POLITECNICO DI TORINO

Master's Degree in Energy and Nuclear Engineering

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Assessing the National Electricity Security in an Energy Transition perspective

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Abstract

As the increasing share of Renewable Energy Sources (RES) gradually replaces energy production from fossil fuels (coal, oil, natural gas), the national energy system is unavoidably tackling an energy transition. As the role of energy is critical for countries' prosperity, the energy transition is evaluated with respect to the Energy Trilemma, defined as the challenge of a secure, affordable and environmentally sustainable energy supply; therefore, the Energy Trilemma dimensions include Sustainability, Equity and Security. In this context, the definition of scientific methods to quantify the monitoring of the evolution of the energy transition is a topic of growing importance. However, as the Energy Trilemma dimensions are not uniquely defined or measurable, numerical indexes must be defined and aggregated for the purpose. Since a comprehensive analysis of the problem is beyond the scope of this document, the aim of the thesis is the definition of methodologies to quantify energy security, and specifically to define indexes for electricity security. Specifically, as the penetration of Variable Renewable Energy (wind and solar power, VRE) into power generation is expected to become more and more relevant, positive effects in terms of environmental sustainability and energy prices are expected; however, implications of high VRE shares include challenges to Electricity Security, as conventional generation from fossil fuels currently guarantees fundamental services to ensure correct system operation. The work is held in the context of a collaboration with ENEA (national agency for new technologies, energy and sustainable economic development), which is monitoring the evolution of the Energy Trilemma for the Italian energy system in its Quarterly Analysis of the National Energy System, computing a synthetic index (ISPRED). In the following, a framework for index computation is defined. Indexes and their aggregation are conceptually defined through the selection and calculation of relevant metrics; the computation process, including identification and referencing of public datasets (and single data inside them), their classification into structured property databases, data storage and public access through dedicated platform, is illustrated. Finally, electricity security for the physical system (generation and grid infrastructures) and the economic system (with focus on commodity markets) is considered with numerical examples.

Summary

As public institutions worldwide, and especially at European and national level, multiply their efforts to fight climate change, the national energy system is unavoidably tackling an energy transition, as energy production from fossil fuels coal, oil, natural gas) is being replaced by renewable energy. However, the effects of the energy transition must be assessed with respect to the dimensions of equity, sustainability and security, composing the Energy Trilemma. The Trilemma is monitored in the national interest by ENEA, the National Agency for new technologies, energy and sustainable economic development, through the definition and monitoring of ISPRED composite index.
In light of this transition, the need for balanced advances in all dimensions of the Energy Trilemma is argued; more in detail, as increasing share of VRE (constituted by wind and solar power) is especially going to impact the power sector, the electricity domain of energy security is expected to be particularly threatened from the transition. The thesis defines a conceptual framework for energy security definition and electricity security assessment in an energy transition perspective; as a result, based on literature review from public institutions, categories for electricity security are defined as System Adequacy, System Flexibility and Stability, Market Idoneity (including both Market Adequacy and Market Efficiency). Threats to each category coming from the energy transition are identified: increasing share of non dispatchable generation is expected to reduce available capacity, threatening System Adequacy; for the same reason, and especially because of VRE intermittency, System Flexibility is threatened; due to technical characteristics of wind and solar power, lack of regulating resources is expected to affect System Stability; increasing share of VRE generation is pushing conventional generation aside from the markets and decreasing market prices, putting at risk Market Adequacy in terms of its ability to remunerate generators providing fundamental services to the system; both lack of resources for correct power system operation and increasing costs of ancillary services threaten Market Efficiency.
Furthermore, a methodology for quantitative assessment is introduced, and a methodology for indexes computation, from data acquisition from datasets, classification according to their attributes and metadata, data storage and free access in

a database, until the computation of relevant metrics and indexes for each category and subsequent aggregation processes, is here illustrated.
Based on literature review from ENEA and the identification of threats from the energy transition, the following indexes are defined: Margin of Minimum Reserve for System Adequacy; Residual Load and Residual Load Ramp for System Flexibility; grid Frequency, Voltage and Inertia Level for System Stability; Clean Spark Spread from all markets and Capacity Market Revenues for Market Adequacy; Accepted Quantities (Sales and Purchases) and Number of Offers on MSD ex-ante and MB, Total Cost of Supply for ancillary services and Available Capacity in Probability from Capacity Market for Market Efficiency.
The computation of selected metrics is used to describe patterns and evolutive scenarios of the Italian power sector with respect to both the physical and the economic system, to be assessed based on numerical examples. For System Flexibility, Residual Load has recently reached minimum values, increasing risk of over-generation and reaching the technical minimum of conventional power plants and anticipating possible scenarios of the energy transition, while Residual Load Ramp has not recently shown criticalities. For Market Adequacy, decreasing Clean Spark Spread foreshadows critical future scenarios at high VRE shares, excepting for power plants operating on service markets; in spite of this, remuneration from Capacity Market appears to compensate remuneration for power plants who are able to guarantee capacity to the system, and appears to be a profitable opportunity even in combination with participation to MSD, at the condition that market offers are kept below a strike price. For Market Efficiency, the recent crisis caused increases in MSD quantities and uplift for Terna, making total cost of supply for ancillary services comparable to MGP market prices; even though increasing demand for ancillary services represents an additional threat to Market Efficiency, about half of dispatchable generators in Italy have already been admitted to Capacity Market, which is expected to compensate lack of capacity.
Overall, the thesis provides a useful starting point in terms of methodology for energy security and electricity security research; in addition, relevant insights are proposed to decision-makers to understand future trends and scenarios of the power sector. Outcomes include the importance of flexible generation for System Flexibility, decreasing profitability of Day-Ahead market, opportunities arising from Capacity Markets, threats to TSO coming from increasing cost of supply for ancillary services. Limitations and recommendations for future research are discussed: improvements are expected in categories selection and indexes definition, especially with respect to System Flexibility; a power grid model for the estimation of frequency, inertia and voltage is left to further studies; finally, the implementation of a database and a demo interface is a starting point for the creation of an integrated, secure and publicly accessible platform.

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I consider this thesis as a team work, which could only be completed thanks to everybody's commitment and company in the research group.
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List of Acronyms

AC	Alternate Current
AIET	Associazione Italiana di Elettrotecnica, Elettronica, Automazione, Informatica e Telecomunicazioni
AMPI	Adjusted Mazziotta-Pareto Index
API	Application Programming Interface
ARERA	Autorità di Regolazione per Energia Reti e Ambiente
BOD	Benefit of the Doubt
DC	Direct Current
DFIG	Doubly Fed Induction Generator
DSO	Distribution System Operator
EEX	European Energy Exchange
ENTSO-E	European Natwork of Transmission System Operators-Electricity
ER	Entity Relationship
EST	Energy Security Transition
ETS	Emissions Trading System
EU	European Union
EUA	European Union Allowance
GHG	Greenhouse gas
GME	Gestore Mercati Energetici
IEA	International Energy Agency
IEM	Internal Energy Market
IPCC	International Panel on Climate Change
IRENA	International Renewable Energy Agency
ISPRED	Indice Sicurezza energetica, PRezzo Energia e Decarbonizzazione
LOLE	Loss of Load Expectation
MB	Mercato di Bilanciamento

ME	Mercato Elettrico
MGP	Mercato del Giorno Prima
MI	Mercato Infragiornaliero
MPE	Mercato Elettrico a Pronti
MPEG	Mercato dei Prodotti Giornalieri
MSD	Mercato dei Servizi di Dispacciamento
NTC	Net Transfer Capacity
PNIEC	Piano Nazionale Integrato Energia e Clima
PPA	Power Purchase Agreement
PSV	Punto di Scambio Virtuale
PUN	Prezzo Unico Nazionale
PV	Photovoltaics
RES	Renewable Energy Sources
RoR	Run-on-River
RSE	Ricerca sul Sistema Energetico
SEN	Strategia Energetica Nazionale
TSO	Transmission System Operator
UML	Unified Modeling Language
VENF	Valore Energia Non Fornita
VRE	Variable Renewable Energy

List of Symbols

η	Power Plants Efficiency
CDP	Available Capacity in Probability
CDPz	Available Capacity in Probability - zone
CMR	Capacity Market Revenue
CNORD	Middle-North
CP	CO_2 Price
CSS	Clean Spark Spread
CSUD	Middle-South
D	Total Load
Da	Self-consumption
Di	Load - zone
Dnt	Total Net Load
Eg	Gas-fired generation
Egd	Gas-fired power generation traded on MSD
Eggp	Gas-fired power generation traded on MGP
Eh	Hydro generation
Ei	Generation from a single commodity
Ep	Pumping consumption
Epv	Photovoltaic generation
Etot	Total generation
Ew	Wind generation
Ewr	RoR Hydro generation
FYPz	Fixed Yearly Premium
Hr	RoR Hydro Installed Capacity
I	Import
N	MSD ex-ante Offers
Nz	MSD ex-ante Offers - zone
OF	Thermal Capacity (Partial Outage)
P	Installed Thermal Capacity - Italy
Pa	Available Thermal Capacity - Italy

Pb	MB Price
Pbz	MB Purchases - zone
Pd	MSD ex-ante Price
Pdz	MSD ex-ante Purchases - zone
Ph	Net Hydro generation
Pi	MI Price
Piz	MI Price - zone
Po	Partial Thermal Capacity Outage
PPb	MB Purchases Price
PPbz	MB Purchases Price - zone
PPd	MSD ex-ante Purchases Price
PPdz	MSD ex-ante Purchases Price - zone
PSb	MB Sales Price
PSbz	MB Sales Price - zone
PSd	MSD ex-ante Sales Price - zone
PSdz	MSD ex-ante Sales Price
PVy	PV production factor
Pz	Installed Thermal Capacity - zone
P*	Equilibrium Price
Qgp	MGP Quantity
Qb	MSD ex-ante Quantity
Qd	MSD Quantity
Qe	EUA tradings on EEX
Qi	MI Quantity
Qiz	MI Quantity - zone
R	Operational Reserve
RL	Residual Load
RLR	Residual Load Ramp
RM%	Margin of Minimum Reserve
SARD	Sardinia
SICI	Sicily
Sb	MB Sales
Sbz	MB Sales - zone
Sd	MSD ex-ante Sales
Sdz	MSD ex-ante Sales - zone
SS	Spark Spread
VR	Variable Renewable generation
W	Wind installed capacity
Wy	Wind production factor

List of Units of Measure

Eur	Euro
GW	Gigawatt
GWh	Gigawatt-hour
Hz	Hertz
MW	Megawatt
MWh	Megawatt-hour
ton	Tonne
TWh	Teraawatt-hour
V	Volt

Chapter 1

Introduction

As the scientific community rises concerns on greenhouse gas (GHG) emissions and their effects on climate change [1], decision-makers worldwide, including European Union (EU) [2] and Italian governments [3], have set progressive environmental targets with the aim of emissions reduction. As the energy sector is estimated to be responsible for 73% of global GHG emissions, typically in the form of CO_2 emissions deriving from fossil fuels combustion [4], decarbonization of the energy sector is currently perceived as one of the most feasible solutions to fight climate change. As a consequence, energy systems worldwide are unavoidably tackling an energy transition: a pathway for the transformation from a fossil-based to a zero-carbon global energy system [5], based on the adoption of Renewable Energy Sources (RES) and nuclear energy.
However, for decades the role of energy systems has also been critical for countries prosperity and competitiveness: since 1923, countries joined the World Energy Council to discuss issues in the world of energy [6]. As such, together with environmental sustainability, the implications of the energy transition must be considered with respect to other relevant dimensions [7]. While energy affordability has always been a priority for countries, historical developments drew their attention to the theme of energy security, especially since the oil crisis of 1973 and the subsequent foundation of International Energy Agency (IEA) [8].
For these reasons, the World Energy Council currently defines the Energy Trilemma [7]. The Energy Trilemma is the «challenge of a secure, affordable and environmentally sustainable energy supply» [9], representing energy sustainability as a triangle made of three sides: security, equity and environmental sustainability (Figure 1.1). [7]. While environmental sustainability and equity dimensions typically benefit from the growth of renewable energy (but controversies exist for both, for example see [10] and [11]), the evolution of energy systems involves all the three sustainability dimensions. As balanced advances in all of them must be ensured in light of the energy transition [7], both opportunities and threats must be considered for these

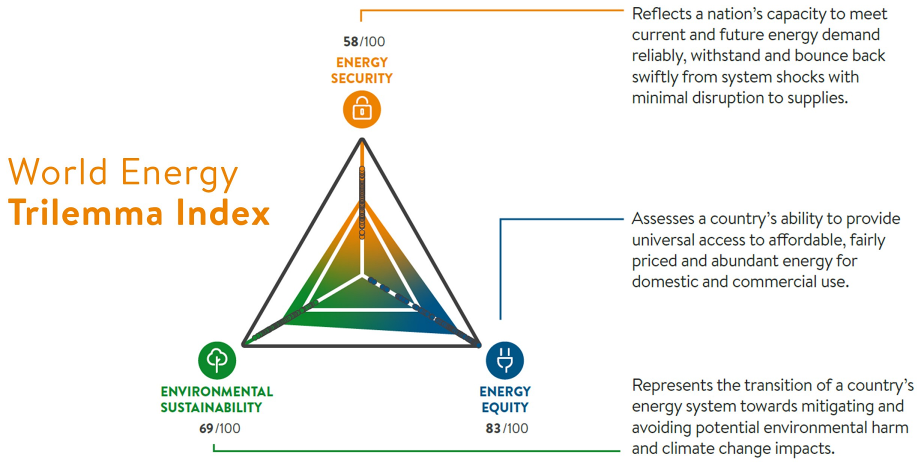

Figure 1.1: Energy Trilemma Dimensions, World Energy Council [7]

dimensions, and specifically for energy security.
In this context, the definition of quantitative methods to monitor the evolution of the Trilemma is a need of increasing relevance, which is usually met by the definition and calculation of numerical indexes. Although reports from the World Energy Council provide comparable results for indexes between different nations [7], countries might perform their own analysis to keep track of the evolution of their energy systems in their most critical aspects. In Italy, this task is assigned in the national interest to ENEA, the National Agency for new technologies, energy and sustainable economic development.
Among the three dimensions of the Energy Trilemma, an assessment of energy security in Italy is considered for this thesis. National energy security is currently referred to three critical commodities: oil, gas, electricity [9]. However, while oil and gas are left to further studies, such as [12], here electricity security is analysed. The work, held by the candidate on behalf of ENEA and the Energy Security Transition Lab from Energy Center in Turin, is intended to define numerical indexes to assess electricity security, and related work-flow and computation methods, in light of the energy transition and the increasing role of renewable energy in power generation.
Chapter 1 is an introduction to the concepts of energy transition and Energy Trilemma, explaining the goal and structure of the thesis; Chapter 2 illustrates the context of the energy transition in Italy, including emissions targets and expected evolutions in the energy mix; based on literature review, Chapter 3 provides a general framework for energy security indexes definition, and its implementation

to electricity security; Chapter 4 focuses on quantitative assessment of electricity security, defining indexes computation and aggregation process, including identification and referencing of public datasets (and single data inside them), data classification into structured property databases, data storage and public access through dedicated platform; Chapter 5 discusses evolutionary trends of electricity security based on numerical results from 2018 to 2020; finally, conclusions are summarized in Chapter 6.

Chapter 2

Emerging scenarios for the energy transition in Italy

Within the international context defined in Chapter 1, EU defined increasingly challenging targets with the goal to fight climate change and make the planet stay "well below" the threshold of a 2 °C global average temperature increase, as stated from the Paris Agreement [13]. The most up-to-date European roadmap is the Green Deal from 2019, with the aim for the EU to become the first continent to reach a net-zero emissions climate target by 2050 [2]. While GHG emissions at European level reduced by 23% since 1990, the same trend is not sufficient to reach climate neutrality by 2050: as such, an intermediate target of a 55% reduction with respect to 1990 levels is set for 2030 [2].
EU directives have been transposed by the Italian government in the Integrated National Energy and Climate Plan (Piano Nazionale Integrato per l'Energia e il Clima, PNIEC), published by the Italian Ministry of Economic Development in December 2019. This document requires RES contribution to total energy consumption in the country to grow at 30 %, according to the evolutive scenario shown in Figure 2.1

Specifically, the largest effort is required from the power sector, as RES contribution to electricity consumption is expected to increase up to 55% by 2030, thanks to country's phase-out from coal by 2025 (Figure 2.2). [3]

Increasing share of renewable energy includes all available resources, but the most relevant growth of power generation is expected to come from wind and solar power, which have the highest growth potential [3]. The evolution of the renewable electricity mix is shown in Figure 2.3. Solar power is expected to become the first renewable source in the national electricity mix, overcoming hydro power and almost tripling total generation with respect to 2017; in parallel, generation from wind farms is going to double, achieving a total value of 40 TWh and getting closer

Figure 2.1: RES share of total energy consumption. Italy, 2011-2030 scenario, PNIEC [3]

to targets for hydro generation. Finally, contributions coming from bioenergy and geothermal energy are going to remain almost stable.

Contextually, installed capacity for renewable energy, currently composing 18% of the total installed capacity, is expected to grow up to 30%; as a result, overall installed capacity in Italy must increase of more than one third, from 115 to 155 GW. The largest contribution to this increase will come from solar photovoltaics, with a more than doubled capacity from 20 to 52 GW; similarly, wind power capacity must double (from about 10 up to 19.3 GW) to meet PNIEC) targets. [3], [14]
Undoubtedly, this evolution of the Italian electricity mix would contribute to meet national and European emission reduction targets; however, as the largest

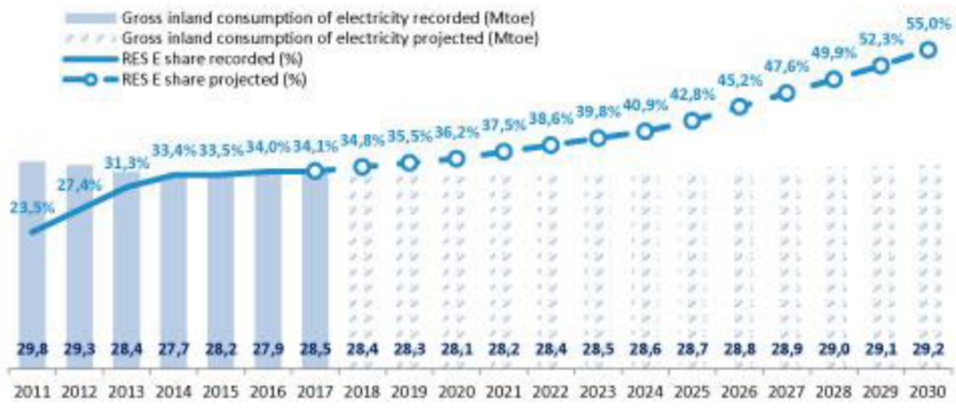

Figure 2.2: RES share of total electricity consumption. Italy, 2011-2030 scenario, PNIEC [3]

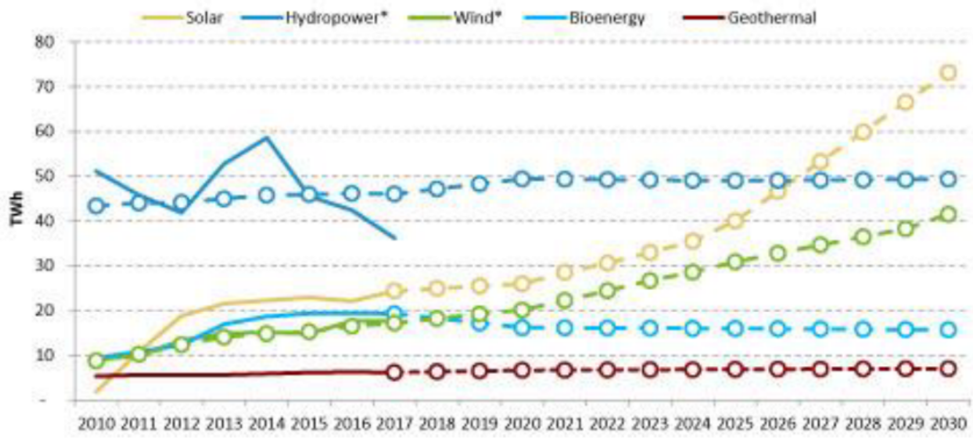

Figure 2.3: RES share of total electricity consumption by source. Italy, 2010-2030 scenario, PNIEC [3]

increase in power generation and installed capacity is expected to come from unconventional energy sources such as wind and solar, their techno-economic characteristics constitute threats to electricity security, as widely described in Chapter 3. Since environmental targets must be reached without compromising energy affordability and security, Italy's National Energy Strategy (Strategia Energetica Nazionale, SEN) from 2017 describes the framework through which the energy transition must be implemented in the country [15]. The document is built according to three fundamental goals, reflecting the three dimensions of the Energy Trilemma [9]:

- meeting European 2030 targets in terms of environmental sustainability with respect to decarbonization of the energy sector;
- reducing the gap in energy prices between Italy and rest of European Union (EU), ensuring competitiveness to the country;
- increasing security and flexibility in energy supply and infrastructures.

ENEA analysis is performed in light of Italy's national targets, which are currently defined according to the aforementioned plans. Specifically, ENEA quarterly analysis is carried out with the aim of assessing the evolution of the Italian energy system with respect to Trilemma dimensions, computing a synthetic index for energy security, prices and decarbonization (Indice Sicurezza energetica, PRezzo Energia e Decarbonizzazione, ISPRED). The main purpose of the analysis is the evaluation of country's progress within the context of the energy transition and according to the targets; nevertheless, the same instrument can also detect anomalies and disruptive effects on the energy system due to economic crisis, such as the recent due to Covid-19 outbreak, able to prefigure future scenarios of the energy transition at high share of VRE. [9]

Chapter 3

Framework definition for energy and electricity security

As the aim of the thesis is a quantitative assessment of electricity security, this section aims to lay down a conceptual framework for energy security definition, and a more detailed one for electricity security. Section 3.1 defines energy security with respect to primary and secondary commodities supply from the external and the home front, and with respect to possible threats to physical and economic systems; as the quantitative assessment of the thesis focuses on electricity security, Section 3.2 is an introduction to the operation of the Italian power system, in terms of both infrastructures and markets; Section 3.3 collects definitions from literature to understand how electricity security can be organized in a systematic analysis, defining its categories; Section 3.4 provides an overview on the energy transition impacts to be monitored with respect to electricity security.

