T_{\text{observation}}$. It is calculated as follow:

$$EnergyUse = \frac{EnergySum}{connectors \times T_{observation} \times meanMaxPower} \tag{4.6}$$

where $T_{\text{observation}}$ is the number of hours for the 2 years considered (2014 and 2015). This value gives interesting results, indeed the total infrastructure capacity provides only 3.56% of its total capability. This clearly emphasizes that the infrastructure are under-utilized, partially explicable by the high idle time occurring for each charging points.

4.2.2.7 The total service ratio

This is the classic ratio which describes the amount of cars per chargers. Rather than comparing merely the chargers, it is more accurate to divide the number of vehicles per number of chargers. In our dataset this shifts the ratio from 25.19 vehicles per column to 15.22 vehicles per connector.

4.2.2.8 Carbon intensity

The last indicator derived from the dataset to evaluate the charging infrastructure of a given country is the carbon intensity. This formula gives the global warming potential from the life cycle analysis of the materials used in the chargers per total energy flowing in CO_{2eq}/MJ. It can be calculated as follows:

$$CarbonIntensity = \frac{2 \times 187.04 \times 10^3 \times \%Nch_{SR} \times SR_{Total}}{Avrcar_{MJ/year} \times \%N_{ch} \times LTime_{Nch}} \tag{4.7}$$

where 187.04 gCO_2/MJ is the carbon intensity of the normal charger obtained in [95], the $\%N_{chSR}$ is the percentage of normal chargers, SR_{Total} is the total number of chargers per vehicle, $Avrcar_{MJ/year}$ is the average energy consumed by a car per year, $\%N_{ch}$ is the percentage of charge actually being performed in this type of charger, and $LTime_{Nch}$ is the lifetime period (10 years). The outcome, after introducing the uncertainty statistical distribution, shows an average indicator carbon intensity of 4.44g $CO_{2eq/MJ}$ with a standard deviation of 0.87.

4.2.3 Considerations from the two articles

Two main articles [77] and [78] have been published related to the EVs dataset provided by ElaadNL. In article [77] a statistical characterization of charging stations has been conducted in which a general description of the database is presented. Furthermore, a multi-modal probability distributions is provided to allow users to reproduce plug-in, plug-out and charging profile with a timestep of 1 minute for weekdays and weekend. These functions are reproduced through a BMM function which serves as a standard real demand profile. Indeed, it may reduce assumptions concerning EVs drivers behaviour. Finally, a discussion on the potential V2G services, based on the idle time, is described.

In the second work [78] a different approach is applied on the dataset. The objective, in this latter, is to develop a methodology to analyse EV charging infrastructure performances and features. In order to do so, 8 indicators were developed and derived from the EVs transactions: energy demand, energy use intensity, chargers intensity distribution, nearest neighbor distance and availability, use time ratio, energy use ratio, total service ratio, and carbon intensity. A fair comparison can be done in relative terms to other datasets due to the lack of real data available. For this reason, these works may help to understand better the role of EVs in the future as well as the adverse and potential benefit that EVs may provoke on the network grid.

4.3 Network Computation Request: The Hague case study

In this section a concrete example of a network computation request in a neighbourhood of The Hague in the Netherlands is provided. This area has been selected because it has a high level of charging stations for EVs, and because the idea is to simulate an example in which a company is willing to expand its brand by installing new charging stations in this area. Several issues will be faced by the company, especially while interacting with the DSO due to the different objectives. In this case, we want to emphasize the network reinforcement required due to the fact that the charging station company is willing to install EVSE in a area of the network which is not ready to host them. Therefore, an expansion of the MV lines is needed and cost evaluation will be calculated. This situation may occur because the company wants to install independently of network constraints but more based on advertising reason, higher utilization ratio expectation, etc. The idea in this exercise is to assess the increased cost of extending the MV layout due to the company's needs. This will help to reflect on how intricate is the development of the grid due to the advent of EVs. Concerning the demand profile, the ElaadNL database is utilized, explained in Chapter 4, which contains the geo-reference location of the charging stations across the Netherlands.

This latter dataset represents in 2019 only 7% of all charging stations, therefore two more maps have been added: EVway [96] and Plugsurging [97], in order to have a more complete picture reaching a global coverage of approximately 95%[10]. In addition, EVway and Plugsurfing website maps contain detailed information regarding the number of charging columns per station, the power, the type of connector available and price per minute/charge.

In our specific case, some of the buses will be endowed with charging stations. This will be done by overlapping the two maps: the distribution network grid and the EVs charging stations one. The composition of charging stations already available

[10]This number has been estimated by comparing EAFO, Plugsurfing and EVway website

is reported in Table 4.2. There are 38 charging columns all equipped with the connector Type2, and up to 6 different output power are present, going from 3.7 kW to 22 kW. This wide range of charging power is inevitably affecting the role of DSOs in designing the network and choosing the most adequate cable. As expected, the lowest power are installed in location close to households, meanwhile more powerful charging columns are installed close to commercial and industrial areas, such as firms, parking and shopping malls. Besides the EV drivers needs, this occurs because the network grid is designed with more powerful cables closer to industrial and commercial areas rather than residential ones.

Table 4.2: Charging station description in the network grid

Charging Stations [No]	Power [kW]	Location
3	22	Industry
2	14	Commercial
22	11	Commercial/Residential
8	7	Residential
1	5	Residential
2	3.7	Residential

4.3.1 DiNeMo platform step-by-step to simulate EVSE network reinforcement

In this case study we will go step by step to illustrate how powerful is DiNeMo in designing from scratch network grids. The dashboard page of DiNeMo is presented in Figure 3.7, and it is composed of 3 main blocks: the network computation request (NCR), the city project and the information area located on the right. The information section shows the last 5 queued requests and the pending notification to join a city project. The first step is to click on *Add New Network Computation Request* and in the new page is necessary to enter a NCR title to the project, which for instance in this case could be *The Hague case study - Charging Station*. Once the NCR title name has been saved we will be redirected to the user homepage where we are able to overview our processed, queued, draft or failed computation requests. The completion phase will now indicate that we reached 25% of the whole process. The next step is to click on the icon showing the world in the completion box, which allows to select the geographical area of interest. Then we type The Hague and we move through OpenStreetMap (within DiNeMo) to select the specific neighbourhood that we are willing to study. The zoom level is blocked to 16, which corresponds to an area of about 1.5 km^2. The image is captured in proximity to the HV/MV substation named Wateringen, located in the south-west part of The Hague. The technical features, expressly of the transformer capacity and voltage level, are available on the Dutch TSO (Tennet) website [98] which provides also a grid map of all the HV/MV substations. After positioning on the area of interest, it is possible to place the HV/MV substation within the map (otherwise DiNeMo will automatically locate it in the centre of the map). The map will be saved and the user redirected to the user's homepage.

(a) (b)

Figure 4.11: OpenStreetMap image of The Hague in (a) and building detection in (b)

For confidentiality reason hereby are reported only those data which should be typed by the user and visible online: power factor is set to 0.95, LV to 0.4 kV, MV to 20 kV, the population density and number of consumers information can be found A new icon (edit parameter) will appear and the completion shifted to 50%. Some of the input parameters, not visible from the user, are inserted according to the results of DSO observatory survey explained in Chapter 2.3.on the website

[99] which is the *Centraal Bureau voor de Statistiek*. The specific area close to the Wateringen trafo has a population density of 1845 consumers per km^2, meanwhile the building composition is as follows: 17.5% for 1 person, 13.2% for 2 persons, 59.3% for 3 persons per building and 10% for more than 4 people in a building. Then the completion bar reaches 75%. The final step consists of clicking on the icon edit settings and select which output files we are willing to keep and download. Figure 4.11 shows the OpenStreetMap image of the area selected in The Hague in (a) and the results of the building detection, derived from the Python code shown in Appendix C in (b). The building detection program may be subject to errors, because it strictly depends on the data inserted by the OpenStreetMap editor of the specific zone.

By having a deeper comparison between the input image on the left, and the building image on the right some differences are visible. For instance, some buildings are plotted as alone, others are subject to a convex procedure, and few are identified based on the landuse (tag available in OSM). This specific tag, as previously mentioned depends on the level of layers available in the map. Indeed, this tag gives information on the type of land, such as residential, commercial, agriculture, industrial etc, which may be relevant in applying a different demand profile in future releases.

(a) (b)

Figure 4.12: Building contour detected map in (a) and placement of connected customers in (b)

Therefore, in those buildings where the landuse tag is available the whole block is detected rather than multiple tiny buildings. This simplify DiNeMo core algorithm when designing the grid, indeed ”less” buildings, thus a lower probability for cables to cross roads or even buildings in some cases. Furthermore, on the other hand, the detection of tiny buildings is another possible source of error because of the relatively small size of the buildings (visible in the north-east part of the The Hague image in (b)). Indeed, this will incur in an area of not connected customers. This phenomena is visible in Figure 4.12 showing in (a) the the black and white image of the buildings identified by the core module. On the right side of Figure 4.12 the contour of buildings is drawn with several small dots. This Figure helps to clarify the error which was mentioned earlier concerning the small size of buildings. Indeed, the software was not able to identify and assign clients to those small houses. In this phase DiNeMo is firstly understanding which are the buildings contour, and secondly defining the number of clients per building based on the density and percentage defined by the user. The connected customers are then highlighted with black dots on the image illustrated on the right side.

4.3.2 DiNeMo NCR result in The Hague

The result of the NCR, thus the design of the distribution network grid, is reported in Figure 4.13. The HV/MV substation is indicated by the green triangle shape in the bottom-right of the image. The substation reduces the voltage level from 150 kV to 20 kV. Within the network there are 34 MV/LV substations that are pictured as blue dots, meanwhile the MV connected customers are highlighted with a big black dots.
The LV connected customers are indicated with a smaller black dot, and are linked through the LV feeders (black lines). The total amount of consumers defined by DiNeMo is 1239, of which 2% are MV consumers, and a total length cable of 3.6 km, of which 30% is of medium voltage lines. The DiNeMo output, thus the designing of a large scale geo-referenced representative distribution network, is unique because it allows to *play* with each bus and define if each consumers can install an EV charging column or for instance if it is already equipped or not with PV panels.

Figure 4.13: The Hague Network Computation Request Result

Moreover, the geo-reference positioning of these buses make it a powerful tool to test real case cities such as in this case for a neighbourhood in The Hague. In addition to the already mentioned data, the DiNeMo platform provides information on the switching devices installed in the network. In our specific case, it is equipped with a 10% of consumers having fuses, 2 breakers and fault detectors plus 27 switchers. The total installed power at LV and MV level is respectively 28.3 MW and 2.5 MW distributed across 1238 supply points.

4.3.2.1 Network reinforcement costs

Figure 4.14 shows the 24 charging stations (38 charging points). The different colors indicate those columns which are available (green), unknown status (grey) and offline (red).

To visualize the charging stations already presented, we overlapped the network image layer and the charging station one to understand which area has been already covered by the network built by DiNeMo in terms of MV cables (which are the one necessary to install Mode 2 charging columns). We can observe that even without superimposing the constraints of the charging columns we already have a good coverage situation in terms of MV network as visible in Figure 4.15 compared to the current situation in Figure 4.14. The main idea was to expand the EVSE coverage and indeed except for 8 charging columns (highlighted with cyan diamond marker) out of 24, the remaining are already close to a MV cables which guarantee the adequate power supply. In a future DiNeMo release we will add the constraints based on the geo-referenced position of charging stations to build the MV network also based on EVSE already installed.

