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Energy Department

Time-dependent analysis of fossil fuel power plants transient operations in energy system modeling

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Extended abstract

Introduction

Over the last decades the world electricity consumptions per capita have experienced a fast growth and this coupled with environmental and energy security issues, have stressed the need to generate electricity in a diversified and more sustainable way. Many nations have experienced a fundamental transformation in terms of electricity generation mix: switching from a fossil fuel-based to a Carbon free energy production by the extended use of Renewable Energy Sources (*RES*). The main drivers that have led to the transformation of the electricity generation mix are: the convenience in diversify energy supply for economic (volatility of fuel prices and energy security reasons) and the public concern about climate changes that implies the reduction of the impact of human activity on environment producing from sources that have low life-cycle emissions and renew them self for free in nature (*RES*).

The electricity production from RES power plants involves additional costs related to the intermittent time profile of their production, which implies additional back-up power, additional balancing costs and higher specific costs of fossil fuel power plants that operate longer at partial load and are started-up or shut-down more frequently in order to provide load following and maintain the entire system in balance: thus nowadays cycling and ramping of fossil fuel power plants are the main source of operational flexibility for an energy system. Cycling is defined [1] as the range of operations in which a plant's output changes, including starting up and shutting down, ramping up and down; additional costs, additional emissions and ramp constraints are associated to these off-design working conditions.

A better understanding of short-term operational implications can help policy decision makers to identify appropriate options that can enhance the flexibility of the electric system and reduce the environmental impact. Governments and policymakers need tools that are able to simulate with high accuracy the functioning of an energy system, in order to evaluate the impact of all the possible solutions and apply cost-effective energy strategies and policies.

A very useful and powerful tool to make simulation and prediction of future energy scenarios is energy systems modeling, that consists in the description, through mathematical equations, of the mechanisms and transformations that link energy supply and demand in an energy system.

The scope of this thesis work, performed in collaboration with *EURAC Research*, is to develop a model that performs a time-dependent analysis of fossil fuel power plants transient operations in order to have a more realistic representation of an energy system.

Literature Review

A literature review has been performed to assess the different aspects of energy modeling and the available state-of-the-art models.
In literature [2, 3] two complementary approaches to energy modeling are distinguished (*Top-down* and *Bottom-up*). *Top-down* models, usually preferred by economists and public administrations, maintain an aggregated view of the energy sectors and of the economy, in order to evaluate the relative influence. Due to the low technological detail, these models are not suited to evaluate or optimize sector-specific decisions and synergies between the system components. However, they are capable to assess the impact of general energy and climate policies on socio-economic indicators such as public welfare, employment and social growth. *Bottom-up*, by contrast, are characterized by high technological detail and provide a detailed picture of the different energy sectors and of the connections between the modeled devices. This accurate description of an energy system's internal relationships allows the user to examine the role of various technologies and their potential synergies. However, these models usually neglect any connection between the energy sectors and the economics of a country. Moreover, given the number of parameters used to describe the various components, they are very reliable on data. *Bottom-up* models are generally used by engineers, who are more interested in analyzing potential technological solutions than the macroeconomic impacts of policies; in this thesis work is preferred the *Bottom-up* approach due to the high technological detail that this kind of model provides, that allow to model the transient operations of fossil fuel power plants.
The *Bottom-up* approach can be adopted to model the unit commitment problem, that consists of scheduling of generating units in order to satisfy demand requirements, overcome possible losses and meet the energy system's constraints (as ramp limits, start-up costs, transmission capacity limits, upper and lower limits on the generating units, power flow limits, decay of efficiency at partial load) at least cost. The implementation of certain constraints turn the unit commitment problem into a complex, non-linear, mixed-integer one, more difficult to solve, thus memory usage and computational time rise exponentially. This is the case of this thesis work: the implementation of the constraints to represent the transient operation of fossil fuel power plants, transforms the unit commitment problem for the dispatch of electricity in a mixed-integer optimization problem.
In last years modeling the unit commitment problem is becoming more challeng-

ing, due to higher complexity of electricity industry operations: thus the recent liberalization of many electricity markets, along with the rapid expansion of *RES*, in particular of *VRES*, such wind and *PV*, have resulted in drastic changes in how generation units are required to operate [4], increasing the frequency of fossil fuel power plants' transient operations. An increased penetration of *VRES*, due to their intermittent, variable and unpredictable nature, requires more flexible power generation units in order to counterbalance the fluctuations of these sources and maintain the system in balance. This required flexibility is usually provided by transient operations of fossil fuel power plants that are required to work longer at partial load and to be started-up more frequently in order to follow the load. The impact and the importance of these transient events could also be greater in future configurations of the energy system with higher *VRES* penetration. Many case studies show that the higher is the penetration of *RES*, the higher are the transient operation of fossil fuel plants and so the associated costs [5], [6], [7].
The literature review has been completed with a thorough analysis of the most established *Bottom-up* models (*OSeMOSYS* [8], *PLEXOS* [9], *EnergyPLAN* [10] and *Oemof* [11]) in order to evaluate how transient events of fossil fuel power plants are analyzed. *OSeMOSYS* does not perform any transient analysis, but is an open-source model, thus is possible to implement new constraint in order to reproduce the behavior of fossil fuel during transient operations; this is not convenient due to the poor time-discretization that does not allow to characterize properly transient operations. *PLEXOS* considers only start-up as transient event; this transient analysis is not time-dependent, thus the start-up costs are not a function of the hours of stop of the plant. The implementation of new constraints to improve the transient analysis is not allowed because the model is not open-source and so no modification of the core-code are allowed. *EPLANopt + CCGT_Model* combines *EnergyPLAN* simulation model with an optimization performed using *Genetic Algorithm (GA)* and a post-processing analysis on the cycling costs of *CCGT* [12]; this model performs just a post-processing analysis: the cycling costs are not considered in the optimization of the electricity dispatch, but calculated a posteriori. *Oemof* introduces only start-up as transient event, thus the costs related to the start-up does not depend on down-time of the plant (hour of stop), power units are modeled as fully-flexible (power output can vary from zero to the maximum in one time-step) and decay of performances during partial operations is not implemented, thus the transient analysis in not time-dependent.
The aforementioned *Bottom-up* models are not able to evaluate in a detailed way the impact of transient operations of fossil fuel power plants (cycling) on the optimization of electricity dispatch. For this reason, the scope of this thesis work is to create a *Bottom-up* model able to represent the behavior of fossil fuel power plants in a detailed and realistic way; the model created performs a time-dependent analysis of fossil fuel power plants' transient operations: this means that the constraints implemented to perform this transient analysis

introduces additional costs, emissions and ramp rate of available power that, for each instant of time, are a function of the hours of stop and of the power output of the plant. The time-dependent transient analysis developed for this thesis work is performed enhancing *Oemof* model and leads to the creation of the denominated *Oemof_Transient* model. In Table i are reported the new features introduced by this model respect to the state of the art.

Model	Open-Source	Scope	Spatial resolution	Temporal resolution	Transient analysis	Constraints for transient analysis	Critical aspects
OSeMOSYS	Yes	optimization	single node	time-slices	➢ no	➢ *no*	➢ *transient analysis is not implemented* ➢ *poor time-discretization*
PLEXOS	No	optimization	single node	user-defined	➢ integrated, ➢ not time-dependent	➢ *start-up costs*	➢ *transient analysis is not time-dependent* ➢ *ramp constraints are not implemented* ➢ *decay of efficiency is not implemented*
EPLANopt model + CCGT_Model	No	optimization	single node	hours	➢ post-processing	➢ *start-up costs* ➢ *ramp constraints* ➢ *decay of efficiency*	➢ *transient analysis is performed a posteriori (not included in the optimization process)*
Oemof	Yes	optimization	multi node	user-defined	➢ integrated, ➢ not time-dependent	➢ *start-up costs*	➢ *transient analysis is not time-dependent* ➢ *decay of efficiency is not implemented*
Oemof_Trasient	Yes	optimization	multi node	user-defined	➢ integrated ➢ time-dependent	➢ *time-dependent start-up costs* ➢ *time-dependent ramp constraints* ➢ *time-dependent decay of efficiency*	➢ *high computational burden*

Table i: Models available in literature and *Oemof_Transient*

Methods and Materials

Oemof_Transient is a unit commitment model that optimizes the dispatch of electricity considering also transient operation of fossil fuel power plants through a time-dependent analysis. *Oemof_Transient* model is created using *Oemof* framework because is suited for the scope of this thesis work by being open-source (the core-code can be modified in order to implement new constraints), adaptable, time-step flexible (temporal resolution and the time discretization are user-defined) and presents high spatial resolution (multi-node approach); these features allow to perform detailed technical analyses of energy systems, thus is possible to set the time discretization in order to recognize the desired transient operation and implement new constraints to model it.

