

POLITECNICO DI TORINO

Master degree in Energy and Nuclear Engineering

Master Degree Thesis

**Energy transition of the Sardinia region
through energy system modelling with
the Calliope framework**



**Politecnico
di Torino**

Supervisor

Prof. Andrea Lanzini

Co-supervisors

Daniele Salvatore Schiera

Riccardo Novo

Francesco Demetrio Minuto

Candidate

Marina Verrascina

Academic Year 2021/2022

Summary

In order to mitigate the climate change the target of the Europe is to achieve the carbon neutrality by 2050, reaching the net carbon emissions equal to zero. This requires an increase in the use of renewable energy reducing power plants with fossil sources. Therefore European countries have committed the phase-down project of coal, that involves a reduction of coal-fired plants. The Italian country planned in its energy strategy the complete phase-out of coal to 2025. In particular, in the Italian region Sardinia the installed capacity of coal power plants is about 1 GW and after the phase-out its energy system will be significantly modified. Therefore the study of the energy system of this region is urgent and energy models could be important tools for this purpose. In this work an energy model of the region Sardinia is built using the open framework Calliope, based on Python language. This framework allows to optimize energy systems with an objective function setting constraints. In this case it is built the energy model of the region and tested for its validation in the dispatching mode, verifying energy fluxes between nodes under the objective function of minimize the cost of the system. After the model is built some possible future scenarios are designed considering the target for the region about capacity installed, planned modifications in the transmission lines and in the demand that will involve the Sardinia. These scenarios are constructed trying to reduce the cost of the system and find possible improvements that can be done starting from these scenarios.

Contents

Introduction	1
I Theoretical background and literature review	6
1 Energy models	7
1.1 Characteristics and advantages of energy models	7
1.2 Open energy modelling	8
1.3 Differences in energy modelling	8
1.4 Optimization problems	11
2 Calliope open-source framework	14
2.1 Creation of model and structure	16
2.2 Model configuration	18
2.3 Technologies	21
2.4 Locations	32
2.5 Scenarios	33
2.6 Run a model	34
2.6.1 Run with command-line	34
2.6.2 Interactive run with Python	34
2.7 Analyze results	35
II Case Study: Energy system model of Sardinia	36
3 Energy system in Sardinia	37
4 Energy model of Sardinia	42
4.1 Locations	42
4.2 Energy demand technology	44
4.3 Import and export transmission lines	46
4.4 Internal transmission lines	50
4.5 Installed capacity of supply technologies	52
4.5.1 Photovoltaic	54
4.5.2 Wind	58

4.5.3	Hydroelectric	60
4.5.4	Thermoelectric	62
5	Validation of model	66
5.1	Estimated energy	66
5.2	Reference costs	68
5.3	Parameters to compare different models	69
5.4	Tests on configuration A	70
5.5	Tests on configuration B	74
5.6	Base model	79
6	Scenarios analysis and results	82
6.1	Potential capacities	82
6.1.1	PV potential	83
6.1.2	Wind onshore potential	83
6.1.3	PV potential and wind onshore potential by province	84
6.1.4	Potential of thermoelectric power plants	88
6.1.5	Potential of hydroelectric	90
6.2	Scenarios description	90
6.2.1	Year 2024	91
6.2.2	Year 2025	93
6.2.3	Year 2030	93
6.2.4	Year 2050	94
6.2.5	Scenarios: best, BAU and worst	94
6.3	Main modifications between scenarios	95
6.3.1	Capacity of wind and photovoltaic systems in scenarios	95
6.3.2	Cost of export and cost of supply	97
6.3.3	Evolution of demand in years	97
6.3.4	Evolution of the efficiency of eolic and photovoltaic systems	98
6.3.5	Evolution of installation cost for PV and wind technology	99
6.4	Discussion of results	102
7	Conclusion	114
A	Appendix	116
A.1	Validation	116
A.2	Scenarios	125
A.3	Scenarios.yaml file	131
	Acknowledgements	149

List of Figures

1	Coal power plants programmed for phase out in 2025, according to Terna [50]	1
2	Main interventions to increase transmission lines, taken from Terna [50] .	2
1.1	Steps of open modelling pipeline taken from source [17]	8
1.2	Geographical coverage and temporal resolution for models with different approaches	11
1.3	Procedure to find the optimal solution with Simplex method. Picture taken from source [6]	13
2.1	Conceptual scheme of Calliope	15
2.2	Most typical structure of files in Calliope	17
2.3	Scheme of supply parent technology [102]	22
2.4	Scheme of supply_plus parent technology [102]	23
2.5	Scheme demand parent technologies [102]	24
2.6	Scheme storage parent technologies [102]	25
2.7	Scheme of transmission parent technologies [102]	26
2.8	Scheme conversion parent of technologies [102]	27
2.9	Scheme of conversion_plus parent technologies [102]	29
3.1	Coal power plants programmed for phase out in 2025 in Sardinia [50] . . .	37
3.2	Climate impact per area. Carbon intensity classification of electricity consumed (gCO_{2eq}/kWh)	38
3.3	Gross capacity installed of power plants in Sardinia [59]	39
3.4	Historical series of gross renewable production by source, Years 2000-2020 (GWh) [30]	39
3.5	Comparison of national and regional composite indicators, for the year 2018	40
3.6	Main interventions to increase foreign trade capacity for Sardinia, adapted from source [50]	41
3.7	Main interventions to increase trade capacity between market areas for Sardinia, adapted from source [50]	41
4.1	Nodes created for locations. Figure adapted from source [16]	43
4.2	Evolution of Energy demand in Sardinia [30]	44
4.3	Transmission lines for export and import of energy adapted from Entsoe grid map [71]	47

4.4	Real electrical connections in Sardinia [16]	50
4.5	Links chosen between locations adapted from source [16]	51
4.6	Distribution of Italian photovoltaic installed capacity at the end of 2020, taken from GSE [66]	54
4.7	Results for photovoltaic energy, obtained from Renewables.ninja for Sardinia region and year 2019 [14]	55
4.8	Results for wind energy, obtained from Renewables.ninja for Sardinia region and year 2019 [14]	59
4.9	File CSV for flooding factor given as input, taken from Italian model [36]	61
5.1	Energy mix of net energy produced in Sardinia in 2019 from Terna [28] .	67
5.2	Capacities, maximum use and medium use of transmission lines in model VA1	71
5.3	Capacities, maximum use and medium use of transmission lines in model VA2	73
5.4	Capacities, maximum use and medium use of transmission lines in model VA3	74
5.5	Configuration more complex called configuration B	75
5.6	Scheme of configuration and transmission capacities in configuration VB1	76
5.7	Scheme of configuration and transmission capacities in configuration VB2	77
5.8	Scheme of configuration and transmission capacities in configurations VB3	77
5.9	Capacity of different technologies installed in Sardinia, classified in provinces	80
5.10	Energy produced by different technologies installed in Sardinia, classified in provinces	80
6.1	Potential Capacity (GW) of Wind Onshore - High wind conditions	83
6.2	Area for the province of Sassari with some protected areas excluded . . .	85
6.3	Area for the province of Oristano without removed protected areas; map taken from Google Earth [77]	85
6.4	Area for the province of Nuoro without removed protected areas; map taken from Google Earth [77]	86
6.5	Area for the province of Sud Sardegna without removed protected areas; map taken from Google Earth [77]	86
6.6	Area for the province of Cagliari without removed protected areas; map taken from Google Earth [77]	87
6.7	Configuration of the model when it is considered the activation of Tyrrhenian Link	94
6.8	Planned evolution of the energy demand in Sardinia. Figure taken from source [32]	98
6.9	Comparison of the evolution of capacity installed in scenarios - option1 . .	102
6.10	Comparison of the evolution of capacity installed in scenarios - option2 . .	102
6.11	Comparison of the evolution of energy produced/exported/supplied - option 1	103
6.12	Comparison of the evolution of energy produced/exported/supplied - option 2	103

6.13	Comparison of the evolution of installed capacities in BAU scenario and base model at 2020-option 1	104
6.14	Comparison of the evolution of installed capacities in BAU scenario and base model at 2020-option 2	104
6.15	Comparison of the evolution of energy produced/exported/supplied in BAU scenario and base model at 2020-option 1	105
6.16	Comparison of the evolution of energy produced/exported/supplied in BAU scenario and base model at 2020 - option 2	105
6.17	Comparison of the evolution of energy produced/exported/supplied in worst scenario and base model at 2020 - option 1	106
6.18	Comparison of the evolution of energy produced/exported/supplied in worst scenario and base model at 2020-option 2	106
6.19	Comparison of the evolution of energy produced/exported/supplied in best scenario and base model at 2020-option 1	107
6.20	Results of energy produced visualized by Calliope for scenario best, year 2025, option 1	107
6.21	Results of energy produced visualized by Calliope for scenario best, year 2030, option 1	108
6.22	Results of energy produced visualized by Calliope for scenario BAU, year 2030, option 1	108
6.23	Distribution of installed capacity in different locations, for the year 2030 - Scenario BAU option 1	109
6.24	Distribution of installed capacity in different locations, for the year 2030 - Scenario BAU option 2	109
6.25	Results of energy produced visualized by Calliope for scenario best, year 2050, option 2	110
6.26	Results of energy produced visualized by Calliope for scenario BAU, year 2050, option 2	110
6.27	Comparison of percentage composition of the energy mix, option 1	111
6.28	Comparison of percentage composition of the energy mix, option 2	111
6.29	Comparison evolution of PV capacity and PNIEC target in 2030	112
6.30	Comparison evolution of PV capacity and PNIEC target in 2030	112

List of Tables

1.1	Some frameworks (F) and energy models (M) with corresponding languages used and references. Table adapted from source [17]	9
1.2	Table of general logic and spatiotemporal resolution extracted from source [19]	9
1.3	Table of technological and economic parameters extracted from source [19]	10
2.1	Decision variables in Calliope [102]	16
2.2	Solution time for pre-built examples, using different solvers taken from the Calliope Documentation [102]	19
2.3	Default and required constraints for the supply parent technology [102] . .	22
2.4	Allowed constraints and allowed costs for the supply parent technology [102]	23
2.5	Default and required constraints for the supply_plus parent technology [102]	23
2.6	Allowed constraints and allowed costs for the supply_plus parent technology [102]	24
2.7	Default and required constraints for the demand parent technology [102] .	24
2.8	Allowed constraints and allowed costs for the demand parent technology [102]	25
2.9	Default and required constraints for the storage parent technology [102] .	25
2.10	Allowed constraints and allowed costs for the storage parent technology [102]	26
2.11	Default and required constraints for the transmission parent technology [102]	27
2.12	Allowed constraints and allowed costs for the transmission parent technology [102]	27
2.13	Default and required constraints for the conversion parent technology [102]	28
2.14	Allowed constraints and allowed costs for the conversion parent technology [102]	28
2.15	Default and required constraints for the conversion_plus parent technology [102]	29
2.16	Allowed constraints and allowed costs for the conversion_plus parent technology [102]	29
4.1	Proportion of demand energy by province using consumed energy in 2019 by Terna [29]	45
4.2	Capacities installed in validation model	53
4.3	Subdivision in data taken from sources and data from assumptions	53

4.4	Coordinates of points (in decimal format) considered to download solar data	56
5.1	Subdivision of energy values taken from Terna [29], SARLUX [101] and values from assumptions	68
5.2	Costs found on references and then used in Calliope as reference costs	69
5.3	Energy produced in tests on configuration A	72
5.4	Energy produced in tests on configuration B	78
5.5	Energy produced in tests on configuration B	78
5.6	Energy produced in tests on configuration A	81
5.7	Values of energy demand, exported, imported and total energy produced in base model	81
6.1	Max installable capacity for different technologies divided into data taken from sources, described below, and data elaborated from references	82
6.2	Evaluation of fraction available area for new renewable technologies	87
6.3	Maximum capacity potential assumed for Sardinia and different provinces	88
6.4	Potential of biomass adapted from source [45]	88
6.5	Potential electric energy produced by biogas from source [100] and assumed potential capacity of biogas power plants installed	90
6.6	Maximum constraint on capacities for photovoltaic and wind systems, for each year, is provided for the Best scenario option 1	96
6.7	Maximum constraint on capacities for photovoltaic and wind systems, for each year, provided for the BAU and worst scenarios, option 1	96
6.8	Percentage of the composition of the total population in provinces in 2032 according to Istat [81]	98
6.9	Multiplying factors for the increase of efficiency of wind and photovoltaic systems	99
6.10	Evolution costs for PV and wind technologies in different scenarios	99
6.11	Main modifications in the evolutions of scenarios for option 1	101
6.12	Percentage maximum and medium use of transmission lines in the year 2050 for different scenarios	113
A.1	Energy produced and expected before the sensitivity analysis	117
A.2	Subdivision between installation costs for different technology between ones taken from references	118
A.3	Costs used to perform the sensitivity analysis	119

Introduction

The necessity to mitigate climate change is an urgent topic for actual society. In 2021 with the COP 26 in Glasgow the need to keep the global temperature below 1.5 °C compared to pre-industrial times is emphasized, implying changes in the climate policies of various countries [42].

The 75% of European greenhouse gas emissions come from the energy sector [63]. In the Italian county, coal is still used to generate electricity, with 6 GW of power plants [50]. These plants represent the 10% of thermoelectric power plants in Italy [50], which are used mostly to cover energy peaks and at the moment are necessary to ensure that the country's energy system is properly structured. Consequently, Italy is trying to replace programmable and conventional sources with non-programmable renewable sources. The coal power plants in Italy need to be dismissed by the year 2025 for the phase-out project, as indicated by the PNIEC [48]. In the Figure 1 there are all plants scheduled for closure by 2025, or that need to convert their production stopping the use of coal.

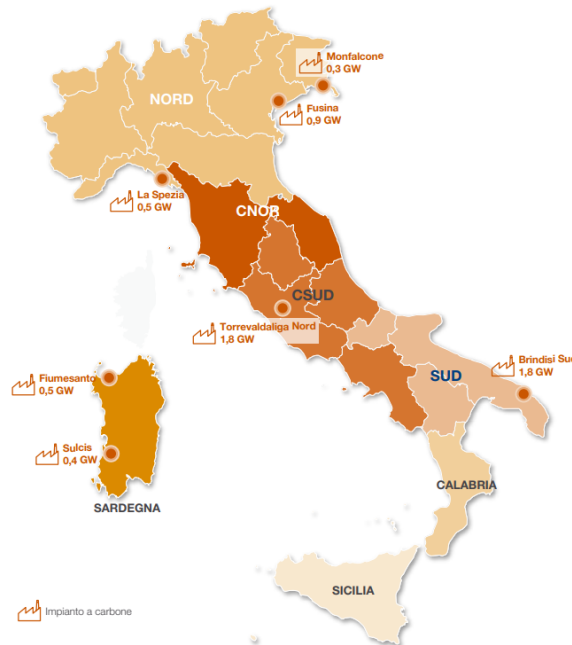


Figure 1: Coal power plants programmed for phase out in 2025, according to Terna [50]

According to Terna, to have a decarbonized electricity system, it is necessary to install new capacity to replace plants that are planned for the decommissioning [50]. In order to vary the energy mix, it is necessary for the electricity transmission network to be able to handle the expected new energy flows. Terna has already planned to expand the electricity grid within the national territory, as in the Figure 2a but also in exchanges with foreign countries, as in the Figure 2b [50]. An important internal Italian connection, planned for the realization, is the Tyrrhenian Link that will connect Sardinia, Sicily and Campania [107].



(a) Interventions between market areas



(b) Interventions for foreign trade capacity

Figure 2: Main interventions to increase transmission lines, taken from Terna [50]

These changes in the energy mix must be tested to see how the energy system can react to them and energy models are useful tools for these assessments. The modelling of an energy system consists of design and manage the operation of an energy system in order to analyze it [31]. The real system can be approximated in an energy model decomposing it, in general using a mathematical programming language [17]. Using results in output of energy models, it is possible to give indications on possible energy decision-making policies to accelerate the energy transition towards renewable sources. Different tools can be used to model an energy system, characterized, for example, by their functions, their programming language and the variables that they permit to use [19]. Depending on the energy system to model and the results to highlight, the tool that it is better to use, may be different. By selecting the energy carriers to use, the costs to allocate and the scale of the problem, it is possible to find the correct tool to use for the modelling of the system under consideration. An interesting tool for the building of energy models is the Calliope framework [18], which can be used from small-scale problem, such as a single building, to a bigger problem as the entire continent. This framework is designed in a way that the user can build a model of the energy system in space and time, creating locations where technologies can be installed and giving time series as input. Calliope allows an intuitive definition of technologies and locations and also provides a visualisation of results. Its open and free licence allows any user to use it and suggest improvements to the tool. Some models have already been produced with Calliope, e.g. the European model [52], the UK model [12], and an Italian model [36] that gives an idea of the entire Italian energy system. In Italy, a region that has an energy system interesting to study is Sardinia, which has two coal power plants still active and planned for the decommissioning in 2025, and some plants considered by Terna essential to the security of the electrical system [50]. In addition, this region, due to its insularity, has a more complex energy system because it is only connected to other energy zones with a few connections, but it also cannot rely on a distributed gas network. In literature, some evaluations on the possible evolution of the energy systems of Sardinia are already done, for example, the more economical evaluation done by "Centro studi di economia e tecnica dell'energia Giorgio Levi Cases" [75]. However, there is not a model that evaluates the entire energy system of Sardinia and its possible evolution in future years, using Calliope.

Consequently, the energy system of Sardinia results useful to study and it is chosen as a case study in this thesis. It is analysed with the Calliope framework, considering just the carrier electricity and using models already created by Calliope as references. First, the energy model of the region of Sardinia is examined, starting from a study of the energy-producing systems located in the region, and using different sources. Due also to the change in the distribution of provincial areas in Sardinia from 2016 in some cases the research of different plants and their classification does not result easy, therefore also some assumptions are done, as explained in the following chapters. In order to construct a model more similar as possible to the actual energy system, five locations are chosen, one location for each provincial capital of Sardinia. Then different locations are connected with links representing approximately the electrical transmission lines of the region. Different configurations of the model are realized and tested to understand which configuration of the model can represent better the real energy system, even if

assumptions and approximations are done. In order to validate the model and consider on its configuration possible improvements, it is run under the operational mode of Calliope, fixing capacities installed and studying the flows of energy. The objective function used is to minimize the cost of the system. The energy produced from different sources, evaluated by Calliope, is then compared with the actual estimated energy from these sources, studying also the use of transmission lines.

The model chosen is then used to develop scenarios on the possible evolution of the energy system of Sardinia, based on possible modifications and projects that could involve the Sardinia region until the year 2050. Three different scenarios are constructed: best, BAU and worst scenarios. The best scenario is the most favorable scenario for the energy system of Sardinia, the BAU (business-as-usual) scenario considers the actual trends in growing technologies, population and energy demand, instead, the worst scenario is the most unfavorable for the energy system of Sardinia. The main modifications considered in different scenarios are: the variation of the energy demand over the years with also the possible increment of energy demand due to the reactivation of the Eurallumina and ex-Alcoa plants, the decrease of the installation cost and increase of efficiency for solar and wind technologies and the variation of the possible installable capacity of solar and wind systems. Starting from these scenarios, two different options are evaluated: the first option gives a maximum capacity for the photovoltaic and wind systems values more constrained, related to the trend of growth more similar to the possible ones, instead in the second option the maximum capacity for these technologies is fixed to the maximum potential for each province, therefore it is less constrained. The capacity of technologies given as maximum constraint is important in scenarios because they are run under the planning mode of Calliope, therefore Calliope finds the capacities to install for each technology based on constraints given by the user. In scenarios the focus is on the possible evolution in years of the energy mix of Sardinia, dismissing in 2025 coal power plants, until the total dismissing of fossil plants in 2050, increasing the capacity of renewable energy, in particular photovoltaic and wind ones.

In conclusion, the Calliope framework is a useful tool to understand the evolution of the new renewable capacity that will be installed in future years in order to decarbonize the energy system for the production of energy. The model constructed and scenarios provided, even if they are an approximation of the actual and possible future energy system of the region, could represent a good base to study the energy model of Sardinia and some possible improvements could be done on this work.

The document of this thesis is structured into two main parts: the first part is almost a literature review of notions useful to build energy models using Calliope, instead the second part is related to the real case study of the energy model of Sardinia. In the first part, there is an overview of the main characteristics of energy models, and a comparison of some tools useful to construct energy models. There is also a brief focus on open energy modelling, to introduce the open framework Calliope. For this tool it is explained how it can be used to construct and study an energy model, considering the Calliope Documentation [102] as a reference, at which it is possible to refer to for more details. The second part of the thesis starts with a general overview of the energy system of Sardinia region, possible projects on the Italian energy system that will involve the region

Sardinia in future years. In chapter 4 there is a description of the construction of the regional energy model, assumptions done and values of capacities installed for different technologies. The model constructed is then validated in chapter 5 in which are presented some tests done for different configurations of the model, until the configuration chosen as base model. After an evaluation of possible maximum potential capacity installable for all technologies used, starting from the base model configuration in chapter 6 it is explained how scenarios are constructed. Finally, different scenarios are compared highlighting how the energy system of Sardinia can react to the decommissioning of coal power plants in 2025, increasing the capacity of photovoltaic and wind systems in years. In section 6.4 there is the discussion of results, also highlighting how with the installation of Tyrrhenian link and Sacoï 3 it is possible to lose less energy and export more energy, installing new capacities in years. Nevertheless, it is shown that there is an increase of the supplied energy required in 2050, related to the periods when solar resource is not available, due to the assumed absence of coal, fossil oil and syngas.

Part I

Theoretical background and literature review

Chapter 1

Energy models

1.1 Characteristics and advantages of energy models

In the last years, the importance in the modification of the energy share is concentrating on the increment of renewable energy. This transition needs to be developed correctly considering the integration with the climate, social and environmental conditions and paying attention also to possible evolutions in the next years [85].

The use of energy models can help in this transition into renewable energy and in the understanding of political decisions to be taken in this field but it could be also useful in the use of energy storage systems, to determine the required amount of their capacity and how collocate their use in the time period. Therefore, with the target to create a system totally decarbonized in the production of energy, the energy models could be useful tools for possible configurations and modifications in the coming energy systems [57].

There are several challenges for energy systems with the increase of renewable energies such as the variability of renewable resources over time and the effect of climatic conditions on them. In fact, it is necessary to understand the amount of capacity of different technologies to install, if it could be useful to increment the transmission lines and also understand the energy fluxes between different areas [36]. Using scenarios in output from these energy models it is possible to find the most suitable decision policies in the renewable transition, highlighting costs and risks of different scenarios.

Model an energy system consists of design and manage the operation of an energy system in order to analyze it [31]. Energy system planning is born in a small, research-driven, government agency context, and nowadays it is changing because it is necessary to drastically reduce greenhouse gas emissions [17].

In a model different types of data usually are used as time series, and geographic data but also tables for costs and configurations of technologies. Sometimes it is also necessary to adapt the original data in a way that the model used can recognize them. In the construction of a model, the real system is decomposed in elements in general with a mathematical programming language [17].

1.2 Open energy modelling

The energy models usually are created in the concept to be accessed to users with different levels of knowledge [57]. Another important target in the development of energy models is transparency: each model should be specified in its limitations, in such a way to be used in the correct context and under correct conditions [57]. This is the reason why the energy models usually are diffused with open licences: this is called open energy modelling. In this case, it is possible to use open software and open data doing some modifications that are available to other users in general on an online platform; in addition in this way, it is also easier to improve the work because other modellers can give their feedback [31]. In the open modelling all the steps followed should be open, as explained in Figure 1.1. The initiative **openmod** [87] unites a community of energy modellers, also collecting data that can be used to create models and different materials for energy models.

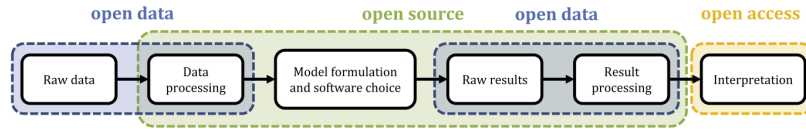


Figure 1.1: Steps of open modelling pipeline taken from source [17]

1.3 Differences in energy modelling

In energy modelling it is possible to distinguish two macro-categories of models:

- **Energy system models** that are useful to plan scenarios in long-term and in the last period are focusing on variable renewable generation;
- **Power system models** that are used mostly for electricity.

Considering that the electricity is transforming into a clean carrier, the energy system models and power system models are strictly correlated [17].

A more specific difference between a model and a framework can be done. In a **model**, data are used, and hypotheses are done depending on the context, instead, a **framework** is a general structure that can be used in different contexts because it is then filled with data to obtain the model [17].

The energy system models can use different methodologies, in fact, there are **optimization models** and **simulation models**. In the first case, the overall system is considered and optimization methods are used to understand possible future scenarios. Instead, the simulation models are used to forecast the evolution of the system with simulation methods [11].

Energy models are usually employed to understand possible modifications in the capacities installed in a system and in this case it refers to **planning models**. Considering the variation of the energy demand and fluctuations due to renewable energy, the planning models are also merged with **operational models** to understand fluxes of energy [11].

The approaches usually used in energy models are of two types: top-down or bottom-up. **Bottom-up models** describe in detail the technologies in the system, instead, the **top-down models** focus on economics and macroeconomic relationships and long-term modifications. It is also possible to integrate both considering an **hybrid** approach [19]. A partial list of energy and power frameworks and some models is present in the Table 1.1.

Table 1.1: Some frameworks (F) and energy models (M) with corresponding languages used and references. Table adapted from source [17]

Name	Type	Description	Language	Reference
Calliope	F	Energy system model framework	Python	Ref. [18]
deeco	F	Operational optimisation model framework	C++	Ref. [88]
GridCal	F	Power system model framework based on PYPOWER	Python	Ref. [91]
oemof	F	Energy system model framework	Python	Ref. [68]
OSeMOSYS	F	Energy system model framework	MathProg, GAMS, Python	Ref. [69]
pandapower	F	Power system model framework based on PYPOWER	Python	Ref. [92]
PYPOWER	F	Power system model framework	Python	Ref. [90]
PyPSA	F	Power system model framework inspired by PYPOWER	Python	Ref. [93]
renpass	M	Power system simulation model (Germany and neighbouring countries)	R	Ref. [94]
renpassGIS	M	German electricity market model	Python	Ref. [74]
SciGRID	M	Transmission grid model	Python	Ref. [109]
TEMOA	F	Energy system model framework	Python	Ref. [70]

Using a model the resolution in the time and in the space is one of the main characteristics that could prefer one model respect another one. Modelling tools have different timesteps and they can be designed for a small-scale problem or even a bigger one, as a continent [19]. In Table 1.2 some models are compared in their purpose, in the approach used and the applicability scale. There is also an attribution of models to numbers, as in the original article [19], that is useful for the graphical representation in Figure 1.2.

Table 1.2: Table of general logic and spatiotemporal resolution extracted from source [19]

Models	#	Purpose	Appr.	Methodology	Temporal resolution	Modelling horizon	Geographical coverage
Calliope	3	I&ODS	BU	LP, MIP	UD	UD	UD
EnergyPlan	16	S,IDS	BU	S	Hourly	1 year	Local → Continental
Oemof (SOLPH)	46	S,I&ODS	All	LP,MILP,PE	Seconds to years	UD	UD
OSeMOSYS	48	IDS	BU	LP	UD (intra-annual)	UD (10–100 y)	Community → Continental
PyPSA	54	I&ODS, PSAT	BU	LP	Hourly	1 year	Local → Continental
renpass	59	ODS,S	BU	S (In) & O (Op)	Typically Hourly	1 year	Regional/National (Western Europe)
Temoa	67	S	BU	LP	Yearly (With UD time-slices)	UD	Regional (UD)

Abbreviations used: **Purpose:** IDS – Investment Decision Support, ODS – Operation Decision Support, S – Scenario. **Approach:** BU – Bottom-up. **Methodology:** S – Simulation, LP – Linear Programming, MIP – Mixed Integer Programming, PE – Partial Equilibrium. **Temporal Resolution/Modelling Horizon/Geographical Coverage:** UD - user-defined

Comparing the frameworks in Table 1.1 it is possible to notice that Calliope or, for example, oemof and OSeMOSYS are energy system model framework. Instead, PyPSA and pandapower are power system frameworks. In Table 1.2 there is also the modelling horizon, that for OSeMOSYS could be between 10 and 100 years.

In renewable generation, it is also important to understand if models can include energy storage, if they are flexible in the demand and, for example, which commodities can be used. In Table 1.3 a comparison of technological and economic parameters is extracted for some models. To have an exhaustive classification it is possible to consult the original article [19].

Table 1.3: Table of technological and economic parameters extracted from source [19]

Models	Calliope	EnergyPlan	Oemof (SOLPH)	OSeMOSYS	PyPSA	renpass	Temoa
#	3	16	46	48	54	59	67
Conv. Gen.	All	All	All	All	All	All	All
Ren. Gen.	All	All	All	All	All	HP, WP, SP, GE, ROR	All
Storage	All	All	All	All	All (Generic)	PHS, CAES, B	All
Grid	NTC	Import/Export	Import/ Export, NTC	None	Non-linear/ Linear Power Flow, NTC	NTC	NTC
Commodities	Electricity, Hydrogen, Heat & Fuels	Electricity, Hydrogen, Heat & Fuels	Electricity, Hydrogen, Heat & Fuels	Electricity	Any commodity	Electricity	Any commodity
Demand sectors	Aggregated	Buildings, Transport & Industry	Buildings, Transport & Industry	Aggregated	Aggregated	Aggregated	Buildings, Transport & Industry
Demand elasticity	Inelastic	Elastic	Inelastic	Elastic	Inelastic	Inelastic	Inelastic
Costs	I, O&M, F, CO2	I, O&M, F, CO2, T	I, O&M, F, CO2, T, B	I, O&M, F, CO2, B	Capital Cost & Marginal	I, O&M, F, CO2	I, O&M, F
Market	Supply/ Demand	Spot	Supply/ Demand	Supply/ Demand	Supply/ Demand	Spot	Supply/ Demand
Emissions	Any pollutant	CO2	Any pollutant	Any pollutant	CO2	CO2	Any pollutant

Abbreviations used: **Ren. Gen:** HP - Hydropower, ROR – Run-of-river, SP – Solar Power, WP – Wind Power, ST – Solar Thermal, WaP – Wave Power, GT –Geothermal, CSP – Concentrated Solar Power, TP – Tidal Power; **Storage:** PHS - Pumped Hydro Storage, CAES – Compressed Air Energy Storage, B – Batteries, H – Hydrogen, TES – Thermal Energy Storage; **Grid:** NTC – Net Transfer Capacity; **Cost:** I – Investment, O&M – Operation & Maintenance, F – Fuel, CO2 – Carbon cost, T – Taxes, B – Balancing costs

Different models with bottom-up, top-down and hybrid approaches are illustrated in Figure 1.2 indicating with areas for different models the geographical coverage and temporal resolution.

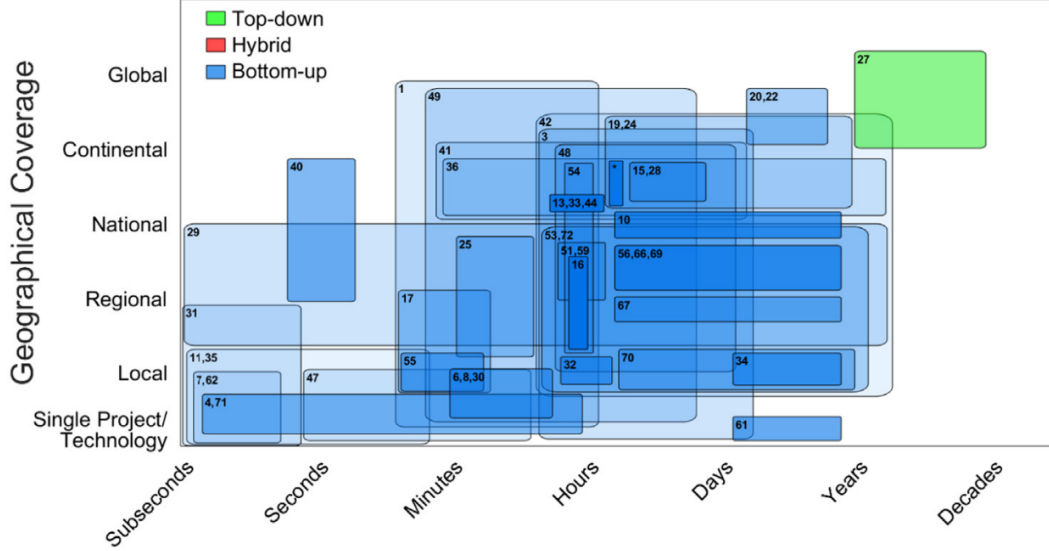


Figure 1.2: Geographical coverage and temporal resolution for models with different approaches, adapted from source [19]. To identify the corresponding models from numbers it is possible to refer to the partial Table 1.2 and Table 1.3 or to the original source for the complete Table.

1.4 Optimization problems

In this thesis a tool that optimizes a model is considered, solving an optimization problem. The optimization problems are used to solve complex situations with a single objective that can be maximized or minimized under some constraints set. In these problems the variables are called decision variables and are limited by constraints [1].

The energy models usually use a linear programming (LP) approach but it is also possible to have mixed-integer linear programming (MILP) approach, in which some variables are integral [19].

In linear programming the objective function is linear and variables and constraints are expressed as a combination of linear equalities and inequalities [61]. To solve optimization problems it is possible to use iterative algorithms; in this case, an initial vector x_0 is selected and the algorithm generates a modified vector x_1 , improving the solution until the best solution is found. Instead, if the objective function is not linear the problems are called non-linear.

The optimization problems are usually presented in a **standard form** as in the following Equations:

$$\begin{aligned}
 & \text{minimize } c_1x_1 + c_2x_2 + \dots + c_nx_n \\
 & \text{subject to} \\
 & a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n = b_1 \\
 & a_{21}x_1 + a_{22}x_2 + \dots + a_{2n}x_n = b_2 \\
 & \dots \\
 & a_{m1}x_1 + a_{m2}x_2 + \dots + a_{mn}x_n = b_m
 \end{aligned} \tag{1.1}$$

In Equation 1.1 there are fixed real constraints (bi's, ci's, aij's), real numbers that should be determined (xi's), the values b are higher or equal to 0 and variables from x_1 to x_n are larger or equal to 0.

From the standard form, an optimization problem can also be expressed in a more **compact form**, in vector notation, as in the following Equation:

$$\begin{aligned}
 & \text{minimize } \mathbf{c}^T \mathbf{x} \\
 & \text{subject to } \mathbf{Ax} = \mathbf{b} \text{ and } \mathbf{x} \geq \mathbf{0}
 \end{aligned} \tag{1.2}$$

In the Equation 1.2: n is the number of decision variables, m is the number of constraints, c^t is an n-dimensional row vector, x is a vector of inequality higher or equal to 0, A is a matrix with dimension m*n and b is m-dimensional vector [1].

A linear problem that has a number of decision variables n and a number of constraints m can be solved by finding a solution called **basic solution** that corresponds to the solution of the initial system Equation 1.1 in which the number of variables is set equals to zero

If all the variables in the basic solution are different than zero the solution is called basic feasible solution [61]. The feasible solution to the constraints corresponding to the minimum value of the objective function is called optimal feasible solution [1].

In optimization problems, it is also possible to consider a **graphical method** to have a geometric representation of the solution of a linear programming problem. The constraints bound the space R^2 into feasible and infeasible regions. Each inequality constraint defines a half-plane and the intersection between these half-planes creates the bounded area of feasible solutions. In this area, each point satisfies all the constraints and the points that maximize or minimize the problem are at vertexes of the bounded area [61].

A useful algebraic procedure to solve linear programming problems is the **Simplex method**. This algorithm to solve the problem, from some initial basic feasible solution, it moves on edges of a polyhedron, which vertices are basic feasible solutions. The direction of this movement is the one that increases the objective function until the optimal solution and it uses a finite number of steps until it reaches the solution [86].

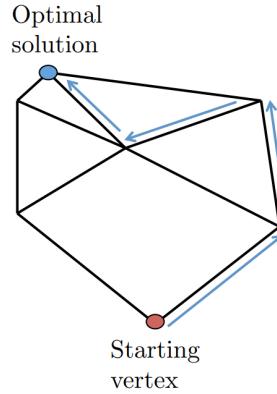


Figure 1.3: Procedure to find the optimal solution with Simplex method. Picture taken from source [6]

Each linear program is associated with the corresponding **dual linear problem** that is the original problem with the same costs and constraints coefficients but the objective function is the opposite one. In fact, if for example, the original problem has the objective function to minimize the cost of the system, the dual problem has the target of maximization of the cost of the system [1]. This concept is also used in energy models when the tool used permits to change the objective function using the same configuration of the system but in one option maximizing the cost of the system and in the other one minimizing it.

In practice to solve a linear programming problem the algorithm is executed by a solver, for example, CPLEX, GUROBI or CBC to obtain the solution of the problem [1].

Chapter 2

Calliope open-source framework

The software used to build the energy model is the open-source Calliope, a linear and non-linear framework capable to build energy system models and develop a spatial-temporal energy system optimization [76]. This software uses a Python language [3] and files in YAML language, additionally it is a framework with a bottom-up approach [76], as explained in section 1.3.

Using Calliope it is possible to implement a high spatial and temporal resolution decided by the user and develop problems of different dimensions, from urban districts to continents [11]. Therefore it is possible to evaluate the behavior of energy systems in time and space, considering fluxes (such as electricity, heat, or gas) between nodes [47].

It is developed by Stefan Pfenninger using an open-source license and behind this choice there is the target to create a flexible and modular definition in models, easily reusable [11]. Calliope is just one of many software and frameworks with an open-source licence to create models for reasons discussed in the section 1.2.

The main target for Calliope is to analyze energy systems with a generation of electricity from different sources, even a lot of renewable technologies. The main elements used are the following [102]:

- **Carrier:** Energy carrier that is used by technology, for example, electricity, heat, or gas;
- **Technology:** Element capable to manage energy producing, using, converting or transporting it;
- **Resource:** Origin of the capability of a technology to produce, removing from or adding energy into the system;
- **Location:** Node where one or more technologies can be set. It is also possible to include more locations in one and connect locations with elements called link.

These elements are defined in the model in an appropriate way that is described in the next section 2.3. In Calliope, it is possible to give also some inputs such as resources, the demand of energy, list of locations and technologies to use. With the target to build an optimization problem, as it is seen below, some constraints are set by default but the user

can impose some constraints also changing them. In the Figure 2.1 a possible conceptual scheme is proposed, to represent how an energy model can be constructed, if Calliope is used to build it.

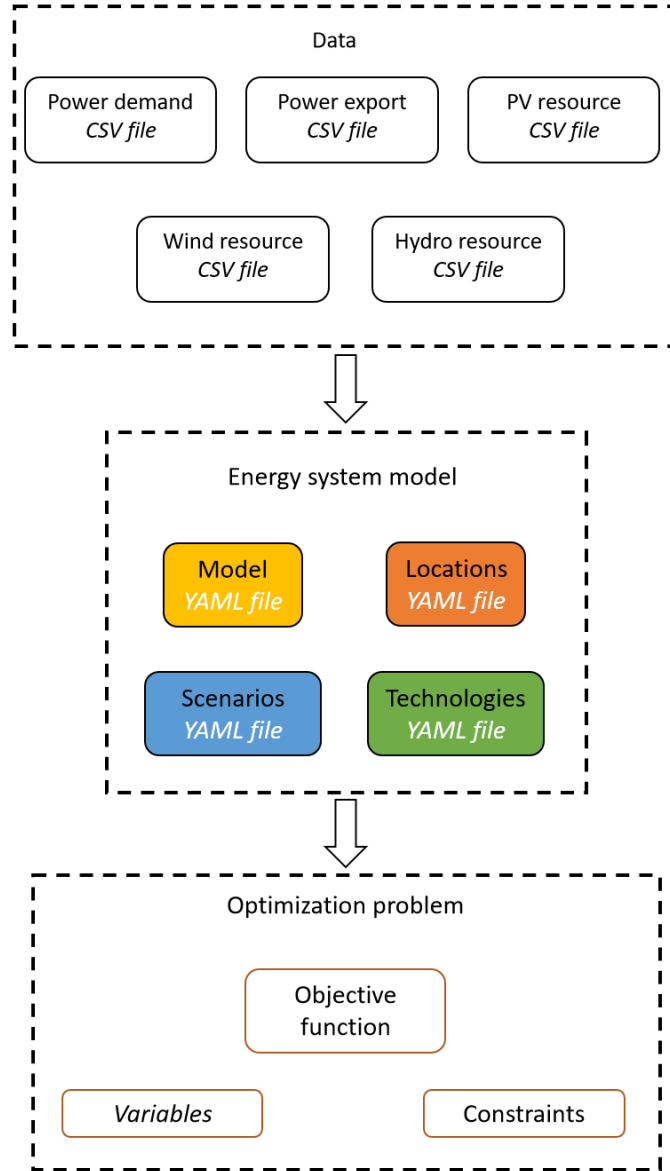


Figure 2.1: Conceptual scheme of Calliope

Once the model is created with the elements mentioned above, since an optimization problem is created, it is necessary to specify the decision variables that in Calliope depend on how technologies are set in the model. In the Table 2.1 there is a list of possible decision variables to be used in an energy system model created by Calliope.

Table 2.1: Decision variables in Calliope [102]

Variable	Dimensions
energy_cap	loc_techs
carrier_prod	loc_tech_carriers_prod, timesteps
carrier_con	loc_tech_carriers_con, timesteps
cost	costs, loc_techs_cost
resource_area	loc_techs_area,
storage_cap	loc_techs_store
storage	loc_techs_store, timesteps
resource_con	loc_techs_supply_plus, timesteps
resource_cap	loc_techs_supply_plus
carrier_export	loc_tech_carriers_export, timesteps
cost_var	costs, loc_techs_om_cost, timesteps
cost_investment	costs, loc_techs_investment_cost
purchased	loc_techs_purchase
units	loc_techs_milp
operating_units	loc_techs_milp, timesteps
unmet_demand	loc_carriers, timesteps
unused_supply	loc_carriers, timesteps

To solve the problem a solver is used selected from glpk, gurobi, CPLEX [79], and cbc and Pyomo library is used [40]. The solver is used in order to find a feasible solution that in this case corresponds to when the supply of a carrier meets the demand of that carrier respecting the objective function selected. In the following section, a more detailed description of how a model is created using Calliope is provided, and how the main elements are defined in the model.