3.1 Energy security definitions and framework

This chapter is intended to select a definition for energy security and define a conceptual framework for its quantitative assessment.
The need for selecting a unique definition rises as no clear consensus on what is energy security exists in literature. In spite of this, the definition is here selected based on the criteria of a clear distinction of energy security from the other dimensions of the Energy Trilemma explained in Chapter 1.
Traditionally, energy security is linked to the concept of the 4 As, including Availability, Accessibility, Affordability and Acceptability. By Availability, physical

availability of resources is intended; Accessibility deals with geopolitical aspects associated with accessing resources; Affordability is linked to end-users economic access to energy and the theme of Energy Poverty; Acceptability implies that public opinion must be aware and supporting energy policies. [16]
According to IEA energy security is "the uninterrupted availability of energy sources at an affordable price" [17]; an even wider definition can be found in [18], defining security as "equitably providing available, affordable, reliable, efficient, environmentally benign, proactively governed and socially acceptable energy services to end-users".
These definitions typically overlap with other energy dimensions, such as equity and sometimes environmental sustainability. Even though energy dimensions can never be fully separated, further definitions focus on aspects specifically related to energy supply. Security is defined by [19] as "the continuity of energy supplies relative to demand"; similarly, [16] defines security as "low vulnerability of vital systems"; consistently with the Energy Trilemma definition, the World Energy Council [7] defines energy security as nation's capacity to meet current and future energy demand reliably, withstand and bounce back swiftly from system shocks with minimal disruption to supplies. The dimension covers the effectiveness of management of domestic and external energy sources, as well as the reliability and resilience of energy infrastructure.
The last definition focuses on energy supply and coincides with the concept of reliability introduced in Section 3.3.1; in addition, the theme of domestic and external fronts of energy supply is introduced. Therefore, the World Energy Council definition is here adopted.
National energy security for Italy depends on the possibility of ensuring the availability of three fundamental commodities: oil, gas and electricity.
When commodities are extracted from natural deposits or imported from foreign countries, they are considered as primary commodities. On the other hand, secondary commodities derive from conversions from primary commodities, usually performed in dedicated infrastructures. As such, the security of commodities depends on both the security of supply for primary commodities and the security of the commodities in the country. In other words, the security of commodities must be ensured with respect to two different fronts: an external front, related to imports, and a domestic front, related to commodities infrastructures and markets.
The external front consists of primary commodities imports. This front is composed by an economic system, formed by import tradings, and a physical system, including the following [12]:

- the source, or the commodity itself;
- a corridor through which the commodity is transmitted. Captive corridors are built onshore, while open-sea are maritime corridors;

- a national Entry Point, where physical infrastructures of different countries are connected.

As the security of primary commodities with respect to the internal front is not critical, security for the domestic front is related to the secondary commodity. Similarly to the external front, it constitutes of a physical system and an economic system.
Specifically, commodity physical infrastructures consist of the following subsystems:

- generation subsystems convert primary commodities into usable secondary commodities;
- transmission subsystem is the physical infrastructures that traditionally transmits the commodity from generation and import subsystems across the country. For natural gas, it consists of transmission pipelines covering the whole territory. As transmission in countries provided with advanced and widespread energy infrastructures is a natural monopoly [20], it is managed by a single operator for each commodity;
- distribution subsystems are the physical infrastructures connected to the transmission subsystem, and delivering the commodity to final users. Companies responsible for the correct operation of physical distribution infrastructures in Europe operate according to a natural monopoly [20];
- foreign interconnection subsystems enable commodity transmission among countries. For the purpose of this thesis, imports represent conversions of primary commodities from foreign countries into secondary commodities available for the Italian energy system. In the example of natural gas, these subsystems can be represented by national Entry Points.

The economic system instead is here classified into the following subsystems:

- commodity markets. They include all markets where the commodity is traded as a secondary commodity, including all tradings in the home front. For natural gas, it includes natural gas markets operated by GME [21] in the country and the Virtual Trading Point operated by Italian gas TSO Snam [22].
- imports. They include all tradings of the commodity as a primary commodity from the external front. For natural gas, international tradings and Stock Markets are included;
- other commodities markets: they include all markets where the commodity itself is not traded, but other relevant commodities to the main one are traded instead;

- investments: as investments decisions affect long-term security for the economic system and decreasing profits might hinder investments on the commodity sector, investments monitoring is required [23].

Finally, the evaluation of energy security are here evaluated in terms of risk conditions, listing and assessing the threats the system is subject to. On both the external and the domestic front, and with respect to both physical and economic systems, energy security is exposed to threats. In general, threats are defined as potential cause of unexpected events, able to jeopardize a system or an organization. Threats are in potency, so they have potential to arise initiative events, which might cause damages or failures to the system; threats can be classified as natural, accidental, intentional and systemic. When initiative events originate from threats, impacts materialize in a certain part of the system; impacts are not in potency, but in act, and they are the cause of damages and failures. Examples of natural threats include extreme meteorological events such as heat wave, tornado, lighting, and also geological hazards like earthquakes, tsunamis, landslides, volcanic eruption; accidental threats include operational mistakes, maintenance failures, and equipment malfunctions; intentional or malicious threats include terrorism or crime including cyber-attacks, rioting, product tampering, explosions bombing; systemic threats involve the evolution of the power system as a whole, and can not be classified into any of the aforementioned typologies. [24]
A review of the framework is proposed below. While this conceptual framework indifferently applies to oil, gas and electricity, this work focuses on electricity security. Therefore, a detailed description of the Italian power system according to the framework, describing commodities, fronts, systems and subsystems, is reported in Section 3.2.

3.2 Operating principles of the Italian power system

Consistently with the framework, electricity can be regarded as a primary (while coming from imports) or a secondary commodity (deriving from the conversion of primary commodities). Primary commodities for Italy currently include the following: oil, gas, coal, biomass, RES. As a consequence, electricity security is evaluated with respect to an external front (related to electricity as a primary commodity coming from foreign countries, and to primary commodities supply) and a home front, where electricity security is evaluated with respect to commodities infrastructures and markets.
The external front includes a physical system (structured into sources, corridors and entry points) and an economic system (consisting of import tradings). Even though the same conceptual framework adopted in Section 3.1 applies to oil and

gas, this front is beyond the scope of the thesis and left to other studies, such as [12].
Similarly to the external front, the home front includes its own physical and economic systems: as electricity security is here evaluated with respect to these systems, an understanding on their operation is necessary. A description of the Italian power system, in terms of both infrastructures and markets, is reported in Section 3.2.1 and Section 3.2.2 respectively.

3.2.1 Physical system

Power system infrastructures composing the physical system can be classified into the following subsystems:

- generation subsystems convert primary commodities into electricity, the usable secondary commodity. Additional sources such as energy storage or demand flexibility are regarded as generation subsystems in the scope of this thesis. Conversion technologies from each source differ by technical and economic parameters, which are the most relevant to the scope of the thesis, as described in Section 3.4;

- transmission subsystem is the physical infrastructure that traditionally transmits the commodity across the country. Although distributed generation and Demand Side Management represent emerging phenomena at national level [25], as described in Section 3.4 transmission grid is still based on a conventional paradigm [24]: centralized generation and imports are the generation side, supplying electricity to the grid; distribution subsystems all over the country represent the load, drawing electricity from the grid. The load varies according to users desires and independently from generation: therefore, a real-time balance between generation and load must be ensured adapting electricity supply to the load. Terna is the Italian Transmission System Operator (TSO) [23], responsible for guaranteeing this real-time balance to the grid and ensuring power flow across transmission grids in the whole country; [26]

- distribution subsytems are the physical infrastructures delivering electricity to final users. Companies responsible for the correct operation of physical distribution infrastructures are called Distribution System Operators or DSOs; [23]

- foreign interconnection subsystems enable power transmission among countries. National transmission lines at European level are interconnected by numerous interconnection, even though limited by their power capacity (Net Transfer Capacity, NTC), and TSOs all belong to the European Newtork of Transmission System Operators called ENTSO-E [23]. According to the framework introduced in Section 3.1, foreign interconnections represent the Entry point for electricity as a primary commodity.

While electricity security from the point of view of DSOs and imports is beyond the scope of the thesis, this work will focus on generation and transmission subsystems. For these subsystems, a focus is proposed in Section 3.2.1 and Section 3.2.1.

Generation subsystem

The role of generation subsystems in the power system consists in the conversion of primary commodities into electricity. Depending on their technical characteristics, power generation units can be classified into different categories:

- primary resources are classified into fossil fuels (coal, gas, oil) or RES (hydro, solar, wind, geothermal energy); biomass is here excluded from these categories, since it is a non-fossil fuel but not fully renewable as well, especially because of its environmental impacts [27]; secondary resources are constituted by electricity itself (for example in the case of pumped hydro energy storage) and reduced electricity consumption (as happening for Demand Side Management) [28];

- generation technologies are classified into conventional (such as coal, oil, natural gas, hydro, biomass, geothermal) and unconventional or Variable Renewable Energy (wind and solar power, VRE) [29]. Conventional technologies have direct grid connection by means of rotating masses [30]. For example, coal and gas-fired power plants generate hot pressurized fluids (hot water in case of Rankine cycles, or a mix between air and gas in case of Joule cycles) from the combustion of fossil fuels and convert it into mechanical energy rotating turbines [31]; similarly, hydro power plants exploit potential energy from water and convert into mechanical energy using hydraulic turbines [32]. For all conventional technologies, mechanical energy must then be converted into alternate current (AC) with electric machines called generators [30].
  Differently, unconventional technologies such as VRE do not allow direct grid connection. Specifically, wind power converts wind energy into mechanical energy using wind turbines, but in this case AC generation does not imply grid connection: in fact, because of wind intermittency, dedicated devices such as fixed speed wind turbines or Doubly Fed Induction Generators (DFIG) are used for this purpose. [30]
  Finally, solar photovoltaics PV converts solar energy into Direct Current DC: as DC can not be directly injected into the grid, an inverter converting it into AC is required and PV is not coupled with the grid [33];

- generators can be classified into dispatchable and non dispatchable units. The former include all units able to schedule production, including coal and gas fired power plants, biomass, waste, reservoir hydro and pumped hydro. The latter include Run-on-River RoR hydro plants, solar and wind farms, whose variability can not be controlled by generators [34];

- finally, based on the unit location, centralized and distributed generation are possible. While centralized configuration is typical of the traditional structure of the power system and includes both conventional generators and VRE, distributed generation typically consists of small scale solar units with the purpose of self-consumption or selling energy back to the grid. As such, pioneers of distributed generation are regarded as the challengers of the system, while owners of centralized power plants are regarded as incumbents [35].

Transmission subsystem

Transmission grid operation is responsibility of TSOs, who ensure that grid balance between generation and load is respected time after time. This balance must not be violated because of energy conservation principles, and especially because of some technical properties of the power system itself. As mentioned in Section 3.2.1, grid balance is maintained by an equilibrium between generation and load: specifically, conventional generators contributing to this equilibrium are grid connected by means of electrical generators. The rotation speed of these rotating machines guarantees that the output current is kept as close as possible to the nominal frequency value of 50 Hz: as these rotating devices are all interconnected by means of the power grid, the frequency of the whole system remains in equilibrium thanks to the generators [30].
Based on the variations detected in grid frequency, machines slightly adjust power generation to keep frequency stable around its nominal value: if frequency is dropping, machines increase their generation and rotating speed to counterbalance the drop; if frequency increase, the opposite phenomenon happens. When unbalances in grid frequency overcome technical limits, generators disconnect from the grid for safety reasons, causing large drops in grid frequency: a positive feedback mechanism is activated, and a grid blackout is possible. As such, TSO prevents unbalances by taking care of the supply of sufficient energy resources on the electricity markets, as well as by dispatching them according to grid constraints. [36]

3.2.2 Economic system

Even though the economic system does not contain any physical infrastructure, it is fundamental to guarantee electricity supply [23]. Specifically, the Italian economic system operates under conditions of free competition and liberalized markets [37]. However, and differently from other commodity markets, the power system is subject to grid constraints which are not reflected in market rules and operation

[23]; moreover, fundamental services to ensure the correct operation of the system are subject to competitive market laws [37], making electricity economic system an exception with respect to its counterparts. The economic system is here classified into the following subsystems:

- electricity markets. They include all markets where electricity is traded as a secondary commodity, including all tradings in the home front; [37]
- imports. They include all tradings of electricity as a primary commodity from the external front;
- other commodities markets: they include natural gas market [21] and the European carbon market [38], as they affect net revenues for generators;
- investments on the power sector: investments decisions affect long-term security for the economic system, as well as decreasing profits might hinder investments on the power sector [23].

While electricity import markets and investments analysis are both beyond the scope of this study, an understanding on the operating principles of energy markets is required. As such, a detailed description of the Italian electricity and commodity markets is reported in the following paragraphs.

Italian electricity markets

Although electricity can be traded independently through financial markets or Power Purchase Agreements [39], the largest volumes of energy are currently traded in spot electricity markets (Mercato Elettrico a Pronti, MPE) [37]. Based on the rules established by Gestore dei Mercati Energetici (GME), Italian electricity markets on MPE are regulated according to a time structure, where generation and load start to be traded for the next day according to forecasts, and forecasting errors are progressively adjusted as the time of physical flows gets closer [37]. As competitive markets are considered a fundamental instrument to reach efficient commodity pricing, Italian electricity markets are based on free competition [37]. With the exception of Mercato dei Prodotti Giornalieri (MPEG), which is not covered by this analysis, the main characteristics of other MPE markets are summarized in this chapter.
MGP (Mercato del Giorno Prima) or Day-Ahead market is used for electricity tradings for the next day. Buyers claim the maximum price they are willing to pay for electricity and their expected demand; sellers offer their generation, according to their plants' expected production, at the minimum price they are willing to receive. Electricity is traded according to economic merit, so that supply and demand curves intersect and the amount of traded electricity is defined. Electricity is traded

at the equilibrium price where the curves meet (marginal cost), regardless from the value of each offer. The same trading procedure is repeated in each bidding area, according to a geographical division of the country: in each zone, a different price is set by the market. The definition of the equilibrium price (or clearing price) is represented in Figure 3.1. The blue line represents offers from generators (Curva di offerta); the black line represents offers from consumers (Curva di domanda); the intersection represents the equilibirium condition: the amount of traded electricity can be obtained through the dashed black line on the x-axis (Quantità di equilibrio), while clearing price can be obtained through the dashed green line on the y-axis (P* - Prezzo di equilibrio).

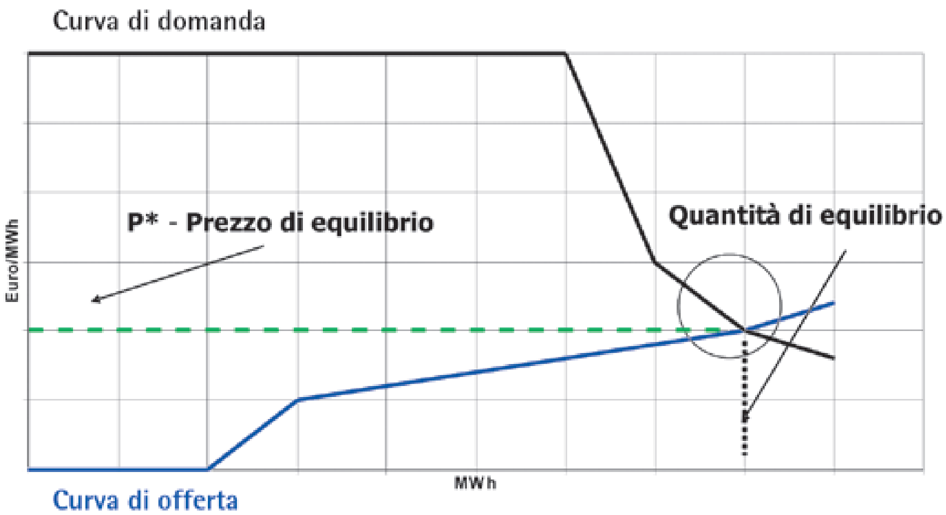

Figure 3.1: Definition of the equilibrium price on energy markets, Gestore dei Mercati Energetici (GME) [37]

Nevertheless, a national electricity price for Italy is defined as a weighted average of all prices and is called Prezzo Unico Nazionale (PUN); both sellers and buyers trade electricity at this national price. [37]
MI (Mercato Infragionaliero) is the Intraday market used by both buyers and sellers to adjust their forecasts of electricity generation and demand. Differently from MGP, electricity is traded at the local bidding zone price, and no national price is defined.[37]
MSD (Mercato dei Servizi di Dispacciamento) is the place to trade electricity for ancillaery services [37]. Italian TSO Terna is the main operator of the market, being it responsible for the correct management and balancing of the Italin transmission grid, ensuring real time equilibrium between supply and demand to the power system [26]. Differently from energy markets (MGP and MI), commodity tradings

on service markets in MSD are not based on the definition of a marginal price [37]. Operators formulate their purchase or sale offers: based on system's need for ancillary services and on merit-order criteria, offers are rejected or accepted by Terna [37]. Operators whose purchase or sale offers are accepted get paid for the same value of the offer, according to a Pay-as-bid methodology [37].
Ancillary services consist of fundamental services managed by Terna in order to ensure the correct operation of the power system, and they are traded in two different markets [40]:

- MSD ex-ante consists of market offers to satisfy Terna's requirement for ancillary services [37]. Ancillary services include congestion management, secondary reserves and tertiary reserves. Congestion management is required to schedule grid operation in order to satisfy technical constraints in power transmission across the grid; secondary reserves guarantee a reserve to be activated by a centralized automatic regulation system, with the purpose of maintaining grid frequency as close as possible to its nominal value of 50 Hz; tertiary reserves are used to restore reserve margins after the activation of secondary reserves; [40]

- Balancing Market (Mercato di Bianciamento, MB) guarantees real-time balance between load and generation, activating reserves accepted during MSD ex-ante for congestion management and ensuring the activation of reserves: secondary reserves are activated to take grid frequency back to its nominal value of 50 Hz in case of deviations; tertiary reserves are activated to restore secondary reserves when activated; primary reserves are activated in a very short time to ensure real-time grid balance between load and generation, before secondary reserves are activated to restore nominal frequency. Balancing markets are divided into two different service typologies: a first one is dedicated to secondary reserves only; a second one include all the other services. [40]

Capacity Market

Although ancillary services include fundamental services for a correct grid operation, they are traded according to the competitive market principle [37]. In spite of this, a Capacity Market has been introduced in 2019, with the goal of providing a revenue to those generators who guarantee power capacity to Terna for power system management [41]. Generators who apply for this specific market ensure long-term power capacity to the system, and get paid at a fixed yearly revenue regardless of their actual energy generation [41]. Italian regulator ARERA fixes a strike price at which all the operators applying to this market can offer energy to Terna: when the price of electricity overcomes this limit, sellers have to give the price difference back to Terna [41].

Although capacity is traditionally provided by dispatchable generators (including energy storage units) also non dispatchable generators such as VRE and Demand Response unit can participate to Capacity Market [41]. Generation units are classified according to their technical properties:

- based on size parameters, units offering at least 10 MVA of capacity are defined Relevant Generation Units;
- based on permissions to operate on different markets, units unauthorized to participate to MGP, or to MSD from at least 6 months, or starting a dismantling procedure, are defined Unavailable Generation Units;
- based on the state of their construction, qualification or possible repowering, generation units can be classified into Existing, New, or Repowering. New and Repowering Units which concluded the authorization process are defined Authorized Generation units
- according to their flexibility characteristics, generation units are defined Flexible Generation Units if meeting the following requirements: start-up time lower than 4 hours; minimum online time lower than 4 hours; minimum offline time lower than 4 hours; an equal or higher gradient with respect to minimum Grid Code required for secondary regulation; minimum over maximum power capacity ratio less or equal than 0.5 (this is assumed to be automatically satisfied by all generators with a start-up time lower than 2 hours) [42]. Minimum online and offline time is automatically satisfied by hydro plants, except for Run-on-River hydro [40].

Accepted units are obliged to offer capacity for MGP and MI, while unsold quantities remain available for MSD.
Capacity market operation is carried out by TSO, which sets competitive auctions where generators apply to ensure long-term capacity: auctions refer to a time span of one year for existing units and 15 years for new generators [43]. Purchased capacity is established based on probabilistic estimations of demand-offer curves in each zone, assuming reliability requirements for the power system as a whole. Specifically, system reliability models include [43]:

- Load scenarios to estimate load curves in each zone.
- Available capacity from each unit, depending on unit typology (efficiency, prevalent fuel), historical data for partial or total outage, incentives; generation profiles for non dispatchable units are estimated based on expected installed capacity and production, with the help of weather forecasts.
- Appropriate equivalent models for transmission constraints between zones.

As a result, this approach defines additional capacity requirements in each area, in such a way that Loss of Load Expectation (LOLE), consisting in the number of hours in a year where load sheds are expected [25], respects reliability constraints.

Natural gas markets

As mentioned in Section 3.2.2, electricity prices and revenues for generators are affected by the evolution of competitive markets for other commodities. Specifically, the operation of natural gas markets is of significant interest for all generators operating in spot electricity markets for two reasons. Firstly, generators operating gas-fired power plants purchase natural gas: purchases can happen on different markets, but natural gas prices in all of them are similar and represent one of the most significant cost items for generators themselves [31]: therefore, the lower the gas price, the higher the profitability of power plants and vice-versa. Secondly, the national electricity price at which all generators on competitive markets are rewarded, regardless of the primary commodity they rely on, is set according to the clearing price principle described in Section 3.2.2: as the clearing price is set according to the merit-order principle, it is frequent that the price of electricity is fixed by the offers from gas-fired generators. For this reason, the higher the price of natural gas, the higher the market price and the corresponding revenues for all generators except for gas-fired power plants [29]. For these reasons, monitoring natural gas markets is of crucial importance when analyzing the economic system from an electricity security perspective.
Differently from electricity, international tradings of natural gas are possible and common: natural gas net imports reached a level of 65.8 Gm^3 of volume in 2018, accounting for more than 10 times the national net production [44]. However, the domestic front is the only one of interest for the analysis.
Natural gas domestic tradings in the wholesale markets mainly happen in the Virtual Trading Point (Punto di Scambio Virtuale, PSV), consisting of 165 Gm^3 and covering about 77% of total wholesale gas tradings [44]. PSV is operated by Snam, Italian TSO for natural gas [22]: average gas price at PSV is estimated by GME newsletters on a monthly basis, as its operation does not allow a unique definition of the gas price [22]. On the contrary, smaller volumes (less than 7 Gm^3) are traded on the new born spot market found by GME. The structure of natural gas spot markets mirrors electricity markets: the main market session is a Day-Ahead market (MGP-Gas), where operators can sell or purchase the commodity according to merit-order principle [21].

Carbon market

Carbon markets have been created worldwide with the purpose of emissions reduction. Specifically, EU carbon market consists of a "cap and trade" system: a

fixed limit ("cap") for total emissions is set by means of allowances, which are made available on a primary market ("trade"). Each allowance (European Union Allowance, EUA represents a permit, sold by EU on primary markets, to emit one of CO_2. The limit is currently in force for specific sectors only, including the power sector: generators operating fossil-based power plants are obliged to purchase the allowances from both primary or secondary markets, and they must stay below emission limits to avoid additional taxation. Money collected from EU are then reinvested for decarbonization purposes. [38]
The primary market is operated on the European Energy Exchange (EEX) platform, and its operating principle is based on auctioning. Differently from other commodities, carbon allowances are not traded on a daily or even hourly basis on the primary market, which is actually open about three days a week (Mondays, Tuesdays and Thursdays) for EUA allocation all over the EU; exceptions are made for Poland and Germany, which represent the largest emitters in absolute value, and carbon trading for these countries is held on Wednesdays and Fridays respectively. [45]
As mentioned, carbon trading is also allowed on secondary markets [46]: as a consequence, carbon price is estimated, based on continuous trading on stock markets, by several agencies. In the following, estimations are assumed to be sufficiently accurate only taking into account primary auctions, while secondary markets are not covered by the analysis.