In *Oemof_Transient* the following time-dependent constraints have been implemented to represent the transient operations of fossil fuel power plants:

- **time-dependent start-up costs**: various start-up costs that are a function of the hours of stop of the plant and depend on the technology adopted.

- **time-dependent ramp constraints**: various ramp constraints that are a function of the hours of stop of the plant and depend on the technology adopted.

- **time-dependent decay of efficiency at partial load**: degradation of performances that is verified when power plants are not producing at full-load (nominal condition); it is implemented as an additional fuel consumption (and thus additional costs and emissions), respect to the ideal case where the efficiency remains constant and equal to the nominal value.

In Figure i the structure of *Oemof_Transient* model is reported for a two-nodes energy system with the connections between the components. The electricity is generated from Renewable Energy Sources (modeled as Source components in yellow) and Fossil Fuel Power Plants (modeled as Transformer components in gray) and is consumed as Electricity Demand (modeled as Sink component in green). The electricity produced can be transferred from one node to the other by Transmission Lines (modeled as Transformer components in gray). If overproduction from Renewable Energy Sources occurs, the electricity excess can be stored with Storage technologies (modeled as Generic Storage components in blue), if Storage is full the electricity is dissipated leading to the so called curtailment.
The dispatch of electricity is performed in *Oemof_Transient* model taking as input data the electricity demand and the generation from *RES* and optimizing the production from fossil fuel power plant considering transient operations, the usage of storage technology and the electricity transferred from one node the the other, without overcoming the constraints and limits on the various components of the energy system.
An effective and useful way to consider and quantify these transient operations in energy system modeling, is the introduction of cycling costs, a parameter used to calculate the costs related to cycling operations of power plants. Cycling costs are a result of both the number and type of starts-up and the operating regime of power plants.

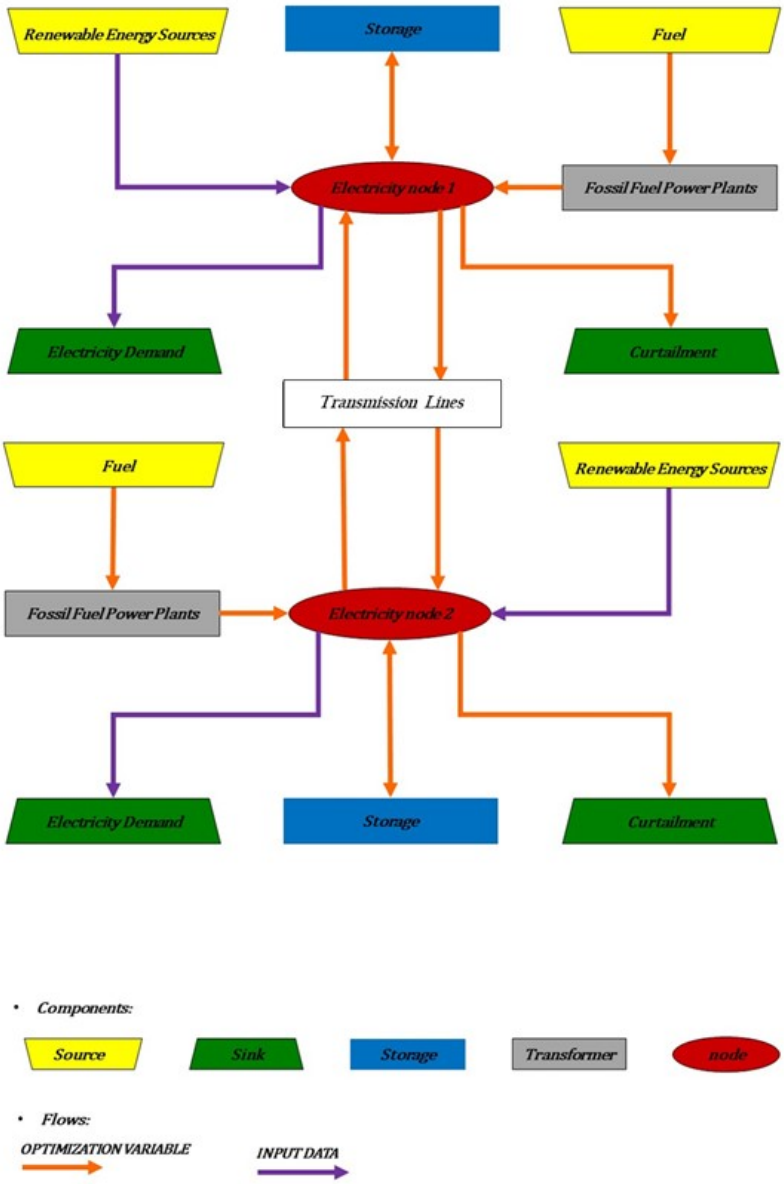

Figure i: *Oemof_Transient* model structure for a two-nodes energy system

Italian case-study

To validate the proposed methodology *Oemof_Transient* model has been applied to an Italian case-study. In the Italian energy system is analyzed considering the situation in 2014 and possible future scenarios in 2050, with higher *VRES* installed capacity. The Italian case is extremely peculiar since the energy system has occurred several changes in the last decade. The high availability of *RES* such as sun and hydro-power, as well as the incentives granted to solar PV and wind turbines in the years after 2010, have converted Italy in one of the leading countries in the European Union for renewable energy.

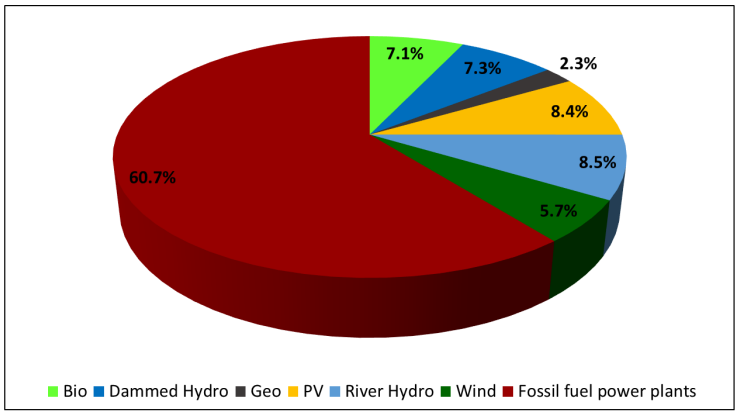

Figure ii: *Oemof_Transient* optimization results: annual electricity generation from the various technologies in *Italy_2014* scenario

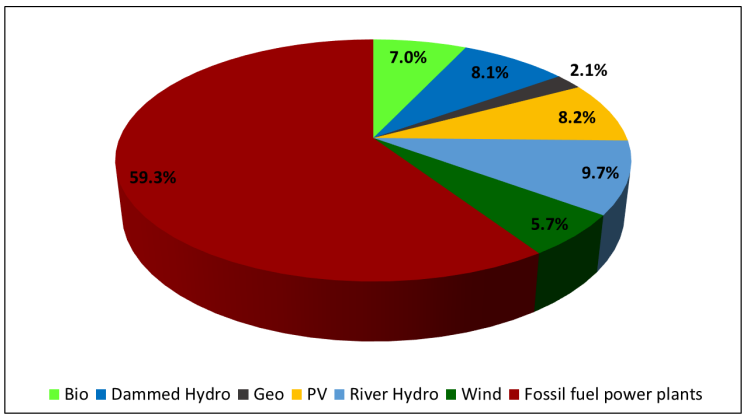

Figure iii: *Terna* data: annual electricity generation from the various technologies in 2014

