MASTER´S DEGREE IN THE ELECTRIC POWER INDUSTRY (MEPI)

MASTER´S THESIS

MODELING THE ITALIAN ELECTRICITY MARKET IN CEVESA MARKET MODEL

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Madrid, July 2023

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MODELING THE ITALIAN ELECTRICITY MARKET IN CEVESA MARKET MODEL

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Collaborative Entity: ICAI-Universidad Pontificia Comillas, INESC TEC

SUMMARY OF THE THESIS

The electric sector is evolving towards the integration of the different systems and markets that compose it, with a great relevance of interconnections, especially in Europe, which is evolving to an internal energy market. The present thesis presents the integration and validation of the Italian system and its interconnections (both internally between different areas and with foreign countries) into CEVESA, which already included the Spanish, French and Portuguese systems. Different case studies are analyzed according to the evolution scenarios based on the EU´s forecasts regarding renewables and fuel prices for the next decade, and their results are described. Finally, the conclusions obtained from the case studies and the advantages of CEVESA with the expansion of this work as a tool for studying the integration of electric systems are summarized.

Keywords: CEVESA, Italy, interconnections, Terna

1. Introduction

The energy sector has been changing rapidly in the last decade, driven by technological advancements, sustainable policies, and globalization. The European electricity market is no exception, and energy and environmental policies are a fundamental part of the agreements considered within the European Union, especially since 2007 when the Lisbon Treaty [1] established that the competence in energy matters is shared between the EU and its member states.

Therefore, in this scenario of change and its influence on other strategic sectors, there is a need to analyze and expand existing electricity market models. This work presents the integration of the Italian electricity system into CEVESA.

2. Project definition and model used

CEVESA is a dynamic model for the planning of the expansion of electricity generation systems. At the beginning of this project, the model included Spain, Portugal and France, and as a result of the thesis, it now also includes Italy. Each country is considered as an independent node with a single price, except Italy, which is modelled as the 7 different zones that this system is divided into. The interconnections between these nodes or zones are also modeled.

CEVESA is based on a conjectural variations equilibrium with price-response conjectures and hourly detail, inelastic energy demand, hydraulic and thermal reserves, and technical constraints of generation resources. The model considers the main agents involved in the market, both in terms of generation and storage.

3. Project development and main results

The first case study is the validation of the Italian electricity market model considering the Italian power system as a single zone without Italian internal interconnections. This first case allows validating the technology-specific productions (the relevance of gas technologies, for example) and electricity prices in Italy. The comparison of CEVESA outputs with actual data from Italy for the year 2019 allows iteratively refining the model and the input data used until acceptable similarity between data and results is achieved.

The second case study focuses on modeling the Italian system by including the Italian inner interconnections and their actual capacities. Therefore, the Italian system of the first case study is divided into the different zones that actually compose it. This case allows for assessing a proper fit against real data from 2019.

The comparison between the first and second cases demonstrates the importance of modeling interconnections and the effects they cause, such as market splitting between the different modeled zones. Additionally, it also shows how, once interconnections have limited capacity, the system's operation is constrained in achieving full efficiency.

The third case study focuses on studying the consequences of a significant increase in renewable generation in one of the zones of the Italian system (Central-North), thus allowing for observing the effects of this increase on prices in the different affected zones, as well as the variation of the interconnection flows. This case study allows verifying that by increasing renewable generation in a zone (that could be either an Italian zone or a country itself), it is possible to reduce its energy dependence on neighboring zones. Indeed, this increase is sensible since it contributes to the expected future decarbonization of the EU system, and also to reduce the dependency of the European countries on Russian gas, something desirable due to the Russia-Ukraine war.

4. Conclusions

The results obtained in the first two case studies validate the proper integration of the Italian electricity market into CEVESA, while the last case illustrates the use of CEVESA as a suitable tool for analyzing hypothetical scenarios of electricity market evolution.

The integration of different markets and the ability of models to incorporate variations caused by changes in specific factors are essential for studying the electrical system. Models like CEVESA provide the necessary flexibility to adapt to new contexts, which in future analyses and research may include scenarios such as the impact of the Ukraine war, new EU countries and key factors in the current electricity landscape.

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1. INTRODUCTION

The interconnections among EU countries are necessary for the security of the electrical supply of the interconnected systems but are also a powerful way to efficiently use and optimize energy resources among the interconnected zones by means of commercial energy and reserve exchanges. They also increase competitiveness between the neighboring systems and facilitate the integration of renewable energy, ensuring affordable electricity prices ([2], [3] and [4]).

Traditionally, planning new interconnections between EU countries was carried out bilaterally between the two countries involved. However, in recent years this is changing, due to the aim of the European Union to reach a greater integration of all European electricity markets to improve the European Electricity Market [5]. The improvement of the European interconnections is now of public interest since this would create a more stable and efficient European power system with a broader mix, able to face unexpected contingencies and to integrate a larger amount of renewable generation. This would also help to better integrate the MIBEL markets (Spain and Portugal), which is currently almost an energy island [6], increasing its robustness with the contribution of France and other neighboring European countries such as Italy. Under better interconnections, the MIBEL will also be a source of renewable generation for other EU stage members, considering its potential expansion of renewable generation.

To analyze the behavior of the EU members states markets, it is necessary to have models representing the different price zones and the effect of the interconnections among them. CEVESA, a market model shared by IIT and INESC TEC, is a dynamic mathematical programming model for the expansion and operation of the MIBEL system [7], where also the French power system is included. CEVESA models interconnected single price areas and allows to simulate market coupling and market splitting, the later occurring when the energy through the interconnections reach their maximum capacity and the prices of the interconnected zones are different.

One of the objectives of this thesis is to expand CEVESA to represent new member states and the corresponding market coupling among the markets considered. Align with this objective, this thesis aims to integrate the Italian electricity market, by looking for data of the Italian power system on public sources, and to validate the new Italian zone in CEVESA by analyzing the Italian market model against different scenarios. Modelling Italian market is of interest for CEVESA for different reasons [8]:

- Economy scale: Italy is the third largest economy in the European Union, so its impact is expected to be very significant.
- Grid integration: Italy is closely integrated into the European electricity grid and is critical energy corridor between North and South Europe.
- Energy demand: Power demand in Italy is significant, and therefore Italy impact on the EU market is not negligible.

1.1. MOTIVATION AND OBJECTIVES

The objective set by the EU consists of integrating the European electricity markets in a unique whole sale market, IEM, in addition to reinforcing the interconnections between them [9]. To simulate the behavior of that new market, some market models must be developed. That new model must consider numerous current aspects of the sector, such as in which direction it is evolving and the possibility of having new irruptive technologies.

As seen in previous section, CEVESA is a powerful model capturing many of these features desired. Currently, the Spanish, Portuguese and French markets are represented. The main objectives of this thesis are to include the Italian market in CEVESA and analyze the influence of it in the MIBEL and France power systems. In particular, different case studies are analyzed with data from 2019, studying the greater integration of renewable energies in the behavior of the mix and prices of the Spanish, Portuguese, French and Italian markets.

1.2. WORK METHODOLOGY

During the development of the thesis, the following tasks have been carried out:

- Task 1: Review the literature and compare different studies and existing approaches to the problem considered.
- Task 2: Find structural data of the generation units, demand and productions of the Italian system.
- Task 3: Study CEVESA model and the adaptation of its formulation to integrate the Italian system. This requires familiarization with the tools used, especially GAMS, as well as with CEVESA, thus being able to define, evaluate and study the results obtained in different case studies.
- Task 4: Data validation.
- Task 5: Scenarios definition. Different scenarios are defined to obtain relevant results.
- Task 6: Simulation and result analysis. The scenarios are simulated, in addition to analyze the obtained results, drawing relevant conclusions.
- Task 7: Thesis redaction, with the detailed explanation of the process followed, scenarios considered, results and conclusions obtained.

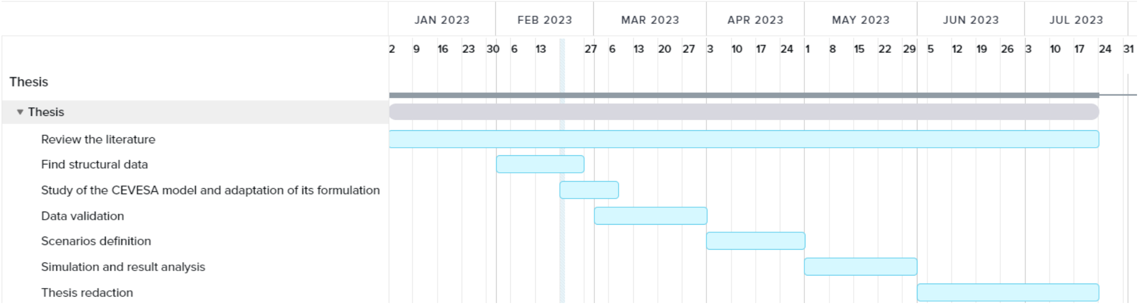

Figure 1. Gantt Chart

1.3. RESOURCES USED

The resources used are:

- GAMS as an algebraic program for modelling a mathematical optimization model
- CEVESA
- Microsoft Office:
  - Excel: For CEVESA database use
  - Word for the thesis redaction

  - PowerPoint to make presentations
- Databases as:
  - ENTSO-E (European Network of Transmission System Operators for Electricity)
  - GME (Gestore dei Mercati Energetici)
  - Terna (Italian Operator System)
- Zotero for references

2. STATE OF ART

The long-term analysis of electricity markets is essential to simulate future international plans and learn from them. Tools and models are required to determine the electricity price in each country, as well as the energy flow between countries through their interconnections. These models help to simulate and understand the behavior of the involved markets, for example, in decision-making processes of investment in new generation and interconnection capacity. In the studies carried out with the tools that model electricity sectors, the following parameters are considered: load and generation in each country and its future forecasts, energy flows between countries through the interconnections, technical constraints of the generation groups, and fixed and variable costs, among others.

Those studies are based in the development of simulations, taking into account different scenarios and temporal horizons such as annual or daily horizons, in order to be able to simulate the maximum possible commercial exchanges respecting different safety criteria.

There are different tools based on dynamic models for multiannual horizons that allow to make these studies, as for example EMMA [10], PRIMES Electricity [11], SEERMAP [12], EU-SysFlex [13], o NEULING [14]. These models are used by companies or researchers to better understand the European power sector and analyze its evolution to propose better routes for a more renewable and sustainable future according to the national energy and climate plans [15]. They are compared with CEVESA in Table 1, Table 2 and Table 3.

Table 1 shows some tools and models of interzonal electricity markets found in the literature, describing the: companies, zones, type, solution and applications. Indicates the company developing the project, countries considered, as well as the current applications of the model.

Table 1. Tools and models of interzonal electricity markets: companies, zones, type, solution and applications [16]

Name of the model	**Developer company**	**Countries of the study**	**Type of model**	**Solution of the simulation**	**Applications**
PRIMES Electricity	E3MLab/NTUA	28 countries members of the European Union	Equilibrium counterpart with EUPHEMIA algorithm formulated as Mixed-Integer Optimization problem	Study of the effect of renewables, the secondary reserve in markets with interconnections	"Clean Energy for all Europeans" for the European Commission in 2016. Decarbonization plans for the EU
EMMA	Neon Energy	Northwestern European Countries (France, Belgium, Germany and Poland)	Economic technician who models the dispatch and investment in power plants	Short or long term calculation of electrical balance. Capacity estimation, hourly prices, and interconnections	Academic papers and consultancy projects for Energy Economics o IET (Institute of Engineering and Technology)
SEERMAP	Fundación REKK. EKC de Serbia está mejorando el modelo	Southeast European countries (Balkans and Hungary) and future enlargements of Romania, Bulgaria and Greece	Static with countries modeled as nodes and their trade limited by transfer capacities	Assessment of solutions for decarbonization together with renewables. Evaluation of the impact of new electrical infrastructures. Identification of market congestion	Sustainable future case studies for low CO2 emission electricity development in South East Europe
EU-Sysflex	Comisión Europea de la Unión Europea	European Union	Flexible Dynamic focused on costumers, grid power sharing and the relationship between DSO and TSO	Estimation of the energy mix focused on renewables, energy exchanges between countries and the variable generation of Virtual Power Plants	Demonstrate the feasibility of new technologies that facilitate the management of distributed resources and their participation in local markets. Differentiate the functions of TSOs (Transmission System Operators) and DSOs (Distribution System Operator)
NEULING	Institute of Energy Economics at the University of Cologne (EWI)	Germany, France, Switzerland, Austria, Belgium, Netherlands, Luxembourg, Denmark, Poland and Czech Republic	Dynamic with high temporal resolution formulated with an NLP (Non-linear programming)	Market Price. Focuses more on consumers with a social perspective	Analyzes the influence on society of the different design decisions of the German electricity market in the next 30 years and the management of border market congestion

CEVESA	IIT/INESC TEC	Spain, Portugal and France	Multinodal Nash equilibrium dynamics that is solved as an equivalent quadratic minimization problem	Analysis of secondary reserve and interconnections. Study of the generation expansion of the Spanish electricity system as the only main node	Study the impact on the electric sector of electric and hydrogen vehicles. Profitability analysis of decarbonization plans with integration of renewable. Influence of interconnections on electricity markets and their price.

As can be seen PRIMES Electricity and EU-Sysflex are the models with the greatest number of countries represented. As with CEVESA, they also include the MIBEL and France power systems. Most models have as objective function the minimization of the system costs which includes generation costs and sometimes auxiliary service costs. However, NEULING model objective function is the welfare maximization considering the response of the demand against the electricity prices. Each of the models has a specific application within the sector. For most of them, these applications are related to the evolution of the electricity sector, decarbonization, as well as the impact of new technologies.

Table 2 analyzes the inputs and hypotheses considered in each of the models, as well as their time horizons, and the generation and storage technologies represented.