3.3 Categories definition for electricity security

As discussed at the beginning of Chapter 3, electricity security can be referred to different kind of threats, jeopardizing an external front (security of supply) and a home front (security of physical infrastructures and markets). Security assessment for the home front, including both physical and economic systems, is referred to different temporal time-scales (from microseconds up to decades): according to this criterion, security can be classified into System Planning (long-term), Scheduling and Operation (medium-term), System Operation (short-term and very short-term). The focus of this study is an assessment of electricity security with respect to systemic threats to both physical and economic systems in the home front. As no unique definitions exist for security in general or specific security categories, a literature review on the subject is reported in Section 3.3.1. After comparisons from cited references, categories are selected for the analysis, and unique definitions are reported to coherently and systematically evaluate electricity security in Section 3.3.2.

3.3.1 Literature Review

In the following paragraph, a literature review on electricity security definitions is collected. As the objective of the analysis is the definition of a conceptual framework for electricity security at national level, priority to definitions is here given to glossaries from TSOs who operate for Italian electricity security. As such, definitions are mostly taken from Italian TSO Terna and European TSOs association ENTSO-E. Nonetheless, in light of the need of detailed analysis for specific categories, and especially with respect to the effect of RES in terms of electricity security, other definitions from literature are reported and compared.

- Reliability is defined by ENTSO-E [24] as the ability of the system to deliver electricity to all points of utilization within acceptable standards and in the amounts desired; similarly, Terna [47] links reliability to other categories, as a combination of availability and security. In both cases, this definition appears to be a very general one in terms of electricity security.

- Adequacy is defined by ENTSO-E [24] as the ability of the power system to supply the load in all the steady states in which the power system may exist considering standards conditions; on the contrary, Terna [47] the ability of the system to provide itself with sufficient productive resources, storage,demand management and transmission capacity to satisfy the expected demand, with an adequacy margin for every time unit. While the former refers to a more general aspect, evaluating electricity security in standard conditions, the latter is related to specific requirements for the energy mix; in addition, Adequacy is currently evaluated from energy markets perspective by ENEA [9].

- Security is defined by ENTSO-E [24] as the ability to withstand sudden disturbances, such as electric short circuits or unanticipated losses of system components or load conditions together with operating constraints; another aspect of security is system integrity, which is the ability to maintain interconnected operations. Similarly, Terna [47] defines security as the ability to cope with sudden disturbances, such as electric short circuits or forced outages for the power system components. Both definitions focus on system reaction to sudden disturbances, so that this definition is complementary to Adequacy definition from ENTSO-E.

- Availability is defined by ENTSO-E [24] as the measure of time during which a generating unit, transmission line, ancillary service or another facility is capable of providing service, whether or not it actually is in service; according to Terna [47], availability is the ability to statically and instantly manage global power and energy customers' demand in the points of connection, taking into account planned and forced outages for the power system components.

It can be estimated by the combination of the availability of each subsystem (generation, transmission, distribution, foreign interconnections). In both cases, this definition focuses on the operation of the physical system.

- Stability is defined by ENTSO-E [24] as the ability of an electric system to maintain a state of equilibrium during normal and abnormal system conditions or disturbances; more specifically, a power system is defined as stable by Terna [47] against a specific perturbation occurring, starting from a pre-set initial permanent operating regime if, after the termination of the transient regime, it returns completely to equilibrium. That is, if the synchronous machinery resumes its speed of synchronisation, there is no separation from the grid, the voltages resume their previous values from before the perturbation (if the perturbation is transient) or values approximating the nominal voltage (if the perturbation is permanent). As such, it can be considered a specific aspect of Security definitions reported above.

- Flexibility definitions can be very general or more specifically related to physical power system [28]. For the purpose of this work, flexibility is intended to cover specific aspects of the analysis. According to IEA [48] power system flexibility is the ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales; similarly, flexibility can be defined as the ability to adapt to changes of the net load by using the available resources in a system [49]. However, while the former definition takes into account variability in both supply and demand, the latter definition refers to a conventional paradigm of the power system, where generation adapts to demand.

- Resilience is defined by Terna [47] as the ability of the system to withstand stress that overcome its handling limits and to come back into normal operating conditions, possibly through temporary interventions. Such stress conditions refer to exceptional stress conditions, such as extreme weather events [25]. Differently from the other categories, resilience is not defined with respect to a specific context of the system, since extreme atmospheric conditions influence the operation of the whole system and do not refere to a specific context.

- Quality is defined by Terna [47] as the ability to guarantee the continuation of the service (no interruptions in energy supply, frequency and voltage within admitted ranges) and the quality of the service itself (voltage level, waveform...). In spite of the wide range of examples reported in the definition, quality traditionally refers to interruptions in energy supply to final users and directly involves the role of DSOs.

- Efficiency is defined by Terna [25] as the ability to manage the electric system coping with security, adequacy and quality requirements, at the minimum total cost for the citizen/user. According to this definition, efficiency refers to economic parameters.

Definitions by source are collected in Table 3.1.

Table 3.1: Literature review for electricity security categories.

	ENTSO-E	TERNA	Other
Reliability	The ability of the system to deliver electricity to all points of utilization within acceptable standards and in the amounts desired	A combination of Availability and Security	
Adequacy	The ability of a power system to supply the load in all the steady states in which the power system may exist considering standards conditions	The ability of the system to provide itself with sufficient productive resources, storage,demand management and transmission capacity to satisfy the expected demand, with an adequacy margin for every time unit.	
Security	The ability to withstand sudden disturbances, such as electric short circuits or unanticipated losses of system components or load conditions together with operating constraints. Another aspect of security is system integrity, which is the ability to maintain interconnected operations.	The ability to cope with sudden disturbances, such as electric short circuits or forced outages for the power system components.	
Availability	A measure of time during which a generating unit, transmission line, ancillary service or another facility is capable of providing service, whether or not it actually is in service	The ability to statically and istantly manage global power and energy customers' demand in the points of connection, taking into account planned and forced outages for the power system components.	
Stability	The ability of an electric system to maintain a state of equilibrium during normal and abnormal system conditions or disturbances	A power system is defined as stable against a specific perturbation occurring, starting from a pre-set initial permanent operating regime if, after the termination of the transient regime, it returns completely to equilibrium. That is, if the synchronous machinery resumes its speed of synchronisation, there is no separation from the grid, the voltages resume their previous values from before the perturbation (if the perturbation is transient) or values approximating the nominal voltage (if the perturbation is permanent)	
Flexibility			The ability of a power system to reliably and cost-effectively manage the variability and The ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales./ The ability to adapt to changes of the net load by using the available resources in a system.
Resilience		The ability of the system to whistand stress that overcome its handling limits and to come back into normal operating conditions, possibly through temporary interventions.	
Quality		The ability to guarantee the continuation of the service (no interruptions in energy supply, frequency and voltage within admitted ranges) and the quality of the service itself (voltage level, waveform...)	
Efficiency		The ability to manage the electric system coping with security, adequacy and quality requirements, at the minimum total cost for the citizen/user.	

3.3.2 Categories selection and definition

Based on literature review from the previous section, a framework including categories for electricity security is proposed in this paragraph.
Electricity security is quantified in terms of Reliability. Reliability is here defined as the probability to meet the demand of electricity in a certain time interval [24]; a condition of high reliability is called robustness; on the contrary, a condition of low reliability is called vulnerability [24]. Reliability is evaluated with respect to the provision of the service to final users (residential, industrial...).

Reliability depends on two attributes: Adequacy and Security. Adequacy is the ability of a power system to supply the load in all the steady states in which the power system may exist considering standards conditions, avoiding abnormal operation [24]; Security is ability of the system to react to unexpected events without interruptions in the service [24]. Adequacy issues expose the system to risk conditions, while security problems can be detected in grid operation.
As such, disturbances in long-term and mid-term operation, which are not immediately affecting the service (System Planning, Scheduling and Operation) are considered threats with respect to the adequacy attribute; on the other hand, disturbances in quantities directly measuring systems performance in the short-term (System Operation) are considered threats with respect to the security attribute.
In addition, categories are here assumed to mainly refer to one of the contexts from the physical system (generation, transmission, distribution, foreign interconnection) or the economic system (market, import trading, investment) introduced in the framework.
Therefore, electricity security categories referring to the Adequacy attribute include the following:

- Adequacy, in terms of both System Adequacy as defined by Terna [47] and Market Adequacy by ENEA [9], referring to the generation/import context and to the market context respectively;
- Flexibility, according to IEA definition [48] and referring to the transmission context;
- Market Efficiency, according to Terna definition [25] and referring to the transmission context.

On the other hand, electricity security categories referring to Security attribute include Stability, and specifically Stability as defined by Terna [47], both referring to the the market context.
A review of selected categories for electricity security within the framework defined previously is reported in Table 3.2.

Table 3.2: Selection and definitions of categories for electricity security.

Category	Definition	Source	Attribute	Context
System Adequacy	The ability of the system to provide itself with sufficient productive resources, storage,demand management and transmission capacity to satisfy the expected demand, with an adequacy margin for every time unit.	Terna	Adequacy	Generation/ import
Flexibility	The ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales.	IEA	Adequacy	Transmission
Stability	A power system is defined as stable against a specific perturbation occurring, starting from a pre-set initial permanent operating regime if, after the termination of the transient regime, it returns completely to equilibrium. That is, if the synchronous machinery resumes its speed of synchronisation, there is no separation from the grid, the voltages resume their previous values from before the perturbation (if the perturbation is transient) or values approximating the nominal voltage (if the perturbation is permanent)	Terna	Security	Transmission
Market Adequacy	The ability of the market to provide itself with sufficient productive resources, storage,demand management and transmission capacity to satisfy the expected demand, with an adequacy margin for every time unit.	Terna	Adequacy	Market
Market Efficiency	The ability to manage the electric system coping with security, adequacy and quality requirements, at the minimum total cost for the citizen/user.	Terna	Adequacy	Market

Availability, resilience and quality categories for electricity security exist in literature but are excluded from the framework of this study. Although their relevance is here acknowledged, and examples of the threats and impacts of the energy transition to these categories are discussed in Section 3.4, these categories can not be contextualized into the previously introduced framework, and are not relevant for this analysis; in addition, they are all affected by lack of quantitative assessment from public institutions, or data from public datasets. Both availability and resilience categories focus on a specific threat (such as extreme atmospheric events or components outage), but involve all the physical contexts, while this study attempts to classify categories according to threatened contexts (systems and subsystems) instead of focusing on the threat itself. Moreover, both lack of data and literature influenced the decision to exclude availability, as the download of generation units outage data is not public [50], while transmission grid outage data is only available as Net Transfer Capacity (NTC) with foreign countries [51]. Resilience is excluded because of the lack of data and tradition in indexes definition, even though proposals can be found in literature ([52], [53]). Finally, quality is evaluated in terms of interruptions of the services to final users [25]: however, data are only available on a yearly basis [54]; in addition, the limitation of interruptions to the service is responsibility of DSOs: as such, it is not affecting security at national level. For these reasons, also quality is not covered in this context.

3.4 Aspects of the energy transition influencing electricity security

According to the framework presented in Section 3.1, energy security - and electricity security for the purpose of this study - are evaluated with respect to threats. As mentioned, threats are classified in two four typologies: natural, accidental, intentional and systemic [24]. For example, climate change is a natural threat which is increasingly influencing power system resilience [25] as defined in Section 3.3.1, by causing extreme atmospheric events [1]. Similarly, cyber-attacks represent an example of malicious or intentional threat: being electricity security of crucial importance for national economy and society, and due to grid digitalization process, cybersecurity is a topic of emerging relevance for electricity security [55].
Undoubtedly, climate change and cyber-attacks currently represent two of the most dangerous threats influencing electricity security worldwide, and specifically in the Italian context. However, the focus of this thesis is on the energy transition and its influence on electricity security, as systemic threats caused by the transition jeopardize the domestic front of national electricity security.
As described in Chapter 2 with respect to the context of the energy transition, the largest increase of RES is expected to involve power generation from Variable Renewable Energy, such as wind and solar power [3]. As VRE penetration in the electricity mix increases, its effects to system Reliability is expected to become more and more significant, and the energy transition to cause threats to electricity security for both the physical and the economic system. Nonetheless, the energy transition is generally beneficial in terms of environmental sustainability and equity [5], and further benefits are desirable for national energy security of supply [15]; even for electricity security itself, with respect to the external front of security of supply, can benefit from large deployment of renewable energy, enabling a reduction on country's dependence from imported primary commodities [15]. However this chapter focuses on the threats caused by the energy transition to electricity security, with respect to both the physical and the economic system. Details on systematic threats to the physical and economic systems are explained throughout the following paragraphs, while summary of the threats of the energy transition with respect to selected categories, and the mechanism through which they impact electricity security, is proposed in Section 3.4,

Physical System

For the physical system, technical characteristics of VRE described in Section 3.2.1 are critical within systems at high share of wind and solar generation.
Being VRE generation non dispatchable, their increasing share in the energy mix has deep implications on the physical system in terms of system Adequacy. In fact, while conventional power system provide reliable power capacity as a reserve to be activated, this is not possible for non dispatchable units. In other words, installing VRE capacity is not equivalent to the installation of dispatchable capacity, as generation from the former can not be scheduled. As a result, reserve margins required for system adequacy are put at risk by the energy transition. [25]
Additional concerns come from the variability of intermittent resources: generation from wind and solar power, as well as RoR hydro, is subject to sudden temporal and spatial variations, which are challenging for transmission system management [34].
Specifically, time variability requires adaptation from the rest of the power system, with the adoption of flexibility solutions of every kind, including energy storage and Demand Side Management [28]: however, with respect to the transmission system, the management of times with very high generation from VRE is challenging because of the risk of over-generation [25]. On one hand, increasing installed wind capacity are expected to become more and more frequently able to generate larger and larger amounts of energy [25]; on the other hand, conventional power plants must withstand technical constraints, such as technical minimum generation and minimum online time, and might not be able to reduce power generation below minimum thresholds [56]: as such, exports of electricity at over-generation times become possible, but curtailments of wind over-generation are expected to be an issue for the transmission system as well [25]. Further challenges for the transmission grid coming from time variability include sudden variation of solar generation: while morning load ramps are typically due to consumers' behaviour, evening ramps due to unavailable solar power are expected to require more flexible generation capacity to be covered [25].
In terms of spatial variability, the availability of wind resource is not as homogeneous as solar energy [34], [33]: as wind generation only increases in specific areas of the country, but load centers remain localized far from wind farms, increasing requirements for power transmission capacity are expected to become key to avoid congestions and wind curtailments [25]. Moreover, large deployment of distributed generation, consisting of small-scale PV units, are challenging the centralized structure of the power system as a whole, requiring for example wider collaboration between TSO and DSOs.
Finally, technical characteristics of unconventional generation represent a threat to grid stability. As described in Section 3.2.1, conventional generators (including all

hydro power technologies) are directly connected to the grid by means of electrical generators. The rotation speed of these rotating machines guarantees that the output current is kept as close as possible to the nominal frequency value of 50 Hz, but increasing share of VRE generation can put this stability at risk. In addition, the presence of massive rotating machines directly connected to the grid guarantees inertia to the system, so that sudden variations can be slowed down by their rotating inertia; moreover, generators are equipped with reactive power, able to provide stability to grid voltage level: with respect to these aspects, increasing share of VRE represent a threat to system stability and security.

Economic System

Among the threats of the energy transition to the economic system, market effects and investment uncertainties are the most relevant. While investments are not discussed in the thesis, an analysis of electricity markets within the context of the energy transition is here reported.
According to the vision of ENTSO-E for European IEM (Internal Energy Market), market operation during the energy transition requires adaptation to physical grid constraints of the power system. Indeed, some of the most relevant aspects for electricity markets are already enabled by current market design, which proved to be successful in terms of tradings across countries, as well as competition and increasing liquidity; however, the same design is unable to fully address market efficiency in an energy transition perspective. [23]
Critical aspects to monitor future market efficiency include the following [23]:

- the ability of the market to reflect grid constraints [23]. Specifically, markets should value electricity taking into account these critical parameters, which are mostly related to characteristics explained in Section 3.4:
  - resources contribution to system adequacy [23]: as conventional generation becomes less and less requested in the Day-Ahead market in favour of renewable generation, their profitability is decreasing [29]. In fact, electricity is sold in MGP according to merit-order principle: in spite of their relatively high investment costs, renewables have almost zero variable costs, which make them willing to produce and sell energy on the markets offering zero price; on the other side, coal and gas-fired power plants are based on fuel combustion, making them more costly in terms of variable costs and so willing to sell energy only at a minimum strike price covering these costs [29]. As a consequence, conventional generators are gradually being pushed away from MGP, and MGP market prices are becoming less and less profitable in terms of both quantities and prices: thus, the survival of power plants providing power capacity to the system

  is put at risk, leading to concerns in terms of system adequacy [25]. A market solution to this problem has been recently introduced through the adoption of Capacity Market;
  - generation flexibility: with growing contribution to temporal variability from VRE resources, the ability of power system components to provide flexibility should be valued by markets too [23], as this flexibility is especially required for ancillary services on MSD;
  - resources location: as the share of wind and solar power increases, power availability is expected to be more and more location dependent, and additional requirements in terms of power transmission capacity are going to be required. Location-dependent market signals would mitigate congestion management for TSOs [23];

- the ability to dispatch energy close-to-real-time [23]. In fact, while the largest amounts of energy are traditionally traded through the Day-Ahead Market, a shift in the energy demand from MGP towards shorter duration and smaller size packages is being observed. More in detail, Intraday Markets and MSD are expected to handle larger volumes in order to balance forecasting errors for generation from wind and solar power. Therefore, prices on these markets must be carefully monitored.

- the ability of TSOs to cooperate with DSOs.

As a consequence of this market design, threats to the economic system deriving from the energy transition are becoming critical. With respect to the specific context of electricity markets, threats involve the ability of the market to remunerate generators who are selling fundamental services, such as dispatchable capacity and flexible generation [25]. Therefore, increasing share of VRE represents a threat to market adequacy. Furthermore, increasing need of ancillary services, such as reserves for grid balancing and congestion management, required to counterbalance forecasting errors due to high shares of VRE are expected to lead to lack of resources and increasing costs of supply for ancillary services [25], representing a threat to market efficiency. Overall, the energy transition represents a cause of threats to market idoneity.

Selection of the threats of the energy transition to electricity security

Based on the analysis from the previous paragraphs, this section provides a selection on the threats to electricity security coming from the energy transition, divided by categories and context, together with the description of the mechanism through which threats materialize and have an impact on the system.

- Increasing share of non dispatchable renewable energy, such as wind and solar power together with RoR hydro, represents a threat for the generation context in terms of System Adequacy. In fact, as installed renewable capacity gradually replaces dispatchable units, lack of capacity at times of peak load and low intermittent generation are expected to reduce the adequacy margins.

- Increasing share of intermittent generation from wind and solar power represents a threat to the transmission context in terms of System Flexibility. As the share of VRE increases, steep ramps in the residual load, defined as the difference between the load and intermittent generation in Section 4.2.2, are more likely to impact the system, especially in the evenings; additionally, higher generation from VRE is expected to increase probability of over-generation, reducing the residual load and pushing conventional generation closer to their technical minimum.

- Increasing share of wind and solar power also represents a threat to the transmission context in terms of System Stability. Since solar units and wind farms are not directly connected to the grid by means of rotating machines, decreasing resources for frequency, inertia and voltage regulation are expected to affect grid operation.

- Renewable generation replacing coal and gas-fired power plants from the Day-Ahead market represents a threat to electricity markets in terms of Market Adequacy. Specifically, decreasing volumes and prices on MGP are going to reduce power plants profitability, which is not acceptable as they still provide fundamental services to the system;

- Increasing participation of renewable energy to the market also represents a threat to electricity markets in terms of Market Efficiency. In fact, decreasing profitability for dispatchable and flexible units is expected to bring the system to lack of capacity and flexibility.

- Finally, increasing generation from VRE represents a threat to electricity in terms of Market Efficiency also because of forecasting errors, implying that more and more expensive ancillary services are going to be traded on MSD.

An overall review of all these aspects is reported in Table 3.3.
7

Table 3.3: Threats and impacts of the energy transition on electricity security.

Category	Threats of the transition	Mechanism of the impact of the transition
System Adequacy	Increasing share of non dispatchable renewable energy	Decreasing adequacy margins at peak loads. especially at times with low intermittent generation
System Flexibility	Increasing share of Variable Renewable Energy	Increasing steepness in residual load ramps, requiring steep variation in flexible generation
		Increasing times of over-generation causing curtailments of renewable energy without adequate capacity of energy storage: ramp down margins issues
System Stability	Technical characteristics of photovoltaics and wind farms	Decreasing resources for inertia regulation
		Decreasing resources for voltage regulation
		Decreasing resources for frequency regulation
Market Adequacy	Decreasing residual load and/or market prices caused by increasing penetration of renewable energy	Decreasing revenues for generators providing fundamental services to the operation of the power system
Market Efficiency		Decreasing availability of dispatchatble resources, increasing need for supply of ancillary services from MSD
	Forecasting error due to non dispatchable generation	

Chapter 4

Quantitative assessment for national electricity security

This chapter is intended to define a general framework for quantitative assessment aspects related to energy transition through the computation of numerical indexes; in addition, it contains the definition of numerical indexes for electricity security, and the implementation of the workflow for the computation of these indexes. In Section 4.1 the workflow, from data collection from datasets, data classification for database design, and computation of indexes of different level of complexity up to a global index for energy transition, is described; in Section 4.2 numerical indexes, based on ENEA activities and literature review, and according to the aspects of the energy transition influencing the power system from Section 3.4, are proposed and the workflow is applied as an example.

4.1 Framework for numerical indexes calculation

The methodology proposed in this section is a framework for indexes computation for the energy transition: being it a general method, its goal is the implementation to all dimensions of the Energy Trilemma and all the domains of each dimension. As such, while a first implementation of the method for electricity security is proposed in Section 4.2, the method is expected to be adapted to other security domains (such as oil, [12]) and to environmental sustainability and equity. Firstly, an overview on the process is given by the following synthetic steps below, and the explanation of the concept map in figure; after that, an extended description of each phase of the proposed workflow is reported.
The method consists of three phases: data acquisition and database design and organization; metrics calculation; indexes calculation and aggreggation. The framework can ben synthetically summarized according to the following steps.

1. Data acquisition and database design and organization.

   (a) Data provider: data are initially available on external data providers. As the starting point of the method is data acquisition, relevant data providers are selected.

      i. Data providers include institutions, national/international organizations and bodies: data are usually made available through websites or online platforms. Data differ by their source typology (data format, possibility of an automatic download, public or private, free or purchased); moreover, data information content varies in terms of class (digital, analog, alphanumeric, ...), time granularity (hourly, daily, yearly...), space granularity (referred to smaller or larger geographical areas), reference area (which geographical areas they refer to); also, data may refer to several sectors (technical, economic, environmental, social, geopolitical, ...).

      ii. When data are not available, assumptions are needed and an additional Self-Estimation Provider is considered for user-defined data.