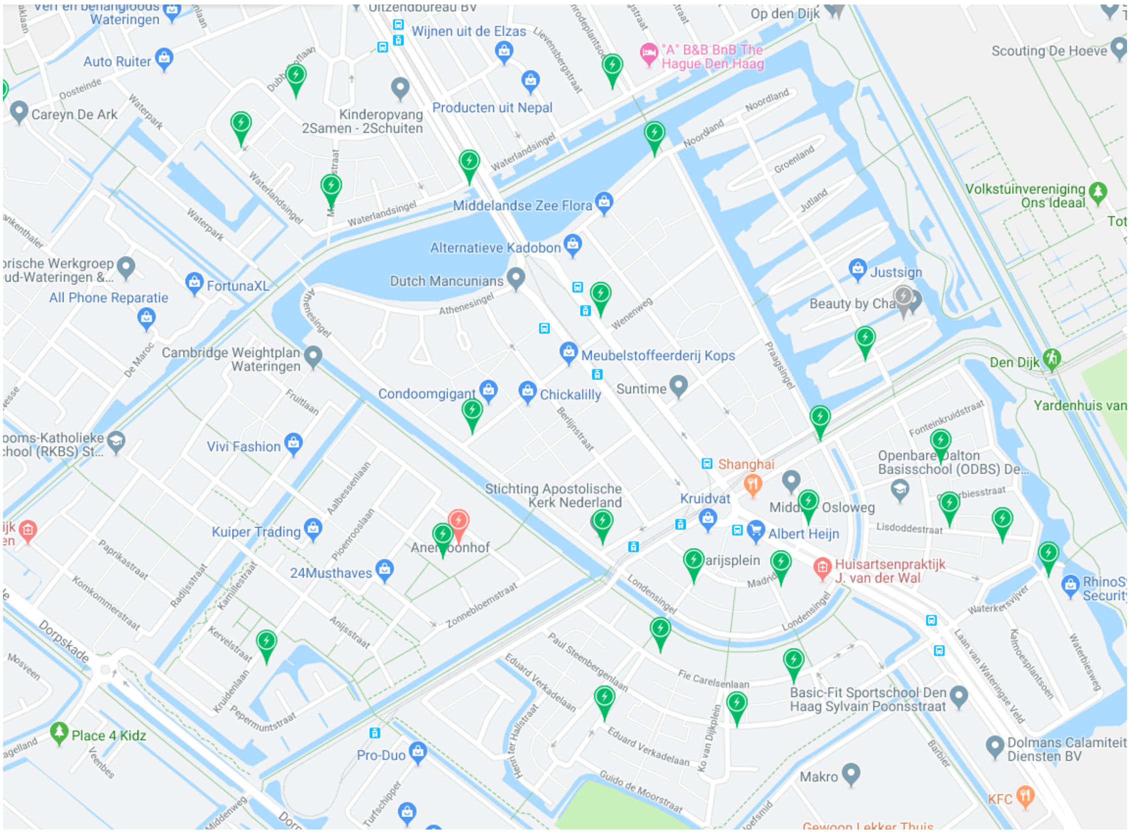


Figure 4.14: Charging Stations map in a neighbourhood in the Hague

Figure 4.15 reproduces the one shown in 4.13 in which charging columns have been superimposed. The dark thin line shows the LV lines, the MV thicker line are plotted in red, and the MV/LV substation with a green squared marker.

Figure 4.15: DiNeMo network grid

The HV/MV substation is plotted with an orange triangle visible in the bottom right corner of the network. Charging stations are designed with two different colors and shape.

Those already close to a MV lines (necessary for the power required by these charging stations) and those who need an extra investment to extend the MV lines network. Therefore is assumed in this exercise that the EVSE maked with a cyan diamond are the new charging stations that the company owning them is willing to install. This situation may occur often in the feature, thus the interaction with local DSO is fundamental to redesign and minimize the investment costs to fulfill the charging stations company needs.

Figure 4.16 shows the network expansion required where the new MV lines are colored in blue. The extra cables have a total length of 368 meters which corresponds to almost 10% increase. Assuming that no new MV/LV substation should be installed, the total cost of the new MV lines is approximately from 16,500 € to 21,000 € for underground installation, meanwhile from 11,700 € to 13,600 € for overhead one.

Figure 4.16: DiNeMo network grid expansion

4.4 Chapter summary and main contribution

The chapter is centralized on electric vehicles and charging infrastructures. It summarizes the two articles published, and presents a case study on the network reinforcement costs necessary to allocate new charging infrastructure system in an urban area. The chapter starts by giving an overview of the state of the art of power-transport sectors interaction. It remarks that EVs fleet growth has kept an increasing rate of around 60% in the last 4 years worldwide, and a similar prosperity is observed for EVSE. In addition, the potential EVs flexibility through Vehicle-to-Everything concept is illustrated, showing that distribution system operator may exploit EVs for voltage control and local congestion.

The first article aims at creating a statistical model capable of reproducing plug-in, plug-out and energy demand profiles of EVs, which help to fill a gap observed in literature. The dataset of 2900 charging points, in the year 2015, registered 400'000 recharges. The most interesting outcomes are listed hereby: the charges during weekdays are an order of magnitude higher than weekends; the peak demand is observed between 6:00 a.m. and 8:00 a.m. in the morning and between 4:00 p.m. and 6:00 p.m.; 85% of the activities occurs before 7:00 p.m.; the multi-modal probability distributions built for plug-in, plug-out, charge and idle time show a good fit through the Kolmogorov-Smirnov test; the night energy demand is negligible. Significant idle time is registered, thus flexibility which may be utilized by DSOs.

In the second article a different perspective is adpoted on the same dataset, in which the objective is to develop a methodology to compare EV charging performances and features. Up to eight indicators are suggested. The energy demand from EVs shows that only 10% of energy is supplied by public EVSE yearly. The energy use intensity and charger's intensity distribution provides useful information on the potential accelerated degradation of the networks. In this specific case, six main area are more densely populated. In addition, the correlation with existing infrastructures indicates 75% to fuel stations, 63% to parking lots, and 62% to population density. The nearest neighbour distance indicator reveals a high availability showing that chargers are installed at acceptable distance across the network. The time and energy use ratio gives insight on how much the infrastructures is exploited. Finally, the carbon intensity evaluate the global warming potential which looks way lower if compared to a normal charger as stated in [95] .

The case study simulates the network reinforcement necessary to host an increased installation of EVSE. At the same time the case study presents a new use of DiNeMo platform. After designing from scratch the network grid with DiNeMo, 8 new fast charging infrastructures are installed close to point of interests. The extra MV

lines and cables have a total cost increase ranging in total from 28,200 € to 34,600. These costs are based on a second survey to DSOs which focused merely on lines, cable and substations technical features and costs. It is interesting to understand how these costs will be shared between consumers and stakeholders involved.
My contribution in this chapter starts by interacting with ElaadNL researchers to obtain the dataset and to deepen the data knowledge. The bigdata has been clean, cluster, and manage in R and Python. In the first article I performed all the statistical analysis of the database, such as PDF, CDF, idle charge time, and GIS distribution of the EVSE across the Netherlands, but only partially those related to the BMM sections. In the second article, I have worked in team to design the eight indicators and I focused on the calculation of the energy deman from EVs, the user time and energy ratios. Concerning the case study, it has been entirely designed, structured and calculated by me. In addition, I have created the new survey to DSOs in order to collect the technical feature and costs of lines, cables and substations.

Chapter 5

DiNeMo - DSOs Validation Methodology

This chapter presents the validation methodology for the distribution network grid designed by DiNeMo. With the help of the Croatian DSO the validation on urban and semiurban area of Varaždin is performed. It is based on article [100].

5.1 Literature review on statistical approaches to validate modelled networks

The scarcity of valuable grid data due mainly to confidential nature leads to the creation of synthetic representative networks which can serve as a case study when planning and analysing distribution networks. In this context, the main issue with the creation of synthetic networks lies in the validation process of them. This key aspect is necessary to prove its realistic representation of the specific area of interest. Different approaches have been found in literature focusing on the creation realistic reference networks and its validation methodology. Among the multiple papers available hereby the most relevant one are reported.

The tool Smart Grid Metric described in [101, 102] was utilized to demonstrate the impact of distributed power generation on synthetic MV test grid. Due to the insufficient data available, the rural network grids were developed differently by using statistics report for load density and Google Earth. Concerning the load density, in the first network they adopted a low population for a large area and a high population for a small area while considering that no load is located outside the residential area.

In the work of Petretto et al. in [103] they also investigate the impact of DER penetration within a MV network with different areas: urban, rural and industrial. The network has been built by combining different common representative feeders. In this research an economic analysis has been conducted where ancillary services were provided in three markets. The flexibility bids is offered directly from an aggregator, a DSO or a DSO coupled with DER.

In order to generate representative distribution networks a statistical tool in [104] has been developed. In this tool firstly, several metrics have been investigated after collecting technical and geographical grid data. Secondly, the grid analysis goal needed to be identified to successfully determine the best method for the generation of the network. The last step consists of the validation of the generated networks with the real one by comparing the performance.

Another interesting study is proposed by [105] in which they used a metric based validation process to compare that the criteria adopted to design actual power system data with public test cases. The metrics utilized in the article are categorized in two groups: metrics of system proportions and the one related to the networks. The first category includes the number of buses per substation, voltage levels, capacity of generators, load bus, etc. The second category describes lines topology and parameters, and the same for transformer characteristics.

To generate synthetic network and validate the metrics from real power system data a methodology is proposed in the work of Birchfield et al. [106]. The compared metrics should satisfy several parameters such as: line topology, geographic intersection, connectivity, Delaunay triangulation overlap, AC power flow convergence and minimum spanning tree of the substations.

The dynamic response and transient stability results of the generated network compared with the real system network is analysed in [107]. In this study the large synthetic network is composed of 2000 buses.

The Network Imitating Method Based on Learning (NIMBLE) was used in [108] to generate a synthetic network. This latter, it has been used to test the resistance to failures in the grid where the importance of bus location and lines was emphasized. In the work of [109] the similarity of optimal power flow in real networks and synthetic grids is analysed. The topology, generation and load data of the synthetic grids have been modeled based on a decomposing techniques: Alternating Direction Method of Multipliers and Evolutionary Algorithm. In the post-processing phase possible modification of the grid are allowed by for instance introducing shunt element or generator contingency. This will increase the number of power flow scenarios.

The construction of synthetic networks based on improving network reliability while minimizing the cost of supplying electricity is proposed in [110]. Furthermore, the quality of supply is also taken into account by using topological metrics such as: shortest-path length, betweenness centrality and degree distribution and clustering coefficient.

The reference networks in [111] were built based on a greenfield and expansion-planning approaches using an heuristic planning algorithms and GIS. In this study the aimed at demonstrating the impact of distributed generation on distribution network cost. Within cities and towns 5 different consumers are classified and utilized. Networks at MV and LV level is built radially and takes into account geographical constraints.

On two large scale distribution reference networks the impact of different levels of EVs penetration is tested in [112]. The paper's outcomes show the increase of energy losses and higher investment costs in those networks where there is a higher EVs penetration, thus highly densely populated areas.

The reference network built in [113] considered in the modeling phase 4 different layers structures: the logical, the topological, the electrical, and the quality of supply ones. These layers help in designing the graph containing nodes and branches; to generate the street map and give information for the geospatial coordinates elements in the network; the load, transformer, lines and cables; and finally the system reliability information, such as protection devices, corrective and preventive maintenance actions, etc.

From the literature it is clear that no universal approaches have been applied to statistically validate neither reference networks input/output either the power flow results. This is mainly attributed to the different level of network data available by the user which may affect the quality of the network itself. Therefore, based on this studies and with the Survey data collected and explained in section 2, the 10 indicators have been developed and described in 2.5. These indicators will be utilized to statistically compare the results of DiNeMo with those obtained from real networks.