Table 2. Tools and models of interzonal electrical markets: hypothesis, technologies and time horizon [16]

Model name	**Inputs and hypothesis**													**Time horizon**	**Generation technologies**						**Storage technologies**		
	CC	**INV**	**DG**	**CG**	**EV**	**H2**	**PD**	**VI**	**SR**	**E**	**CMR**	**CP**	**PCOMB**		**COG**	**BIO**	**TERM**	**HIDR**	**VPP**	**REN**	**BOMB**	**BAT**	**HID**
EMMA	YES	YES	NO	YES	NO	NO	NO	NO	YES	NO	YES	YES	NO	1 year by time slots	YES	NO	YES	YES	NO	YES	YES	NO	NO
PRIMES Electricity	YES	YES	NO	YES	NO	NO	YES	YES	YES	YES	NO	YES	YES	Schedule until 2030	YES	YES	YES	YES	NO	YES	YES	YES	NO
SEERMAP	NO	NO	NO	YES	NO	NO	NO	NO	NO	YES	YES	YES	YES	Until 2050	NO	YES	YES	YES	NO	YES	YES	NO	NO
EU-Sysflex	YES	YES	YES	YES	YES	NO	YES	YES	YES	NO	YES	YES	YES	Until 2030 (EU objective)	YES	YES	YES	YES	YES	YES	YES	YES	NO
NEULING	NO	YES	NO	YES	NO	NO	NO	YES	YES	NO	YES	YES	YES	Multiannual until 2050	NO	NO	YES	YES	NO	YES	YES	NO	NO
CEVESA	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	Multiannual by hourly sections until 2030	YES	YES	YES	YES	NO	YES	YES	YES	YES

Abbreviations:

- CC: Commercial contracts between countries
- INV: Investments
- DG: Distributed generation
- CG: Centralized generation
- EV: Electric vehicles
- H2: Hydrogen production
- PD: Political decisions on future plans
- VI: Unexpected variations in demand or generation
- SR: Secondary reserve
- E: Emission as an output
- CMR: Marginal cost of renewables=0
- CP: Coal price
- PCOMB: Fossil fuel price

Generation and storage abbreviation:

- COG: Cogeneration
- BIO: Biomass
- TERM: Thermal
- HIDR: Hydro
- VPP: Virtual Power Plants
- REN: Renewables (solar and wind)
- BOM: Pumping
- BAT: Batteries
- HID: Hydrogen

Table 2 shows that EMMA and SEERMAP are the models that consider a smaller number of inputs and hypotheses, making these not resemble reality as much as other existing models. Only CEVESA and models used in EU-Sysflex project are able to analyze the influence in the electricity market of the hydrogen market and the electric vehicle resources. Both are technologies which are being developed at great speed and may have a relevant impact in the coming years.

In relation with the times horizons, models up to 2050 are usually not simulated on an hourly basis. Only CEVESA has an hourly resolution although, to reduce the computational complexity, only a reduce set of years from the simulation horizon is considered.

Regarding the generation portfolio, renewable, thermal and hydro are the only ones that are present in all models. It should be noted that models used in EU-Sysflex project are the only ones that represents VPP. In relation to storage technologies, CEVESA is the only model with three storage technologies considered, pump storage units, batteries, and hydrogen storage. Another interesting difference of CEVESA is the inclusion of the expansion of distributed generation, which is significantly increasing and expected to increase even more with the development of self-consumption and energy communities.

Table 3 shows the interconnections, the technical limitations and the markets that are modelled in each tool. It also shows the type of code used (private or available for download).

Table 3. Tools and models of interzonal electricity markets [16]

Model name	**Interconnections**				**Technical limitations**										**Market**		**Code**
	Internationals	**NA**	**NTC/K**	**MC**	**CCT**	**AT**	**RG**	**CPA**	**GE**	**PR**	**TD**	**AS**	**PMA**	**MPL**	**Daily**	**Intraday**	
EMMA	YES	NO	NTC	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO	GAMS
PRIMES Electricity	YES	NO	K	YES	YES	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES	YES	GAMS/CPLEX/PATH
SEERMAP	YES	NO	NTC	YES	YES	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES	NO	Private code
EU-Sysflex	YES	NO	NTC	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES	NO	YES	YES	Private code
NEULING	YES	YES	NTC	NO	YES	YES	YES	YES	NO	NO	YES	NO	YES	NO	YES	NO	Private code
CEVESA	YES	NO	NTC	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES	NO	GAMS/CPLEX with private code

Interconnection related abbreviations:

- NA: National
- NTC/K: Net Transfer Capacity or Kirchoff
- MC: Market coupling

Technical limits related abbreviations:

- CCT: Thermodynamic cycle cost
- AT: Activity time (minimum or maximum)
- RG: Generation ramps
- CPA: Stop and start costs
- GE: Generators efficiency
- PR: Politics restrictions
- TD: Transmission and distribution
- AS: Auxiliary services
- PMA: Minimum starting power
- MPL: Market price limits

It is important to represent electrical interconnections in a model because they enable the transfer of electrical energy between different electrical systems, having a significant impact on the energy markets. As shown in Table 3, not all models consider them in the same way. NEULING, which only models Germany, considers the interconnections of the different areas within the country.

PRIMES and CEVESA consider a greater number of technical limitations making them more accurate (on the contrary, SEERMAP is the one which consider fewer technical limitations). In particular, CEVESA includes Unit Commitment thermal plants constraints and also the corresponding for hydrogen and electric vehicle. Both technologies are considered the best option to decontaminate land traffic [17], making relevant to represent their impact on the market models. At the same time, CEVESA models markets coupling and splitting, which not all the models consider. This is also important because it helps to understand better how energy markets are related in different regions and how the energy exchanges between them can be optimized [18].

3. CEVESA

3.1. CEVESA DESCRIPTION

CEVESA [7] is a multi-year model for the operation and expansion of the electric power generation systems of Portugal, Spain, France and Italy (included during this thesis), open to future expansions. Those countries are represented as independent nodes of a single price connected by electrical interconnections. CEVESA is based on a conjectural variations equilibrium with price-response conjectures with hourly detail, inelastic energy demand, hydraulic and thermal reserves, and technical constraints of generation resources. CEVESA determines investment and operation decisions at a single optimization level, and the simulation is resolved with a quadratic minimization cost objective function equivalent to the conjectural equilibrium.

The model considers investments made by power generating companies (GENCOs) in large scale thermal and renewable plants, as well as by customers distributed in local generation and storage (DER). It also considers secondary reserves [19], [20], centralized storage, or a simplified model of the hydrogen economy. Electric power generation is represented at the supply level unit, taking into account its technical characteristics (e.g., for thermal power plants, start-up and shut down costs, efficiencies, generation ramps, emissions, maximum and minimum power). A technology representation is also considered for future GENCOs investments analysis. Customers exchange energy with the grid in both buying and selling directions according to their rates and can invest in renewable technologies depending on the sector of activity to which they belong (industrial, commercial and residential).

The balance between generation and demand is hourly, and for the case of generation expansion, it guarantees the supply security in each modeled electric system. In addition to the electric sector, CEVESA models the transportation sector. It considers investment in electric vehicles (PEV), internal combustion vehicles (CEV), and hydrogen vehicles (H2CV) and their storage. To do this, infrastructure, price, fuel storage, and other costs are considered as inputs to the model.

As CEVESA takes into account the electric generation and consumption sectors, hydrogen generation and consumption, and electric and green hydrogen vehicles, it is possible to simulate future scenarios considering the interaction between these sectors. The outputs of CEVESA are hourly prices, production per supply unit, CO2 emissions, and investments in new generation and storage capacity. The model helps with long-term planning of the represented systems and analysis of predicted trends in prices, interconnections, and technology evolution of energy generation and storage. The model allows for long-term planning of the systems, and it represents and analysis of predicted trends in prices, interconnections, and productions, in the face of possible future scenarios. Several studies have already been conducted with CEVESA, such as determining the synergies between renewable generation and plug-in electric vehicles [7] or analyzing future decarbonization scenarios [21]. This project focuses on the inclusion of the Italian system.

3.2. CEVESA FORMULATION

3.2.1. Basic modeling hypotheses

The following assumptions have been made:

- Hydro technology
  To avoid over-optimization of the hydro technology, a set of sensible constraints have been set based on detailed analysis of real productions and cleared reserves. In addition, to be able to extrapolate these constraints to different hydro years, constraints parameters have been correlated with inflows. See [20] for more details on the hydro statistical constraints considered.
- Thermal technology
  Thermal technologies have been modeled taking into account their lifespan, ramp-up and ramp-down rates, as well as the startup and shutdown costs associated with them. Similarly, it is worth noting that they have been modeled using different types of technology.
- Renewable technology

Renewable generation is modeled by technology, considering wind and solar. It is worth noting that in the modeling process, the spillovers of these technologies have been taken into account.

- Demand

  The demand curve is hourly. It is assumed to be inelastic i.e. consumers are not sensitive to changes in electricity prices.

- CO_2 emissions

  CEVESA considers that the only technologies that emit CO_2 are coal, gas and fuel.

3.2.2. Formulation

For the sake of simplicity, in this section a basic formulation of the constraints and objective function affected by the Italian power system is shown. The sets, indexes, parameters and variables used are included in the following tables:

Table 4. Model indexes

z	Zone	7 zones in Italy
t	Technology	T: Thermal, H: Hydro, R: Renewable (solar and wind)
h	Hour	
a	Year	
u	Offer unit	

Table 5. Model parameters

$C_{u,a}^{V}$	Variable cost	€/MWh
$C_{u,a}^{ON}$, $C_{u,a}^{OFF}$	Start-up, shut-down costs	€
$C_{u,a}^{E}$	CO_2 emissions costs	€/tCO_2
$D_{z,h,a}$	Hourly demand	MWh
$Q_{z,h,a}^{PRED}$	Expected pre-dispatched energy	MWh
$ZU_{z,u}$	Determine if a unit belongs to a zone	Binary
$NEX_{,z,h,a}$	Net exchanges from European countries not modelled to z	MWh
$EM_{u,h,a}$	Specific CO_2 emissions per unit	tCO_2/MWh

Table 6. Model positive variables

$q_{u,h,a,z}$	Generated power (hydro and thermal)	MW
ct	Total system operation cost	€
$flow_{z,z´,h,a}$	Interconnection flow between zones (positive for export)	MWh
$b_{u,h,a,z}$	Pumping of hydro units	MWh
$vert_{z,h,a}$	Spillage in the system	MWh

Table 7. Model binary variables

$y_{u,h,a,z}$	Start-up decision	Binary
$z_{u,h,a,z}$	Shut-down decision	Binary

The most important equations of the model are:

- Objective function

The model can be run in operation or investment modes. In this thesis, only the operation mode has been analyzed, having the analysis of generation expansion as a future line of development. The objective function of CEVESA considered in this project consists of minimizing the total electric costs of the seven different zones in which Italy is divided, so the analysis of the influence of market power on price determination is also beyond the scope of this work. The mathematical formulation of the objective function is as follows:

$$ct = \sum_{z,u \in T \cap \mathrm{ZU}_{\mathrm{z,u}}} \sum_{h} \sum_{a} [C^{V}_{u,a} \cdot q_{u,h,a,z} + C^{ON}_{u,a} \cdot y_{u,h,a,z} + C^{OFF}_{u,a} \cdot z_{u,h,a,z} + C^{E}_{u,a} \cdot EM_{u,h,a} \cdot q_{u,h,a,z}]$$

Equation 1. Objective function

- Energy balance

Below is the formulation of the energy balance equation that ensures that production always meets the hourly demand of each country taking into account international and internal exchanges (this last only for the case of Italy). In addition to the technical constraints of the supply units and others necessary for the representation of the transport and hydrogen sectors, which are not detailed in this section for simplicity (some are compiled in [20]), this is the most important constraint of the model since its dual variable leads to the electricity price in each country.

$$Q^{PRED}_{z,h,a} + \sum_{u \in T \cap \mathrm{ZU}_{\mathrm{z,u}}} q_{z,u,h,a} + \sum_{u \in R \cap \mathrm{ZU}_{\mathrm{z,u}}} q_{z,u,h,a} + \sum_{u \in H \cap \mathrm{ZU}_{\mathrm{z,u}}} q_{z,u,h,a} - vert_{z,h,a} = D_{z,h,a} + \sum_{u \in H \cap \mathrm{ZU}_{\mathrm{z,u}}} b_{u,h,a,z} + \sum_{z':z' \neq z} flow_{z,z',h,a} + NEX_{z,h,a} \quad \forall z,h,a$$

Equation 2. Energy balance

4. INPUT DATA FOR THE ITALIAN SYSTEM

4.1. TECHNOLOGIES AND GENERATION DATA

All generation data has been obtained from the ENTSO-E Transparency platform [22]. This ensures that authorized and reliable sources of information are being used, which adds validity and rigor to the results and conclusions obtained in this study.

For hydro technologies, data has been considered for both conventional and pumping hydro.

For thermal power plants whose closure year was not an input data in ENTSOE [22], a useful life of 50 years from their opening year has been set.

Regarding energy generation, there was also the need of assigning ENTSO-E generation units or technologies to those considered in CEVESA, which has a different level of aggregation. The adopted solution was to relate both types of technologies as shown in the Table 8.

Table 8. Grouping of ENTSO-E technologies in CEVESA

CEVESA	**ENTSO-E**
COG	Biomass, Waste
C	Fossil Brown Coal/Lignite, Fossil Hard Coal
CC	Fossil Gas
FG	Fossil Oil
HTURB	Hydro Pumped Storage Aggregated
BTURB*	Hydro Pumped Storage Consumption

HCONV	Hydro Water Reservoir
NU	Nuclear
Others	Other, other renewable
Solar	Solar
Solar T	Solar Thermal
Wind	Wind Onshore

*With a negative sign because it represents consumption

This adaptation is crucial for result analysis and serves as a reference for subsequent simulations and comparisons of generation technologies.

4.2. INSTALLED CAPACITY

The future renewable, hydro and thermal installed capacity that appears in the Italian NECP (PNIEC in Italy, standing for Piano Nazionale Integrato per l'Energia e il Clima 2030) [23], considered Italy as a whole country. To consider the future installed capacity per zone, the installed capacity in the last year for which data are available (2022) has been projected to the future linearly, with origin in data from 2022, until the year 2030, considering the data provided by NECP on installed powers for the years 2025 and 2030.

It should be noted that NECP only provides data on installed power for the entire Italian system. To include it in CEVESA, the power to be installed in each zone for the years indicated in NEPC is the same percentage of the total as the existing in 2022.

Figure 2 shows the installed capacity for each of the technologies considered of the Italian system for year 2019.