Elaboration of *Terna* [13] data

The situation in 2014 is analyzed to validate the *Oemof_Transient* model and quantify the impact of cycling costs on the actual Italian energy system. The results of the optimizations with the data on Italian electricity sector, in order to prove the validity and the reliability of the methodology adopted. Considering the assumptions and approximation introduced, the results of the optimization are consistent with the real data on the Italian energy system. *Oemof_Transient* model is validated by comparing the results of the optimization for 2014 with the actual values of CO_2 emissions and electricity generation (Figure ii and Figure iii) provided by *Terna*, *ISPRA*, *IEA* and *World Bank*.
For 2014 two scenarios are considered: *Italy_2014* scenario is representative of the real configuration of the Italian electricity sector, where all the different technology of fossil fuel power plants are introduced in the model and the other scenario (*Italy_2014_CCGT*), where fossil fuel power plants are modeled only by *CCGT*; this scenario is created for comparison with scenarios at 2050, because it is assumed that in future configuration of the energy system, in order to reduce *GHG* emissions and provide flexibility to generation side, the only technology adopted for fossil fuel power plants is *CCGT*. This assumption is in accordance with the national strategy for future development of the Italian energy system: thus from the official reference document, *Strategia Energetica Nazionale (SEN)* [14] (last version published in 2017), the general picture that emerges is a push to solar and wind power and is also stated the possibility of a complete phase-out from coal fueled power plants.
The scenarios at 2050 (*Italy_2050*) created for *Oemof_Transient* model, are obtained considering different penetration of *VRES* and allow to quantify the higher importance of fossil fuel power plants transient operations in this new configurations of the Italian energy system. These scenarios have been developed evaluating the potentialities of variable renewable energy sources such as *PV* and wind power in terms of new installations and overall installed power. In particular four scenarios are created (where '*%*' indicates the percentage of *VRES* installed capacity respect maximum potential): *VRES_25%*, *VRES_50%*, *VRES_75%* and *VRES_100%*.
Table ii summarizes the data adopted to create the various scenarios (*Italy_2014*, *Italy_2014_CCGT* and *Italy_2050*) and these data are set as input for the model.

Data	**Source**
Hourly distributions for *RES*	*Terna* [13, 15], *GSE*[16–21]
Installed capacity for *RES*	*Terna*[13, 15], *GSE*[21]
Maximum potential for *VRES* installed capacity	[22], [23]
Installed capacity for fossil fuel power plants	*Terna* [13, 15, 24, 25]
Electricity demand	*Terna* [13]
Installed capacity for *PHS* technologies	*Terna* [13]

Table ii: Sources used for the development of *Italy_2050* scenarios for *Oemof_Transient* model

In the analysis performed in this thesis work only the transient operations of *CCGT* are considered , because nowadays are the main source of flexibility for an energy system, thus these power units operate longer at partial load and have to be started-up or shut-down more frequently in order maintain the entire energy system in balance and counterbalance the fluctuations of *VRES*; so the time-dependent constraints are applied only to this technology. The costs and the characteristics related to the different types of start of *CCGT* are difficult to define, indeed in literature different values are reported; in this work are adopted the start-up costs related to three different studies on *CCGT* lead to the creation of different scenarios for *Oemof_Transient* model: the optimistic scenario with lowest start-up costs [26] (named Best case), the scenario with medium start-up costs [27] (named Average case) and the pessimistic scenario with higher star-up costs [5] (named Worst case). Thus for each configuration of the energy system three different optimizations (one for each scenario) are performed changing start-up costs and leaving unchanged the other constraints and parameters.Table iii summarizes the configurations of the Italian energy system evaluated through the optimizations performed by *Oemof_Transient*.

Scenarios	***VRES* installed capacity**	**Fossil fuel power plants**
Italy_2014	*Terna*'s data in 2014	all technologies
Italy_2014_CCGT	*Terna*'s data in 2014	only *CCGT*
Italy_2050_VRES_25%	25% of $VRES_{\max}$	only *CCGT*
Italy_2050_VRES_50%	50% of $VRES_{\max}$	only *CCGT*
Italy_2050_VRES_75%	75% of $VRES_{\max}$	only *CCGT*
Italy_2050_VRES_100%	$VRES_{\max}$	only *CCGT*
$\boldsymbol{VRES_{\max}}$	***PV*** *[GW]* 121	**Wind** *[GW]* 49

Table iii: Configurations evaluated with *Oemof_Transient* model

Optimizations results

Firstly it is evaluated how the time-dependent constraints implemented in this thesis work affect the optimization dispatch problem. In Figure iv, v and vi are reported the results of the optimization with constraints on *CCGT* for the first week of July in 2014 in the macro-region North, considering the three different scenarios analyzed (Best, Average and Worst case); for each figure : on the top matching between electricity demand and generation, in the center number of starts of *CCGT* differentiated by start-up modes, while on the bottom Average Load factor (electricity produced from *CCGT* at time t divided by the maximum amount of electricity that can be generated from the *CCGT* that are turned on) as function of time.

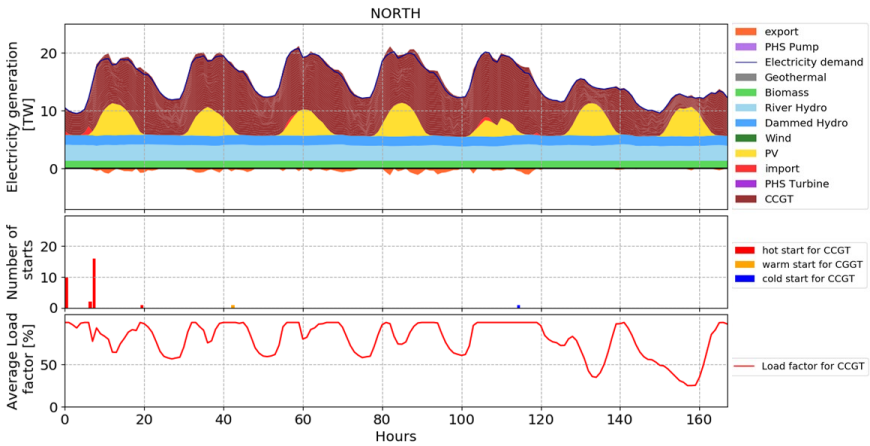

Figure iv: Results for Italy in 2014 considering high start-up costs (Worst case).

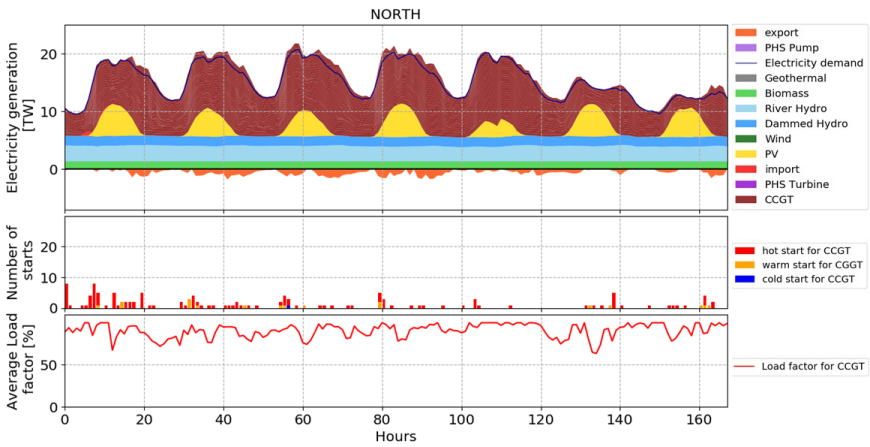

Figure v: Results for Italy in 2014 considering medium start-up costs (Average case).