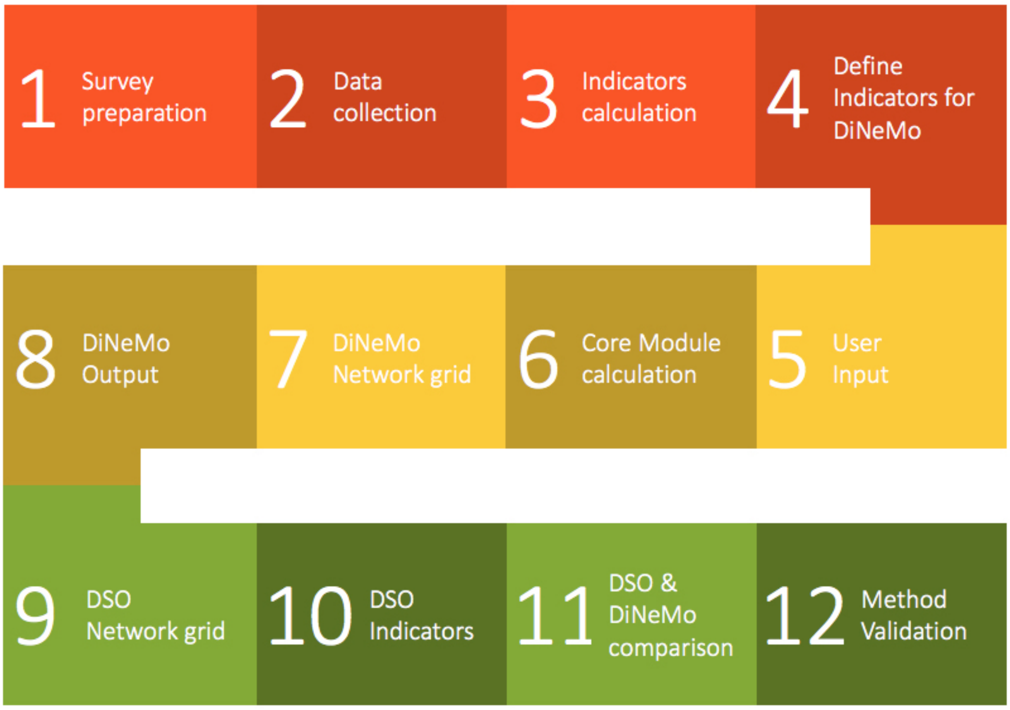


Figure 5.1: DiNeMo validation methodology structure

A flow diagram of whole steps necessary for the validation of the DiNeMo output is pictured in Figure 5.1. The reddish steps represent survey phase in which data the survey questions are defined, the data area collected, the indicators and parameters are calculated, and finally the 10 indicators are defined. Those 10 indicators (listed in Table 5.1, such as the number LV consumers per MV consumers serve as a part of the input necessary to perform a network computation request in DiNeMo. They are utilized as a constraints in an iterative process, as visible in Figure 3.4, until the difference between the network indicators and those of the DSOs is within the margin set in the core module of DiNeMo. On top of this, there are two more layers of input; the one inserted by the user like the number of consumers in the area, the MV voltage level, the position of the substation; and the one of the catalog equipment which gives technical information concerning the lines, cables and substations based on the country. Then the core module process the distribution network grid of interest. The DiNeMo outputs are obtained, in several formats such as excel, MATLAB and shapefile, and from those it is possible to calculate the 10 indicators. The one produced by DiNeMo are then compared with DSO one in order to validate the network grid designed by the platform.

5.2 The importance of validating reference networks

The importance of the validation lies in the increased stakeholder acceptance, which are more prone to utilize these networks and test real cases scenarios. Beside the 10 indicators which will be presented and compared in the next section, here the idea is to provide a more general view on the criteria selected for the validation. These criteria can be grouped in the following aspects:

- realistic physical layout
- realistic system size
- realistic topology and components
- representative voltage profiles
- realistic reconfiguration options
- comprehensive load specification
- computational requirements

The physical layout of the designed network should resemble as much as possible a real geographical area in order to increase stakeholder acceptance, and in particular DSOs and researchers. Thus is key that the network matches the demographics and topology of the area of interest. This will also guarantee the possibility of implementing future communication layers. To validate this criterion it is necessary to statistically compare the geographic coordinates of buses, equipment, feeders and substations. The second criterion listed is the realistic system size, indeed it is fundamental to have a network size coherent with the real one, at least in terms of scalability. This size "*check*" would also help the utilization of advanced algorithms for more complex networks. In this specific case the validation requires the comparison between DSOs indicators such as the number of MV/LV substation per HV/MV, with the one calculated by DiNeMo.

Another key aspect in the validation of the reference networks produced in DiNeMo is the reasonable similarity in terms of topology and components adopted. For this reason, a second survey is launched mainly focusing on lines, cables and substation technical characteristics. Indeed, it is key to ensure a realistic power flow results, which is able to reproduce feasible voltage drops as well as electrical losses. To obtain this result, it is necessary to have a proper number of transformer within the network with adequate technical features. The same concept should be extend to LV and MV lines.

The representative voltage profile criteria is highly important for distribution system operations. Even if, aware that until now DSOs are performing power flow analysis merely at MV level in their network, it is evident that due to the introduction of new stakeholders this aspect may be relevant in the future even at LV level. Therefore volt/var control, DERs and analysis of reactive power is becoming more and more important also at distribution level. This element can be validated by comparing the voltage profiles of DiNeMo consumers, both LV and MV, with real one of the same area.

To obtain a realistic reconfiguration options it is crucial to implement in the network the correct count of switches, re-closers, fuses and circuit breakers. Thus to validate these parameters it is necessary to perform a statistical comparison, plus the help of experts to understand the correctness of the network configuration. On top of all these criteria a comprehensive load specification and computational requirements should also be considered. In fact, the power flow quality and solution times should not threaten the use of several scenarios for advance cases. It is therefore necessary that the solution is reached in reasonable time and that converge while having no violations.

The Figure 1.1 describes the whole validation process in the creation of the representative reference networks, of a given area of interest. The process is subdivided in 3 main phases: phase 1 is related to the data collection, phase 2 to the creation of the reference networks and phase 3 focuses explicitly on the validation process.
The first phase lasted approximately 1-2 years of work, excluding the first DSO Observatory survey conducted in 2014. An extensive literature review has been performed to understand the status of the available distribution network grids (as described in Chapter 3). The lack of geo-referenced network layout and the limited information shared by European DSO has created a huge gap between researcher's need and real case studies. Indeed, the majority of the studies found in literature are limited to IEEE layout and few networks directly provided by DSOs to research groups. To overcome the limited shared number of proven and validated distribution network a second version of the DSO survey is conducted more oriented on the technical features of those DSOs subject to unbundling. After the collection of data, these data have been clustered according to several metrics and 36 indicators were developed. These indicators are used to design the network layout and its configuration. Furthermore, they describe the difference among DSOs in Europe and how they manage loads and EVSE.
The second phase of the validation process consists mainly of the creation of the reference networks which should be able to reproduce a realistic physical layout, system size, topology and components implemented. For this reason, this phase aimed, with the help of nical partner Comillas Universidad [114] who developed the core module of DiNeMo, at understanding the key aspects in the design of distribution network grids.
The physical and structural attributes describe all the components, such as line length, number of MV/LV per HV/MV, etc. associated with a distribution network grid. To achieve an even more realistic result a small survey is conducted focusing on lines, cables and substations characteristics. The operational attributes represent the line flow and bus voltages which are key when researchers are willing to perform power flow or optimal power flow analysis in the distribution networks. The last box of phase 2 is the reference network creation which represents the DiNeMo platform.

The third phase titled validation process is composed of 2 main elements: the expert validation and, the statistical validation. A subset of the 36 indicators, described and presented in Table 2.5, are utilized for the statistical validation. The indicators are listed hereby:

- The number of LV consumers per MV consumers is the ratio measuring the level of commercial and industrial consumers supplied by the DSO. Extremely different values of this indicator occur among DSOs result. This is due to the diverse size and population supplied by each DSO, as well as type of supplied area (urban, semi-urban or rural areas).

- The LV circuit length per LV consumer describes the location and distance between consumers, as well as their distribution in the observed area. Higher values of the indicator refer to the big areas where population density is very small and consumers are more spread, while in small areas, such as city centers with a big population, the value is smaller.

- The LV underground ratio is calculated as the ratio between the length of LV underground cables and total length of LV network (considering both underground cables and overhead lines). Different values of LV underground ratio correspond to rural (less than 30%), semi-urban (30%-80%) and urban areas (more than 80%).

- The number of LV consumers per MV/LV substation depends on the spread of consumers in the supplied area giving an idea of the size of low voltage network below each MV/LV substation. We distinguish higher ratio in urban area with higher density and lower ratio in rural area where consumers are more dispersed.

- The capacity of MV/LV substation per LV consumer is the ratio between total installed capacity of MV/LV substation and the total number of LV consumers considering peak average power of consumers, energy efficiency of the devices and simultaneity factor depending on the size of the household and number of people per household. Therefore, it provides an indication of the power installed below each MV/LV substation.

- MV circuit length per MV supply point is the ratio between total length of MV network and number of MV supply points, considering both MV consumers and MV/LV substations. This indicator is important for understanding the capacity for installing future distributed generation.

- The MV underground ratio is the ratio between MV underground cable length and total length of MV network, counting both underground cables and overhead lines. The value is lower for rural and higher for urban areas.

- Number of MV supply points per HV/MV substation is the total number of MV supply points, both MV consumers and MV/LV substations, divided by the number of HV/MV substations in the observed area. This indicator is of significant importance because it highlights how industrialized or commercial the area supplied by the DSO is.

- Typical transformation capacity of MV/LV secondary substations in rural areas is usually lower comparing to urban areas. This difference occurs because of smaller electricity density in rural areas, as well as bigger distance between consumers.

The mean, median, minimum and maximum values, calculated at European level from the data collected in the DSO Observatory survey are plotted in Table 5.1.

Table 5.1: European DSOs indicators values

Indicator	Mean	Median	Min	Max
Number of LV consumers per MV consumers	671	401	22	1946
Number of LV consumers per MV consumers	0.03	0.025	0.012	0.16
LV underground ratio (%)	66	75	11	99
Number of LV consumer per MV/LV substation	86	76	17	230
MV/LV substation capacity per LV consumer (kVA/LV consumer)	4.76	3.88	2.1	13
MV circuit length per MV supply point (km/MV supply point)	1.06	1.04	0.54	1.77
MV underground ratio (%)	59	61	10	100
Number of MV supply points per HV/MV substation	155	127	33	460

On top of the statistical validation the role of expert (DSOs, researchers, etc.) it is crucial to receive feedback in the design of distribution networks. For this reason, a collaboration project with several European DSOs aiming at validating urban distribution grids developed through the DiNeMo platform is launched.

5.3 Real case scenario

It is extremely important to validate the representative network modeled built with DiNeMo in order to demonstrate its reliability and accuracy for the output parameters, thus that the network of observed area is a fair representation of real situation. Thanks to the collaboration with the Croatian DSO, HEP – Operator distribucijskog sustava d.o.o., a statistical validation of the networks has been performed. Indeed, the DSO provided the 10 indicators for a small urban area in Croatia, and in particular the city of Varaždin. In this validation process two case studies for the city of Varaždin have been distinguish: the city center (urban case) and an industrial area located in the east side of the center (semi-urban case).
The validation is done by statistically comparing the 10 indicators described in chapter 2 as being the most valuable ones for the construction of a representative network.

5.3.1 Validation on Varaždin urban area

As previously mentioned, the first case study focuses at the urban level. Indeed, Figure 5.2 taken from OpenStreetMap shows the city center of Varaždin, and the red circle located in the bottom right part of the image indicates the HV/MV substation. The grey cables are the transmission lines which are heading from the TS Varaždin substation to another one located in a more peripheral area of Varaždin. The substation TS Varaždin has three different transformer levels: 110/35 kV, 110/20 and 110/10 kV.
Until now, DiNeMo is capable of designing the grid downstream one single HV/MV substation, therefore it has been selected a 110 kV/10 kV transformer with the capacity of supplying up to 31.5 MVA. The city center is composed of few main roads, and according to [97], up to 15 EV public charging stations have been installed, which are equipped with different types of connectors (combo, type2 and chademo).

Moreover, there are different EVSE power levels ranging from 11 kW, 22 kW to 50 kW. In the future, charging stations will be most likely installed close to significant point of interest such as supermarkets, cinemas, shop areas, etc. Indeed, the observed area has several potential installation points due to the more than 10 cafes and restaurants, 7 banks, 3 schools, 3 university departments and a hospital.
Moreover, there are 20 potential parking lots which can be transformed and utilized as a virtual vehicle-to-grid service to support, for instance, the network during the hours of peak demand. For this reason, the aim of this simulation is to test the network reliability under a deeper penetration of charging stations which are installed in the above mentioned point of interests.