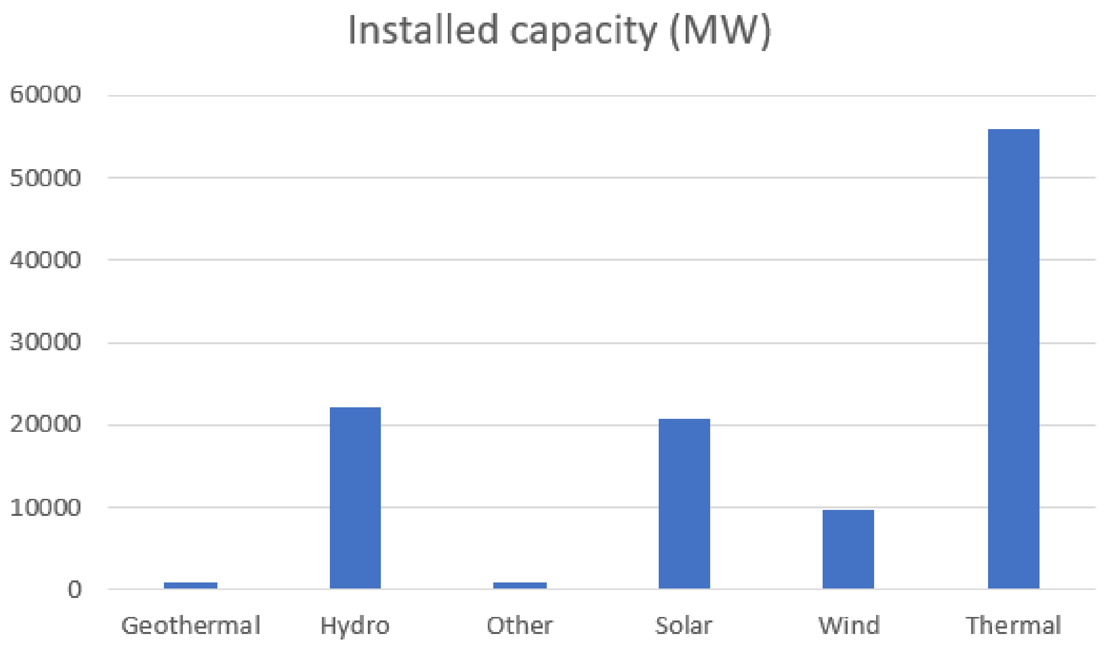

Figure 2. Installed capacity per technology of Italy 2019

4.3. DEMAND

All demand data has been obtained from the ENTSO-E Transparency platform [22]. The demand data are by zones and has a resolution of 15 minutes. Since the demand inputs in CEVESA have an hourly resolution, an average has been taken of the 4 periods of 15 minutes that make up an hour. The years for which data has been obtained from ENTSO-E and included as inputs in CEVESA range from 2018-2022. For future case studies simulating future years (from 2022 to 2050), the demand is calculated as an annual increase of 0,6% starting from the year 2022.

4.4. INTERCONNECTION CAPACITY AND ITALIAN EXPORTS

Both the capacity of existing interconnections and the hourly energy exported/imported by each zone in Italy have been obtained from the ENTSO-E Transparency platform [22]. The capacity data of the interconnections are by zones, with an annual resolution. The data obtained are from 2018 to 2022. For the years after 2022 until 2050, the capacity of the interconnections has been considered identical to that of the year 2022. The imports/exports of Italy, both from internal interconnections and international ones, are data with an hourly resolution. The data are from 2018 to 2022.

It should be noted that in the case study where Italy is considered as a single zone, all international exports/imports have been added to the total demand.

4.5. COST OF THERMAL POWER PLANTS

The costs of thermal power plants considered in this study are based on the data provided by JRC Open Power Plants Database [24]. Note that all data for all generation units were not present in the JRC file, although it was available for most of them. For those plants where ramp-up and ramp-down data was not available in that database, the values presented in Table 9 have been used.

Table 9. Ramp-up and ramp-down values for thermal units not included in JRC database

Tech	**Ramp-Up (% of installed net capacity per minute)**	**Ramp-Down (% of installed net capacity per minute)**
FG	0,006	-0,008
CC	0,012	-0,014
CIB	0,011	-0,013

4.6. FUEL PRICES AND CO_2 EMISSIONS PRICES

Fuel prices and CO_2 are obtained from graphs of Aleasoft Energy Forecasting [25]. CEVESA considers that the only technologies that emit CO_2 are coal, gas and fuel. Although nuclear power plants also emit CO_2, the amount, compared to those of other thermal plants, can be considered negligible as discussed in [26] [27].

5. STUDY CASES: INTEGRATION OF ITALY IN CEVESA

The year 2019 has been chosen as the base for model validation because the latest version of CEVESA was validated for the MIBEL and France using this year. Additionally, it is the most recent year in which the electricity sector did not experience unexpected irregularities like those that occurred in 2020 or 2021 due to COVID-19 or in 2022 due to the Russia-Ukraine conflict.

5.1 DEFINITION OF STUDY CASES

In this section, the three case studies conducted in this thesis are presented. These cases have allowed to validate the model of the Italian system.

Case 1: In the first case, Italy has been modeled as a single price zone. The international interconnections between Italy and other countries have been considered, but not the internal interconnections between the different price zones within this market. The objective of this case is to verify that this first and simplified modelling approach performs correctly by validating it with real data from 2019. This is a relevant preliminary step towards including the seven existing zones in the Italian electricity market.

Case label: “ITA_[zone code]-uniquezone-2019”, where the codes zones could be:

- N: North
- CN: Center-North
- S: South
- CS: Center-South
- SIC: Sicily
- SAR: Sardinia
- CAL: Calabria

i.e. if the label is “ITA_N-uniquezone-2019”, it means that the graph shows the prices of the North zone in the study case that does not considers the interconnections between the different existing zones, for the year 2019.

The objective of represents the different price zones obtained from CEVESA is to show that, as there are no limitations through the interconnections, and the resulted prices in all the zones are the same.

Case 2: In this case, in addition to the international interconnections mentioned in case 1, the interconnections between different price zones within Italy have been included. The objective of this case is to validate CEVESA but considering the real market clearing that takes into account all price zones and finite interconnection capacities among these price zones, that may, in some cases, lead to market splitting.

Case label: “ITA_[zone code]-7zones-2019” where the codes zones could be:

- N: North
- CN: Center-North
- S: South
- CS: Center-South
- SIC: Sicily
- SAR: Sardinia
- CAL: Calabria

i.e. if the label is “ITA_N-7zones-2019”, it means that the graph shows the prices of the North zone, in the study case that considers the interconnections between the different existing zones, for the year 2019.

Case 3: In this last case, the amount of renewable energy (solar and wind) generated in the Central-Northern zone has been multiplied by 10 to test the model under extreme RES penetration scenarios. The intention is to validate again the model, verifying that the congestion of the internal interconnections between different zones performs properly reflecting the saturation due to the high RES penetration and the correspondent market splitting. Likewise, the aim is to observe the price differences that can occur when some of the interconnection reach their commercial capacity limit.

Case label: “ITA_[zone code]-solar10-2019”, where the codes zones could be:

- N: North
- CN: Center-North
- S: South
- CS: Center-South
- SIC: Sicily
- SAR: Sardinia
- CAL: Calabria

i.e. if the label is “ITA_N-solar10-2019”, it means that the graph shows the prices of the North zone, in the study case that considers an increase of x10 in generation of renewable energy (solar and wind), for the year 2019.

Currently (year 2023), the Italian electrical system is divided into 7 zones as shown in Figure 3. However, in the year for which the model validation was performed (2019), the Italian electrical system was divided into 6 zones, as shown in Figure 4. This difference is due to the inclusion of the Calabria zone in the system 2021. The model validation and all case studies are conducted with 6 zones, without considering Calabria.

Figure 3. Zones and interconnections modeled in CEVESA from 2021 onwards

Figure 4. Zones and interconnections modeled in CEVESA prior to 2021

Running the simulation for the year 2019 in CEVESA, considering only the Italian electrical system and with hourly resolution, takes approximately 1 hour.

5.2. CASE 1: SIMULATION OF ITALIAN SYSTEM 2019 AS A SINGLE ZONE

5.2.1. Scenario description

This case study is to validate the Italian electricity system performance considering it as a single price zone. This allows to simplify the model so that the international interconnections are simplified by considering fixed exchanges based on historical data. The capacities of the internal interconnections between different zones within the Italian electricity system are assumed to be infinite.

The other countries already modelled in CEVESA have been deactivated to focus solely on simulating the Italian system.

This preliminary step towards integrating interconnections between different zones is crucial due to its capability to perform prior model validation, before the complex modeling of internal interconnections, CEVESA enables users to validate the model beforehand. To achieve this, the results obtained from the model are compared with real data from the year 2019.

The volume of data used is extensive, both in terms of supply units and historical series, and multiple different data sources have been utilized. Therefore, this process is not trivial and has required an intensive iterative phase to verify the quality of the incorporated data.

The iterative process followed was as follows:

1. Intensive search for all necessary data: demand, generation, existing power plants and their data, international and national interconnections, etc.
2. Data processing, adapting the demand data to have hourly resolution, adjusting the existing interface to accommodate the varying data of different generators within Italy.
3. Linking the Excel interface with CEVESA in GAMS.

4. Once everything was linked, the model had to be thoroughly debugged.
5. Basic simulations were conducted to ensure that all required technologies were producing power and to verify that the generation matched the demand.
6. Final model simulation

5.2.2. Results

The first case study of the Italian electrical system simulated with CEVESA allows to validate the structural and historical data of the Italian system by comparing the output of CEVESA with real data from the year 2019. This comparison is shown in Figure 5.

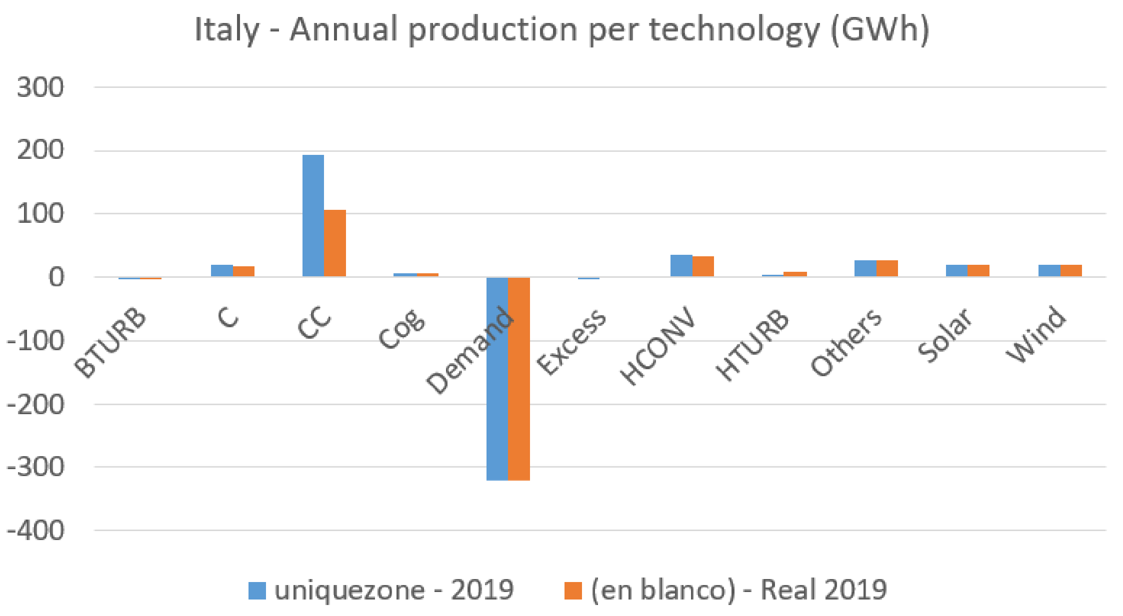

Figure 5. Case 1: Annual production per technology

It can be observed how, despite not specifically modeling the internal interconnections of the Italian electrical system, the results show a great similarity (except for CC technology) between the productions calculated by the model and the real ones. This confirms a reasonable behavior of CEVESA when applied to the Italian system.

However, it should be noted a significant difference in productions for the CC technology. This is because the real data coming from the ENTSO-E database seems to be incomplete, or that they have being interpreted in a wrong way. Indeed, when computing the balance for several selected hours with ENTSO-E data, and it was verified that the sum of productions does not match the total demand, including the interconnections.

To be more specific, Table 10 shows the data for the Central-North zone on 12/06/2019 at 10 am in a concrete manner, so that the information mentioned in the previous section can be verified.

Table 10. Mismatch between the production and demand data

Demand	4652 MWh
Biomass Production	32 MWh
Fossil Gas Production	780 MWh
Fossil Oil Production	10 MWh
Geothermal Production	648 MWh
Hydro Run of River Production	308 MWh
Hydro Reservoir Production	74 MWh
Other Production	214 MWh
Solar Production	914 MWh
Wind Production	8 MWh
Interconnection Flow Center-South>Center-North	1129 MWh
Interconnection Flow N>CN	803 MWh

This leads us to a total demand of 6584 MWh while the production is 2988 MWh.

Despite this issue, it was considered that the model provides sensible results and behaves properly, reproducing reasonably the Italian system behavior, even if no internal zones have yet been considered.

This initial analysis confirms the relevance of gas technology in the energy production of the Italian system.

Figure 6 shows the real and computed North-Zone prices for the first week of 2019. Since Italy is being considered in CEVESA as a single zone, it was compared to the average of the actual prices of the existing zones in Italy. In other words, the actual price considered in this case study is the average of prices in the 6 zones for each hour of the year. This actual price is indicated by the label "ITA – ITA average – Real 2019".

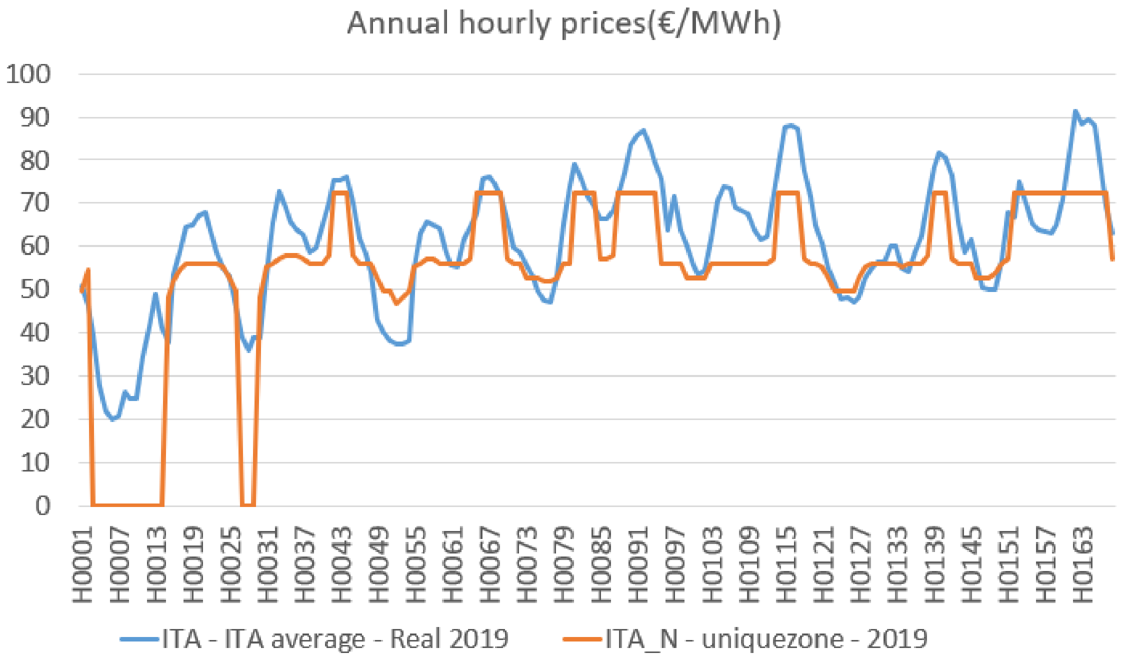

Figure 6. Case 1: North average annual hourly prices

The figures shown below represent the price results obtained by CEVESA for each of the zones, without considering the interconnections. This allows us to observe how, in the absence of internal interconnections in the model, al zones have the same price curve for the first week of the year 2019.