2.1 Creation of model and structure

The construction of the model below is described taken as a reference the Calliope Documentation [102], in which it is possible to find more information about Calliope.

An easy way to create a new model in Calliope is to use the two already created templates: a **national scale** or an **urban scale** example model. It is possible to call them using the Calliope new command followed by the name of the model that is chosen by the user:

```
calliope new model_name
```

By default, this command creates a copy of the national scale built-in example model but it is possible to create instead a copy of the urban built-in model in the following way:

```
calliope new model_name --template=urban_scale
```

Starting from these templates and modifying them is easier than compiling an empty model.

The typical and easier file tree of a model built in Calliope has the layout proposed in the Figure 2.2, which can be more or less full of csv files and details, according to the user requirements.

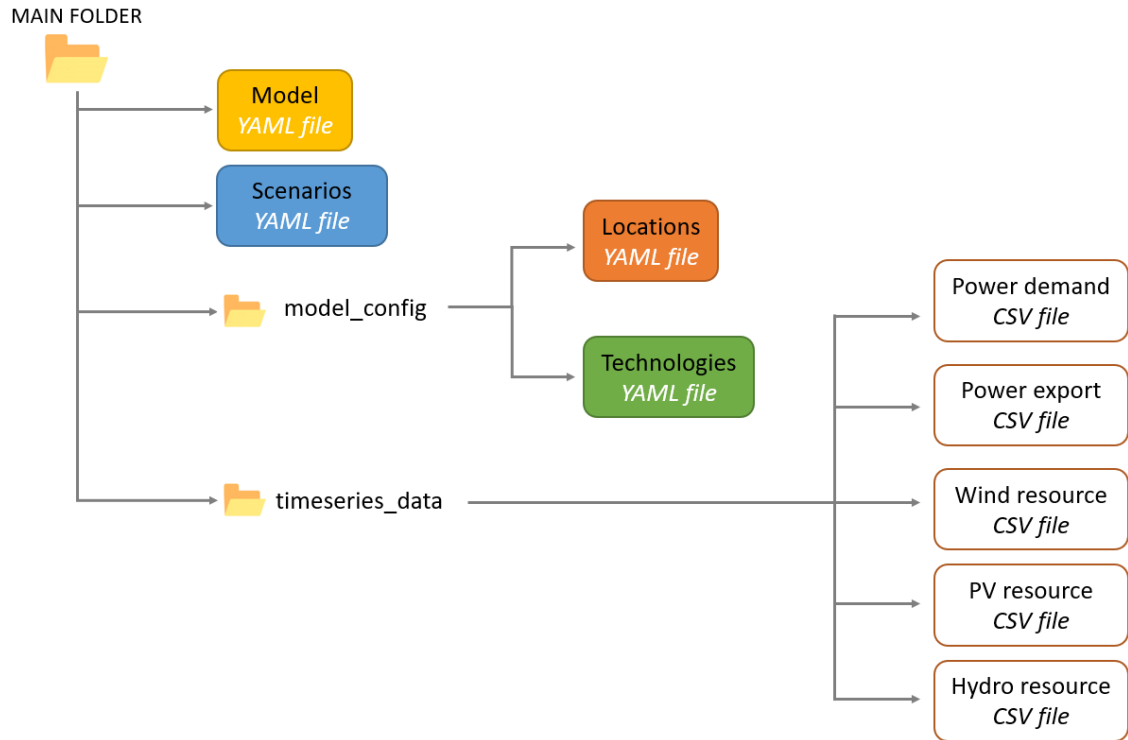


Figure 2.2: Most typical structure of files in Calliope

As seen in the Figure 2.2 in a model built with Calliope the model, locations, technologies and scenarios are defined in a file with YAML format, a language that is easily intuitive for the user but usable for different programming languages [108]. In this case the locations and technologies files are in a folder called *model_config*. Instead, the timeseries file are given in CSV format, usually in a folder called *timeseries_data*.

2.2 Model configuration

The file **model.yaml** permits to configure the main characteristics of the model and in order to understand it better, different parts of this file are analyzed in detail. The possible configurations or constraints and default setting usable in a model created for Calliope, are present in the Chapter 1.9.1 *Model configuration* of the Calliope Documentation [102]. In the *model.yaml* file there are the keys (top-level headings): **model** and **run**.

At first all files that need to be imported are specified, in this case just locations, technologies and scenarios:

```
import:
  - 'model_config/techs.yaml'
  - 'model_config/locations.yaml'
  - 'scenarios.yaml'
```

In the following part the name of the model is given, with the timeseries data path and the interval of time to consider for the model. By default Calliope considers the interval of time in the format YYYY-MM-DD hh:mm:ss where YYYY is the year considered, MM is the month, DD is the day and this can be followed by hh that is the hour, mm is the minute and eventually also ss that is the second considered. The time horizon in Calliope of a model is one year.

```
model:
  name: Sardinia Model #name chosen for the model
  calliope_version: 0.6.7 #version of Calliope used
  timeseries_data_path: 'timeseries_data' #path to data used for time
                                series
  subset_time: ['2019-01-01', '2019-12-31'] #interval of time considered
                                in the model
  time:
    function: resample
    function_options: {'resolution': '3H'} #function to use a timestep
                                different than 1 hour
```

Under the key **time** it is possible to define a function to adjust the time series that are given to the model. A possible function that can be used is the **resample** function that permits to extend to more than one hour the timestep to reduce for example the computational time to run the model.

In the last part of *model.yaml* file the **run** configuration is defined, in particular the solver to use and the type of run. All possible run configurations are listed in Section 1.9.2 *Run configuration* of the Calliope Documentation [102]. Below a possible part of the code under the key **run** is reported :

```
run:
  solver: cplex #solver chosen
  mode: plan #planning mode of run
  #another option of run is operation with for example 48 hours of
                                horizon and 24 hours of window
  #operation:
  #  horizon: 48
```



```
#    window: 24
ensure_feasibility: True #find a solution creating the unmet demand
bigM: 1e6 #cost associated to the unmet demand
objective_options.cost_class: {monetary: 1} #here it is possible to
                                define another objective function
                                , other cost classes or assign
                                weights to cost classes
```

The solver chosen in this case is CPLEX, a commercial solver with an academic license offered by IBM [79] and, on the IBM website, all possible parameters for CPLEX configuration can be found [80]. This solver is chosen because it is also recommended by the Calliope Documentation [102], as the solver Gurobi, for the reduced time to solve a model if compared to others.

In Table 2.2 the different computational times are provided to run the built-in urban and national examples with different solvers, over 1 year, interval 1 hour, at the University of Cambridge using a high-performance computing cluster and imposing maximum time for run equals to 5 hours.

Table 2.2: Solution time for pre-built examples, using different solvers taken from the Calliope Documentation [102]

Solver	Solution time	
	National model	Urban model
GLPK	4:35:40	>5 hours
CBC	0:04:45	0:52:13
Gurobi (1 thread)	0:02:08	0:03:21
CPLEX (1 thread)	0:04:55	0:05:56
Gurobi (4 thread)	0:02:27	0:03:08
CPLEX (4 thread)	0:02:16	0:03:26

In Calliope there are three modes to **run a model**: plan, operate or spores. In the first case, the model is run in **planning mode** and all the capacity of technologies are determined by the model; this is also the default mode of run. Instead, the second case is the **operational mode**, in which the capacities of technologies are imposed by the user and with a receding horizon algorithm the model manages the fluxes of different energy carriers in the system [102]. This type of run is introduced in Calliope considering that in an optimization problem it is not always possible to know exactly in a specific time all the parameters to use, but for example, only a few days in advance [46]. To simulate this situation it is possible to use the **rolling horizon** to run the model, with capacities of technologies fixed. Modelling optimization is performed on complete time series but in smaller parts called scheduling horizons. On each horizon, the model is optimized to run only one sub-period called the scheduling window, therefore the horizon is larger than the window. In the remaining part of the horizon, not included in the window, there is a forecast period that is used to get more information for the scheduling window. In this case, the optimization considers the current system conditions and the future forecast [46].

In the energy transition there are also new necessities, for example, consider that renewable energy generation can vary with the place where the sun and wind capacities are installed, how far is the place where the energy is used, social problems and land use [36]. In order to answer to these questions Calliope has a most recent type of run called **SPORES** tested on an energy model created for the Italian country [36]. This type of run permits to have Spatially-explicit Practically Optimal REsultS, at first the model is run using the mode plan, consequently it is chosen the number of spores to generate and the model is run again more times in order to have a solution with cost in a range around the optimal cost [102].

There are two types of different objective functions that is possible to use:

- **Minimize or maximise total system cost:** For a cost class or a set of cost classes

$$\begin{aligned} \min : z = & \sum_{loc::tech_{cost},k} (cost(loc :: tech, cost = cost_k) * weight_k) + \\ & \sum_{loc::carrier,timestep} (unmet_demand(loc :: carrier, timestep) * bigM) \end{aligned} \quad (2.1)$$

$$\begin{aligned} \max : z = & \sum_{loc::tech_{cost},k} (cost(loc :: tech, cost = cost_k) * weight_k) - \\ & \sum_{loc::carrier,timestep} (unmet_demand(loc :: carrier, timestep) * bigM) \end{aligned} \quad (2.2)$$

- **Check feasibility:** Dummy target, to check for conflicting constraints

$$\min : z = 1 \quad (2.3)$$

By default, the objective function is to minimize the total system cost, therefore if another objective function is not specified, the target of the optimization in Calliope is to create a final model with the minimum cost on cost classes.

As shown in the code above under the key *run* there is the voice **ensure_feasibility** that is a configuration for the run that by default is imposed to False, as can be seen in the section 1.9.2 *Run configuration* of the Calliope Documentation [102]. It is possible to be sure that the solver finds a solution for the problem, by changing the configuration to:

```
ensure_feasibility: True
```

In this case, if there is a mismatch between supply (total energy produced) and demand (total energy consumed) of energy on different carriers, it is created a decision variable called **unmet_demand**. This variable is associated with a high cost called bigM and is set by default to 10^9 . The value of this bigM should be appropriated for the problem, which means to find a value not too high or the convergence of the problem could be compromised.

Therefore Calliope performs an energy balance summing energy produced (*carrier_prod*),

energy consumed (*carrier_con*) and energy exported (*carrier_export*) on locations, technologies and timesteps as following:

$$\begin{aligned}
 & \sum_{loc::tech::carrier_{prod} \in loc::carrier} carrier_{prod}(loc :: tech :: carrier, timestep) + \\
 & \sum_{loc::tech::carrier_{con} \in loc::carrier} carrier_{con}(loc :: tech :: carrier, timestep) + \\
 & \sum_{loc::tech::carrier_{export} \in loc::carrier} carrier_{export}(loc :: tech :: carrier, timestep) \\
 & \forall loc :: carrier \in loc :: carriers, \forall timestep \in timesteps
 \end{aligned} \tag{2.4}$$

In Calliope costs are defined with the concept of cost classes. In the `model.yaml` code, with `objective_options`, arguments are passed to the objective functions and in this voice, the types of cost classes are given. The default cost class is called *monetary*, for example, it is also possible to account emissions with a dedicated cost class and then it is possible to add different weights to costs, considered in Equation 2.2 and in Equation 2.1. The way costs are used in Calliope is explained in the section 2.3 and it is described in more detail in the Calliope Documentation [102].

2.3 Technologies

The technologies in Calliope are defined by the user based on main characteristics taken from a parent: a group of technologies that can be already defined in Calliope or defined by the user. All these abstract technology groups, already defined in Calliope, are the following [102]:

- Supply;
- Supply_plus;
- Demand;
- Storage;
- Transmission;
- Conversion;
- Conversion_plus.

When the user specifies a parent for technology, this technology acquires the features set for the corresponding parent: default constraints, required constraints, allowed constraints, and allowed costs. Changing the parent means changing the configuration of the technology, therefore all the categories cited. In the following part, a list of some characteristics of the different parent technologies is presented, taking information from Calliope Documentation [102], that can be consulted to have an exhaustive description of technologies in Calliope.

Supply technology

In Calliope, a carrier can be used, called `carrier_con`, or produced, called `carrier_prod`. As can be seen from the Figure 2.3 a technology with the parent supply takes the resource available and transforms it into a carrier produced using the installed capacity of the technology defined and, if it is set, with the efficiency of the technology. This parent is used for example for different technologies that produce energy in the model.

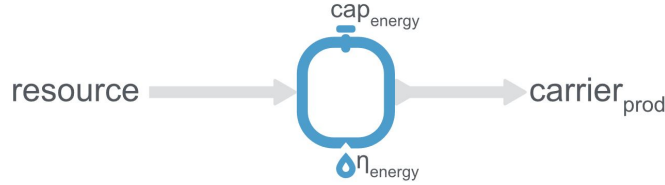


Figure 2.3: Scheme of supply parent technology [102]

In Table 2.3 the list of default constraints and required constraints acquired from the parent supply is presented. Instead, the possible constraints to set and costs to use, for a supply technology, are in the Table 2.4. The various constraints and costs, listed in the Tables below, are explained when they are used in the different technologies and models in chapter 4. It is also possible to find the full description of constraints and costs for different parents of technologies, in Section 1.9.6 *Abstract base technology groups* of Calliope Documentation [102].

Table 2.3: Default and required constraints for the supply parent technology [102]

PARENT: SUPPLY		
default constraints		
essentials	constraints	costs
parent:	energy_prod: true	{ }
	resource: inf	
	resource_unit: energy	
required_constraints		
-		

Table 2.4: Allowed constraints and allowed costs for the supply parent technology [102]

PARENT: SUPPLY		
allowed_constraints		allowed_costs
energy_cap_equals	lifetime	depreciation_rate
energy_cap_equals_systemwide	resource	energy_cap
energy_cap_max	resource_area_equals	export
energy_cap_max_systemwide	resource_area_max	interest_rate
energy_cap_min	resource_area_min	om_annual
energy_cap_min_use	resource_area_per_energy-cap	om_annual_investment_fraction
energy_cap_per_unit	resource_min_use	om_con
energy_cap_scale	resource_scale	om_prod
energy_eff	resource_unit	purchase
energy_prod	units_equals	resource_area
energy_ramping	units_equals_systemwide	
export_cap	units_max	
export_carrier	units_max_systemwide	
force_resource	units_min	

Supply_plus technology

Some additional constraints can be applied if the technology is configured with the parent **supply_plus** instead of the parent supply. For example, an additional storage can be specified, using this parent, as in Figure 2.4. The list of constraints and costs for the supply_plus technologies are present in Tables 2.5 and 2.6. This technology for example can be used for a photovoltaic system with storage.

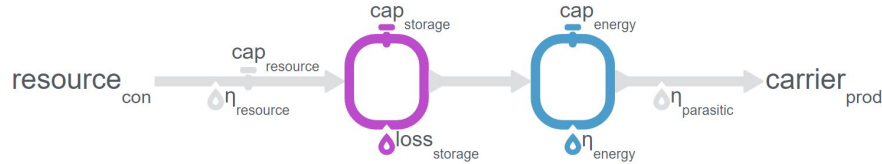


Figure 2.4: Scheme of supply_plus parent technology [102]

Table 2.5: Default and required constraints for the supply_plus parent technology [102]

PARENT: SUPPLY_PLUS		
default constraints		
essentials	constraints	costs
parent:	energy_prod: true	{}
	resource: inf	
	resource_eff: 1.0	
	resource_unit: energy	
required constraints		
-		

Table 2.6: Allowed constraints and allowed costs for the supply_plus parent technology [102]

PARENT: SUPPLY_PLUS		
allowed_constraints		allowed_costs
charge_rate	resource_area_max	depreciation_rate
energy_cap_per_storage_cap_min	resource_area_min	energy_cap
energy_cap_per_storage_cap_max	resource_area_per_energy_cap	export
energy_cap_per_storage_cap_equals	resource_cap_equals	interest_rate
energy_cap_equals	resource_cap_equals_energy_cap	om_annual
energy_cap_equals_systemwide	resource_cap_max	om_annual_investment_fraction
energy_cap_max	resource_cap_min	om_con
energy_cap_max_systemwide	resource_eff	om_prod
energy_cap_min	resource_min_use	purchase
energy_cap_min_use	resource_scale	resource_area
energy_cap_per_unit	resource_unit	resource_cap
energy_cap_scale	storage_cap_equals	storage_cap
energy_eff	storage_cap_max	
energy_prod	storage_cap_min	
energy_ramping	storage_cap_per_unit	
export_cap	storage_initial	
export_carrier	storage_loss	
force_resource	units_equals	
lifetime	units_equals_systemwide	
parasitic_eff	units_max	
resource	units_max_systemwide	
resource_area_equals	units_min	

Demand technology

A technology with the parent **demand** transforms a carrier consumed in a resource for the technology and it is used for the energy demand technology in the energy model. Compared to a technology of parent supply it is defined negatively in the model [102].



Figure 2.5: Scheme demand parent technologies [102]

Table 2.7: Default and required constraints for the demand parent technology [102]

PARENT: DEMAND		
default constraints		
essentials	constraints	costs
parent:	energy_con: true	{}
	force_resource: true	
	resource_unit: energy	
required constraints		
resource		

Table 2.8: Allowed constraints and allowed costs for the demand parent technology [102]

PARENT: DEMAND		
allowed_constraints		allowed_costs
energy_con	resource_area_equals	om_con
force_resource	resource_scale	
resource	resource_unit	

Storage technology

The parent **storage** for a technology permits to store an amount of energy of the carrier given as input before giving it as output.

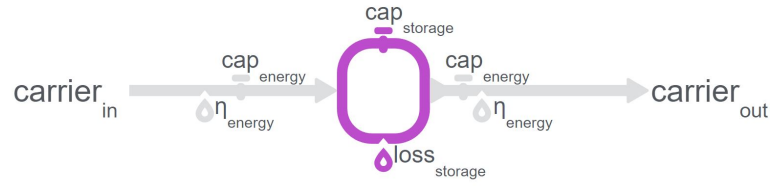


Figure 2.6: Scheme storage parent technologies [102]

Table 2.9: Default and required constraints for the storage parent technology [102]

PARENT: STORAGE		
default constraints		
essentials	constraints	costs
parent:	energy_con: true	{}
	energy_prod: true	
	storage_cap_max: inf	
required constraints		
-		

Table 2.10: Allowed constraints and allowed costs for the storage parent technology [102]

PARENT: STORAGE		
allowed_constraints		allowed_costs
charge_rate	export_carrier	depreciation_rate
energy_cap_per_storage_cap_min	force_asynchronous_prod_con	energy_cap
energy_cap_per_storage_cap_max	lifetime	export
energy_cap_per_storage_cap_equals	storage_cap_equals	interest_rate
energy_cap_equals	storage_cap_max	om_annual
energy_cap_equals_systemwide	storage_cap_min	om_annual_investment_fraction
energy_cap_max	storage_cap_per_unit	om_prod
energy_cap_max_systemwide	storage_initial	purchase
energy_cap_min	storage_loss	storage_cap
energy_cap_min_use	storage_time_max	
energy_cap_per_unit	storage_discharge_depth	
energy_cap_scale	units_equals	
energy_con	units_equals_systemwide	
energy_eff	units_max	
energy_prod	units_max_systemwide	
energy_ramping	units_min	
export_cap		

Transmission technology

The parent **transmission** is used to consume a carrier in one location and transmits it to another location becoming the carrier produced in that location.

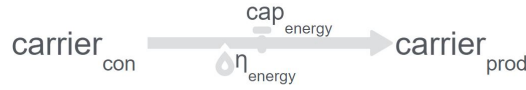


Figure 2.7: Scheme of transmission parent technologies [102]

Table 2.11: Default and required constraints for the transmission parent technology [102]

PARENT: TRANSMISSION		
default constraints		
essentials	constraints	costs
parent:	energy_con: true	{}
	energy_prod: true	
required_constraints		
-		

Table 2.12: Allowed constraints and allowed costs for the transmission parent technology [102]

PARENT: TRANSMISSION	
allowed_constraints	allowed_costs
energy_cap_equals	depreciation_rate
energy_cap_max	energy_cap
energy_cap_min	energy_cap_per_distance
energy_cap_per_unit	interest_rate
energy_cap_scale	om_annual
energy_con	om_annual_investment_fraction
energy_eff	om_prod
energy_eff_per_distance	purchase
energy_prod	purchase_per_distance
force_asynchronous_prod_con	
lifetime	
one_way	

Conversion technology

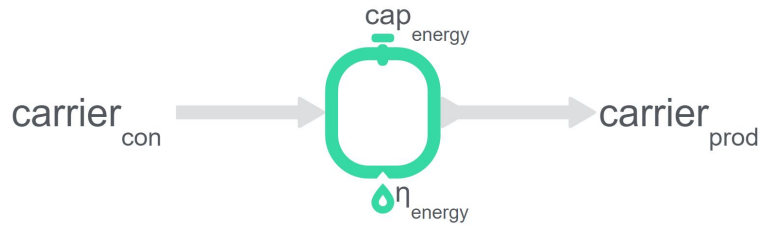


Figure 2.8: Scheme conversion parent of technologies [102]

To transform the energy of one carrier, that is consumed, to another type of carrier that in this case becomes produced, it is defined as a technology under the parent conversion.

Table 2.13: Default and required constraints for the conversion parent technology [102]

PARENTS: CONVERSION		
default constraints		
essentials	constraints	costs
parent:	energy_con: true	{}
	energy_prod: true	
required constraints		
-		

Table 2.14: Allowed constraints and allowed costs for the conversion parent technology [102]

PARENTS: CONVERSION		
allowed constraints		allowed costs
energy_cap_equals	energy_prod	depreciation_rate
energy_cap_equals_systemwide	energy_ramping	energy_cap
energy_cap_max	export_cap	export
energy_cap_max_systemwide	export_carrier	interest_rate
energy_cap_min	lifetime	om_annual
energy_cap_min_use	units_equals	om_annual_investment_fraction
energy_cap_per_unit	units_equals_systemwide	om_con
energy_cap_scale	units_max	om_prod
energy_con	units_max_systemwide	purchase
energy_eff	units_min	

Conversion_plus technology

For the parent conversion, there is also the possibility to transform one or more than one carriers to one or more types of carrier with the parent conversion_plus.

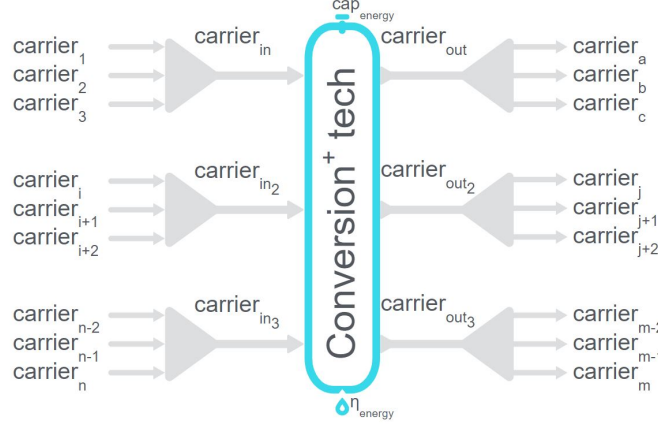


Figure 2.9: Scheme of conversion_plus parent technologies [102]

Table 2.15: Default and required constraints for the conversion_plus parent technology [102]

PARENTS: CONVERSION_PLUS		
default constraints		
essentials	constraints	costs
parent:	energy_con: true	{}
	energy_prod: true	
required constraints		
-		

Table 2.16: Allowed constraints and allowed costs for the conversion_plus parent technology [102]

PARENTS: CONVERSION_PLUS		
allowed constraints		allowed costs
carrier_ratios	energy_prod	depreciation_rate
energy_cap_equals	energy_ramping	energy_cap
energy_cap_equals_systemwide	export_cap	export
energy_cap_max	export_carrier	interest_rate
energy_cap_max_systemwide	lifetime	om_annual
energy_cap_min	units_equals	om_annual_investment_fraction
energy_cap_min_use	units_equals_systemwide	om_con
energy_cap_per_unit	units_max	om_prod
energy_cap_scale	units_max_systemwide	purchase
energy_con	units_min	
energy_eff		

The section of technology is one of the most important in a model created using Calliope and all the technologies used are defined in a **techs.yaml** file, of which parts are extrapolated as the example below, to explain how to set up technologies. In this YAML file there is a key called *tech*, such as *model* in the *model.yaml* file.

All technologies that are used in the model should be defined already in this file and then applied to corresponding locations. For each technology *essentials*, *constraints* and *costs* sections are defined under the key *techs*. For example to represent the use of fossil oil, a technology with the same name is specified, in addition a color to visualize this technology in results plot and usually also the parent and the type of carrier produced or used by the technology, as follows:

```
techs:
  fossil_oil:
    essentials:
      name: 'Fossil oil' #name of the technology to define
      color: '#ffa07a' #HTML code of color to visualize the
                        technology in plots
      parent: supply #type of parent to apply to the technology
      carrier_out: electricity #type of carrier given as output from
                              the technology
```

Additionally to the technology, under the key *techs*, some constraints are added to limit decision variables and all possible constraints that can be set are available in section 1.9.3 *Per-tech constraints* of the user guide of Calliope [102].

In the following part of the code there is an example of how the resource, the installed capacity, the energy efficiency and ramping for the technology and the lifetime are defined under *constraints*:

```
techs:
  fossil_oil:
    constraints:
      resource: inf #no limit on resource
      energy_cap_max: 40000 #kW maximum capacity that can be
                           installed for the
                           technology with coherent
                           unit decided by the user
      energy_eff: 0.35 #energy efficiency
      energy_ramping: 0.6
      lifetime: 35
```

If the resource is given to a supply-plus technology the production of the carrier by this technology is limited by the resource in the following way:

$$\begin{aligned} resource_con(loc :: tech, timestep) &\leq available_resource(loc :: tech, timestep) \\ \forall loc :: tech \in loc :: techs_{supply+} \quad \forall timestep \in timesteps \end{aligned} \quad (2.5)$$

To use all the resources for the technology, in a specific location it can be set:

```
force_resource: True
```

and in this case for each timestep, the resource consumed is equal to the available resource. In this case, the available resource is the resource given, scaled to the resource scale if it is given with the constraint *resource_scale*, different from the default unitary value.

In the Calliope Documentation [102] different modes to limit the resource can be found, for example with the constraint **resource** it is limited the amount of the resource available in units expressed as kWh, or kWh/m² or kWh/kW. The units of measure in Calliope are defined by the user in the way the constraints are applied or the way the files are given as input; there is an indication of possible units of measure for different constraints in section 1.9.3 *Per-tech constraints* of Calliope Documentation [102]. Instead in the section 1.11.3 *Mathematical formulation* of this guide all the equations, imposed in the code of Calliope, can be found.

For a technology defined in Calliope it is possible to give a maximum amount of capacity that can be installed using the constraint **energy_cap_max** or the exact capacity installed with the constraint **energy_cap_equals**. This can be useful for example in the planning mode of run because Calliope finds the optimal capacities installed under the limit of the maximum capacity given. The constraints on the capacity can be applied as follows:

$$\begin{aligned} & \text{if } \text{energy}_{cap,equals,systemwide}(loc :: tech) \forall tech \in techs \\ & \sum_{loc} \text{energy}_{cap}(loc :: tech) = \text{energy}_{cap,equals,systemwide}(loc :: tech) \end{aligned} \quad (2.6)$$

$$\begin{aligned} & \text{if } \text{energy}_{cap,max,systemwide}(loc :: tech) \forall tech \in techs \\ & \sum_{loc} \text{energy}_{cap}(loc :: tech) \leq \text{energy}_{cap,max,systemwide}(loc :: tech) \end{aligned} \quad (2.7)$$

$$\text{otherwise } \sum_{loc} \text{energy}_{cap}(loc :: tech) \text{ is unconstrained} \quad (2.8)$$

It is important to notice that the constraint **energy_cap_max** is transformed into **energy_cap_equals** in the operational mode because, as discussed above, this type of run works with capacities fixed.

The **energy ramping** is the unit of the fraction on an hour to limit maximum carrier production to only a part of the maximum capacity, to increase it by that fraction at each timestep. The maximum ramping rate is defined as follows:

$$\begin{aligned} \text{max_ramping_rate}(loc :: tech :: carrier, timestep) = \\ \text{energy}_{ramping}(loc :: tech, timestep) * \text{energy}_{cap}(loc :: tec) \end{aligned} \quad (2.9)$$

In the last section of the techs.yaml file the costs for the technology are attributed. By default all available costs are set to 0 for each cost class and possible costs, that can be set, are present in section 1.9.4 *Per-tech costs* of user guide [102] with possible units of measure.

In this technology taken as an example, there is only the monetary cost class setting an interest rate, the cost to install the capacity of this technology (`energy_cap`), the cost of production (`om_prod`) and consumption (`om_con`) and the annual cost of operation and maintenance (`om_annual`):

```
costs:
  monetary:
    interest_rate: 0.10
    energy_cap: 0 #eur/kW already installed
    om_prod: 0.023 #eur/kWh
    om_annual: 32 #eur/kW/year
    om_con: 0.01 #eur/kWh
```

2.4 Locations

In Calliope, the problem is solved not only in time but also in space, defining locations. As for the technologies, also the locations are defined in a YAML file usually called *locations.yaml*. A location is a point in space, a node that identifies a house, a power plant, a city, a region or even a continent. In a location using technologies, the user sets if there is a generation or consumption of energy [47]. The first key in this YAML file is *locations* and, under it, for each location, the different technologies used in that location are specified. Before this assignment, each technology should be already defined in *techs.yaml* file.

It is also possible to apply other constraints or costs to technologies for example to give the resource as a CSV file, even in the file for locations. In the following part, there is an example of how a region can be defined by installing the technology photovoltaic listed in the *techs.yaml* file :

```
locations:
  region1: #definition of region called region1
    techs:
      pv: #technology for photovoltaic system installed in region1
        constraints:
          resource: file=pv_resource.csv #timeseries of solar
                                resource
          energy_cap_equals: 141900 #exact installed capacity
                                #of technology, in units coherent decided by the user
```

In this case, a file in CSV format is given for the resource of solar energy and the exact installed capacity with the constraint *energy_cap_equals* that can be done also in the *techs.yaml* file.

It is also possible to indicate the coordinates of locations, in this way Calliope evaluates the distance between them.

Each location is connected to another one by transmission technologies defined under *links*, capable to transport energy of a carrier between locations [102]. Also, this type of technology should be defined already in *techs.yaml* file.

```
links: #way to connect locations
  region1,region2: #two regions defined in locations.yaml file
    techs:
      ac_transmission: #transmission line technology
        constraints:
          energy_cap_max: 10000 #maximum capacity
        costs.monetary:
          energy_cap: 100 #cost of installed capacity
```

Even for transmission lines, costs can be defined, which are listed in Section 1.9.4 *Per-tech costs* of Calliope Documentation [102].

2.5 Scenarios

In energy modelling is useful to run the same model varying just some constraints or costs; for this reason in Calliope scenarios and overrides are introduced. There is a file *scenarios.yaml* where it is possible to define blocks of YAML with modifications to the original model, called **overrides**. In this way, it is possible to override constraints for technologies, or change the interval of time to consider, or even introduce new constraints. Each override has a different name and more than one overrides can be added to construct a scenario. In the following part is presented an example of code of possible scenarios taken from the Calliope Documentation [102]:

```
scenarios:
  high_cost_2005: ["high_cost", "year2005"]
  high_cost_2006: ["high_cost", "year2006"]
overrides:
  high_cost: #override to change the cost of installed capacity of
              onshore_wind technology
    techs.onshore_wind.costs.monetary.energy_cap: 2000
  year2005: #override to change the interval of time considered to year
            2005
    model.subset_time: ['2005-01-01', '2005-12-31']
  year2006: #override to change the interval of time considered to year
            2006
    model.subset_time: ['2006-01-01', '2006-12-31']
```

In this case, two scenarios (*high_cost_2005* and *high_cost_2006*) are defined and each one of them includes two overrides defined in the same file. In this way, it is possible to run the model with the scenario chosen, as in the following section 2.6.

2.6 Run a model

After defining all main components and configuring the main parts of the model, it is possible to run the original model or a scenario of this energy model [102]. This can be done in two ways:

- using the command- line
- run in an interactive way with Python

2.6.1 Run with command-line

To run the original model the command run of Calliope can be used in the following way:

```
calliope run model.yaml
```

Instead in order to run the scenario can be used the same command but specifying the name of the scenario, which must be already defined in the file scenario.yaml:

```
calliope run model.yaml --scenario=name_scenario
```

2.6.2 Interactive run with Python

Another way to run the model is to use the interactive run with Python; in this case, at first the package calliope is imported:

```
import calliope
```

The original model is built based on configurations defined in model.yaml using the model class:

```
model = calliope.Model('path/to/model.yaml')
```

After the model is built it is run and the type of run (plan or operate) is defined in model.yaml file:

```
model.run()
```

Instead, to run a scenario of the energy model, after imported calliope, even in this case, the Model class is used in the following way:

```
model = calliope.Model('model.yaml', scenario='name_scenario')
```


2.7 Analyze results

After the model is built, and it is run, if Calliope finds a feasible solution depending on the objective function chosen, it is possible to analyze the results provided.

There are integrated commands in Calliope permitting to plot results, in particular, some useful ones are:

```
model.plot.timeseries() #plot of results in the subset interval chosen
model.capacity() #histograms of installed capacity for different
                  technologies
model.transmission() #plot of transmission network created for the model
model.plot.flows() #plot of transmission networks with energy flows
```

These commands can be modified in order to obtain desired results, for possible modifications or more information it is possible to consult the Calliope Documentation [102]. Inputs and results can be also saved in CSV format to be studied in more detail, using the following codes depending if the run is done by command-line or not:

```
calliope run name_model.yaml --save_csv=results.csv #run with command-line
model.to_csv('save_path') #run with Python
```

Calliope has a lot of other possible functions and some of them are described in the chapter 4, but it is possible to consult the Calliope Documentation for more details [102].

Part II

Case Study: Energy system model of Sardinia

Chapter 3

Energy system in Sardinia

The only Italian region that has still active more than one coal power plant is the Sardinia region, with the two power plants in the Figure 3.1.

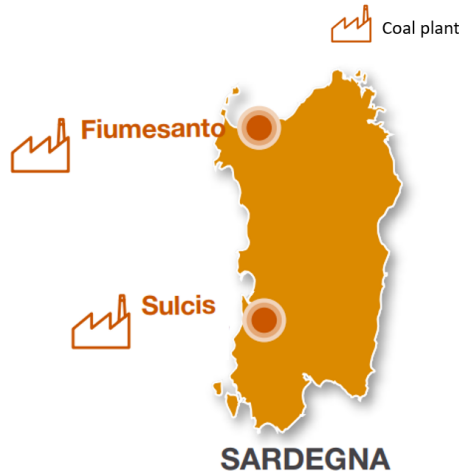


Figure 3.1: Coal power plants programmed for phase out in 2025 in Sardinia [50]

Also due to the presence of a lot of generation from coal in Sardinia's energy mix, the carbon emissions from this region are very high, as can also be seen in Figure 3.2. This region has a particular energy system; being an island, it is also necessary to ensure the region's energy security. From the analysis done by Terna, the region Sardinia has an inadequate and insecure system with the actual energy transmission capacity connecting the rest of Italian country, in case of dismission of coal power plants. Without the actual generation from coal power plants, if the Sapei connection is out of service, many Sardinian consumers could be disconnected from the electrical network [50]. The number of hours in a year when this detachment is likely to occur, because expected demand exceeds the available resources, is called Loss of Load Expectation (LOLE) [43]. According to Terna this value for Sardinia exceeds the limit of 3 hours per year, consequently, the region requires new installed capacity and a new connection called Tyrrhenian Link.

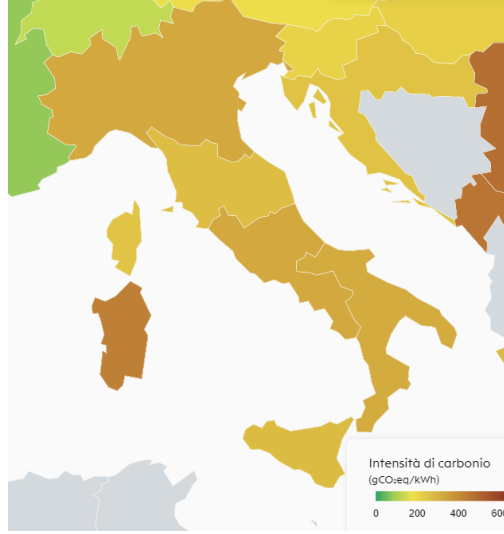


Figure 3.2: Climate impact per area. Carbon intensity classification of electricity consumed (gCO_{2eq}/kWh). Figure taken from Electricity Maps [82], representative of April 2022

This connection will connect Sardinia through Sicily to Campania as in Figure 3.7 and its project is scheduled to be fully operational in 2028, but by the end of 2025, the part connecting Sicily to Campania could already be finished [56].

The phase-out situation, the presence of a network that is not very well-structured and the generation of energy that has many non-programmable sources, cause the necessity of a detailed analysis of the evolution of the Sardinian electricity system.

In this region, the following production power plants are considered essential to the security of the electrical system [58], increasing the importance of the study of this energy system:

- Biopwer Sardegna;
- Assemini;
- Sulcis;
- Sarlux;
- Fiumesanto.

Looking at the evolution of the installed capacity for energy production, it can be seen from Figure 3.3 that there is a gradual increase in renewable, wind and photovoltaic, installed capacity. At the same time, the share of installed thermoelectric still remains very high in 2020, as in Figure 3.3.

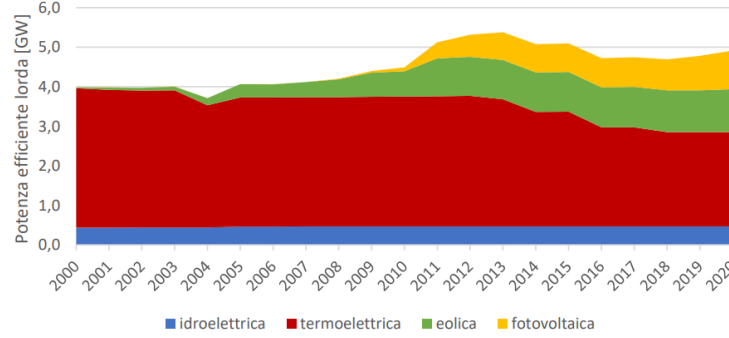


Figure 3.3: Gross capacity installed of power plants in Sardinia [59]

Considering just the renewable production in the region, it is possible to notice from Figure 3.4 that from 2010 there is an increase in the energy produced by photovoltaic and wind systems.

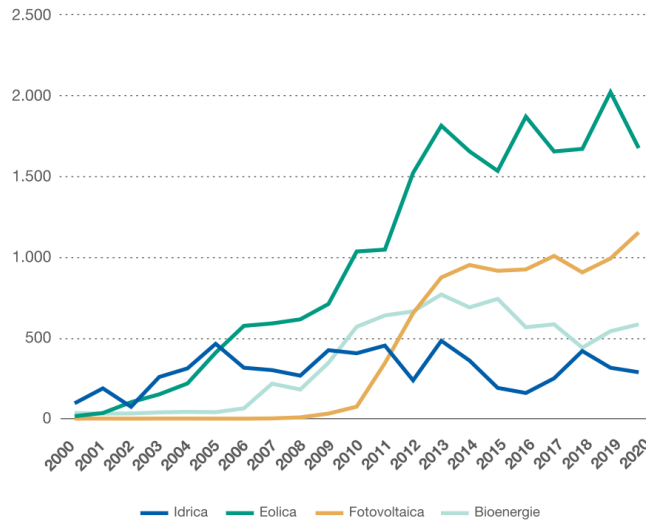


Figure 3.4: Historical series of gross renewable production by source, Years 2000-2020 (GWh) [30]

Considering the common goals of the 2030 Agenda [84], for the UN member countries, it is possible to compare Sardinia's positioning with the Italian average in Figure 3.5. Gross final energy consumption from renewable sources in 2017 was 27.5 %, above the national one equals 18.3 %. However, there are energy targets that can be improved, for example on service continuity, although 2018 already showed an improvement in energy

sustainability for Sardinia compared to the previous year [98].



Figure 3.5: Comparison of national and regional composite indicators, for the year 2018. The number 100 indicates the performance of Italy in 2030. Figure adapted from source [98]

Over the years the region of Sardinia takes part in several organizations with the target to mitigate climate change impacts and improve energy sustainability. The region has adopted global and local planning and programming tools by taking part in initiatives such as RegionsAdapt and Covenant of Mayors and studying strategies to adapt the region to climate change [97].

In the Energy and Environmental Plan of the Region of Sardinia (PEARS) [7] and its two subsequent monitoring reports [26] [27], the characteristics of the Sardinian energy system are highlighted in more detail. In these documents, it is also emphasized that the region of Sardinia lacks a complete natural gas distribution network and that this methanisation process, which is already partly underway, must be integrated into the energy system in the most correct way.

In this thesis, the natural gas problem in Sardinia is not considered in the case study, as it is studied in PEARS [7] and in some reports such as RSE's forecast of gas transport in Sardinia from 2020 to 2040 [41].

In order to increase the renewable generation in the region it is necessary that the electricity transmission lines in the region are able to sustain this capacity. As described before, Terna has some network expansion projects and for the region of Sardinia [50], a renewal of the connection cable with Corsica, the Sacoi 3, is planned, as in the Figure 3.6, and a connection cable with Sardinia and the peninsula with the Tyrrhenian link as in the Figure 3.7.



Figure 3.6: Main interventions to increase foreign trade capacity for Sardinia, adapted from source [50]



Figure 3.7: Main interventions to increase trade capacity between market areas for Sardinia, adapted from source [50]

Chapter 4

Energy model of Sardinia

To build the energy model of the region Sardinia using Calliope at first locations and technologies are identified to be included in the model and it is defined how to configure them.

As first, the model created needs to be **validated to verify that the dispatch of energy** is quite representative of the real one. This phase of validation of the model is done in the **operation run mode**, with capacities of technologies fixed, to manage fluxes of energy.

After this phase **different scenarios to improve the energy system** are created based on possible trends and decisions and the results are analyzed. These scenarios are designed considering future projects that will involve the energy system of Sardinia.