   (b) Dataset: data belong to tables called datasets and made available from data providers. Different acquisition methods from datasets are possible.

      i. Automatic scraping from the website, use of API if available, and implementation of dedicated scripts for download are preferred if possible.

   (c) Database: datasets usually contain more data than required for the analysis; in addition, data with various characteristics (different source typology and information content) are mixed. As such, relevant data from datasets are structured in a database. Database is designed according to an Entity Relationship model or ER model, where data are categorized according to

      i. Attributes: parameters related to data information content or identifying data

         A. Name
         B. Value
         C. Unit of measure
         D. Reference area
         E. Start time
         F. End time
         G. Data ID (Numerical ID) and alphanumerical code

   ii. Metadata: parameters labelling data but unrelated to information content
      A. Source, including data provider and typology (directly extracted or user-defined, data format, automatically downloadable, public or private, free or not)
      B. Class (analogical or digital, alphanumerical, topographic, . . .)
      C. Time granularity (hourly, daily, monthly, quarterly, yearly)
      D. Spatial granularity (district/province, zone, country, region/macro-area, global)
      E. Username of the author of data addition to database
      F. Date of addition to database
   iii. Sector (technical, environment, economic, social, geo-political)

2. Metrics calculation.
   (a) Data extraction from database: after data structuring, the database is used to feed the computation process.
   (b) Basic Figures definition.
      i. Relevant data describing a useful aspect of the analysis without further elaboration are labelled as Basic Figures.
      ii. Basic Figures categorization according to
         A. Name
         B. Data ID (Numerical ID) and alphanumerical code
         C. Symbol
         D. Definition
         E. Unit of measure
         F. Source
   (c) Metrics definition as combinations of other quantities. Data that are not significant by themselves, but are only useful after combination, are used to compute metrics. Differently from Basic Figures, metrics are indirectly obtained by data combination and not directly available from database.
      i. Simple Metrics computation: calculated with operations involving data from database. They describe a useful aspect of the analysis (similarly to Basic Figures).
      ii. Derived Metrics computation: elaboration of Simple metrics and Basic Figures. They are always used to quantify aspects related to wider categories.

iii. Metrics categorization according to
   A. Name
   B. Data ID (Numerical ID) and alphanumerical code
   C. Symbol
   D. Description (short sentence)
   E. Formula
   F. Unit of measure

3. Indexes calculation and aggregation.

   (a) Index definition: narrative definition for relevant indexes. Different dimensions, domains, categories require different indexes.
   (b) Normalization: computed metrics are normalized in such a way that comparisons between quantities with different units of measure are possible.
   (c) Index calculation: normalized metrics are combined with mathematical methods to obtain an index. Among the aggregation methods, weighted averages, numerical methods (AMPI, [57]; BOD, [58]) and ranking methods (Multi Criteria Decision Analysis, [59]) can be mentioned.
   (d) Indexes aggregation: indexes combination at different levels.
      i. Intra-domain aggregation: index aggregation inside the same domain (e.g. combination of metrics referring to electricity security).
      ii. Inter-domain aggregation: index aggregation from different domains (e.g. electricity, gas and oil security indexes are combined for a multi-domain description of energy security).
      iii. Global aggregation: a global index is defined combining environmental sustainability, security and equity indexes. For the Italian energy system, this index is called ISPRED and is monitored in the national interest by ENEA.

The whole process is graphically represented in the concept map shown in Figure 4.1.

Differently from mind maps, which focus on a single concept with a radial structure, concept maps are ideal to represent and link multiple concepts [60]. The choice of a concept map representation is justified by the top-down hierarchical structure of the framework: reading the map from right to left, the definition of a global index represents the top level of the hierarchy, which branches out into indexes at dimension, domain and category level and down to metrics and data. Differently from tree diagrams, concept maps are defined according to a node-link paradigm, where items are nodes and relationships are links [60]. Therefore, concept maps

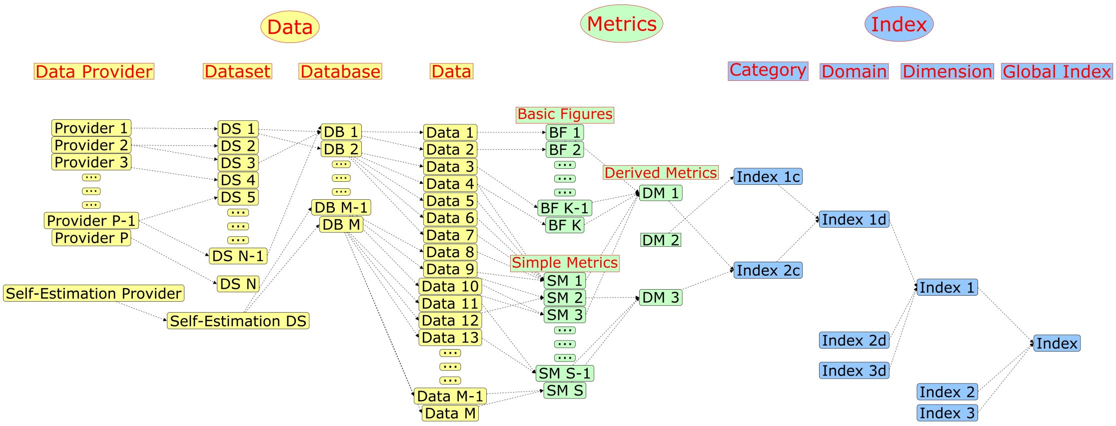

Figure 4.1: Framework for indexes calculation. From left to right, data acquisition and database organization (yellow), metrics calculation (green), indexes calculation and aggregation (blue). *Cmap Tools*

can be used to create multiple parent-child connections between items [60]. The same approach can be adopted to represent the workflow creating an UML activity diagram [60], which is beyond the scope of this work, but required for a better understanding of the procedure and left to future research. Finally, a significant aspect of the process in a future perspective is related to the research of the most appropriate tools for its implementation. While the full development of digital tools for data acquisition and storage, as well as for indexes computation and aggregation, requires professional cybersecurity skills and is not part of the thesis, a demo model based on the creation of a PostgreSQL database and a Python graphical interface is proposed; the code, together with screenshots from the database and the appendix, can be found in Appendix A. The purpose of the combination between these tools is the creation of an Open Source Intelligence, containing publicly accessible data and indexes, as well as a secure and user-friendly system to for data storage and access. A full ER model is going to be conceived: data represent entities, data information content are their attributes and metadata, and relationships are going to link data with their sources and authors; the purpose of such a model is a rigorous data categorization and an easy access for the users. The demo sample is composed by a coding part that stores sample data and attributes into a PostgreSQL database, and a graphical interface where data can be extracted and shown for a desired time interval. In a future perspective, also indexes computation, storage and access are going to be implemented in the interface, and plotted for comparison in the desired intervals or shown according to requested time granularity.

4.2 Indexes for national electricity security

The definition of the framework for quantitative assessment of the Energy Trilemma dimensions is here implemented to electricity security. A review on the indexes currently used by ENEA and their framing in the new methodology here described is proposed in Section 4.2.1; further indexes are introduced in Section 4.2.2, based on the assessment of the impacts of the energy transition with respect to each category identified for electricity security.

4.2.1 Indexes review within the framework context

Several indexes for electricity security can be identified in literature. Analogously to literature review on electricity security from Section 3.3.1, indexes and proposals from institutions and public authorities are preferred for this study. As the purpose of the thesis is the evaluation of electricity security at national level, which is analysed in the national interest by ENEA, indexes from ENEA quarterly reports are reported. In order to analyse trends in electricity security, no ex-ante forecasting is provided within this context, and an ex-post approach based on real data (or their close estimations) is adopted.
Specifically, ENEA analysis [9] is based on the assessment of quarterly average values of the following metrics:

- Margin of Minimum Reserve [Load %] is currently in use to assess System Adequacy. In the thesis framework as defined in Section 4.1, this margin is a Derived Metric, deriving from the summation of relevant Basic Figures and Simple Metrics. Specifically, it takes into account the hourly contribution to the reserve from available thermal capacity, imports, hydro power and intermittent generation, decreased by total demand and required operational reserve (a confidential constant value taken from ENEA datasets):

  $$RM\% = 100 * \frac{P-Po+Ph+I+VR-(D+R)}{D+R} \quad [\%]$$

  Available thermal capacity comes from the difference between installed thermal capacity and capacity outage. Installed thermal capacity comes from an estimation of national installed thermal capacity P_i on hourly basis: starting from yearly values P_y for each zone on January the 1st, national values are obtained

  $$P = \sum_{i=1}^{M} Pz \quad [MW]$$

  and a constant hourly increment of capacity is assumed.

  $$P_{i+1} = P_i + \frac{P_{y+1}-P_y}{365} \quad [MW]$$

A constant outage factor is taken from ENEA datasets to take into account power plants outage.

$$Po = Pa * OF \quad [MW]$$

While net foreign exchange is directly extracted from Terna datasets, hydro net contribution is computed as the difference between gross generation and pumping consumption (Table 4.3), and contribution from PV and wind power is adjusted (Table 4.3) based on discrepancies between hourly data available from datasets and yearly reports from Terna, which are assumed to be more accurate.

- Hourly Variation of Intermittent Generation [Load %] is currently in use to assess System Flexibility. It represents the ramps in wind and solar generation hour by hour, as a share total net load from the previous hour.

$$\Delta VR = 100 * \frac{VR_{i+1} - VR_i}{Dnt} \quad [\%]$$

As already described for Adequacy, intermittent generation from datasets is adjusted based on discrepancies between hourly data available from datasets and yearly reports from Terna; total net load comes from the difference between total load and self-consumption, which is not considered in terms of grid operation:

$$Dnt = D - Da \quad [MW]$$

- Clean Spark Spread [Eur/MWh] is currently in use to assess Market Adequacy. This indicator is commonly found in literature [61] to establish whether conventional gas generators receive adequate remuneration from Day Ahead markets. It is defined as the difference between electricity prices minus fuel costs (gas prices divided by an average power plant efficiency) and emissions costs

$$CSS = PUN - \frac{PSV}{\eta} - CP \quad [\frac{Eur}{MWh}]$$

where the difference between electricity prices and fuel costs is commonly known as Spark Spread [61]; for power plants efficiency, an average value from ENEA datasets is considered; carbon price comes from the conversion of a monthly estimation of CO_2 price into emission costs for gas-fired plants as defined by ENEA. Thus, differently from the other metrics, Clean Spark Spread is not evaluated starting from hourly values, but on monthly basis.

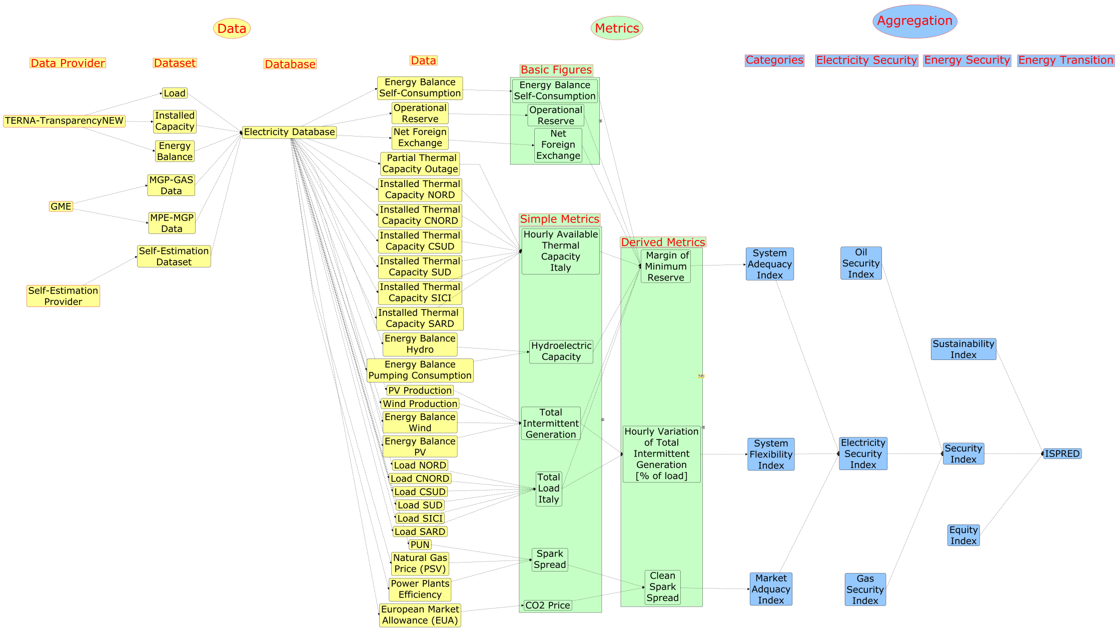

Figure 4.2: Framework for electricity security index. From left to right, data acquisition and database organization (yellow), metrics calculation (green), index calculation and aggregation (blue). *Cmap Tools*

The description of the whole calculation process for these metrics within the framework developed in Section 4.1 is proposed in (Figure 4.2).

In the following, a review on the computation process for each derived metric is proposed. Details on index framing into the framework can be found in the tables. Table 4.1 reports data categorization according to their attributes (excluding start and end time) and metadata, as described in Section 4.1; a legenda to understand the meaning of each item in the table is reported in Appendix B.

Table 4.1: Data classification for ENEA electricity security indexes.

SECTOR	ID	ATTRIBUTE				METADATA																
		Name	Reference Area	Symbol	Unit of Measure	Class	Time Granularity						Spatial Granularity					Source				
						A/G/L/T	Gh	Gd	Gm	Tr	Gy	Sp	Ds	Zn	Ct	Rg	Gb	Prodivder	D/U	Format	B/V	P/F
Technical Data	DT1	Installed Thermal Capacity	NORD	*Pz*	MW	A	-	-	-	-	X	-	-	X	-	-	-	Terna-TransparencyNEW	D	xlsx	B	F
	DT2	Installed Thermal Capacity	CNORD	*Pz*	MW	A	-	-	-	-	X	-	-	X	-	-	-	Terna-TransparencyNEW	D	xlsx	B	F
	DT3	Installed Thermal Capacity	CSUD	*Pz*	MW	A	-	-	-	-	X	-	-	X	-	-	-	Terna-TransparencyNEW	D	xlsx	B	F
	DT4	Installed Thermal Capacity	SUD	*Pz*	MW	A	-	-	-	-	X	-	-	X	-	-	-	Terna-TransparencyNEW	D	xlsx	B	F
	DT5	Installed Thermal Capacity	SICI	*Pz*	MW	A	-	-	-	-	X	-	-	X	-	-	-	Terna-TransparencyNEW	D	xlsx	B	F
	DT6	Installed Thermal Capacity	SARD	*Pz*	MW	A	-	-	-	-	X	-	-	X	-	-	-	Terna-TransparencyNEW	D	xlsx	B	F
	DT7	Themal Capacity (Partial) Outage	-	*OF*	-	A	-	-	-	-	-	X	-	-	X	-	-	User-Defined (ENEA)	U	-	V	F
	DT8	Energy Balance Hydro	ITA	*Eh*	GWh	A	X	-	-	-	-	-	-	-	X	-	-	Terna-TransparencyNEW	D	xlsx	B	F
	DT9	Energy Balance Pumping Consumption	ITA	*Ep*	GWh	A	X	-	-	-	-	-	-	-	X	-	-	Terna-TransparencyNEW	D	xlsx	B	F
	DT10	Energy Balance Photovoltaic	ITA	*Epv*	GWh	A	X	-	-	-	-	-	-	-	X	-	-	Terna-TransparencyNEW	D	xlsx	B	F
	DT11	Energy Balance Wind	ITA	*Ew*	GWh	A	X	-	-	-	-	-	-	-	X	-	-	Terna-TransparencyNEW	D	xlxs	B	F
	DT12	Wind Production Factor (sum of hourly values over the year / yearly value)	ITA	*Wy*	-	A	-	-	-	-	X	-	-	-	X	-	-	User-Defined (ENEA)	U	-	V	F
	DT13	PV Production Factor (sum of hourly values over the year / yearly value)	ITA	*PVy*	-	A	-	-	-	-	X	-	-	-	X	-	-	User-Defined (ENEA)	U	-	V	F
	DT14	Net Foreign Exchange	ITA	*I*	MWh	A	X	-	-	-	-	-	-	-	X	-	-	Terna-TransparencyNEW	D	xlsx	B	F
	DT15	Operational Reserve	ITA	*R*	MW	A	-	-	-	-	-	X	-	-	X	-	-	Martedì 30 luglio 2019 —129—Commissione X 5-01809 Benamati: Su questioni relative alla sicurezza del sistema elettrico nazionale.	D	-	V	F
	DT16	Load	NORD	*Di*	MW	A	X	-	-	-	-	-	-	X	-	-	-	Terna-TransparencyNEW	D	xlsx	B	F
	DT17	Load	CNORD	*Di*	MW	A	X	-	-	-	-	-	-	X	-	-	-	Terna-TransparencyNEW	D	xlsx	B	F
	DT18	Load	CSUD	*Di*	MW	A	X	-	-	-	-	-	-	X	-	-	-	Terna-TransparencyNEW	D	xlsx	B	F
	DT19	Load	SUD	*Di*	MW	A	X	-	-	-	-	-	-	X	-	-	-	Terna-TransparencyNEW	D	xlsx	B	F
	DT20	Load	SICI	*Di*	MW	A	X	-	-	-	-	-	-	X	-	-	-	Terna-TransparencyNEW	D	xlsx	B	F
	DT21	Load	SARD	*Di*	MW	A	X	-	-	-	-	-	-	X	-	-	-	Terna-TransparencyNEW	D	xlsx	B	F
	DT22	Energy Balance Self-consumption	ITA	*Da*	GWh	A	X	-	-	-	-	-	-	-	X	-	-	Terna-TransparencyNEW	D	xlsx	B	F
	DT23	Power Plants Efficiency	-	η	%	A	-	-	-	-	X	-	-	-	X	-	-	User-Defined (ENEA)	U	-	V	F
																	-					
Economic Data	DE1	Prezzo Unico Nazionale	ITA	*PUN*	Eur/MWh	A	X	-	-	-	-	-	-	-	X	-	-	GME	D	pdf	B	F
	DE2	Natural Gas Price at Punto di Scambio Virtuale	ITA	*PSV*	Eur/MWh	A	-	-	X	-	-	-	-	-	X	-	-	GME	D	pdf	B	F
	DE3	European Market Allowance	EU	*EUA*	Eur/ton	A	-	-	X	-	-	-	-	-	-	X	-	User-Defined (ENEA)	U	-	V	F

With respect to the context previously introduced, metrics are divided into Basic Figures (Table 4.2), Simple Metrics (Table 4.3) and Derived Metrics. Simple metrics do not include all the calculation steps, but only the most significant to be stored and compared in time in the view of the author.

Table 4.2: Basic Figures for ENEA electricity security indexes.

ID	Name	Symbol	Definition	Unit of measure	Source
BF01	Net Foreign Exchange	I	Net electricity exchange from foreign countries, as the difference between imports and exports.	GWh	Terna-TransparencyNEW
BF02	Operational Reserve	R	Amount of generation fleet that must satisfy the unbalance between load and supply due to aleatory variations of the demand, load forecasting errors, unplanned capacity outage (for instance due to breakdown), unforeseen variations in foreign exchange plans.	MW	Martedì 30 luglio 2019 — 129 — Commissione X 5-01809 Benamati: Su questioni relative alla sicurezza del sistema elettrico nazionale.
BF03	Energy Balance Self-consumption	Da	Hourly energy consumption to be excluded from total load.	MWh	Terna-TransparencyNEW

Table 4.3: Simple Metrics for ENEA electricity security indexes.

ID	Name	Symbol	Description	Formula	Unit
SM1	Hourly Available Thermal Capacity Italy	Pa	Hourly available thermal capacity at net of outage.	$P - Po$	MW
SM2	Hydroelectric Generation	Ph	Net Hydro generation with respect to pumping consumption.	$(Eh + Ep) * 1000$	MW
SM3	Intermittent Generation	VR	Generation from intermittent renewables (Wind and PV).	$(\frac{Ew}{Wy} + \frac{Epv}{PVy}) * 1000$	MW
SM4	Total Load Italy (self-consumption included)	D	Hourly demand from the national grid to supply net internal consumption and self-consumption included.	$\sum_{i=1}^{M} Di$	MW
SM5	Spark Spread	SS	Difference between the price received by generators for the generated electricity and the cost of the natural gas needed to produce that electricity.	$PUN - \frac{PSV}{\eta}$	Eur/MWh
SM6	CO_2 Price	CP	Emissions costs for gas-fired power plants per electric output unit.	$0.411 * EUA$	Eur/MWh

4.2.2 Metrics proposals for indexes calculation

Based on the analysis of electricity security definitions and categories from Section 3.3.2, together with the identification of the threats to electricity security from the energy transition as described in Section 3.4, proposals for new indexes are developed in this chapter.

Some of the aspects influencing electricity security introduced in Section 3.4 are not considered for this analysis: as the thesis focuses, in terms of infrastructures, on generation and transmission subsystems, the threats coming from distributed generation and lack of cooperation between TSO and DSOs are overtaken. With respect to the other threats, metrics proposals are conceived with the purpose to measure how much the system, according to real values, is put into risk conditions with respect to each category: relatively to the adequacy attribute, risk conditions are considered in terms of system ability to prevent failures in standard conditions; for security attribute, indexes focus on the reaction of the system to disturbances. Proposed metrics are to be computed as quarterly average values and include the following:

- Margin of Minimum Reserve [Load %] is selected to assess System Adequacy. As the goal of the analysis is an ex-post evaluation based on real data, the assessment of this metric on a hourly basis is considered suitable to measure the impact coming from decreasing availability of dispatchable thermal capacity, as discussed in Section 3.4. For this study, the metric is computed with respect to net total load, as self-consumption must not be covered in terms of system adequacy:

$$RM\% = 100 * \frac{P-Po+Ph+I+VR-(Dnt+R)}{Dnt+R} \quad [\%]$$

- Two metrics are selected to assess System Flexibility, in order to measure the impact coming from increasing share of intermittent generation. Even though the purpose of this metric is the detection of sudden ramps in the system, two main limitations affect the usefulness of the analysis: firstly, VRE variations do not measure any real impact on the system itself, which should be analysed in terms of required ramps from conventional generation units; secondly, ramps normalization with respect to the load prevents the metric from showing the magnitude of the problem in absolute value. In addition, ramping issues do not include the problem of over-generation, together with risks of curtailing renewable energy and reaching technical minimum constraints for conventional generation. As a results, the following metrics to be computed on a hourly basis are proposed:

  – Residual Load is a derived metric representing the difference between net total load and non dispatchable generation [56].

  $$RL = Dnt - VR - Ewr \quad [MW]$$

  Decreasing Residual Loads put at risk both conventional power plants, which are likely to approach their technical minimum, and intermittent generation, which gets closer to over-generation conditions and curtailment risk. Due to limitations in the knowledge of flexibility properties for the Italian electricity mix (Chapter 5), Residual Load is here considered as a useful metric with respect to the adequacy attribute, regardless from the actual characteristics of the generation fleet.