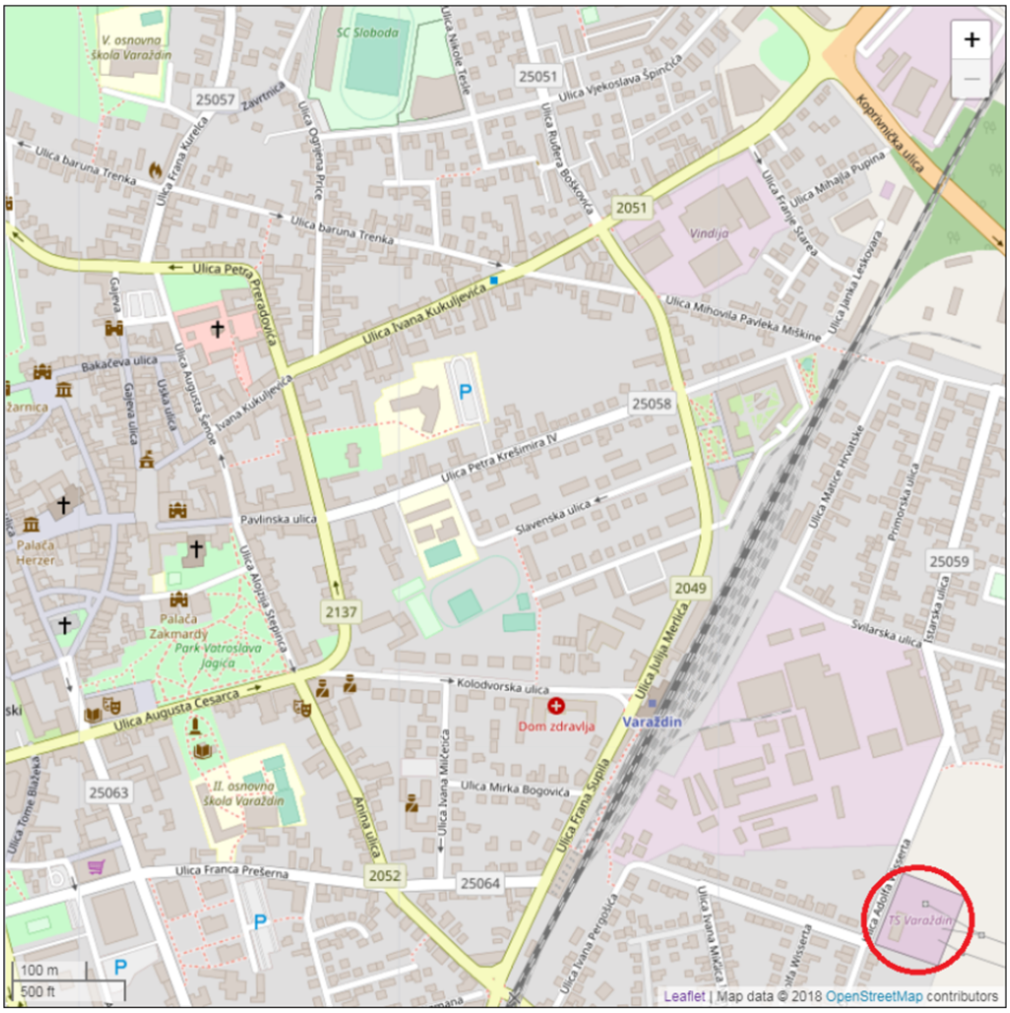


Figure 5.2: Varaždin city center OpenStreetMap image

Once the input parameters have been inserted, as described in 3.5, DiNeMo will process the network computation request and several outputs are available for the users. One of these outputs is the network image shown in Figure 5.3. Like for the image in Figure 5.2 the HV/MV substation is located in the bottom right of the network designed by DiNeMo and it is highlighted with a green triangle. On the same image, the red lines represent the overhead lines and underground cables at MV level, meanwhile the LV feeders are represented with black color.

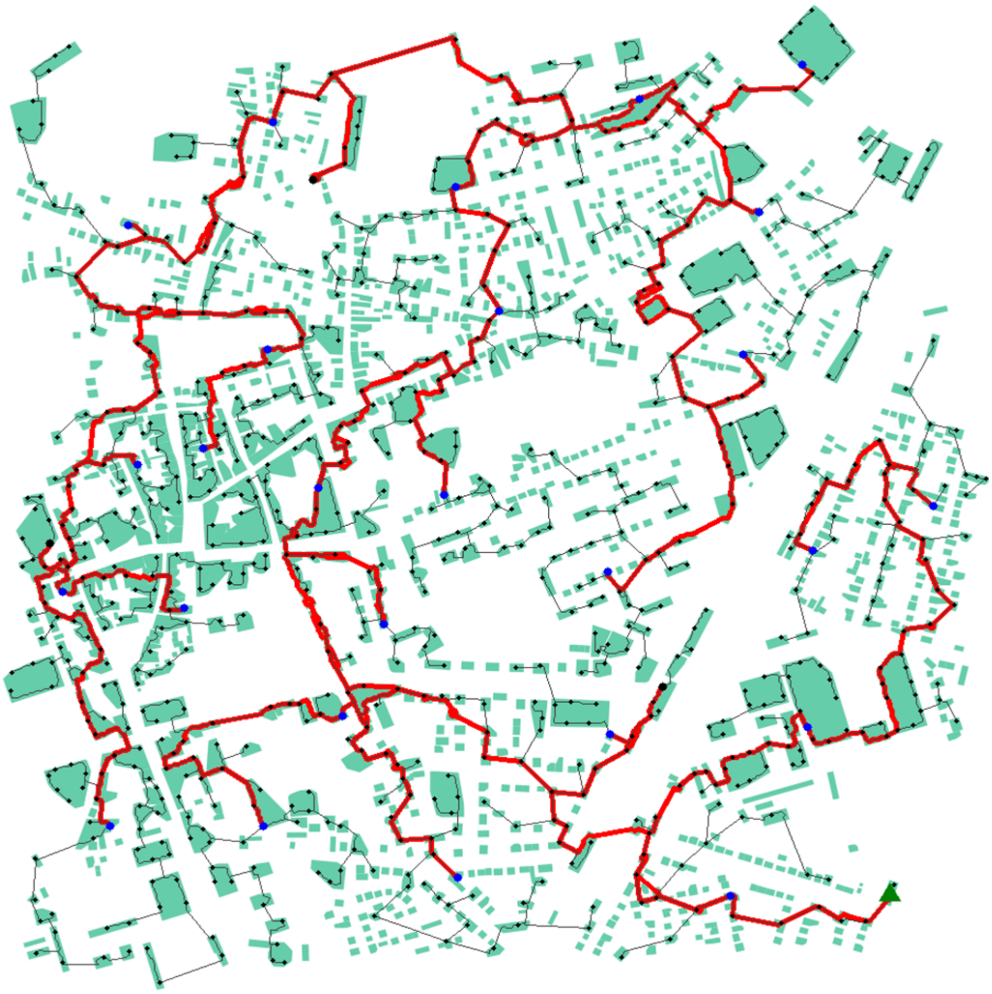


Figure 5.3: Network image of Varaždin city center in DiNeMo

The total circuit length is 90.2 km, where 57.6 km are LV feeders which have an average length of 51 meters. The underground LV feeders represent 39% of all the LV power lines, and have a length which goes from few meters to almost 550 meters. As expected, the numbers concerning the MV network are very different; indeed the average length of MV lines is an order of magnitude higher than the LV ones, and reached a median value of 455 meters. The 29 MV/LV substations are plotted with blue solid circles, of which 50% have a capacity of 400 kVA. They transform the voltage from 10 kV to 0.4 kV. The connected consumers, colored in black and divided per voltage level (square shape for LV and bigger black circles for MV ones), are located on the perimeter of each building. This network designed by DiNeMo is equipped with 45 switches, 165 fuses devices and 6 circuit breakers. Additionally, emerges from Figure 5.3 that the number of lines crossing the roads is minimized. The validation methodology consists of comparing the real network indicators, provided by the DSO, and those calculated from the designed network of DiNeMo. Table 5.2 shows interesting results concerning indicators comparison. Basically two networks were created with DiNeMo, where firstly were inserted the indicators of the operating DSO in Varaždin, and secondly those of the national Croatian average data (taken from the DSOs Observatory database). The Table 5.2 illustrates in column one the indicators, in the second column, the indicators based on the real Varaždin network operated by the DSO, in the third one the results of the network computation request designed by DiNeMo, the fourth column lists the Croatian average value collected from the DSO Observatory survey, and finally the fifth column presents the values of the indicators obtained by DiNeMo network where average DSO Croatian values have been inserted.

Table 5.2: Indicators comparison for the urban Varaždin area

Indicator	DSO_U_Varaž	DiNeMo_U_Varaž	DSO_Croatia	DiNeMo_Croatia
#1 Number of LV consumers per MV consumers	723	791	1077	1213
#2 LV circuit length per LV consumer (km/LV consumer)	0.020	0.018	0.041	0.015
#3 LV underground ratio (%)	46%	39%	30%	29%
#4 Number of LV consumer per MV/LV substation	90.9	96.0	92.5	107.0
#5 MV/LV substation capacity per LV consumer (kVA/LV consumer)	5.22	5.57	3.69	5.64
#6 MV circuit length per MV supply point (km/MV supply point)	0.90	1.12	1.48	1.2
#7 MV underground ratio (%)	62%	95%	43%	97%
#8 Number of MV supply points per HV/MV substation	69	33	105	37

It is worth to remark, before looking at the results, that in this exercise a subarea of Varaždin city center is analyzed, meanwhile the DSO's values are taken from a broader area, thus considering also some peripheral neighborhood. Indicator #1 presents the number of LV consumers per MV consumers, and it points out that a higher value is observed in DiNemo, for both cases, thus local and national simulations, compared to the one provided by the Croatian DSO. More specifically, this difference is limited to only 9% when using the local DSO value, and up to 30% for the national one. This divergence is reasonable because in this case study DiNeMo has been applied principally on a urban area which is composed of several MV supply points because of the several points of interests plus the presence of the train station. This effect is also translated to indicator #8, in both cases (local and national), indeed in the local case, the number of MV supply points per HV/MV substation of 69 compared to 33 in DiNeMo.

Concerning indicator #2, due to the fact that a more dense area has been taken into consideration (consumes are positioned much closer to each other), a smaller value is registered in DiNeMo networks compared to the real data of the DSO. On top of this, DiNeMo is designed to minimize the circuit length based on the investment costs of lines and substations, therefore users should always expect for an optimal configuration.

Indicator #3, LV underground ratio, is smaller in DiNeMo networks, and it is more marked in the local situation rather than setting the national Croatian DSO DSO, HEP – Operator distribucijskog sustava d.o.o.

There are 3 indicators, #4, #5 and #6 which show a very good correlation with the real ones, in particular when applying the local input parameters.

The MV underground parameter, indicator #7, has a higher value in DiNeMo compared to the DSO one. This occurs because, in the network computation request a higher density has been inserted due to the fact that only the city center has been considered rather than the entire city. The higher density implies a higher MV underground ratio. In addition, the algorithm, designing the network, while taking into account also environmental constraints, minimizes cables crossing buildings and for this reason the result of indicator #7 is 95%.

Indicator #8 is calibrated with the national DSO value and interdependent with indicator #1, therefore in this specific case is smaller.

5.3.2 Validation on Varaždin semi-urban area

In this second case study the same HV/MV substation is supplying a different area, and in particular a semi-urban area of Varaždin. Figure 5.4 shows the OpenStreetMap image where the substation is highlighted with a red circle in the bottom left side. Differently, from the previous case (urban area), most of the land in the northern part of the image represents industries and big factories.