Figure 7 shows the Center North hourly prices, resulted from case 1, for the first week of the year 2019.

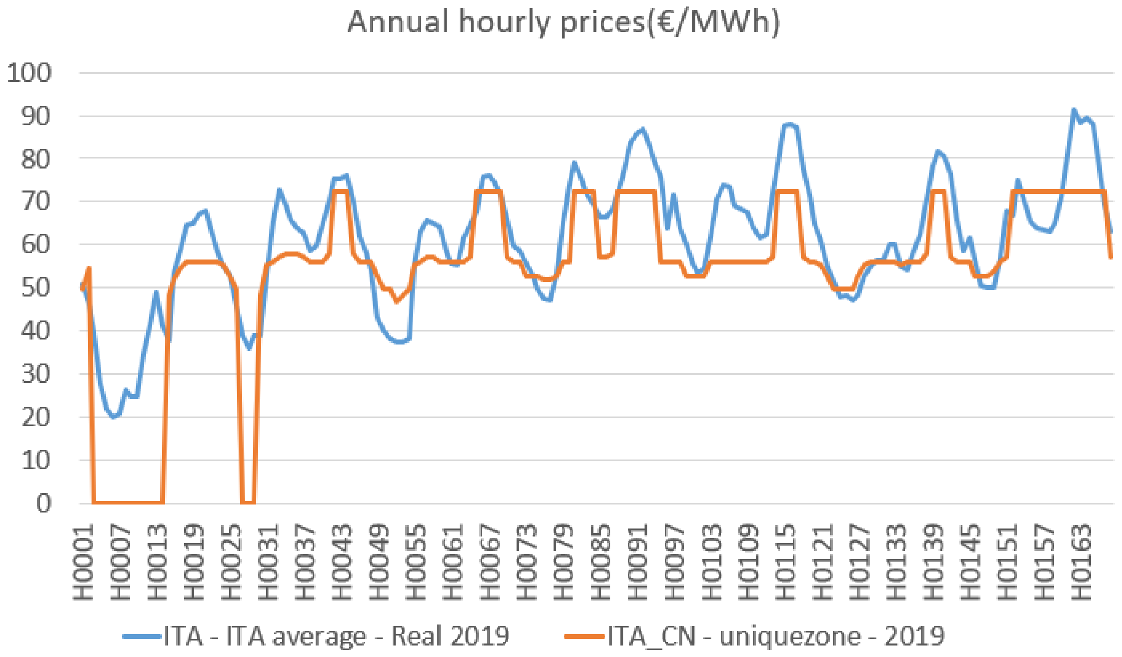

Figure 7. Case 1: Center-North average annual hourly prices

Figure 8 shows the South hourly prices, resulted from case 1, for the first week of the year 2019.

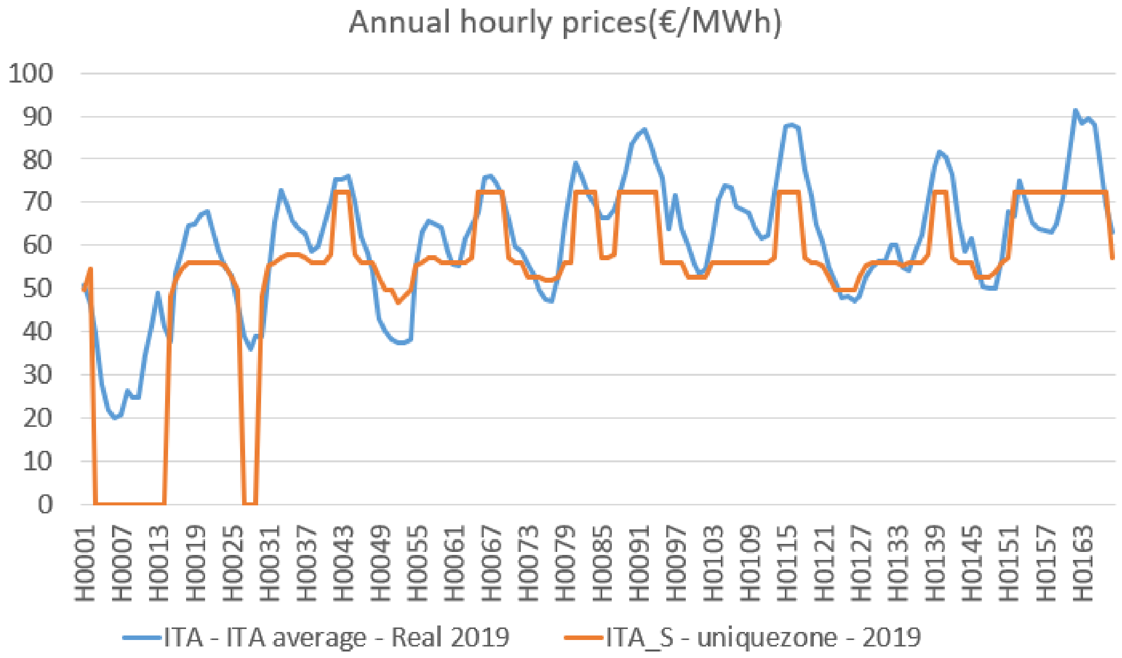

Figure 8. Case 1: South average annual hourly prices

Figure 9 shows the Center South hourly prices, resulted from case 1, for the first week of the year 2019.

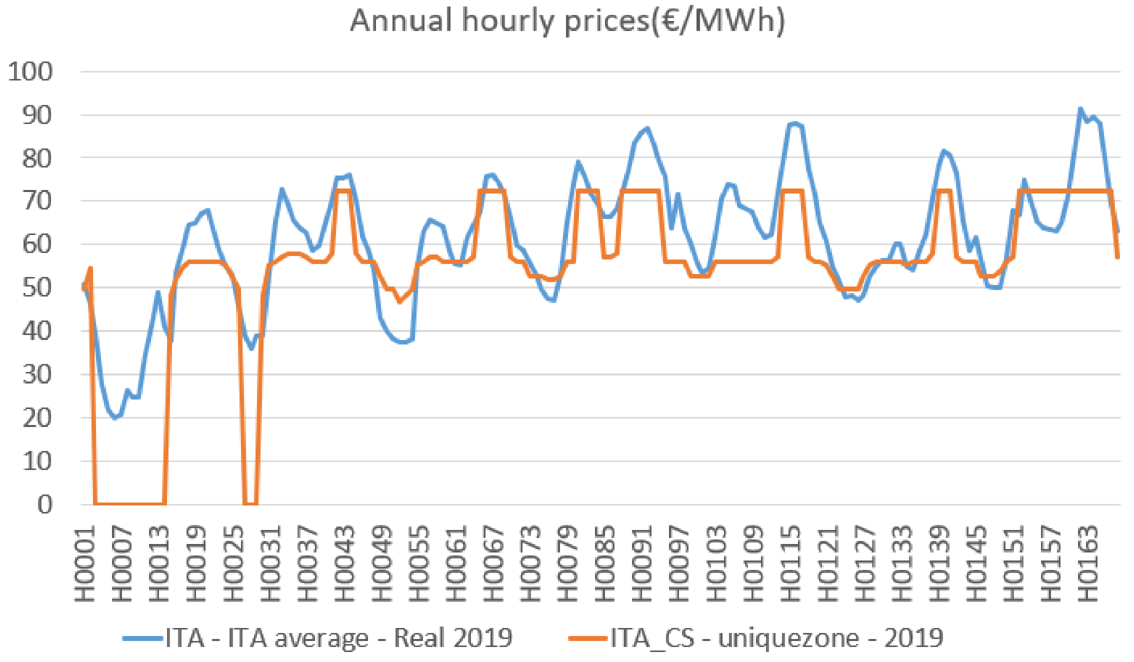

Figure 9. Case 1: Center-South average annual hourly prices

Figure 10 shows the Sardinia hourly prices, resulted from case 1, for the first week of the year 2019.

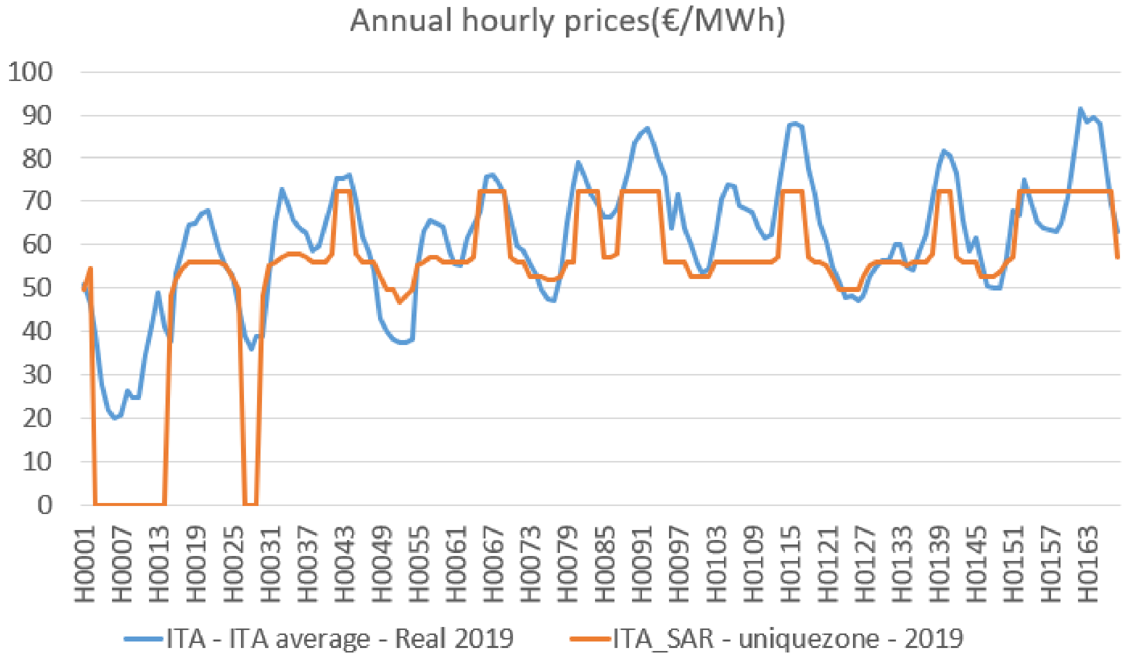

Figure 10. Case 1: Sardinia average annual hourly prices

Figure 11 shows the Sicily hourly prices, resulted from case 1, for the first week of the year 2019.

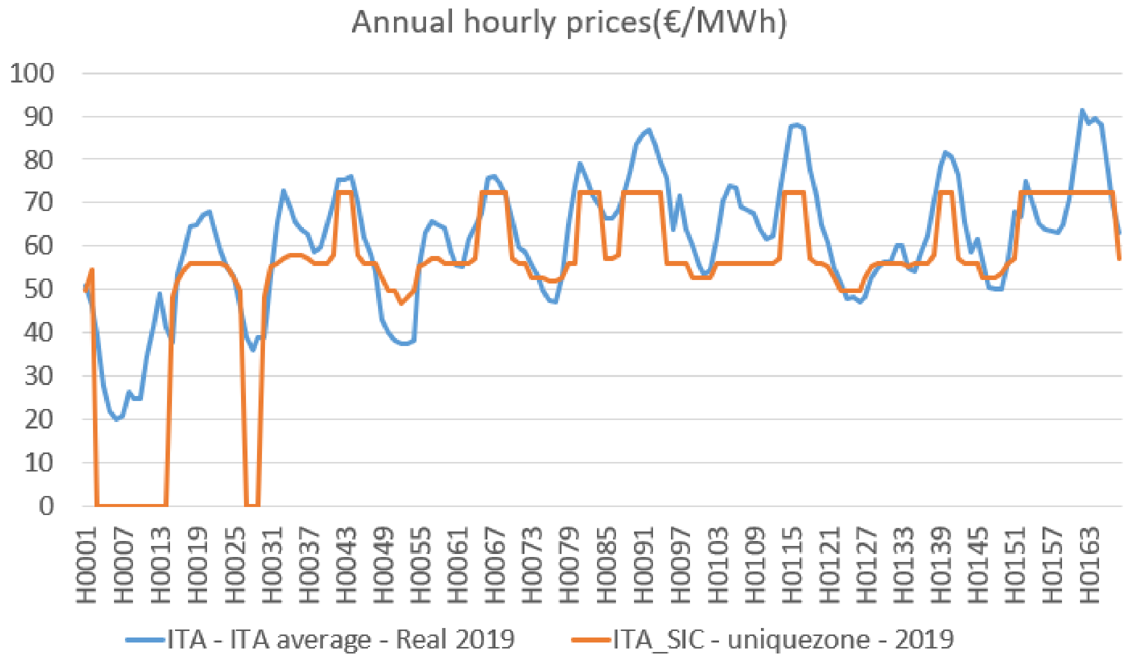

Figure 11. Case 1: Sicily average annual hourly prices

It can be observed that the results computed by CEVESA are similar and follow the same variability as the real averaged price of Italy considered as a single zone (arithmetic average of the prices of the 7 zones). This also helps to support the proper behavior of CEVESA in modelling the Italian system. Note that differences as these ones or larger always happen with this type of models.

In this case study, it can be observed that all zones have the same price throughout the represented hours.

5.3. CASE 2: SIMULATION OF ITALIAN SYSTEM FOR 2019 WITH 7 PRICE ZONES

5.3.1. Scenario description

In this case study, the same data as in the previous case has been used, but the following additional data has been added to the model.

Table 11. Input data 7 zones Italy

Data	**Source**
Interconnections capacity between de different zones	ENTSO-E [22]

After studying the Italian system as a single zone and validating the results of this model against real data, this case study simulates the Italian electricity system in a realistic manner. It considers the internal interconnections among the different zones into which the Italian system is divided: North, Central-North, South, Central-South, Sardinia, Sicily, and Calabria. Although all zones have been considered in the implementation of the model, CEVESA has been implemented to consider the existing zones for each year. If the model is executed for years prior to 2021, it would consider 6 zones. However, if it is executed for years after 2021, it would consider the current 7 zones. As the validation of the model is with 2019 real data, Calabria has not been considered in this thesis.

The main objective of this case study is to analyze the accuracy of the modeling of the Italian system against real data from the year 2019, considering both the country's international interconnections and internal interconnections.

5.3.2. Results

In the second case study, which includes modeling different zones of the Italian system, as well as the interconnections between them, it is necessary to validate the model considering the different results obtained by CEVESA in each zone compared to the actual data from the year 2019.

As a reminder, Table 12 is attached below as a summary of the nomenclature used in the legend of the various graphs.

Table 12. Labels indexes

ITA_[zone code]-uniquezone-2019	Represents the prices for the zone corresponding to the zone code indicate, for the scenario that considers Italy as a unique zone for the year 2019
ITA_[zone code]-7zones-2019	Represents the prices for the zone corresponding to the zone code indicate, for the scenario that considers the different zones of Italy for the year 2019
ITA_[zone code]-Real2019	Represents the real prices for the zone corresponding to the zone code indicate for the year 2019

Figure 12 represents the hourly prices for the first week of the year in North zone of the system for the first and second case studies. It is worth noting once again that the model is being validated for the year 2019, so the Calabria zone (currently existing in the Italian system) does not appear in the analyzed results, as this zone was included in the system in the year 2021.