  - Residual Load Ramp is a derived metric representing the evolution of the difference between net total load and non dispatchable generation hour by hour [56].

    $$RLR = Dnt_{i+1} - (VR_{i+1} + Ewr_{i+1}) + Dnt_i - (VR_i + Ewr_i) \quad [MW]$$

    Increasing ramps represent a challenge to system flexibility, as they require improved flexibility from conventional generation to react to sudden variations from non dispatchable renewables. Due to limitations in the knowledge of flexibility properties for the Italian electricity mix (Chapter 5), Residual Load Ramp is here considered as a useful metric with respect to the adequacy attribute, regardless from the actual characteristics of the generation fleet.

- For System Stability, the risk of inadequate availability resources for frequency, voltage and inertia regulation is discussed in Section 3.4. As a consequence, Frequency [Hz], Voltage [V] and Inertia Level [-] are all proposed to be monitored to measure the impact coming from the lack of these resources; as these metrics directly measure quantities affecting system performance, they relate to the security attribute. Even though actual values for these quantities are not publicly available, their estimations are expected to be based on technical characteristics of online units hour by hour. However, System Stability assessment is beyond the scope of this thesis and left to further studies.

- For Market Adequacy, threats coming from decreasing remuneration from competitive markets to conventional generation are quantified in terms of the following two metrics:

  - Clean Spark Spread [Eur/MWh] is evaluated with respect to all markets: MGP, MI, MSD ex-ante, MB. Similarly to ENEA analysis, Clean Spark Spread is computed on a monthly basis: in fact, natural gas prices are only available at daily level from GME datasets, while the same price at PSV is published on a monthly basis. As numerical differences are proven to be negligible, and the larger gas volumes are traded on PSV but not through GME platform [44], the latter value is adopted. Furthermore, carbon prices from primary auctions are only available three days a week [45]: being the only official source for the analysis, their monthly weighted average is preferred for carbon pricing.
    The computation process of Clean Spark Spread for MGP is here described, but it can be easily extended to the other markets by computing weighted average prices for all of them.

    * As a first step, hourly values of Clean Spark Spread are computed with the well known formula [61], extending monthly PSV gas price

to each hour. The only exception comes from MI calculations, where Spark Spread is computed directly on monthly basis.

$$SS = PUN - \frac{PSV}{\eta} \quad [\frac{Eur}{MWh}]$$

In all cases, contribution from the fuel cost decreases Spark Spread, with the exception of MSD purchases: in this case, saved fuel due to reduced generation represents a financial saving for generators.

* Hourly share of power generation from gas-fired power plants traded on MGP is assumed to be constant and equal to the share of gas in total generation.

  $$Eggp = \frac{Eg}{Etot} * Qgp \quad [MWh]$$

  where total generation is computed as the sum of single generation items.

  $$Etot = \sum_{i=1}^{M} Ei \quad [MWh]$$

* The same approach is adopted for MSD: however, for the computation of gas share in these markets, VRE and RoR hydro contributions are excluded.

  $$Egd = \frac{Eg - glsVR - glsHr}{Etot} * Qd \quad [MWh]$$

* A weighted average of Spark Spread is computed on a monthly basis. The weighting factor is the estimation of traded quantities from gas-fired power plants on the market (in this case MGP).

  $$SS_i = \frac{\sum_{i=1}^{M} SS_i * Eggp}{\sum_{i=1}^{M} Eggp} \quad [Eur/MWh]$$

* Similarly, a monthly weighted average with respect to traded quantities on the Italian session of EEX is obtained for carbon price. At first, the value is obtained in Eur/ton and then converted into Eur/MWh according to the same conversion factor adopted by ENEA for gas-fired power plants.

  $$CP = 0.411 * \frac{\sum_{i=1}^{M} EUA_i * Qe}{\sum_{i=1}^{M} Qe} \quad [Eur/MWh]$$

– Capacity Market Revenues are quantified and converted into Eur/MWh to calculate a unique Market Adequacy index. However, as the full conversion process requires knowledge in the aggregation methods and possibly of the actual operation and revenues of generation units participating to the market, only a simple weighted average of the revenues is proposed in this study.

$$CMR = \frac{\sum_{i=1}^{M} CDPz * FYPz}{\sum_{i=1}^{M} CDPz} \quad [Eur/MW]$$

- For Market Efficiency, threats coming from decreasing availability of conventional resources for ancillary services are measured with the following metrics:

- Available Capacity in Probability on Capacity Market [MW], computed as a sum of accepted capacities from Capacity Markets from datasets on a yearly basis.

$$CDP = \sum_{i=1}^{M} CDPz \quad [MW]$$

- Number of offers on MSD ex-ante [-] from datasets as a sum of zonal values on a hourly basis.

$$N = \sum_{i=1}^{M} Nz \quad [-]$$

In addition, threats coming from increasing demand and prices of conventional resources for ancillary services are measured with the following metrics;

- MSD ex-ante and MB Accepted Quantities (Purchases and Sales, [MWh]) on a hourly basis. These values are computed as a sum of zonal values from datasets.

$$Pd = \frac{\sum_{i=1}^{M} Pdz}{10^6} \quad [TWh]$$

$$Sd = \frac{\sum_{i=1}^{M} Sdz}{10^6} \quad [TWh]$$

- MSD ex-ante and MB total cost of supply $[\frac{Eur}{MWh}]$ on a monthly basis, as provided by Terna in terms of uplift.

The whole set of metrics selected for the analysis is reported in Table 4.4.

Since a concept map showing the full methodology for indexes computation would be of difficult readability, the workflow is here separated into the following steps. A classification of required data from datasets for proposed indexes (excluding stability index) is shown in Table 4.5. Data are classified in terms of their attributes (exluding start and time, as well as reference area) and metadata, as described in Section 4.1. Finally, computed indexes starting from derived metrics, together with subsequent aggregation levels, are shown in Figure 4.3.

Table 4.4: Metrics proposals for electricity security indexes.

Category		**Metrics Proposal**
System Adequacy	Adequacy	Margin of Minimum Reserve [%]
System Flexibility & Stability	Flexibility	Residual Load Ramp [%] Residual Load [MW]
	Stability	Frequency [Hz] Voltage [V] Inertia Level [-]
Market Idoneity	Market Adequacy	Clean Spark Spread for all markets [Eur/MWh] Capacity Market Revenue [Eur/MWh]
	Market Efficiency	MSD/MB Offers [-] Capacity Market CDP [MW] MSD/MB Sales [MWh] MSD/MB Purchases [MWh] MSD/MB Cost of Supply [$\frac{Eur}{MWh}$]

Table 4.5: Data categorization for proposed indexes.

SECTOR	ID	ATTRIBUTE			METADATA																	
		Name	Symbol	Unit of Measure	Class	Time Granularity						Spatial Granularity					Source					
					A/G/L/T	Gh	Gd	Gm	Tr	Gy	Sp	Ds	Zn	Ct	Rg	Gb	Provider	D/U	Format	W/M	B/V	P/F
Technical Data	DT1	Installed Thermal Capacity	*P*	GW	A	-	-	-	-	X	-	-	-	X	-	-	Terna-TransparencyNEW [41]	D	xlsx	-	B	F
	DT2	Themal Capacity (Partial) Outage	*OF*	-	A	-	-	-	-	-	X	-	-	X	-	-	User-Defined (ENEA)	U	-	-	V	F
	DT3	Energy Balance Hydro	*Eh*	GWh	A	X	-	-	-	-	-	-	-	X	-	-	Terna-TransparencyNEW [62]	D	xlsx	-	B	F
	DT4	Energy Balance Pumping Consumption	*Ep*	GWh	A	X	-	-	-	-	-	-	-	X	-	-	Terna-TransparencyNEW [62]	D	xlsx	-	B	F
	DT5	Energy Balance Photovoltaic	*Epv*	GWh	A	X	-	-	-	-	-	-	-	X	-	-	Terna-TransparencyNEW [62]	D	xlsx	-	B	F
	DT6	Energy Balance Wind	*Ew*	GWh	A	X	-	-	-	-	-	-	-	X	-	-	Terna-TransparencyNEW [62]	D	xlsx	-	B	F
	DT7	Wind Production Factor (sum of hourly values over the year / yearly value)	*Wy*	-	A	-	-	-	-	X	-	-	-	X	-	-	User-Defined (ENEA)	U	-	-	V	F
	DT8	PV Production Factor (sum of hourly values over the year / yearly value)	*PVy*	-	A	-	-	-	-	X	-	-	-	X	-	-	User-Defined (ENEA)	U	-	-	V	F
	DT9	Net Foreign Exchange	*I*	MWh	A	X	-	-	-	-	-	-	-	X	-	-	Terna-TransparencyNEW [62]	D	xlsx	-	B	F
	DT10	Operational Reserve	*R*	MW	A	-	-	-	-	-	X	-	-	X	-	-	Martedì 30 luglio 2019 —129—Commissione X 5-01809 Benamati: Su questioni relative alla sicurezza del sistema elettrico nazionale.	D	-	-	V	F
	DT11	Total Load	*D*	MW	A	X	-	-	-	-	-	-	-	X	-	-	Terna-TransparencyNEW [63]	D	xlsx	-	B	F
	DT12	Energy Balance Self-consumption	*Da*	GWh	A	X	-	-	-	-	-	-	-	X	-	-	Terna-TransparencyNEW [62]	D	xlsx	-	B	F
	DT13	Power Plants Efficiency	η	%	A	-	-	-	-	-	X	-	-	X	-	-	User-Defined (ENEA)	U	-	-	V	F
	DT14	PV Installed Capacity	*PV*	MW	A	-	-	-	-	X	-	-	-	X	-	-	Terna-TransparencyNEW [41]	D	xlsx	-	B	F
	DT15	Wind Installed Capacity	*W*	MW	A	-	-	-	-	X	-	-	-	X	-	-	Terna-TransparencyNEW [41]	D	xlsx	-	B	F
	DT16	RoR Hydro Installed Capacity	*Hr*	MW	A	-	-	-	-	X	-	-	-	X	-	-	ENTSO-E-Transparency Platform [64]	D	xlsx	-	B	F
	DT17	RoR Hydro Generation	*Ewr*	MWh	A	X	-	-	-	-	-	-	-	X	-	-	ENTSO-E Transparency Platform [65]	D	xlsx	-	B	F
	DT18	Gas-fired Generation	*Eg*	MWh	A	X	-	-	-	-	-	-	-	X	-	-	ENTSO-E Transparency Platform [65]	D	xlsx	-	B	F
	DT19	Available Capacity in Probability	*CDPz*	MW	A	-	-	-	-	X	-	-	X	-	-	-	Terna [66], [67]	D	pdf	-	B	F
	DT20	Gas-fired Installed Capacity	*Pg*	MW	A	X	-	-	-	-	-	-	-	X	-	-	ENTSO-E Transparency Platform [64]	D	xlsx	-	B	F
	DT21	Generation from single commodity	*Ei*	MW	A	X	-	-	-	-	-	-	-	X	-	-	ENTSO-E Transparency Platform [65]	D	xlsx	-	B	F
																-						
Economic Data	DE1	Prezzo Unico Nazionale	*PUN*	Eur/MWh	A	X	-	-	-	-	-	-	-	X	-	-	GME [68]	D	xml	-	B	F
	DE2	Natural Gas Price at Punto di Scambio Virtuale	*PSV*	Eur/MWh	A	-	X	-	-	-	-	-	-	X	-	-	GME [69]	D	xlsx	-	B	F
	DE3	European Market Allowance	*EUA*	Eur/ton	A	-	X	-	-	-	-	-	-	X	-	-	EEX [45]	U	xls	-	V	F
	DE4	MGP Quantities	*Qgp*	MWh	A	X	-	-	-	-	-	-	-	X	-	-	GME [68]	D	xml	-	B	F
	DE5	MI Quantities	*Qiz*	MWh	A	-	-	X	-	-	-	-	-	X	-	-	GME [69]	D	pdf	-	V	F
	DE6	MI Prices	*Piz*	Eur/MWh	A	-	-	X	-	-	-	-	-	X	-	-	GME [69]	D	pdf	-	B	F
	DE7	MSD ex-ante Purchases	*Pdz*	MWh	A	X	-	-	-	-	-	-	X	-	-	-	GME [68]	D	xml	-	V	F
	DE8	MSD ex-ante Sales	*Sdz*	MWh	A	X	-	-	-	-	-	-	X	-	-	-	GME [68]	D	xml	-	B	F
	DE9	MSD ex-ante Purchases Price	*PPdz*	Eur/MWh	A	X	-	-	-	-	-	-	X	-	-	-	GME [68]	D	xml	-	V	F
	DE10	MSD ex-ante Sales Prices	*PSdz*	Eur/MWh	A	X	-	-	-	-	-	-	X	-	-	-	GME [68]	D	xml	-	B	F
	DE11	MSD ex-ante Offers	*Nz*	-	A	X	-	-	-	-	-	-	X	-	-	-	GME [68]	D	xml	-	V	F
	DE12	MB Purchases	*Pbz*	MWh	A	X	-	-	-	-	-	-	X	-	-	-	GME [68]	D	xml	-	B	F
	DE13	MB Sales	*Sbz*	Eur/MWh	A	X	-	-	-	-	-	-	X	-	-	-	GME [68]	D	xml	-	V	F
	DE14	MB Purchases Price	*PPbz*	Eur/MWh	A	X	-	-	-	-	-	-	X	-	-	-	GME [68]	D	xml	-	B	F
	DE15	MB Sales Prices	*PSbz*	Eur/MWh	A	X	-	-	-	-	-	-	X	-	-	-	GME [68]	D	xml	-	V	F
	DE16	Fixed Yearly Premium	*FYPz*	Eur/MW	A	-	-	-	-	X	-	-	X	-	-	-	Terna [66] [67]	D	pdf	-	B	F
	DE17	EUA tradings on EEX [45]	*Qe*	ton	A	-	X	-	-	-	-	-	-	X	-	-	EEX	U	xls	-	V	F

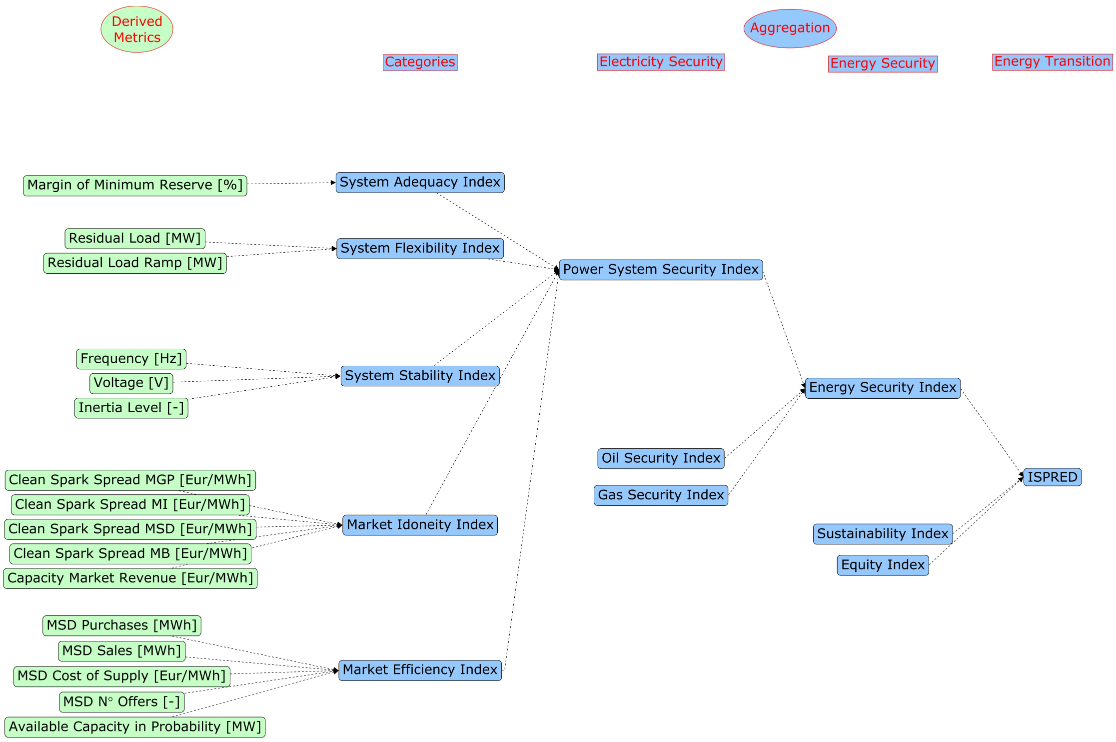

Figure 4.3: Concept Map for indexes computation and aggregation starting from Derived Metrics.

Chapter 5

Evolutive trends of electricity security

The aim of this chapter the identification of evolutive patterns of national electricity security in an energy transition perspective. Specifically, metrics identified in Section 4.2.2 with respect to System Flexibility and Market Idoneity are computed on a monthly basis for the first three quarters (from January to September) from 2018 to 2020.

5.1 System Flexibility

As discussed in Section 3.3.2, System Flexibility is here considered in terms of threats coming from generation and load variability. At first, an analysis of technical flexibility capability in the Italian electricity mix is attempted, with the purpose to understand the magnitude of the problem; after that, as no public information regarding is available for its accurate characterization, flexibility is assessed in terms of the adequacy attribute using the metrics defined in Section 4.2.2.
Based on the outcomes of Capacity Market bids, where around 35 GW of existing capacity has been accepted, at least 29 GW of existing dispatchable capacity do not meet flexibility requirements defined by Terna, while the same requirements are met by 4 GW of capacity only. ([66], [67]). Even considering an optmistic scenario scenario, where all the remaining dispatchable capacity not participating to Capacity Market meets the same requirements, it can be stated that more than one third of dispatchable generation fleet currently lacks of flexibility. As 60 GW of thermal capacity [14], and more than 10 GW of dispatchable hydro (water reservoirs or pumped hydro, [64]) are currently installed in the country, the share of unflexible capacity would be at least 42%.
As a consequence, decreasing Residual Load and increasing ramps are expected

expose the system to threat conditions, and their historical patterns are here analyzed in order to detect upcoming criticalities of the energy transition. As observed in Figure 5.1, monthly average Residual Loads [MW] reached exceptionally low values in 2020, due to combined effects of increased renewable generation and load drop due to economic crisis. As a consequence, risk of over-generation and curtailment of clean renewable energy increased, as well as risk of getting closer to technical minimum of convetional generation. The same trend is observed with

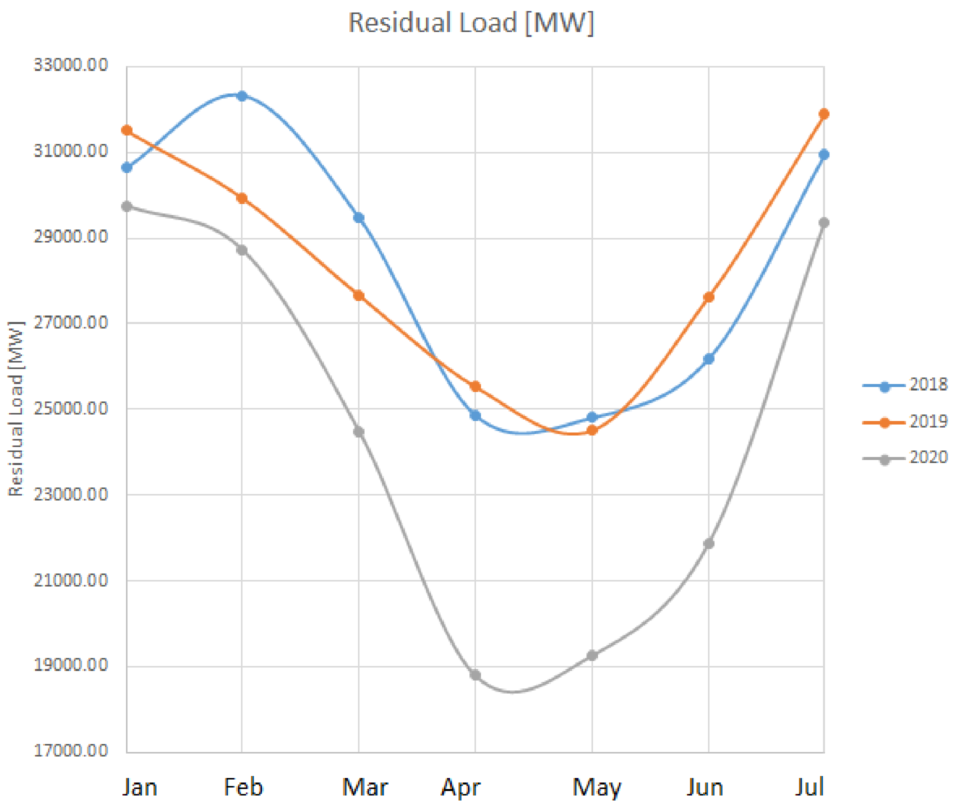

Figure 5.1: Residual Load, January-August 2018-2020. Monthly average.

duration curves (Figure 5.2, showing on the x-axis for how many hours residual in the same period each value of Residual Load on the y-axis has been overcome. Differently from average values, whose purpose is to measure the average risk of over-generation, the duration curve can be used in combination with a threshold to be defined according to technical properties of the generation fleet. However, the definition of this threshold is currently hindered by lack of public data and beyond the scope of this study. Similarly, Residual Load Ramps have been computed for the same period. Differently from Residual Load, no issues in the absolute value of Residual Load Ramps have been detected in 2020. As total load faced a general

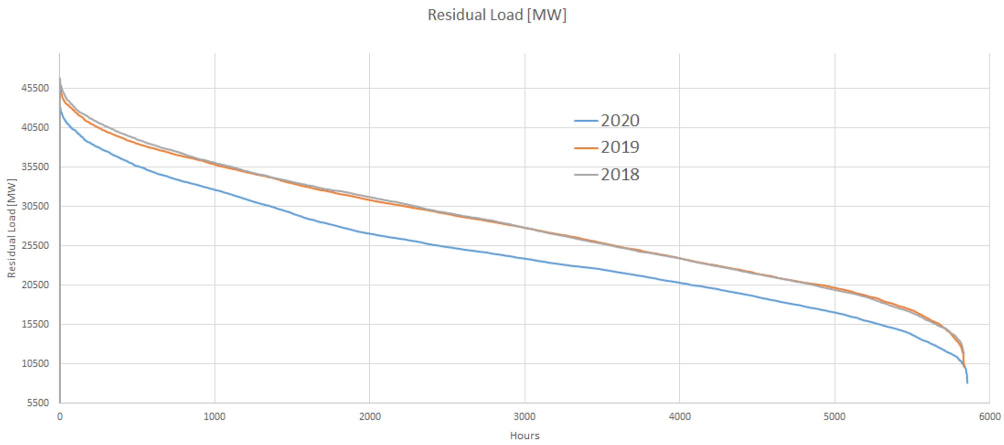

Figure 5.2: Residual Load, January-August 2018-2020. Horuly duration curves.

reduction due to the economic crisis, ramps in non dispatchable generation have been mitigated (Figure 5.3). The same patterns are shown by duration curves

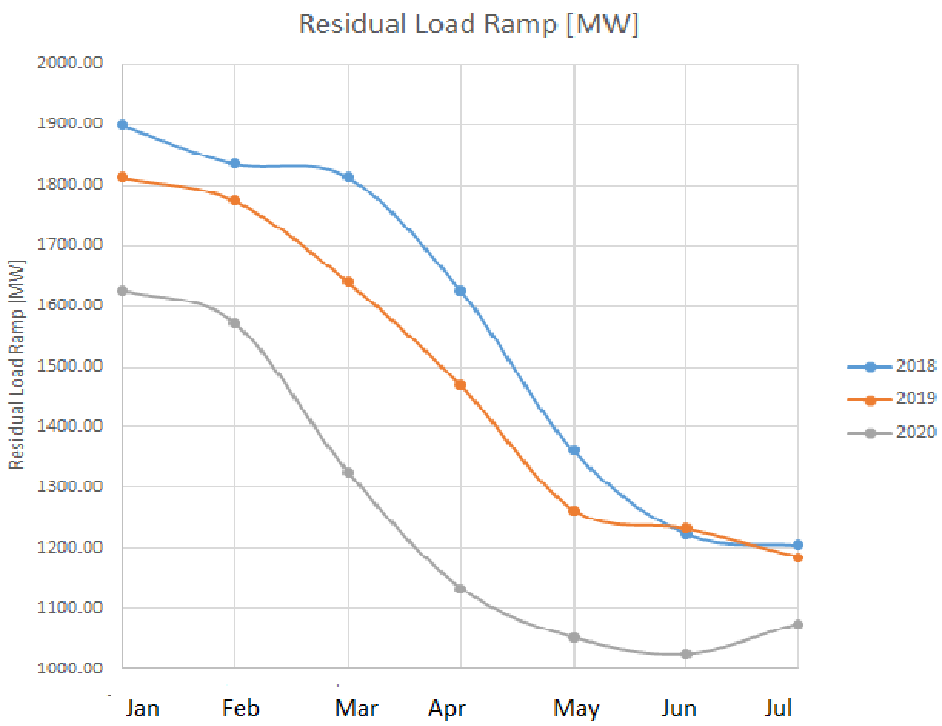

Figure 5.3: Residual Load Ramp, January-August 2018-2020

(Figure 5.3). Similarly to Residual Load duration curves, identification of thresholds to identify risk conditions is here recommended, but beyond the scope of the study due to lack of data.