4.1 Locations

In order to consider the energy model in the space, initially **five locations** are chosen as aggregates of different larger or smaller cities. In particular, each location is representative of one of the five provinces of Sardinia and this assumption takes into account power plants, usually located near provincial capitals, and the distribution on the region of the electrical connections, which is explained further below for each configuration created. In addition, it is also considered that the data available for the region in most cases includes just one value for each province.

Therefore locations are created initially as in the Figure 4.1 to test the model and subsequently they are modified in the validation phase to align energy flows more closely with Sardinia's actual energy flows.

As it can be seen from Figure 4.1, it is created also a node called N1 between these locations, which geographical coordinates correspond to the city of Ollara. The position of this point in the map is chosen considering that is mostly in the middle of locations created and that the configuration of the electric system in the region in that point branches off into multiple links.

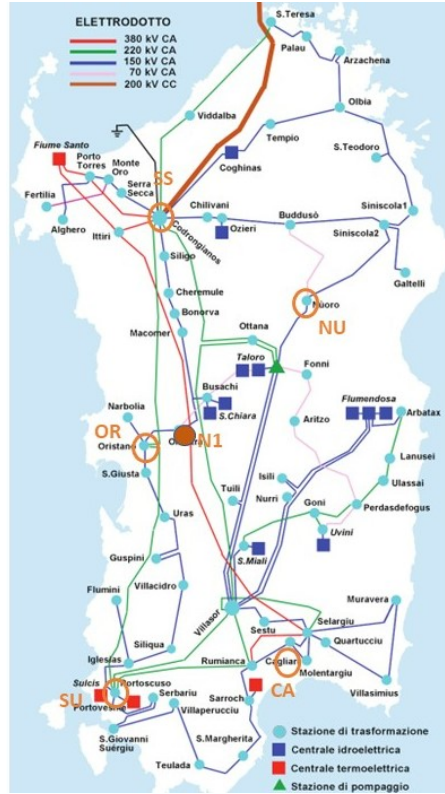


Figure 4.1: Nodes created for locations. Figure adapted from source [16]. Abbreviations used: CA=Cagliari, SU=Sud Sardegna, NU=Nuoro, OR=Oristano, SS=Sassari.

As previously announced in section 2.4, locations are mainly defined in a YAML file usually called '**locations.yaml**', and possible additions to their characteristics can be made with scenarios and overrides. In the YAML file under the key *locations* are specified all locations and for each location the technologies installed and their constraints are set. For example in the following part of code for the location of Cagliari the technology for the photovoltaic power plants is specified and it is possible to apply some constraints, as explained before:

```
locations:
  cagliari: #location representative of the province Cagliari
    techs:
      pv_farm: #photovoltaic power plants technology
    constraints:
```

In Calliope each location can be specified in its coordinates and in this model each location has the coordinates of the corresponding capital of the province, therefore for example the location called 'cagliari' has the coordinates of the city of Cagliari, taken from Google Maps [78]:

```
coordinates: {x: 39.21666700, y: 9.11666700}
```

4.2 Energy demand technology

In order to have a model of Sardinia as comparable as possible to the energy situation in the region, it is provided to model the energy demand of the region. In this case, it is inserted in the model as a timeseries of the demand of energy and in this case it is considered for the year 2019, even if the installed capacities of technologies are more representative of the year 2020. This choice is done considering the availability of data and the year 2019 is considered more realistic for the time period due to the reduction of energy demand [30], caused by COVID-19 that affected Italy mostly in 2020 [95].

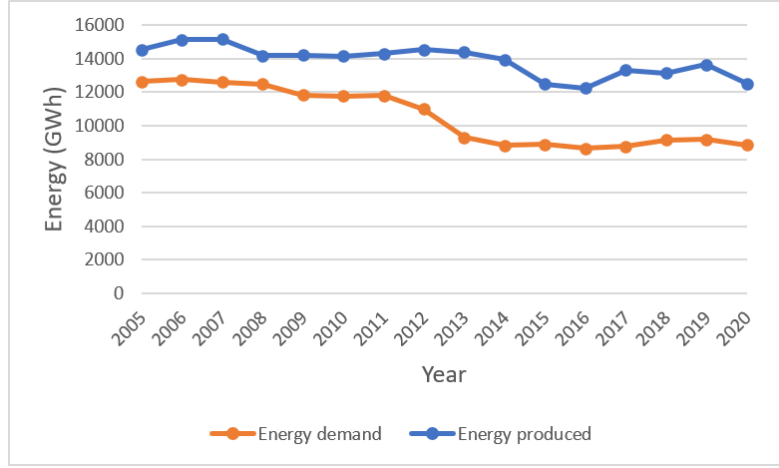


Figure 4.2: Evolution of Energy demand in Sardinia [30]

From the Figure 4.2 it is also possible to notice that there is a reduction of required energy and energy production in 2020 compared to the previous year. In fact, in 2019 the gross energy demand is 9'171.5 GWh, and net of losses it is 8'472.4 GWh [29].

The reduction of consumption of energy in 2020 affects the entire Italy, in fact, the net energy consumed in the country is 301.8 TWh in 2019 [29] and it reduces to 283.8 TWh in 2020 [30].

Limited to just the Sardinia region the net energy required in 2020 is 7'983 GWh [30], less than 2019 of about 500 GWh [103].

For the timeseries of energy demand is chosen the year 2019, instead the year 2020, because it is more comparable to the energy demand in 2018, in fact in 2020 the national net demand of energy is 303.4 TWh and in the Sardinia region to 8'424.7 GWh [20]. From the Figure 4.2 it is also possible to notice in last years the region always has a required energy below the produced one.

Hourly energy demand data in Sardinia were downloaded from ENTSOE 'Total Load Forecast - Year Ahead' [24] selecting the column of Actual Total that includes losses without stored energy and it is equal to:

$$Actual\ Total\ Load = Net\ Generation - Exports + Imports - Absorbed\ Energy \quad (4.1)$$

From the Entsoe website [24] data for the year 2019 are downloaded and converted from MW into kW to be easily used in the model and for some missing values in the file it is used a linear interpolation between previous and next values, with the **interpolate** function of the Python library 'pandas' [37]. In addition, the last element corresponding to the 1st of January 2020 is removed, to evaluate the demand in the year 2019.

Calliope requires the energy demand for each location, therefore due to this missing information, it is assumed a proportion based on annual energy consumption for each province in Sardinia, which is possible to find on Terna website [39].

Starting from values of annual energy consumed in 2019 in each province [29], it is obtained a proportion on annual total net consumption of energy in Sardinia that corresponds to 8'472.5 GWh [29]. The energy consumed in different provinces in 2019 and the relative proportion assumed to subdivide the demand can be found in Table 4.1. The timeseries of energy demand for Sardinia are generated from the original file downloaded from Entsoe multiplied hourly by the proportions mentioned.

Table 4.1: Proportion of demand energy by province using consumed energy in 2019 by Terna [29]

Province	Energy consumed (GWh)	Proportion
Cagliari	3'470.2	0.4096
Nuoro	658.1	0.0777
Oristano	564.1	0.0666
Sassari	1'951.6	0.2303
Sud Sardegna	1'828.5	0.2158

At the end, it is obtained a CSV file called *demand_power.csv* with hourly energy demand data for the Sardinia for each province of Sardinia and representative of the year 2019. This file is inserted in the model defining the energy demand as a technology of parent **demand**, under the key *techs* in the file called *techs.yaml* for each location, as in the following code:

```
techs:
  demand_electricity:
    essentials:
      name: 'Electrical demand'
      color: '#072486'
      parent: demand
      carrier: electricity
```

The hourly energy demand for each province is passed to the model in the file *locations.yaml* under the key *locations*, as a constraint of the technology, the file in CSV format is given to the technology:

```
locations:
  cagliari:
    techs:
      demand_electricity:
        constraints.resource: file=demand_power.csv:cagliari
```

In this case, the file *demand_power* is generated as a timeseries with one column for each province and the demand of energy of Cagliari is passed by selecting the corresponding column of the file, in the following way:

```
:cagliari
```

This configuration is the same for all provinces, defined as locations.

4.3 Import and export transmission lines

The region of Sardinia exports and imports a relevant amount of energy, in fact according to Terna the net energy, considering the total energy produced reduced to the imported one, in the year 2019 is 3'491.5 GWh [29].

The Sardinia is connected to other Italian regions by two main transmission lines: **Sacoi and Sapei**, and it is connected to Corsica by the **Sarco**, as indicated in the Figure 4.3. The export and import data about Sardinia are downloaded for the year 2019 from the **ENTSOE Transparency Platform** website, selecting the Cross border Physical flow [22]. These files correspond to the physical, i.e. actual average flows of measured energy transferred between the bidding zones of the market as close to reality as possible, but no later than one hour after the operational period. From this website the energy fluxes imported to Sardinia and exported from Sardinia are downloaded by selecting the following files for the year 2019:

- Link 'SARD-CSUD';
- Link 'SARD-SACOAC';
- Link 'SARD-SACODC'.

In the files downloaded there are missing values because they are actual measured values. To include them in the model the following adjustments are done to the original files:

- For **isolated missing values**, a linear interpolation between previous and next values is made with the **interpolate** function [37] as done for the energy demand;
- For a **missing day**, an average is made between the energy values in that hour on a couple of previous and next available days;

- For **missing months** (only for the 'SACODC-SARD' connection), the 2019 values of Scheduled Commercial Exchanges [23] downloaded from ENTSOE are substituted to "Cross-border physical flows" [22] for that period, considering that on a monthly basis the values are quite comparable;
- The last element in the file, corresponding to the 1st January 2020 is removed from the file, to evaluate the energy in the year 2019.

Therefore the file obtained for each link downloaded is then divided into import and export columns for the Sardinia and all import values are summed creating the file '**import.csv**'. The same is done with export values creating the file: '**export.csv**' and values are converted from MW to kW.

In the energy model Calliope permits to define the import and the export as two different technologies, as done in a model constructed for the Italian country using Calliope [36], and for the region of Sardinia, in this case, is done as follows. In the file *techs.yaml* under the key *techs* are defined:

- A technology representative of the necessity of Sardinia of energy as import from the rest of Italy and from Corsica, called '**el.import**';
- A technology to represent the export of excess of energy produced in Sardinia, given to the rest of Italy and to Corsica, called '**el.export**'.

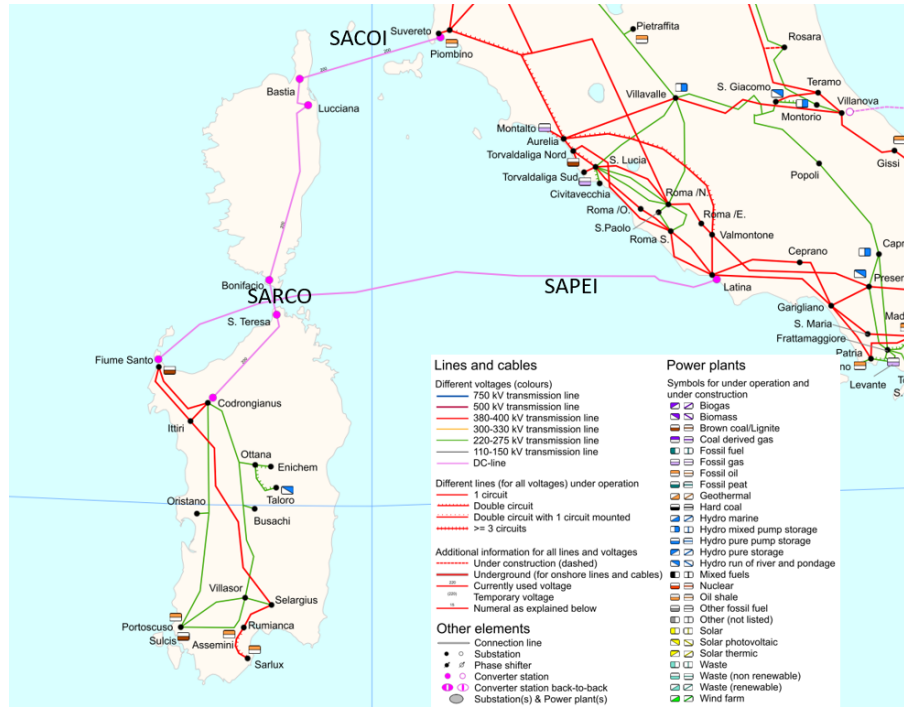


Figure 4.3: Transmission lines for export and import of energy adapted from Entsoe grid map [71]

The resource is defined in an approximated way using a constraint of 1'400 MW, which is the maximum capacity of the transmission lines Sacoï, Sapei and Sarco if summed. In this case, the technology for the import of energy has the constraint '**force_resource: True**' and **unitary efficiency** considering that with this technology actual values of energy imported are given. The constraint 'energy_prod: True' instead represents a way that the region has to obtain the energy needed. The values of exported energy are also converted into negative ones because they are as demand for the model, in fact the technology for the exported energy has the parent demand, as in the following code:

```
techs:
  el_import:
    essentials:
      name: 'Electricity import'
      color: '#ff0000' #edv
      parent: supply_plus
      carrier_out: electricity
    constraints:
      resource: 1400000 # kW sacoi+sapei+sarco
      force_resource: True
      energy_prod: True
      resource_eff: 1
      lifetime: 40
    costs:
      monetary:
        om_prod: 0.10838 #eur/kWh peak price of energy
        #representative of 2019, on https://www.mercatoelettrico.
        #org/It/Statistiche/ME
        #DatiSintesi.aspx

  el_export:
    essentials:
      name: 'Electricity export'
      color: '#E68A31'
      parent: demand
      carrier_in: electricity
    constraints:
      resource: -6e6 #infinite sink, the resource csv file is given
      #force_resource: true by default
      in locations
    costs:
      monetary:
        om_con: -0.10838 #eur/kWh peak price energy representative
        #of 2019, on https://www.mercatoelettrico.org/It/
        #Statistiche/ME/
        #DatiSintesi.aspx
```

In this model, just one carrier is created and it is called electricity, which represents the electric energy supplied or consumed in the model. In the cost class monetary there are two types of costs:

- om_prod is the cost of production expressed in price/kWh;
- om_con is the cost of consumption expressed in price/kWh.

In this case, the cost of production and consumption of energy is chosen equal to the peak price of energy found on GME website [21] but with opposite value, as done in the model of the UK country [12]. The base model is forced to take the import and export as in CSV files given, to represent more close as possible the real energy situation of Sardinia, instead more importance to these prices is given in scenarios.

In the model as a first approximation the only point considered connected to export and import energy transmission lines is Sassari, therefore in the yaml file for locations it is given as a timeseries for the resource the CSV file for the export and import energy downloaded [22] and modified as described before, in the following way:

```
locations:
  sassari:
    techs:
      el_export: # export excess electricity
        constraints:
          resource: file=export.csv
      el_import: #import energy
        constraints:
          resource: file=import.csv
```

4.4 Internal transmission lines

In the model the locations are connected with links and to decide how to approximate the model with links between locations, it is considered the real configuration of the electrical system of Sardinia, in the Figure 4.4.

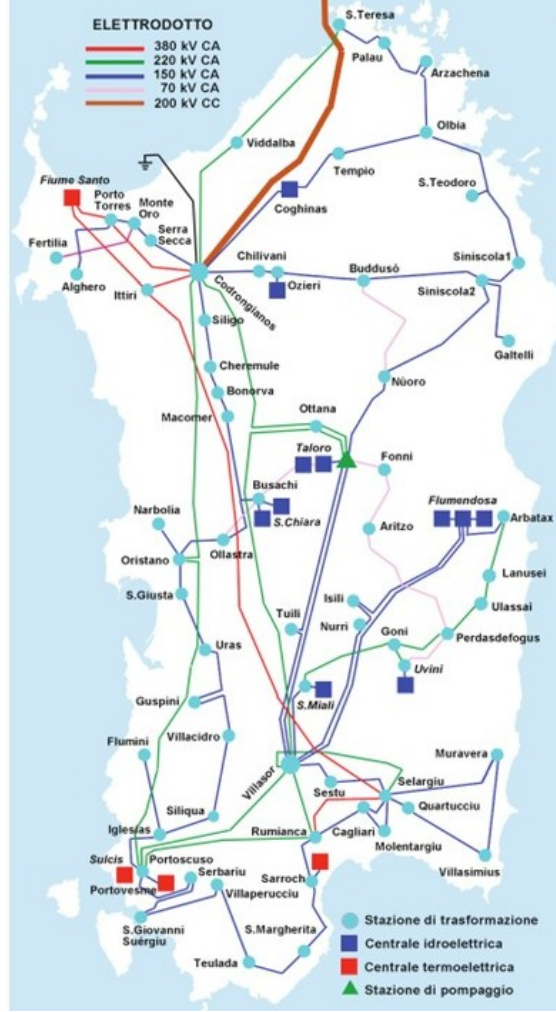


Figure 4.4: Real electrical connections in Sardinia [16]

In the region there are different types of transmission lines for the internal distribution of energy:

- Transmission lines at 380 kV CA;
- Transmission lines at 220 kV CA;
- Transmission lines at 150 kV CA;
- Transmission lines at 70 kV CA.

Starting from the electrical configuration of the region and considering also how the nodes are chosen, the links between locations are identified in first approximation as in the Figure 4.5.



Figure 4.5: Links chosen between locations adapted from source [16]

The links between locations are an **approximation of the actual transmission lines** present and in this case, a single connection is constructed as first approximation. The maximum capacity of a link is evaluated by considering which connections are present in the area where the links cross. This thesis is not focused on the reproduction of an electricity network equal to the real regional one. Nevertheless, the transmission lines are modeled to manage the energy fluxes between the most major nodes of the dispatchment of energy in the region, which are not uniformly present in the region.

As shown in Figure 4.4, the power line at 150 kV voltage is the one that mostly connects the territory and the transmission lines with higher voltage are used mainly to connect power plants. In fact, the transmission line at 380 kV connects basically the area of Sassari to the one of Cagliari. Looking at the Figure 4.5 it is possible to notice that there is also a power line at 70 kV, but in this case it is not considered due to its low voltage. In the first version of the model just seven transmission lines are created to connect locations and the maximum capacity of each connection is approximated considering which types of transmission lines are present in that area. In order to understand the capacity of transmission lines that better approximate the real electrical connections in

the region, different modifications are done to the network and to the capacity of these links as explained in the chapter 5.

Using the rated power per trio of conductors given by Terna [38] and considering a power factor of 0.9, the following capacities of transmission lines are taken as starting points:

- 900 MW for the power line at 380 kV;
- 180 MW for the power line at 220 kV;
- 117 MW for the power line at 150 kV.

The transmission lines are defined using a technology called *power_lines* using the parent transmission. In this case, it is defined also and energy efficiency of 0.98 and a cost per unit of distance:

```
techs:
  power_lines: #almost as free transmissison
    essentials:
      name: 'Electrical power distribution'
      color: '#6783E3'
      parent: transmission
      carrier: electricity
    constraints:
      energy_eff: 0.98 #energy efficiency
      lifetime: 25
    costs:
      monetary:
        interest_rate: 0.10
        energy_cap_per_distance: 0.01 #unit kWgross^-1/distance
```

4.5 Installed capacity of supply technologies

In the first phase, the model should be validated, therefore the installed capacity of technologies is specified because, as already explained, in this phase the planning mode of run is used.

The year considered for capacities installed of different technologies is the **2020** for which there is the availability of the majority of data on Terna website. In the Table 4.2 there are the installed capacities and technologies considered in this phase of validation of the model, for different provinces.

Table 4.2: Capacities installed in validation model

Technology	Installed Capacity (MW)					
	Sardinia	Cagliari	Nuoro	Oristano	Sassari	Sud Sardegna
PV farm	555.0	141.9	79.5	81.2	137.9	114.4
PV rooftop	418.7	107.1	60.0	61.3	104.1	86.3
PV tot	973.7	249.0	139.5	142.5	242.0	200.7
Wind onshore	1'087.5	46.5	134.3	102.3	556.9	247.5
Hydroelectric	466.4	47.7	312.1	30.3	37.6	38.7
Bioliquld	37.0	0.0	37.0	0.0	0.0	0.0
Solid biomass	49.8	35.8	1.0	0.0	0.0	13.0
Biogas	21.0	6.4	2.0	2.5	5.0	5.0
Fossil oil	369.0	229.0	140.0	0.0	0.0	0.0
Coal	1'230.0	0.0	0.0	0.0	640.0	590.0
Syngas	575.0	575.0	0.0	0.0	0.0	0.0
Total (MW)	4'809.4	1'189.4	765.9	277.6	1'481.5	1'094.9

These capacities are taken from sources when available and in absence of clear data some hypotheses are done. In the Table 4.3 there is a distinction between data taken from references and data derived from assumptions.

Table 4.3: Subdivision in data taken from sources and data from assumptions

Technology	Installed power capacity (MW)	
	From reference	Assumed
PV tot	973.7	
PV farm		555.0
PV rooftop		418.7
Wind (onshore)	1'087.5	
Hydroelectric	466.4	
Bioliquld		37.0
Solid biomass		49.8
Biogas		21.0
Fuel oil	369.0	
Coal	1'243.0	
Syngas	590.0	

For the technology of photovoltaic the installed capacity in Sardinia is given in the document of Terna of 2020 [30], the same is valid for the wind technology and hydroelectric technology. Other hypotheses and sources about the capacities used in the model are described in detail technology by technology in the following sections.

4.5.1 Photovoltaic

At the end of 2020 in Sardinia it is installed the 4.5 % of total photovoltaic capacity of the Italian one, as can be seen from the Figure 4.6.

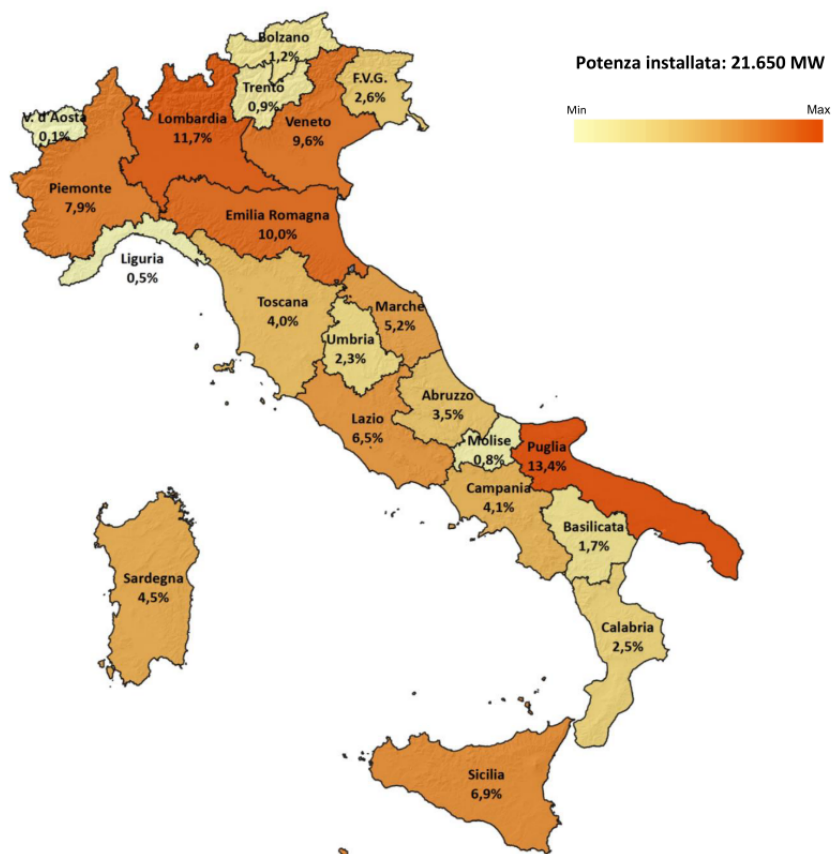


Figure 4.6: Distribution of Italian photovoltaic installed capacity at the end of 2020, taken from GSE [66]

Solar energy resource

Photovoltaic energy gives a time-varying output power and it is a resource that is difficult to predict in an accurate way because it also varies with weather conditions [13].

As mentioned in the Calliope guide [102], there is the tool Renewables.ninja that permits to simulate the power output from photovoltaic power plants in different cities [89]. This tool is created by Stefan Pfenninger and Iain Staffell [14] [15] and it is based on **NASA MERRA reanalysis** [4] and CM-SAF's SARAH dataset (Copyright 2015 EUMETSAT) [10].

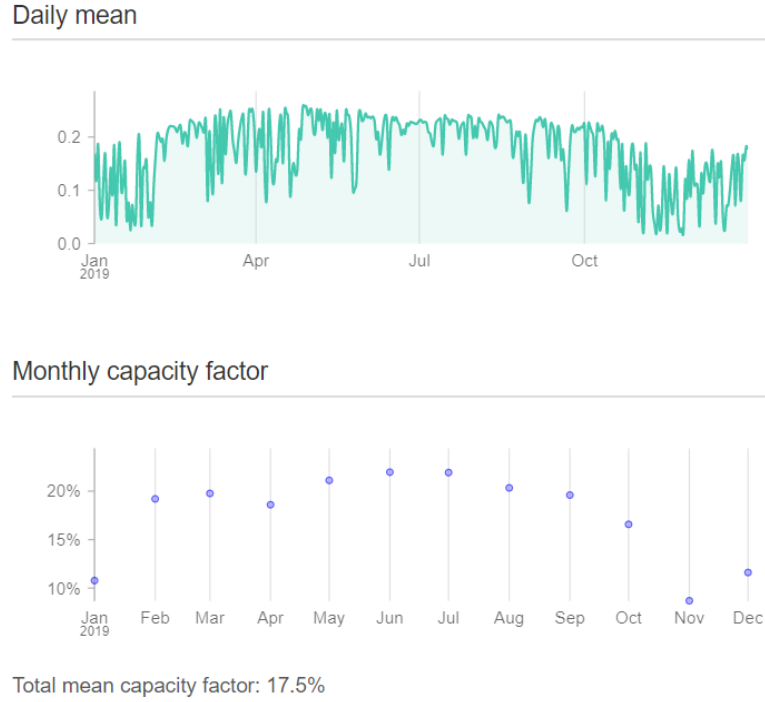


Figure 4.7: Results for photovoltaic energy, obtained from Renewables.ninja for Sardinia region and year 2019 [14]

For solar energy, the tool starting from irradiance data gives the power output using the **GSEE model** (Global Solar Energy Estimator) created by **Stefan Pfenninger** [13].

In this tool for different countries, the output of power from photovoltaic panels is included considering the panel efficiency and inverter losses of 10% [13].

In order to be used in the model, as done in the UK model constructed using Calliope by Stefan Pfenninger [12], hourly values are downloaded, selecting the irradiance **G direct in kW/m^2 , for fixed panels, with 35° of tilt and 180° of azimuth**. These choices are done considering that it is evaluated a single input file for the solar resource, for the PV farm technology and PV rooftop technology. In this way, a possible value of tilt for both technologies is selected.

In the energy model of Sardinia, for installed capacities of technologies, only five locations

are considered, which coordinates correspond to the provincial capital of Sardinia. To be included in the model, five points in the Sardinia map are selected and for each point is downloaded the file in **CSV format** from Renewables.ninja [89] with the hourly output power data for the year 2019. Coordinates of these points are selected choosing just one point for each province area and each point has mostly average solar power capacities of that area. The points selected are listed in the Table 4.4.

Table 4.4: Coordinates of points (in decimal format) considered to download solar data

Province	Coordinates
Cagliari	39.1339; 8.9358
Nuoro	40.2965; 9.2941
Oristano	39.9802; 8.6428
Sassari	40.6232; 9.2972
Sud Sardegna	38.9813; 8.7567

Pv rooftop and PV farm installed capacity

In this model, there is a subdivision between the photovoltaic power plants classified as PV farms and PV rooftop systems. As discussed before the total photovoltaic installed power is taken for the Sardinia region from Terna [30].

According to this GSE report [66], at the end of 2020 in Sardinia the 43% of photovoltaic installations are of the non-ground type, e.g. on buildings, sheds or roofs and the other ones are ground installations, such as solar farms. Considering these data, in the model of Sardinia it is assumed that the 43% of photovoltaic systems are PV systems of non-ground type, in this case for simplicity called PV rooftop and the remaining part is ground type, in this case called PV farm. Therefore it is assumed that the **43% of the total photovoltaic installed capacity for each province is of PV rooftop type** and the remaining part is ground type, in this case called PV farm.

In the model the PV technology is specified in the file *techs.yaml* and two technologies are created:

- **pv_farm** corresponds to photovoltaic power plants;
- **pv_rooftop** corresponds to non-ground type systems.

In the following part, there is the code of the *techs.yaml* file for the definition of the photovoltaic technologies:

```
techs:
  pv_farm:
    essentials:
      name: 'Photovoltaic power farm-scale'
      color: '#ffe4b5'
      parent: supply_power_plus
    constraints:
      resource_unit: energy_per_cap #change resource unit in kWh/kW
      lifetime: 25
    costs:
      monetary:
```

```

        interest_rate: 0.10
        energy_cap: 677 # eur/kW reference Model Italy
        om_prod: 0 # eur/kWh considered null cost of production,
                    # reference Model Italy
        om_con: 0 # eur/kWh free resource, reference Model Italy
        om_annual: 18.35 # eur/kW/y reference Renewable Power
                        # Generation Costs in
                        # 2019 (IRENA)

pv_rooftop:
  essentials:
    name: 'Photovoltaic power distributed'
    color: '#FFD700'
    parent: supply_power_plus
  constraints:
    resource_unit: energy_per_cap #change resource unit in kWh/kW
    lifetime: 25
  costs:
    monetary:
      interest_rate: 0.10
      energy_cap: 871 #eur/kW reference Model Italy
      om_prod: 0 #eur/kWh considered null cost of production,
                # reference Model Italy
      om_con: 0 #eur/kWh free resource, reference Model Italy
      om_annual: 27 #eur/kW/y reference Model Italy

```

The technologies `pv_farm` and `pv_rooftop` are defined under the parent 'supply_power_plus' that is created by the user in the `techs.yaml` file as a new technology group in the following way:

```

tech_groups:
  supply_power_plus:
    essentials:
      parent: supply_plus
      carrier: electricity

```

In this way, the original parent for the technology is the parent `supply_plus`, discussed above, but it is specified already the carrier as `electricity`. For the resource it is given a unit with the command:

```

resource_unit: energy_per_cap

```

This is done as in the Italian model [36], in this way it is modified the default value 'energy' (kWh) for the unit of the resource, and it is changed into *kWh/kW*. This choice is done considering that the file of solar energy is downloaded from Renewable.ninja [89] **as a capacity factor** setting 1 kW of installed capacity.

This file is given in input as a constraint for the resource, in this case it is inserted in the *location.yaml* file.

The configuration for the technology is done for all locations but here is given for example the location 'cagliari':

```

locations:
  cagliari:
    techs:

```

```

pv_farm:
  constraints:
    resource: file=pv_resource_sardegna_electricity.csv
    energy_cap_equals: 141900 #kW
pv_rooftop:
  constraints:
    resource: file=pv_resource_sardegna_electricity.csv
    energy_cap_equals: 107100 #kW

```

In this way considering how the file of solar resource is downloaded [89], how the technology for pv is set and that the time step in Calliope is 1 hour, the resource is evaluated in the following way:

$$energy_{produced\ in\ 1h}\ (kWh) = CF_{renewable.ninja} \left(\frac{kWh_{produced}}{kW_{installed}} \right) * energy_{cap}\ (kW_{installed}) \quad (4.2)$$

If it is not specified the column of the file that must be taken from the file, Calliope takes the column with the name of the location in fact the file is created with the timeseries of solar resource, with all locations data in columns corresponding to their names. In this case, the installed capacity of the technology is set with the command *energy_cap_equals* because at the beginning it is required to validate the model, therefore the exact values of installed capacities are set.

It is also possible to use the command *energy_cap_max* but in the run mode *operate* is converted to *energy_cap_equals*. Solar energy is considered a free resource, therefore it is considered the cost of production and consumption null. Other costs for the technology are detailed in Appendix A.

4.5.2 Wind

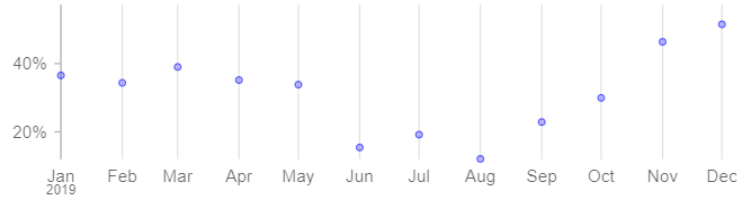
Like solar energy, wind power production is also time-varying with weather conditions and also has correlations with human activity. In the tool Renewable.ninja [89] it is possible to download the timeseries of the wind power output, which is converted from wind speed, and then insert as a dataset in **Renewable.ninja** [89] using the **VWF model** (Virtual Wind Farm) by Iain Staffell [15] [89].

Also in this case five points in the Sardinia map are selected to download the file in **CSV format** from Renewable.ninja with the hourly output power data for the year **2019**. It is selected one point for each province area but in this case coordinates of those points are the same used for solar energy in Table 4.4, because they are selected considering both solar and wind average characteristics.

Daily mean



Monthly capacity factor



Total mean capacity factor: 31.2%

Figure 4.8: Results for wind energy, obtained from Renewables.ninja for Sardinia region and year 2019 [14]

To download the file in the format CSV it is chosen a turbine **Vestas V90 2000**, selecting **1kW power with hub height 80m**, as done in the model UK by Stefan Pfenninger [12].

Considering what is reported on Terna website [104] in the model of Sardinia just onshore wind turbines are included, and not offshore ones, in 2020 for the installed capacity. As done for the technology *pv-farm* and *pv-rooftop* in the file *techs.yaml* it is defined the technology and set the unit of the resource, also in this case, to kWh/kW because even in this case the file from Renewables.ninja [89] is downloaded as a capacity factor.

```
techs:
  wind:
    essentials:
      name: 'On-shore wind power'
      color: '#87cefa'
      parent: supply_power_plus
    constraints:
      resource_unit: energy_per_cap #change resource unit into kWh/
                                   kW
      lifetime: 20
    costs:
      monetary:
        interest_rate: 0.10
        energy_cap: 1600 # eur/kW reference IRENA Power Generation
                        Costs 2020
```

```

om_prod: 0 # eur/kWh considered null cost of production,
           reference Model Italy
om_con: 0 # eur/kWh free resource, reference Model Italy
om_annual: 40 # eur/kW/y assumed considering Renewable
              Power Generation
              Costs in 2019 (IRENA)

```

Even the technology for wind energy is defined with the tech group created and called *supply_power_plus*. Instead in the file *location.yaml* it is given the file downloaded from Renewables.ninja [89] and the value of installed capacity of that technology.

```

locations:
  cagliari:
    techs:
      wind:
        constraints:
          resource: file=wind_resource_sardegna_electricity.csv
          energy_cap_equals: 46500 #kW

```

Considerations done for the configuration of the photovoltaic technologies are the same for the wind technologies.

4.5.3 Hydroelectric

Even in this case, it is considered the installed capacity in 2020 reported on Terna website [104]. For simplicity it is considered a generic type of hydroelectric power plant and the definition of the technology in the *techs.yaml* file is done as follows:

```

techs:
  hydro:
    essentials:
      name: 'Hydroelectric power'
      color: '#64D7CE'
      parent: supply_plus
      carrier_out: electricity
    constraints:
      resource_unit: energy_per_cap #change resource unit in kWh/kW
      energy_eff: 0.9 #reference https://www.sciencedirect.com/
                      topics/engineering/
                      hydroelectric-power
      lifetime: 70 #considered different types of plants
    costs:
      monetary:
        interest_rate: 0.10
        energy_cap: 3227 #eur/kW supposed considering Model Italy
                        and Model UK
        om_annual: 50 #eur/kW/y assumed considering Renewable
                     Power Generation
                     Costs in 2019 (IRENA)
        om_prod: 0.02652 #eur/kWh from sensitivity analysis done
        om_con: 0 #eur/kWh free resource

```

The capacity of hydroelectric power plants is modified adding to the actual capacity of Cagliari also the hydroelectric power plant of Flumendosa with a capacity of 45.6 MW [8]

that is removed from the hydroelectric capacity of Nuoro. This choice is done considering that in the Figure 4.4 the Flumendosa hydroelectric plant is connected to the location Cagliari and has not a real connection to Nuoro, therefore it is considered more realistic to attribute its capacity to the location of Cagliari in this model to better study the energy flows. For the hydroelectric resource is done the **hypothesis that it is not possible to use all the water present in reservoirs**, as done in the model of Italy, even if it corresponds to the year 2015. Therefore it is provided a file in a **CSV** format as a constraint for the resource, **taken from the model of Italy** [36], that corresponds to the flood factor of reservoirs, as in Figure 4.9. This factor at a given instant is the

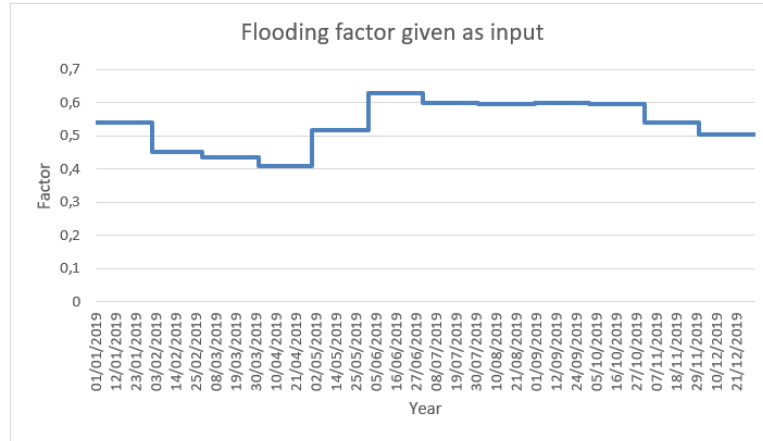


Figure 4.9: File CSV for flooding factor given as input, taken from Italian model [36]

percentage ratio between the reserve in electrical energy of the system and the capacity in electrical energy of the system itself [105]. In this case, the CSV file is given in the *location.yaml* file, as follows:

```
locations:
  cagliari:
    techs:
      hydro:
        constraints:
          resource: file=hydro_creato_dalombardi.csv
          energy_cap_equals: 47700 #kW
          #Flumendosa hydroelectric power plant in Cagliari
```

Using the CSV file for the resource of the hydroelectric energy the energy produced by the hydroelectric power plants installed is multiplied each hour by the corresponding value in the CSV file in the following way:

$$\text{Actual energy produced in 1h (kWh)} = \text{Flood factor} * \text{Energy produced (kWh)} \quad (4.3)$$

4.5.4 Thermoelectric

In Sardinia different types of thermoelectric power plants are present and they use different sources of energy, but accurate values of installed capacities are not always available for the year 2020. Consequently, to have a detailed classification of sources for different thermoelectric power plants some hypotheses are done, also because the region Sardinia changes the subdivision of provinces in 2016.

Thermoelectric generation is supposed done by **bioenergy** sources that, in this case, are bioliquids and biogas and from other sources more traditional: solid biomass (including urban wastes), coal, fuel oil and syngas.

The installed capacities considered are derived from an assessment made taking into account the list of plants in Sardinia in year 2020 according to ENTSOE website [33], Atlaimpianti website (access done in July 2022) [67] and the document called "Secondo rapporto di monitoraggio del PEARS" [27] in particular the Table 7-7. In addition, it is also consulted the website of 'SardegnaAmbiente' [99] and looked for the various plants to obtain the installed capacity of thermoelectric power plants that use bioenergy sources and more traditional ones. In particular in order to find the proper installed capacity in Sardinia for the solid biomass it is also consulted an article about Energy Production from Solid Biomass in Southern Italy [44].

For the capacity of biogas power plants it is considered the PEARS document [7], its second update [27] and different plants on Fera website [72]. For the biogas, it is also considered that the potentiality is estimated at 1'600 GWh for each year in Sardinia but it is just used the 10% of this amount [5]. Due to the absence of clear data about biogas, considering all references cited it is done an estimation of capacity installed as in Table 4.2. In the category of bioenergies two different technologies are created:

- *bioliquid*: technology representing power plants that use bioliquid to produce electric energy;
- *biogas*: technology that represents all power plants that use biogas to produce electric energy.

In the following part there is the code of how bioenergies technologies are defined:

```
techs:
  bioliquid:
    essentials:
      name: 'Bioliquid'
      color: '#98FB98'
      parent: supply
      carrier_out: electricity
    constraints:
      resource: inf
      energy_eff: 0.36 #reference Model Italy
      lifetime: 20
    costs:
      monetary:
        interest_rate: 0.10
        energy_cap: 2901 #eur/kW supposed same as biogas
        om_prod: 0.023 #eur/kWh reference Model Italy
```

```

        om_con: 0.22 #eur/kWh reference Model Italy
        om_annual: 30 #eur/kW/y reference Model Italy
    biogas:
        essentials:
            name: 'Biogas power plant'
            color: '#90EE90'
            parent: supply
            carrier_out: electricity
        constraints:
            resource: inf
            energy_eff: 0.36 #supposed as bioliquid
            lifetime: 20
        costs:
            monetary:
                interest_rate: 0.10
                energy_cap: 2901 #eur/kW reference Model Italy
                om_prod: 0.0184 #eur/kWh reference Model Italy
                om_annual: 120 #eur/kW/y reference Model Italy
                om_con: 0.04 #eur/kWh reference Model Italy

```

The two technologies are defined with the parent supply discussed above and the configuration of these technologies is similar, in fact there are any limits on the resource with as output carrier the electricity. It is also defined the efficiency of the technologies. For other thermoelectric power plants other four technologies are defined:

- *solid_biomass*: technology for power plants that producing electric energy using solid biomass, including urban waste;
- *fossil_oil*: technology representing power plant that use fossil oil source to produce electric energy;
- *coal*: technology created to represent power plant with coal as source;
- *syngas*: technology created for the power plant with IGCC (Integrated Gasification Combined Cycle) that uses Sarroch refinery waste to make syngas.