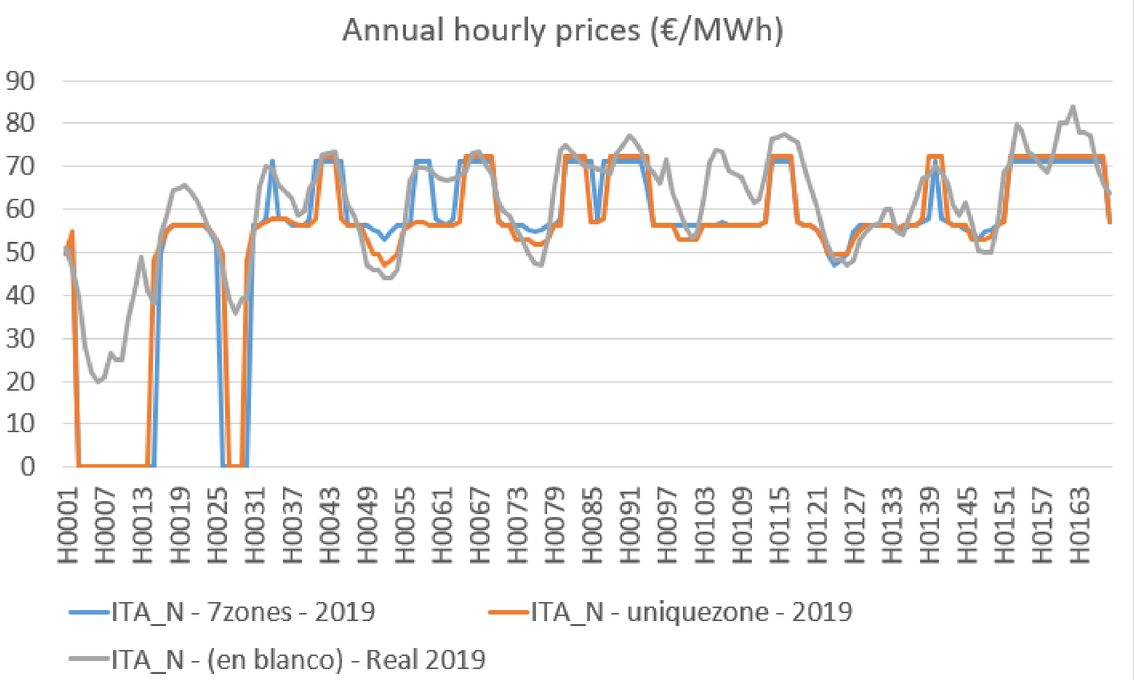

Figure 12. Case 2: North average annual hourly prices

Figure 13 shows the Center North hourly prices, resulted from case 1 and 2, for the first week of the year 2019.

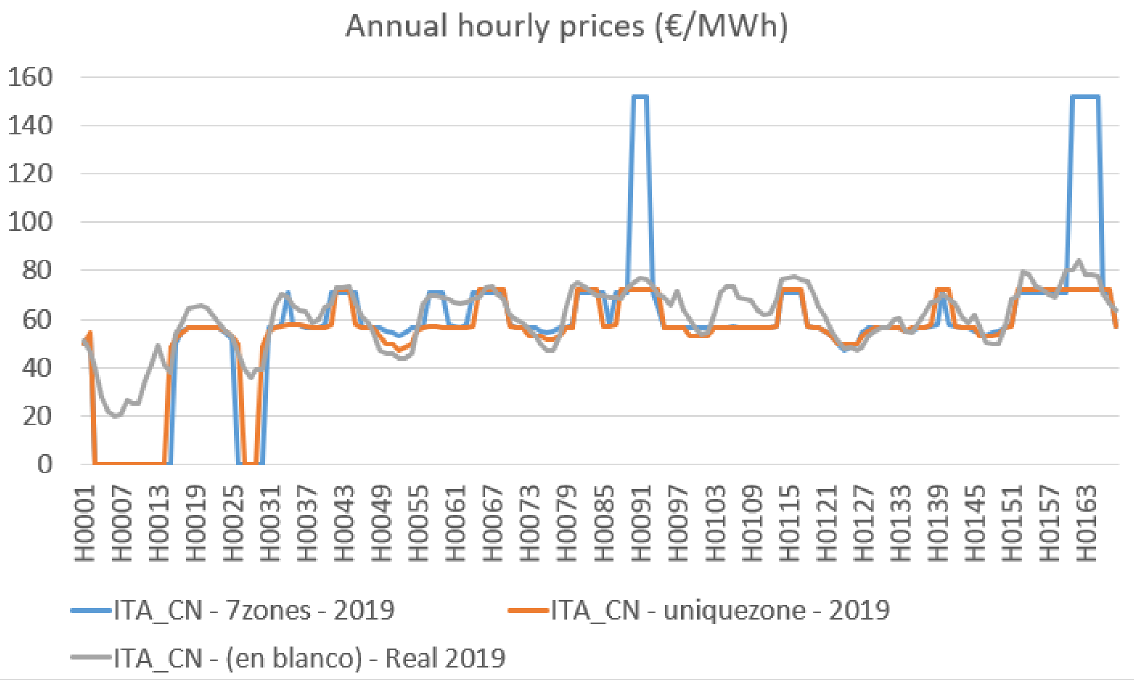

Figure 13.Case 2: Center-North average annual hourly prices

Figure 14 shows the South hourly prices, resulted from case 1 and 2, for the first week of the year 2019.

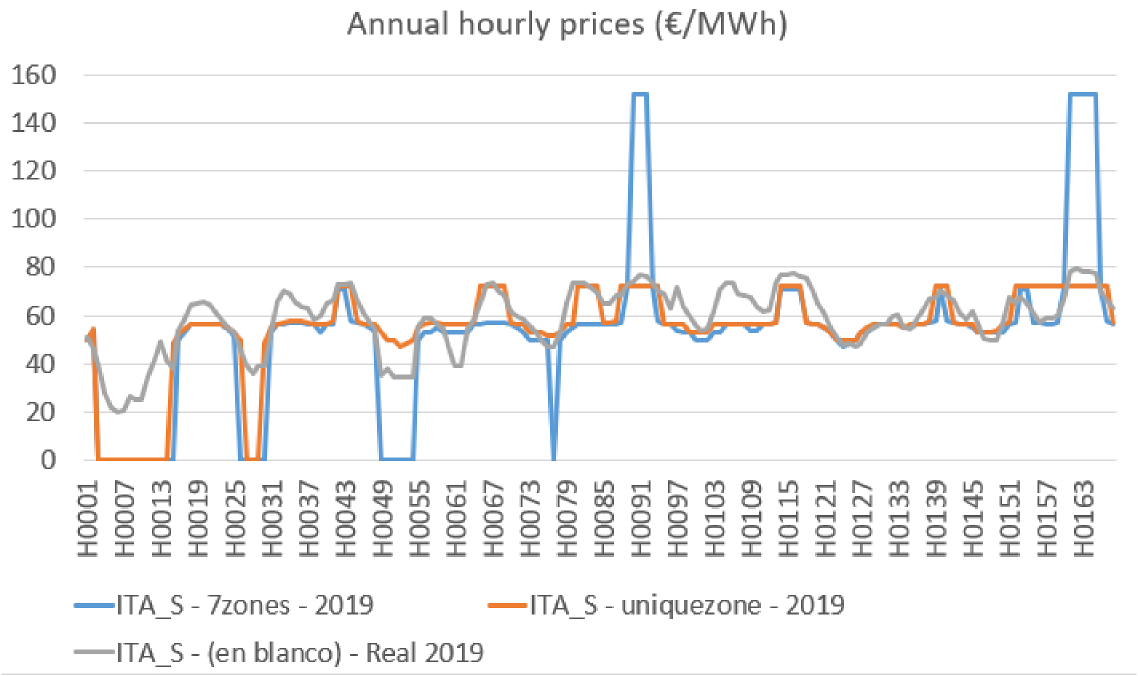

Figure 14.Case 2: South average annual hourly prices

Figure 15 shows the Center South hourly prices, resulted from case 1 and 2, for the first week of the year 2019.

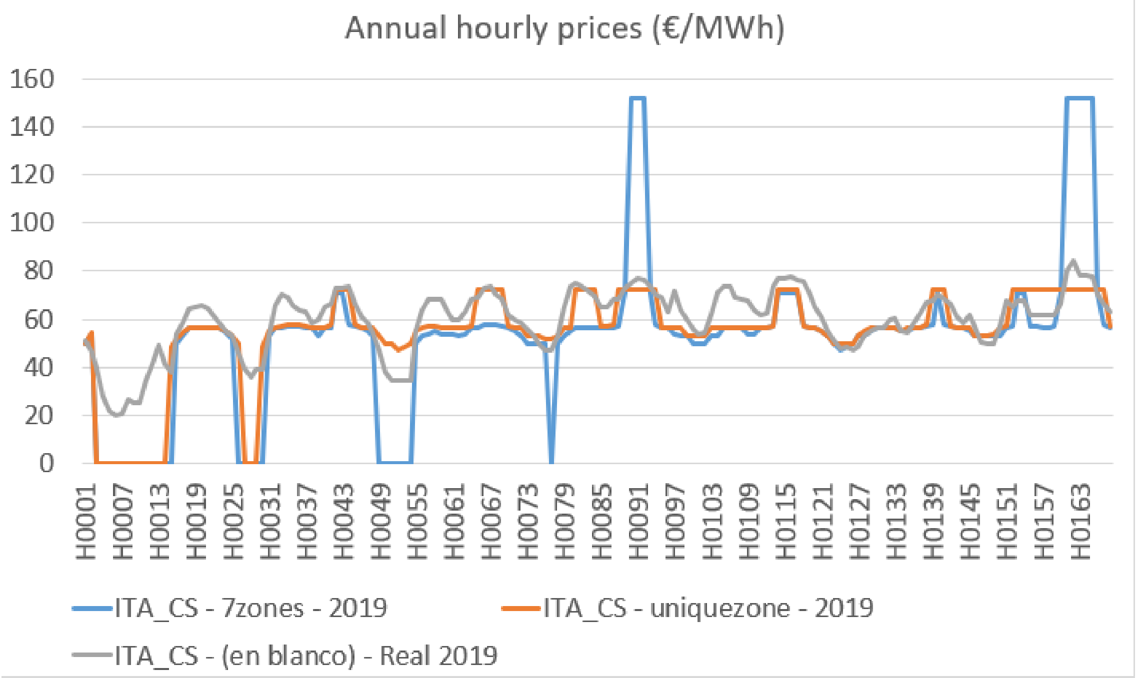

Figure 15. Case 2: Center-South average annual hourly prices

Figure 16 shows the Sardinia hourly prices, resulted from case 1 and 2, for the first week of the year 2019.

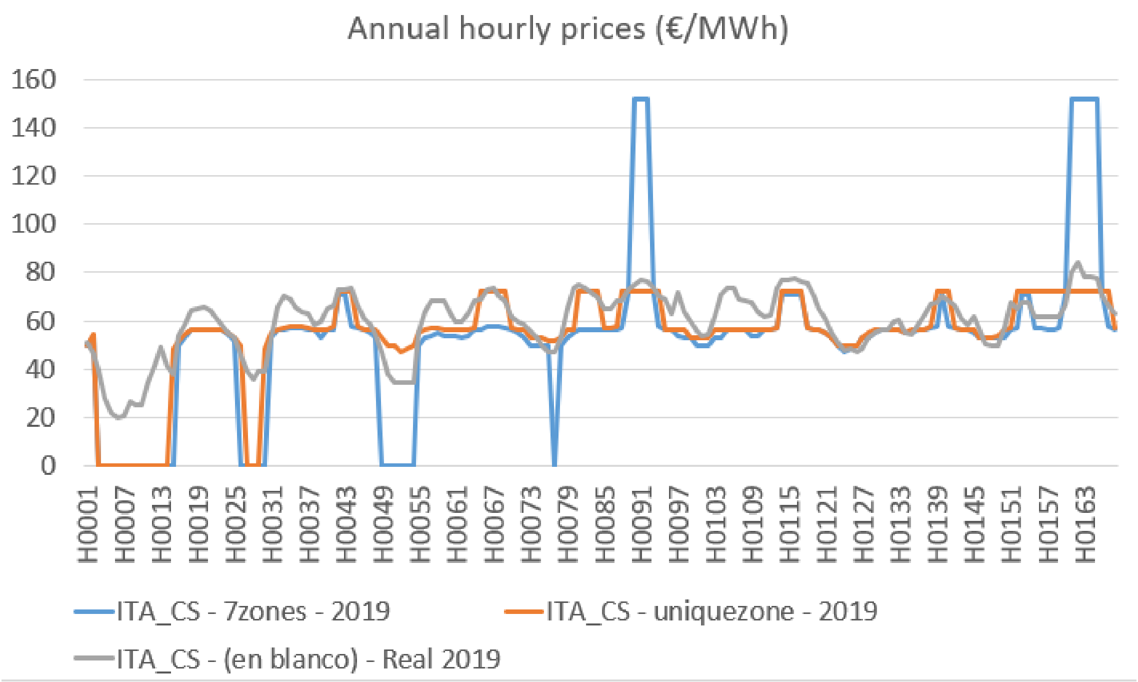

Figure 16. Case 2: Sardinia average annual hourly prices

Figure 17 shows the Sicily hourly prices, resulted from case 1 and 2, for the first week of the year 2019.