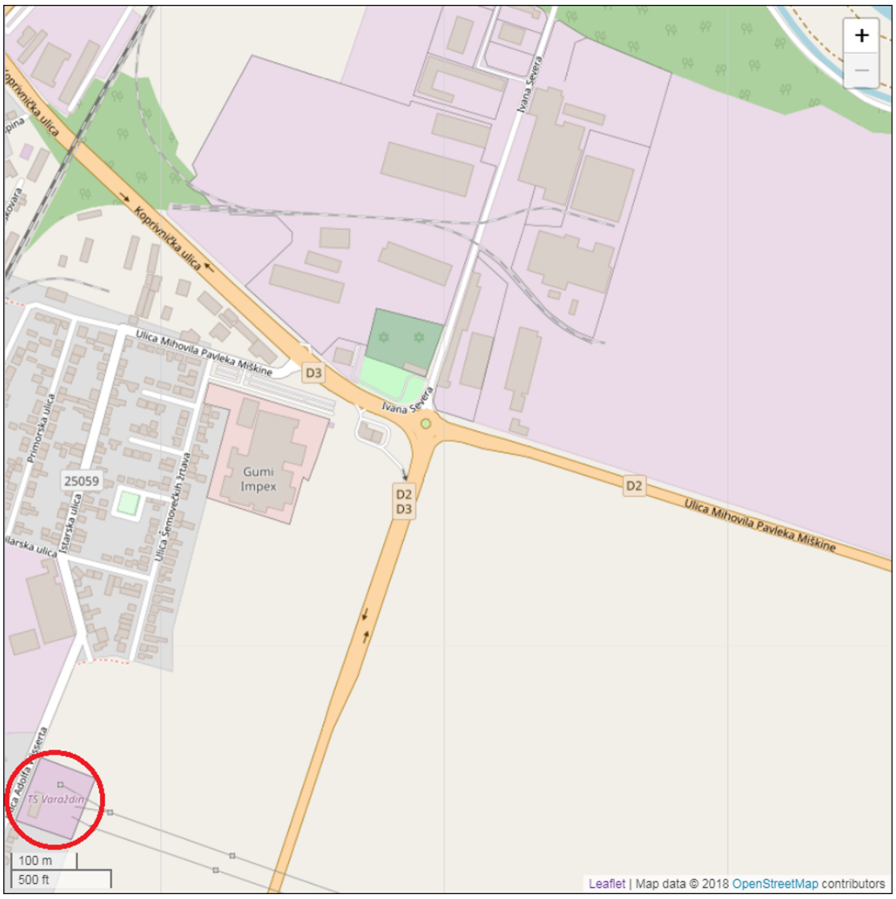


Figure 5.4: Varaždin semi-urban area in OpenStreetMap image

This drastic difference is observable also in the new indicator results, as well as in the lower number of consumers, which have an absolute value of almost 1000 consumers. In this semi-urban area the total circuit length is 46.6 km, of which 43% is MV lines due to the high industrialization of the whole network. Moreover, the average value of LV feeders length is 30 meters, thus one half compared of the urban case. This feature may be explained by the fact that connected consumers are clustered in 3 or 4 main zones within the network. In addition, the network is composed of 25 MV/LV substations with a higher percentage of transformer with a capacity of 1000 kVA compared to the urban case. Table 5.3 shows the indicators of the semi-urban Varaždin area based on DSO and DiNeMo results. Indicator #1 simulates a lower value for DiNeMo compared the one calculated from the Croatian DSO because of the density utilized in the network computation request.

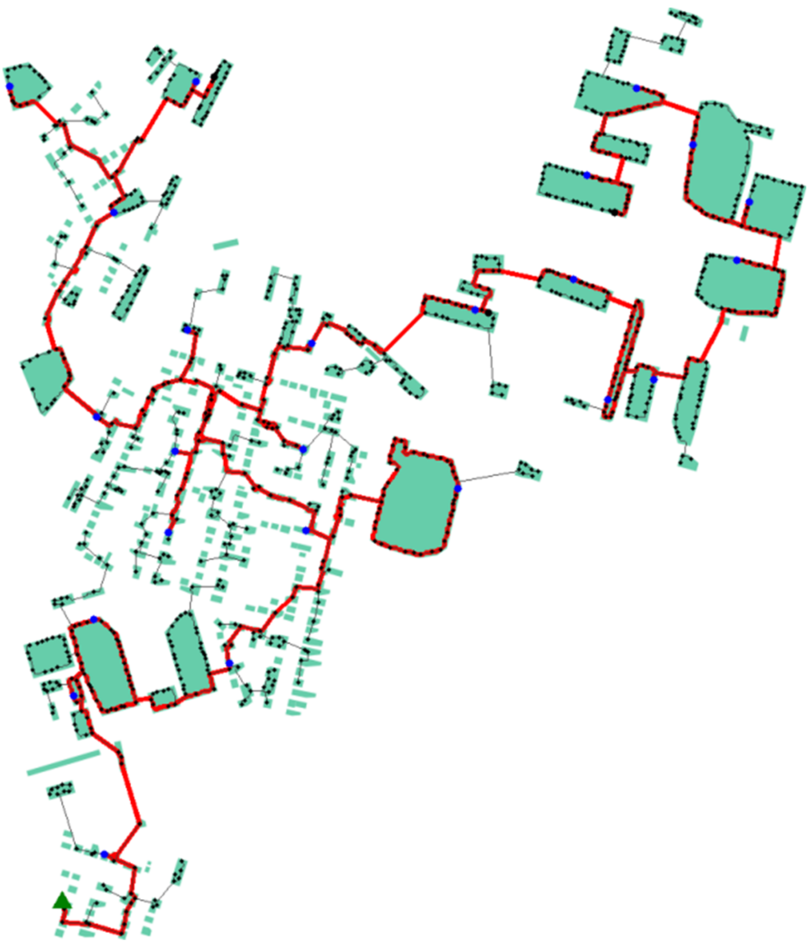


Figure 5.5: Varaždin semi-urban network

By having a look at Figure 5.4, it is clear that the blocks of buildings are located close to each other thus resulting in a shorter distance between consumers. This buildings distribution cause to the indicator #2 to be shorter in DiNeMo compared to the one provided by the DSO. Indicator #3, LV underground ratio, has a good correlation with the DiNeMo output. Differently from the urban case, the area of supply is concentrated and restricted, and this effect reduces the number of MV supply points which is very small and reached 25, of which 3 are MV consumers and 22 MV/LV substations. The comparison of urban network with the semi-urban one gives the following outcomes: the number of LV consumers is smaller in 5.4 compared to 5.2, the same occurs for indicator #6 and consequently for the number of MV supply points per HV/MV substation. Regarding indicator #7, the MV underground ratio, the observed semi-urban area has a a lower value in DiNeMo compared to the one provided by the DSO. This happens because the DSO value consider also more urban areas.

Table 5.3: Indicators comparison for the semi-urban Varaždin area

Indicator	DSO_S_Varaž	DiNeMo_S_Varaž
#1 Number of LV consumers per MV consumers	723	672
#2 LV circuit length per LV consumer (km/LV consumer)	0.020	0.013
#3 LV underground ratio (%)	46%	41%
#4 Number of LV consumer per MV/LV substation	90.9	106
#5 MV/LV substation capacity per LV consumer (kVA/LV consumer)	5.22	5.52
#6 MV circuit length per MV supply point (km/MV supply point)	0.90	0.90
#7 MV underground ratio (%)	62%	51%
#8 Number of MV supply points per HV/MV substation	69	25

5.3.3 Power flow analysis

As already described in section 3.4.1.3, DiNeMo outputs are diverse: excel tables containing information about overhead lines and underground cables, switching devices, consumers' maximum rated power, HV/MV and MV/LV substations, images of grid layout and MATLAB file with branch, node and generator data required for AC power flow simulation in MATPOWER.

5.3.3.1 MATPOWER input data description

The substation utilized is a 110 kV / 10 kV with rated capacity of 31.5 MVA. In the urban network designed by DiNeMo there are 35 10 kV /0.4 kV substations in total. Out of them there are 19 substations with a rated capacity of 400 kVA, 12 with 630 kVA, and 2 with 1000 kVA.

The population density, thus the number of consumers per building, inserted is based on the Croatian population census published online in [115]. The number of consumers per building are defined as follows: 24.34% for 1, 64.51% for 3, 9.71% for 5, and 1.44% for 7 consumers. Regarding the demand profiles utilized in the network, they are based on the dataset provided to the JRC from the Italian national regulatory authority ARERA. These demand profiles are then scaled and normalised in order to fit the size of Varaždin distribution network capacity. The number of buses in the whole network exceeds the number of demand profiles provided by ARERA by almost 3 times. To overcome this issue, the scaled demand profiles are randomly assigned to each bus, before running a MATPOWER simulation. This is performed by applying a Monte Carlo method with 10'000 iterations. The exact same approach is applied to EVSE in which the demand profile is taken from the article [77]. Indeed, the profiles are assigned to different bus location within the grid. As proposed in [116], at least one charging points is required for every 15 electric vehicles. Two different types of penetration level, which is based on the number of buses in the network, have been applied in this study: 10% (as a most probable future realization based on EAFO [86]) and 20% (as an extreme one) with a charging power of 22 kW as being the only one present according to [96] in Varaždin. For these two penetration levels the impact on the voltage deviation is analyzed for the 1194 buses of the networks, due to the increased demand provoked by EVs recharges.

5.3.3.2 Results of AC power flow in MATPOWER

The Newton-Raphson method of the MATPOWER package in the programming language Matlab has been utilized to perform AC power flow analysis of the urban case with a tolerance of 1e-08. The most critical hour, based on the demand profile, has been detected at 8:00 p.m., and it is the most demanding in terms of voltage drop. For this reason, the Monte Carlo simulation is performed only for this specific time interval. The outcomes of the AC power flow analysis are reported in Figure 5.6 with 0% on the left, and 10% on the right of EVSE penetration. The colored dots shown in Figure 5.6 are the same one plotted in Figure 5.3.

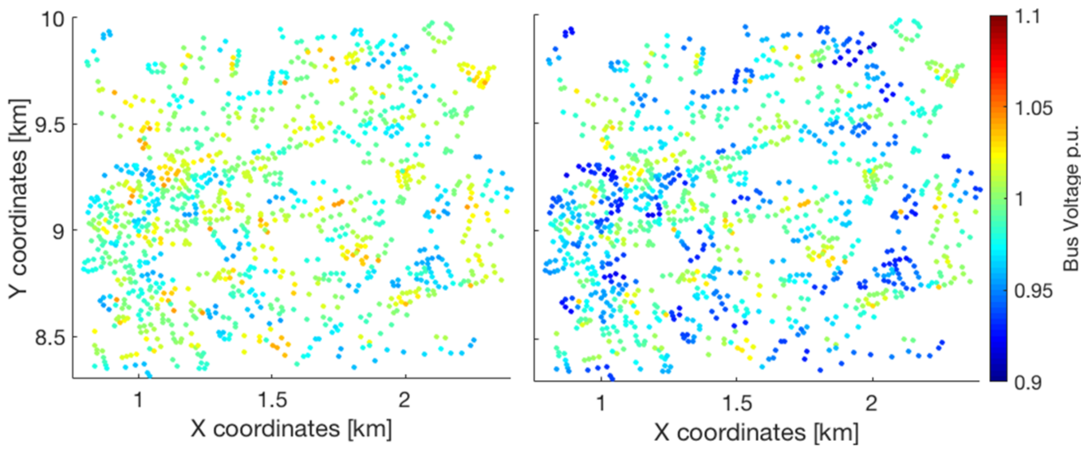


Figure 5.6: Bus voltage deviation in Varaždin urban area with 0% of EVSE (left) and with 10% of EVSE (right)

Figure 5.6 on the left illustrates the average voltage in per unit after 10'000 iterations for each bus of the whole network where no charging station installation have been applied. Indeed, only consumer demand profiles in each bus are randomly assigned (Monte Carlo simulation is also applied for the demand profile). In this case the average voltage value, among all the buses, is 0.9967 p.u. and having an aggregated demand of 61.3 MWh. This amount is seen from the HV/MV substation located in the bottom right side of the network. The total losses are 2.5% of the total aggregated demand. On the same Figure but on the right side is provided the image showing the voltage variation due to a 10% penetration of installed charging stations. Compared to the case on the left (0% of EVSE penetration) the total demand increases 11%, and in parallel also the losses reach 3%. At 8:00 p.m. the mean voltage value drops to 0.9777 p.u., and considering the 10.000 Monte Carlo iterations, the 5% of the buses have voltage magnitude below 0.9 p.u.

This example clearly indicates that in the urban area of Varaždin a 10% penetration of EVSE (Figure 5.6 on the right) is already heavily affecting the whole network. Indeed, the voltage drop is intense in those buses located far from the substation. It is evident the proliferation of blue dots, which indicates, based on the color bar, the voltage drop. Even worse is the situation for 20% of EVSE penetration, which sees even higher voltage deviation, with an average voltage value of 0.95 p.u., therefore threatening the quality of services and requiring either network reinforcement or smart EV charging.