In the file for technologies, all different technologies are specified in the following way:

```

techs:
    solid_biomass:
        essentials:
            name: 'Solid biomass power plant'
            color: '#ADFF2F'
            parent: supply
            carrier_out: electricity
        constraints:
            resource: inf
            energy_eff: 0.15 #reference Model Italy
            lifetime: 25 #reference: https://www.irena.org/publications/
                                2015/Jan/Biomass-for-Heat
                                -and-Power
        costs:
            monetary:
                interest_rate: 0.10

```

```

        energy_cap: 2901 #eur/kW supposed same as biogas
        om_prod: 0.0118 #eur/kWh reference Model Italy
        om_annual: 59 #eur/kW/y reference Model Italy
        om_con: 0.15 #eur/kWh reference Model Italy
fossil_oil:
    essentials:
        name: 'Fossil oil'
        color: '#ffa07a'
        parent: supply
        carrier_out: electricity
    constraints:
        resource: inf
        energy_eff: 0.35 #reference Model Italy
        energy_ramping: 0.6 #reference Model Italy
        lifetime: 35 #reference Model Italy
    costs:
        monetary:
            interest_rate: 0.10
            energy_cap: 1876 #eur/kW assumed as coal
            om_prod: 0.023 #eur/kWh reference Model Italy
            om_con: 0.01 #eur/kWh reference Model Italy
            om_annual: 32 #eur/kW/y reference Model Italy
coal:
    essentials:
        name: 'Coal plant traditional'
        color: '#F4A460'
        parent: supply
        carrier_out: electricity
    constraints:
        resource: inf
        energy_eff: 0.4 #reference https://iea.blob.core.windows.net/assets/ae17da3d-e8a5-4163-a3ec-2e6fb0b5677d/Projected-Costs-of-Generating-Electricity-2020.pdf
        energy_ramping: 0.6 #reference Model UK
        lifetime: 35 #reference Model Italy
    costs:
        monetary:
            interest_rate: 0.10
            energy_cap: 1876 #eur/kW reference Model UK
            om_prod: 0.0013 #eur/kWh reference Model Italy
            om_con: 0.01 #eur/kWh supposed considering https://atb-archive.nrel.gov/electricity/2019/summary.html#nzvex89z
            om_annual: 44.20 #eur/kW/y assumed considering https://www.power-technology.com/analysis/featurepower-plant-om-how-does-the-industry-stack-up-on-cost-4417756/

```

```

syngas:
  essentials:
    name: 'Syngas'
    color: '#FA8072'
    parent: supply
    carrier_out: electricity
  constraints:
    resource: inf
    energy_eff: 0.48 #reference https://power.mhi.com/products/
                                igcc#:~:text=IGCC%20can%
                                20increase%20net%
                                20efficiency,pulverized%
                                20coal%2Dfired%20power%
                                20plants.

    energy_ramping: 0.8 #supposed
    lifetime: 25 #reference https://www.sciencedirect.com/topics/
                                engineering/integrated-
                                gasification-combined-
                                cycle-plant

  costs:
    monetary:
      interest_rate: 0.10
      energy_cap: 2244.71 #eur/kW reference: Techno-Economic
                                Assessment of IGCC
                                Power Plants Using
                                Gas Switching
                                Technology to
                                Minimize the Energy
                                Penalty of CO2
                                Capture

      om_prod: 0.0184 #eur/kWh from sensitivity analysis
      om_con: 0.01699 #eur/kWh reference:
#http://www.costanteinvernizzi.it/Site_1/
                                Downloadable_Documents_7_files
                                /carbone_3vellini.pdf

      om_annual: 80 #eur/kW/y assumed considering https://www.
                                power-technology.com/
                                analysis/featurepower
                                -plant-om-how-does-
                                the-industry-stack-up
                                -on-cost-4417756/

```

Even these technologies are defined with the parent supply and with electricity as the carrier in output, but in this case, it is also imposed. For these technologies are set the energy efficiency and the **energy ramping** giving the ramping rate, in this way the energy produced is increased not instantaneously but in each hour just to a fraction.

Chapter 5

Validation of model

After the model is built it should be validated in order to represent the actual energetic situation in the region of Sardinia. This is important to understand which are the weak points and in this way the model can find possible improvements, useful for the energy policies of the region.

In order to validate the model, it is considered that the phase of validation in the model constructed for the UK country [12] using Calliope, is done in the operational mode of run, therefore in the dispatching mode. This validation is done by searching a behavior of model similar to the real one and doing an economic evaluation of technologies.

In the absence of further detailed information on the validation phase of energy systems of this type, a methodology for tests and variations, to be done on the model, is created. In this case, the objective function is still the default one of minimize the cost of the system but in this dispatch mode, with the run type "operational" described in chapter 2. In this way, the target is to try to use the model built for Sardinia and try to obtain the estimated energy produced. In addition, the aim is to simulate energy fluxes transmitted between locations that are as close to real flows as possible.

5.1 Estimated energy

To understand if the model is enough representative of the real energy situation of Sardinia, each configuration of the model is compared to actual data of energy produced in Sardinia when it is possible. In the Terna document [29] there is an indication of the energy mix of energy production in Sardinia reported in Figure 5.1.

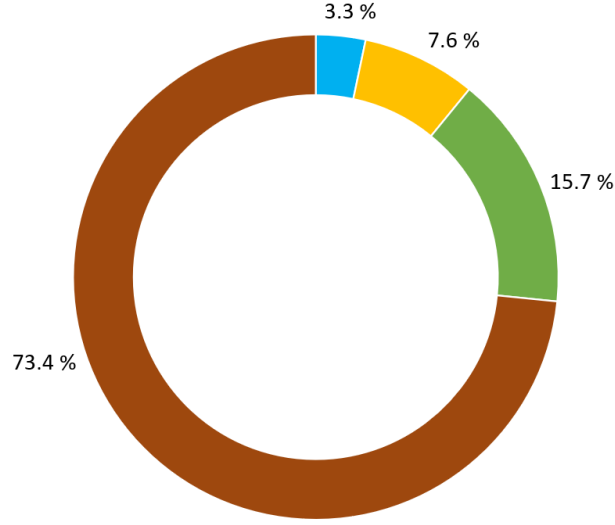


Figure 5.1: Energy mix of net energy produced in Sardinia in 2019 from Terna [28]

For each technology used in the model, an expected energy that should be obtained from the model is found, obtaining the energy mix in the Table 5.1. In that Table, there is a subdivision of energy values taken from sources, in particular values from Terna of actual energy produced in Sardinia in 2019 from photovoltaic, wind, hydroelectric resources and using the thermoelectric with bioenergy and traditional resources. To subdivide the energy produced in more detail, until values in Table 5.1, some assumptions are done as described below.

The energy produced by the PV farm technology ($E_{prod_pv_farm}$) is evaluated using the following formula:

$$E_{prod_pv_farm} = (Pv_farm\ capacity\ installed / Total\ pv\ capacity\ installed) * Energy\ estimated\ total\ pv \quad (5.1)$$

Similarly, the energy produced by the PV rooftop ($E_{prod_pv_rooftop}$) technology is evaluated as follows:

$$E_{prod_pv_rooftop} = (Pv\ rooftop\ capacity\ installed / Total\ pv\ capacity\ installed) * Energy\ estimated\ total\ pv \quad (5.2)$$

In the Terna document [29] the thermoelectric energy produced is divided into energy produced by bioenergy and energy produced by traditional resources. In this thesis, it is considered included in energy produced by bioenergy from Terna only the energy by bioliquid and biogas. This assumption is done considering that the plant "Biopower" in the province of Nuoro has a gross energy production of 322 GWh [7] and this value is considered as energy produced by bioliquid. The remaining energy produced by bioenergy is attributed to biogas production considering that is coherent if all biogas power plants have a production almost to 8 GWh in the year as the plant of Decimoputzu [73], therefore it is considered a maximum production of 184 GWh from biogas.

The other part of thermoelectric production is considered produced by solid biomass, fossil oil, coal and syngas. The energy produced by syngas is 4 TWh [101] instead Terna [29] indicates an energy production by solid resources of 4.4 TWh, by biomass and biodegradable waste of 541.9 GWh. In the report of Terna is not indicated precisely which sources are utilized in which power plants, therefore also the other references cited before are used to do an assumption of possible estimated energy. The biodegradable waste could be used to produce biogas, therefore it is estimated a solid biomass energy production removing from 541.9 GWh the energy estimated by biogas, obtaining 357.9 GWh as energy estimated by solid biomass. The power plant of Fiume Santo in 2012 produced almost 4 TWh using coal and fossil oil. On the basis of data found it is estimated production by coal of around 4 TWh, and the remaining amount of energy produced by traditional resources in thermoelectric power plants is attributed to fossil oil technology with estimated 517 GWh.

All estimated values of energy are reported in the Table 5.1.

Table 5.1: Subdivision of energy values taken from Terna [29], SARLUX [101] and values from assumptions

Technology	Estimated expected energy (GWh)	From source/ Assumption
Total pv	975.5	TERNA 2019
Pv farm	556.0	Assumed
Pv rooftop	419.5	Assumed
Wind (onshore)	2014.2	TERNA 2019
Hydroelectric	418.2	TERNA 2019
Bioliqum	322.0	Assumed
Biogas	184.0	Assumed
Total bioenergy thermoelectric	510.8	TERNA 2019
Solid biomass	357.9	Assumed
Fossil oil	517.1	Assumed
Coal	4027.1	Assumed
Syngas	4000.0	SARLUX
Traditional thermoelectric	8891.1	TERNA 2019
Total thermoelectric	9401.9	TERNA 2019

These estimated energies are taken as reference for comparison to the different configurations of the model, considering the capacities installed as in Table 4.2, taking into account possible uncertainties due to assumptions done.

5.2 Reference costs

Initially, a research for costs is done, by searching when possible from other models made with Calliope or literature sources, until the values in the Table 5.2 using references described in detailed in the Appendix A.

The values in the Table 5.2 are taken as reference for different configurations of the model.

Table 5.2: Costs found on references and then used in Calliope as reference costs.
References are specified in Appendix A

Technology	Installation cost (euro/kW)	O&M annual (euro/kW/y)	Cost of production (om_prod) (euro/kWh)	Cost of consumption (om_con) (euro/kWh)	Interest rate	om_con+om_prod (euro/kWh)
Pv farm	677	18.4	0.0000	0.0000	0.1	0.0000
Pv rooftop	871	27.0	0.0000	0.0000	0.1	0.0000
Wind (onshore)	1'600	40.0	0.0000	0.0000	0.1	0.0000
Hydroelctic	3'227	50.0	0.0265	0.0000	0.1	0.0265
Bioliquid	2'901	30.0	0.0230	0.2200	0.1	0.2430
Biogas	2'901	120.0	0.0184	0.0400	0.1	0.0584
Solid biomass	2'901	59.0	0.0118	0.1500	0.1	0.1618
Fossil oil	1'876	32.0	0.0230	0.0100	0.1	0.0330
Coal	1'876	44.2	0.0013	0.0100	0.1	0.0113
Syngas	2'245	80.0	0.0184	0.0170	0.1	0.0354

5.3 Parameters to compare different models

In order to compare models created between them it is calculated the RMS (Root Mean Square) using the following formula for a single observation:

$$RMS = \sqrt{\sum (E_{model} - E_{estim})^2} \quad (5.3)$$

The model is studied also in the amount of energy in links between locations extrapolating the capacity used hour by hour in the various links, from the folders that Calliope can generate in CSV format with the following code:

```
model.to_csv('path_file')
```

The lines are analyzed by calculating the maximum utilization of each line during the year and obtaining the relative percentage with the Equation 5.4.

$$\%Max\ use = Max\ capacity\ used\ in\ link / Capacity\ installed\ for\ the\ link \quad (5.4)$$

Each transmission line in Calliope is used between two locations in two directions. The maximum capacity used is evaluated in both ways in each line using the following code, for example for the link between Sassari and Nuoro:

```
#creation of dataframe for maximum capacity used
df_link_max=pd.DataFrame(columns=['max1(MW)', 'max2(MW)'], index=['SS-
NU', 'SS-N1', 'SU-N1', 'SS-OR', 'N1-
OR', 'NU-N1', 'N1-CA', 'OR-SU', 'SU-
CA'])

#maximum capacity used from Sassari to Nuoro
df_link_max['max1(MW)'].loc['SS-NU']=df_linkSS[(df_linkSS["locs"] == '
nuoro')].max().iloc[-1]

#maximum capacity used from Nuoro to Sassari
df_link_max['max2(MW)'].loc['SS-NU']=df_linkNU[(df_linkNU["locs"] == '
sassari')].max().iloc[-1]
```

It is also evaluated the percentage medium use of transmission lines with the Equation 5.5.

$$\%Medium\ use = Medium\ capacity\ used\ in\ link / Capacity\ installed\ for\ the\ link \quad (5.5)$$

Similarly to the maximum capacity used in links, it is evaluated the medium capacity used of each transmission line using the following code, for example for the link between Sassari and Nuoro:

```
#creation of dataframe for medium capacity used
df_link_med=pd.DataFrame(columns=['med1(MW)', 'med2(MW)'], index=['SS-
NU', 'SS-N1', 'SU-N1', 'SS-OR', 'N1-
OR', 'NU-N1', 'N1-CA', 'OR-SU', 'SU-
CA'])

#medium capacity used from Sassari to Nuoro
df_link_med['med1(MW)'].loc['SS-NU']=df_linkSS[(df_linkSS["locs"] == '
nuoro')].mean().iloc[-1]

#medium capacity used from Nuoro to Sassari
df_link_med['med2(MW)'].loc['SS-NU']=df_linkNU[(df_linkNU["locs"] == '
sassari')].mean().iloc[-1]
```

The various models constructed are first evaluated by comparing the annual energies produced by the model with those estimated in the Table 5.1.

Energy flows are also evaluated using the Equation 5.4 and Equation 5.5, mainly to find out which capacity of the transmission lines is most consistent, analysing how the model reacts.

Comparing models it is also important to evaluate the unmet demand which is the difference between the supply and the demand as explained in the chapter 2. All these models are run with the option:

```
ensure_feasibility: True
```

In this way, the model finds the solution but it is necessary to check the CSV file generated for the unmet demand by Calliope and understand the cause and the location of this unmet demand, if present.

5.4 Tests on configuration A

The model initially proposed is the one described in the previously chapter 4 in an easier configuration, that is called Configuration A with capacities installed for different technologies in Table 4.2. The capacities of transmission lines used are indicated in Figure 5.2 and are evaluated considering the document of Terna as the capacity for the trio of conductors [38] as indicated in previous chapter 4. In this case, it is considered that one link in the model includes more than one real cable and the maximum capacity of real cable is estimated as follows:

- line at 380 kV with capacity 900 MW;
- line at 220 kV with capacity 180 MW;

- line at 150 kV with capacity 117 MW;

The capacities of lines in the model are evaluated as a sum of the maximum of each real link that they include, obtaining values in Figure 5.2.

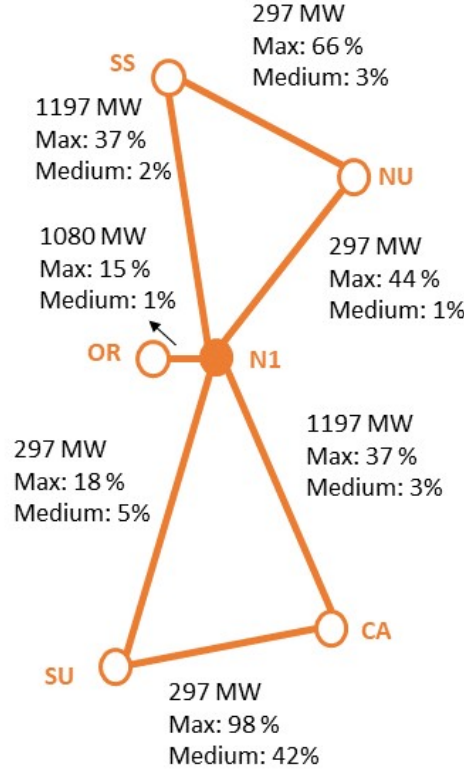


Figure 5.2: Capacities, maximum use and medium use of transmission lines in model VA1

The energy mix produced by Calliope for the configuration in Figure 5.2 is indicated in Table 5.3.

This energy mix is due to the costs used to run the model and that some costs are higher than others, therefore Calliope decides to not use these technologies. The transmission lines in this configuration are not uniformly used in the region, as can be seen in Figure 5.2 and only the link between Cagliari and Sud Sardegna is used at maximum the 98% of its capacity. The Sardinia does not have a very intense electricity grid as can be seen in Figure 4.4 and in this model the transmission lines approximate the real ones including more than one cable. Instead, the real transmission lines are diversified and the maximum flow in each line is lower than the sum of the capacities of more than one line.

Table 5.3: Energy produced in tests on configuration A

Energy produced (GWh)			
Technology	Name configuration		
	VA1	VA2	VA3
Pv tot	1'499	1'499	1'499
Pv farm	855	855	855
Pv rooftop	645	645	645
Wind (onshore)	3'289	3'289	3'289
Hydroelectric	558	559	559
Bioenergy	0	0	0
Traditional	6'818	6'820	6'820
Total thermoelectric	6'818	6'820	6'820
Unmet demand	0	0	0

Therefore it is constructed another model (VA2) decreasing the maximum capacity of each line using a medium value of capacity in the following way:

- If lines at 380 kV, 220 kV and 150 kV are present in the same area the maximum capacity of the line at 380 kV is evaluated as a medium between 900 MW, 180 MW and 117 MW;
- If lines at 220 kV and 150 kV are present in the same area the maximum capacity of the line at 220 kV is evaluated as an average between 180 MW and 117 MW;
- If lines at 380 kV and 220 kV are present in the same area the maximum capacity of the line at 380 kV is evaluated as an average between 900 MW and 180 MW;
- If two lines at 380 kV and one line at 150 kV are present in the same area the maximum capacity of the lines at 380 kV is evaluated as an average between 900 MW, 900 MW and 117 MW;
- If two lines at 220 kV and one line at 150 kV are present in the same area the maximum capacity of the lines at 220 kV is evaluated as an average between 180 MW, 180 MW and 117 MW.

In this way the values of capacities for links obtained are the ones in Figure 5.3. The energy mix obtained from this simulation (VA2) is similar to the one obtained by the configuration VA1 in Figure 5.2 but the usage of the lines is more uniform, as can be seen in the Figure 5.3. In this model, it is considered the line between node N1 and the location of Oristano that includes the line at 380 kV and the line at 220 kV but this link with these capacities is not used a lot. Therefore it is decreased the capacity of this link from 720 MW to 265.5 MW to represent the line at 220 kV and the line of 150 kV that are present in that area, evaluating the maximum capacity of the line at 220 kV as an average between 180 MW and 117 MW obtaining the configuration VA3 in the Figure 5.4.

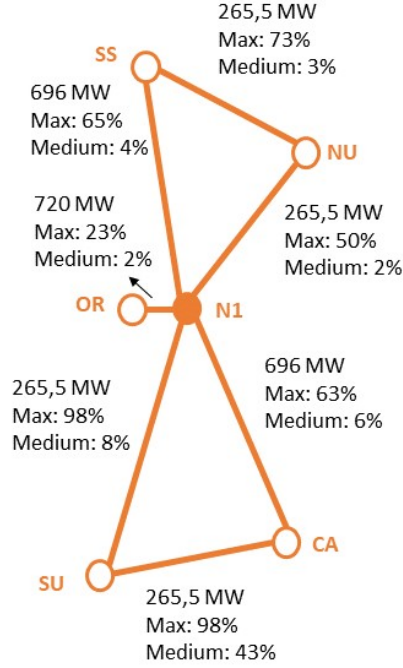


Figure 5.3: Capacities, maximum use and medium use of transmission lines in model VA2

In this model, the energy mix is still the same but the link between the node N1 and Oristano is used more, in terms of maximum and medium percentages. From these configurations tested it is noticed that the energy mix is not influenced doing not significant variations in the topology configuration of the network.

In order to represent better the region Sardinia it is constructed a more complicated network starting from configuration A and adding lines and points to consider the real configuration of transmission lines in Figure 4.4, with a new configuration called B.

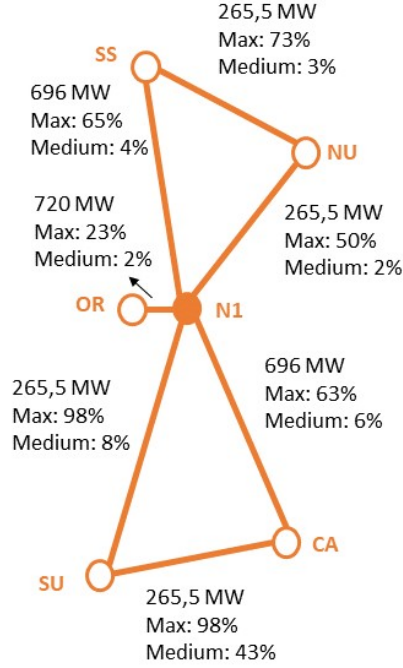


Figure 5.4: Capacities, maximum use and medium use of transmission lines in model VA3

5.5 Tests on configuration B

An evolution of the configuration called A is the one proposed in Figure 5.5 and called configuration B. In this case, two nodes are added, not for newly installed capacities of technologies but just for the import and export of energy between Sardinia and the rest of Italy and abroad. In particular, the Sarco and Sacoi are given as import and export file at the location of Santa Teresa (ST) and the Sapei is given as import and export file at the location of Fiume Santo (FS) with the code reported in the following part:

```
# locations for import and export connections
santa_teresa: #SARCO +SACOI
  techs:
    el_export: # export excess electricity
      constraints:
        resource: file=Export_Sardegna_crossborderST.csv:
                  el_export #
                  SARCO+SACOI
    el_import: #import eletricity needed
      constraints:
        resource: file=Import_Sardegna_crossborderST.csv:
                  el_import #
                  SARCO+SACOI
  coordinates: {x: 41.249458737095914, y: 9.18228610698874}
fiume_santo: #SAPEI
  techs:
```



```

el_export: # export excess electricity
constraints:
    resource: file=Export_Sardegna_crossborderFS.csv:
                el_export #
                SAPEI

el_import: #import eletricity needed
constraints:
    resource: file=Import_Sardegna_crossborderFS.csv:
                el_import #
                SAPEI

coordinates: {x: 40.80475255695234, y: 8.280497658610829}

```

The node N1 in this case is moved in a point where links branches and therefore moved to the location with the following coordinates:

```

N1: # location below Macomer
coordinates: {x: 40.22358298279619, y: 8.779904074601498}

```

The black link between Nuoro and node N1 is defined as a dummy link with a capacity imposed to 1000 GW because in that area there is not present that physical connection but it is useful for the energy flows in this approximated model. Instead, the configuration of technologies remains the same as configuration A and also the estimated energy Table 5.1 and costs taken as reference in Table 5.2.



Figure 5.5: Configuration more complex called configuration B

The capacities of transmission lines are evaluated as in the model VA1 adapted to the different configurations obtaining the capacities in the Figure 5.6, for this configuration called VB1.

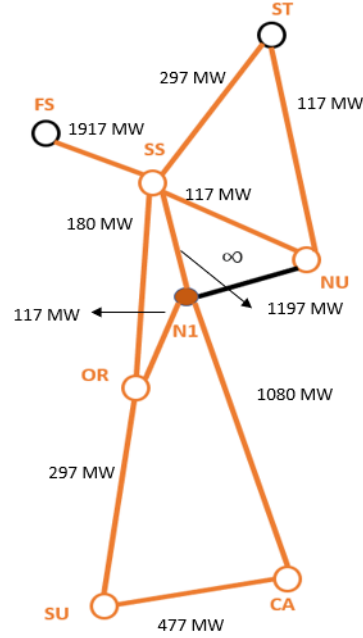


Figure 5.6: Scheme of configuration and transmission capacities in configuration VB1

In this case, the energy mix is similar to the one obtained in tests on configuration A, with the same costs used to run the model. Even using configuration B it is done a modification on the maximum capacity of lines, using the same procedure for transmission capacities as in model VA2 obtaining values in the Figure 5.7.

In this case, the energy mix produced by the model is almost the same as the model VB1 but the unmet demand is higher of about 0.12 GWh which means that the supply does not match the demand more times that the model VB1. Considering that the unmet demand in the model VB2 is concentrated in Santa Teresa this can be due to the reduced capacity of the link between Santa Teresa and Nuoro, because in that area the real transmission lines are more extended than ones in the model. Therefore, another simulation is done increasing the capacity of the link between Santa Teresa and Nuoro from 117 MW to 170 MW, obtaining the configuration VB3 in Figure 5.8. In this way, the unmet demand is decreased by 0.14 GWh respect to the previous model VB2.

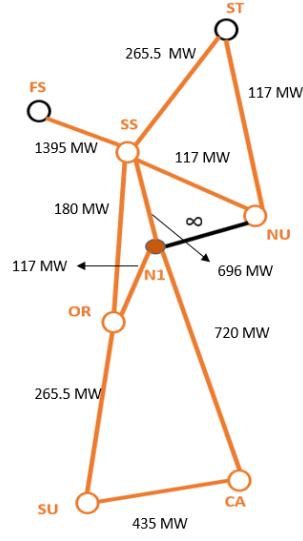


Figure 5.7: Scheme of configuration and transmission capacities in configuration VB2

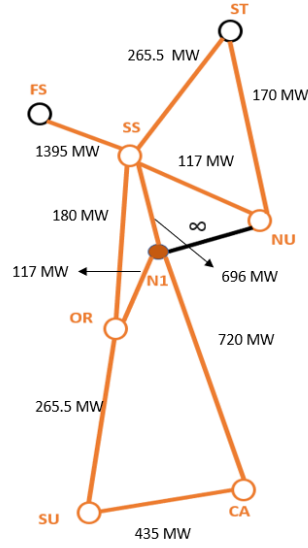


Figure 5.8: Scheme of configuration and transmission capacities in configurations VB3

This configuration B is also used to run a sensitivity analysis to understand the effect of *om_prod* and *om_con* on the energetic mix produced by the model. This sensitivity analysis is done starting from costs found in other models created using Calliope [36] [12] and references, as indicated in Appendix A, where it is possible to find more details.

Table 5.4: Energy produced in tests on configuration B

Energy produced (GWh)			
Technology	Name configuration		
	VB1	VB2	VB3
Pv tot	1'500	1'500	1'500
Pv farm	856	855	856
Pv rooftop	644	645	644
Wind (onshore)	3'289	3'289	3'289
Hydroelectric	554	560	560
Bioenergy	0	0	0
Traditional	6'894	6'887	6'887
Total thermoelectric	6'894	6'887	6'887
Unmet demand	0.476	0.593	0.455

In the Table 5.5 it is provided an indication of the use of lines, using the maximum percentage and medium percentage of the use of different lines in model B. In the columns max1 and med1 there is the maximum and medium percentage of use of the link, from the first location to the second one in the name of the link. For example from Sassari to Santa Teresa for the link SS-ST (Sassari- Santa Teresa). In columns max2 and med2 there is the percentage corresponding to the opposite direction of the same link.

Table 5.5: Energy produced in tests on configuration B

Connection link	Configuration of model B											
	VB1				VB2				VB3			
	max 1	max 2	med 1	med 2	max 1	max 2	med 1	med 2	max 1	max 2	med 1	med 2
SS-ST	98%	82%	23%	4%	98%	92%	25%	5%	98%	92%	25%	5%
SS-FS	51%	24%	19%	1%	70%	33%	26%	1%	70%	33%	26%	1%
ST-NU	96%	98%	4%	13%	98%	98%	4%	14%	68%	98%	2%	10%
SS-NU	65%	98%	0%	6%	65%	98%	0%	6%	82%	98%	0%	5%
SS-N1	36%	12%	1%	0%	61%	21%	2%	0%	61%	21%	2%	0%
SS-OR	48%	98%	6%	7%	48%	98%	6%	7%	48%	98%	6%	7%
N1-OR	26%	98%	0%	2%	26%	97%	0%	2%	29%	98%	0%	2%
N1-CA	39%	14%	2%	0%	58%	21%	2%	0%	58%	24%	2%	0%
OR-SU	38%	93%	1%	3%	44%	98%	1%	3%	42%	98%	1%	3%
SU-CA	98%	10%	63%	0%	98%	11%	69%	0%	98%	11%	69%	0%

Some tests are done on configuration B to understand how the model is working. It is considered more realistic to use the import and export cable connected to Santa Teresa and not Sassari, to distribute better the energy flows in lines, more real to the actual ones. Instead, the coal power plant of Fiumesanto is considered directly in the location of Sassari for better use of lines. It is also done a sensitivity analysis of the cost of production and consumption for different technologies to understand how these costs affect the production of energy from different sources. It is attributed more importance to these costs because in the operational mode of run the investment cost and fixed costs are not influent. More details about this analysis on costs are provided in the Appendix A.

5.6 Base model

After some tests on the model, a model that is considered validated is chosen, taking into account that is related to some uncertainties. Nevertheless, this model is chosen after some tests on configurations described and since it is modified and improved in scenarios. Comparing the energy produced by the model using Calliope, with the ones estimated from Terna in Table 5.1, for pv, wind, hydroelectric, bioenergy and thermoelectric energy it is obtained a value of RMS of 2489 GWh.

The uncertainties are caused also by the classification of energy produced in Sardinia by different sources and capacities installed in provinces. In fact, it is not easy to find the exact values of these data, also because region Sardinia changes the distribution of its province after the year 2016. The configuration for transmission lines is the one used in the simulation VB3, in Figure 5.8, because after these simulations is the one that seems working better.

In the Figure 5.9 the installed capacity of technologies in the locations is provided, i.e. in different provinces of Sardinia.

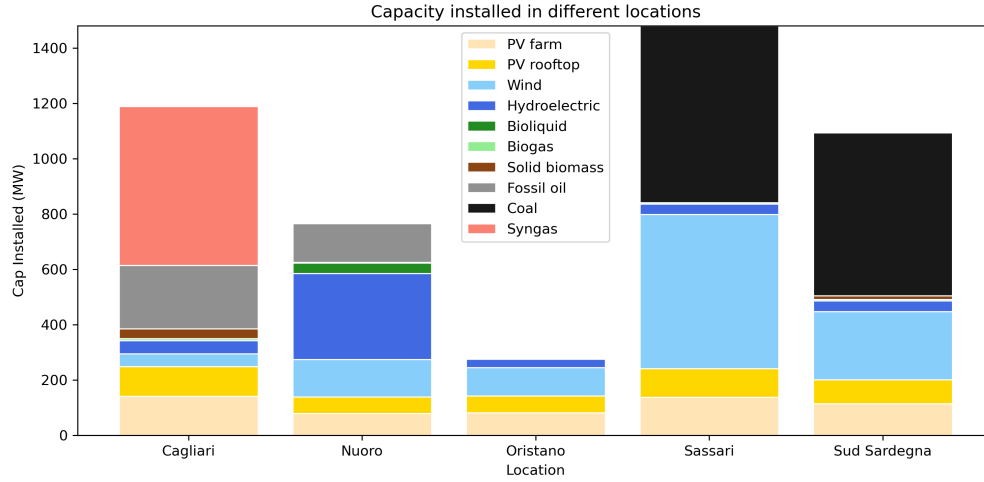


Figure 5.9: Capacity of different technologies installed in Sardinia, classified in provinces

In Figure 5.9 the bigger capacity installed is in the provinces of Sassari, Sud Sardegna and Cagliari, with a big capacity of coal power plants in Sassari and Sud Sardegna. Instead, in Cagliari there is a big Integrated coal gasification combined cycle (IGCC) power plant for syngas production.

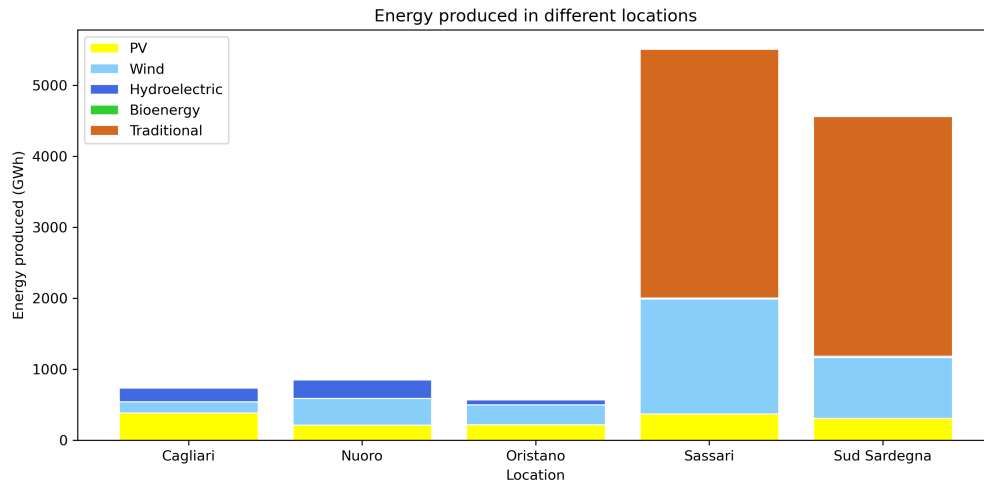


Figure 5.10: Energy produced by different technologies installed in Sardinia, classified in provinces

As can be seen in Figure 5.10 the energy produced in different provinces simulated with the model chosen, is concentrated in Sassari and Sud Sardegna, where there are the two big coal power plants.

Table 5.6: Energy produced in tests on configuration A

Link connection	Percentage use of lines in base model			
	max 1	max 2	med 1	med 2
SS-ST	98%	92%	25%	5%
SS-FS	70%	33%	26%	1%
ST-NU	68%	98%	2%	10%
SS-NU	82%	98%	0%	5%
SS-N1	59%	21%	2%	0%
SS-OR	48%	98%	6%	7%
N1-OR	47%	97%	0%	2%
N1-CA	58%	21%	2%	0%
OR-SU	44%	95%	1%	3%
SU-CA	98%	11%	69%	0%

From the Table 5.6 it is possible to notice that the lines in the northern part of Sardinia near Santa Teresa and Fiume Santo are on average more used, because those lines are the only ones that permit the export and import of electricity for the region. The values of energy demand, imported, exported and total energy produced are reported in the Table 5.7. More information on the choice of this model can be found in Appendix A.

Table 5.7: Values of energy demand, exported, imported and total energy produced in base model

Energy (TWh)		Note
Total produced	12.2	Found by Calliope
Imported	0.5	From CSV input
Exported	-4.1	From CSV input
Demand	-8.6	From CSV input

Chapter 6

Scenarios analysis and results

6.1 Potential capacities

In order to identify the most significant scenarios it is necessary to know the maximum potentials in terms of installable capacities of different technologies.

Due to the absence of the various maximum potentials for all technologies in the region, the maximum potential for each individual technology that could be installed in Sardinia is calculated or found in different references. In the Table 6.1 the maximum potentials considered are divided into data taken from sources and data derived from sources but elaborated for this model, as described below.

Table 6.1: Max installable capacity for different technologies divided into data taken from sources, described below, and data elaborated from references

Technology	Maximum capacity (MW)	
	From reference	Elaborated
PV tot		54'840.0
PV farm	50'760.0	
PV rooftop	4'080.0	
Wind (onshore)	60'415.0	
Hydroelectric		466.4
Bioliqid		37.0
Solid biomass		58.5
Biogas		220.0
Fuel oil		369.0
Coal		1'243.0
Syngas		590.0

6.1.1 PV potential

The potential of photovoltaic capacity that can be installed can be found in the Joint Research Centre Data Catalogue, in particular in the datasets from ENSPRESO (ENergy Systems Potential Renewable Energy SOurces) [54]. In ENSPRESO there are technical potentials that can be used for energy models on renewable energy and they are provided at the national level (NUTS0) and regional one (NUTS2) until the year 2050. The solar potentials available in this dataset consider the irradiation data and the area available for solar systems [25]. The potential is derived assuming a solar irradiation value of 170 W/m^2 [54], the value of 3% coverage of artificial areas and other factors for the technical context, economic, social and environmental ones [25].

For the region of Sardinia in ENSPRESO [54] it is evaluated a potential capacity of 50'760 MW for the solar power plants, in this case represented by the technology called PV farm. Instead for the potential of photovoltaic systems on buildings, rooftops and in general of non-ground type in ENSPRESO it is estimated a small size potential of 4'080 MW. These potentials are evaluated for the entire region of Sardinia, but in this thesis are adapted in the section below to be divided into different provinces of Sardinia, in order to increase the capacity of these technologies in the model in years.

6.1.2 Wind onshore potential

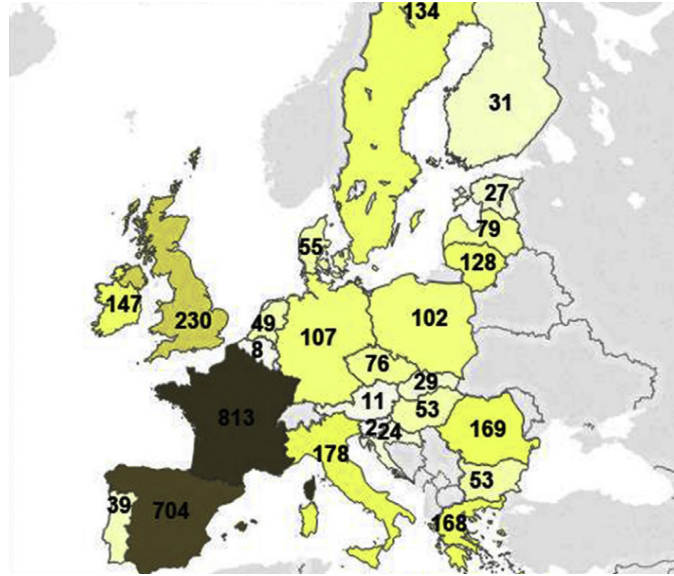


Figure 6.1: Potential Capacity (GW) of Wind Onshore - High wind conditions. Only available areas with Capacity Factor higher than 20%, with 300 W/m^2 specific power for wind turbine at 100m hub height. Reference scenarios. Figure adapted from source [25]

Even for the wind onshore potential, it is possible to use the ENSPRESO [54] datasets. In this case it is considered the scenario "Reference" provided in this dataset that foresees maintaining the actual requirements for areas, where it is not possible to install and

actual setback distances [25]. The hub height of wind turbines considered is 100 m and the potential includes wind turbines with a capacity factor more than 0.15. The potential evaluated in this way for the Sardinia region is 60.415 GW [54] of maximum installable capacity of wind onshore, instead in the Figure 6.1 there are potentials for European countries. All of these potentials refer to the Reference scenario described before. As can be seen from the potentials in this Figure, the potential of onshore wind capacity for Europe is 3'400 GW with a production of 8'400 TWh, and in this case corresponds to the 16% of the European total area [25].

6.1.3 PV potential and wind onshore potential by province

The potentials found in ENSPRESO [54] for photovoltaics capacity and wind onshore capacities are regional values. In order to assess the provincial potential of Sardinia for these technologies, an evaluation, which considers a large number of protected areas in the region, is done. The project "Progetto Natura" contains geographic banks with the main protected natural areas. This project is created with the aim of protecting and enhancing areas in order to maintain some fragile ecosystems and protect animal and plant species with a view to protecting biodiversity [55]. In these areas the following zones are included:

- **Protected areas** registered in the Official List of Protected Areas divided into National Parks, Marine Protected Nature Areas, Marine Nature Reserves, State Nature Reserves, and Regional Parks and Nature Reserves;
- **Important Bird Areas** identified for the significant presence of species essential for conservation;
- **Wetlands of International Importance** are areas such as marshes or areas with the presence of water with particular importance especially for water birds and with wetland ecosystems to be protected;
- **Rete Natura 2000 areas** consisting of Sites of Community Importance and Special Protection Areas. In these areas, human activities are allowed for e.g. economic and social needs, but with a conservative and sustainable use of the land.

The protected areas in Sardinia can be seen on Geoportale Nazionale [64] where on the map all the areas identified by the "Progetto Natura" can be seen. It is evaluated on Google Earth in an approximated way the area of each province and removed the area corresponding to the protected one, to understand a possible proportion between available provincial areas and the total provincial area.

In Figure 6.2, Figure 6.3, Figure 6.4, Figure 6.5, Figure 6.6 there is an approximated evaluation of areas not protected from "Progetto Natura" for different provinces. Then all these areas are summed, to evaluate the fraction of each provincial not-protected area on the total of not protected areas. These fractions are then multiplied to the potential capacity of Sardinia. This is done for the photovoltaic potential, both PV farm and PV rooftop, and for wind onshore potential obtaining results in Table 6.3.



Figure 6.4: Area for the province of Nuoro without removed protected areas; map taken from Google Earth [77]



Figure 6.5: Area for the province of Sud Sardegna without removed protected areas; map taken from Google Earth [77]



Figure 6.6: Area for the province of Cagliari without removed protected areas; map taken from Google Earth [77]

Table 6.2: Evaluation of fraction available area for new renewable technologies

Province	Evaluated not protected areas (km2)	Fraction available for new renewables	Percentage available for new renewables
Cagliari	635	0.0440	4%
Nuoro	3'306	0.2290	23%
Oristano	1'873	0.1297	13%
Sassari	5'067	0.3509	35%
Sud Sardegna	3'558	0.2464	25%

It is not considered to install offshore wind capacity considering that the projects for offshore wind turbines in Sardinia are not much evolved. In addition, there are some protected areas and heavily travelled areas, and in the northern part of Sardinia there is a protected area called Pelagos sanctuary for the protection of marine mammals [96].

Table 6.3: Maximum capacity potential assumed for Sardinia and different provinces

Technology	Maximum potential Capacity (MW)					
	Sardinia	Cagliari	Nuoro	Oristano	Sassari	Sud Sardegna
PV farm	50'760.0	2'233.4	11'624.0	6'583.6	17'811.7	12'507.3
PV rooftop	4'080.0	179.5	934.3	529.2	1'431.7	1'005.3
PV tot	54'840.0	2'413.0	12'558.4	7'112.7	19'243.4	13'512.6
Wind onshore	60'415.0	2'658.3	13'835.0	7'835.8	21'199.6	14'886.3
Hydroelectric	466.4	47.7	312.1	30.3	37.6	38.7
Bioliqum	37.0	0.0	37.0	0.0	0.0	0.0
Solid biomass	58.5	37.2	2.3	0.9	2.6	15.6
Biogas	220.0	38.9	40.0	35.8	51.6	53.7
Fossil oil	369.0	229.0	140.0	0.0	0.0	0.0
Coal	1'243.0	0.0	0.0	0.0	640.0	590.0
Syngas	590.0	575.0	0.0	0.0	0.0	0.0

6.1.4 Potential of thermoelectric power plants

For fossil oil, coal and syngas it is not considered to install new capacity for these systems in order to prepare the energy system to decarbonization in the production of energy. Therefore the maximum potential evaluated is the capacity already installed in 2020, i.e. in the base model.