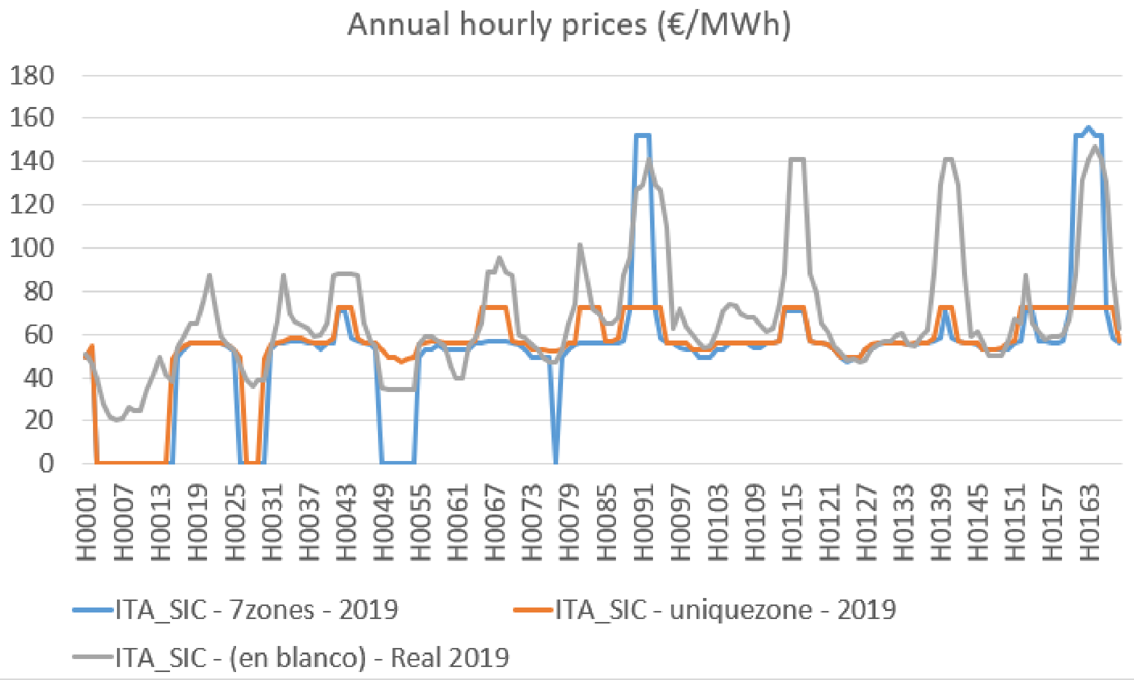

Figure 17. Case 2: Sicily annual hourly prices

It is interesting to analyze the interconnections as well. Since this case study considers different zones, the capacities of the national interconnections are a limitation for the imports/exports of energy.

The figures shown below allow to analyze how the maximum capacity of the interconnections can limit the system's operation. These graphs show the results obtained in both the first and second case studies, making it easy to compare the outcomes for the first week of the year 2019.

The graphs are divided into two parts: “7 zones” and “uniquezone”. Each part illustrates the energy results through the interconnections for the same hours of the year, for both the “7 zones” and “uniquezone” case studies respectively.

In addition, there are blue boundary lines in each of the presented scenarios. These lines indicate the maximum capacity of the interconnection. For these “7zones” case study, the maximum interconnection capacity has been established for each zone. As mentioned in paragraph 4.4, the data has been extracted from ENTSO-E [22]. NTC refers to the Net Transfer Capacity of the interconnections.

The results of the interconnections obtained for the first case study (single zone), where the capacity was high enough to never reach saturation and therefore not limit the system's operation, are compared with the current case study where the real maximum capacity of the interconnections has been included, simulating real-world operation.

Figure 18 shows the resulting flows of interconnections from the North zone to the other connected zones for case 1 and case 2, during the first week of the year 2019.

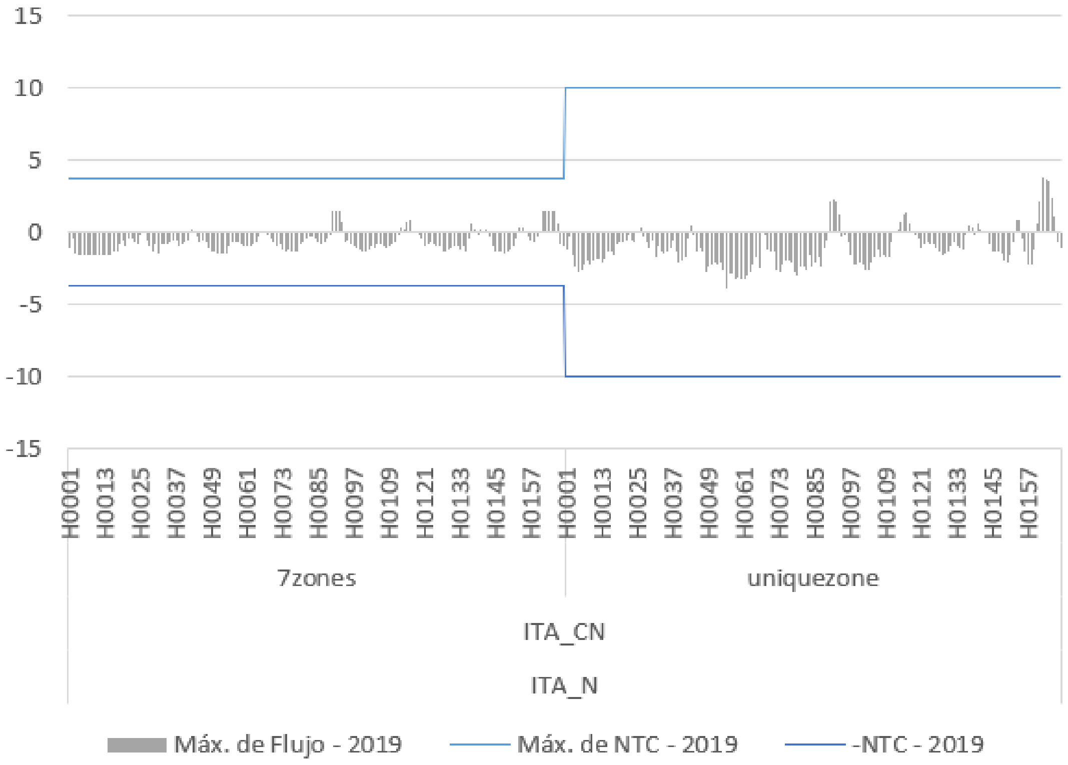

Figure 18. Case 2: Interconnections flows North

Figure 19 shows the resulting flows of interconnections from the Center-North zone to the other connected zones for case 1 and case 2, during the first week of the year 2019.

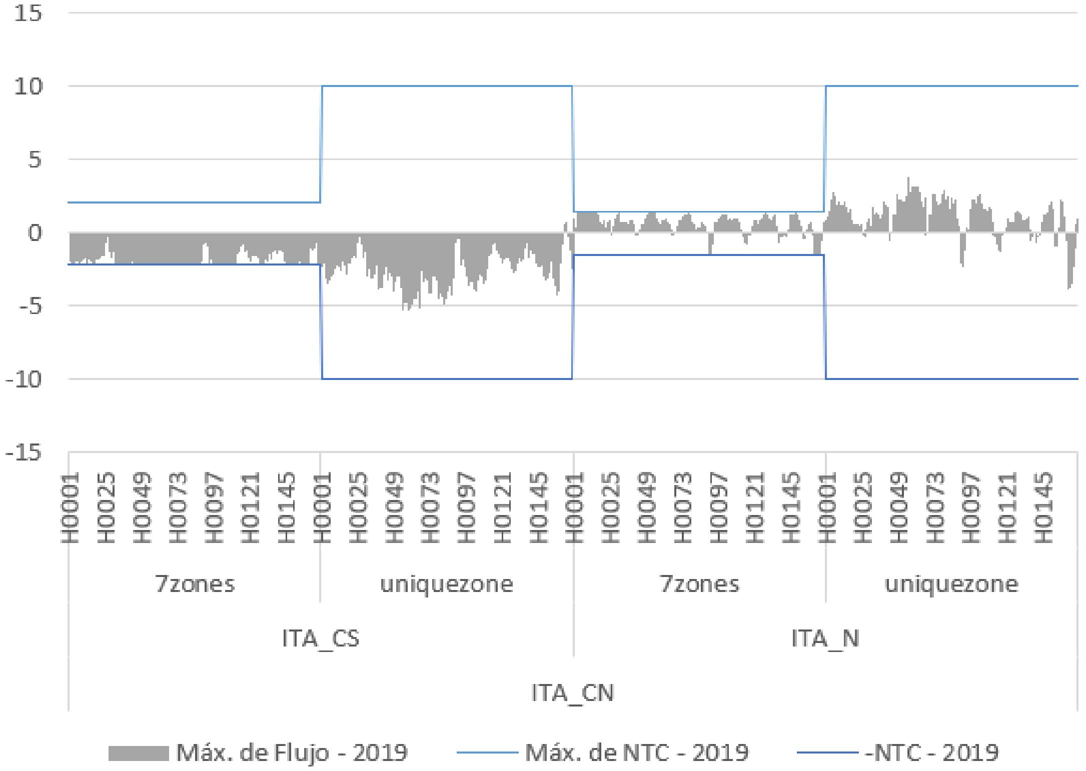

Figure 19. Case 2: Interconnections flows Center-North

Figure 20 shows the resulting flows of interconnections from the South zone to the other connected zones for case 1 and case 2, during the first week of the year 2019.

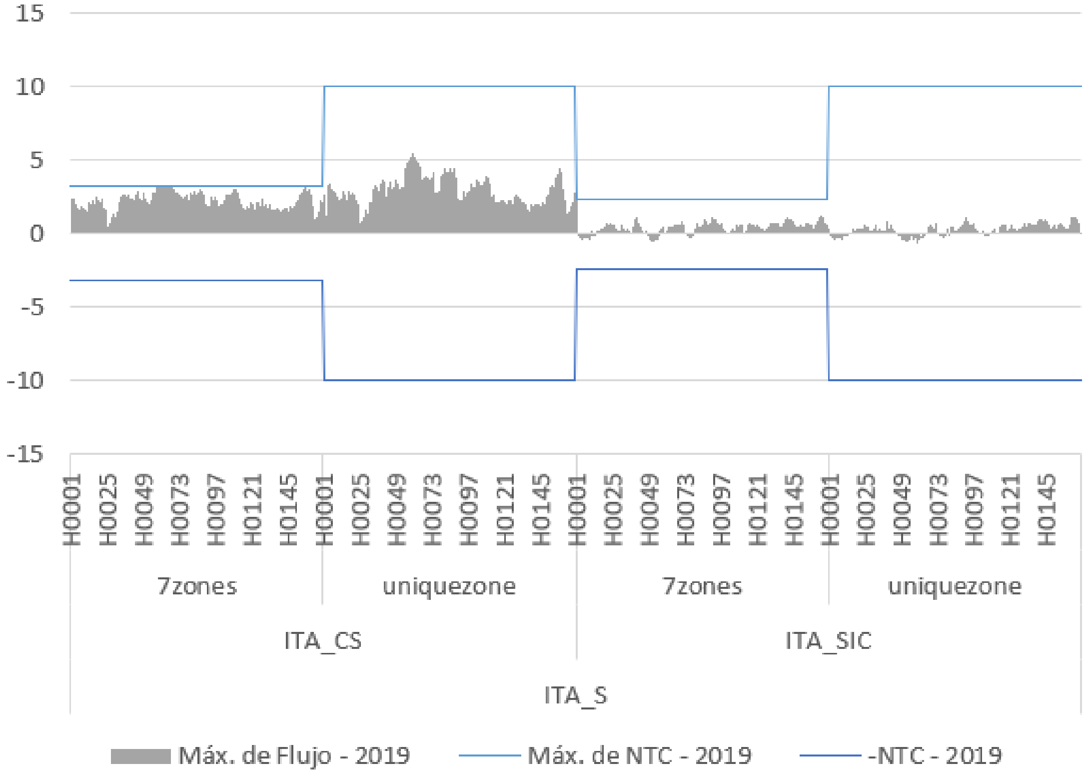

Figure 20. Case 2: Interconnections flows South

Figure 21 shows the resulting flows of interconnections from the Center-South zone to the other connected zones for case 1 and case 2, during the first week of the year 2019.

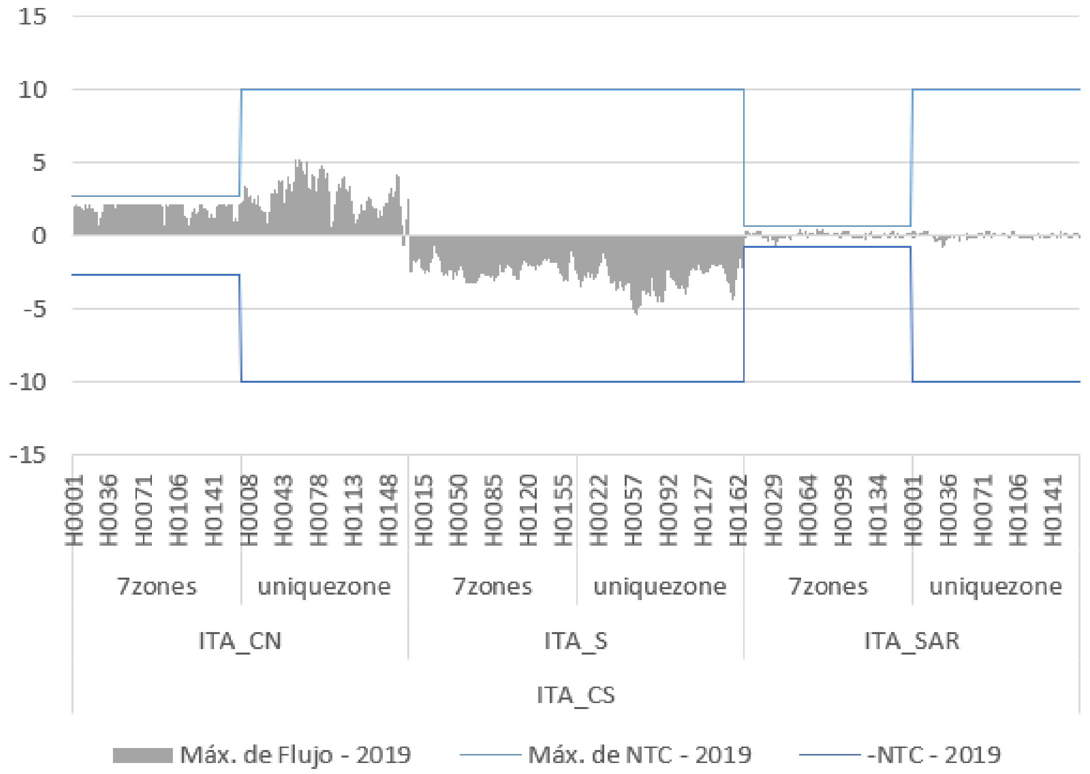

Figure 21. Case 2: Interconnections flows Center-South

Figure 22 shows the resulting flows of interconnections from the Sardinia zone to the other connected zones for case 1 and case 2, during the first week of the year 2019.