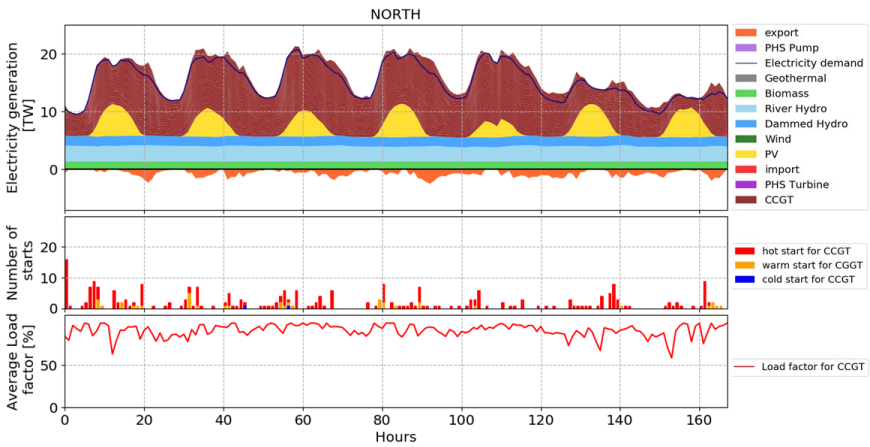

Figure vi: Results for Italy in 2014 considering low start-up costs (Best case).

The following constraints are introduced in the optimizations: three start-up costs (hot, warm and cold start), one ramp constraints and decay of efficiency at partial load. It is possible to notice from the graphs that changing the start-up costs, the constraints affect in different way the optimization dispatch problem: with low start-up costs (Best case) the constraint on the decay of efficiency at partial is the most influent, thus *CCGT* are forced to work at higher loads and so higher efficiency, the number of starts is higher and power plants are started-up more frequently respect to the other cases (Average and Worst); with high start-up costs (Worst case) the impact of the constraints is different, in particular in this case the influence of start-up costs is higher respect to the decay of efficiency, thus the number of starts is reduced at minimum, *CCGT* are started-up less frequently and only if strictly necessary and they works longer at lower loads; with medium start-up costs (Average case) the optimization results are more similar to the case with low start-up costs (Best case).
Finally a comparison of the results for the various scenarios (*Italy_ 2014_ CCGT* and *Italy_ 2050*) is performed; in particular single node vs multi-node approach, CO_2 emissions, overproduction from *VRES* and cycling costs are analyzed in detail.
The results of optimizations on CO_2 have been compared to the targets on *GHG* emissions set by the Europe Union for 2020 [28], 2030 [29] and 2050 [30]. In *Oemof_ Transient* model is analyzed only the electricity sector, so the values of CO_2 emissions for the other sectors are considered constants and equal to the values at 2014. By comparing the results of the optimizations on CO_2 emissions with the targets set by the Europe Union, can be concluded that, it is not possible to act only on the electricity sector to obtain higher reductions in CO_2 emissions to meet the targets for 2030 (*EU2030*) and for 2050 (*Energy Roadmap 2050*).

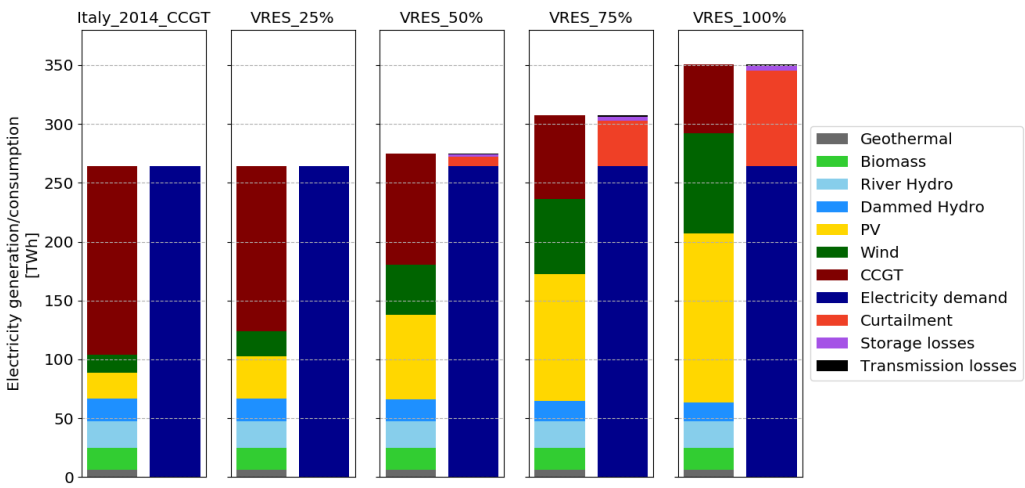

Figure vii: *Oemof_ Transient* optimizations results: Annual electricity balance for *Italy_ 2014_ CCGT* and *Italy_ 2050* scenarios

In Figure vii the annual electricity balance are reported for the various configurations of the Italian energy system. It can be highlighted that as the installed capacity and thus the production from *VRES* increase (passing from 2014 to 2050 scenarios), the electricity generation from fossil fuel power plants is reduced and the usage of *PHS* technologies is higher. The results of the optimizations showed that the actual transmission constraints and *PHS* installed capacity are not sufficient to absorb the over-generation from *VRES*, thus curtailment is verified in configurations of the energy system with high values of *VRES* installed capacity, as shown in Figure vii.
The growing installed capacity of *VRES* (passing from 2014 scenario to the ones for 2050) introduces in the solutions higher costs and higher reductions in CO_2 emissions. The amount of money saved due to the lower annual fuel consumptions does not compensate the annual costs associated the higher values of *VRES* installed capacity and the higher specific cycling costs, as depicted in Figure viii, where is reported the relative increase in total annual costs as function of the relative decrease in annual CO_2 emissions respect to *Italy_2014_CCGT* scenario, for the different configurations of the Italian energy system; considering the maximum value of *VRES* installed capacity (*VRES_100%* scenario) is possible to obtain a reduction in CO_2 emissions higher than 60% for the multi-node configurations. Looking at the figure is possible to observe that the total annual cost and annual emissions rise when constraints on *CCGT* are introduced in the optimizations (Best case, Average case and Worst Case) and as the cycling costs increase (high start-up costs assumed or high values of *VRES* installed capacity); thus the transient operations of fossil fuel power plants, modeled by the constraints, introduced additional costs and emissions in the optimizations.
In order to perform a complete analysis, the Italian energy system is evaluated also adopting a single node approach (without considering transmission losses and transmission constraints) for the same configurations described above. Results show that the single node approach underestimates costs and emissions in configurations of the energy system with high values of *VRES* installed capacity, by about 4% and 9% respectively in the scenario with maximum *VRES* installed capacity (*VRES_100%*). In *Italy_2014_CCGT* scenario the use of a single-node approach does not produce different results on curtailment, because the limited *VRES* installed capacity allow to exploit the whole over-generation. The multi-node approach is particularly relevant for a territory like Italy, where the majority of the wind and *PV* installed capacity is located in the south while the *PHS* power plants are mainly located in the North.
The time-dependent constraints created in *Oemof_Transient* to model the transient operations of fossil fuel power plants, introduce in the optimizations additional costs (cycling costs) due to starts-up and off-design operations.
From the results it is highlighted that as the *VRES* installed increases, specific cycling costs rise (from *Italy_2014_CCGT* to *VRES_100%* scenario), thus the profile of production is more intermittent and the equivalent hours of *CCGT*

are reduced; this behavior is also experienced in other case studies.
Results show that the impact of transient operations of fossil fuel power plants is not negligible, thus with constraints on *CCGT*, specific costs increase from 5% to about 30%.