For bioliqum source, the maximum potential of capacity is considered, the capacity already installed in 2020, because it is not found an exact possible and coherent evolution of this source, even in the PEARS of Sardinia [7].

For the potential of solid biomass, an evaluation based on different references is done. It is considered a possible potential energy produced from solid biomass divided into forest resources, agricultural residues and other solid biomass of 311.5 GWh/y [45] as in Table 6.4.

Table 6.4: Potential of biomass adapted from source [45]

MAXIMUM POTENTIAL ENERGY PRODUCED FROM SOLID BIOMASS IN SARDINIA	
Possible electric energy from Forests (GWh/y)	50.6
Possible electric energy from Agricultural Residues (GWh/y)	105.2
Possible electric energy from others Solid Biomass (GWh/y)	155.7
Total (GWh/y)	311.5

Taking this potential energy, considering 7000 equivalent hours for these systems, it is possible to obtain an installed capacity for solid biomass systems of 44.5 MW. This potential for solid biomass results coherent with the value found in the ENEA assessment of regional solid biomass potential [2]. In this potential is added also the actual installed capacity in the base model, for electricity recovery from waste of 14 MW, assumed considering references [33] [27], due to the absence of a potential installed capacity for wastes. Finally, it is obtained the total potential from solid biomass for the Sardinia equals to 58.5 MW.

In order to subdivide the total solid biomass potential into the provincial one, it is considered a document about the evaluation of the potential of biomass for the Sardinia region [100], but that takes into account the older subdivision of provinces of Sardinia into:

- Sassari
- Nuoro
- Cagliari
- Oristano
- Ogliastra
- Olbia-Tempio
- Medio Campidano
- Carbonia-Iglesias

This document provides an evaluation of this provincial potential from different sources: solid biomass, biogas and bioliquid. In order to consider the actual subdivision into provinces of Sardinia, the data in this document are adapted incorporating and modifying in an approximated way the provincial data as follows:

- The actual province of Sassari includes the older province Sassari and the old province Olbia-Tempio;
- The province of Oristano is considered corresponding to the older one;
- The actual province of Nuoro includes the older one and the province of Ogliastra;
- The province of Sud Sardegna includes the old provinces of Medio Campidano, Carbonia-Iglesias and one-half of the production of the old province of Cagliari;
- The actual province of Cagliari is reduced with respect to the older one, therefore its production is reduced to just half of the production of the older province of Cagliari. The remaining part is considered in the province of Sud Sardegna.

In this document [100], the production by direct thermochemical processes is done using: straw, thistle plants, vine, olive, citrus and orchard prunings, green maintenance, forestry and arboriculture, waste from wine and oil production processes, waste from the wood industry, sheep and goat wool, frying oils. In this case the potential of solid biomass to produce electric energy, is evaluated by taking into account for the production of solid biomass the tonnes per year used of: straw, citrus and orchards, vine pruning, olive pruning, and green maintenance. Using these data it is possible to find the assumed provincial potential of solid biomass in Table 6.3.

The evaluation of the potential of capacities of power plants that use biogas is similar to the one done for solid biomass. The possible maximum installable capacity of biogas power plants is evaluated, considering two possible options of equivalent hours, in the option of the plant working for 7'000 hours in the year it is possible to consider a capacity of power plants of 228.6 MW to have a productivity of 1'600 GWh in the year [100]. Instead, it is possible to consider a capacity of biogas power plants of 200 MW if the equivalent hours are increased to 8'000 hours.

Table 6.5: Potential electric energy produced by biogas from source [100] and assumed potential capacity of biogas power plants installed

Potential energy (GWh/y)	Equivalent hours (h)	Capacity (MW)
1600	7'000	228.6
	8'000	200

In this case, it is considered a maximum potential capacity between the two found, equal to 220 MW of biogas power plant capacity. For biogas production, the following sources are considered: livestock manure, slaughterhouse waste, vegetation water, artichoke waste, and tomato waste [100]. As for solid biomass, these data are divided for the old provinces of Sardinia, so they are adapted in the same way for the new provinces of Sardinia, obtaining the provincial potential of biogas in Table 6.3.

6.1.5 Potential of hydroelectric

The potential capacity of hydroelectric systems is considered equal to the capacity installed in 2020 because it is assumed that the potential of hydro run-of-river and hydro reservoirs is already enough exploited and it has not a good new potential [52].

6.2 Scenarios description

In the targets of this thesis, there is also the study of the possible evolutions of the energy system of Sardinia in future years, creating possible scenarios. In order to construct the scenarios, the basic model is considered and the planning of the scenarios is done on the basis of major projects and changes that will affect the region of Sardinia in the coming years. The scenarios are defined in an approximate way, with respect to reality, but they can be a basis for future refinements and modifications.

Starting from the basic model that is representative of Sardinia’s energy system as it is in years 2019/2020, scenarios are constructed for the following years:

- 2024;
- 2025;
- 2030;
- 2050.

The choice of scanning in these years for the scenarios is discussed in detail below. From 2025 there is a forecast increase in energy demand for the Sardinia region, which will continue to grow until 2050. About transmission lines that connect Sardinia with Corsica and the rest of Italy, there are two projects planned: the Tyrrhenian Link from 2028 [107], designed as in Figure 3.7 and the Sacoi 3 in substitution of Sacoi 2 connection, as in Figure 3.6. All these changes in the energy system of Sardinia are planned with the target to have a totally decarbonized energy system.

6.2.1 Year 2024

This scenario is constructed in order to design an intermediate scenario between the base model, representative of the situation in 2019/2020 and the total decommissioning of coal-fired power plants, planned for the year 2025. In fact, in this scenario it is assumed that the 50% of coal power plants’ capacities are already dismissed. The maximum installable capacity for the technology biogas and for the technology solid_biomass is set equal to the maximum potential in Table 6.3 for an easier configuration and to not force too much the model. Instead, the technology fossil oil, coal and syngas have the exact installed capacity as a constraint, i.e. the base model capacity, defined in locations.yaml file, as can be seen in the Appendix A. These assumptions on solid biomass, biogas, fossil oil and syngas are done also for other scenarios.

This scenario is also useful to test the new configuration of the model, in particular for the supply and export of energy from the region. In the base model for the export it is considered a resource given as a CSV file and it is used the default configuration of the parent demand, to use all the available resource with the constraints:

```
force_resource: True
```

For the scenarios, it is considered a similar configuration for the export of energy with the technology **el_export**. In this case, it is not forced to use all the available resources setting the constraint `force_resource` to `False`. The value of the resource is imposed equal to the corresponding capacity of the connection that exports the energy from the region. For example, for Santa Teresa the resource of `el_export` is imposed equal to the capacity of Sarco and Sacoi; the same is done for the location Fiume Santo with the connection Sapei. In this way, the resource is evaluated as in Equation 2.5. Therefore the technology `el_export` is configured as the Italian model built with Calliope [36], as in the following code, in the `techs.yaml` file:

```

techs:
  el_export:
    essentials:
      name: 'Electricity export'
      color: '#C70039'
      parent: demand
      carrier_in: electricity
    constraints:
      force_resource: False #not forced to use all the available
                             resources
    costs:
      monetary:
        om_con: -0.10 #export revenue

```

For the energy imported in Sardinia for scenarios is not considered anymore the technology el_import but it is created a new technology called **supply_grid_power**, set as in the following code in the techs.yaml file:

```

techs:
  supply_grid_power:
    essentials:
      name: 'Supply grid'
      color: '#C5ABE3'
      parent: supply_plus
      carrier: electricity
    constraints:
      resource: inf
      energy_prod: True #defined as technology that produces energy
      resource_eff: 1
      lifetime: 40
    costs:
      monetary:
        om_prod: 0.2 #cost for the supply of energy

```

Also for the supply_power_grid the technology is almost defined as done for the Italian model [36], with an infinite resource for the supply of energy and unitary efficiency. In the file locations.yaml the resource for the export and the supply is given at different locations, in the following way:

```

santa_teresa: #SARCO +SACOI
  techs:
    el_export:
      constraints:
        resource: -4e5 #kW
    supply_grid_power:
      constraints:
        energy_cap_max: 400000 #kW
  coordinates: {x: 41.249458737095914, y: 9.18228610698874}
fiume_santo: #SAPEI
  techs:
    el_export:
      constraints:
        resource: -1e6 #kW
    supply_grid_power:

```

```
constraints:
    energy_cap_max: 1000000 #kW
coordinates: {x: 40.80475255695234, y: 8.280497658610829}
```

The rest of the model is defined as in the base model, as described in chapter 4. The mode of run of the scenario is the planning mode, in which Calliope finds the capacities of different technologies to install with the target to minimize the cost of the system, with the objective function chosen.

6.2.2 Year 2025

In 2025 it is planned a complete phase-out of coal [50], therefore it is set to zero the installed capacity of coal power plants, increasing the maximum possible installable capacities for photovoltaic, wind, solid biomass and biogas systems. It is not considered already the installation of the Tyrrhenian link because it is planned until the end of 2025 just the east part of the connection [51], that will connect Sicily to the Campania as in the Figure 3.7. The configuration of capacities and technologies is the same as discussed in subsection 6.2.1.

From the year 2025 in Sardinia it is possible a reactivation of the Eurallumina and ex-Alcoa plants, that is considered, with an increment of 2 TWh of the energy demand.

6.2.3 Year 2030

The configuration at the year 2030 is provided because it can be useful to compare data obtained from the model to the energy mix planned by PNIEC in 2030. In addition, starting from the year 2027 it is planned a substitution of the link Sacoi 2 with the link Sacoi 3, increasing the capacity of this connection of 100 MW [106]. When in the configuration of the model it is considered the Sacoi3 already active, the resource for the export technology in Santa Teresa (ST) is increased from -4e5 to -5e5 kW, instead, the possible maximum installed capacity of the technology supply_power_plus is set to 500 MW.

From 2028 it is also planned the new Tyrrhenian link connection to Sicily and Campania [107], as discussed before configured as in Figure 3.7. In order to model the system, when it is considered in the model the Tyrrhenian link, a new location is created corresponding to the point where the Tyrrhenian Link will be created: Terra Mala (TM). In this case, this new location is connected to Cagliari with a dummy link, just to consider the new export and import cable, as in Figure 6.7.

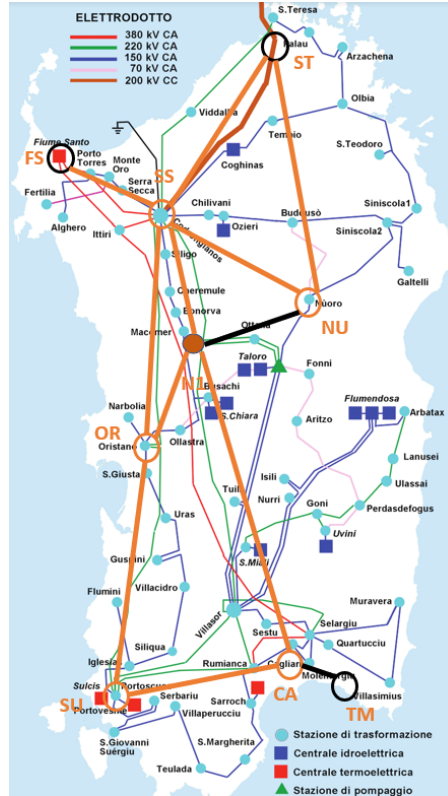


Figure 6.7: Configuration of the model when it is considered the activation of Tyrrhenian Link

6.2.4 Year 2050

In scenarios, it is designed the year 2050 considering the target for Europe to have a decarbonized system in 2050, with the European Green Deal project [62]. The target is to have an economy with zero net greenhouse gas emissions, therefore in this year in all scenarios, it is considered a total decommissioning of coal, fossil oil, and syngas power plants, in order to understand how the energy model of Sardinia can react to this modification. This change is also coupled with an increasing demand for electricity, as described above, assuming that it can remain the same as the PNIEC forecast for 2040, or that continues to grow, depending on the scenario.

6.2.5 Scenarios: best, BAU and worst

The evolution in years of the energy model of Sardinia is studied in three different scenarios:

- Scenario **best** that is the most favorable for the Sardinian energy system;
- Scenario **BAU (Business As Usual)** that represents the evolution of energy models following the actual trend and without important modifications and new

projects;

- Scenario **worst** that is the most unfavorable for the Sardinian system.

The three scenarios are analyzed increasing the maximum installable capacity of PV and wind in two ways (two options), to have a comparison of results provided by Calliope. The major differences between scenarios, in the two different options, involve:

- The maximum constraint on the installable capacity for wind and photovoltaic systems;
- Possible increment of the energy demand;
- Possible increment of photovoltaic and wind efficiency;
- Possible reduction of photovoltaic and wind installation costs;
- Possible activation of two new links for export and import.

6.3 Main modifications between scenarios

In order to realize three scenarios that could represent the evolution of the energy system of Sardinia from the more optimistic possibility to the more pessimistic possibility, or considering the actual evolution, some parameters are changed between one scenario and another one, year by year.

6.3.1 Capacity of wind and photovoltaic systems in scenarios

In order to consider scenarios more realistic as possible to the target for the Sardinia region, it is considered that PNIEC planned an installed capacity of 2.08 GW for photovoltaic systems and 2.2 GW for wind systems in 2030 in Sardinia [32].

In order to get the trend of the growth of installed capacity in Sardinia in the various provinces, the capacities of photovoltaic and wind power plants are analyzed in the various years. Due to the change of Sardinia's subdivision into new provinces, only the years since 2017 have been considered. The minimum installable capacity for wind and photovoltaic systems, considered in different scenarios, is the one installed in the base model. Instead for the maximum installable capacity for each province, two cases are considered:

- OPTION 1: A possible trend of capacity installed that considers the actual growth of installed capacity in years in different provinces (with a possible increase including at 2030 the PNIEC target);
- OPTION 2: Take the theoretical potential capacity as the constraint for maximum capacity, free of the real trend of installation.

In this way, option 1 is more constrained because the maximum installable capacity for wind and photovoltaic systems is limited to the trend of its evolution in previous years, instead the model is less restricted in option 2, giving only the maximum potential.

The maximum constraint on capacities for photovoltaic and wind systems, for each year, is provided for the Best scenario in Table 6.6 and for BAU and worst scenarios in Table 6.7, both for options 1. For the best scenario, the capacity installed is found using the actual trend of growth in different provinces increased considering in this evolution a maximum installed capacity in 2030 equals to the PNIEC target, i.e. 2'200 MW for photovoltaic and 2'080 MW for wind systems. Instead for BAU and the worst scenarios for option 1, the maximum installed capacity given as a constraint is the one that follows the actual trend of evolution of installed capacity in provinces. For option 2 these maximum constraints are just set equal to the maximum potential in Table 6.3.

Table 6.6: Maximum constraint on capacities for photovoltaic and wind systems, for each year, is provided for the Best scenario option 1

Maximum renewable capacity (MW) - Scenario best option 1							
Technology	Year	Sardinia	Cagliari	Nuoro	Oristano	Sassari	Sud Sardegna
PV farm	2024	815	157	168	108	200	182
	2025	872	165	171	120	217	200
	2030	1'254	188	285	162	308	311
	2050	2'547	392	619	295	617	624
PV rooftop	2024	615	118	127	82	151	138
	2025	658	125	129	90	163	151
	2030	946	142	215	123	232	234
	2050	1'921	295	467	223	465	471
Wind (onshore)	2024	1'422	67	250	160	610	335
	2025	1'515	70	280	175	630	360
	2030	2'080	90	480	270	730	510
	2050	3'732	163	1'073	535	1'005	957

Instead for scenarios BAU and worst, the maximum capacities given for PV and wind technology are reported in Table 6.7, for option 1, because for option 2 they correspond to the maximum potential.

Table 6.7: Maximum constraint on capacities for photovoltaic and wind systems, for each year, provided for the BAU and worst scenarios, option 1

Maximum renewable capacity (MW) - Scenarios BAU and worst option 1							
Technology	Year	Sardinia	Cagliari	Nuoro	Oristano	Sassari	Sud Sardegna
PV farm	2024	691	228	88	85	167	122
	2025	721	245	90	86	175	124
	2030	890	348	99	92	217	134
	2050	1'666	861	135	113	385	173
PV rooftop	2024	521	172	66	64	126	92
	2025	544	185	68	65	132	94
	2030	671	262	75	69	164	101
	2050	1'257	649	102	85	290	130
Wind (onshore)	2024	1'149	47	163	102	565	273
	2025	1'171	51	173	102	566	279
	2030	1'262	55	222	103	573	310
	2050	1'609	57	416	103	599	435

6.3.2 Cost of export and cost of supply

If in the base model the energy exported and imported are constrained by a resource with a CSV file, instead in scenarios these energies are constrained just to the capacity of links unable to transfer these quantities of energy. Therefore the cost of the exported energy and supplied energy to Sardinia acquires more importance. Consulting the GME [65] it is possible to notice the big variation in the cost of energy, in particular taking into account the period between September 2022 and November 2022. In the model of Italy done using Calliope [36] the cost of exported energy is set equal to the one of imported energy but negative, instead in the UK model [12] the cost of supplied energy is increased considering an additional cost for transmission and operation. Testing costs for exported and imported energy, choosing the same cost for these technologies, but opposite in the sign, the model imports energy and then exports it. Therefore it is chosen a representative cost of exported energy of -0.1 eur/kWh and a cost for imported energy increased to 0.2 eur/kWh, considering an additional cost for transmission and operation. In this way, the model imports energy only if the energy produced can not satisfy the demand of energy.

6.3.3 Evolution of demand in years

For the scenarios the energy demand is modified in years, considering the planned demand for Sardinia up to 2040 evaluated from RSE [32], as can be seen in Figure 6.8. The data in this Figure confirm the prevision of PNIEC that in 2030 the energy demand will be equal to 10.5 TWh, reaching 11.1 TWh in 2040. From the year 2025 it is planned a possible reactivation of the aluminum industry (reactivation of the Eurallumina and ex-Alcoa plants) that will cause an increase of 2 TWh of energy demand. In the evolution of the energy demand in Figure 6.8 it is also considered the possible evolution in the use of heating and cooling systems and the increase of energy required by electric vehicles. [32]. Taking into account the data provided, on the basis of different configurations, the following assumptions on the energy demand are done:

- The demand in 2024 is considered equal to the one in 2019;
- The demand in 2030 is assumed increased of 120 GWh, and in 2050 of 1 TWh respect to the 2019, excluded the possible increment due to the activation of Eurallumina;
- When it is considered the activation of Eurallumina, the energy demand is increased of 2 TWh in the province Sud Sardegna, the place where it is planned to be reactivated.

To proportion the provincial increase of energy demand, it is considered that according to Istat the population in Sardinia is decreasing, and will continue to decrease in a uniform way in different provinces [81] over the years. It is evaluated the proportion of the provincial population in 2032 (maximum future data) on the total population in Sardinia in that year, as in Table 6.8. These proportions are used to distribute the increment of energy demand (excluding Eurallumina) in 2030 and 2050.

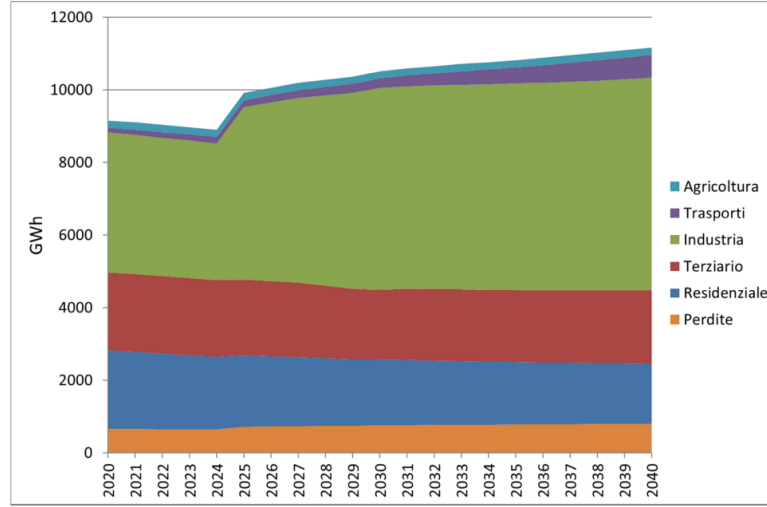


Figure 6.8: Planned evolution of the energy demand in Sardinia. Figure taken from source [32]

Table 6.8: Percentage of the composition of the total population in provinces in 2032 according to Istat [81]

Province	Percentage composition of population at 2032 in provinces of Sardinia
Cagliari	27%
Nuoro	12%
Oristano	9%
Sassari	30%
Sud Sardegna	21%

6.3.4 Evolution of the efficiency of eolic and photovoltaic systems

In scenarios, it is considered an increase of the efficiency of wind and photovoltaic systems in future years. For the evolution of photovoltaic efficiency, it is considered that for photovoltaic cells with intermediate characteristics the efficiency is increased by about of 3% (18% to about 21%) in about 10 years [9]. Therefore it is considered that each year the efficiency is increased by about a factor of 0.003. To consider this increment in the model, taking into account the definition of the technology `pv_farm` and `pv_roofoot`, the increment in the efficiency is included in the model modifying the original file for the photovoltaic resource, from `Renewables.ninja` as described in chapter 4. Instead, wind energy is considered the evolution of capacity factor in years [60] but the modification of the efficiencies is done in a way that the original file for the resource from `renewable_ninja` does not exceed the unitary value. The multiplied factors considered to increment the original resources CSV file are in Table 6.9

Table 6.9: Multiplying factors for the increase of efficiency of wind and photovoltaic systems

Multiplying factor for efficiency					
Scenario	Tech	2024	2025	2030	2050
Best	PV	1.115	1.119	1.136	1.202
	wind	1.111	1.113	1.124	1.168
Bau	PV	1.015	1.018	1.033	1.093
	wind	1.010	1.012	1.022	1.062
Worst	PV	1.012	1.015	1.031	1.091
	wind	1.011	1.012	1.022	1.050

6.3.5 Evolution of installation cost for PV and wind technology

In order to realize three scenarios that can evaluate the use of renewable resources in a different way, the efficiency of PV and wind technology is changed in years depending on the scenario. In particular, it is considered that the cost per kWh in future years will reduce for both technologies according to [83].

This reduction is proportioned in years and it is assumed that the installation cost for photovoltaic systems will decrease by the same amount in percentage. The same is done for wind technology analyzing the forecast evolution of its costs per kWh in years [53]. Finally, the values in Table 6.10 are considered in the different scenarios for the installation costs of PV and wind technologies.

Table 6.10: Evolution costs for PV and wind technologies in different scenarios

Installation cost (eur/kW)					
Scenario	Technology	2024	2025	2030	2050
Best	PV farm	298	298	230	68
	PV rooftop	383	383	296	87
	wind	1'143	1143	1'006	594
BAU	PV farm	474	474	325	95
	PV rooftop	610	610	418	122
	wind	1'326	1'326	1'234	1'143
Worst	PV farm	812	812	569	149
	PV rooftop	1'045	1'045	732	192
	wind	1463	1'463	1'417	1'371

To better understand the main differences between different models it is provided a Table 6.11 with the list of modifications in the evolution of each scenario, for option 1 provided. Option 2 has exactly the same inputs except for the constraint on the maximum capacity of photovoltaic and wind energy that is always equal to the maximum potential in Table 6.3 for every year.

The BAU scenario considers a possible evolution of the energy system of Sardinia in years, starting from the base model, using the actual trend of growth of efficiency and installation costs for PV and wind and the actual growth of installed capacity in provinces,

for option 1. The increment of the energy demand is considered in years but it is not included a possible reactivation of Eurallumina plant. Instead, the worst scenario respect to the previous one needs to face also an energy demand increased for the reactivation of Eurallumina plant, in addition to the reduced trend of efficiency and installation costs. The best scenario considers a maximum possible installed capacity for PV and wind systems increased using the PNIEC target in 2030, for option 1. The efficiencies of PV and wind and their installation costs in years are more favorable than other scenarios. In this case, it is also considered the installation of Tyrrhenian Link and Sacoi 3 for the export and import of electric energy and it is supposed that the Eurallumina plant is not reactivated. In this case from 2040 to 2050, the energy demand is not incremented, incrementing the energy demand by just 600 GWh respect to the base model.

Table 6.11: Main modifications in the evolutions of scenarios for option 1

Models option 1				
	Year	2024	2025	2030
Best	Max capacity PV and wind	Trend installation with PNIEC 2024	Trend installation with PNIEC 2025	Trend installation with PNIEC 2030
	Coal	Reduction 50%	Dismissed	Dismissed
	Fossil oil	As in base model	As in base model	Dismissed
	Syngas	As in base model	As in base model	Dismissed
	Energy demand	As in base model	As in base model	Incremented of 120 GWh respect base model (assumed equals to 2040)
	Links	As in base model	As in base model	New Tyrrhenian link, new Sacoï 3 that replaces Sacoï2
	Installation cost PV and wind	Reduction of installation cost renewable 2025 best (supposed equals to 2025)	Reduction of installation cost renewable 2025 best	Reduction of installation cost renewable 2030 best
	Efficiency PV and wind	Increase of renewable efficiency 2024 best	Increase of renewable efficiency 2025 best	Increase of renewable efficiency 2030 best
	Max capacity PV and wind	Actual trend of installation 2024	Actual trend of installation 2025	Actual trend of installation 2030
	Coal	Reduction 50%	Dismissed	Dismissed
BAU	Fossil oil	As in base model	As in base model	As in base model
	Syngas	As in base model	As in base model	Dismissed
	Energy demand	As in base model	As in base model	Incremented of 1 TWh respect base model
	Links	As in base model	As in base model	As in base model
	Installation cost PV and wind	Reduction of installation cost renewable 2025 BAU (supposed equals to 2025)	Reduction of installation cost renewable 2025 BAU	Reduction of installation cost renewable 2030 BAU
	Efficiency PV and wind	Increase of renewable efficiency 2024 BAU	Increase of renewable efficiency 2025 BAU	Increase of renewable efficiency 2030 BAU
	Max capacity PV and wind	Actual trend of installation 2024	Actual trend of installation 2025	Actual trend of installation 2030
	Coal	Reduction 50%	Dismissed	Dismissed
	Fossil oil	As in base model	As in base model	Dismissed
	Syngas	As in base model	As in base model	Dismissed
WORST	Energy demand	As in base model	Activation of Eurallumina	Incremented of 1 TWh respect base model + Eurallumina
	Links	As in base model	As in base model	As in base model
	Installation cost PV and wind	Reduction of installation cost renewable 2025 worst (supposed equals to 2025)	Reduction of installation cost renewable 2025 worst	Reduction of installation cost renewable 2030 worst
	Efficiency PV and wind	Increase of renewable efficiency 2024 worst	Increase of renewable efficiency 2025 worst	Increase of renewable efficiency 2030 worst
	Max capacity PV and wind	Actual trend of installation 2024	Actual trend of installation 2025	Actual trend of installation 2030
	Coal	Reduction 50%	Dismissed	Dismissed
	Fossil oil	As in base model	As in base model	Dismissed
	Syngas	As in base model	As in base model	Dismissed
	Energy demand	As in base model	Activation of Eurallumina	Incremented of 1 TWh respect base model + Eurallumina
	Links	As in base model	As in base model	As in base model
	Installation cost PV and wind	Reduction of installation cost renewable 2025 worst (supposed equals to 2025)	Reduction of installation cost renewable 2025 worst	Reduction of installation cost renewable 2030 worst
	Efficiency PV and wind	Increase of renewable efficiency 2024 worst	Increase of renewable efficiency 2025 worst	Increase of renewable efficiency 2030 worst

6.4 Discussion of results

The results obtained with the model by Calliope are provided for the options described before, presenting some graphs to better understand the energy mix and its evolution. Initially, there are provided the graphs of the evolution of capacity installed and energy produced/supplied/exported for all scenarios, in the case of option 1 and in the case of option 2.

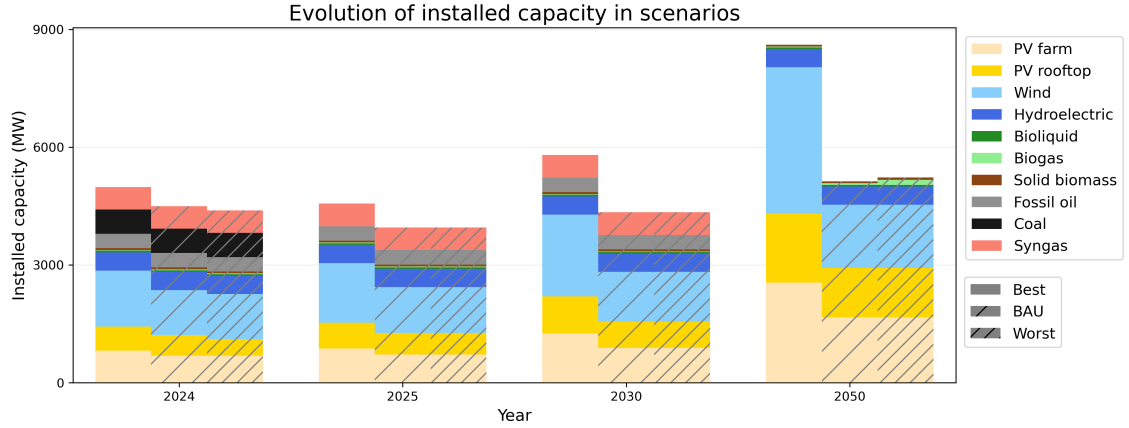


Figure 6.9: Comparison of the evolution of capacity installed in scenarios - option1

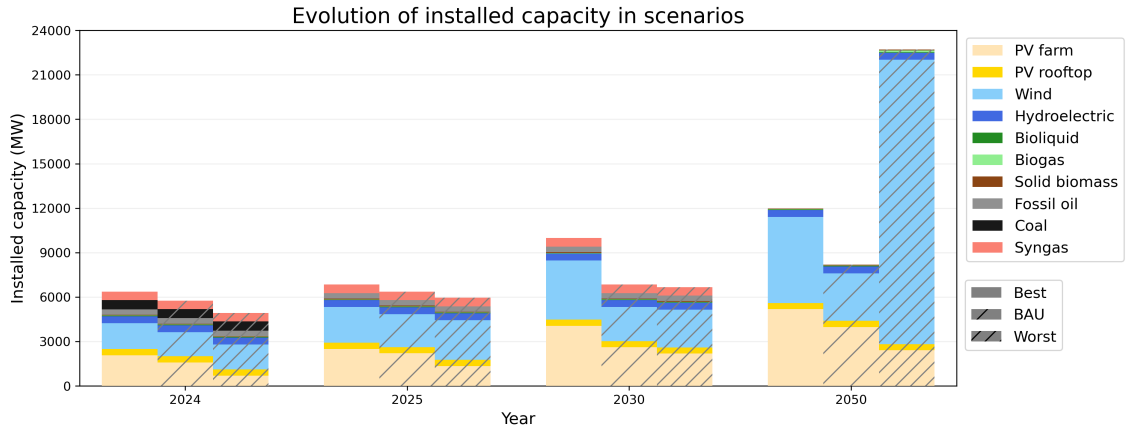


Figure 6.10: Comparison of the evolution of capacity installed in scenarios - option2

Comparing the capacities installed by Calliope in Figure 6.9 the trend of the evolution of PV and wind installed capacity continues to grow in a way almost linear in years. In fact, in this case Calliope advises to install almost in all provinces and years the maximum capacity constrained in different scenarios, that depending on the scenario is more or less representative of the actual trend of growth.

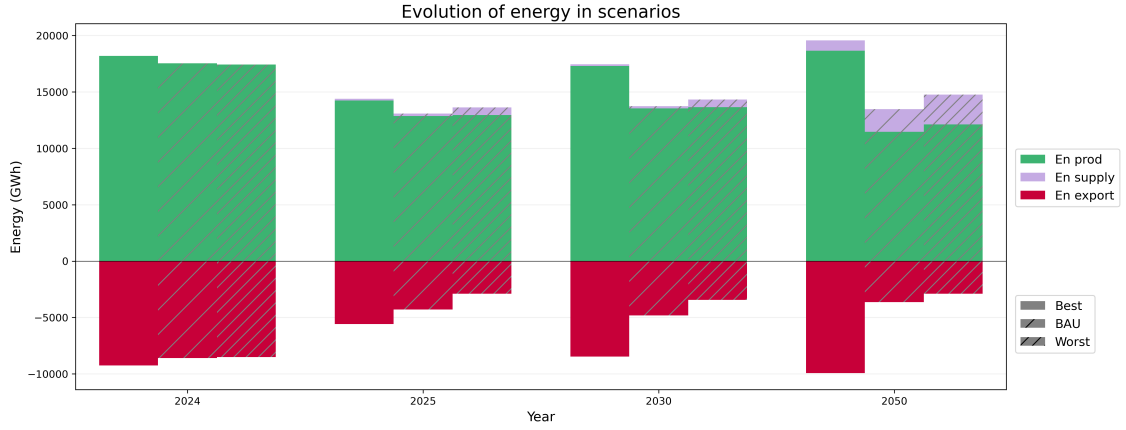


Figure 6.11: Comparison of the evolution of energy produced/exported/supplied - option 1

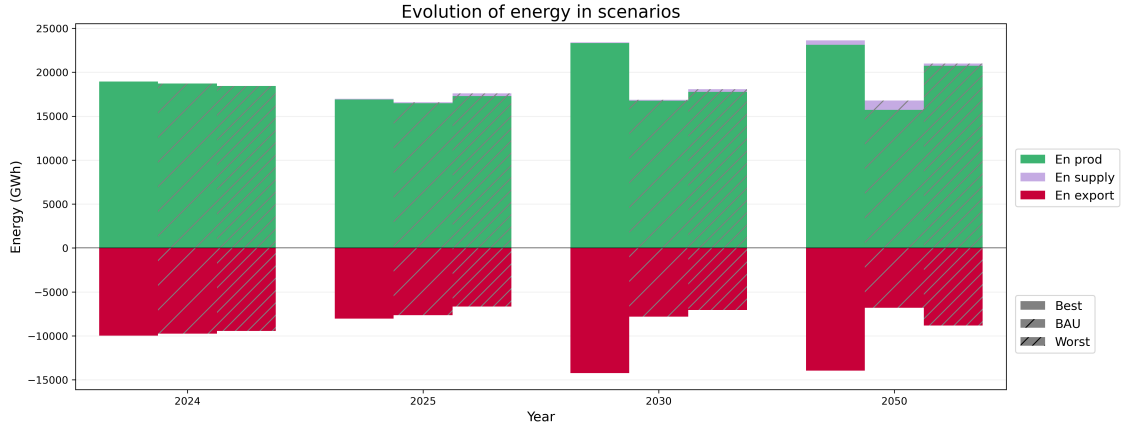


Figure 6.12: Comparison of the evolution of energy produced/exported/supplied - option 2

Instead in option 2 in Figure 6.10 with fewer constraints on maximum capacities, Calliope finds values of installed capacity higher than actual trends of growth. In particular in 2050 in the worst scenario to face the higher energy demand, due also to the presence of Eurallumina demand, Calliope installs a lot of wind energy in particular in the province of Sud Sardegna. Even if this capacity is maybe not realistic until the year 2050, it is representative of the capacity that should be installed in that year in order to increase the energy exported from Sardinia respect the year 2020, considering the worst conditions for the regional energy system. In this case in fact the energy exported in the year corresponds to 8'811.6 GWh, with the need for energy supplied of 270.6 GWh. It is also possible to consider that in this configuration the transmission line from Sud Sardegna to Cagliari is used in the year at 88% of its capacity and the one from Sud Sardegna to Oristano at 80%, therefore big energy is supplied to other locations from Sud Sardegna in this case. In both options the capacity of coal is reduced, as a constraint, of 50% in

2024 and to 0% in 2025, instead syngas and fossil oil capacities are equal until 2050, a year in which they are considered equal to 0.

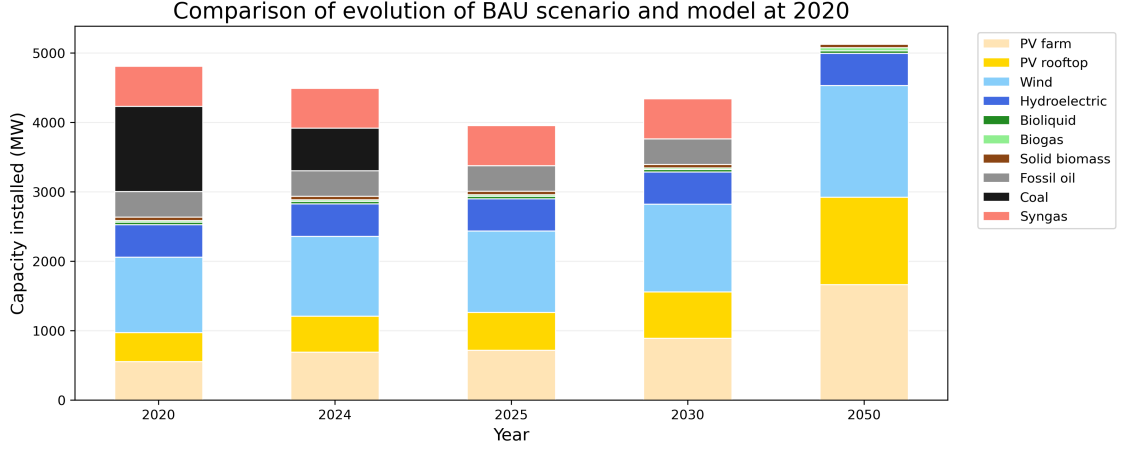


Figure 6.13: Comparison of the evolution of installed capacities in BAU scenario and base model at 2020-option 1

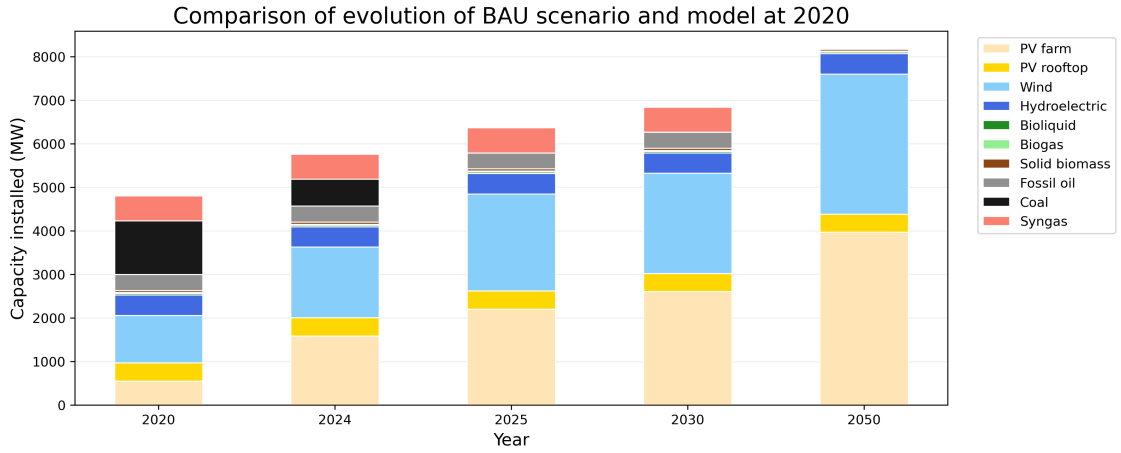


Figure 6.14: Comparison of the evolution of installed capacities in BAU scenario and base model at 2020-option 2

It can be seen in Figure 6.13 that starting from the year 2020, i.e. the base model configuration, the capacity installed in BAU scenario, for option 1, decreases until 2025. The renewable capacity installed follows the trend of actual installation growth and continues to grow until 2050.

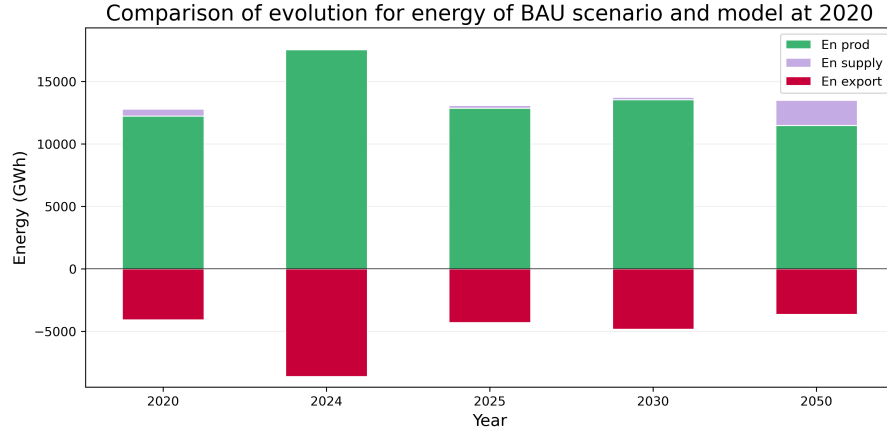


Figure 6.15: Comparison of the evolution of energy produced/exported/supplied in BAU scenario and base model at 2020-option 1

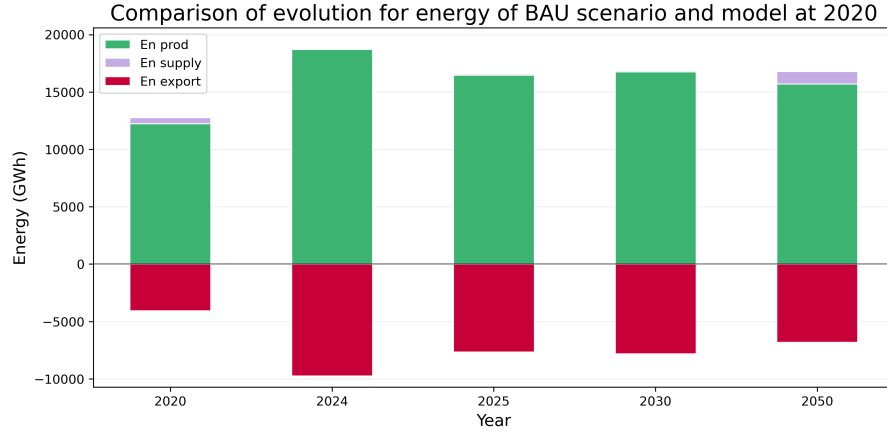


Figure 6.16: Comparison of the evolution of energy produced/exported/supplied in BAU scenario and base model at 2020 - option 2

If the **50% of coal power plants remain active in 2024**, with the energy demand of the base model, the energy produced in the region is enough to **export a bigger amount of energy** in 2024, as can be seen in Figure 6.15. Instead, with the closure of coal power plants in 2025, the amount of energy exported can be maintained only by continuing to install new PV and wind capacity, following the current trend of installation. In particular, studying the scenario BAU in 2025, for option 1, to have an exported energy of almost 4'300 GWh and imported energy of 212 GWh in this scenario the new photovoltaic capacity of 291.4 MW and new wind capacity of 83.6 MW, respect to the base model, are considered installed in 2025. Instead considering to reach the target of PNIEC in 2030, the new installed capacity from 2020 to 2025, is about 556 MW for PV and 428 MW for wind. These capacities could permit to export more energy than the year 2020, as in Figure Figure 6.19.