5.4 Chapter summary and main contribution

In this chapter a statistical validation methodology, on the networks grids designed by DiNeMo, has been developed. Statistical methods adopted in literature are presented, and the results points out that no universal approach is defined to validate networks. Therefore, in collaboration with Comillas University which has decennial experience in validating the Spanish grid operated by the TSO Red Eléctrica, 10 indicators were developed. The indicators focus merely on the technical features at LV and MV level, which are a subset of the 36 indicators calculated based on the survey to DSOs. To prove the effectiveness of these indicators a real case study is presented in collaboration with the Croatian DSO, HEP - Operator distribucijskog sustava d.o.o. on a urban and semi-urban area. From the distribution network layout provided by the DSO the 10 indicators were compared with those obtained by DiNeMo with promising results. Out of the 10 indicators, the MV underground parameter one reveals the least correlation between DiNeMo output and real case. In addition, beside the statistical validation methodology the impact of electric vehicle's demand at peak time is analysed on the urban area. The voltage deviation for each bus is monitored, and with a penetration of 10% of EVSE it results in a 5% of them having a voltage magnitude below the safe range. This test case on the urban area of Varaždin clearly indicates that even a low penetration of charging infrastructures may lead to heavy effects on the network reliability. I have conducted the review of the different statistical approaches available in literature, as well as highlighted the importance of validating reference networks. Then I have utilized DiNeMo to create the two networks, calculated the indicators, and compared it with those of the DSO. Finally, I have performed the power flow analysis with MATPOWER and analysed the voltage fluctuations under the different EVSE penetration. The innovative aspect of this case study is the fact that a cooperation between DSOs and expert in the field may be fruitful for both sides. Indeed, DSOs may launch calls to test different aspects on the network without providing the exact layout of the grid but rather few key technical indicators.

Chapter 6

Conclusions

This thesis is concluded with an overview and final remarks on distribution system operators considering the current limitations and new challenges that this sector is going to tackle, with a special attention on the role of electric vehicles charging stations. Some suggestions for future research are also presented.

6.1 Modelling and results

The thesis work has three main objectives. From the distribution system operators perspective, the main objective is to investigate how the technical and non technical features differentiate among DSO networks in Europe. From the modelling perspective, the second main objective is firstly to define a method which incorporates the previous findings to properly design a tool able to reproduce representative urban networks, and secondly to validate them through a statistical methodology. From the electric vehicle's infrastructure perspective, the third main objective is firstly to understand the electric vehicles demand behaviour and develop models capable of reproducing them, and secondly to assess, through a methodology, the EVs charging infrastructure features and performances.

The main findings regarding the DSO level analysis are summarised in the following list.

- The technical aspects concerning DSOs derived from the survey were analysed.
  - A clear picture of distribution grids is presented by gathering and clustering network structure, network design, reliability indexes and distributed generation indicators. Large ranges have been observed for several indicators that highlight the differences among the existing DSOs in designing and operating their grids.
  - Combined with the literature review, the DSO Observatory project findings confirms the importance of providing an open data platform due to the limited existence in the number, size and geo-referenced network grids.
- The smart grid dimension describes the new challenges threatening the DSOs.
  - The remuneration tariffs of DSOs in most of the cases are based either on energy consumption (volumetric) or on contracted power (capacity based). Those ranging from purely volumetric to purely capacity based ones. Indeed, in the new emerging scenario, the different approach might play a relevant role in facilitating the distributed generation integration.
  - The data exchange interface between DSOs and transmission system operators (TSOs) highlights once again complete different approaches in which communication and data sharing occur either frequently (such as real-time) or only in case of urgent situation or when mandatory. This reluctant behaviour can represent a barrier towards an overall improvement of the electricity market. Indeed, a more transparent and frequent share of data can potentially offer new opportunities for final consumers.
  - The development of demand response and demand side management programs are implemented only by few DSOs. At the moment, only few consumers have financial benefits in accepting a shifting request from a DSO.
  - The smart metering roll-out situation has shown unexpected outcome. Indeed, in certain Member States where the Cost-Benefit-Analysis proved negative, some DSOs decided to undertake the smart meters roll-out. This occurs because they consider it as a breakthrough technology to improve consumer's and grid infrastructure monitoring.

The main findings regarding the modelling level analysis are summarised in the following list.

- The development of a Distribution Network Modelling platform aim at facing the lack of available synthetic distribution networks.
  - DiNeMo is the new platform that aims to provide stakeholders in the electricity sector with a solid tool based on real data and capable to reproduce the representative distribution grid of a given area of interest.
  - The construction of the distribution network grids is based on several network indicators built upon the DSO Observatory survey. The layout is geo-referenced and takes into account the geographical location of buildings, street topology and environment aspects.
  - DiNeMo output are diverse, going from consumers and substations shapefiles to MATPOWER files. All these information can be utilized to perform different scenarios, such as testing the maximum installation of photovoltaic panels within the observed urban area.
- A statistical methodology to validate representative distribution networks grid has been developed.
  - The reliability of the network developed by DiNeMo is verified through a statistical methodology developed in collaboration with European DSOs. It is based on 10 selected indicators calculated from DiNeMo, which are compared with the real ones provided by the DSOs.
  - The results show that DiNeMo is capable of designing with good accuracy both urban and semi-urban areas of interest below a HV/MV substations. This is possible with few inputs provided by the user and the DSO's data collected from the DSO survey.

The main findings regarding the electric vehicle's infrastructure level analysis are summarised in the following list.

- The study conducted on the a large dataset of electric vehicles charging columns (2900) show interesting outcomes including energy demand, plug-in and plug-out behaviour.
  - Among the 30.000 EV users utilizing the Netherlands charging columns infrastructure, 25% of the energy demand is supplied in the weekend. Moreover, daily plug-in and plug-out distribution profiles highlighted remarkable differences among weekdays and weekends.
  - Multi-modal probability distributions were identified fora number of relevant variables, and were handled through a Beta Mixture Model approach. A statistical analysis of connected, idle and charge times provided the following results: 50% of the recharges last for less than 4 hours; the idle time depends on the geographical location of the charging station, and on average it lasts also for 4 hours.
- A second analysis on the Dutch dataset has been used to define a methodology, composed of eight indicators, allowing a comparison among EV public charging infrastructures.
  - The analysed database reveals a low energy use ratio and high availability of the infrastructure, which consequently indicates a low energy flows through the network. Thus causing a low allocation of the carbon intensity, which reflects into a higher value compared to the one found in literature.
  - The correlation between fuel station, parking lots, and population density indicates a moderate to strong parameter, which indicates that the network distribution is appropriate. The idle time revealed that the network could be over dimensioned, which may sound reasonable at the early stage of EV adoption. There is a moderate charger and geographic concentration in terms of energy demand.

On the whole, the results from this thesis show that the increasing attention toward the distribution sector should not be underestimated by the main actors, which appears to have complete different approaches in terms of smart grid projects. It is urgent for policy makers and stakeholders involved to align DSOs to a common strategy to tackle the introduction in the distribution network grids of new players. The DiNeMo tool may be used to perform preliminary research studies concerning the installation of new charging infrastructure, renewable energy installation or network reinforcement analysis.

6.2 Recommendations for further research

The current analysis may be furthered by including the implications on ancillary services, thus, on novel electricity market models, and on costs and benefits of the EV integration into the electrical grid. When the number of EVs will become higher, further issues will likely appear, such as the possible unavailability of charging locations in a charging station, taking into account the probability that the EV is charged or queued at its arrival. On the operation side, the possible queuing will have to be handled through appropriate communication before the EV arrival. On the planning side, the risk of being not served will be included in the planning problems aimed at determining the location and sizing of new EV charging infrastructure. Results of this kind can help policy makers, companies and network operators devise better strategies, economic tariffs and ad-hoc incentives and penalties to enhance the value of tomorrow's EV fleet and to minimise its impact on the grid infrastructure. Regarding the distribution network modelling platform perspective (DiNeMo) several improvements can be applied like incorporating different layers, such as street topology, economic and social information, in order to transform the platform into a holistic tool for designing the city of tomorrow. This will help facing the challenges and opportunities of tomorrow's electricity distribution systems. The most three relevant future activities that can be done to improve the platform are listed hereby:

- The inclusion of extra database already internally available at the JRC such as: PVGIS dataset which provides the solar irradiation of the area under study and the global human settlement dataset which gives the population density. This latter, has also historical record which may be considered for future scenarios;

- Network constraints may increase the quality of DiNeMo output such as LV, MV and HV lines and cables position. In addition to this, the charging infrastructure location can be an added value in designing the grid;

- The expansion of the area of interest can be important especially if coupled with gas at the distribution level. Moreover, the coupling with the transmission grid may be an added value to DiNeMo.

Appendix A

Appendix - DSO survey

JRC - DSO Observatory 2018 Survey

Fields marked with * are mandatory.

* Contact Person

* Email

Note

Please note that:

- The following form is dedicated to DSO with 100.000 or more customers.
- The latest available information should be used to complete the form.
- If a field is mandatory and is unknown or cannot be disclosed: please fill in with "Unknown" or "Not answer" or a zero (in case a value is expected)
- If you have any comment, please leave it below:

1. Identification

Please fill in one survey for each DSO in each Country (e.g.: if your DSO is active in multiple countries, please fill a survey for each Country).

* 1.1 Company/Association:

* 1.2 Phone:

* 1.3 Email:

1.4 Address (only if you wish to receive a printed copy of JRC DSO Observatory Report)

2. General information (Distribution Business - Basic Figures, Structure & Ownership)

A. BASIC INFORMATION

* 2.1 Legal Name of the DSO

* 2.2 Country:

- Albania
- Andorra
- Armenia
- Austria
- Belarus
- Belgium
- Bosnia and Herzegovina
- Bulgaria
- Croatia
- Cyprus
- Czech Republic
- Denmark
- Estonia
- Finland
- France
- Germany
- Greece
- Hungary
- Iceland

- Ireland
- Italy
- Latvia
- Liechtenstein
- Lithuania
- Luxembourg
- Macedonia
- Malta
- Moldova
- Monaco
- Montenegro
- Netherlands
- Norway
- Poland
- Portugal
- Romania
- Russia
- San Marino
- Serbia
- Slovakia
- Slovenia
- Spain
- Sweden
- Switzerland
- Turkey
- Ukraine
- United Kingdom

*2.3 Regions and/or municipalities covered

*2.4 Distributed Annual Energy (on average)

GWh

*2.5 Area of Distribution Activity (approximately)

km

3. Technical Data

B. CUSTOMERS SERVED

* 3.1 Please complete the following table

Please, check that the total adds the partials

	Value
Total Number of Customers connected	
Number of LV (< 1 kV) Customers	
Number of MV (1- 36 kV) Customers	
Number of HV (> 36 kV) Customers	

C. DSO NETWORK LENGTH PER VOLTAGE LEVEL (KM)

* 3.2 Please complete the following table

Please, check that the total adds the partials

	Value
Total	
LV (< 1 kV)	
of that Overhead	
of that Underground	
MV (1-36 kV)	
of that Overhead	
of that Underground	
HV (> 36 kV)	
of that Overhead	
of that Underground	

D. ELECTRIC MOBILITY

* 3.3 Charging points connected to the DSO network.

	Number	Notes
Number of charging points for Electric Vehicles connected to the DSO network		
- Of which number of charging points owned and operated by the DSO itself		
- Of which number of other charging points owned and operated by third parties (e.g. market players):		

E. SUBSTATIONS

* 3.4 Please complete the following table

Please, check that the total adds the partials

	Value
Number of HV/MV Substations	
Total installed capacity of HV/MV Substations (MVA)	
Number of MV/LV Secondary Substations	
Total installed capacity of MV/LV Secondary Substations (MVA)	
Total installed capacity of generation connected (MW)	
Installed capacity of generation connected to LV networks (MW)	
Number of electric vehicle public charging points	
- Of which number of charging points owned and operated by the DSO itself	
- Of which number of other charging points owned and operated by third parties (e.g. market players):	

* 3.5 Reliability indexes (annual value of each reliability index for long unplanned interruptions).

** mark with "X" where applicable. This refers to whether the voltage levels are considered for the evaluation of the index

	Value	LV**	MV**	HV**
SAIDI (min./customer)				
SAIFI (int./customer)				

* 3.5.1 Please fill in the following table in case your reliability indexes are not the proposed ones.