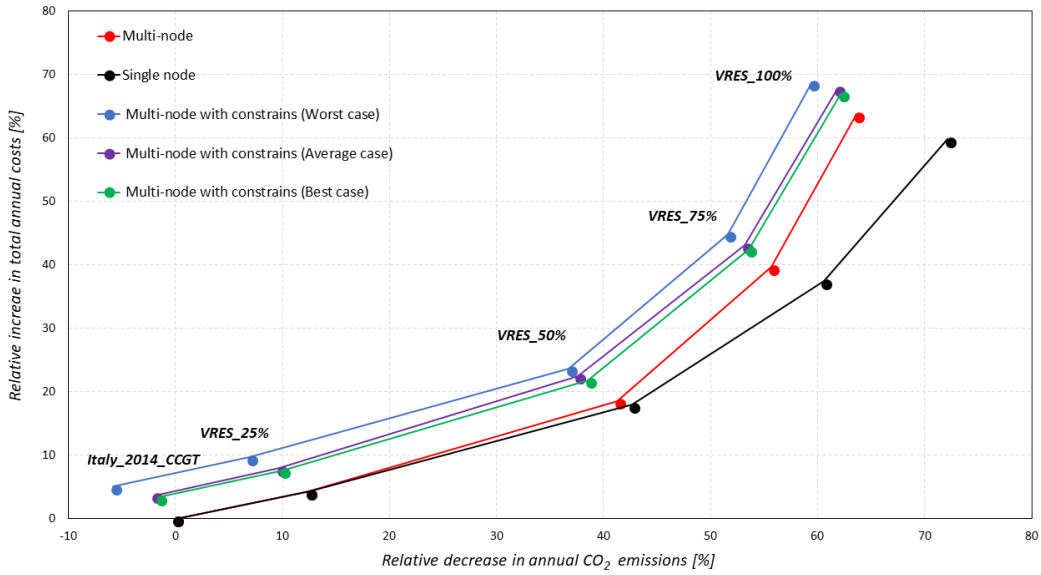

Figure viii: Results of the optimizations over one year for *Italy_ 2014_ CCGT* and *Italy_ 2050* scenarios considering single node, multi-node and multi-node with constraints on *CCGT* configurations: *Relative increase in total annual costs* vs *Relative decrease in annual CO_2 emissions*

Conclusions

The model created in this work have been developed to improve the analysis of the transient operations of fossil fuel power plants in energy system modeling. This objective has been reached moving toward different directions: high temporal and spatial resolution (hourly time-step and multi-node approach) and high technological details (constraints on fossil fuel power plants) .
The transient operations of fossil fuel power plants have been analyzed at different levels of integration of *VRES* and this analysis has been performed implementing new constraints in *Oemof* by taking advantage of its features (open source, high temporal and spatial resolution), and leads to the creation of *Oemof_Transient* model, a *Bottom-up* multi-node model that performs the optimization of the dispatch of electricity based on costs, considering also the transient operations of fossil fuel power plants that are modeled by time-dependent constraints (the constraints introduces additional costs, emissions and ramp rate of available power that, for each instant of time, are a function of the hours of stop and the power output of the plant).

The improvements of *Oemof_Transient* model with respect of the state-of-the-art of energy modeling are given by the multi-node modeling approach coupled to the hourly based dispatch optimization accounting for time-dependent constraints to model with accuracy the transient operations of fossil fuel power plants.
From the results is highlighted that the higher is the penetration of *VRES*, the higher are the transient operation of fossil fuel plants and so the associated specific costs and emissions.
The analysis performed in this thesis work emphasizes the importance to consider the transient operations of fossil fuel power plants in energy system with high *VRES* penetration. The model developed (*Oemof_Transient* model) analyzes in detail these transient operations, but high computational times are required to perform an optimization, thus the time-dependent constraints created increase the complexity of the problem.
The time-dependent transient analysis created opens up to model that evaluate the best solutions in terms of flexibility for an energy system by comparing cycling of fossil fuel power plants with other strategies that better exploit the over-production from *VRES* by storing (e.g. electric batteries) or converting in other forms of energy (e.g.: thermal energy, hydrogen obtained by electrolysis) this excess of electricity. Efforts should be made to allow an accurate integration of the intermittent *VRES*, since such technologies (PV modules and wind turbines) nowadays represent some of the best options available to face environmental (climate change) and energy security issues (security of supply).

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Abstract

Key words: Energy modeling, *Oemof*, *VRES*, Fossil fuel power plants, Cycling.

The growing electricity consumptions coupled with environmental and energy security issues, have stressed the need to produce electricity in a diversified and more sustainable way. Many nations have experienced a fundamental transformation in terms of electricity generation mix: switching from fossil fuel-based to a Carbon free energy production by the increased exploitation of *VRES*. Their integration, due to the intermittent and unpredictable nature, requires flexible power generation units in order to counterbalance the fluctuations of these sources and maintain the energy system in balance. This required flexibility is usually provided by cycling (transient operations) of fossil fuel power plants, that involves additional costs and emissions: these power units are required to work longer at partial load and to be started-up or shut-down more frequently. A better understanding of short-term operational implications can help policy-makers to identify appropriate options that can enhance the flexibility of an energy system and reduce the environmental impact. A very useful tool is energy modeling that allows, through mathematical equations, to simulate and optimize actual or future configurations of energy systems. Usually, in order to reduce the computational time, transient operations of fossil fuel power plants are not modeled, however, these events are very relevant in energy systems with high penetration of *VRES* and their impact should be analyzed more in detail. The scope of this thesis work, performed in collaboration with *EURAC Research*, is to develop a model that performs a time-dependent analysis of fossil fuel power plants transient operations in order to have a more realistic representation of an energy system. These time-dependent transient analysis is performed enhancing *Oemof* model and leads to the creation of the denominated *Oemof_Transient*, a *Bottom-up* multi-node model that performs the optimization of the dispatch of electricity based on costs, considering also the transient operations of fossil fuel power plants that have been modeled through the implementation of new constraints (time-dependent start-up costs, time-dependent ramp constraints and time-dependent decay of efficiency at partial load). The model has been applied to the Italian energy system, considering the configurations in 2014 and possible future scenarios with higher *VRES* installed capacity.

Sommario

Parole chiave: Modellazione di sistemi energetici, *Oemof*, *FERV*, Impianti fossili, Cycling.

I crescenti consumi elettrici, insieme a problemi di impatto ambientale e sicurezza energetica, hanno portato alla produzione di energia elettrica in modo diversificato e più sostenibile. In molti stati si sono verificati cambiamenti nel mix energetico: passando da una produzione di energia elettrica basata sui combustibili fossili ad una priva di emissioni di carbonio, grazie al maggiore sfruttamento di *Fonti di Energia Rinnovabile Variabile* (*FERV*). A causa della natura intermittente e imprevedibile, queste fonti richiedono flessibilità nella generazione di elettricità al fine di controbilanciare le loro fluttuazioni e mantenere il sistema energetico in equilibrio. Questa flessibilità è solitamente fornita dal cycling (transitori) degli impianti fossili, che comporta emissioni e costi aggiuntivi: questi impianti sono spinti a lavorare più a lungo ai carichi parziali e vengono accesi e spenti più frequentemente. Una migliore comprensione delle implicazioni operative a breve termine può aiutare le amministrazioni a individuare soluzioni che possano migliorare la flessibilità e ridurre l'impatto ambientale. Uno strumento molto utile è la modellazione di sistemi energetici che consente, tramite equazioni matematiche, di simulare e ottimizzare configurazioni attuali o future. Generalmente, al fine di ridurre i tempi di calcolo, i transitori degli impianti fossili non vengono modellati; tuttavia queste operazioni sono molto rilevanti in sistemi energetici ad alta penetrazione di *VRES* e il loro impatto dovrebbe essere analizzato più in dettaglio. Lo scopo di questa tesi, realizzata in collaborazione con *EURAC Research*, è di sviluppare un modello che performi un'analisi tempo-dipendente dei transitori degli impianti fossili per avere una rappresentazione più realistica di un sistema energetico. Quest'analisi è stata realizzata migliorando il modello esistente *Oemof* e porta alla creazione di *Oemof_Transient*: è un modello *Bottom -up* e multi-nodo che ottimizza il dispacciamento dell'elettricità sulla base dei costi, considerando anche i transitori degli impianti fossili che sono stati modellati attraverso l'implementazione di nuovi vincoli (costi di accensione tempo-dipendenti, vincoli di rampa tempo-dipendenti e decadimento dell'efficienza ai carichi parziali). Il modello è stato applicato al sistema energetico Italiano, considerando la configurazione reale e possibili scenari futuri con valori di capacità installata di *VRES* più elevati.