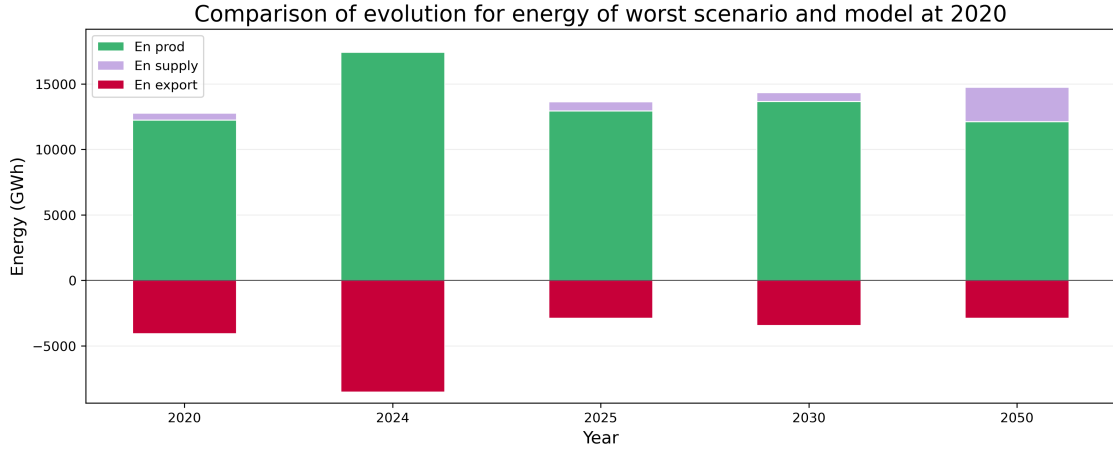


Figure 6.17: Comparison of the evolution of energy produced/exported/supplied in worst scenario and base model at 2020 - option 1

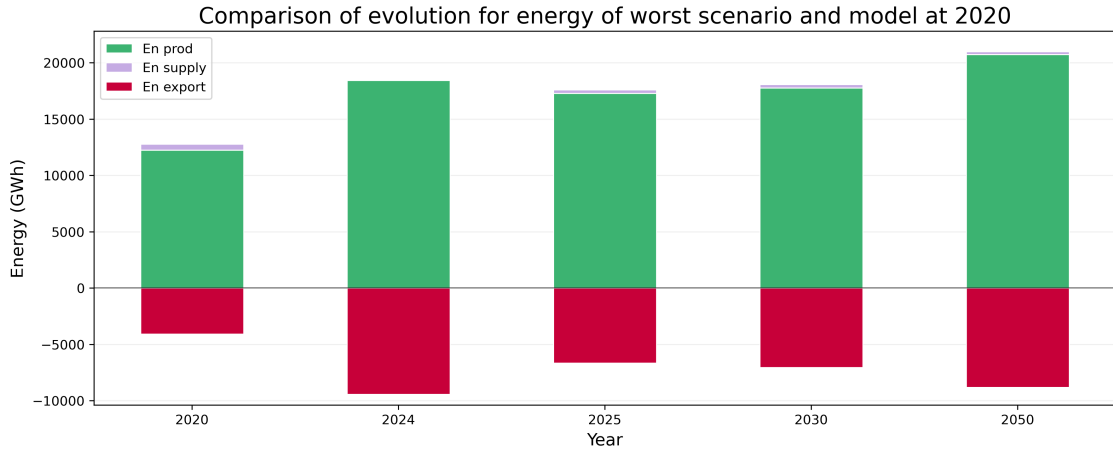


Figure 6.18: Comparison of the evolution of energy produced/exported/supplied in worst scenario and base model at 2020-option 2

Analysing the best scenario in option 1, comparing the Figure 6.20 and Figure 6.22 it is possible to notice that **with the installation of Tyrrhenian link and Sacoi 3** considered in 2030, the region can **export more energy in excess** than the year 2025, with the capacity installed planned by PNIEC in that year. In fact, comparing the year 2030 in scenario best in Figure 6.21 with the new export links and the BAU scenario without them in Figure 6.22, it is possible to notice that **with the actual trend of installation of pv and wind capacities, without the installation of Tyrrhenian link and Sacoi 3, more energy that could be exported is loss**. In fact, especially in presence of the solar resource Calliope advises to export the available energy, but cables often are saturated and do not permit the export of more energy.

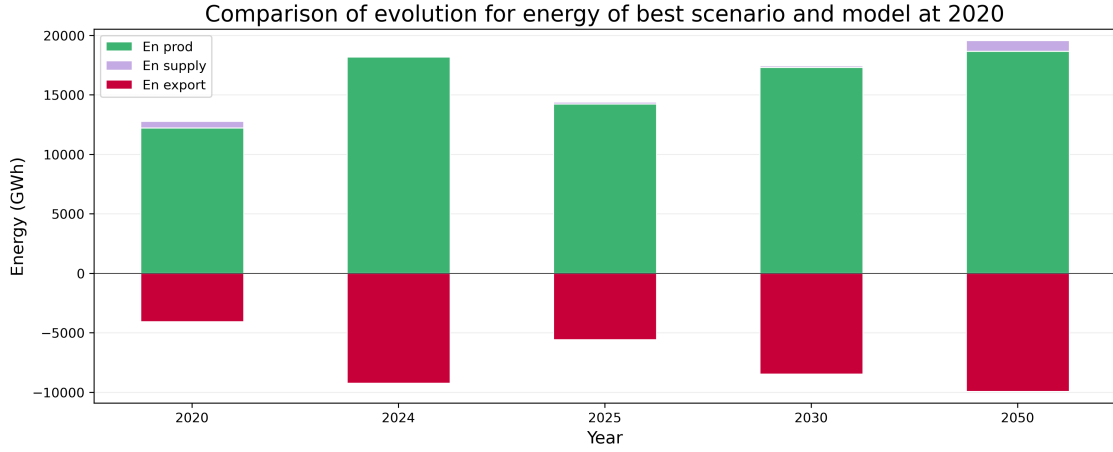


Figure 6.19: Comparison of the evolution of energy produced/exported/supplied in best scenario and base model at 2020-option 1

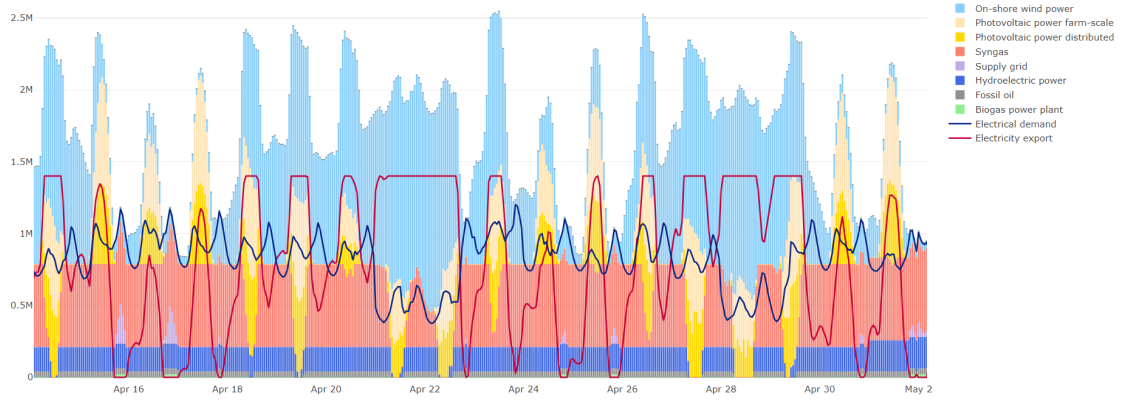


Figure 6.20: Results of energy produced visualized by Calliope for scenario best, year 2025, option 1

In Figure 6.23 the distribution of installed capacity in different provinces, for the year 2030 and option 1, is provided. These capacities are the ones constrained more in the definition, but if they are compared to the capacities in Figure 6.24 that represents option 2, in the second option in Sassari in 2030 Calliope decides to install a lot of capacity of PV farm. Even the wind capacity is consistent in Sassari, in fact this point has a location on the map near the export points and at the moment, in 2020, it has also an active coal plant.

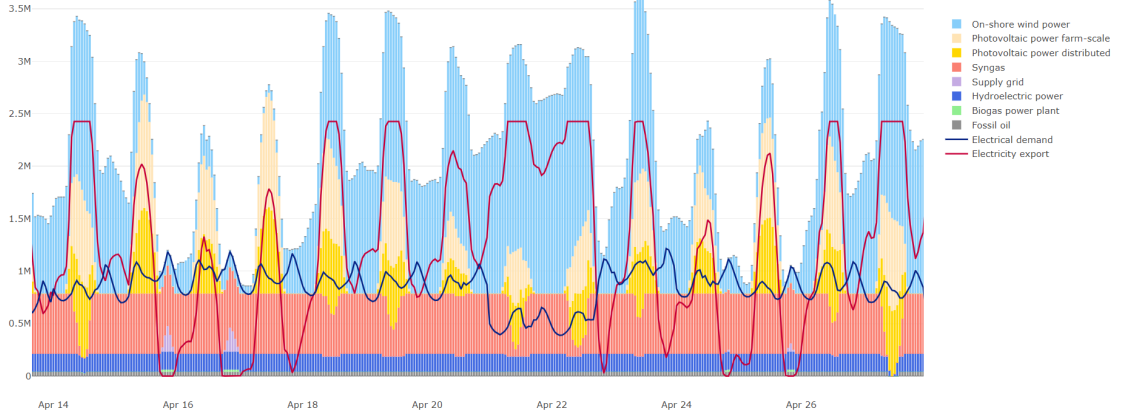


Figure 6.21: Results of energy produced visualized by Calliope for scenario best, year 2030, option 1

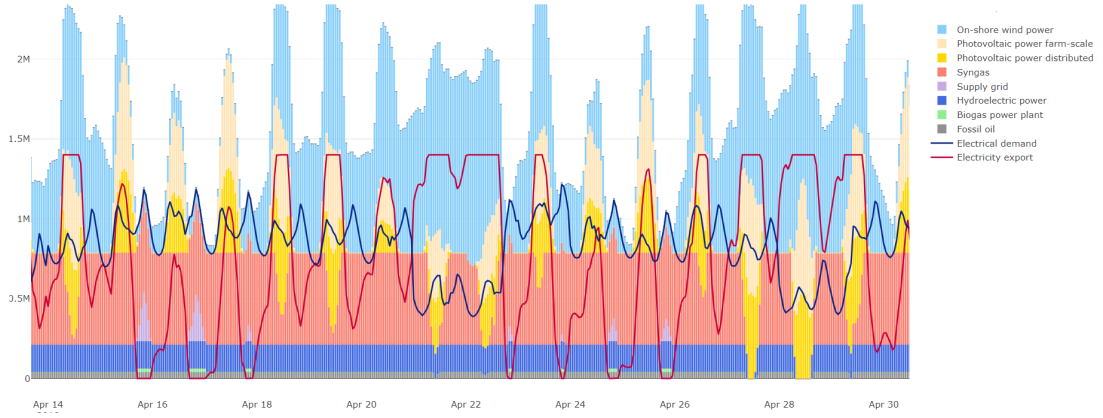


Figure 6.22: Results of energy produced visualized by Calliope for scenario BAU, year 2030, option 1

Dismissing coal power plants from 2025, taking the actual trend of growth, with the increase of demand in 2030, and then in 2050 when also fossil oil and syngas are not used, in BAU scenario it is possible to see that the **energy required will increase to 2'008 GWh, in the year 2050**. Instead, the exported energy is reduced to 3'629 GWh, about 400 GWh less than base model.

Looking at the Figure 6.11, analysing the worst scenario, from the 2025 with the **dismissing of coal power plants**, if there is also a **reactivation of the Eurallumina plant** the **energy exported in Sardinia decreases** and the **energy supplied increases** in years until the maximum value in 2050.

Even considering option 2 in Figure 6.16, where the constraint of maximum capacity is decisely higher than the actual trend of growth, in 2050 the export reduces and it is necessary more supply of energy respect to the base model.

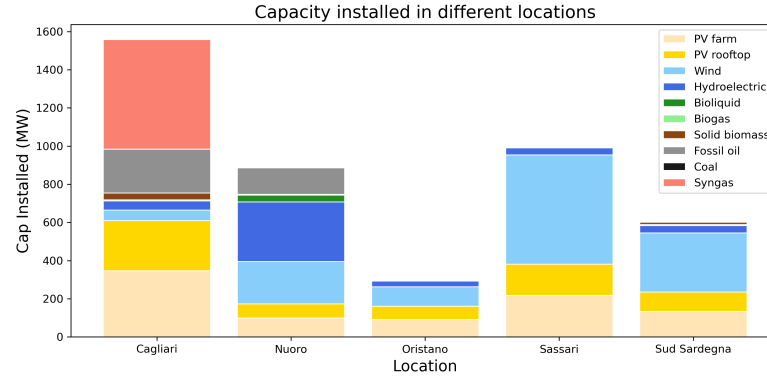


Figure 6.23: Distribution of installed capacity in different locations, for the year 2030 - Scenario BAU option 1

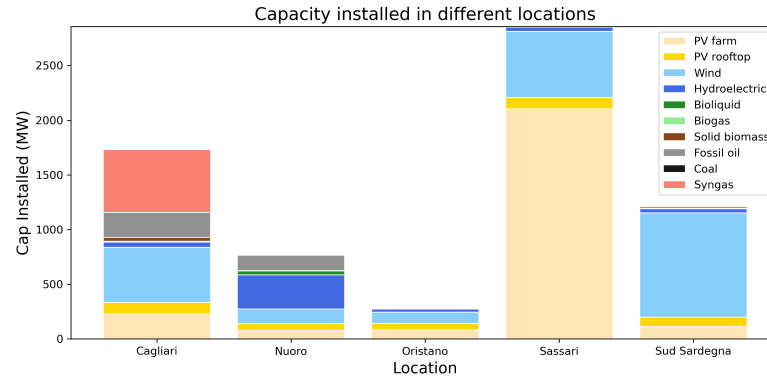


Figure 6.24: Distribution of installed capacity in different locations, for the year 2030 - Scenario BAU option 2

In this case, Calliope finds a solution in which the export of energy is bigger than the one in 2020, if compared to option 1. Instead, the supply of energy, even if it is bigger than the one in 2020, is reduced with respect to the more constrained option 1 in the same year.

If for option 1 all scenarios are compared in the year 2050, considering the Figure 6.11, it is possible to notice that **proceeding with the trend of new installed capacity more similar to the real ones, after the dismissal of coal in 2025 it is still required an amount of energy, that in the worst scenario exceeds the year 2020.** In Figure 6.26 is evident that even in option 2, with these increased capacities in 2050, also in this case when it is not present solar resource, the system requires supplied energy. At the same time, in this configuration without the Tyrrhenian link and the Saco 3, it is reached the maximum possible use of exported capacity cables for most of the time, in presence of solar resource.

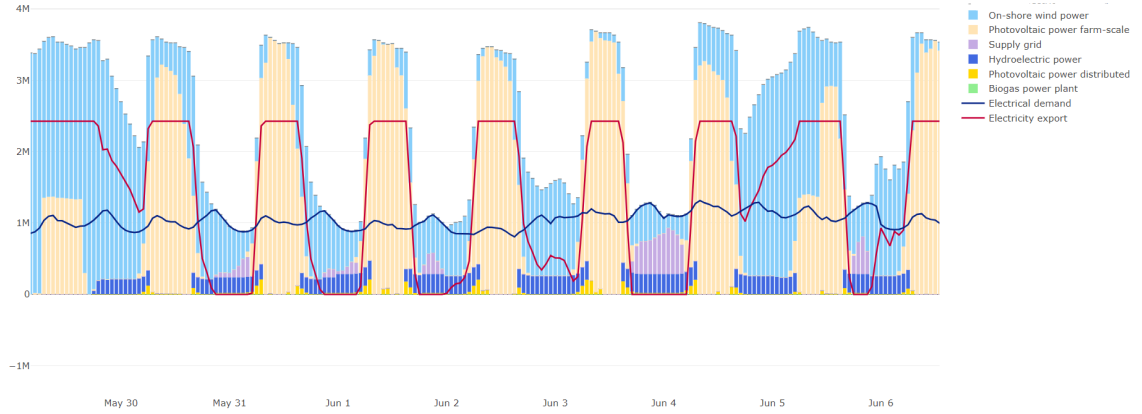


Figure 6.25: Results of energy produced visualized by Calliope for scenario best, year 2050, option 2

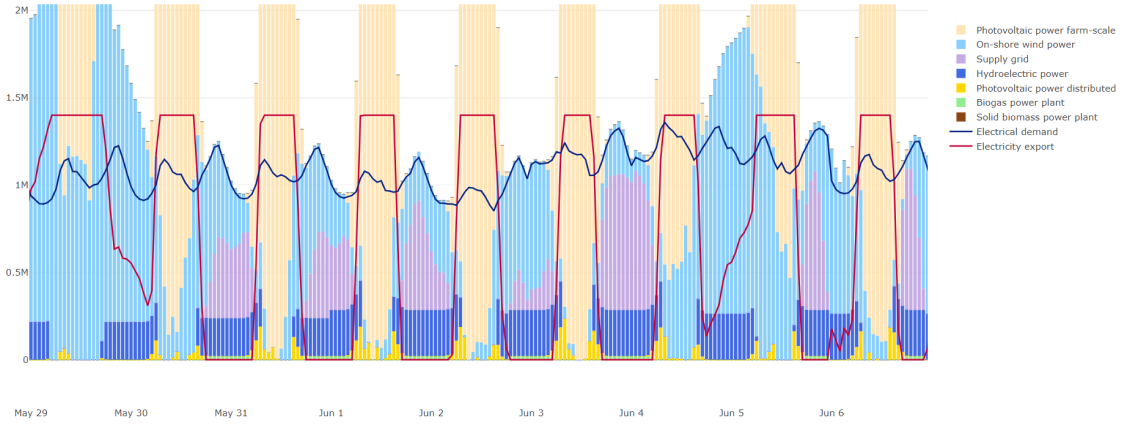


Figure 6.26: Results of energy produced visualized by Calliope for scenario BAU, year 2050, option 2

If it is instead analysed the scenario best at 2050, in which there is the availability of the Tyrrhenian Link and the Saco3, in the Figure 6.25 is clear that the supplied energy is reduced in this case, because the energy demand in 2050 is less than the BAU and worst scenarios. But also, in this case, the supplied energy is required, in absence of solar resource. The **solar resource is useful to have exported energy**, that with these capacities installed reaches the maximum capacity available of export cable. In order to provide an idea of how the composition of the energy mix could evolve, according to the scenarios created, some graphs are provided with the percentage of energy produced by different technologies in the energy mix.

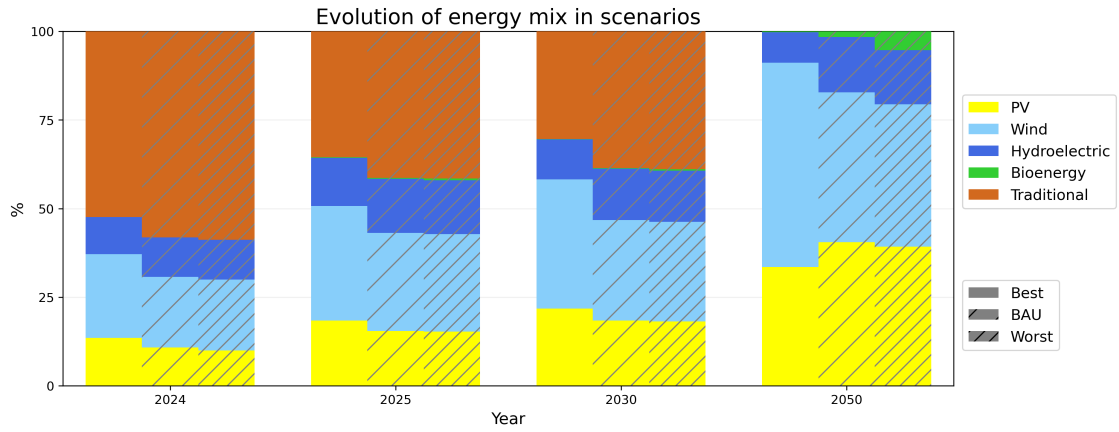


Figure 6.27: Comparison of percentage composition of the energy mix, option 1

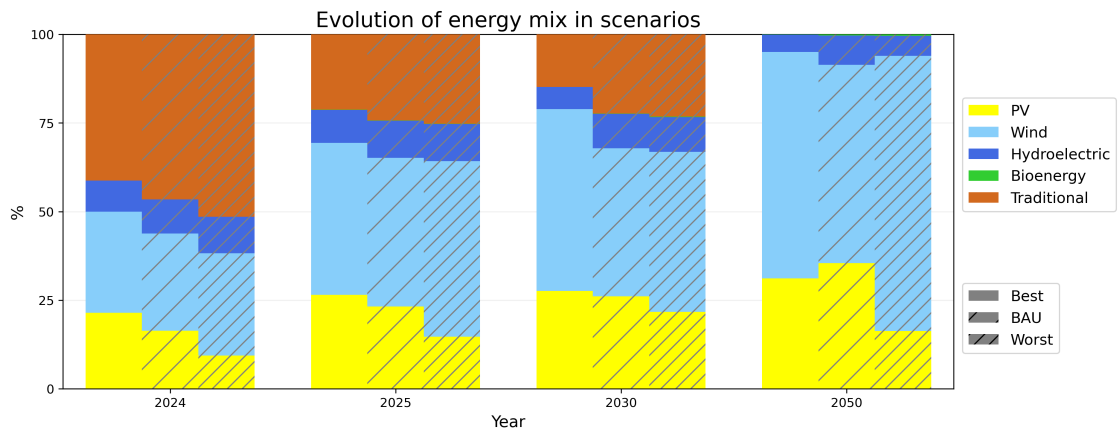


Figure 6.28: Comparison of percentage composition of the energy mix, option 2

As can be seen in Figure 6.27 and Figure 6.28 following the actual trend of installed capacity in BAU and worst scenario, Calliope advises to increment the percentage of bioenergy in the energy mix to face the increment in demand in 2050 and continue to export the energy in Figure 6.11. An idea of the installed capacity obtained by Calliope in option 2, with fewer constraints on the maximum capacity, and the target on PV and wind capacity provided by PNEIC for the year 2030, is reported in Figure 6.29 and Figure 6.30.

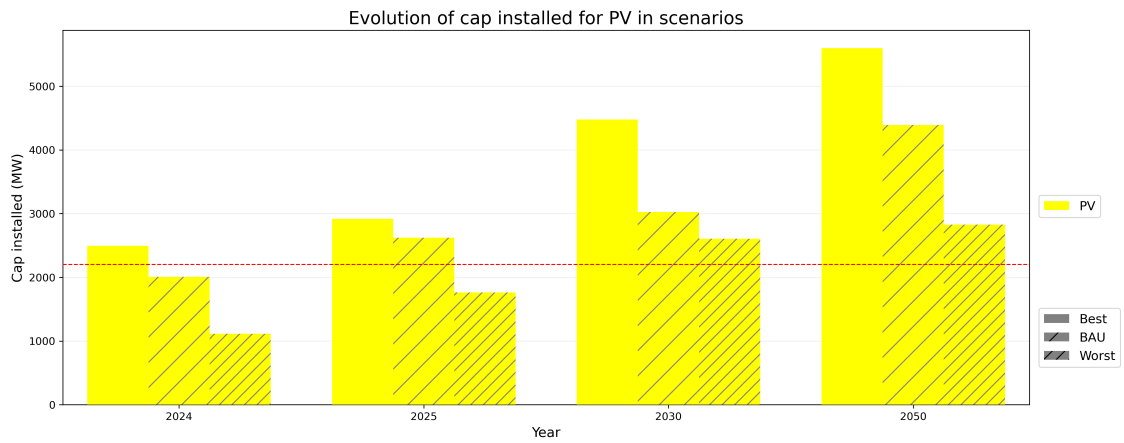


Figure 6.29: Comparison evolution of PV capacity and PNIEC target in 2030

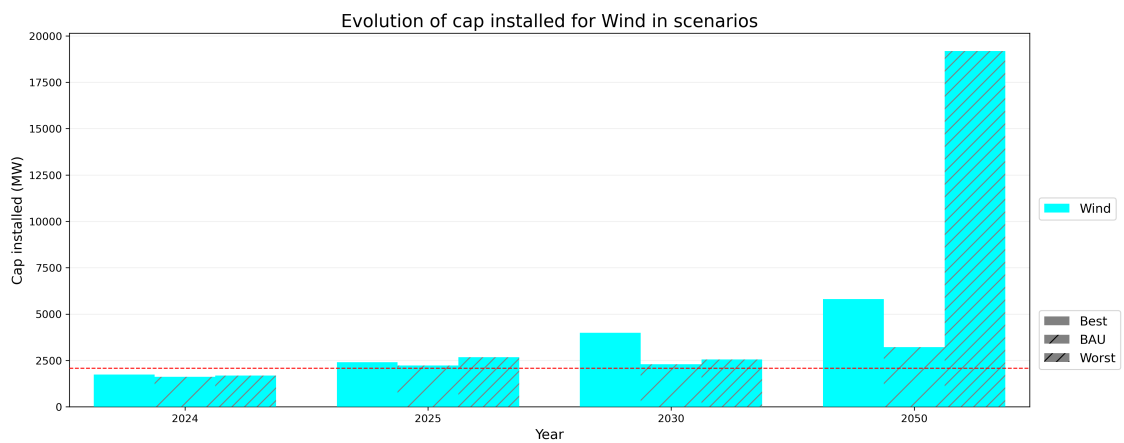


Figure 6.30: Comparison evolution of PV capacity and PNIEC target in 2030

In order to understand how the transmission line use is modified in the year 2050, when it is considered the maximum capacity of PV and wind systems, it is provided in Table 6.12 the percentage maximum and medium use, as done before for the base model in chapter 4.

Table 6.12: Percentage maximum and medium use of transmission lines in the year 2050 for different scenarios

Connection link	Use of transmission lines in scenarios at 2050											
	Best				BAU				Worst			
	max 1	max 2	med 1	med 2	max 1	max 2	med 1	med 2	max 1	max 2	med 1	med 2
SS-ST	98%	37%	40%	1%	98%	98%	15%	4%	98%	98%	11%	7%
SS-FS	72%	28%	32%	1%	72%	70%	21%	13%	72%	70%	17%	18%
ST-NU	0%	98%	0%	71%	98%	98%	20%	44%	98%	98%	15%	36%
SS-NU	98%	98%	7%	83%	98%	98%	2%	32%	98%	98%	2%	27%
SS-N1	98%	98%	8%	17%	98%	98%	13%	22%	98%	98%	20%	16%
SS-OR	98%	98%	4%	60%	98%	98%	31%	23%	98%	98%	56%	14%
N1-OR	98%	98%	3%	44%	98%	98%	9%	10%	98%	98%	31%	5%
N1-CA	98%	54%	49%	1%	98%	98%	29%	18%	98%	98%	33%	13%
OR-SU	98%	98%	12%	20%	91%	98%	16%	12%	98%	98%	50%	2%
SU-CA	98%	72%	61%	4%	98%	98%	8%	1%	98%	98%	1%	15%

In Table 6.12 at 2050 a lot of lines reaches the maximum percentage in the year in this configuration of the model. From these results, it is interesting to notice that maybe the new installation of capacity in the region should be coupled with the extension or increment of transmission lines.

Chapter 7

Conclusion

In conclusion, this work provides an energy model of the region Sardinia approximating the real energy system in this region. After a validation phase of this model, it is used to provide scenarios on the possible evolution of the energy mix in years, considering the variation of some parameters and main projects planned for the energy system of Sardinia.

The model chosen after the validation phase is tested with some configurations and it can be considered an approximation of the energy system of the region, even if there are some uncertainties. In fact, the locations considered for the installed capacity in the model are just five, therefore an approximation of the distribution of the installed capacity in the region is done. Also, the transmission lines, even if they are modeled and tested to represent as more as possible the real ones, in the real system they are more branched, of course, than the ones in the model.

The real energy system of Sardinia results enough critical due to its insularity characteristic and the connection with other zones constrained to few cables. In addition, this region, at the moment, exports a big amount of energy and this needs to be considered in the model and in its possible evolution because it could be a necessity of energy for other bidding zones.

An obstacle found in this work is related to the research of capacities installed, estimated energies and maximum potential capacities from different sources. In fact, it is difficult in some cases to find exact data on literature, due also to the change in the distribution of regional provinces after the year 2016.

The scenarios constructed result useful to represent the evolution of the energy mix in years for the region, from the situation that has the less impact on the energy system, to the worst situation for the energy system.

From results obtained using Calliope [18] it is found that in 2024 the reduction of coal by 50% could be an option for the region to export more energy. Nevertheless, with the target to decarbonize the energy system in the production of energy dismissing the coal power plants in 2025, it is necessary to install new pv and wind capacity to continue to face the energy demand and the actual exported energy. The installation of Tyrrhenian link and Sacoï 3 is a good option that could permit to export a bigger amount of energy from the region, in particular in the moments in the day when there is a solar resource.

Instead, considering the dismissing of coal, fossil oil and syngas plants in 2050, the energy supplied increases in the moment when solar resource is not present. This is valid if it is considered to maintain the trend of installation of PV and wind technology similar to the actual ones, and almost the same exported energy.

Considering also the reactivation of the Eurallumina plant, and the increase of the energy demand that this reactivation should cause, with the actual trends, the energy exported from the region is reduced and the supplied energy increased.

According to Terna, to dismiss the coal power plants it is necessary to install a new capacity of 500 MW and to realize the new Tyrrhenian link connection [50]. If results provided by Calliope are considered, installing in BAU scenario, for option 1, in 2025 a new capacity of almost 380 MW it is possible to maintain an export of about 4'300 GWh, similar to the 4'070 GWh of the year 2020. But this scenario considers that there is not an increase of demand. If instead the demand is increased with the reactivation of Eurallumina plant, i.e. the worst scenario, under the assumption to install the same capacities, the exported energy is reduced to 2'900 GWh, therefore these data on installed capacities are in accordance with the ones provided by Terna.

After the analysis of results obtained, Calliope results a good tool for the construction of the energy model, mainly for the construction of scenarios. Its intuitive definition of technologies and locations permits to define also a region composed of different urban districts, connected between them. The model, as it is constructed, could be expanded introducing, for example, a technology to simulate the storage, since in scenarios results that an amount of energy is loss when cables, able to export energy, are saturated. In particular, it can be considered a storage for photovoltaic technology, because this resource results to increase the availability of energy to export in moments when it is present.

In future developments of this work, it could be considered a possible extension of the lines and assess their impact on the energy production mix over the years. Another interesting extension of the work could be to integrate in this project, in which the only carrier considered is the electricity, the presence of other carriers. For example, it is possible to integrate into the project a possible gas network, which extension is a current topic in Sardinia in recent years.

Appendix A

Appendix

A.1 Validation

The validation phase of the model is done by changing the model many times in order to represent the energy system of Sardinia as near as possible to the actual one.

The capacities installed for power plants are considered in the system concentrated in the cities of Cagliari, Nuoro, Oristano, Sassari and Sud Sardegna but in the real region are obviously more distributed. Even the transmission lines in the model as described in chapter 4 are more approximated than real ones. Therefore it is necessary to consider that it is built an approximated model that can not correspond totally to the real situation.

It is also important to notice that Calliope is an optimization framework, therefore when it is built the model and it is run using Calliope, this framework tries to optimize the model. In this case, it is run in operational mode with as objective function the minimization of the cost of the system, therefore Calliope tries to optimize the dispatch of energy minimizing the cost of the system. Considering the software and the model, different modifications are done in order to understand which configuration is the one that better represents the real system.

At first it is built the model using the configuration called A. After some changes to the model it is done a sensitivity analysis to understand the effect of little modifications on costs on the configuration called B. In particular in the operational mode the costs that are more significative are the cost of production (om_prod) and the cost of consumption (om_con) and the sensitivity analysis is done changing these two costs.

It can be noticed that the effect of change om_prod or om_con is almost the same. For simplicity the cost om_prod and om_con are changed incorporating both in one, om_con is imposed to 0 when it is changed for a technology and included in the value of om_prod. This analysis is done starting from costs taken as reference ones, in Table 5.2 except for the hydroelectric technology for which the analysis starts considering it as a free resource. The sum of om_prod and om_con is reported in Table A.3 with the starting costs of *om_prod* and *om_con* summed for the different sensitivity analyses done. The analysis is done starting from the hydroelectric energy, that with these costs is producing a lot of energy respect to the estimated value as in the Table A.1, because it has a production and consumption cost set equal to zero, as wind and solar energy.

Table A.1: Energy produced and expected before the sensitivity analysis

Technology	Expected energy (GWh)	Energy produced in model (GWh)
Pv farm	556.035	851
Pv rooftop	419.465	642
Wind (onshore)	2014.2	3284
Hydroelectric	418.2	1966
Bioliquld	316	0
Biogas	194.8	0
Solid biomass	346.9	0
Fossil oil	517.1	0
Coal	4027.1	5520
Syngas	4000	2

The cost of consumption can be considered as the cost of fuel and these three technologies are assumed free resources, but hydroelectric power plants can have production costs for example for pumps. Therefore it is performed a sensitivity analysis changing the cost of production starting from hydroelectric energy to understand the effect of the variation of this cost on the energy produced by this technology but also on the energy mix. In Table A.3 it is presented the steps done to perform the sensitivity analysis starting from the left to the right part. Initially, it is done a rougher analysis to understand which is the interval of cost of production that generates a value of hydroelectric energy as near as possible to the expected value. Then it is performed a finer analysis varying the cost of production only at that interval, to obtain the value of 0.02652 €/kWh. This value is used in the model to proceed with the sensitivity analysis of syngas, in the same way, doing the analysis on technologies in the following order:

- Hydroelectric;
- Syngas;
- Wind;
- PV farm and PV rooftop;
- Solid biomass;
- Bioliquld;
- Biogas;
- Fossil oil;
- Coal.

As a result of this analysis, the costs of different technologies can permit to allow the use of one technology respect another one, and use this technology to produce the estimated energy. But when all analyses are performed it can be noticed that using all the costs obtained from this analysis the energy produced by different technologies is not more the expected one, in fact the hydroelectric power plants are not producing energy anymore and the photovoltaic energy produced is reduced. This is caused by the optimization on costs done by Calliope and that it tries to use the more convenient technology. These sensitivity analysis are useful to understand that the effect of changing the cost of production and consumption is almost the same on different technologies. Different technologies can be used by Calliope to produce energy with the objective function to minimize the cost of the system only if all costs for different technologies are comparable.

The costs are taken from sources when it is possible or in other cases, some assumptions are done. In Table A.2 there is a classification on installation costs taken from references and those assumed.

Table A.2: Subdivision between installation costs for different technology between ones taken from references (IEA [34], IRENA [35], Model of Italy [36], Model of UK [12], article on IGCC [49] and costs from assumptions.

Technology	Installation cost (eur/kW/y)	From resource	Assumptions done
Pv farm	677	Model Italy	
Pv rooftop	871	Model Italy	
Wind (onshore)	1600	IRENA 2020	
Hydroelectric	3227	Model Italy	
Bioliquid	2901	Model Italy	
Biogas	2901	Model Italy	
Solid biomass	2901		Supposed some as Biogas
Fossil oil	1876	EIA	
Coal	1876	Model UK	
Syngas	2245	Techno-Economic Assessment of IGCC Power Plants	

Table A.3: Costs used to perform the sensitivity analysis

Technology	Initial costs considered	om_prod+om_con (eur/kWh)											
		Hydroelectric 1	Hydroelectric 2	Syngas	Syngas2	Wind	Wind 2	PV	PV 2	Solid biomass	Solid biomass 2	Bioliqid	Bioliqid 2
Pv farm	0	0	0	0	0	0	0	0.01÷ 0.045	0.025÷ 0.0295	0.026	0.026	0.026	0.026
Pv rooftop	0	0	0	0	0	0	0	0.01÷ 0.045	0.025÷ 0.0295	0.026	0.026	0.026	0.026
Wind (onsore)	0	0	0	0	0	0.01÷ 0.04	0.025÷ 0.029	0.026	0.026	0.026	0.026	0.026	0.026
Hydroelectric	0	0 ÷ 0.05	0.02 ÷ 0.0296	0.02652	0.02652	0.02652	0.02652	0.02652	0.02652	0.02652	0.02652	0.02652	0.02652
Bioliqid	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.001÷ 0.061	0.02÷ 0.028
Biogas	0.0584	0.0584	0.0584	0.0584	0.0584	0.0584	0.0584	0.0584	0.0584	0.0584	0.0584	0.0584	0.0584
Solid biomass	0.1618	0.1618	0.1618	0.1618	0.1618	0.1618	0.1618	0.1618	0.1618	0.001÷ 0.141	0.02÷ 0.029	0.0254	0.0254
Fossil oil	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0÷ 0.028	0.026÷ 0.028
Coal	0.0113	0.0113	0.0113	0.0113	0.0113	0.0113	0.0113	0.0113	0.0113	0.0113	0.0113	0.0113	0.01÷ 0.08
Syngas	0.03539	0.03539	0.03539	0÷ 0.5	0.0240÷ 0.0258	0.0251	0.0251	0.0251	0.0251	0.0251	0.0251	0.0251	0.0251

Locations.yaml file

```

locations:
  cagliari:
    techs:
      pv_farm:
        constraints:
          resource: file=pv_resource_sardegna_electricity.csv
          energy_cap_equals: 141900 #kW
      pv_rooftop:
        constraints:
          resource: file=pv_resource_sardegna_electricity.csv
          energy_cap_equals: 107100 #kW
      wind:
        constraints:
          resource: file=wind_resource_sardegna_electricity.csv
          energy_cap_equals: 46500 #kW
      hydro:
        constraints:
          resource: file=hydro_creato_dalombardi.csv
          energy_cap_equals: 47700 #kW Flumendosa hydroelectric
                                                    power plant
                                                    considered in
                                                    Cagliari
      fossil_oil:
        constraints:
          energy_cap_equals: 229000 #kW
      syngas:
        constraints:
          energy_cap_equals: 575000 #kW
      coal:
        constraints:
          energy_cap_equals: 0
      bioliquid:
        constraints:
          energy_cap_equals: 0
      solid_biomass:
        constraints:
          energy_cap_equals: 35800 #kW
      biogas:
        constraints:
          energy_cap_equals: 6400 #kW
      demand_electricity:
        constraints.resource: file=demand_power.csv:cagliari
      coordinates: {x: 39.21666700, y: 9.11666700}
  nuoro:
    techs:
      pv_farm:
        constraints:
          resource: file=pv_resource_sardegna_electricity.csv
          energy_cap_equals: 79500 #kW
      pv_rooftop:
        constraints:
          resource: file=pv_resource_sardegna_electricity.csv
          energy_cap_equals: 60000 #kW

```

```

wind:
  constraints:
    resource: file=wind_resource_sardegna_electricity.csv
    energy_cap_equals: 134300 #kW
hydro:
  constraints:
    resource: file=hydro_createo_dalombardi.csv
    energy_cap_equals: 312100 #kW not considered
                                Flumendosa
                                hydroelectric
                                power plant
fossil_oil:
  constraints:
    energy_cap_equals: 140000 #kW
bioliquid:
  constraints:
    energy_cap_equals: 37000 #kW
solid_biomass:
  constraints:
    energy_cap_equals: 1000 #kW
coal:
  constraints:
    energy_cap_equals: 0
syngas:
  constraints:
    energy_cap_equals: 0
biogas:
  constraints:
    energy_cap_equals: 2000 #kW
demand_electricity:
  constraints.resource: file=demand_power.csv:nuoro
coordinates: {x: 40.32006100, y: 9.32807800}
oristano:
  techs:
    pv_farm:
      constraints:
        resource: file=pv_resource_sardegna_electricity.csv
        energy_cap_equals: 81200 #kW
    pv_rooftop:
      constraints:
        resource: file=pv_resource_sardegna_electricity.csv
        energy_cap_equals: 61300 #kW
    wind:
      constraints:
        resource: file=wind_resource_sardegna_electricity.csv
        energy_cap_equals: 102300 #kW
    hydro:
      constraints:
        resource: file=hydro_createo_dalombardi.csv
        energy_cap_equals: 30300 #kW
    bioliquid:
      constraints:
        energy_cap_equals: 0
    solid_biomass:
      constraints:

```

```

        energy_cap_equals: 0
    biogas:
        constraints:
            energy_cap_equals: 2500 #kW
    coal:
        constraints:
            energy_cap_equals: 0
    fossil_oil:
        constraints:
            energy_cap_equals: 0
    syngas:
        constraints:
            energy_cap_equals: 0
    demand_electricity:
        constraints.resource: file=demand_power.csv:oristano
    coordinates: {x: 39.90581900, y: 8.59160800}
sassari:
    techs:
        pv_farm:
            constraints:
                resource: file=pv_resource_sardegna_electricity.csv
                energy_cap_equals: 137900 #kW
        pv_rooftop:
            constraints:
                resource: file=pv_resource_sardegna_electricity.csv
                energy_cap_equals: 104100 #kW
        wind:
            constraints:
                resource: file=wind_resource_sardegna_electricity.csv
                energy_cap_equals: 556900 #kW
        hydro:
            constraints:
                resource: file=hydro_creato_dalombardi.csv
                energy_cap_equals: 37600 #kW
        bioliquid:
            constraints:
                energy_cap_equals: 0
        solid_biomass:
            constraints:
                energy_cap_equals: 0
        fossil_oil:
            constraints:
                energy_cap_equals: 0
        coal:
            constraints:
                energy_cap_equals: 640000 #kW
        syngas:
            constraints:
                energy_cap_equals: 0
        biogas:
            constraints:
                energy_cap_equals: 5000 #kW
        demand_electricity:
            constraints.resource: file=demand_power.csv:sassari
    coordinates: {x: 40.72666700, y: 8.55916700}