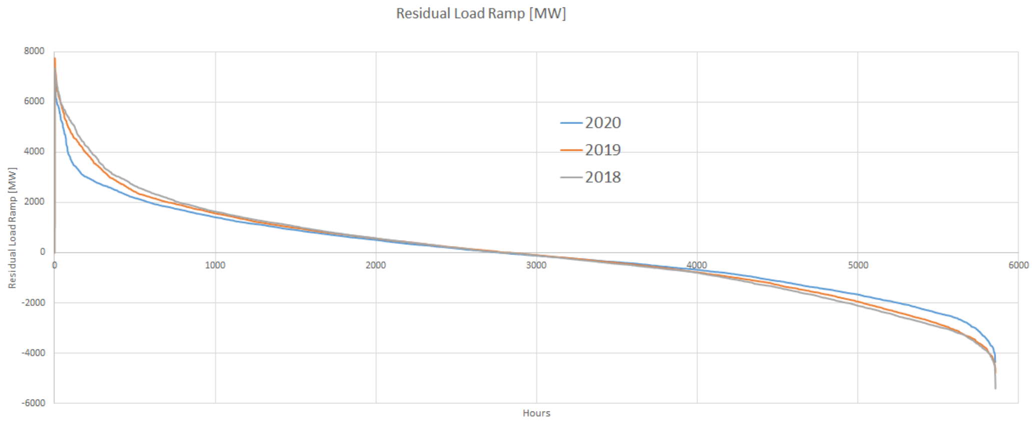

Figure 5.4: Residual Load Ramp, January-August 2018-2020. Horuly duration curves.

5.2 Market Idoneity

According to the framework defined in Section 4.2.2 electricity security with respect to market categories is assessed with a unique Market Idoneity indexes, coming from the aggregation of indexes computed for Market Adequacy and Efficiency. Even though the aggregation process is not covered by this study, computed metrics for both categories are discussed in the following chapters.

5.2.1 Market Adequacy

As explained in Section 4.2.2, Market Adequacy assessment with respect to gas-fired power plants profitability is conducted computing Clean Spark Spread [Eur/MWh] on all markets and revenues from the new born Capacity Market. In the following, market quantities and prices are computed and analysed as a preliminary step (Table 5.1).

The most significant patterns are identified on MGP, where decreasing prices and volumes are expected to reduce profitability for gas-fired generation, and MSD ex-ante, where the combination of increasing quantities and fluctuating prices is expected to increase remunerations. On the other hand, MI prices are closer to MGP (Appendix C), while no significant patterns are identified for MB. As such,

Table 5.1: Review on electricity market quantities and prices, January-September 2018-2020.

		MGP				MI				MSD ex-ante				MB			
Month		**PUN [Eur/MWh]**	ΔPUN [%]	**Qgp [TWh]**	ΔQgp [%]	**Pi [Eur/MWh]**	ΔPi [%]	**Qi [TWh]**	ΔQi [%]	**Pd [Eur/MWh]**	ΔPd [%]	**Qd [TWh]**	ΔQd [%]	**Pb [Eur/MWh]**	ΔPb [%]	**Qb [TWh]**	ΔQb [%]
Jan	2018	49.00		25.63		48.51		2.32		64.99		1.74		53.77		1.26	
	2019	67.65	38%	26.32	3%	66.82	38%	2.54	10%	105.51	62%	1.55	-11%	63.87	19%	1.18	-7%
	2020	47.47	-30%	26.16	-1%	47.36	-29%	2.01	-21%	58.16	-45%	1.79	16%	53.68	-16%	1.47	25%
Feb	2018	57.00		24.05		56.56		1.94		88.38		1.46		49.70		1.18	
	2019	57.67	1%	23.59	-2%	57.61	2%	2.15	11%	83.73	-5%	1.13	-23%	55.15	11%	1.33	13%
	2020	39.30	-32%	23.99	2%	39.13	-32%	2.12	-2%	51.41	-39%	1.46	30%	54.41	-1%	1.25	-6%
Mar	2018	56.91		25.48		56.24		2.25		91.63		1.77		50.84		1.33	
	2019	52.88	-7%	24.57	-4%	51.63	-8%	2.15	-5%	67.72	-26%	1.47	-17%	54.01	6%	1.44	8%
	2020	31.99	-40%	22.09	-10%	32.03	-38%	1.95	-9%	44.31	-35%	2.47	68%	57.95	7%	1.56	9%
Apr	2018	49.39		22.16		49.22		2.04		101.00		1.75		52.12		1.23	
	2019	53.35	8%	22.39	1%	53.88	9%	2.17	6%	126.54	25%	1.60	-8%	57.60	11%	1.29	5%
	2020	24.81	-53%	18.42	-18%	24.97	-54%	1.66	-23%	89.70	-29%	2.84	77%	52.64	-9%	1.46	13%
May	2018	53.48		23.94		53.24		1.98		105.87		1.73		51.27		1.16	
	2019	50.67	-5%	23.54	-2%	51.72	-3%	2.19	11%	123.20	16%	1.66	-4%	55.01	7%	1.35	16%
	2020	21.79	-57%	21.26	-10%	21.72	-58%	1.96	-10%	87.41	-29%	2.67	61%	49.91	-9%	1.27	-5%
Jun	2018	57.25		24.72		57.74		1.90		97.18		1.48		48.56		1.43	
	2019	48.58	-15%	24.89	1%	48.40	-16%	2.20	16%	73.26	-25%	2.80	89%	45.06	-7%	1.45	2%
	2020	28.01	-42%	22.57	-9%	27.91	-42%	2.17	-1%	85.12	16%	2.10	-25%	46.26	3%	1.08	-25%
Jul	2018	62.69		27.48		61.55		2.15		84.89		1.43		57.21		1.45	
	2019	52.31	-17%	28.48	4%	52.68	-14%	2.25	5%	83.20	-2%	1.70	19%	42.34	-26%	1.72	18%
	2020	38.01	-27%	26.39	-7%	37.90	-28%	2.09	-7%	59.20	-29%	1.64	-4%	41.38	-2%	1.45	-16%
Aug	2018	67.71		24.26		66.30		2.11		67.08		1.34		57.82		1.20	
	2019	49.54	-27%	24.41	1%	49.90	-25%	2.05	-3%	86.05	28%	1.49	11%	46.56	-19%	1.48	24%
	2020	40.32	-19%	23.92	-2%	40.12	-20%	2.07	1%	74.60	-13%	1.95	31%	37.39	-20%	1.40	-5%
Sep	2018	76.32		24.25		74.78		2.11		82.68		1.64		69.91		1.43	
	2019	51.18	-33%	24.61	1%	50.49	-32%	1.92	-9%	75.63	-9%	1.82	11%	45.60	-35%	1.45	2%
	2020	48.80	-5%	24.10	-2%	48.11	-5%	2.15	12%	76.39	1%	1.57	-14%	47.32	4%	1.08	-25%

Clean Spark Spread from MGP and MSD ex-ante is computed and commented. According to datasets and metrics from Section 4.2.2, 2020 monthly average values for Clean Spark Spread on MGP are reported in Table 5.2.

Table 5.2: Clean Spark Spread on MGP, January-September 2020.

	PSV [Eur/MWh]	**Spark Spread [Eur/MWh]**	**EUA [Eur/ton]**	**Eggp [MWh]**	**Clean Spark Spread [Eur/MWh]**
Jan	13.34	25.27	24.41	11369500.54	15.24
Feb	10.8	21.34	23.91	8987584.59	11.52
Mar	10.11	16.33	20.21	7274257.24	8.03
Apr	8.73	10.35	20.13	5904571.07	2.08
May	6.62	11.03	19.57	5934653.14	2.99
Jun	6.01	18.84	23.42	7981839.99	9.22
Jul	6.56	27.93	27.57	10843491.37	16.60
Aug	8.45	26.50	26.47	10348110.32	15.62
Sep	11.67	30.00	27.61	10442811.69	18.65

Due to decreasing traded volumes on MGP, as well as decreasing national price (Table 5.1), and in spite of the reduction of gas price and emissions costs, a drop in the profitability of the Day-Ahead market for gas-fired generation is observed. Similarly, results fot MSD ex-ante are shown in Table 5.3. In spite of reduced electricity prices on MSD, decreasing gas prices lead to an increase in Clean Spark Spread.

Table 5.3: Clean Spark Spread on MSD ex-ante, January-September 2020.

	Spark Spread MSD Upward [Eur/MWh]	Spark Spread MSD Downward [Eur/MWh]	Gas MSD Upward [MWh]	Gas MSD Downward [MWh]	Clean Spark Spread Upward [Eur/MWh]	Clean Spark Spread Downward [Eur/MWh]
Jan	58.63	47.80	761415.43	440050.96	48.60	57.83
Feb	53.58	41.82	597265.05	348621.58	43.75	51.64
Mar	59.77	29.94	784573.45	657334.87	51.46	38.24
Apr	139.15	21.25	896044.53	688423.51	130.87	29.53
May	138.37	17.12	827854.93	622681.33	130.33	25.16
Jun	131.29	18.10	729991.88	542727.05	121.66	27.73
Jul	77.41	26.68	654458.73	447743.07	66.08	38.01
Aug	83.57	34.32	920104.82	404699.62	72.69	45.20
Sep	77.33	46.37	725816.83	320333.00	65.98	57.72

Trends from 2020 show dramatic fall in profitability for power plants only operating on MGP. Nevertheless, the impact of MSD revenues depends on the amount of traded volumes on this market. To show how increasing quantities on MSD can offer profitable opportunities to generators, an example is here reported. Figure 5.5 total revenues (Eur/MWh) for gas-fired power plants trading in all markets, with a proportion based on the average proportions computed in each month. If power plants operated on the market according to this average (trading around 10% of their total generation on MSD and the rest on MGP, see Appendix D), their gains would mainly derive from ancillary services, which would be able to compensate lack of revenues from Day Ahead market.

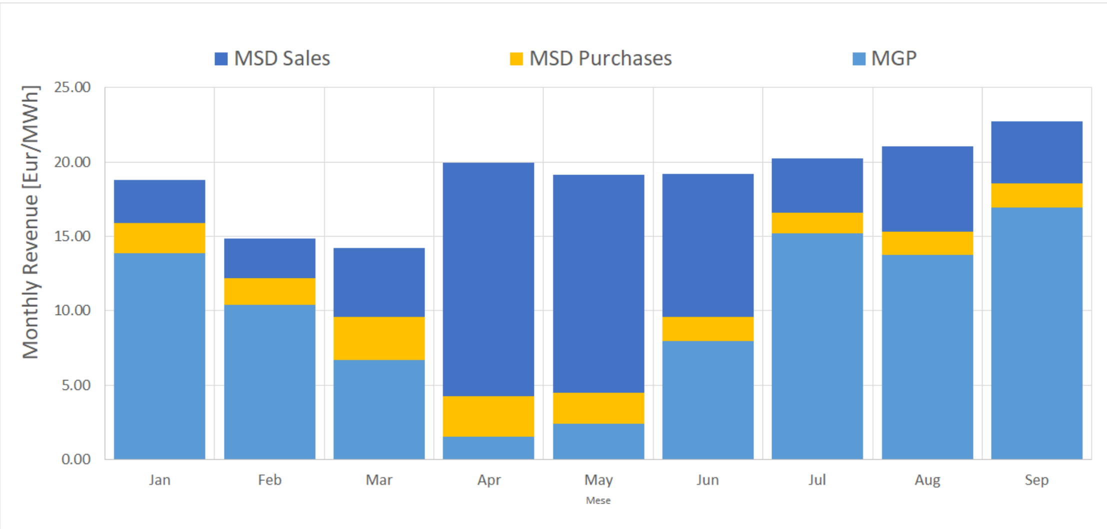

Figure 5.5: Variable Compensation for Capacity Market.

Due to aforementioned uncertainties, starting from 2022 additional revenues for generation units of every typology, including gas-fired power plants, are going to come from Capacity Markets. This market guarantees an yearly revenue for accepted capacity, which is equal to 33000 Eur/MW or a hourly revenue of 3.77 Eur/MW for existing generation units ([66], [67]). Overall, the average revenue computed in this

framework is CMR=31739.63 Eur/MW for 2022 and CMR=33979.87 Eur/MW for 2023 (Appendix F).
Even though generators are obliged to offer their capacity on MGP, and unsold quantities on MSD, they can still receive regular profits from competitive markets: only the difference between a reference price of electricity and a strike price, defined by ARERA according to the variable costs of a peak Open Cycle Gas Turbine, is given back to Terna Figure 5.6. Strike price is usually set by Terna around 125 Eur/MWh ([70], [71]): as a result, based on the analysis of market prices from Table 5.1, generators are not expected to give back revenues from MGP, while this is expected to happen for MSD, where electricity prices are frequently higher than the strike price. As such, Capacity Markets are certainly profitable to generators who can not operate on MSD, while cash-flow for the rest of the generation fleet depends on traded volumes and trading prices for ancillary services. More specifically, generators offering at lower prices than the strike price do not give back any compensation to Terna, and capacity markets represent additional and secured revenues. For generators selling at higher prices, compensation becomes possible and comparisons between expected losses and guaranteed revenues are needed.

<table>
<tr><th></th><th></th><th colspan="2">Prezzo di Riferimento</th></tr>
<tr><th></th><th>Capacità contrattualizzata</th><th>Prezzo Offerto <= Prezzo Strike</th><th>Prezzo Offerto > Prezzo Strike</th></tr>
<tr><td>MGP/MI</td><td>Accettata in esito ai Mercati dell’Energia</td><td colspan="2">Pr. Rif. : prezzo MGP$_z$</td></tr>
<tr><td rowspan="3">MSD</td><td>Offerta ma non accettata o non Offerta nei Mercati dell’Energia
e
Offerta e accettata nel MSD</td><td rowspan="2">Pr. Rif. : max (Prezzo MGP$_z$; Prezzo Strike)</td><td>Pr. Rif. : max (Prezzo MGP$_z$; Prezzo offerto in MSD)</td></tr>
<tr><td>Offerta ma non accettata o non Offerta nei Mercati dell’Energia
e
Offerta e non accettata nel MSD</td><td>Pr. Rif. : max [(Prezzo MGP$_z$; min (Prezzo offerto sul MSD ; Max Prezzo MSD)]</td></tr>
<tr><td>Offerta e non accettata nei Mercati dell’Energia e non offerta nel MSD
o
non presentata né nei Mercati dell’Energia né nel MSD</td><td colspan="2">Sistema Adeguato
Pr. Rif. : max (Prezzo MGP$_z$; Max Prezzo MSD)
Sistema non Adeguato → Evento di scarsità
Pr. Rif. : VENF</td></tr>
</table>

Figure 5.6: Variable Compensation for Capacity Market, [72]

5.2.2 Market Efficiency

With respect to Market Efficiency, metrics defined with respect to increasing demand and prices of ancillary services in Section 4.2.2 include Accepted Quantities (both Purchases and Sales) and total cost of supply on MSD ex-ante and MB. As such, Accepted Quantities from 2018 to 2020, in a period from January until September, are computed, and results for MSD ex-ante are shown in Figure 5.7; in addition, historical trends for total cost of supply for TSO from Terna, commonly known as uplift, for the same period are presented in Figure 5.8.

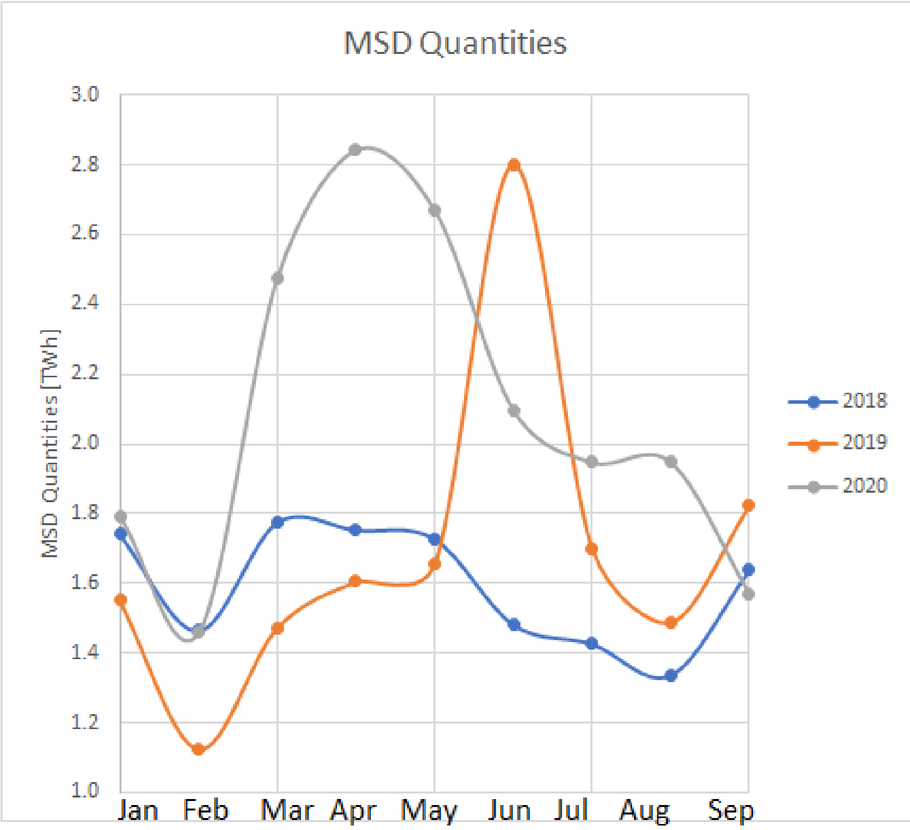

Figure 5.7: Accepted Quantities on MSD ex-ante. January-September 2018-2020.

As shown in the figures, Accepted Quantities sharply increased in 2020, with peaks from the period from March to May; however, increased demand for ancillary services in July and August remained higher than previous years, while June represents an exception, as 2019 exceptionally high quantity is probably due to record heat wave [73]. Specifically, these trends in terms of quantities are driven by increased tradings in both Sales and Purchases, even though the main contribution comes from Sales: figures describing this phenomenon are reported in Appendix E.

In terms of total cost of supply, uplift from Terna shows a peak from March until June 2020, and remained higher than previous years during the third quarter as well. However, uplift does not follow the same pattern as MSD quantities, since the impact of prices might counterbalance volumes. As such, in order to describe more in detail evolutionary trends of Market Efficiency, an analysis on market prices and quantities for each market as reported in Table 5.1 is required.
In the period from January to May 2020, decreasing consumption and subsequent increment in the share of renewable energy Section 5.1 caused a drop in both prices

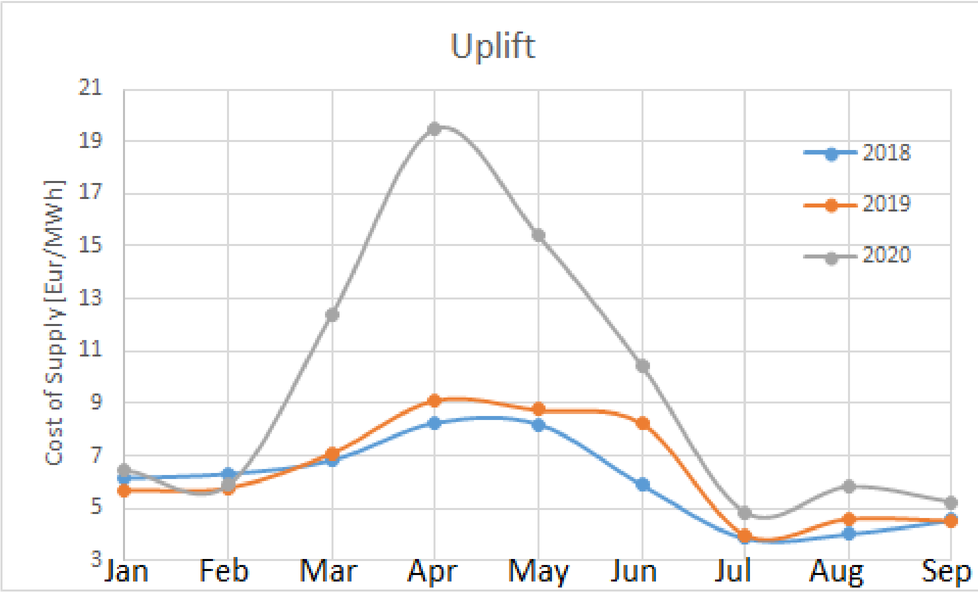

Figure 5.8: Uplift. January-September 2018-2020.

and quantities traded on energy markets (MGP and MI; on the other hand, an increment from traded quantities on MSD ex-ante is observed. Even though this trend has been emphasized during the first half of the year, data show that this is a long-term effect which is not being reversed yet. However, trends in energy prices are more difficult to understand in terms of demand-offer law. In fact, while trends on energy markets show decreasing prices in coincidence with decreasing demand, this is not necessarily true for ancillary services.
For example, the drop of purchases prices on MSD ex-ante from March to May 2020 compensated increased quantities, while the same did not happen for sales. As a result, since sales volumes are larger than purchases, the overall uplift during this period increased. Differently, the heat record wave experienced by the system in 2019 lead to increased quantities for both sales and purchases, but both have been counterbalanced by price reduction. Therefore, uplift values reported in Table 5.4 do not show anomalies in June 2019, while 2020 values increased with respect to previous years, and almost doubled in April and May. In this period, the increment of the uplift made supply costs coming from ancillary services almost comparable with national energy price from MGP, as shown by the uplift over PUN ratio: this phenomenon is expected to become more and more relevant for the economic system, and has been reduced but not reversed in the last quarter (July-September 2020).
Finally, no significant patterns can be identified with respect to Balancing Markets for 2020: as such, plots for these markets are not reported, even though monitoring

of their quantities and prices remains crucial for electricity security assessment.