Introduction

Electricity plays a key role in modern society: this is demonstrated by the fast growth of the world electricity consumptions per capita over the last decades (as can be noticed from Figure 0.1 [31]).

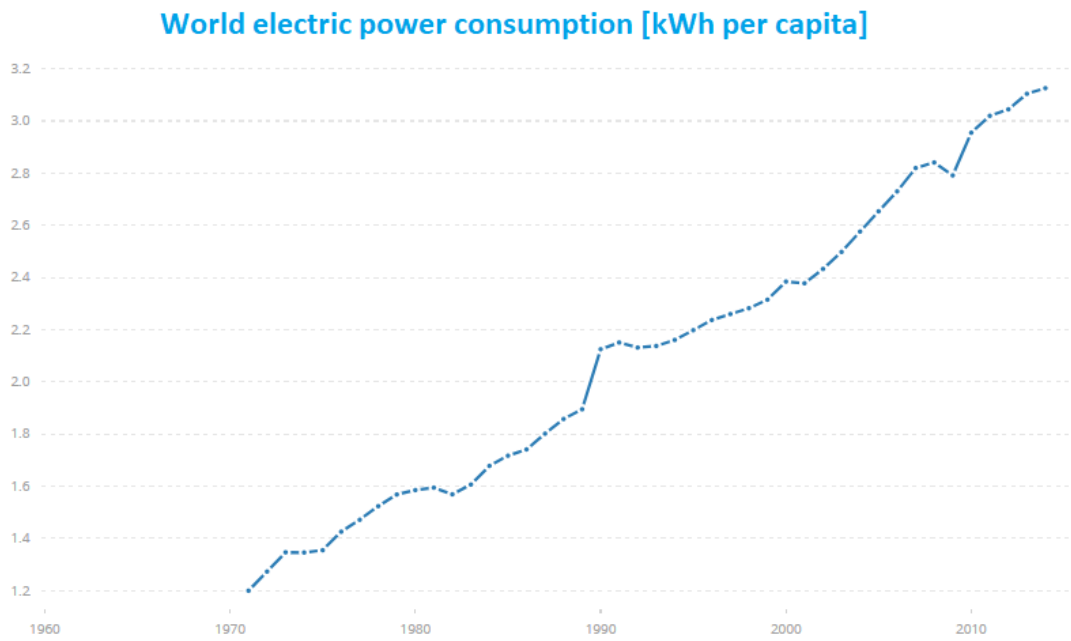

Figure 0.1: Evolution of world electricity consumption

World Bank data

The growing electricity consumptions coupled with environmental and energy security issues, have stressed the need to produce electricity in a diversified and more sustainable way.
Many nations have experienced a fundamental transformation in terms of electricity generation mix: switching from a fossil fuel-based to a Carbon free energy production by the extended use of *Renewable Energy Sources (RES)*.
The main drivers that have led to the transformation of the electricity generation mix are: the convenience in diversify energy supply for economic (volatility of fuel

prices and energy security reasons) and the public concern about climate changes that implies the reduction of the impact of human activity on environment producing from sources that have low life-cycle emissions and renew them self for free in nature (*RES*).
Nowadays energy security is an issue that is gaining increasing importance due to the high dependence of our society on energy and to the liberalization of the European energy markets that increased competition for energy resources.
Energy security is the association between national security and the availability of natural resources for energy consumption: it is defined by the *International Energy Agency (IEA)* as the uninterrupted availability of energy sources at an affordable price [32].
Therefore, the diversification of the energy supply (e.g. with the installation of RES plants) is fundamental for nations that do not possess natural reservoirs of fossil fuel on their territory and rely on import of electricity, oil and gas from other countries.
The growing public concerns about climate changes and other environmental issues, such as air pollution, the reduction of the ozone layer and the depletion of fossil fuels have pushed governments to introduce incentive schemes, suitable tariffs, subsidies and policies in order to promote generation from *RES*.
Originally with the Montreal Protocol (1987) [33] and Kyoto Protocol (1997) [34], and recently with the Paris Agreement, resulting from the *21st United Nations Framework Convention on Climate Change Conference Of the Parties (COP21, 2015)* [35], various decisions were taken in order to reduce the emissions of *Green House Gases (GHG)* and increase the penetration of *RES*.
The transition towards a "low-carbon economy" is one of the main objectives of the European environmental and energy policies: the European Commission has set targets for *RES* and many European countries have approved incentive schemes aiming to meet these targets. In particular in 2007 European Union has started *EU2020*, a strategy for competitive, sustainable and secure energy; the targets, to be reached in 2020 are: reduction of *GHG* emissions by 20% (with respect to 1990), 20% of gross energy consumption produced from *RES* and to make a 20% improvement in energy efficiency (with respect to the Business as usual (*BAU*) scenario) [28]. In 2013, with *EU2030* [29] more ambitious targets were set to be achieved before 2030 for the same indicators (*EU2020*): 40% cut in *GHG* emissions, 27% share of *RES* and 27% energy efficiency improvement. After 2030 there are no targets set by the European Council, but in the study *Energy Roadmap 2050* [30] the European Union foresees an 80% reduction in *Green House Gases (GHG)* respect to 1990 levels.
The world energy scenario is changing: in the last 10 years a fast growth of electricity production from *Photo-Voltaic (PV)* solar panels and wind farms have been occurred almost globally.

The generation of renewable power has grown considerably, providing significant environmental (lower pollutant emissions) and energy (higher security of supply) benefits, but also involving additional costs and requiring higher flexibility from power generating units.
The development of renewable power has been possible thanks to very high subsidies, which are (directly or indirectly) paid by electricity consumers.
The electricity production from *RES* power plants involves additional costs related to the intermittent time profile of their production, which implies additional back-up power, additional balancing costs and higher specific costs of conventional power plants that operate longer at partial load and have to be started-up or shut-down more frequently in order to provide load following and maintain the entire system in balance.
The integration of variable *RES* gives a new dimension to the problem of balancing power (matching power supply and power demand): an increased operational flexibility of the energy system is required.
Flexibility is referred to the capability of a power system to withstand sudden and rapid changes in supply and demand (load-following) in a reliable manner [36].
The flexibility of an electric system can be enhanced in many different ways: through storage technologies as Pumped hydro storage (*PHS*) and batteries, cycling of fossil fuel power plants, demand side management and demand side linked approaches, (e.g. the use of electric vehicles for storing excess electricity), expansion of transmission system infrastructure including smart grids and ancillary services.
It is also possible to improve the flexibility of an energy system by converting the excess of electricity produced by *RES* in other forms of energy (thermal energy, hydrogen obtained by electrolysis) [37].
To assess the value and the feasibility of the various energy system solutions, it has to be considered the electricity market or utility service context.
Nowadays cycling and ramping of fossil fuel power plants are the main source of operational flexibility for an energy system.
Cycling is defined [1] as the range of operations in which a plant's output changes, including starting up and shutting down, ramping up and down; additional costs, additional emissions and ramp constraints are associated to these off-design working conditions.
In providing these capabilities, fossil fuel power plants have to operate less time at full load providing more frequent starts.
Combined cycle gas turbine power plants (*CCGTs*) power plants play a key role in modern electric power systems: thanks to the lower decay of performance at partial load and better flexibility options (as lower start-up time and higher ramp rate) respect to other technology (e.g coal power plants), *CCGTs* are the main sources of flexibility for an energy system [38].
The function of *CCGTs* power plants have faced a significant evolution with the advent of *RES*, in particular of Variable Renewable Energy Source (*VRES*) such