```



```

sud_sardegna:
  techs:
    pv_farm:
      constraints:
        resource: file=pv_resource_sardegna_electricity.csv:
                                sudsardegna
        energy_cap_equals: 114400 #kW
    pv_rooftop:
      constraints:
        resource: file=pv_resource_sardegna_electricity.csv:
                                sudsardegna
        energy_cap_equals: 86300 #kW
    wind:
      constraints:
        resource: file=wind_resource_sardegna_electricity.csv:
                                sudsardegna
        energy_cap_equals: 247500 #kW
    hydro:
      constraints:
        resource: file=hydro_createo_dalombardi.csv
        energy_cap_equals: 38700 #kW
    coal:
      constraints:
        energy_cap_equals: 590000 #kW
    solid_biomass:
      constraints:
        energy_cap_equals: 13000 #kW
    fossil_oil:
      constraints:
        energy_cap_equals: 0
    bioliquid:
      constraints:
        energy_cap_equals: 0
    biogas:
      constraints:
        energy_cap_equals: 5000 #kW
    syngas:
      constraints:
        energy_cap_equals: 0
    demand_electricity:
      constraints.resource: file=demand_power.csv:sud_sardegna
    coordinates: {x: 39.16680300, y: 8.59160800}
# locations for import and export connections
santa_teresa: #SARCO +SACOI
  techs:
    el_export: # export excess electricity
      constraints:
        resource: file=Export_Sardegna_crossborderST.csv:
                                el_export #
                                SARCO+SACOI
    el_import: #import eletricity needed
      constraints:
        resource: file=Import_Sardegna_crossborderST.csv:
                                el_import #
                                SARCO+SACOI

```

```

    coordinates: {x: 41.249458737095914, y: 9.18228610698874}
fiume_santo: #SAPEI
  techs:
    el_export: # export excess electricity
      constraints:
        resource: file=Export_Sardegna_crossborderFS.csv:
          el_export #
          SAPEI
    el_import: #import electricity needed
      constraints:
        resource: file=Import_Sardegna_crossborderFS.csv:
          el_import #
          SAPEI
    coordinates: {x: 40.80475255695234, y: 8.280497658610829}
# connection node
N1:
  coordinates: {x: 40.22358298279619, y: 8.779904074601498} #
    location near macomer
links:
  #links for locations for import and export-start
  sassari,fiume_santo:
    techs:
      power_lines:
        constraints:
          energy_cap_equals: 1395000 #1917000 #kW elettrodotto
            380kV+380kV+150kV
  sassari,santa_teresa:
    techs:
      power_lines:
        constraints:
          energy_cap_equals: 265500 #180000 #kW elettrodotto
            220kV
  #links for locations for import and export-end
  #internal connections
  santa_teresa,nuoro:
    techs:
      power_lines:
        constraints:
          energy_cap_equals: 170000 #180000 #117000 #kW
            elettrodotto
            150kV
  nuoro,sassari:
    techs:
      power_lines:
        constraints:
          energy_cap_equals: 117000 #kW elettrodotto 150kV
  sassari,N1:
    techs:
      power_lines:
        constraints:
          energy_cap_equals: 696000 #kW elettrodotto 380Kv+220kV
            +150kV
  N1,nuoro:
    techs:
      power_lines:

```

```

        constraints:
            energy_cap_equals: 1000000000 #kW dummy link
sassari,oristano:
    techs:
        power_lines:
            constraints:
                energy_cap_equals: 180000 #kW elettrodotto 220kV
N1,oristano:
    techs:
        power_lines:
            constraints:
                energy_cap_equals: 117000 #kW elettrodotto 150kV
N1,cagliari:
    techs:
        power_lines:
            constraints:
                energy_cap_equals: 720000 #kW elettrodotto 380kV+220kV
                                EVENTUALMENTE
                                AGGIUNGERE ANCHE
                                150kV
cagliari,sud_sardegna:
    techs:
        power_lines:
            constraints:
                energy_cap_equals: 435000 #kW elettrodotto 220kV+220kV
                                +150kV
sud_sardegna,oristano:
    techs:
        power_lines:
            constraints:
                energy_cap_equals: 265500 #kW elettrodotto 220kV+150kV

```

A.2 Scenarios

Locations.yaml file

```

locations: #cap_min installed corresponding to 2019/2020
    cagliari:
        techs:
            pv_farm:
                constraints:
                    resource: file=pv_resource_sardegna_electricity.csv
                    energy_cap_min: 141900 #kW
                    #energy_cap_max: 156800 #kW
            pv_rooftop:
                constraints:
                    resource: file=pv_resource_sardegna_electricity.csv
                    energy_cap_min: 107100 #kW
                    # energy_cap_max: 118300 #kW
            wind:
                constraints:
                    resource: file=wind_resource_sardegna_electricity.csv
                    energy_cap_min: 46500 #kW

```

```

        # energy_cap_max: 66800 #kW
hydro:
  constraints:
    resource: file=hydro_creato_dalombardi.csv
    energy_cap_equals: 47700 #kW Flumendosa hydroelectric
                                power plant
                                considered in
                                Cagliari

fossil_oil:
  constraints:
    energy_cap_equals: 229000 #kW

syngas:
  constraints:
    energy_cap_equals: 575000 #kW

solid_biomass:
  constraints:
    energy_cap_min: 35800 #kW
    energy_cap_max: 37200 #kW

bioliquid:
  constraints:
    energy_cap_equals: 0 #kW

coal:
  constraints:
    energy_cap_equals: 0 #kW

biogas:
  constraints:
    energy_cap_min: 6400 #kW
    # energy_cap_max: 8400 #kW
    energy_cap_max: 38900 #kW

demand_electricity:
  constraints.resource: file=demand_power.csv:cagliari
coordinates: {x: 39.21666700, y: 9.11666700}

nuoro:
  techs:
    pv_farm:
      constraints:
        resource: file=pv_resource_sardegna_electricity.csv
        energy_cap_min: 79500 #kW
        # energy_cap_max: 168100 #kW
    pv_rooftop:
      constraints:
        resource: file=pv_resource_sardegna_electricity.csv
        energy_cap_min: 60000 #kW
        # energy_cap_max: 126800 #kW
    wind:
      constraints:
        resource: file=wind_resource_sardegna_electricity.csv
        energy_cap_min: 134300 #kW
        # energy_cap_max: 250000 #kW
    hydro:
      constraints:
        resource: file=hydro_creato_dalombardi.csv

```

```

        energy_cap_equals: 312100 #kW not considered
                                Flumendosa
                                hydroelectric
                                power plant

fossil_oil:
    constraints:
        energy_cap_equals: 140000 #kW
bioliquid:
    constraints:
        energy_cap_equals: 37000 #kW
solid_biomass:
    constraints:
        energy_cap_min: 1000 #kW
        energy_cap_max: 2300 #kW
biogas:
    constraints:
        energy_cap_min: 2000 #kW
        # energy_cap_max: 8600 #kW
        energy_cap_max: 40000 #kW
coal:
    constraints:
        energy_cap_equals: 0
syngas:
    constraints:
        energy_cap_equals: 0
demand_electricity:
    constraints.resource: file=demand_power.csv:nuoro
coordinates: {x: 40.32006100, y: 9.32807800}

oristano:
    techs:
        pv_farm:
            constraints:
                resource: file=pv_resource_sardegna_electricity.csv
                energy_cap_min: 81200 #kW
                # energy_cap_max: 108300 #kW
        pv_rooftop:
            constraints:
                resource: file=pv_resource_sardegna_electricity.csv
                energy_cap_min: 61300 #kW
                # energy_cap_max: 81700 #kW
        wind:
            constraints:
                resource: file=wind_resource_sardegna_electricity.csv
                energy_cap_min: 102300 #kW
                # energy_cap_max: 160000 #kW
        solid_biomass:
            constraints:
                energy_cap_min: 0 #kW
                energy_cap_max: 900 #kW
        hydro:
            constraints:
                resource: file=hydro_creato_dalombardi.csv
                energy_cap_equals: 30300 #kW
        biogas:

```

```

        constraints:
            energy_cap_min: 2500 #kW
            # energy_cap_max: 7700 #kW
            energy_cap_max: 35800 #kW
    bioliquid:
        constraints:
            energy_cap_equals: 0
    fossil_oil:
        constraints:
            energy_cap_equals: 0
    coal:
        constraints:
            energy_cap_equals: 0
    syngas:
        constraints:
            energy_cap_equals: 0
    demand_electricity:
        constraints.resource: file=demand_power.csv:oristano
    coordinates: {x: 39.90581900, y: 8.59160800}

sassari:
    techs:
        pv_farm:
            constraints:
                resource: file=pv_resource_sardegna_electricity.csv
                energy_cap_min: 137900 #kW
                # energy_cap_max: 199500 #kW
        pv_rooftop:
            constraints:
                resource: file=pv_resource_sardegna_electricity.csv
                energy_cap_min: 104100 #kW
                # energy_cap_max: 150500 #kW
        wind:
            constraints:
                resource: file=wind_resource_sardegna_electricity.csv
                energy_cap_min: 556900 #kW
                # energy_cap_max: 610000 #kW
        hydro:
            constraints:
                resource: file=hydro_creato_dalombardi.csv
                energy_cap_equals: 37600 #kW
        coal:
            constraints:
                energy_cap_equals: 320000 #kW
        biogas:
            constraints:
                energy_cap_min: 5000 #kW
                # energy_cap_max: 11100 #kW
                energy_cap_max: 51600 #kW
        solid_biomass:
            constraints:
                energy_cap_min: 0 #kW
                energy_cap_max: 2600 #kW
        bioliquid:
            constraints:

```

```

        energy_cap_equals: 0
fossil_oil:
    constraints:
        energy_cap_equals: 0
syngas:
    constraints:
        energy_cap_equals: 0
demand_electricity:
    constraints.resource: file=demand_power.csv:sassari
coordinates: {x: 40.72666700,y: 8.55916700}

sud_sardegna: #carbonia
techs:
    pv_farm:
        constraints:
            resource: file=pv_resource_sardegna_electricity.csv:
                                sudsardegna

            energy_cap_min: 114400 #kW
            # energy_cap_max: 182400 #kW
    pv_rooftop:
        constraints:
            resource: file=pv_resource_sardegna_electricity.csv:
                                sudsardegna

            energy_cap_min: 86300 #kW
            # energy_cap_max: 137600 #kW
    wind:
        constraints:
            resource: file=wind_resource_sardegna_electricity.csv:
                                sudsardegna

            energy_cap_min: 247500 #kW
            # energy_cap_max: 335000 #kW
    hydro:
        constraints:
            resource: file=hydro_createo_dalombardi.csv
            energy_cap_equals: 38700 #kW
    coal:
        constraints:
            energy_cap_equals: 295000 #kW
    solid_biomass:
        constraints:
            energy_cap_min: 13000 #kW
            energy_cap_max: 15600 #kW
    biogas:
        constraints:
            energy_cap_min: 5000 #kW
            # energy_cap_max: 11600 #kW
            energy_cap_max: 53700 #kW
    fossil_oil:
        constraints:
            energy_cap_equals: 0
    bioliquid:
        constraints:
            energy_cap_equals: 0
    syngas:
        constraints:

```

```

        energy_cap_equals: 0
    demand_electricity:
        constraints.resource: file=demand_power.csv:sud_sardegna
    coordinates: {x: 39.16680300, y: 8.59160800}
# locations for import and export connections
santa_teresa: #SARCO +SACOI
    techs:
        el_export: # export excess electricity
        constraints:
            resource: -4e5
        supply_grid_power:
        constraints:
            energy_cap_max: 400000 #kW
    coordinates: {x: 41.249458737095914, y: 9.18228610698874}
fiume_santo: #SAPEI
    techs:
        el_export: # export excess electricity
        constraints:
            resource: -1e6
        supply_grid_power:
        constraints:
            energy_cap_max: 1000000 #kW
    coordinates: {x: 40.80475255695234, y: 8.280497658610829}
# connection node
N1:
    coordinates: {x: 40.22358298279619, y: 8.779904074601498} #
                                location near macomer

links:
#links for locations for import and export-start
sassari,fiume_santo:
    techs:
        power_lines:
        constraints:
            energy_cap_equals: 1395000
sassari,santa_teresa:
    techs:
        power_lines:
        constraints:
            energy_cap_equals: 265500
#links for locations for import and export-end
santa_teresa,nuoro:
    techs:
        power_lines:
        constraints:
            energy_cap_equals: 170000
nuoro,sassari:
    techs:
        power_lines:
        constraints:
            energy_cap_equals: 117000
sassari,N1:
    techs:
        power_lines:
        constraints:
            energy_cap_equals: 696000

```



```

N1,nuoro:
  techs:
    power_lines:
      constraints:
        energy_cap_equals: 1000000000 #kW dummy link as
                                   infinite supply
sassari,oristano:
  techs:
    power_lines:
      constraints:
        energy_cap_equals: 180000
N1,oristano:
  techs:
    power_lines:
      constraints:
        energy_cap_equals: 117000
N1,cagliari:
  techs:
    power_lines:
      constraints:
        energy_cap_equals: 720000
cagliari,sud_sardegna:
  techs:
    power_lines:
      constraints:
        energy_cap_equals: 435000
sud_sardegna,oristano:
  techs:
    power_lines:
      constraints:
        energy_cap_equals: 265500

```

A.3 Scenarios.yaml file

```

# Overrides used for scenarios
#50% reduction of coal in locations.yaml
scenarios:
  #option1
  best_2024_B: ['max_cap_pniec_2024','inst_cost_2025_best','cost01export_supply02','effpvwind_best_24']
  best_2025_B: ['max_cap_pniec_2025','inst_cost_2025_best','cost01export_supply02','effpvwind_best_25','no_coal']
  best_2030_B: ['max_cap_pniec_2030','inst_cost_2030_best','cost01export_supply02','tyrrhenian','sacoi3','demand2030_N0eurallumina','no_coal','effpvwind_best_30']

```

```

best_2050_B: ['max_cap_pniec_2050', 'inst_cost_2050_best', '
              cost01export_supply02', '
              tyrrhenian', 'sacoi3', '
              demand2050_N0eurallumina', 'no_oil',
              'no_syngas', 'no_coal', '
              effpvwind_best_50']
BAU_2024_B: ['max_cap_N0pniec_2024', 'inst_cost_2025_bau', '
              cost01export_supply02', '
              effpvwind_BAU_24']
BAU_2025_B: ['max_cap_N0pniec_2025', 'inst_cost_2025_bau', '
              cost01export_supply02', 'no_coal',
              'effpvwind_BAU_25']
BAU_2030_B: ['max_cap_N0pniec_2030', 'inst_cost_2030_bau', '
              cost01export_supply02', 'no_coal',
              'demand2030_N0eurallumina', '
              effpvwind_BAU_30']
BAU_2050_B: ['max_cap_N0pniec_2050', 'inst_cost_2050_bau', '
              cost01export_supply02', 'no_coal',
              '
              demand2050_N0euralluminaINCREASED',
              'no_oil', 'no_syngas', '
              effpvwind_BAU_50']
worst_2024_B: ['max_cap_N0pniec_2024', 'inst_cost_2025_worst', '
               cost01export_supply02', '
               effpvwind_worst_24']
worst_2025_B: ['max_cap_N0pniec_2025', 'inst_cost_2025_worst', '
               cost01export_supply02', 'no_coal',
               'demand_with_eurallumina', '
               effpvwind_worst_25']
worst_2030_B: ['max_cap_N0pniec_2030', 'inst_cost_2030_worst', '
               cost01export_supply02', 'no_coal',
               'demand_with_eurallumina2030', '
               effpvwind_worst_30']
worst_2050_B: ['max_cap_N0pniec_2050', 'inst_cost_2050_worst', '
               cost01export_supply02', 'no_coal',
               'demand_2050_witheurallumina
               INCREASED', 'no_oil', 'no_syngas',
               'effpvwind_worst_50']
#option2 max capacity pv and wind with max potential
best_2024_Bmax: ['max_tecn', 'inst_cost_2025_best', '
                 cost01export_supply02', '
                 effpvwind_best_24']
best_2025_Bmax: ['max_tecn', 'inst_cost_2025_best', '
                 cost01export_supply02', '
                 effpvwind_best_25', 'no_coal']
best_2030_Bmax: ['max_tecn', 'inst_cost_2030_best', '
                 cost01export_supply02', '
                 tyrrhenian', 'sacoi3', '
                 demand2030_N0eurallumina', '
                 no_coal', 'effpvwind_best_30']

```

```

best_2050_Bmax: ['max_tecn', 'inst_cost_2050_best', '
                cost01export_supply02', '
                tyrrhenian', 'sacoi3', '
                demand2050_N0eurallumina', 'no_oil',
                'no_syngas', 'no_coal', '
                effpvwind_best_50']
BAU_2024_Bmax: ['max_tecn', 'inst_cost_2025_bau', 'cost01export_supply02',
                'effpvwind_BAU_24']
BAU_2025_Bmax: ['max_tecn', 'inst_cost_2025_bau', 'cost01export_supply02',
                'no_coal', 'effpvwind_BAU_25']
BAU_2030_Bmax: ['max_tecn', 'inst_cost_2030_bau', 'cost01export_supply02',
                'no_coal', '
                demand2030_N0eurallumina', '
                effpvwind_BAU_30']
BAU_2050_Bmax: ['max_tecn', 'inst_cost_2050_bau', 'cost01export_supply02',
                'no_coal', '
                demand2050_N0euralluminaINCREASED',
                'no_oil', 'no_syngas', '
                effpvwind_BAU_50']
worst_2024_Bmax: ['max_tecn', 'inst_cost_2025_worst', '
                cost01export_supply02', '
                effpvwind_worst_24']
worst_2025_Bmax: ['max_tecn', 'inst_cost_2025_worst', '
                cost01export_supply02', 'no_coal',
                'demand_with_eurallumina', '
                effpvwind_worst_25']
worst_2030_Bmax: ['max_tecn', 'inst_cost_2030_worst', '
                cost01export_supply02', 'no_coal',
                'demand_with_eurallumina2030', '
                effpvwind_worst_30']
worst_2050_Bmax: ['max_tecn', 'inst_cost_2050_worst', '
                cost01export_supply02', 'no_coal',
                'demand_2050_witheurallumina',
                INCREASED', 'no_oil', 'no_syngas', '
                effpvwind_worst_50']

overrides:
  max_cap_pniec_2024:
    locations.cagliari.techs.pv_farm.constraints.energy_cap_max:
        156800 #kW
    locations.cagliari.techs.pv_rooftop.constraints.energy_cap_max:
        118300 #kW
    locations.cagliari.techs.wind.constraints.energy_cap_max: 66800 #
        kW
    locations.nuoro.techs.pv_farm.constraints.energy_cap_max: 168100 #
        kW
    locations.nuoro.techs.pv_rooftop.constraints.energy_cap_max:
        126800 #kW
    locations.nuoro.techs.wind.constraints.energy_cap_max: 250000 #kW
    locations.oristano.techs.pv_farm.constraints.energy_cap_max:
        108300 #kW
    locations.oristano.techs.pv_rooftop.constraints.energy_cap_max:
        81700 #kW
    locations.oristano.techs.wind.constraints.energy_cap_max: 160000 #
        kW

```

```

locations.sassari.techs.pv_farm.constraints.energy_cap_max: 199500
                                #kW
locations.sassari.techs.pv_rooftop.constraints.energy_cap_max:
                                150500 #kW
locations.sassari.techs.wind.constraints.energy_cap_max: 610000 #
                                kW
locations.sud_sardegna.techs.pv_farm.constraints.energy_cap_max:
                                182400 #kW
locations.sud_sardegna.techs.pv_rooftop.constraints.energy_cap_max
                                : 137600 #kW
locations.sud_sardegna.techs.wind.constraints.energy_cap_max:
                                335000 #kW
max_cap_pniec_2025:
locations.cagliari.techs.pv_farm.constraints.energy_cap_max:
                                165300 #kW
locations.cagliari.techs.pv_rooftop.constraints.energy_cap_max:
                                124700 #kW
locations.cagliari.techs.wind.constraints.energy_cap_max: 70000 #
                                kW
locations.nuoro.techs.pv_farm.constraints.energy_cap_max: 171000 #
                                kW
locations.nuoro.techs.pv_rooftop.constraints.energy_cap_max:
                                129000 #kW
locations.nuoro.techs.wind.constraints.energy_cap_max: 280000 #kW
locations.oristano.techs.pv_farm.constraints.energy_cap_max:
                                119700 #kW
locations.oristano.techs.pv_rooftop.constraints.energy_cap_max:
                                90300 #kW
locations.oristano.techs.wind.constraints.energy_cap_max: 175000 #
                                kW
locations.sassari.techs.pv_farm.constraints.energy_cap_max: 216600
                                #kW
locations.sassari.techs.pv_rooftop.constraints.energy_cap_max:
                                163400 #kW
locations.sassari.techs.wind.constraints.energy_cap_max: 630000 #
                                kW
locations.sud_sardegna.techs.pv_farm.constraints.energy_cap_max:
                                199500 #kW
locations.sud_sardegna.techs.pv_rooftop.constraints.energy_cap_max
                                : 150500 #kW
locations.sud_sardegna.techs.wind.constraints.energy_cap_max:
                                360000 #kW
max_cap_pniec_2030:
locations.cagliari.techs.pv_farm.constraints.energy_cap_max:
                                188100 #kW
locations.cagliari.techs.pv_rooftop.constraints.energy_cap_max:
                                141900 #kW
locations.cagliari.techs.wind.constraints.energy_cap_max: 90000 #
                                kW
locations.nuoro.techs.pv_farm.constraints.energy_cap_max: 285000 #
                                kW
locations.nuoro.techs.pv_rooftop.constraints.energy_cap_max:
                                215000 #kW
locations.nuoro.techs.wind.constraints.energy_cap_max: 480000 #kW

```

```

locations.oristano.techs.pv_farm.constraints.energy_cap_max:
    162500 #kW
locations.oristano.techs.pv_rooftop.constraints.energy_cap_max:
    122600 #kW
locations.oristano.techs.wind.constraints.energy_cap_max: 270000 #
    kW
locations.sassari.techs.pv_farm.constraints.energy_cap_max: 307800
    #kW
locations.sassari.techs.pv_rooftop.constraints.energy_cap_max:
    232200 #kW
locations.sassari.techs.wind.constraints.energy_cap_max: 729900 #
    kW
locations.sud_sardegna.techs.pv_farm.constraints.energy_cap_max:
    310700 #kW
locations.sud_sardegna.techs.pv_rooftop.constraints.energy_cap_max
    : 234400 #kW
locations.sud_sardegna.techs.wind.constraints.energy_cap_max:
    510100 #kW
max_cap_pniec_2050:
locations.cagliari.techs.pv_farm.constraints.energy_cap_max:
    391500 #kW
locations.cagliari.techs.pv_rooftop.constraints.energy_cap_max:
    295400 #kW
locations.cagliari.techs.wind.constraints.energy_cap_max: 162800 #
    kW
locations.nuoro.techs.pv_farm.constraints.energy_cap_max: 619500 #
    kW
locations.nuoro.techs.pv_rooftop.constraints.energy_cap_max:
    467300 #kW
locations.nuoro.techs.wind.constraints.energy_cap_max: 1072600 #kW
locations.oristano.techs.pv_farm.constraints.energy_cap_max:
    295400 #kW
locations.oristano.techs.pv_rooftop.constraints.energy_cap_max:
    222800 #kW
locations.oristano.techs.wind.constraints.energy_cap_max: 534900 #
    kW
locations.sassari.techs.pv_farm.constraints.energy_cap_max: 616600
    #kW
locations.sassari.techs.pv_rooftop.constraints.energy_cap_max:
    465100 #kW
locations.sassari.techs.wind.constraints.energy_cap_max: 1005000 #
    kW
locations.sud_sardegna.techs.pv_farm.constraints.energy_cap_max:
    623800 #kW
locations.sud_sardegna.techs.pv_rooftop.constraints.energy_cap_max
    : 470600 #kW
locations.sud_sardegna.techs.wind.constraints.energy_cap_max:
    956600 #kW
inst_cost_2025_best:
techs.pv_farm.costs.monetary.energy_cap: 298 #eur/kW
techs.pv_rooftop.costs.monetary.energy_cap: 383 #eur/kW
techs.wind.costs.monetary.energy_cap: 1143 #eur/kW
inst_cost_2025_bau:
techs.pv_farm.costs.monetary.energy_cap: 474 #eur/kW
techs.pv_rooftop.costs.monetary.energy_cap: 610 #eur/kW

```

```

    techs.wind.costs.monetary.energy_cap: 1326 #eur/kW
inst_cost_2025_worst:
    techs.pv_farm.costs.monetary.energy_cap: 812 #eur/kW
    techs.pv_rooftop.costs.monetary.energy_cap: 1045 #eur/kW
    techs.wind.costs.monetary.energy_cap: 1463 #eur/kW
inst_cost_2030_best:
    techs.pv_farm.costs.monetary.energy_cap: 230 #eur/kW
    techs.pv_rooftop.costs.monetary.energy_cap: 296 #eur/kW
    techs.wind.costs.monetary.energy_cap: 1006 #eur/kW
inst_cost_2030_bau:
    techs.pv_farm.costs.monetary.energy_cap: 325 #eur/kW
    techs.pv_rooftop.costs.monetary.energy_cap: 418 #eur/kW
    techs.wind.costs.monetary.energy_cap: 1234 #eur/kW
inst_cost_2030_worst:
    techs.pv_farm.costs.monetary.energy_cap: 569 #eur/kW
    techs.pv_rooftop.costs.monetary.energy_cap: 732 #eur/kW
    techs.wind.costs.monetary.energy_cap: 1417 #eur/kW
inst_cost_2050_best:
    techs.pv_farm.costs.monetary.energy_cap: 68 #eur/kW
    techs.pv_rooftop.costs.monetary.energy_cap: 87 #eur/kW
    techs.wind.costs.monetary.energy_cap: 594 #eur/kW
inst_cost_2050_bau:
    techs.pv_farm.costs.monetary.energy_cap: 95 #eur/kW
    techs.pv_rooftop.costs.monetary.energy_cap: 122 #eur/kW
    techs.wind.costs.monetary.energy_cap: 1143 #eur/kW
inst_cost_2050_worst:
    techs.pv_farm.costs.monetary.energy_cap: 149 #eur/kW
    techs.pv_rooftop.costs.monetary.energy_cap: 192 #eur/kW
    techs.wind.costs.monetary.energy_cap: 1371 #eur/kW
cost01export_supply02:
    techs.el_export.costs.monetary.om_con: -0.1
    techs.supply_grid_power.costs.monetary.om_prod: 0.2
effpvwind_BAU_24:
    locations.cagliari.techs.pv_farm.constraints.resource: file=
                                                pv_bau_24.csv:cagliari
    locations.cagliari.techs.pv_rooftop.constraints.resource: file=
                                                pv_bau_24.csv:cagliari
    locations.cagliari.techs.wind.constraints.resource: file=
                                                wind_bau_24.csv:cagliari
    locations.nuoro.techs.pv_farm.constraints.resource: file=pv_bau_24
                                                .csv:nuoro
    locations.nuoro.techs.pv_rooftop.constraints.resource: file=
                                                pv_bau_24.csv:nuoro
    locations.nuoro.techs.wind.constraints.resource: file=wind_bau_24.
                                                csv:nuoro
    locations.oristano.techs.pv_farm.constraints.resource: file=
                                                pv_bau_24.csv:oristano
    locations.oristano.techs.pv_rooftop.constraints.resource: file=
                                                pv_bau_24.csv:oristano
    locations.oristano.techs.wind.constraints.resource: file=
                                                wind_bau_24.csv:oristano
    locations.sassari.techs.pv_farm.constraints.resource: file=
                                                pv_bau_24.csv:sassari
    locations.sassari.techs.pv_rooftop.constraints.resource: file=
                                                pv_bau_24.csv:sassari

```

```

locations.sassari.techs.wind.constraints.resource: file=
                                wind_bau_24.csv:sassari
locations.sud_sardegna.techs.pv_farm.constraints.resource: file=
                                pv_bau_24.csv:sudsardegna
locations.sud_sardegna.techs.pv_rooftop.constraints.resource: file=
                                =pv_bau_24.csv:sudsardegna
locations.sud_sardegna.techs.wind.constraints.resource: file=
                                wind_bau_24.csv:sudsardegna
effpvwind_best_24:
locations.cagliari.techs.pv_farm.constraints.resource: file=
                                pv_best_24.csv:cagliari
locations.cagliari.techs.pv_rooftop.constraints.resource: file=
                                pv_best_24.csv:cagliari
locations.cagliari.techs.wind.constraints.resource: file=
                                wind_best_24.csv:cagliari
locations.nuoro.techs.pv_farm.constraints.resource: file=
                                pv_best_24.csv:nuoro
locations.nuoro.techs.pv_rooftop.constraints.resource: file=
                                pv_best_24.csv:nuoro
locations.nuoro.techs.wind.constraints.resource: file=wind_best_24
                                .csv:nuoro
locations.oristano.techs.pv_farm.constraints.resource: file=
                                pv_best_24.csv:oristano
locations.oristano.techs.pv_rooftop.constraints.resource: file=
                                pv_best_24.csv:oristano
locations.oristano.techs.wind.constraints.resource: file=
                                wind_best_24.csv:oristano
locations.sassari.techs.pv_farm.constraints.resource: file=
                                pv_best_24.csv:sassari
locations.sassari.techs.pv_rooftop.constraints.resource: file=
                                pv_best_24.csv:sassari
locations.sassari.techs.wind.constraints.resource: file=
                                wind_best_24.csv:sassari
locations.sud_sardegna.techs.pv_farm.constraints.resource: file=
                                pv_best_24.csv:sudsardegna
locations.sud_sardegna.techs.pv_rooftop.constraints.resource: file=
                                =pv_best_24.csv:sudsardegna
locations.sud_sardegna.techs.wind.constraints.resource: file=
                                wind_best_24.csv:sudsardegna
effpvwind_worst_24:
locations.cagliari.techs.pv_farm.constraints.resource: file=
                                pv_worst_24.csv:cagliari
locations.cagliari.techs.pv_rooftop.constraints.resource: file=
                                pv_worst_24.csv:cagliari
locations.cagliari.techs.wind.constraints.resource: file=
                                wind_worst_24.csv:cagliari
locations.nuoro.techs.pv_farm.constraints.resource: file=
                                pv_worst_24.csv:nuoro
locations.nuoro.techs.pv_rooftop.constraints.resource: file=
                                pv_worst_24.csv:nuoro
locations.nuoro.techs.wind.constraints.resource: file=
                                wind_worst_24.csv:nuoro
locations.oristano.techs.pv_farm.constraints.resource: file=
                                pv_worst_24.csv:oristano

```

```

locations.oristano.techs.pv_rooftop.constraints.resource: file=
    pv_worst_24.csv:oristano
locations.oristano.techs.wind.constraints.resource: file=
    wind_worst_24.csv:oristano
locations.sassari.techs.pv_farm.constraints.resource: file=
    pv_worst_24.csv:sassari
locations.sassari.techs.pv_rooftop.constraints.resource: file=
    pv_worst_24.csv:sassari
locations.sassari.techs.wind.constraints.resource: file=
    wind_worst_24.csv:sassari
locations.sud_sardegna.techs.pv_farm.constraints.resource: file=
    pv_worst_24.csv:sudsardegna
locations.sud_sardegna.techs.pv_rooftop.constraints.resource: file=
    =pv_worst_24.csv:sudsardegna
locations.sud_sardegna.techs.wind.constraints.resource: file=
    wind_worst_24.csv:sudsardegna
effpvwind_worst_25:
    locations.cagliari.techs.pv_farm.constraints.resource: file=
        pv_worst_25.csv:cagliari
    locations.cagliari.techs.pv_rooftop.constraints.resource: file=
        pv_worst_25.csv:cagliari
    locations.cagliari.techs.wind.constraints.resource: file=
        wind_worst_25.csv:cagliari
    locations.nuoro.techs.pv_farm.constraints.resource: file=
        pv_worst_25.csv:nuoro
    locations.nuoro.techs.pv_rooftop.constraints.resource: file=
        pv_worst_25.csv:nuoro
    locations.nuoro.techs.wind.constraints.resource: file=
        wind_worst_25.csv:nuoro
    locations.oristano.techs.pv_farm.constraints.resource: file=
        pv_worst_25.csv:oristano
    locations.oristano.techs.pv_rooftop.constraints.resource: file=
        pv_worst_25.csv:oristano
    locations.oristano.techs.wind.constraints.resource: file=
        wind_worst_25.csv:oristano
    locations.sassari.techs.pv_farm.constraints.resource: file=
        pv_worst_25.csv:sassari
    locations.sassari.techs.pv_rooftop.constraints.resource: file=
        pv_worst_25.csv:sassari
    locations.sassari.techs.wind.constraints.resource: file=
        wind_worst_25.csv:sassari
    locations.sud_sardegna.techs.pv_farm.constraints.resource: file=
        pv_worst_25.csv:sudsardegna
    locations.sud_sardegna.techs.pv_rooftop.constraints.resource: file=
        =pv_worst_25.csv:sudsardegna
    locations.sud_sardegna.techs.wind.constraints.resource: file=
        wind_worst_25.csv:sudsardegna
effpvwind_worst_30:
    locations.cagliari.techs.pv_farm.constraints.resource: file=
        pv_worst_30.csv:cagliari
    locations.cagliari.techs.pv_rooftop.constraints.resource: file=
        pv_worst_30.csv:cagliari
    locations.cagliari.techs.wind.constraints.resource: file=
        wind_worst_30.csv:cagliari

```



```

locations.nuoro.techs.pv_farm.constraints.resource: file=
                                pv_worst_30.csv:nuoro
locations.nuoro.techs.pv_rooftop.constraints.resource: file=
                                pv_worst_30.csv:nuoro
locations.nuoro.techs.wind.constraints.resource: file=
                                wind_worst_30.csv:nuoro
locations.oristano.techs.pv_farm.constraints.resource: file=
                                pv_worst_30.csv:oristano
locations.oristano.techs.pv_rooftop.constraints.resource: file=
                                pv_worst_30.csv:oristano
locations.oristano.techs.wind.constraints.resource: file=
                                wind_worst_30.csv:oristano
locations.sassari.techs.pv_farm.constraints.resource: file=
                                pv_worst_30.csv:sassari
locations.sassari.techs.pv_rooftop.constraints.resource: file=
                                pv_worst_30.csv:sassari
locations.sassari.techs.wind.constraints.resource: file=
                                wind_worst_30.csv:sassari
locations.sud_sardegna.techs.pv_farm.constraints.resource: file=
                                pv_worst_30.csv:sudsardegna
locations.sud_sardegna.techs.pv_rooftop.constraints.resource: file=
                                =pv_worst_30.csv:sudsardegna
locations.sud_sardegna.techs.wind.constraints.resource: file=
                                wind_worst_30.csv:sudsardegna
effpvwind_worst_50:
locations.cagliari.techs.pv_farm.constraints.resource: file=
                                pv_worst_50.csv:cagliari
locations.cagliari.techs.pv_rooftop.constraints.resource: file=
                                pv_worst_50.csv:cagliari
locations.cagliari.techs.wind.constraints.resource: file=
                                wind_worst_50.csv:cagliari
locations.nuoro.techs.pv_farm.constraints.resource: file=
                                pv_worst_50.csv:nuoro
locations.nuoro.techs.pv_rooftop.constraints.resource: file=
                                pv_worst_50.csv:nuoro
locations.nuoro.techs.wind.constraints.resource: file=
                                wind_worst_50.csv:nuoro
locations.oristano.techs.pv_farm.constraints.resource: file=
                                pv_worst_50.csv:oristano
locations.oristano.techs.pv_rooftop.constraints.resource: file=
                                pv_worst_50.csv:oristano
locations.oristano.techs.wind.constraints.resource: file=
                                wind_worst_50.csv:oristano
locations.sassari.techs.pv_farm.constraints.resource: file=
                                pv_worst_50.csv:sassari
locations.sassari.techs.pv_rooftop.constraints.resource: file=
                                pv_worst_50.csv:sassari
locations.sassari.techs.wind.constraints.resource: file=
                                wind_worst_50.csv:sassari
locations.sud_sardegna.techs.pv_farm.constraints.resource: file=
                                pv_worst_50.csv:sudsardegna
locations.sud_sardegna.techs.pv_rooftop.constraints.resource: file=
                                =pv_worst_50.csv:sudsardegna
locations.sud_sardegna.techs.wind.constraints.resource: file=
                                wind_worst_50.csv:sudsardegna

```

```

effpvwind_best_25:
    locations.cagliari.techs.pv_farm.constraints.resource: file=
        pv_best_25.csv:cagliari
    locations.cagliari.techs.pv_rooftop.constraints.resource: file=
        pv_best_25.csv:cagliari
    locations.cagliari.techs.wind.constraints.resource: file=
        wind_best_25.csv:cagliari
    locations.nuoro.techs.pv_farm.constraints.resource: file=
        pv_best_25.csv:nuoro
    locations.nuoro.techs.pv_rooftop.constraints.resource: file=
        pv_best_25.csv:nuoro
    locations.nuoro.techs.wind.constraints.resource: file=wind_best_25
        .csv:nuoro
    locations.oristano.techs.pv_farm.constraints.resource: file=
        pv_best_25.csv:oristano
    locations.oristano.techs.pv_rooftop.constraints.resource: file=
        pv_best_25.csv:oristano
    locations.oristano.techs.wind.constraints.resource: file=
        wind_best_25.csv:oristano
    locations.sassari.techs.pv_farm.constraints.resource: file=
        pv_best_25.csv:sassari
    locations.sassari.techs.pv_rooftop.constraints.resource: file=
        pv_best_25.csv:sassari
    locations.sassari.techs.wind.constraints.resource: file=
        wind_best_25.csv:sassari
    locations.sud_sardegna.techs.pv_farm.constraints.resource: file=
        pv_best_25.csv:sudsardegna
    locations.sud_sardegna.techs.pv_rooftop.constraints.resource: file
        =pv_best_25.csv:sudsardegna
    locations.sud_sardegna.techs.wind.constraints.resource: file=
        wind_best_25.csv:sudsardegna

effpvwind_best_30:
    locations.cagliari.techs.pv_farm.constraints.resource: file=
        pv_best_30.csv:cagliari
    locations.cagliari.techs.pv_rooftop.constraints.resource: file=
        pv_best_30.csv:cagliari
    locations.cagliari.techs.wind.constraints.resource: file=
        wind_best_30.csv:cagliari
    locations.nuoro.techs.pv_farm.constraints.resource: file=
        pv_best_30.csv:nuoro
    locations.nuoro.techs.pv_rooftop.constraints.resource: file=
        pv_best_30.csv:nuoro
    locations.nuoro.techs.wind.constraints.resource: file=wind_best_30
        .csv:nuoro
    locations.oristano.techs.pv_farm.constraints.resource: file=
        pv_best_30.csv:oristano
    locations.oristano.techs.pv_rooftop.constraints.resource: file=
        pv_best_30.csv:oristano
    locations.oristano.techs.wind.constraints.resource: file=
        wind_best_30.csv:oristano
    locations.sassari.techs.pv_farm.constraints.resource: file=
        pv_best_30.csv:sassari
    locations.sassari.techs.pv_rooftop.constraints.resource: file=
        pv_best_30.csv:sassari

```

```

locations.sassari.techs.wind.constraints.resource: file=
                                wind_best_30.csv:sassari
locations.sud_sardegna.techs.pv_farm.constraints.resource: file=
                                pv_best_30.csv:sudsardegna
locations.sud_sardegna.techs.pv_rooftop.constraints.resource: file=
                                =pv_best_30.csv:sudsardegna
locations.sud_sardegna.techs.wind.constraints.resource: file=
                                wind_best_30.csv:sudsardegna
effpvwind_best_50:
locations.cagliari.techs.pv_farm.constraints.resource: file=
                                pv_best_50.csv:cagliari
locations.cagliari.techs.pv_rooftop.constraints.resource: file=
                                pv_best_50.csv:cagliari
locations.cagliari.techs.wind.constraints.resource: file=
                                wind_best_50.csv:cagliari
locations.nuoro.techs.pv_farm.constraints.resource: file=
                                pv_best_50.csv:nuoro
locations.nuoro.techs.pv_rooftop.constraints.resource: file=
                                pv_best_50.csv:nuoro
locations.nuoro.techs.wind.constraints.resource: file=wind_best_50
                                .csv:nuoro
locations.oristano.techs.pv_farm.constraints.resource: file=
                                pv_best_50.csv:oristano
locations.oristano.techs.pv_rooftop.constraints.resource: file=
                                pv_best_50.csv:oristano
locations.oristano.techs.wind.constraints.resource: file=
                                wind_best_50.csv:oristano
locations.sassari.techs.pv_farm.constraints.resource: file=
                                pv_best_50.csv:sassari
locations.sassari.techs.pv_rooftop.constraints.resource: file=
                                pv_best_50.csv:sassari
locations.sassari.techs.wind.constraints.resource: file=
                                wind_best_50.csv:sassari
locations.sud_sardegna.techs.pv_farm.constraints.resource: file=
                                pv_best_50.csv:sudsardegna
locations.sud_sardegna.techs.pv_rooftop.constraints.resource: file=
                                =pv_best_50.csv:sudsardegna
locations.sud_sardegna.techs.wind.constraints.resource: file=
                                wind_best_50.csv:sudsardegna
effpvwind_BAU_25:
locations.cagliari.techs.pv_farm.constraints.resource: file=
                                pv_bau_25.csv:cagliari
locations.cagliari.techs.pv_rooftop.constraints.resource: file=
                                pv_bau_25.csv:cagliari
locations.cagliari.techs.wind.constraints.resource: file=
                                wind_bau_25.csv:cagliari
locations.nuoro.techs.pv_farm.constraints.resource: file=pv_bau_25
                                .csv:nuoro
locations.nuoro.techs.pv_rooftop.constraints.resource: file=
                                pv_bau_25.csv:nuoro
locations.nuoro.techs.wind.constraints.resource: file=wind_bau_25.
                                csv:nuoro
locations.oristano.techs.pv_farm.constraints.resource: file=
                                pv_bau_25.csv:oristano