Table 5.4: Cost of supply on MSD (uplift) as a fraction of Day-Ahead price, January-September 2018-2020.

Month		**Uplift [Eur/MWh]**	**PUN [Eur/MWh]**	**Uplift/PUN [%]**
Jan	2018	6.14	55.14	13%
	2019	5.7	73.35	8%
	2020	6.45	53.92	14%
Feb	2018	6.31	63.31	11%
	2019	5.78	63.45	10%
	2020	5.89	45.19	15%
Mar	2018	6.82	63.73	12%
	2019	7.11	59.99	13%
	2020	12.4	44.39	39%
Apr	2018	8.23	57.62	17%
	2019	9.14	62.49	17%
	2020	19.5	44.31	79%
May	2018	8.18	61.66	15%
	2019	8.76	59.43	17%
	2020	15.4	37.19	71%
Jun	2018	5.89	63.14	9%
	2019	8.25	56.83	15%
	2020	10.42	28.01	37%
Jul	2018	3.87	66.56	6%
	2019	3.97	56.28	7%
	2020	4.83	42.84	11%
Ago	2018	4.04	71.75	6%
	2019	4.59	54.13	8%
	2020	5.82	46.14	13%
Sep	2018	4.56	80.88	6%
	2019	4.50	55.68	8%
	2020	5.22	54.02	10%

In addition, metrics defined with respect to decreasing availability of resources in Section 4.2.2 include Available Capacity in Probability on Capacity Market and the number of Offers on MSD ex-ante. Accepted quantities on Capacity Market for 2022 and 2023 are taken from Figure F.1 and Figure F.2 respectively (Appendix F): total accepted capacity, including both existing and new units all over the country and abroad, reached almost 41 GW for 2022 and more than 43 GW in 2023, and they constitute about half of total dispatchable generation in the Italian electricity

mix. For the computation of electricity security indexes, increasing values of CDP represent increased Market Efficiency. The same applies to the number of offers, whose analysis is not covered by this study.
Finally, based on the analysis of Capacity Market compensations, another benefit from capacity payment to Market Efficiency is identified. As compensation mechanisms incentivize generators to keep prices lower than the strike price, a possible global effect of this market could be limiting MSD prices. This effect would limit the total cost of supply, becoming beneficial in terms of Market Efficiency.

Chapter 6

Conclusions

The main achievements of the study are summarized in this paragraph; they include the definition of a conceptual framework for energy security definition and indexes computation, as well as the definition of numerical indexes and the most relevant results in terms of evolutive scenarios of the Italian power system.
Firstly, the thesis successfully achieved to structure an original conceptual framework for energy security definition and electricity security assessment in an energy transition perspective. The framework constitutes a support to upcoming security studies, as further studies of the energy transition influence on energy security can be framed in this context, and the same approach can be adopted for the analysis of other revolutionary aspects for energy security, such as climate change or cyber attacks.
Secondly, the framework for quantitative assessment of the Energy Trilemma through numerical indexes is expected to be useful in terms of systematisation of the computation process: automatic extraction of data from datasets, data categorization according to a uniform database design, data storage and public access make the whole process more secure and transparent, as well as easily replicable also in terms of metrics calculation and indexes aggregation. The implementation of a database and a graphical interface represents the starting point for the creation of an integrated platform, where data and results are securely and publicly available.
Apart from methodological contributions to scientific research, the most relevant outcomes of the study are addressed to decision-makers. As electricity security is one of the main goals of future energy policies, an insight on future scenarios of the power system in terms of grid flexibility and market adequacy and efficiency is proposed. Flexibility analysis covers a relevant knowledge gap, showing how decreasing residual loads are expected to become permanent at high VRE share, increase risk of curtailment of renewable energy and lead more frequently conventional generation close to technical minimum: as such, the need for flexible generation units, able to adapt power generation according to load patterns, is here acknowledged. Market

Adequacy is especially relevant for both investment decisions and market design: decreasing Clean Spark Spread on MGP foreshadows critical future scenarios at high VRE shares for conventional generation; however, interesting remuneration opportunities from MSD emerged, showing the market value of flexible generation when it comes to investment decisions; moreover, emerging Capacity Market is proven to be promising for an economic support to existing inflexible generation; surprisingly, Capacity Market appears to be beneficial even in combination with participation to competitive markets for ancillary services, at the condition that MSD offers are kept lower than a strike price defined by ARERA. Interestingly for TSO and policy-makers, Market Efficiency is put at risk by increasing cost of supply and required quantities for ancillary services; however, Capacity Market is expected to have a positive influence on both aspects, guaranteeing available capacity and incentivizing generators to keep MSD prices lower than the strike price.

As research on electricity security is constantly evolving, several aspects are left to further studies. Firstly, categories definition for conceptual framework is never final, and further categories can be added; secondly, the importance of the assessment of electricity security in the national interest, especially with respect to data management, requires a professional approach to digital tools implementation, for instance taking into account data protection. With respect to indexes definition, research on further indexes for System Flexibility, for instance involving thresholds in flexibility capability of the system, is recommended; as data for grid Frequency, Voltage and Inertia are not available, the development of quantitative models for the power grid is left to dedicated studies; for all indexes, and especially for Market Idoneity, the selection of the most suitable aggregation methods is requested, especially taking into account overlaps and correlations between metrics.

Overall, the study provides an insight on electricity security, defining a conceptual and operational framework for security assessment, and providing numerical examples for selected indexes able to prefigure future scenarios of the energy transition.

List of Tables

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Appendix A

Demo Interface

```
from IPython import get_ipython
get_ipython().magic('reset -sf')

#import math
import tkinter as tk
from tkinter import *
from tkinter import ttk
import psycopg2
from PIL import ImageTk, Image
import time
from datetime import date
import csv

# %% CONNECT for DB Creation
conn = psycopg2.connect("dbname=First_DB user=postgres password=
    powergroup")
cursor = conn.cursor()

# %% EXTRACT AND SAVE DATA
#create tables
#CLASSE DI DATO: varchar + integer + double precision
#Query in SQL?

# 1) Create tables structure (temporary)

'''
cursor.execute("""CREATE TABLE power (
        day integer,
        hour integer,
        pun float,
        quantity float,
```

```
        gasgen float
        )""")
'''

'''
cursor.execute("""CREATE TABLE gas (
        day integer,
        price float
        )""")
'''

# 2) Access Dataset to extract relevant data + Postgres Upload
'''
f_contents = open('power.csv', 'r')
reader = csv.reader(f_contents)
next(reader)
cursor.copy_from(f_contents, "power", columns=('day', 'hour', 'pun',
    'quantity', 'gasgen'), sep=",")
#sto aggiungendo in coda!
f_contents.close()
'''

'''
f_contents = open('gas.csv', 'r')
reader = csv.reader(f_contents)
next(reader)
cursor.copy_from(f_contents, "gas", columns=('day', 'price'), sep
    =",")
#sto aggiungendo in coda!
f_contents.close()
'''

#save data into lists

conn.commit()
conn.close()

# %% Tkinter GUI

# Class Definition
window = tk.Tk()

#Properties
window.title("Interface Demo - Menu")
window.iconbitmap("est.ico")
window.configure(background="blue")

#Time: definition + update every 1000 ms
```

```
lt = tk.Label(window, text="", height=2, width=20, relief="solid", bg
    ="white")
def clock():
     lt.config(text = date.today().strftime('%d/%m/%Y    ') + time.
    strftime("%H") + ":" + time.strftime("%M") + ":" + time.strftime("
    %S"))
     lt.after(1000, clock)

#Methods Definition: Buttons + Grid Positioning
# --> sono i comandi attivati dai pulsanti (output+posizionamento)

'''
conn = psycopg2.connect("dbname=First_DB user=postgres password=
    etooreleone")
cursor = conn.cursor()
'''

'''
cursor.execute("SELECT * FROM table_sqrt")
i=0
for sample in curso:
     for j in range(len(sample)):
          e = Entry(my_w, width=10, fg='blue')
          e.grid(row=i, column=j)
          e.insert(END, sample[j])
     i=i+1

conn.commit()
conn.close()
'''


#Window and commands
def openm():
     menu = tk.Tk()
     menu.title("Interface Demo - Homepage")
     menu.geometry("800x800")
     menu.iconbitmap("est.ico")
     menu.configure(background="blue")


# %%   def functions to be actioned by clicking buttons on the menu


     #read data input
     def beg(event):
          global inbeg
          inbeg = int(inyear.get() + inmonth.get() + inday.get())
          return()
```

```
    def end(event):
        global inend
        inend = int(endyear.get() + endmonth.get() + endday.get())
        return()

    #display data output
    def datashow():

        #case: invalid data input
        if inbeg > inend:
                errlab=tk.Label(menu, text = "Please Change Date Interval", fg='red', bg='white')
                errlab.grid(sticky="w", columnspan=20, pady=1)
        #columnspan: numero di colonne occupate da ciascun widget

        else:
            datawind = tk.Tk()
            datawind.title("Data Table")
            datawind.geometry("500x500")

            #output table creation
            my_tree = ttk.Treeview(datawind)

            #scrollbars
            vsb = ttk.Scrollbar(datawind, orient="vertical", command=my_tree.yview)
            vsb.pack(side=RIGHT, fill=Y)
            osb = ttk.Scrollbar(datawind, orient="horizontal", command=my_tree.xview)
            osb.pack(side=BOTTOM, fill=X)

            #Data table structure:
            conn = psycopg2.connect("dbname=First_DB user=postgres password=powergroup")
            cursor = conn.cursor()

            #read columns from Database (structured in Astah) and add to output table
            cursor.execute("SELECT * FROM gas LIMIT 0")
            colnames = [desc[0] for desc in cursor.description]

            my_tree['columns'] = colnames
            my_tree.column("#0", width=0)
            my_tree.column(colnames[0], width=1, anchor = CENTER)
            my_tree.column(colnames[1], width=1, anchor = CENTER)
            #my_tree.column("sparkspread", width=1, anchor = CENTER)
            my_tree.heading("#0", text="")
            my_tree.heading("day", text="Date")
```

```
        my_tree.heading("price", text="Gas Price [Eur/MWh]")
        #my_tree.heading("sparkspread", text="")

        #data saving into list and display

        cursor.execute("SELECT * FROM gas")
        gasprice = []
        i=0
        #definisco un flag per stabilire quali date mostrare e quali no
        #si potrebbe usare dei simboli >=<, ma il flag è più generale
        flag=0
        for jj in cursor:
            gasprice.append(jj[1])
            if jj[0] == inbeg and flag==0:
                flag=1
            if flag == 1:
                my_tree.insert(parent = '', index='end', iid=i, text='', values = (jj[0], jj[1]))
            if jj[0] == inend and flag==1:
                flag=0
            i=i+1
            my_tree.pack(fill=BOTH, expand=1)

        '''
        i=0
        for sample in cursor:
            for j in range(len(sample)):
                e = Entry(datawind, width=10, fg='black', bg='white')
                e.grid(row=i, column=j)
                e.insert(END, sample[j])
                #END = Aggiunge in coda
            i=i+1
        '''
        conn.commit()
        conn.close()

        lex = tk.Button(datawind, text='Exit', bg="white", command = datawind.destroy)
        lex.pack(anchor="e")

#display indexes output
def indshow():
    outind = tk.Label(menu, text = "Indexes are currently unavailable", fg='red', bg='white')
    outind.grid(sticky="w", columnspan=6, pady=1)

```

```
    outdat=tk.Label(menu, text = "Date Interval", bg='white', font='Helvetica 10 bold')
    outdat.grid(sticky="w", columnspan=10)


    begdat=tk.Label(menu, text = "Starting Date:", bg='white')
    begdat.grid(sticky="w", columnspan=20, pady=(10,1))

    laby=tk.Label(menu, text = "Year", bg='white')
    laby.grid(row=2, column=0, sticky="w")
    years = [2020]
    inyear=ttk.Combobox(menu, values=years, width=4)
    inyear.bind("<<ComboboxSelected>>", beg)
    inyear.grid(row=2, column=1, sticky="w", padx=(0,5))

    labm=tk.Label(menu, text = "Month", bg='white')
    labm.grid(row=2, column=2, sticky="w")
    months = ["%.2d" % i for i in range(1,4)]
    inmonth=ttk.Combobox(menu, values=months, width=2)
    inmonth.bind("<<ComboboxSelected>>", beg)
    inmonth.grid(row=2, column=3, sticky="w", padx=(0,5))

    labd=tk.Label(menu, text = "Day", bg='white')
    labd.grid(row=2, column=4, sticky="w")

    days = ["%.2d" % i for i in range(1,32)]
    inday=ttk.Combobox(menu, values=days, width=2)
    inday.bind("<<ComboboxSelected>>", beg)
    inday.grid(row=2, column=5, sticky="w", padx=(0,5))

    enddat=tk.Label(menu, text = "Ending Date:", bg='white')
    enddat.grid(sticky="w", columnspan=20, pady=(10,1))

    laby=tk.Label(menu, text = "Year", bg='white')
    laby.grid(row=4, column=0, sticky="w")
    endyear=ttk.Combobox(menu, values=years, width=4)
    endyear.bind("<<ComboboxSelected>>", end)
    endyear.grid(row=4, column=1, sticky="w", padx=(0,5))

    labm=tk.Label(menu, text = "Month", bg='white')
    labm.grid(row=4, column=2, sticky="w")
    endmonth=ttk.Combobox(menu, values=months, width=2)
    endmonth.bind("<<ComboboxSelected>>", end)
    endmonth.grid(row=4, column=3, sticky="w", padx=(0,5))

    labd=tk.Label(menu, text = "Day", bg='white')
    labd.grid(row=4, column=4, sticky="w")
    endday=ttk.Combobox(menu, values=days, width=2)
    endday.bind("<<ComboboxSelected>>", end)
```

```
    endday.grid(row=4, column=5, sticky="w", padx=(0,5))

    emptylab = tk.Label(menu, text='', bg='blue')
    emptylab.grid()

    options_label = tk.Label(menu, text='Options', bg='white', font='
   Helvetica 10 bold')
    options_label.grid(sticky="w", columnspan=10, pady=1)
    ldat = tk.Button(menu, text='Show Gas Price Data', command =
   datashow, bg='white')
    lind = tk.Button(menu, text='Show Indexes', command = indshow, bg
   ='white')
    ldat.grid(sticky="w", columnspan=10)
    lind.grid(sticky="w", columnspan=10)

    lex = tk.Button(menu, text='Exit', bg="white", command = menu.
   destroy)
    lex.grid(sticky="w", columnspan=10)
    scrl = Scrollbar(menu, orient='vertical', command='pages')
    out = tk.Label(menu, text="Output", font='Helvetica 10 bold')
    out.grid(sticky="w", columnspan=6, pady=(30,0))
    menu.mainloop()


#Methods Definition: Labels + Positioning
dname = tk.Label(text = "Power System Security Assessment - Demo
    Platform", fg="red", bg="blue", font='Calibri 27 bold')
logo = ImageTk.PhotoImage(Image.open("est.png"))
lex = tk.Button(window, text='Exit', width=20, height = 4, bg="white"
    , borderwidth=1, relief="solid", command = window.destroy)
lmenu = tk.Button(window, text='Menu', width=20, height =4, bg="white
    ", borderwidth=1, relief="solid", command = openm)

#posso aggiungere STATE = DISABLED / padx,pady per dimensioni
#la funzione command non vuole le parentesi, è un'eccezione
dname.grid(column=1, pady=20, sticky="n", columnspan = 3)
logolabel = tk.Label(window, image = logo).grid(row=1, column=1,
    columnspan=3, padx=100, pady=5)
lmenu.grid(row=3,column=1, pady=50, sticky="e")
lex.grid(row=3, column=3, pady=50, sticky="w")
lt.grid(column=2, pady=40)
clock()


## Constant loop to update windows in real time
window.mainloop()
```

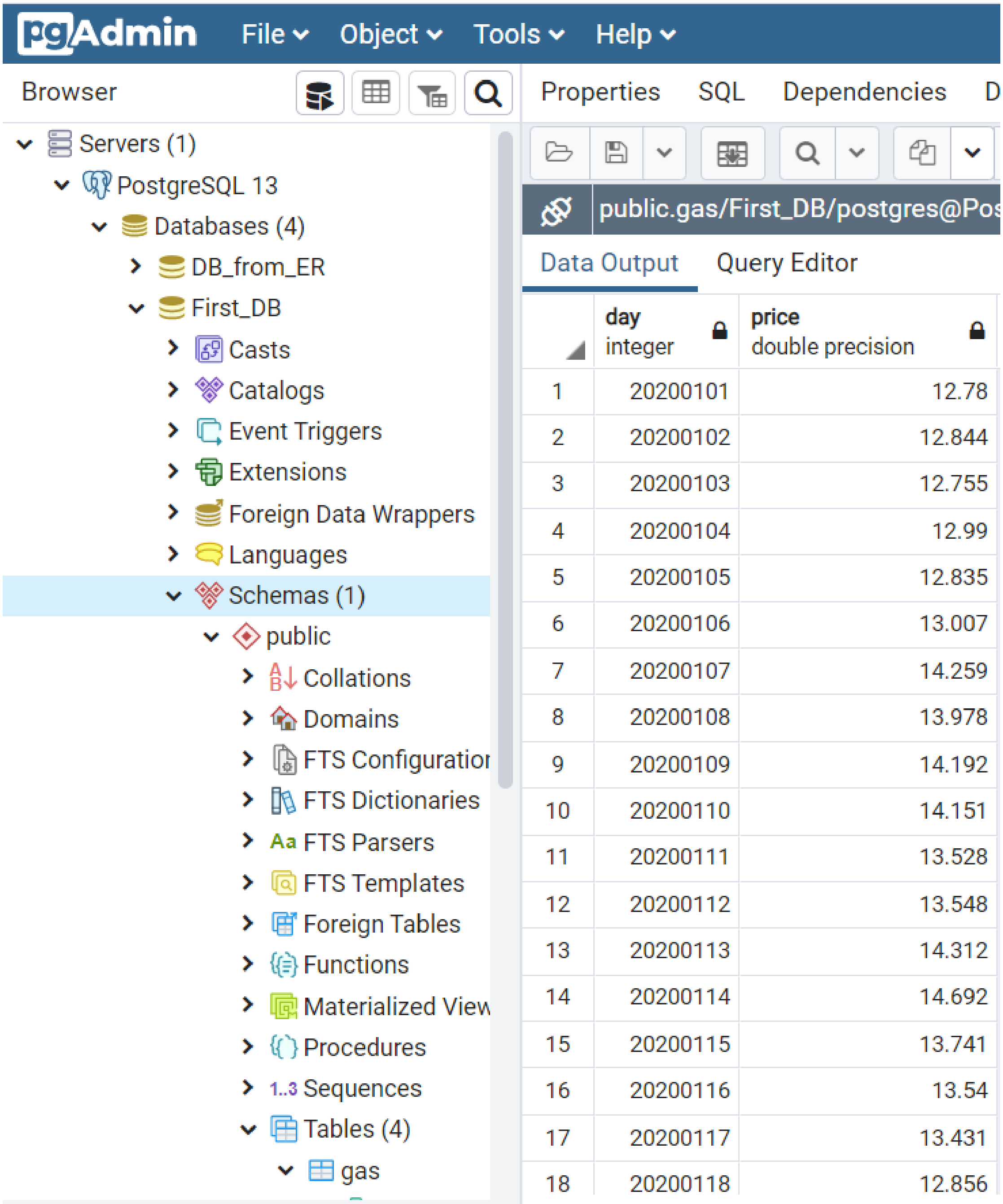

Figure A.1: PostgreSQL Database example - gas price.

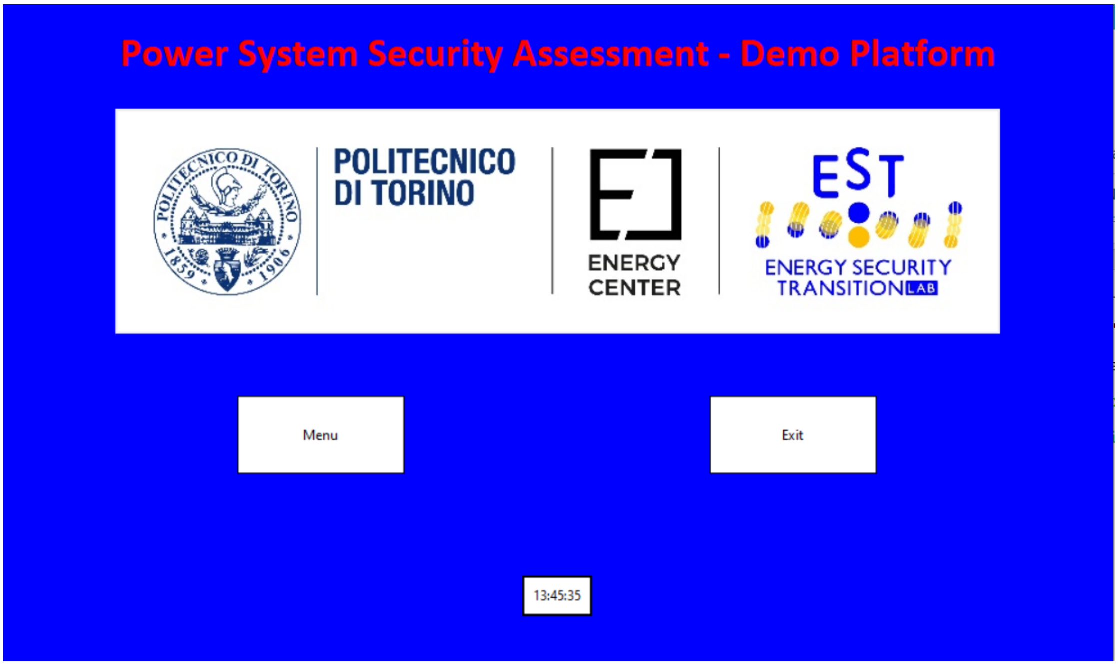

Figure A.2: Demo Interface home page.