as wind and *PV*: *CCGTs* are increasingly required to rapidly vary load levels in order to counterbalance the fluctuations of *RES*, satisfying overall system demand and maintaining the system in balance.
A better understanding of short-term operational implications can help policy decision makers to identify appropriate options that can enhance the flexibility of the electric system and reduce the environmental impact.
Governments and policymakers need tools that are able to simulate with high accuracy the functioning of an energy system, in order to evaluate the impact of all the possible solutions and apply cost-effective energy strategies and policies.
A very useful and powerful tool to make simulation and prediction of future energy scenarios is energy systems modeling, that consists in the description, through mathematical equations, of the mechanisms and transformations that link energy supply and demand in an energy system.
It is possible to classify the different energy models in terms of conceptual framework between: *top-down* models, aim at depicting an aggregated view of the energy sectors focused on economy, in order to evaluate the macro-economic impacts of policies and investments and *bottom-up* models, that are focused on the technology analysis.
Both types of energy models present different advantages and limitations and develop a more detailed analysis on different aspects of the energy system.
The approach used in this work is the bottom-up because the focus is on the technology analysis.
The methodology for this thesis work has been developed in collaboration with *Regional Energy Modelling (RegEnMod)*, a project of *EURAC Research*'s Institute for Renewable Energy, based in Bolzano, which task is to assess the impact (present and future) of *RES* and the definition of the best mix of technologies for the South Tyrol and Italian energy systems in order to support the definition of the energy strategy.

RES distributions on Italian territory

The case study for this work is the Italian electric system, due to the relatively high penetration of *RES*; indeed in the years between 2008 and 2013, thanks of a very strong system of incentives, *PV* panels and wind turbines faced a rapid growth all over the territory: the power generation from *RES* has increased by 23 TWh.
The growing installed capacity of *RES* has drastically modified the Italian generation mix and the power plants management strategies: fossil fuel power plants have to cycle more frequently in order to counterbalance the fluctuation of *RES* and maintain the system in balance.
Looking at the distributions of *RES* along the Italian territory (Figure 0.2), according to data collected from *Terna*, Italian transmission system operator (*TSO*), is pointed out a fundamental and critical issue of the Italian electric system: while *PV* installed power is homogeneously distributed, the majority of wind turbines are placed in the south of Italy in contrast to the available installed capacity of pumped hydro storage (*PHS*) concentrated in the north.
It is fundamental in the creation of a model for the Italian energy system, to adopt a multi-node approach in order to obtain more realistic results (considering the real spatial distributions of *RES* and grid transmission constraints) and do not underestimate cycling costs and possible curtailment from *RES*.

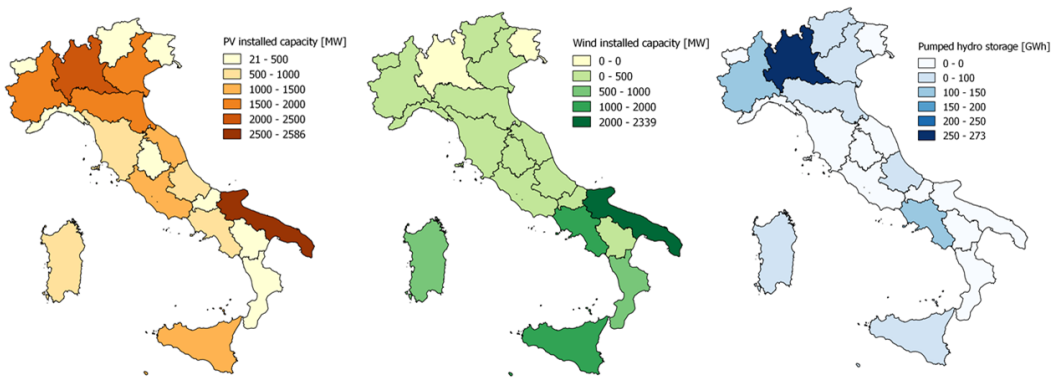

Figure 0.2: Installed capacity of *VRES* and *PHS* power plants at 2014

Elaboration of Terna data [13]

Objectives of the thesis

The aim of this thesis work is to perform a time-dependent analysis of transient operations of fossil fuel power plants in energy system modeling in order to have a more realistic representation of an energy system.
Usually, in order to reduce the computational time, the transient operations of fossil fuel power plants are not considered in energy system modeling, however, these transients could be relevant in system with high penetration of renewable energy sources (*RES*) and their impact should be analyzed more in detail.
The transient events considered are the cycling and ramping of fossil fuel power plants: additional costs, emissions and ramp constraints are associated to these partial-load working conditions.
The impact of the transient operations of fossil fuel power plants is evaluated using *Oemof* [11], a computer model for energy systems optimization . *Oemof* (*Open Energy Modeling Framework*) is an open source model written in python programming language. It's main characteristics are to be versatile (possibility to modify or add new components and constraints to an energy systems), time-step-flexible and multi-regional. The power plants in *Oemof* are fully-flexible (power output can vary from zero to the maximum in one time step) and the decay of efficiency during partial load operations is not considered.
In order to perform a detailed transient analysis additional constraints have to be implemented, in particular the following time-dependent constraints are created: start-up costs, ramp constraints and decay of performance at partial load .
The model created, named *Oemof_Transient*, is a *bottom-up* model, with integrated the transient analysis of fossil fuel power plants, that performs the optimization of the dispatch of electricity based on costs.
This methodology is applied to the Italian case, very suitable due to the high installed capacity of *RES*. The developed model simulates one year on an hourly basis.
Due to the spatial characteristics of the Italian already installed renewable generation park, a multi-node approach is adopted in the model to do not underestimate curtailment and cycling costs: six macro-regions are implemented, that correspond to the actual configuration of the Italian electric system composed by six main zones defined by grid transmission constraints.
In order to evaluate the impact of the transient events of fossil fuel power plants and to estimate the growing influence of these events in possible future configurations of the energy system with higher penetration of *RES*, different scenarios are considered: one related to the 2014 (reference scenario) and others relative to possible future configurations at 2050 with higher *RES* installed capacity.

Outline

The work is organized as follows:

Chapter 1 Description of the energy models present in literature, differentiating the approach. Then the transient events are classified and a brief overview on some interesting case studies is performed.

Chapter 2 It is presented the methodology developed to create a model that performs the time-dependent analysis of transient events. *Oemof* structure and working principles are explained, as well as the implementation of the constraints to represent the transient events of fossil fuel power plants.

Chapter 3 Explanation on how the model has been applied to the Italian case-. First the 2014 Italian reference scenario is presented and validated and then possible future configurations at 2050 of the Italian electric system are introduced.

Chapter 4 Comparison and analysis of the optimizations' results in order to evaluate of the impact of the transient operations of fossil fuel power plants on the reference scenario and on future scenarios at 2050.

Chapter 5 Presentation of the achievements reached and conclusive remarks.

Chapter 1

Literature Review

In this chapter is given a brief overview on energy modeling, the unit commitment problem is defined, transient operations of fossil fuel power plants are described and some interesting case studies are presented.