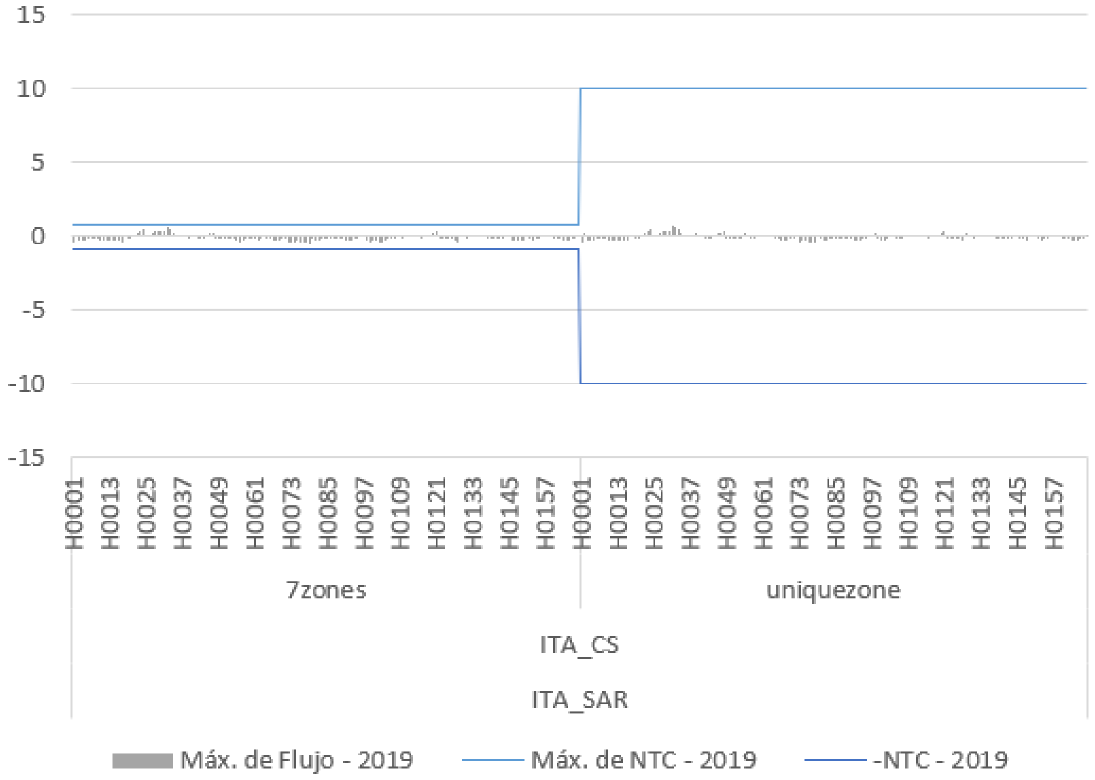

Figure 22.Case 2: Interconnections flows Sardinia

Figure 23 shows the resulting flows of interconnections from the Sicily zone to the other connected zones for case 1 and case 2, during the first week of the year 2019.

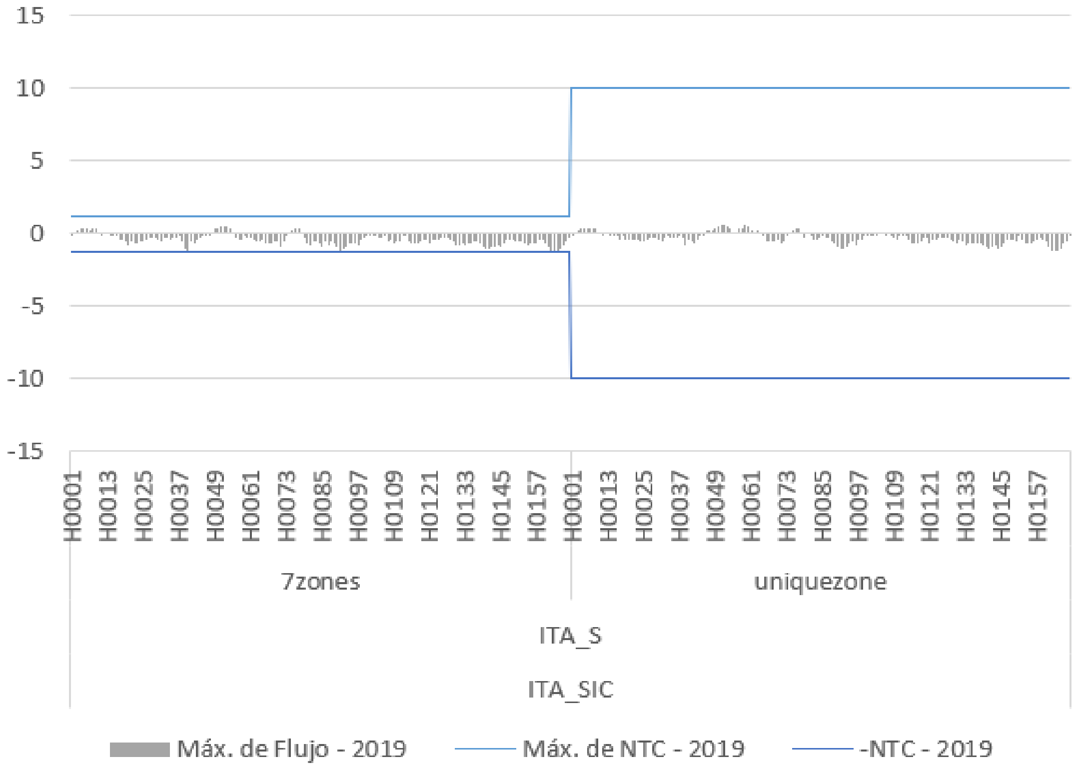

Figure 23. Case 2: Interconnections flows Sicily

In Figure 19, it can be observed that in the first case study (unique zone) when there was no capacity limitation on the interconnection between the Central-North and Central-South zones, the simulated flow exceeds the capacity of the assigned line in the current case study (7 zones).

However, with the maximum capacities of the interconnections included, it can be seen in Figure 19 how they become saturated, resulting in price differences between the different zones, also known as "market splitting" as shown below in Figure 24, during the first week of 2019.

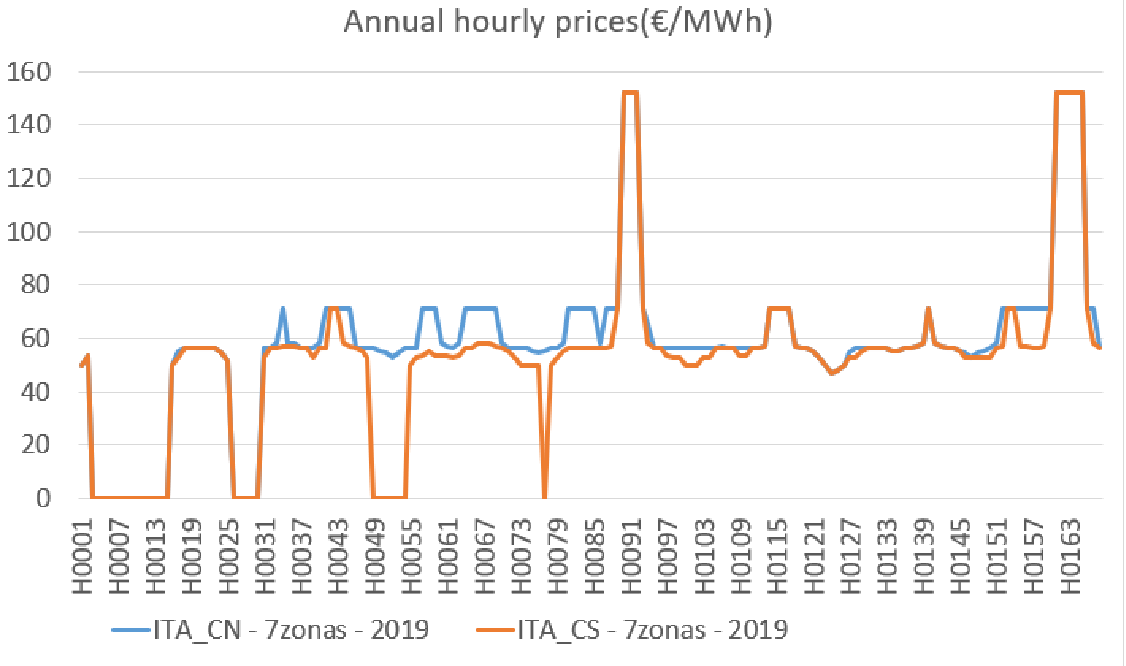

Figure 24. Case 2: Center-North vs Center-South annual hourly prices

The interconnection acts as a constraint that prevents the system from operating as efficiently as possible. When the interconnection is saturated, it indicates that marginal technologies are cheaper in one zone compared to another, but there is not enough capacity to import/export that generation, resulting in that energy having to be generated by a more expensive unit in the destination zone.

Another clear example can be seen in Figure 19, where the interconnection between the Central-North and Central-South zones is congested for a significant portion of the time. As mentioned previously, when the interconnection is congested, a price difference occurs between the two zones, as can be observed in Figure 24, which represents the prices obtained for the first week of 2019.

5.4. CASE 3: SIMULATION OF THE ITALIAN SYSTEM 2019 WITH A X10 INCREASE IN RENEWABLE GENERATION IN THE CENTRAL-NORTHERN ZONE

5.4.1. Scenario description

The third case study simulates the Italian electricity system with an increase of 10 of the renewable generation (solar and wind) in the Central-North zone. This scenario aims to validate the model's performance under a significant increase in renewable energy generation.

By multiplying the renewable energy (solar and wind) generation in the Central-North zone, we can observe the impact of a substantial renewable energy capacity expansion on the system. This case allows us to analyze the behavior of the system when one specific zone experiences a significant increase in renewable energy generation.

The main objectives of this case study are twofold. Firstly, it aims to validate the model's ability to handle a large-scale integration of renewable energy sources within a specific zone. Secondly, it seeks to evaluate the performance of the model in terms of congestion management in the internal interconnections between different zones.

By simulating the increased renewable generation, we can observe how the system responds in terms of power flows through and congestion in the internal interconnections and market prices per zones. This analysis provides insights into the system's ability to handle and accommodate a significant increase in renewable energy, as well as its effect on market dynamics and congestion management.

Additionally, the case study allows us to compare the results and identify any differences in market prices and congestion levels between the scenarios with increased renewable generation and the baseline scenario.

Overall, the third case study provides valuable insights into the behavior of the Italian electricity system when a specific zone experiences a significant increase in renewable energy generation, helping us understand the system's dynamics and assess its capability to integrate higher levels of renewable energy in a realistic scenario.

5.4.2. Results

In the third case study, which models a tenfold increase in renewable energy (wind and solar) in the Central-North zone, it allows us to verify that the model functions correctly and also enables to observe the saturation that occurs in the interconnections.

The Figure 25 and Figure 26 display the hourly prices for the first week of the year for this third case study, both for the Central-North zone and the Central-South zone, as well as the comparison between them.

As a reminder, Table 13 is attached below as a summary of the nomenclature used in the legend of the various graphs.

Table 13. Labels indexes

ITA_[zone code]-uniquezone-2019	Represents the prices for the zone corresponding to the zone code indicate, for the scenario that considers Italy as a unique zone for the year 2019
ITA_[zone code]-7zones-2019	Represents the prices for the zone corresponding to the zone code indicate, for the scenario that considers the different zones of Italy for the year 2019
ITA_[zone code]-Real2019	Represents the real prices for the zone corresponding to the zone code indicate for the year 2019

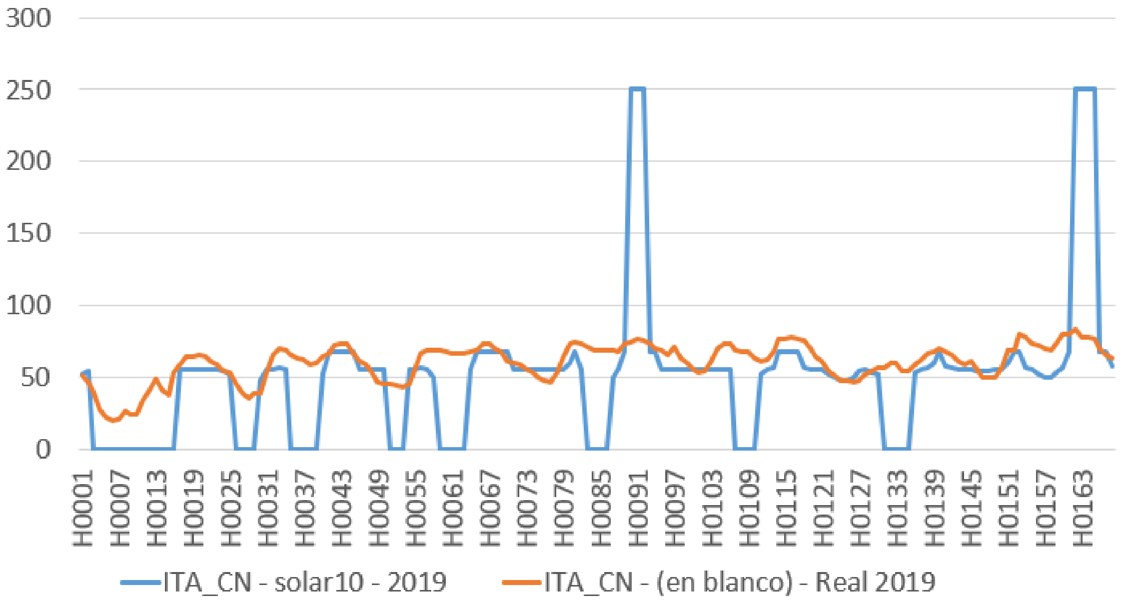

Figure 25. Case 3: Center-North average annual hourly prices

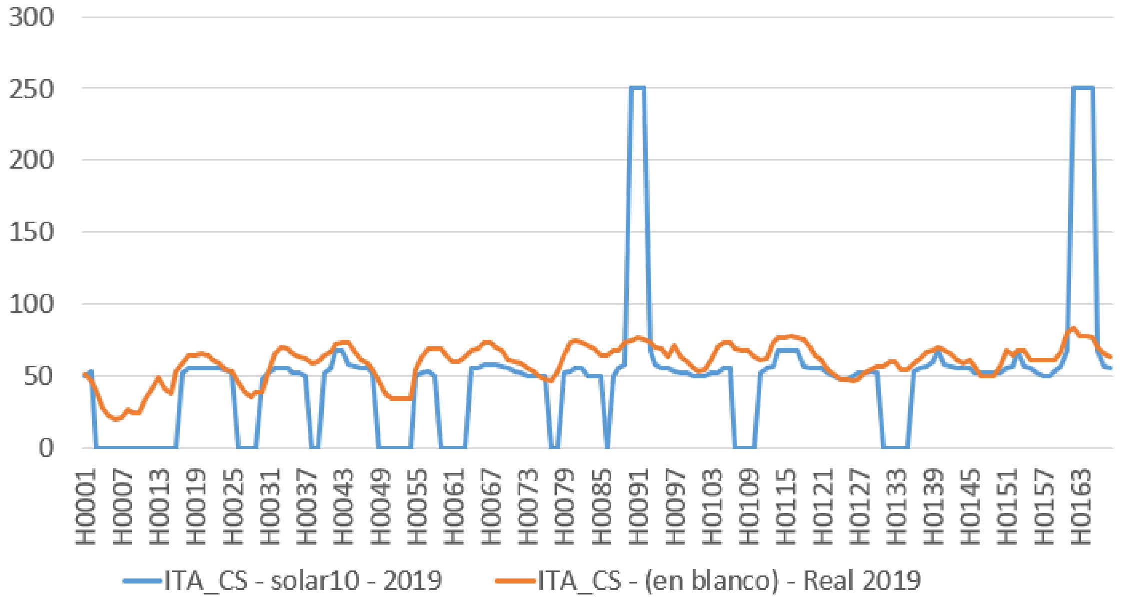

Figure 26. Case 3: Center-South average annual hourly prices

Figure 27 shows the prices obtained from the Center-North and Center-South zones in the current case study during the first week of the year 2019.