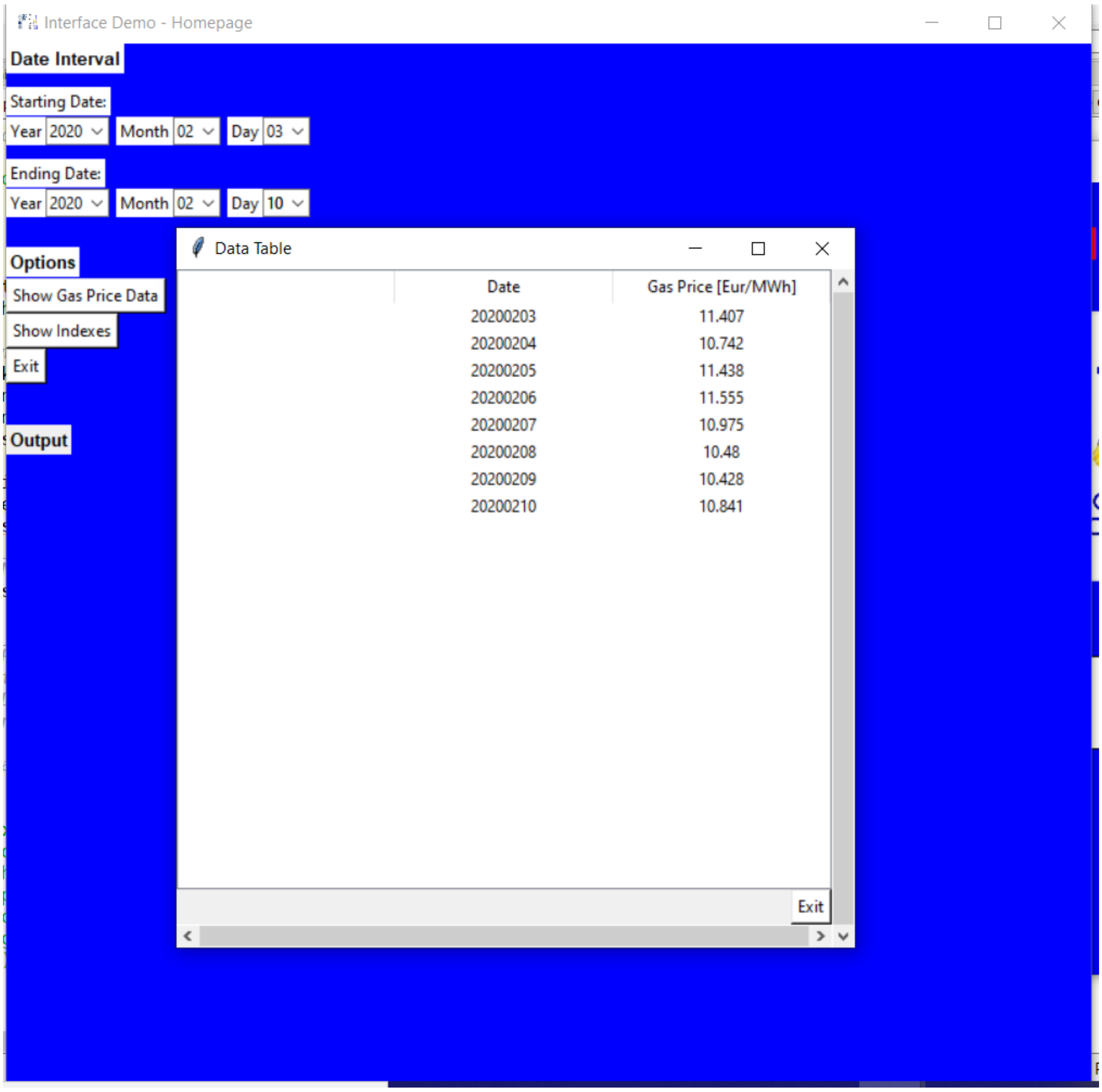

Figure A.3: Demo interface example - gas price.

Appendix B

Legenda for data categorization

A	Analogic
G	Digital
L	Alphanumerical
T	Topographical
Gh	Hourly
Gd	Daily
Gm	Monthly
Tr	Quarterly
Gy	Yearly
Sp	Spot
Ds	District/Province
Zn	Zone
Ct	Country
Rg	Region
Gb	Global
D	Direct from Dataset
U	User defined
B	Public
V	Private
P	Purchased
F	Free

Appendix C

MI Prices

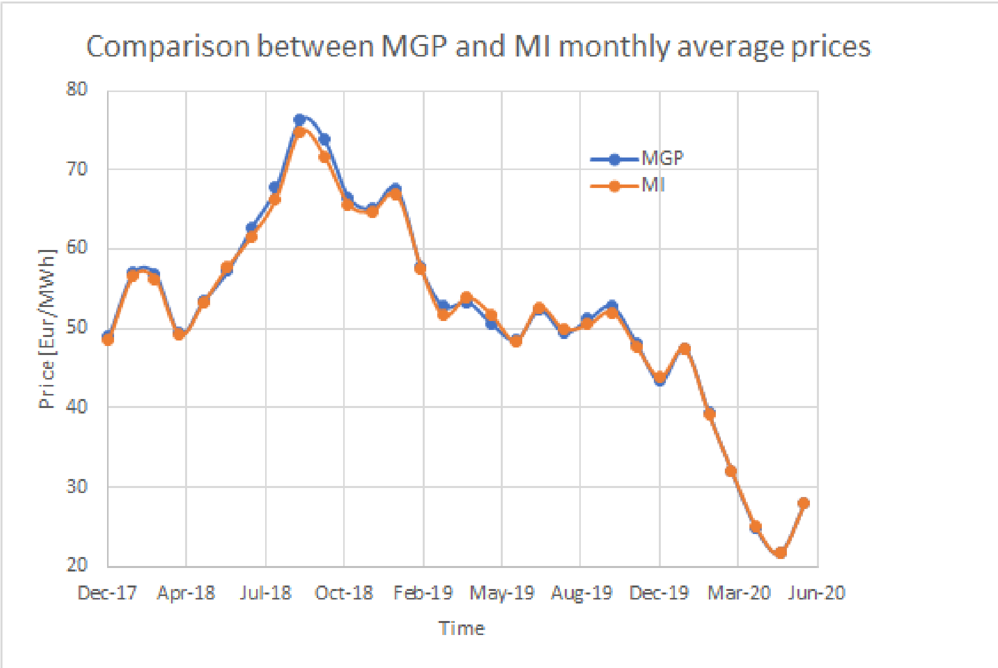

Figure C.1: Comparison between prices on MGP and MI, January 2018 - June 2020.

Appendix D

Total revenues from MGP and MSD

Table D.1: Total revenues from MGP and MSD for power plants trading energy and services according to average market shares, January-September 2020.

	MGP				**MSD Up**			**MSD Down**			**Total Volumes**	**Revenues MGP**	**Revenues MSD Up**	**Revenues MSD Down**
	Eur/MWh	Eur/MWh	MWh	**share**	Eur/MWh	MWh	**share**	Eur/MWh	MWh	**share**	**MWh**	Eur/MWh	Eur/MWh	Eur/MWh
Jan	47.47	15.30	11369500.54	0.904	48.60	761415.43	0.061	57.83	440050.96	0.035	12570966.93	13.84	2.94	2.02
Feb	39.3	11.49	8987584.59	0.905	43.75	597265.05	0.060	51.64	348621.58	0.035	9933471.22	10.39	2.63	1.81
Mar	31.99	7.99	7274257.24	0.835	51.46	784573.45	0.090	38.24	657334.87	0.075	8716165.55	6.67	4.63	2.88
Apr	24.81	1.96	5904571.07	0.788	130.87	896044.53	0.120	29.52	688423.51	0.092	7489039.11	1.54	15.66	2.71
May	21.79	2.96	5934653.14	0.804	130.33	827854.93	0.112	25.16	622681.33	0.084	7385189.40	2.38	14.61	2.12
Jun	28.01	9.24	7981839.99	0.862	121.66	729991.88	0.079	27.73	542727.05	0.059	9254558.91	7.97	9.60	1.63
Jul	38.01	16.71	10843491.37	0.908	66.08	654458.73	0.055	38.01	447743.07	0.037	11945693.17	15.17	3.62	1.42
Aug	40.32	15.51	10348110.32	0.887	72.69	920104.82	0.079	45.20	404699.62	0.035	11672914.77	13.75	5.73	1.57
Sep	48.8	18.63	10442811.69	0.909	65.98	725816.83	0.063	57.72	320333.00	0.028	11488961.52	16.93	4.17	1.61

Appendix E

MSD ex-ante. Accepted Quantities and Prices

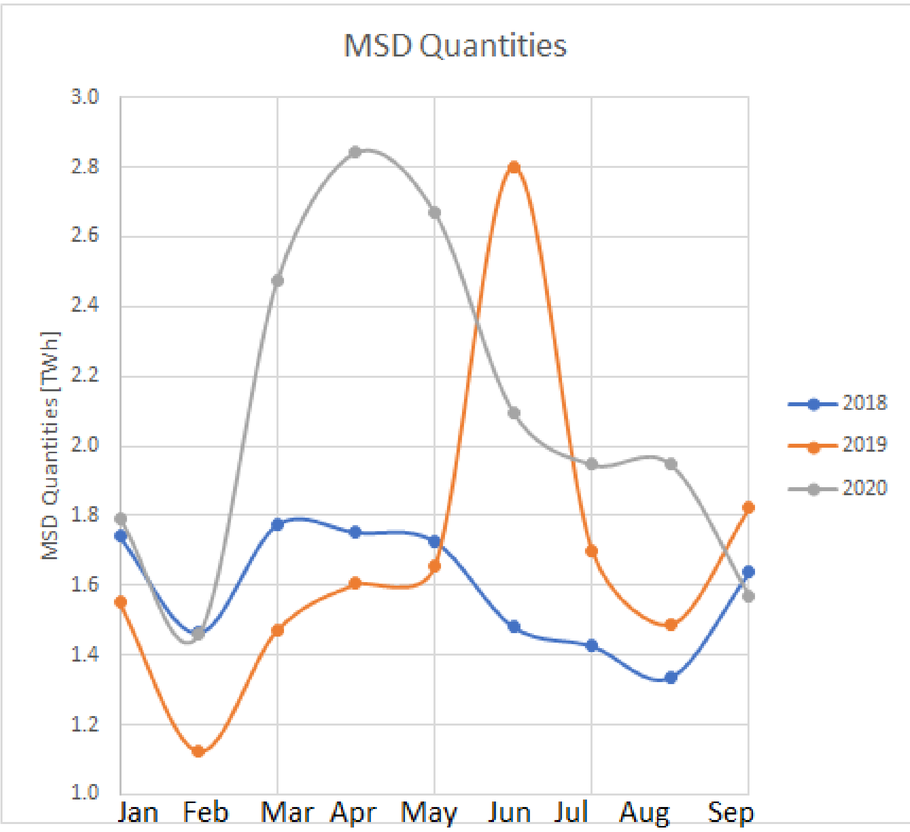

Figure E.1: Accepted Quantities on MSD ex-ante, January-September 2018-2020.

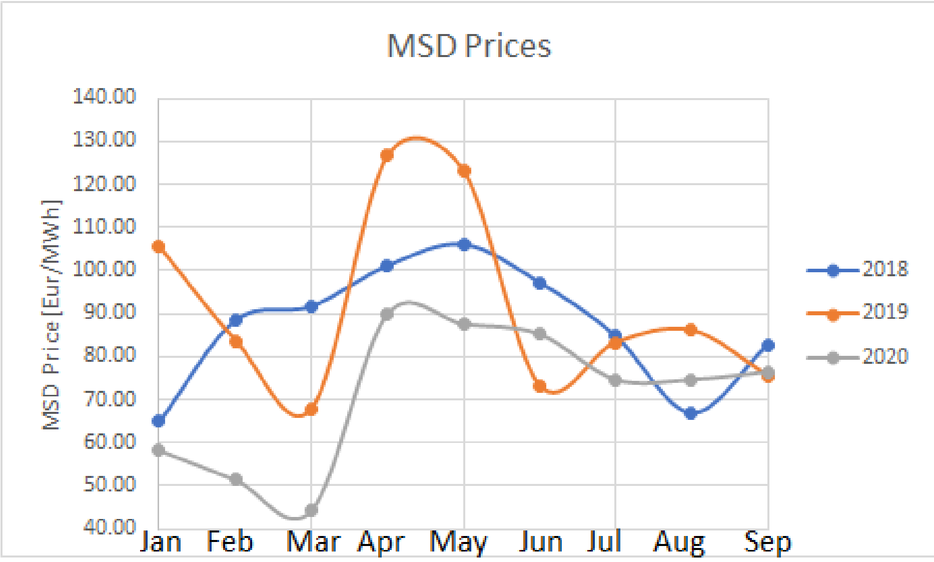

Figure E.2: Average Prices on MSD ex-ante, January-September 2018-2020.

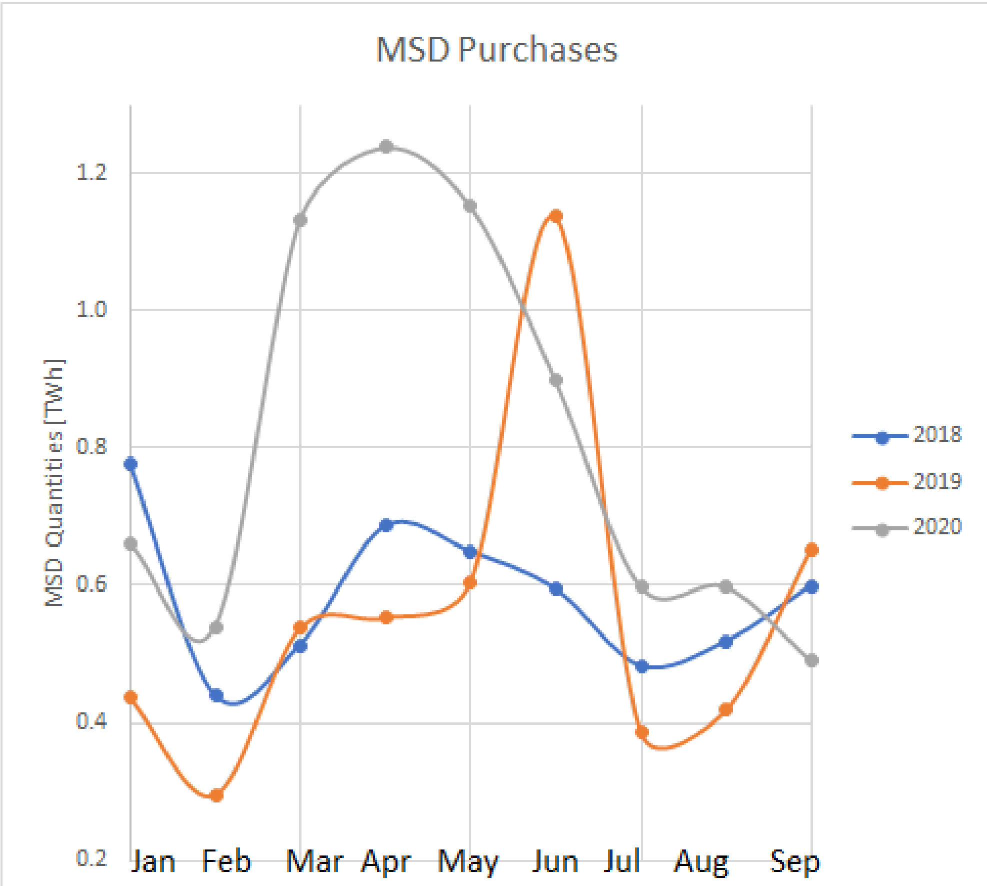

Figure E.3: Purchased Quantities on MSD ex-ante, January-September 2018-2020.

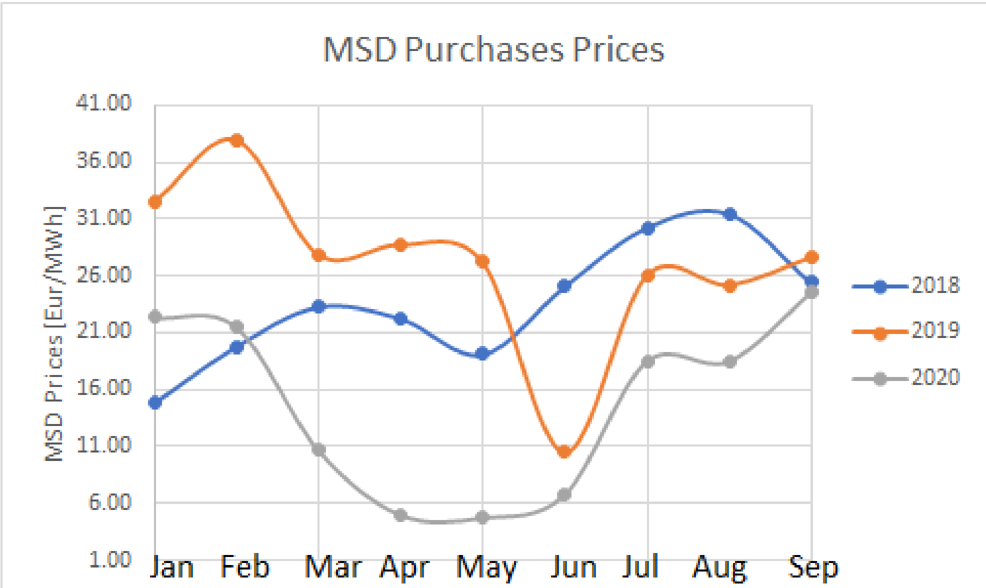

Figure E.4: Purchase Prices on MSD ex-ante, January-September 2018-2020.

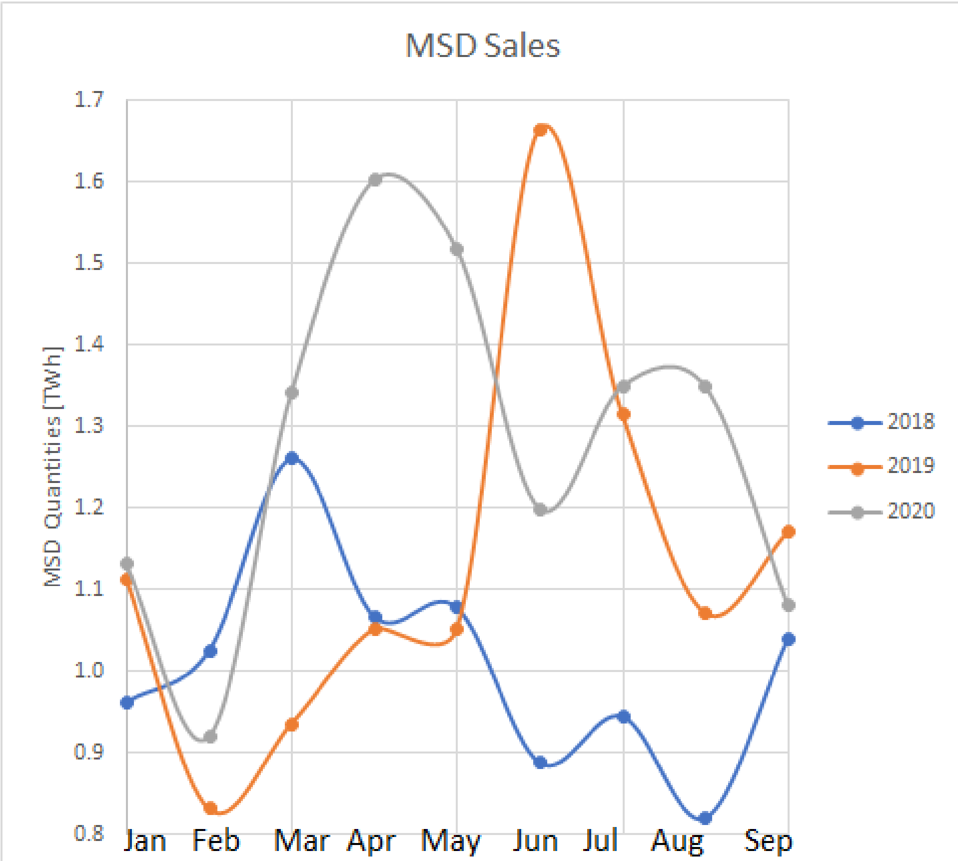

Figure E.5: Saled Quantities on MSD ex-ante, January-September 2018-2020.

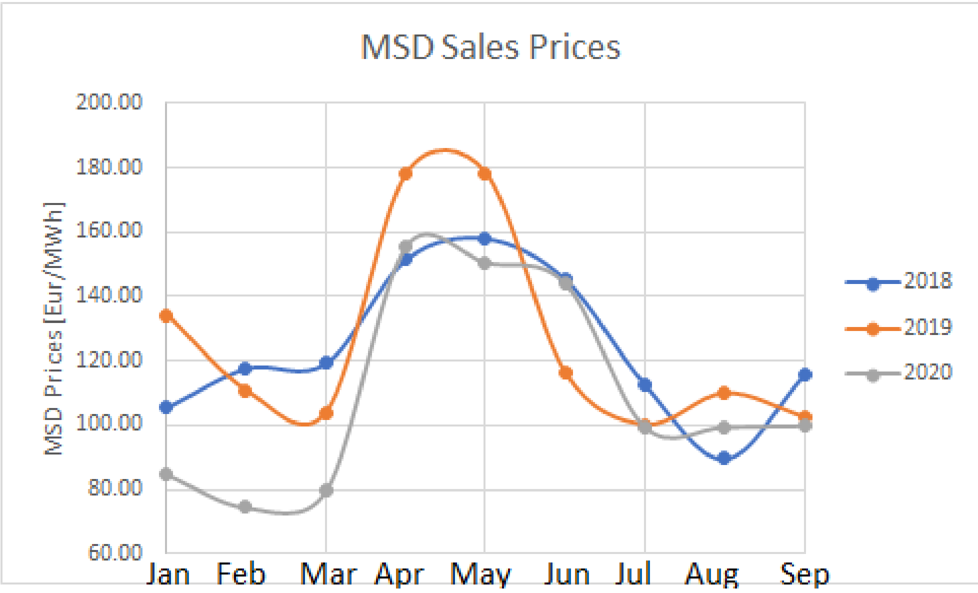

Figure E.6: Sale Prices on MSD ex-ante, January-September 2018-2020.

Appendix F

Capacity Market

CDP	Capacity [MW/y]	Revenue [Eur/MW/y]
CDP Italia Esistente	34758	33000
CDP Italia Nuova	1767	75000
Estero Nord	4241	4400
Estero Centro Sud	104	3449
Estero Sud	49	4000
Totale	40919	31739.63

Figure F.1: Available Capacity in Probability on Capacity Market 2022

CDP	Capacity [MW/y]	Revenue [Eur/MW/y]
CDP Italia Esistente	35013	33000
CDP Italia Nuova	4004	75000
Estero Nord	4241	4400
Estero Centro Sud	104	4949
Estero Sud	49	3999
Totale	43411	33979.87

Figure F.2: Available Capacity in Probability on Capacity Market 2023

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