** mark with "X" where applicable. This refers to whether the voltage levels are considered for the evaluation of the index

	Reliability Index*	Unit	Value	LV**	MV**	HV**
1						
2						

4. DSO and the Smart Grid dimension

*4.1 DSO as a user of non-frequency ancillary services

	Yes/No	Notes
Is your company managing Demand Response and/or Demand Side Management or Flexibility programs?		
If yes, who decides on the final consumption?		
Can you please provide some links to relevant public documents explaining the programs used?		
Does your company manage prosumers?		
Does your company manage active consumers?		
If yes, can you provide some links to relevant public documents?		

*4.2 Remote control of substations

	Number	Notes
Number of HV/MV Substations remotely controlled		
Number of MV/LV Substations remotely controlled		

*4.3 DSO/TSO data management

	Yearly/monthly/weekly/hourly	Notes
What data on the network conditions does your company share with the relevant TSO [more than one choice allowed]:		
- demand and generation forecasts		
- scheduled data of each power-generating facility		
- real time measurements (SCADA)		
- ex-post measurements (metered data)		
What data on the network conditions does your company receives from the relevant TSO (please specify)?		

*4.4 Smart Metering (ONLY FOR COUNTRIES WHERE DSO ROLLS OUT SMART METERING - SEE http://ses.jrc.ec.europa.eu//smart-metering-deployment-european-union)

	% of rolled-out smart meters up to now on total end-customers	Notes
Is your company proceeding with the smart metering roll-out provided by Dir. 72/2009 (80% of electricity consumers by 2020		
Additional information		

5. Additional technical data

*5.1 Would you like to provide additional data? If is it so, please choose among the three categories (one or more):

- ☐ Network structure
- ☐ Distributed generation
- ☐ Reliability
- ☐ I can't provide additional data
- ☐ Other (Please specify)

Other (please specify):

5.2 Network structure

*5.2.1 Network Data

	Value
Typical transformation capacity of HV/MV Substations (MVA)	
Typical transformation capacity of the MV/LV Secondary Substations in urban areas (kVA)	
Typical transformation capacity of the MV/LV Secondary Substations in rural areas (kVA)	
Average number of MV/LV Secondary substations per feeder in urban areas	
Average number of MV/LV Secondary substations per feeder in rural areas	
Average length per MV feeder in urban areas	
Average length per MV feeder in rural areas	
Number of TSO-DSO interconnection points	
Voltage levels of the distribution networks (kV)	
Typical number of voltage levels concatenated in distribution (for example 1 LV level, 1 MV levels and 1 HV level)	

*5.2.1 Degree of automation in the MV network [Type of smart grid automation equipment and penetration]:

	Substations equipped with Monitoring/Automation Equipment*	Degree of penetration (low/medium/high)**	Percentage of substations equipped with these equipment (%)
1			
2			
3			
4			
5			

5.3 Distributed generation

*5.3.1 Generation connected to distribution network (ONLY!)

	Total Installed Capacity [MW]	Total Gross Electricity Generation [GWh]	Connected to LV (1kV) [%]	Connected to MV (1-36 kV) [%]	Connected to HV (>36kV) [%]
Photovoltaic					
Wind					
Biomass					
Waste					
Hydro					

5.4 Reliability

5.4.1 Are the reliability indexes measured per type of area?

e.g. Rural/Urban

- ◯ Yes
- ◯ No

5.4.2 If yes, in what areas? What are the reliability indexes (annual value of each reliability index per type of area, for long unplanned interruptions)?

	Value
Urban-SAIDI (min./cust.)	
Urban-SAIFI (int./cust.)	
Rural-SAIDI (min./cust.)	
Rural-SAIFI (int.cust.)	

5.4.3 Please fill in the following table in case your reliability indexes or area type are not the proposed ones

	Area type	Reliability Index	Units	Value
Area 1				
Area 2				
Area 3				
Area 4				

6. DSOs & the Clean Energy Package

The Clean Energy Package (Proposal for a Regulation on the Internal Electricity Market - recast) provides for the creation of a new DSO entity at European level (art. 49, 50, 51) "*in order to promote the completion and functioning of the internal market in electricity, and to promote optimal management and a coordinated operation of distribution and transmission systems*"

(Please note that these questions are only for an informative purpose and do not bind the DSO to any sort of legal obligation.)

6.1 With reference to the DSO mentioned in question 2.1 (legal name of the DSO) and related to the Country mentioned in question 2.2, would your company be interested in a direct participation in the future EU DSO Entity?

- [ ] Yes
- [ ] No

6.2 On which topics your company might be interested in providing expertise within the DSO entity to be established?

- [ ] Coordinated operation and planning of transmission and distribution networks
- [ ] Integration of renewable energy resources, distributed generation and other resources embedded in the distribution network
- [ ] Development of demand response
- [ ] Digitalisation of distribution networks including deployment of smart grids and intelligent metering systems
- [ ] Data management, cyber security and data protection
- [ ] Other (please specify)

Comments

Appendix B

Appendix - DiNeMo platform layout

DiNeMo is the new platform we are building to provide stakeholders in the electricity sector with a solid tool that based on real data is capable to reproduce the representative distribution grid of a given area of interest.

The platform is also bound to become the virtual place where diverse users, with different roles, will collaborate with the aim of building reliable models to be used in order to design and develop the smart cities of tomorrow.

ENTER IN DiNeMo

Contact us

European Commission

JOINT RESEARCH CENTRE

Smart Electricity System and Interoperability

dinemo

DiNeMo (Distribution Network Models module)

MARIO ROSSI

Search ...

add new
NETWORK COMPUTATION REQUEST

add new
CITY PROJECT

MY NETWORK COMPUTATION REQUEST

TITLE

TITLE

TITLE *Draft*

MORE

MY CITY PROJECTS

TITLE

TITLE

TITLE *Draft*

MORE

dinemo

DiNeMo (Distribution Network Models module)

MARIO ROSSI

ADD NEW NETWORK COMPUTATION REQUEST

Title *

SAVE DRAFT NEXT CANCEL

dinemo

DiNeMo (Distribution Network Models module)

MARIO ROSSI

< GO BACK

Search ...

MY NETWORK COMPUTATION REQUEST

TITLE	CRETCREATED AT	LAST UPDATE	STATUS	CITY PROJECT	COMPLETION	ACTIONS
Network's name	2019-06-13 12:55:23	2019-08-14 12:43:21	*Draft*		25%	
Network's name 1	2018-02-24 13:45:23	2018-04-20 18:45:20	*Processed*	√	100%	
Network's name 2	2019-05-29 09:32:45	2019-06-03 10:18:45	*Queued*		100%	

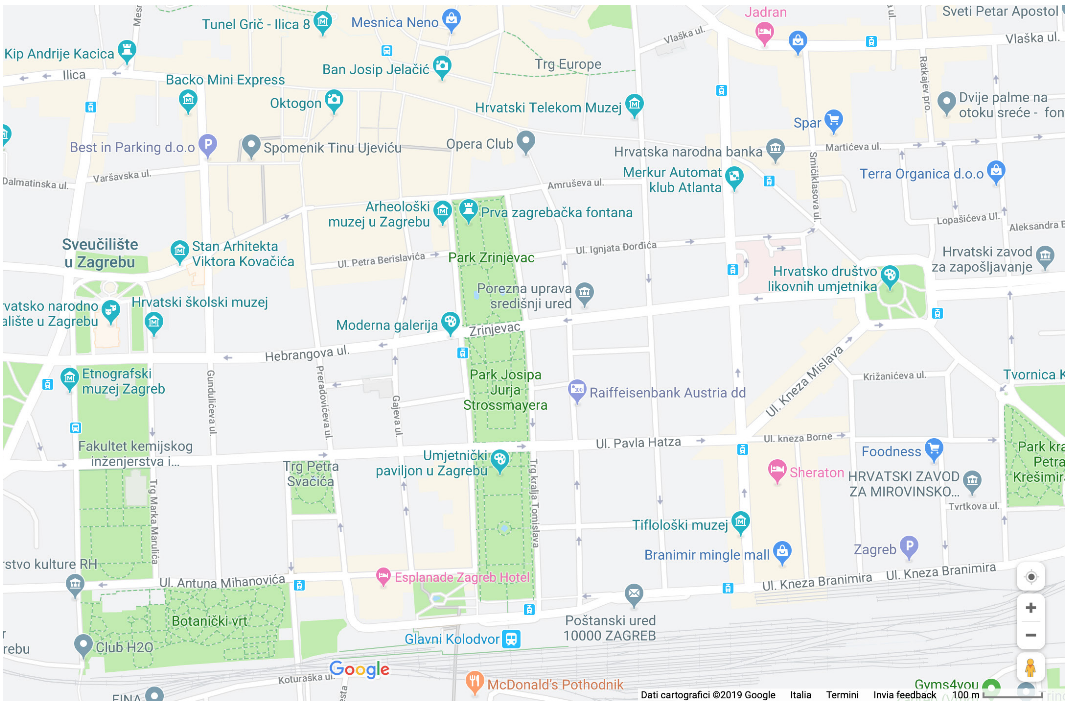
DiNeMo (Distribution Network Models module) MARIO ROSSI

ADD NEW NETWORK COMPUTATION REQUEST

1. Search in the map. Use the default zoom 16. The first step is to indicate the areayou want to process throught the platform.

Lorem ipsum

SEARCH



SAVE DRAFT NEXT CANCEL

DiNeMo (Distribution Network Models module) **MARIO ROSSI**

ADD NEW NETWORK COMPUTATION REQUEST

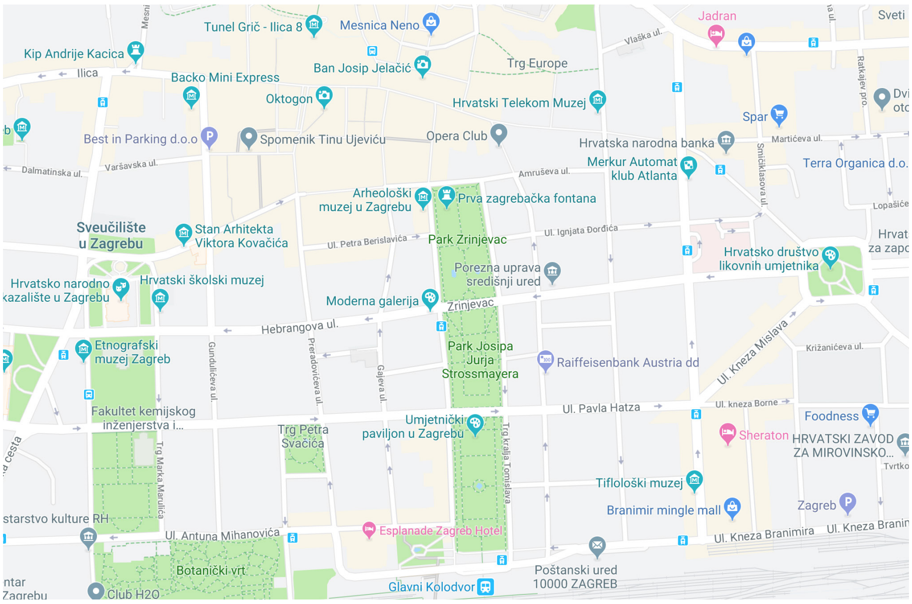
2. From proposed Search results, choose the one representing your area of interest.