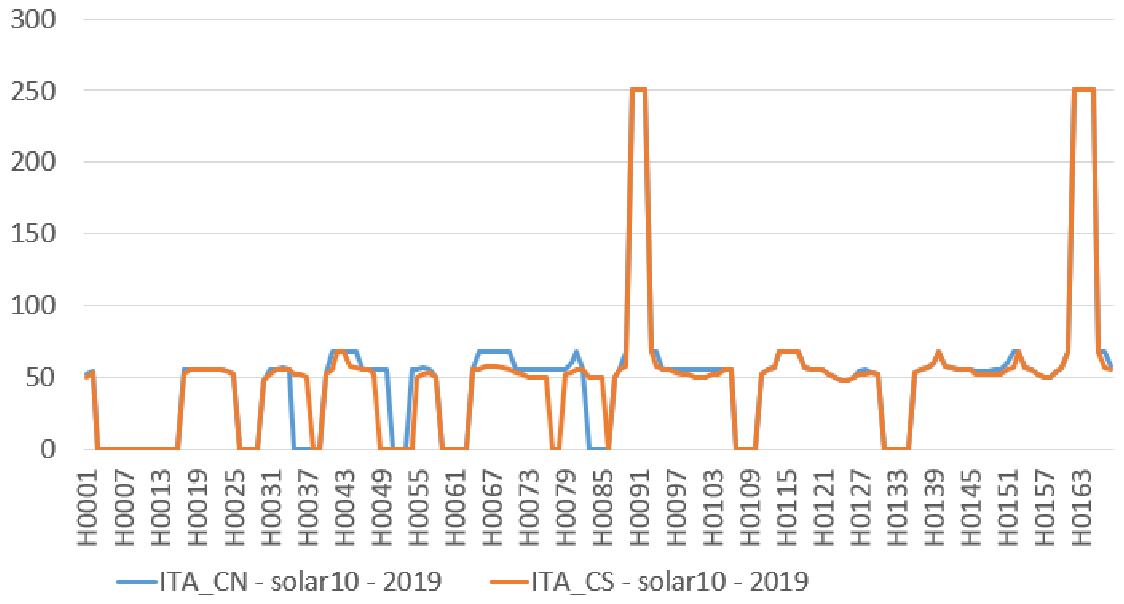

Figure 27. Case 3: Center-South vs Center-North average annual hourly prices

The results obtained from CEVESA for the interconnections of the Central-North zone are shown in Figure 28. They illustrate how a x10 increase in renewable generation in the Central-North zone truly affects the system as a whole.

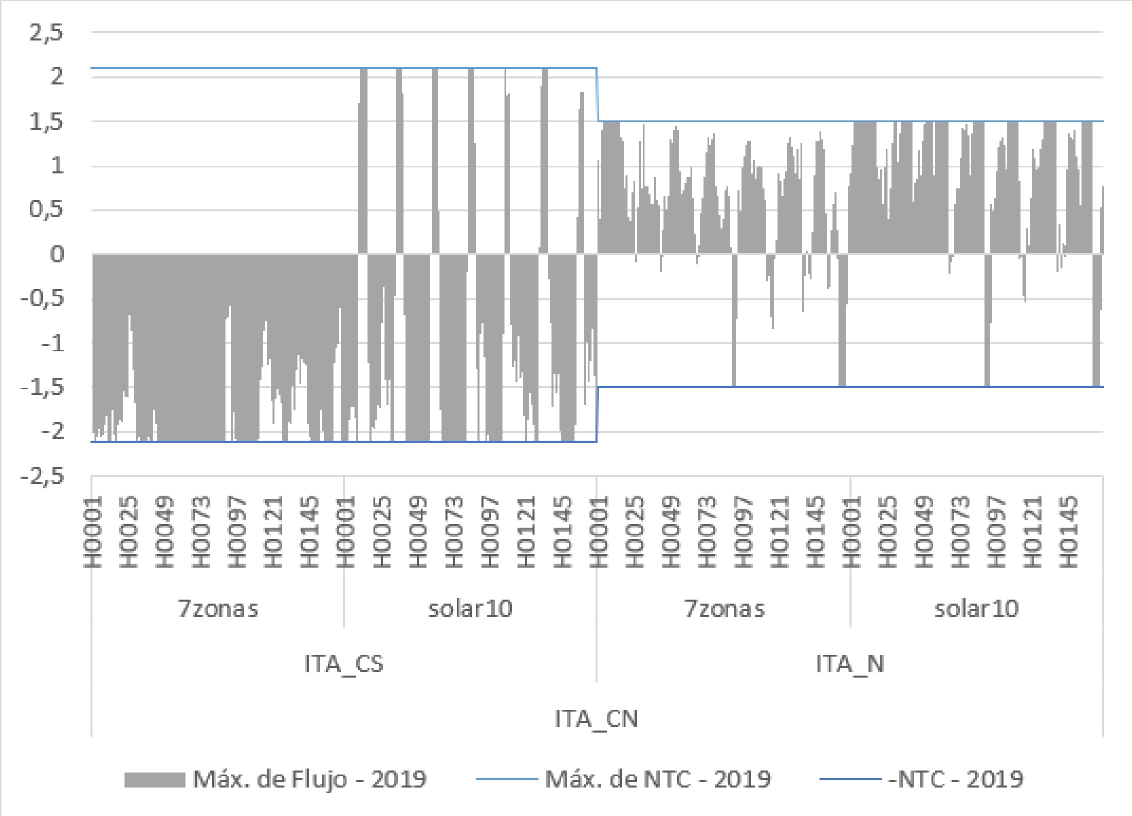

Figure 28. Case 3: Interconnections flows Center-North

It is clear in the graphs shown above how the energy imported by the Central-North zone from the Central-South zone has significantly decreased between the second case study and the current one. In fact, it is worth noting that at certain moments, the Central-North zone even exports energy to the Central-South zone, which was not the case previously.

This change is due to the fact that in the current case study, the Central-North zone has a higher renewable generation capacity, with a considerably lower price compared to other technologies. Energy is used in all zones as a single market until the interconnections become congested. As a result, the overall operation of the system becomes much more efficient and cost-effective compared to the scenario where this renewable energy is not available.

Considering the interconnection between the Central-North and North zones, it can be observed that multiplying the renewable generation in the Central-North zone by a factor of 10 leads to a higher congestion of the interconnection. This is because the exports from the Central-North zone to the North zone increase significantly. The price comparison between both zones is shown in Figure 29.

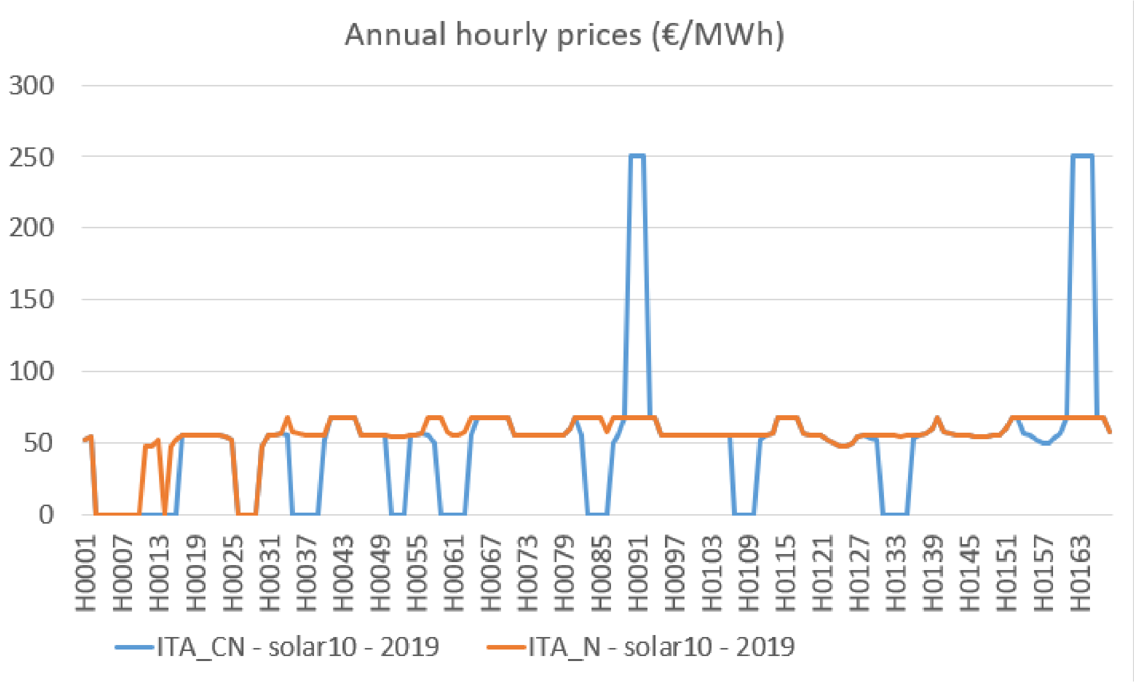

Figure 29. Case 3: Annual hourly prices of Center-North vs North

It can be observed that, in general, the Central-North zone tends to have lower prices compared to the North zone. In some moments during this first week depicted in the graph, there are price spikes in the Central-North zone, which coincide with the hours when the interconnection is congested due to energy import from the North zone to the Central-North zone.

This confirms that the interconnections are functioning correctly within the model, and CEVESA adequately simulates all market situations, including market splitting.

5.5. LIMITATIONS OF THE MODEL

The model presents some limitations, such as the difference between Italy's production in 2019 modeled in CEVESA and the actual demand, as commented on the paragraph 5.2.2 of this thesis.

Even when CEVESA only simulates Italy, imports and exports with other countries must be considered, even if those countries are not included in the simulation.

As mentioned in paragraph 4.4, it should be noted that in the case study where Italy is considered as a single zone, all international exports/imports have been included in the total demand. The data for international exports/imports are sourced from ENTSO-E [22]. The sum of the energies through these interconnections was included as part of the demand, considering them as additional consumption.

6. ALIGNMENT WITH SUSTAINABLE DEVELOPMENT GOALS

The Sustainable Development Goals aim all countries to commit to caring for the environment. Given the basic need to consume energy in our daily lives, producing increasingly cleaner energy from various renewable sources such as wind or solar, among others, would be a great advance for society.

International interconnections play a fundamental role in integrating renewable energies between the systems of different countries. The administration of this type of technology (mainly solar and wind) is complex because they are non-manageable energies. Therefore, they are not produced when demand requires it. Through the interconnections, power can be sent or received from other systems so that renewable energy is not lost.

The European Union (EU) has established as a target for 2030 the reduction of net CO2 emissions by 55%, thus paving the way to neutrality in 2050 for the EU [29]. The United Nations defined 17 Sustainable Development Goals (SDG), thus ensuring the prosperity and protection of the planet, with goals that must be achieved in the next 15 years.

Figure 30. Sustainable development goals

Therefore, the thesis and the improvement of international interconnections are aligned with the following objectives:

Goal 7, guarantee access to affordable, safe, sustainable, and modern energy. The interconnections promote the use of renewable energies that are more sustainable and help to reduce the price difference between markets, making energy a more affordable good for everyone.

Goal 9, build resilient infrastructures, promote sustainable industrialization and encourage innovation. This thesis is directly linked to innovation and improvement in the European electricity sector. To increase interconnections with new lines and substations and, in turn, renewable power plants, especially wind and solar, it is necessary to build modern infrastructures sustainability.

Goal 12, guarantee sustainable consumption and production patterns. Sustainable consumption depends on each citizen of community to which they belong. Still, these can be influenced if they start with a sustainable production focused on conserving our planet and not on the pure benefit of the electricity market. With a good analysis of interconnections and the increase in renewables, public and private companies in the electricity sector can be encouraged to consider this type of technology for their future investment plans.

Goal 17, revitalize the Global Partnership for Sustainable Development. The integration of the European electrical systems in the IEM through the interconnections strengthens the relations between the member countries. If this IEM project is extended to other countries outside the EU, it will encourage the creation of the World Alliance starting with the electricity market.

7. CONCLUSIONS

The European electricity sector is constantly evolving on its path towards decarbonization, and models like CEVESA help to study and guide the impact of these changes.

In this project, the integration of the Italian electricity system into CEVESA has been carried out as an expansion of a model that allows for the representation of national electricity systems within the Internal Electricity Market (IEM) and their interconnections. In this regard, interconnections are fundamental for the progression of the IEM as they enable the integration of systems with more competitive generation resources, improve security of supply, and consequently reduce energy costs. An increase in interconnection leads to price convergence because technologies that produce in one country or price zone can be substituted by more cost-effective alternatives from other countries or price zones, such as renewable technologies. This would also positively contribute to the evolution of the system towards decarbonization.

In 2020, the Integrated National Energy and Climate Plan 2030 (PNIEC) [23] was developed, with specific objectives set for installed capacity of different technologies, renewable energy growth, and CO2 emissions. Some of the assumptions made in the plan are now outdated due to a greater increase in renewables than initially planned or the ongoing conflict between Russia and Ukraine, necessitating new updates to align the plan with the current circumstances.

The case studies in this work have led to the conclusion that a significant increase in renewable generation in some zones of Italy, as proposed in the third case study, will have a positive effect in reducing the output of thermal power plants, achieving energy independence for certain regions within the country, which promotes a more stable market.

Regarding internal interconnections within the Italian system, their inclusion in the model allows for a comprehensive analysis. In particular, the simulation has enabled the analysis of congestion in internal interconnections between different zones, revealing that congestion can lead to price differentials between zones, emphasizing the importance of managing and expanding transmission infrastructure to mitigate congestion and promote more efficient market outcomes.

The successful validation of the model with real data from 2019 instills confidence in its ability to replicate the behavior of the Italian electricity market. This validation step has resulted crucial to ensure the accuracy and reliability of the model's results.

8. FUTURE DEVELOPMENTS

CEVESA is a model of the European electricity sector that allows the analysis of the electricity price and production behavior under different future scenarios. It also enables the study of the impact of other sectors such as transportation or hydrogen on the electricity sector. Until now, the MIBEL and France markets had been modeled, and with this thesis, the extension of CEVESA to Italy has been carried out, including data from its electrical system.

Since CEVESA is a constantly evolving model, several challenges that could be the subject to future developments can be proposed. Some of them are listed here:

- Simulate the MIBEL, France and Italy electricity markets with their international interconnections, thus verifying that the model as a whole works correctly.
- Represent France and Italy secondary reserve as it is now currently modeled for Spain and Portugal.
- Include the study of the secondary reserve coordination through interconnections.
- Include electricity generation investment decisions in the Italian power system.
- In later phases, CEVESA might be expanded with the inclusion of other new relevant European countries, like the UK.

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