```

```

locations.oristano.techs.pv_rooftop.constraints.resource: file=
    pv_bau_25.csv:oristano
locations.oristano.techs.wind.constraints.resource: file=
    wind_bau_25.csv:oristano
locations.sassari.techs.pv_farm.constraints.resource: file=
    pv_bau_25.csv:sassari
locations.sassari.techs.pv_rooftop.constraints.resource: file=
    pv_bau_25.csv:sassari
locations.sassari.techs.wind.constraints.resource: file=
    wind_bau_25.csv:sassari
locations.sud_sardegna.techs.pv_farm.constraints.resource: file=
    pv_bau_25.csv:sudsardegna
locations.sud_sardegna.techs.pv_rooftop.constraints.resource: file=
    =pv_bau_25.csv:sudsardegna
locations.sud_sardegna.techs.wind.constraints.resource: file=
    wind_bau_25.csv:sudsardegna
effpvwind_BAU_30:
    locations.cagliari.techs.pv_farm.constraints.resource: file=
        pv_bau_30.csv:cagliari
    locations.cagliari.techs.pv_rooftop.constraints.resource: file=
        pv_bau_30.csv:cagliari
    locations.cagliari.techs.wind.constraints.resource: file=
        wind_bau_30.csv:cagliari
    locations.nuoro.techs.pv_farm.constraints.resource: file=pv_bau_30
        .csv:nuoro
    locations.nuoro.techs.pv_rooftop.constraints.resource: file=
        pv_bau_30.csv:nuoro
    locations.nuoro.techs.wind.constraints.resource: file=wind_bau_30.
        csv:nuoro
    locations.oristano.techs.pv_farm.constraints.resource: file=
        pv_bau_30.csv:oristano
    locations.oristano.techs.pv_rooftop.constraints.resource: file=
        pv_bau_30.csv:oristano
    locations.oristano.techs.wind.constraints.resource: file=
        wind_bau_30.csv:oristano
    locations.sassari.techs.pv_farm.constraints.resource: file=
        pv_bau_30.csv:sassari
    locations.sassari.techs.pv_rooftop.constraints.resource: file=
        pv_bau_30.csv:sassari
    locations.sassari.techs.wind.constraints.resource: file=
        wind_bau_30.csv:sassari
    locations.sud_sardegna.techs.pv_farm.constraints.resource: file=
        pv_bau_30.csv:sudsardegna
    locations.sud_sardegna.techs.pv_rooftop.constraints.resource: file=
        =pv_bau_30.csv:sudsardegna
    locations.sud_sardegna.techs.wind.constraints.resource: file=
        wind_bau_30.csv:sudsardegna
effpvwind_BAU_50:
    locations.cagliari.techs.pv_farm.constraints.resource: file=
        pv_bau_50.csv:cagliari
    locations.cagliari.techs.pv_rooftop.constraints.resource: file=
        pv_bau_50.csv:cagliari
    locations.cagliari.techs.wind.constraints.resource: file=
        wind_bau_50.csv:cagliari

```

```

locations.nuoro.techs.pv_farm.constraints.resource: file=pv_bau_50
                                .csv:nuoro
locations.nuoro.techs.pv_rooftop.constraints.resource: file=
                                pv_bau_50.csv:nuoro
locations.nuoro.techs.wind.constraints.resource: file=wind_bau_50.
                                csv:nuoro
locations.oristano.techs.pv_farm.constraints.resource: file=
                                pv_bau_50.csv:oristano
locations.oristano.techs.pv_rooftop.constraints.resource: file=
                                pv_bau_50.csv:oristano
locations.oristano.techs.wind.constraints.resource: file=
                                wind_bau_50.csv:oristano
locations.sassari.techs.pv_farm.constraints.resource: file=
                                pv_bau_50.csv:sassari
locations.sassari.techs.pv_rooftop.constraints.resource: file=
                                pv_bau_50.csv:sassari
locations.sassari.techs.wind.constraints.resource: file=
                                wind_bau_50.csv:sassari
locations.sud_sardegna.techs.pv_farm.constraints.resource: file=
                                pv_bau_50.csv:sudsardegna
locations.sud_sardegna.techs.pv_rooftop.constraints.resource: file
                                =pv_bau_50.csv:sudsardegna
locations.sud_sardegna.techs.wind.constraints.resource: file=
                                wind_bau_50.csv:sudsardegna
no_coal:
    locations.sassari.techs.coal.constraints.energy_cap_equals: 0
    locations.sud_sardegna.techs.coal.constraints.energy_cap_equals: 0
no_oil:
    locations.cagliari.techs.fossil_oil.constraints.energy_cap_equals:
                                0
    locations.nuoro.techs.fossil_oil.constraints.energy_cap_equals: 0
    locations.oristano.techs.fossil_oil.constraints.energy_cap_equals:
                                0
no_syngas:
    locations.cagliari.techs.syngas.constraints.energy_cap_equals: 0
tyrrhenian:
    locations.terra_mala.techs.el_export.constraints.resource: -1e6 #
                                kW
    locations.terra_mala.techs.supply_grid_power.constraints.
                                energy_cap_max: 1000000 #kW
    locations.terra_mala.coordinates: {x: 39.20195152062984, y: 9.
                                342385220255565}
links:
    cagliari,terra_mala.techs.power_lines.constraints.
                                energy_cap_equals:
                                1000000000
sacoi3: #add 100MW to santa teresa substituting sacoi 2 with sacoi3
    locations.santa_teresa.techs.el_export.constraints.resource: -5e5
                                #kW
    locations.santa_teresa.techs.supply_grid_power.constraints.
                                energy_cap_max: 500000 #kW
demand2030_N0eurallumina:

```

```

locations.cagliari.techs.demand_electricity.constraints.resource:
    file=
    demand_2030_N0eurallumina.csv
    :cagliari
locations.nuoro.techs.demand_electricity.constraints.resource:
    file=
    demand_2030_N0eurallumina.csv
    :nuoro
locations.sassari.techs.demand_electricity.constraints.resource:
    file=
    demand_2030_N0eurallumina.csv
    :sassari
locations.oristano.techs.demand_electricity.constraints.resource:
    file=
    demand_2030_N0eurallumina.csv
    :oristano
locations.sud_sardegna.techs.demand_electricity.constraints.
    resource: file=
    demand_2030_N0eurallumina.csv
    :sud_sardegna
demand2050_N0eurallumina:
    locations.cagliari.techs.demand_electricity.constraints.resource:
        file=
        demand_2050_N0eurallumina.csv
        :cagliari
    locations.nuoro.techs.demand_electricity.constraints.resource:
        file=
        demand_2050_N0eurallumina.csv
        :nuoro
    locations.sassari.techs.demand_electricity.constraints.resource:
        file=
        demand_2050_N0eurallumina.csv
        :sassari
    locations.oristano.techs.demand_electricity.constraints.resource:
        file=
        demand_2050_N0eurallumina.csv
        :oristano
    locations.sud_sardegna.techs.demand_electricity.constraints.
        resource: file=
        demand_2050_N0eurallumina.csv
        :sud_sardegna
max_cap_N0pniec_2024: #set minimum capacities the ones planned to
                        reach 2030 pniec target (regione)
#agliari
locations.cagliari.techs.pv_farm.constraints.energy_cap_max:
    228000 #kW
locations.cagliari.techs.pv_rooftop.constraints.energy_cap_max:
    172000 #kW
locations.cagliari.techs.wind.constraints.energy_cap_max: 46500 #
    kW
#nuoro
locations.nuoro.techs.pv_farm.constraints.energy_cap_max: 88100 #
    kW
locations.nuoro.techs.pv_rooftop.constraints.energy_cap_max: 66500
    #kW

```

```

locations.nuoro.techs.wind.constraints.energy_cap_max: 163300 #kW
#oristano
locations.oristano.techs.pv_farm.constraints.energy_cap_max: 85400
#kW
locations.oristano.techs.pv_rooftop.constraints.energy_cap_max:
64400 #kW
locations.oristano.techs.wind.constraints.energy_cap_max: 102400 #
kW
#sassari
locations.sassari.techs.pv_farm.constraints.energy_cap_max: 166900
#kW
locations.sassari.techs.pv_rooftop.constraints.energy_cap_max:
125900 #kW
locations.sassari.techs.wind.constraints.energy_cap_max: 564600 #
kW
#sud sardegna
locations.sud_sardegna.techs.pv_farm.constraints.energy_cap_max:
122500 #kW
locations.sud_sardegna.techs.pv_rooftop.constraints.energy_cap_max
: 92400 #kW
locations.sud_sardegna.techs.wind.constraints.energy_cap_max:
272500 #kW
max_cap_NOpniec_2025: #set minimum capacities the ones planned to
reach 2030 pniec target
#cagliari
locations.cagliari.techs.pv_farm.constraints.energy_cap_max:
245100 #kW
locations.cagliari.techs.pv_rooftop.constraints.energy_cap_max:
184900 #kW
locations.cagliari.techs.wind.constraints.energy_cap_max: 51000 #
kW
#nuoro
locations.nuoro.techs.pv_farm.constraints.energy_cap_max: 89900 #
kW
locations.nuoro.techs.pv_rooftop.constraints.energy_cap_max: 67900
#kW
locations.nuoro.techs.wind.constraints.energy_cap_max: 173000 #kW
#oristano
locations.oristano.techs.pv_farm.constraints.energy_cap_max: 86400
#kW
locations.oristano.techs.pv_rooftop.constraints.energy_cap_max:
65200 #kW
locations.oristano.techs.wind.constraints.energy_cap_max: 102400 #
kW
#sassari
locations.sassari.techs.pv_farm.constraints.energy_cap_max: 175300
#kW
locations.sassari.techs.pv_rooftop.constraints.energy_cap_max:
132200 #kW
locations.sassari.techs.wind.constraints.energy_cap_max: 565900 #
kW
#sud sardegna
locations.sud_sardegna.techs.pv_farm.constraints.energy_cap_max:
124400 #kW

```

```

locations.sud_sardegna.techs.pv_rooftop.constraints.energy_cap_max
: 93800 #kW
locations.sud_sardegna.techs.wind.constraints.energy_cap_max:
278800 #kW
max_cap_NOpniec_2030: #set minimum capacities the ones planned to
reach 2030 pniec target

#cagliari
locations.cagliari.techs.pv_farm.constraints.energy_cap_max:
347700 #kW
locations.cagliari.techs.pv_rooftop.constraints.energy_cap_max:
262300 #kW
locations.cagliari.techs.wind.constraints.energy_cap_max: 55000 #
kW

#nuoro
locations.nuoro.techs.pv_farm.constraints.energy_cap_max: 98900 #
kW
locations.nuoro.techs.pv_rooftop.constraints.energy_cap_max: 74600
#kW
locations.nuoro.techs.wind.constraints.energy_cap_max: 221600 #kW
#oristano
locations.oristano.techs.pv_farm.constraints.energy_cap_max: 91700
#kW
locations.oristano.techs.pv_rooftop.constraints.energy_cap_max:
69200 #kW
locations.oristano.techs.wind.constraints.energy_cap_max: 102500 #
kW

#sassari
locations.sassari.techs.pv_farm.constraints.energy_cap_max: 217200
#kW
locations.sassari.techs.pv_rooftop.constraints.energy_cap_max:
163800 #kW
locations.sassari.techs.wind.constraints.energy_cap_max: 572500 #
kW

#sud sardegna
locations.sud_sardegna.techs.pv_farm.constraints.energy_cap_max:
134100 #kW
locations.sud_sardegna.techs.pv_rooftop.constraints.energy_cap_max
: 101100 #kW
locations.sud_sardegna.techs.wind.constraints.energy_cap_max:
309900 #kW
max_cap_NOpniec_2050: #set minimum capacities the ones planned to
reach 2030 pniec target

#cagliari
locations.cagliari.techs.pv_farm.constraints.energy_cap_max:
860700 #kW
locations.cagliari.techs.pv_rooftop.constraints.energy_cap_max:
649300 #kW
locations.cagliari.techs.wind.constraints.energy_cap_max: 57000 #
kW

#nuoro
locations.nuoro.techs.pv_farm.constraints.energy_cap_max: 134700 #
kW
locations.nuoro.techs.pv_rooftop.constraints.energy_cap_max:
101600 #kW
locations.nuoro.techs.wind.constraints.energy_cap_max: 416000 #kW

```



```

#oristano
locations.oristano.techs.pv_farm.constraints.energy_cap_max:
    112900 #kW
locations.oristano.techs.pv_rooftop.constraints.energy_cap_max:
    85200 #kW
locations.oristano.techs.wind.constraints.energy_cap_max: 102900 #
    kW
#sassari
locations.sassari.techs.pv_farm.constraints.energy_cap_max: 384800
    #kW
locations.sassari.techs.pv_rooftop.constraints.energy_cap_max:
    290300 #kW
locations.sassari.techs.wind.constraints.energy_cap_max: 598900 #
    kW
#sud sardegna
locations.sud_sardegna.techs.pv_farm.constraints.energy_cap_max:
    172700 #kW
locations.sud_sardegna.techs.pv_rooftop.constraints.energy_cap_max
    : 130300 #kW
locations.sud_sardegna.techs.wind.constraints.energy_cap_max:
    434500 #kW
demand_with_eurallumina: #demand at 2025 with active Eurallumina plant
locations.cagliari.techs.demand_electricity.constraints.resource:
    file=demand_with_eurallumina.
    csv:cagliari
locations.nuoro.techs.demand_electricity.constraints.resource:
    file=demand_with_eurallumina.
    csv:nuoro
locations.sassari.techs.demand_electricity.constraints.resource:
    file=demand_with_eurallumina.
    csv:sassari
locations.oristano.techs.demand_electricity.constraints.resource:
    file=demand_with_eurallumina.
    csv:oristano
locations.sud_sardegna.techs.demand_electricity.constraints.
    resource: file=
    demand_with_eurallumina.csv:
    sud_sardegna
demand_with_eurallumina2030: #demand at 2025 with active Eurallumina
    plant
locations.cagliari.techs.demand_electricity.constraints.resource:
    file=
    demand_2030_witheurallumina.
    csv:cagliari
locations.nuoro.techs.demand_electricity.constraints.resource:
    file=
    demand_2030_witheurallumina.
    csv:nuoro
locations.sassari.techs.demand_electricity.constraints.resource:
    file=
    demand_2030_witheurallumina.
    csv:sassari

```

```

locations.oristano.techs.demand_electricity.constraints.resource:
                                file=
                                demand_2030_witheurallumina.
                                csv:oristano
locations.sud_sardegna.techs.demand_electricity.constraints.
                                resource: file=
                                demand_2030_witheurallumina.
                                csv:sud_sardegna
demand_2050_witheuralluminaINCREASED:
locations.cagliari.techs.demand_electricity.constraints.resource:
                                file=
                                demand_2050_witheurallumin
aINCREASED.csv:cagliari
locations.nuoro.techs.demand_electricity.constraints.resource:
                                file=
                                demand_2050_witheurallumina
INCREASED.csv:nuoro
locations.sassari.techs.demand_electricity.constraints.resource:
                                file=
                                demand_2050_witheurallumina
INCREASED.csv:sassari
locations.oristano.techs.demand_electricity.constraints.resource:
                                file=
                                demand_2050_witheurallumina
INCREASED.csv:oristano
locations.sud_sardegna.techs.demand_electricity.constraints.
                                resource: file=
                                demand_2050_witheurallumina
INCREASED.csv:sud_sardegna
demand2050_N0euralluminaINCREASED:
locations.cagliari.techs.demand_electricity.constraints.resource:
                                file=
                                demand_2050_N0eurallumina
INCREASED.csv:cagliari
locations.nuoro.techs.demand_electricity.constraints.resource:
                                file=
                                demand_2050_N0eurallumina
INCREASED.csv:nuoro
locations.sassari.techs.demand_electricity.constraints.resource:
                                file=
                                demand_2050_N0eurallumina
INCREASED.csv:sassari
locations.oristano.techs.demand_electricity.constraints.resource:
                                file=
                                demand_2050_N0eurallumina
INCREASED.csv:oristano
locations.sud_sardegna.techs.demand_electricity.constraints.
                                resource: file=
                                demand_2050_N0eurallumina
INCREASED:sud_sardegna

```

Acknowledgements

I'm grateful for the opportunity to develop this thesis to my supervisor *Prof. Andrea Lanzini* and co-supervisors *Francesco Demetrio Minuto*, *Riccardo Novo* and *Daniele Salvatore Schiera*.

This work allowed me to practice on a real energy system, an activity that I've never done before.

I would like to extend my deepest gratitude to my parents that permit me to follow this university carrier until the end. Even if I'm sure that it is just a new beginning.

I'm also extremely grateful to my sister, who has always been close to me.

Last but not least, I could not have undertaken this journey without the support and patience of all those people who have remained close to me over these years in the good times, and in the more challenging ones. Without leaving anyone out, I would like to thank the people that have been present in my life during this time, this university career and the moments since my childhood.

Bibliography

- [1] D. G. Luenberger and Y. Ye, *Linear and Nonlinear Programming*, Third, Springer, Ed. 2008.
- [2] l'Energia e l'Ambiente ENEA Ente per le Nuove tecnologie, «Censimento potenziale energetico biomasse, metodo indagine, atlante biomasse su web-gis», 2009.
- [3] G. Van Rossum and F. L. Drake, *Python 3 Reference Manual*. Scotts Valley, CA: CreateSpace, 2009, ISBN: 1441412697.
- [4] M. M. Rienecker, M. J. Suarez, R. Gelaro, *et al.*, «Merra: Nasa's modern-era retrospective analysis for research and applications», *Journal of Climate*, vol. 24, pp. 3624–3648, 14 Jul. 2011, ISSN: 08948755. DOI: 10.1175/JCLI-D-11-00015.1.
- [5] R. autonoma della Sardegna, «Documento di indirizzo sulle fonti energetiche rinnovabili in sardegna - studio sulle potenzialità energetiche delle biomasse», 2013. [Online]. Available: https://www.regione.sardegna.it/documenti/1_461_20131216100125.pdf.
- [6] L. Leal-Taixé, «Multiple object tracking with context awareness», 2014. [Online]. Available: <http://arxiv.org/abs/1411.7935>.
- [7] S. Murroni, A. Triverio, M. F. Murua, and A. Damiano, «Piano energetico ed ambientale della regione sardegna 2014-2020 proposta tecnica», 2014. [Online]. Available: https://www.regione.sardegna.it/documenti/1_274_20140226122339.pdf.
- [8] E. acque della Sardegna. «3a integrazione all'elenco di opere del sistema idrico multisettoriale regionale di competenza gestionale dell'enas in applicazione dell'art. 30 della l.r. 19/06». (2014), [Online]. Available: https://www.regione.sardegna.it/documenti/1_179_20181126103047.pdf.
- [9] G. Kiss, H. Jansen, V. L. Castaldo, and L. Orsi, «The 2050 city», vol. 118, Elsevier Ltd, 2015, pp. 326–355. DOI: 10.1016/j.proeng.2015.08.434.
- [10] R. Müller, U. Pfeifroth, C. Träger-Chatterjee, J. Trentmann, and R. Cremer, «Digging the meteosat treasure-3 decades of solar surface radiation», *Remote Sensing*, vol. 7, pp. 8067–8101, 6 2015, ISSN: 20724292. DOI: 10.3390/rs70608067.
- [11] S. Pfenninger, «Multi-scale energy systems modeling of the renewable energy transition», Ph.D. dissertation, Imperial College London Department of Civil and Environmental Engineering, 2015.

- [12] S. Pfenninger and J. Keirstead, «Renewables, nuclear, or fossil fuels? scenarios for great britain's power system considering costs, emissions and energy security», *Applied Energy*, vol. 152, pp. 83–93, Aug. 2015, ISSN: 03062619. DOI: 10.1016/j.apenergy.2015.04.102.
- [13] S. Pfenninger and I. Staffell, «Long-term patterns of european pv output using 30 years of validated hourly reanalysis and satellite data», *Energy*, vol. 114, pp. 1251–1265, 2016, ISSN: 0360-5442. DOI: <https://doi.org/10.1016/j.energy.2016.08.060>. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0360544216311744>.
- [14] —, «Long-term patterns of european pv output using 30 years of validated hourly reanalysis and satellite data», *Energy*, vol. 114, pp. 1251–1265, Nov. 2016, ISSN: 03605442. DOI: 10.1016/j.energy.2016.08.060.
- [15] I. Staffell and S. Pfenninger, «Using bias-corrected reanalysis to simulate current and future wind power output», *Energy*, vol. 114, pp. 1224–1239, Nov. 2016, ISSN: 03605442. DOI: 10.1016/j.energy.2016.08.068.
- [16] M. D. Vincenzi and G. Fasano, «Elettrificazione della sardegna microclimates for the conservation of wooden cultural heritage objects view project ultraviolet solar radiation models view project», 2016. [Online]. Available: <https://www.researchgate.net/publication/303287441>.
- [17] S. Pfenninger, L. Hirth, I. Schlecht, *et al.*, «Opening the black box of energy modelling: Strategies and lessons learned», *Energy Strategy Reviews*, vol. 19, pp. 63–71, Jan. 2018, ISSN: 2211467X. DOI: 10.1016/j.esr.2017.12.002.
- [18] S. Pfenninger and B. Pickering, «Calliope: A multi-scale energy systems modelling framework», *Journal of Open Source Software*, vol. 3, p. 825, 29 Sep. 2018. DOI: 10.21105/joss.00825.
- [19] H. K. Ringkjøb, P. M. Haugan, and I. M. Solbrekke, «A review of modelling tools for energy and electricity systems with large shares of variable renewables», *Renewable and Sustainable Energy Reviews*, vol. 96, pp. 440–459, Nov. 2018, ISSN: 18790690. DOI: 10.1016/j.rser.2018.08.002.
- [20] Terna. «Rapporto statistico regionale 2018». (2018), [Online]. Available: https://download.terna.it/terna/Statistiche%20Regionali_2018_8d7b93cbf9ad480.pdf.
- [21] G. G. M. Energetici, *Dati di sintesi mpe-mgp*, <https://www.mercatoelettrico.org/It/Tools/Accessodati.aspx?ReturnUrl=%2fit%2fStatistiche%2fME%2fDatiSintesi.aspx>, 2019.
- [22] entsoe. «Trasparenza platform cross-border physical flow». (2019), [Online]. Available: [https://transparency.entsoe.eu/transmission-domain/physicalFlow/show?name=\&defaultValue=false\&viewType=TABLE\&areaType=BORDER_BZN\&atch=false\&dateTime.dateTime=21.09.2022+00:00|CET|DAY\&border.values=CTY|10YIT-GRTN-----B!BZN_BZN|10Y1001A1001A893_BZN_BZN|10Y1001A1001A74G\&dateTime.timezone=CET_CEST\&dateTime.timezone_input=CET+\(UTC+1\)+/+CEST+\(UTC+2\)](https://transparency.entsoe.eu/transmission-domain/physicalFlow/show?name=\&defaultValue=false\&viewType=TABLE\&areaType=BORDER_BZN\&atch=false\&dateTime.dateTime=21.09.2022+00:00|CET|DAY\&border.values=CTY|10YIT-GRTN-----B!BZN_BZN|10Y1001A1001A893_BZN_BZN|10Y1001A1001A74G\&dateTime.timezone=CET_CEST\&dateTime.timezone_input=CET+(UTC+1)+/+CEST+(UTC+2)).

- [23] —, «Trasparency platform scheduled commercial exchanges», 2019. [Online]. Available: [https://transparency.entsoe.eu/transmission-domain/r2/scheduledCommercialExchangesDayAhead/show?name=\&defaultValue=true\&viewType=TABLE\&areaType=BORDER_BZN\&atch=false\&dateTime.dateTime=21.09.2022+00:00|CET|DAY\&border.values=CTY|10YIT-GRTN-----B!BZN_BZN|10Y1001A1001A893_BZN_BZN|10Y1001A1001A74G\&direction.values=Export\&direction.values=Import\&dateTime.timezone=CET_CEST\&dateTime.timezone_input=CET+\(UTC+1\)+/+CEST+\(UTC+2\)](https://transparency.entsoe.eu/transmission-domain/r2/scheduledCommercialExchangesDayAhead/show?name=\&defaultValue=true\&viewType=TABLE\&areaType=BORDER_BZN\&atch=false\&dateTime.dateTime=21.09.2022+00:00|CET|DAY\&border.values=CTY|10YIT-GRTN-----B!BZN_BZN|10Y1001A1001A893_BZN_BZN|10Y1001A1001A74G\&direction.values=Export\&direction.values=Import\&dateTime.timezone=CET_CEST\&dateTime.timezone_input=CET+(UTC+1)+/+CEST+(UTC+2)).
- [24] —, «Trasparency platform total load - day ahead / actual», 2019. [Online]. Available: [https://transparency.entsoe.eu/load-domain/r2/totalLoadR2/show?name=\&defaultValue=false\&viewType=TABLE\&areaType=BZN\&atch=false\&dateTime.dateTime=26.09.2022+00:00|CET|DAY\&biddingZone.values=CTY|10YIT-GRTN-----B!BZN|10Y1001A1001A74G\&dateTime.timezone=CET_CEST\&dateTime.timezone_input=CET+\(UTC+1\)+/+CEST+\(UTC+2\)](https://transparency.entsoe.eu/load-domain/r2/totalLoadR2/show?name=\&defaultValue=false\&viewType=TABLE\&areaType=BZN\&atch=false\&dateTime.dateTime=26.09.2022+00:00|CET|DAY\&biddingZone.values=CTY|10YIT-GRTN-----B!BZN|10Y1001A1001A74G\&dateTime.timezone=CET_CEST\&dateTime.timezone_input=CET+(UTC+1)+/+CEST+(UTC+2)).
- [25] P. Ruiz, W. Nijs, D. Tarvydas, *et al.*, «Enspreso - an open, eu-28 wide, transparent and coherent database of wind, solar and biomass energy potentials», *Energy Strategy Reviews*, vol. 26, p. 100379, 2019, ISSN: 2211-467X. DOI: <https://doi.org/10.1016/j.esr.2019.100379>. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2211467X19300720>.
- [26] R. autonoma della Sardegna, «Piano energetico ed ambientale della regione sardegna 2015-2030 primo rapporto di monitoraggio», 2019. [Online]. Available: https://www.regione.sardegna.it/documenti/1_461_20190402172259.pdf.
- [27] —, «Piano energetico ed ambientale della regione sardegna 2015-2030 secondo rapporto di monitoraggio», 2019. [Online]. Available: https://www.regione.sardegna.it/documenti/1_461_20200429125804.pdf.
- [28] Terna, «Pubblicazioni statistiche consumo di energia elettrica per fonte», 2019. [Online]. Available: <https://www.terna.it/it/sistema-elettrico/statistiche/pubblicazioni-statistiche>.
- [29] —, «Rapporto statistico regionale 2019». (2019), [Online]. Available: https://download.terna.it/terna/Statistiche%20Regionali_2019_8da3e69c41d27b9.pdf.
- [30] —, «Rapporto statistico regionale 2020». (2019), [Online]. Available: https://download.terna.it/terna/Statistiche%20Regionali_2020_8da3e688a4231ad.pdf (visited on 2020).
- [31] T. Brown. «Energy system modelling summer semester 2020, lecture 12». (2020), [Online]. Available: <https://nworbmot.org/courses/esm-2020/lectures/esm-lecture-12.pdf>.
- [32] R. R. S. Energetico. «Approvvigionamento energetico della regione sardegna (anni 2020-2040)». (2020), [Online]. Available: https://www.arera.it/allegati/operatori/pds/200731_RSE_Studio_Infrastrutture_Sardegna_FINALE.pdf.
- [33] entsoe, «Installed capacity per production unit», 2020. [Online]. Available: <https://transparency.entsoe.eu/dashboard/show>.

- [34] IEA, «Projected costs of generating electricity 2020», 2020. [Online]. Available: <https://www.iea.org/reports/projected-costs-of-generating-electricity-2020>.
- [35] IRENA, «Renewable power generation costs in 2019», 2020. [Online]. Available: [https://www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019#:~:text=Electricity\%20costs\%20from\%20utility\%2Dscale, hour\%20\(kWh\)\%20in\%202019..](https://www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019#:~:text=Electricity\%20costs\%20from\%20utility\%2Dscale, hour\%20(kWh)\%20in\%202019..)
- [36] F. Lombardi, B. Pickering, E. Colombo, and S. Pfenninger, «Policy decision support for renewables deployment through spatially explicit practically optimal alternatives», *Joule*, vol. 4, pp. 2185–2207, 10 Oct. 2020, ISSN: 25424351. DOI: 10.1016/j.joule.2020.08.002. [Online]. Available: <https://linkinghub.elsevier.com/retrieve/pii/S2542435120303482>.
- [37] T. pandas development team, *Pandas-dev/pandas: Pandas*, version 1.1.4, Feb. 2020. DOI: 10.5281/zenodo.3509134. [Online]. Available: <https://doi.org/10.5281/zenodo.3509134>.
- [38] Terna. «Caratteristiche generali delle linee elettriche aeree facenti parte della rtn». (2020), [Online]. Available: <https://download.terna.it/terna/0000/0113/81.pdf>.
- [39] —, «Pubblicazioni statistiche consumo di energia elettrica per settore», 2020. [Online]. Available: <https://www.terna.it/it/sistema-elettrico/statistiche/pubblicazioni-statistiche>.
- [40] M. L. Bynum, G. A. Hackebeil, W. E. Hart, *et al.*, *Pyomo-optimization modeling in python*, Third. Springer Science & Business Media, 2021, vol. 67.
- [41] R. R. S. Energetico. «Studio rse sullo sviluppo delle infrastrutture energetiche della sardegna - fase 2: Approfondimento sulle modalità di trasporto del gnl/gas naturale all'interno della sardegna (anni 2020-2040)». (2021), [Online]. Available: https://www.arera.it/allegati/operatori/pds/Rapporto_RSE_Sardegna_FASE_2.pdf.
- [42] ISPRA. «I principali risultati della cop26 di glasgow». (2021), [Online]. Available: <https://www.isprambiente.gov.it/it/archivio/notizie-e-novita-normative/notizie-ispra/2021/11/26a-conferenza-delle-parti-sul-cambiamento-climatico>.
- [43] lightbox. «A come adeguatezza». (2021), [Online]. Available: <https://lightbox.terna.it/it/insight/adeguatezza>.
- [44] C. Moliner, E. Arato, and F. Marchelli, «Current status of energy production from solid biomass in southern italy», *Energies*, vol. 14, no. 9, 2021, ISSN: 1996-1073. DOI: 10.3390/en14092576. [Online]. Available: <https://www.mdpi.com/1996-1073/14/9/2576>.
- [45] —, «Current status of energy production from solid biomass in southern italy», *Energies*, vol. 14, 9 May 2021, ISSN: 19961073. DOI: 10.3390/en14092576. [Online]. Available: <https://www.mdpi.com/1996-1073/14/9/2576>.

-
- [46] B. Pickering and R. Choudhary, «Quantifying resilience in energy systems with out-of-sample testing», *Applied Energy*, vol. 285, p. 116 465, 2021, ISSN: 0306-2619. DOI: <https://doi.org/10.1016/j.apenergy.2021.116465>. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0306261921000313>.
- [47] G. Pontes Luz and R. Amaro e Silva, «Modeling energy communities with collective photovoltaic self-consumption: Synergies between a small city and a winery in portugal», *Energies*, vol. 14, 2021. DOI: 10.3390/en14020323. [Online]. Available: <https://www.mdpi.com/1996-1073/14/2/323>.
- [48] M. dello Sviluppo Economico, «Piano nazionale integrato per l'energia e il clima», 2021. [Online]. Available: [\textbf{https://download.terna.it/terna/Terna_Rapporto_Adeguatezza_Italia_2021_8d9a51d27ad741c.pdf}](https://download.terna.it/terna/Terna_Rapporto_Adeguatezza_Italia_2021_8d9a51d27ad741c.pdf).
- [49] S. Szima, C. A. D. Pozo, S. Cloete, *et al.*, «Techno-economic assessment of igcc power plants using gas switching technology to minimize the energy penalty of co2 capture», *Clean Technologies*, vol. 3, pp. 594–617, 3 Sep. 2021, ISSN: 25718797. DOI: 10.3390/cleantechnol3030036.
- [50] Terna, «Rapporto adeguatezza italia», 2021. [Online]. Available: https://download.terna.it/terna/Terna_Rapporto_Adeguatezza_Italia_2021_8d9a51d27ad741c.pdf.
- [51] —, «Tyrrhenian link: Terna presenta al mite la richiesta di autorizzazione per la tratta ovest, tra sicilia e sardegna». (2021), [Online]. Available: <https://www.terna.it/it/media/comunicati-stampa/dettaglio/tyrrhenian-link-richiesta-autorizzazione-tratta-ovest>.
- [52] T. Tröndle and B. Pickering, *Euro-Calliope*, version 1.2.0.dev, Dec. 2021. DOI: 10.5281/zenodo.3949793.
- [53] R. Wiser, J. Rand, J. Seel, *et al.*, «Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050», *Nature Energy*, vol. 6, pp. 555–565, 5 May 2021, ISSN: 20587546. DOI: 10.1038/s41560-021-00810-z.
- [54] E. Commission, *Joint research centre data catalogue enspreso - an open data, eu-28 wide, transparent and coherent database of wind, solar and biomass energy potentials*, <https://data.jrc.ec.europa.eu/collection/id-00138>, 2022.
- [55] D. P. Natura, *Progetto natura banche dati geografiche delle principali aree naturali protette*, 2022.
- [56] la Repubblica. «Terna: 3,7 miliardi per tyrrhenian link, operativo da fine 2025». (2022), [Online]. Available: https://finanza.repubblica.it/News/2022/10/04/terna_3_7_miliardi_per_tyrrhenian_link_operativo_da_fine_2025-155/.
- [57] D. Süsser, B. Pickering, L. Hülk, and S. Pfenninger, «Open energy system modelling to support the european green deal», *F1000Research*, vol. 11, 2022, ISSN: 1759796X. DOI: 10.12688/f1000research.121619.1.

-
- [58] Terna, *Impianti di produzione essenziali per la sicurezza del sistema elettrico ai sensi dell'articolo 63, comma 63.1, dell'allegato a alla delibera dell'arera n. 111/06 - elenco valido per l'anno 2022*, https://download.terna.it/terna/Allegato_A27%20-%20anno%202022_8d9a5da0f9074fc.pdf, 2022.
- [59] S. Terna, *Scenario di domanda di energia elettrica e gas naturale relativi alla regione sardegna*, https://download.terna.it/terna/Sardegna_documento_scenario_energia_elettrica_gas_2022_8da71982eb8304e.pdf, 2022.
- [60] U. S. E. P. Agency. «Renewable energy fact sheet: Wind turbines». (), [Online]. Available: https://www.epa.gov/sites/default/files/2019-08/documents/wind_turbines_fact_sheet_p100il8k.pdf.
- [61] A. D. Belegundu and T. R. Chandrupatla, *Optimization Concepts and Applications in Engineering*. DOI: <https://doi.org/10.1017/CB09780511975905>.
- [62] E. Commission. «Long-term strategy for 2050». (), [Online]. Available: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_it.
- [63] —, «Questions and answers - making our energy system fit for our climate targets». (), [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/QANDA_21_3544.
- [64] M. dell'ambiente. «Geoportale nazionale». (), (visited on 2022).
- [65] G. M. Energetici. «Mercato del giorno prima». (), [Online]. Available: <https://www.terna.it/it/media/comunicati-stampa/dettaglio/tyrrhenian-link-richiesta-autorizzazione-tratta-ovest> (visited on 11/2022).
- [66] G. S. Energetici. «Rapporto statistico solare fotovoltaico». (), [Online]. Available: https://www.gse.it/documenti_site/Documenti%20GSE/Rapporti%20statistici/Solare%20Fotovoltaico%20-%20Rapporto%20Statistico%20GSE%202020.pdf (visited on 2020).
- [67] G. G. S. Energetici, *Atlaimpianti*, https://atla.gse.it/atlaimpianti/project/Atlaimpianti_Internet.html.
- [68] «Energy system model framework». (), [Online]. Available: <https://oemof.org/>.
- [69] «Energy system model framework». (), [Online]. Available: <http://www.osemosys.org/>.
- [70] «Energy system model framework». (), [Online]. Available: <https://temoacloud.com/>.
- [71] entsoe. «Grid map». (), [Online]. Available: <https://www.entsoe.eu/data/map/> (visited on 09/24/2022).
- [72] Fera. «Biogas plants». (), [Online]. Available: <https://www.ferasrl.it/progetto/pabillonis/>.
- [73] —, «Progetto decimopotzu». (), [Online]. Available: <https://www.ferasrl.it/progetto/decimputzu/>.

- [74] «German electricity market model». (), [Online]. Available: <https://osf.io/kp4mh/>.
- [75] C. studi di economia e tecnica dell'energia Giorgio Levi Cases. «Una valutazione socio-economica dello scenario rinnovabili per la sardegna». (), [Online]. Available: <https://www.wwf.it/uploads/sardegna-def.pdf>.
- [76] N. Golinucci, N. Stevanato, F. Inzoli, *et al.*, «Comprehensive and integrated impact assessment framework for development policies evaluation definition and application to kenya»,
- [77] Google, <https://www.google.it/intl/it/earth/>.
- [78] —, *Openmod open energy modelling initiative*, <https://www.google.it/maps>.
- [79] IBM, *Ibm cplex optimizer*, <https://www.ibm.com/it-it/analytics/cplex-optimizer>.
- [80] —, *List of cplex parameters*, <https://www.ibm.com/docs/en/icos/12.10.0?topic=cplex-list-parameters>.
- [81] Istat. «Demografia in cifre». (), [Online]. Available: <https://demo.istat.it/app/?i=PPC&l=it>.
- [82] E. Maps. «Impatto climatico per area». (), [Online]. Available: <https://app.electricitymap.org/zone/IT-SAR?wind=true&solar=false>.
- [83] R. Naam. «Solar's future is insanely cheap». (), [Online]. Available: <https://rameznaam.com/2020/05/14/solars-future-is-insanely-cheap-2020/>.
- [84] C. N. di Informazione delle Nazioni Unite. «Obiettivi per lo sviluppo sostenibile». (), [Online]. Available: <https://unric.org/it/agenda-2030/>.
- [85] Niet, Taco, Kuling, and Kamaria. «Introduction to energy modelling». (), [Online]. Available: <https://summit.sfu.ca/item/20738>.
- [86] D. Oleksandr. «Mathematics for business and economics». (), [Online]. Available: <https://www.math.wsu.edu/students/odykhovychnyi/M201-04/>.
- [87] *Openmod open energy modelling initiative*, <https://www.openmod-initiative.org/>.
- [88] «Operational optimisation model framework». (), [Online]. Available: <https://github.com/robbiemorrison/deeco>.
- [89] S. Pfenninger and I. Staffell. «Renewables.ninja». (), [Online]. Available: <https://www.renewables.ninja/> (visited on 2019).
- [90] «Power system model framework». (), [Online]. Available: <https://github.com/rwl/PYPOWER>.
- [91] «Power system model framework based on pypower». (), [Online]. Available: <https://www.advancedgridinsights.com/gridcal>.
- [92] «Power system model framework based on pypower». (), [Online]. Available: <https://arxiv.org/abs/1709.06743>.

- [93] «Power system model framework inspired by pypower». (), [Online]. Available: <https://pypsa.readthedocs.io/en/latest/>.
- [94] «Power system simulation model (germany and neighbouring countries)». (), [Online]. Available: <https://github.com/fraukewiese/renpass>.
- [95] M. della Salute, *Covid-19*, <https://www.salute.gov.it/portale/nuovocoronavirus/homeNuovoCoronavirus.jsp>.
- [96] P. Sanctuary. «Presentation of the pelagos sanctuary». (), [Online]. Available: <https://www.sanctuaire-pelagos.org/en/>.
- [97] R. autonoma della Sardegna. «Cambamenti climatici». (), [Online]. Available: <https://portal.sardegna.sira.it/web/sardegnaambiente/cambiamenti-climatici>.
- [98] —, «Costruiamo insieme sardegna2030». [Online]. Available: https://www.regione.sardegna.it/documenti/1_964_20210311172115.pdf.
- [99] —, «Sardegna ambiente». [Online]. Available: <https://www.sardegnaambiente.it/>.
- [100] R. autonoma della Sardegna Assessorato dell'Industria, «Documento di indirizzo sulle fonti energetiche rinnovabili in sardegna studio sulle potenzialità energetiche delle biomasse». [Online]. Available: https://www.regione.sardegna.it/documenti/1_461_20131216100125.pdf.
- [101] Sarlux. «Produzione di energia». (), [Online]. Available: <https://www.sarlux.saras.it/it/cosa-facciamo-produzione-energia/>.
- [102] B. P. Stefan Pfenninger, *Calliope documentation release 0.6.8*, <https://calliope.readthedocs.io/en/stable/>.
- [103] Terna, «Dati statistici consumi». [Online]. Available: https://download.terna.it/terna/6-CONSUMI_8d9cecfdb0ebb54.pdf.
- [104] —, «Pubblicazioni statistiche capacità impianti di generazione». (), [Online]. Available: <https://www.terna.it/it/sistema-elettrico/statistiche/pubblicazioni-statistiche>.
- [105] —, *Riserva in energia elettrica e fattore di invaso dei serbatoi stagionali in italia alla fine di ciascun mese*, <https://download.terna.it/terna/0000/0112/10.pdf>.
- [106] —, «Sa.co.i. 3: L'importante opera di rinnovo dello storico collegamento tra toscana, corsica e sardegna». (), [Online]. Available: <https://www.terna.it/it/progetti-territorio/progetti-incontri-territorio/terna-incontra-toscana-sardegna>.
- [107] —, «Tyrrhenian link: Il doppio collegamento sottomarino tra sicilia, sardegna e penisola». (), [Online]. Available: <https://www.terna.it/it/progetti-territorio/progetti-incontri-territorio/Tyrrhenian-link>.
- [108] *The official yaml web site*, <https://yaml.org/>.
- [109] «Transmission grid model». (), [Online]. Available: <http://www.scigrid.de/>.