Lorem ipsum

SEARCH

Search results:

- Lorem ipsum, dolor sit amet, consectetuer adipiscing elit
- Lorem ipsum, dolor sit amet, consectetuer adipiscing elit
- Lorem ipsum, dolor sit amet, consectetuer adipiscing elit
- Lorem ipsum, dolor sit amet, consectetuer adipiscing elit
- Lorem ipsum, dolor sit amet, consectetuer adipiscing elit
- Lorem ipsum, dolor sit amet, consectetuer adipiscing elit



SAVE DRAFT NEXT CANCEL

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ADD NEW NETWORK COMPUTATION REQUEST

3. The third step is to capture the image needed for processing, click the capture button.

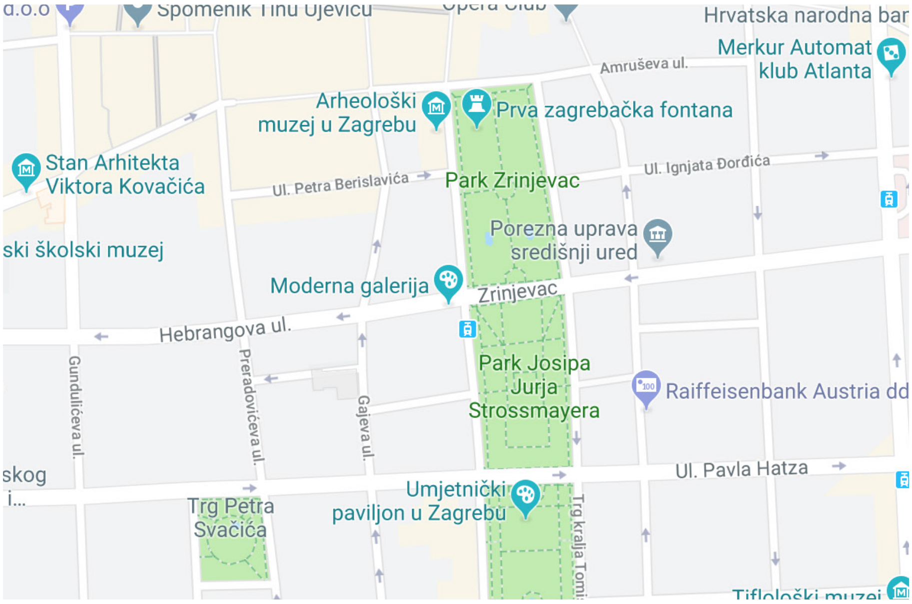
CAPTURE ZOOM TO COORDS

Coordinates of the centre of the map

Latitude	Longitude	Zoom level

Coordinates of the top left corner

Top left x	Top left y



SAVE DRAFT NEXT CANCEL

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ADD NEW NETWORK COMPUTATION REQUEST

4. The fourth step is to indicatein the map the location of substation. It is possible to indicate itwith a click on the map, or enter the coordinates.

Coordinates of the centre of the map

45.98740	15.84207	16

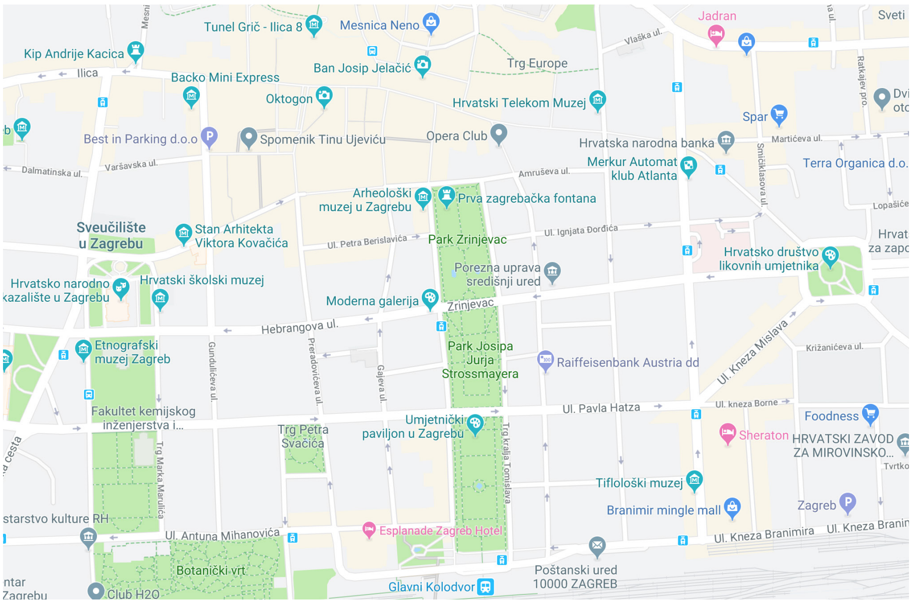
Coordinates of the top left corner

574.8392	5478.9270

HM/MV Substation Location

TRANSFORM

Latitude	Longitude
Location X (km)	Location Y (km)



SAVE DRAFT NEXT CANCEL

DiNeMo (Distribution Network Models module)

MARIO ROSSI

< GO BACK

Search ...

MY NETWORK COMPUTATION REQUEST

TITLE	CRETCREATED AT	LAST UPDATE	STATUS	CITY PROJECT	COMPLETION	ACTIONS
Network's name	2019-06-13 12:55:23	2019-08-14 12:43:21	*Draft*		50%	
Network's name 1	2018-02-24 13:45:23	2018-04-20 18:45:20	*Processed*	√	100%	
Network's name 2	2019-05-29 09:32:45	2019-06-03 10:18:45	*Queued*		100%	

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DiNeMo (Distribution Network Models module) **MARIO ROSSI**

ADD NEW NETWORK COMPUTATION REQUEST

NETWORK'S NAME

Draft *created on* ***2019 - 06 - 16 12:55:32***

Parameters

Power factor and Voltage

Power factor *	Low voltage *	Medium voltage *
0.00 - 1.00	kV	kV

Consumers

Density *	Maximum demand of a LV *	Maximum demand of a MV *
nr/km2	kW	kW

Number of consumers

Number of consumers per building

Probability of the Number of consumers per building (%)

▲ Advanced mode

Transformation capacity of LV substations (lower and upper limits in kVA) *	Transformation capacity of MV substations (upper limits in kVA) *
nr/km2	kW

Lines

TYPE	CLASSIFICATION	R(OHMS/KM)	X(OHMS/KM)	AMPACITY (A)	VOLTAGE (kV)
OVERHEAD	LV_IA_1	400	0.40	0.92	7.9700000000
OVERHEAD	LV_IA_1	400	0.40	0.92	7.9700000000
OVERHEAD	LV_IA_1	400	0.40	0.92	7.9700000000
OVERHEAD	LV_IA_1	400	0.40	0.92	7.9700000000
UNDERGROUND	LV_IA_1	400	0.40	0.92	7.9700000000
UNDERGROUND	LV_IA_1	400	0.40	0.92	7.9700000000
UNDERGROUND	LV_IA_1	400	0.40	0.92	7.9700000000
UNDERGROUND	LV_IA_1	400	0.40	0.92	7.9700000000

Substations

TYPE	CLASSIFICATION	CAPACITY (KVA)	SECONDARY VOLTAGE(KV)	NO LOAD LOSES (KW)	LOAD LOSSES (KW)
INTERURBAN	LV_IA_1	400	0.40	0.92	7.9700000000
INTERURBAN	LV_IA_1	400	0.40	0.92	7.9700000000
INTERURBAN	LV_IA_1	400	0.40	0.92	7.9700000000
INTERURBAN	LV_IA_1	400	0.40	0.92	7.9700000000
URBAN	LV_IA_1	400	0.40	0.92	7.9700000000
URBAN	LV_IA_1	400	0.40	0.92	7.9700000000
URBAN	LV_IA_1	400	0.40	0.92	7.9700000000
URBAN	LV_IA_1	400	0.40	0.92	7.9700000000

SAVE DRAFT NEXT CANCEL

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DiNeMo (Distribution Network Models module)

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< GO BACK

Search ...

MY NETWORK COMPUTATION REQUEST

TITLE	CRETCREATED AT	LAST UPDATE	STATUS	CITY PROJECT	COMPLETION	ACTIONS
Network's name	2019-06-13 12:55:23	2019-08-14 12:43:21	*Draft*		75%	
Network's name 1	2018-02-24 13:45:23	2018-04-20 18:45:20	*Processed*	√	100%	
Network's name 2	2019-05-29 09:32:45	2019-06-03 10:18:45	*Queued*		100%	

dinemo

DiNeMo (Distribution Network Models module)

MARIO ROSSI

ADD NEW NETWORK COMPUTATION REQUEST

NETWORK'S NAME

Draft *created on* ***2019 - 06 - 16 12:55:32***

Select for each category the information you would like to keep at the end of the DiNeMo elaboration.

○ **Select / Unselect all**

Consumers

- ● Lorem ipsum
- ○ Lorem ipsum
- ○ Lorem ipsum
- ○ Lorem ipsum

Distribution lines

- ● Lorem ipsum
- ○ Lorem ipsum
- ○ Lorem ipsum

HV / MV Substation

- ● Lorem ipsum
- ○ Lorem ipsum
- ○ Lorem ipsum

Mat power

- ○ Lorem ipsum
- ○ Lorem ipsum
- ● Lorem ipsum
- ○ Lorem ipsum

MV / LV Substation

- ● Lorem ipsum
- ○ Lorem ipsum
- ○ Lorem ipsum

Network image

- ● Lorem ipsum

Summary

- ● Lorem ipsum

Switching devices

- ● Lorem ipsum
- ○ Lorem ipsum
- ○ Lorem ipsum

Switching devices (N)

- ● Lorem ipsum
- ○ Lorem ipsum
- ○ Lorem ipsum

SAVE DRAFT CANCEL

dinemo

DiNeMo (Distribution Network Models module)

MARIO ROSSI

< GO BACK

Search ...

MY NETWORK COMPUTATION REQUEST

TITLE	CRETCREATED AT	LAST UPDATE	STATUS	CITY PROJECT	COMPLETION	ACTIONS
Network's name	2019-06-13 12:55:23	2019-08-14 12:43:21	*Draft*		100%	
Network's name 1	2018-02-24 13:45:23	2018-04-20 18:45:20	*Processed*	√	100%	
Network's name 2	2019-05-29 09:32:45	2019-06-03 10:18:45	*Queued*		100%	

Appendix C

Appendix - Python programming code

Point of interests Python Code

```
import osmnx as ox

# Extract from the polygon the point of interests
all_pois = ox.pois_from_polygon(ox.utils.bbox_to_poly(north,south,east,west))

# Count point of interests per type
pois = all_pois['amenity'].value_counts()

# Save point of interest
pois.to_csv('Point_of_interest_of_the_selected_zone.csv')
```

Node centrality Python Code

```
import osmnx as ox
```

```
G = ox.graph_from_polygon(ox.utils.bbox_to_poly(north,south,east,west), network_type='dri
G = ox.project_graph(G)

# edge closeness centrality: convert graph to a line graph so edges become
nodes and vice versa
edge_centrality = nx.closeness_centrality(nx.line_graph(G))

# list of edge values for the orginal graph
ev = [edge_centrality[edge + (0,)] for edge in G.edges()]

# color scale converted to list of colors for graph edges
norm = colors.Normalize(vmin=min(ev)*0.8, vmax=max(ev))
cmap = cm.ScalarMappable(norm=norm, cmap=cm.inferno)
ec = [cmap.to_rgba(cl) for cl in ev]

# color the edges in the original graph with closeness centralities in the
line graph
fig, ax = ox.plot_graph(G, fig_height=12, bgcolor='k', axis_off=True, node_size=0,
node_color='w', node_edgecolor='gray', node_zorder=2, edge_color=ec, edge_linewidth=1.5,
edge_alpha=1)
```

Building detection Python Code

```
import sys
import osmnx as ox

def CreateImage():
extension = 'png'

# Assign assign map coordinates
north = AA.AAAA
south = BB.BBBB
```

```
east = CC.CCCC
west = DD.DDD

try:
# Extract the polygon area
polygon = ox.utils.bbox_to_poly(north, south, east, west)

# Create a graph with the buildings within the polygon
gdf = ox.footprints.footprints_from_polygon(polygon,
footprint_type='building', retain_invalid=False)

# Apply a convex hull process to the buildings geometry
gdf['geometry'] = gdf['geometry'].convex_hull

# Modify the coordinates
gdf=ox.projection.project_gdf(gdf, to_crs=None, to_latlong=False)

# Create the image with the current configuration
fig, ax = ox.footprints.plot_footprints(gdf, fig=None, ax=None,
color='mediumaquamarine', bbox=None, figsize=(13.47,13.47),
bgcolor='w',set_bounds=False, save=True, show=False,
close=False, filename=place, file_format=extension, dpi=96)

pass
except Exception as e:
print("Something went wrong: " + str(e))
sys.exit(0)
else:
print('saved image')
sys.exit(1)

return None
```

Substation & power lines location Python Code

```
import osmnx as ox

# Graph creation
G = ox.graph_from_bbox(north=north, south=south, east=east, west=west,
retain_all=True,
truncate_by_edge=True,
simplify=False,
network_type='none',
infrastructure='way["power" "line"]')

# Figure plot
fig, ax = ox.plot_graph(ox.project_graph(G))
```

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