1.1 Energy modeling

Energy modeling consists in the description, through a mathematical equations, of the mechanisms, transformations and exchanges that occurs in an energy system; the system analyzed can be can be a stand-alone application, a municipality, a region, a nation or a continent.
The process of modeling energy systems is accompanied by challenges inherently connected with mathematical modeling, (an energy model basically consists in a set of equations and constraints).
Energy modeling contributes variously to system operations, engineering design and energy policy development: energy models are usually intended to evaluate actual and future possible configurations of an energy system, in order to support decision making for policy optimization and policy evaluation.
Policy optimization is intended as the investigation of the energy system layout that satisfies user-defined boundary conditions according to an optimization criteria defined by the user or the programmer.
Policy evaluation means assessing the impacts of predefined policies and investment strategies on the energy system and on the economics of the considered entity.
Modeling of energy systems has a long tradition : linear programming LP was first used for capacity expansion planning of generators in regulated markets in the 1950s [39]. After the oil crisis in 1970s, due to environmental concerns, the focus moved from capacity planning towards sustainable energy supply [40].
In recent years, global warming concerns and energy security issues have stimulate an energy system transformation process in many countries involving large

penetration of *VRES*), that are characterized by an intermittent nature (they are highly variable and have a limited predictability).
As a result, energy systems face an increasing demand for flexibility and stronger integration between the energy sectors (electricity, heat and transport), so an higher level of detail (as a time-dependent analysis of units transients operations, multi-node approach, cross-sectoral analysis, accurate temporal resolutions) is required in the implementation of an energy model.
In the 21st century, due to modern realities, challenges in energy system modeling are gaining in magnitude and importance: modelers are confronted with a rising complexity of energy systems and high uncertainties on different levels, so obtaining affordable results is getting more difficult.
Hilpert et al. in their work [41], categorize the diverse challenges in energy modeling by:

- Complexity: sector coupling, temporal or regional resolution, input data, result processing (an increasing complexity of models is accompanied by a rising amount and complexity of inputs and results).

- Uncertainty: epistemic, aleatory, linguistic, decision, planning.

- Interdisciplinary modeling: integrate perspectives that are not captured by standard economic or engineering approaches (inclusion of human dimension, energy-water-food interdependencies , social factors).

- Scientific standards: transparency, repeatability (ability to repeat an experiment and come to the same results), reproducibility (results can be repeated by a different researcher in a different computer environment), scrutiny (identifying inconsistencies or faults, so called bugs), scientific progress.

- Model utilization : usability, applicability, result communication and interpretation.

Computer based energy modeling consists in the implementation of a process that simulate the functioning of an energy system in order to analyze it.
Such a process can only be performed in practice through the introduction of approximations, that are aimed at simplifying the problem in order to face common issues such as lack of available data and long computational time: a model is always a simplified representation of real system.
Mathematical optimization is used to determine the least-cost solutions; costs can be the real one or fictitious (e.g. optimization on CO_2 emissions).
Results of the optimization may be the system feasibility, *Green House Gases (GHG)* emissions, annual or cumulative costs, natural resource use and energy efficiency of the system under investigation.
Typical criteria for categorizing models are:

- **Top-down** (macro-economic relationship of components) Vs **Bottom-up** (technology specific).

- **Optimization** (optimal technology choice for the analyzed system) Vs **Simulation** (replicate associations and interrelationships among the different elements of the analyzed system).

- **Partial equilibrium** (single sector or a subset of it) Vs **Equilibrium** (cross-sectoral, e.g.: transport, power and heat sectors).

As stated in [3], models can also be classified according to the time horizon considered: in particular *Static* models and *Long-term* models are distinguished.
Static models perform an yearly or monthly evaluation of the considered energy system, providing an instantaneous picture of how it works in real-life situation. The configuration of the system is fixed and cannot change in time. Since their time horizon is limited, with consequent savings in term of computational time, such models can include a very detailed time discretization: usually these models perform hourly energy balances for the whole year, therefore dividing the time horizon in a sequence of 8760 time-slices.
Long-term models instead are able to evaluate the evolution of an energy system in a considered timespan. In such models, most parameters are time-bound and therefore the energy system is allowed to change, according to exogenous variables, endogenous ones or a mixture of the two.
A wide range of techniques are employed, ranging from broadly economic to broadly engineering: in some energy models the technical description is very accurate and covers a lot of different components with detailed information about their working principles and their costs.
In some others, the focus is not on the precision of the technologies characterization, but rather on the representation of the connections between the energy

system and the macro-economics of the analyzed energy system.
In order to understand the approach used in this work, is crucial to comprehend the different approaches adopted by energy models programmers and the advantages and limitations related to them.
The main distinction in the energy modeling world is based on the representation of the analyzed system: the focus can be on the economic contest or on technological detail. This distinction has been investigated by Herbst et al. in [2], as well as in [3] by Després et al.
There are different approaches in the literature for the energy system modeling, which can be grouped into two main categories: *Top-down* energy models and *Bottom-up* energy models.
The *Top-down* approach is mainly applied in economy and public administration where the objective is to assess the aggregated effects of energy policies in monetary units. This approach has the advantage of evaluating the impacts of the energy sector on other sectors like welfare, employment and social growth providing a macroeconomic analysis for the whole system.
Bottom-up models by contrast are characterized by high technological detail. This approach is applied by engineers in order to identifies and analyses specific energy technologies, investments options and future alternatives of the energy system.
In this thesis work is preferred the *Bottom-up* approach due to the high technological detail that this kind of model provides.

1.1.1 Top-down approach

Top-down energy models maintain an aggregated view of the energy sectors and of the economy, in order to evaluate the relative influence.
These models generally work by solving market balance problems, trying to maximize the consumer's welfare.
Driven by demographic growth, economic development and price trends macroeconomic *Top-down* models are usually preferred by economists and public administrations in the evaluation of the economic costs and environmental effects of energy or climate policies, as *carbon tax*, emission trading schemes, feed-in tariffs of renewable energy sources.
On the other hand, due to the low technological detail, these models are not suitable to evaluate or optimize sector-specific decisions. Moreover, this approach leads to the underestimation of non-monetary barriers and opportunities.

1.1.2 Bottom-up approach

In *Bottom-up* models the focus is on the high degree of technological detail in the energy system.
A *Bottom-up* model consists in a set of interconnected component, each one described in the most possible realistic way using specific parameters and constraints.
The high level of technological detail combined with mechanisms that link different sectors and components, allow to evaluate sector-specific and technology-specific policies that can best exploit the synergy effects that typically occur in an energy system.
Bottom-up models use a business economics approach for the economic evaluation of the technologies simulated: the only market considered is the one related to the energy sectors and any assumption on macro-economic data is strictly exogenous.
As a result, the objective of maximizing the public welfare is translated into the minimization of the energy system costs.
A limitation of this kind of models is their heavy dependency on data availability and credibility, since more and more input parameters are needed when increasing the accuracy of the components description.
This approach is usually adopted by engineers and natural scientists, who are more interested in analyzing potential technological solutions than the macro-economic impacts of policies.
Bottom-up models can either be *optimization* or *simulation* models. *Optimization* models are used to find an optimal set of technologies that minimize the costs of an energy system, while simulation models test the behavior of a real energy system layout.
In the latest years, efforts have been made to include also non-price policies combined with a certain degree of technological innovation , leading to the creation of the so-called *Hybrid* models that benefit from the advantages of both the afore-mentioned approaches.

1.1.3 Top-down vs. Bottom-up

In the analysis of how energy policies impacts on the economy, *Top-down* models are more suited than *Bottom-up* ones.
The main difference between these models is the focus of the analysis. *Top-down* energy models are focused on the analysis of economic and social effects using endogenous assessments.
Furthermore the *Top-down* modeling approach tends to underestimate non-monetary problems like lack of knowledge, group-specific interests of technology producers or whole sale.
Top-down models are focused on monetary terms and because of that they move

in favor of monetary related policies or emission certificates and regulatory policies.
Bottom-up energy models are characterized by a high degree of technological detail; energy demand and supply technologies are presented in a very detailed picture of the present situation and future projections.
For these reasons, the evaluation of technological progress or effects of policies for certain technologies are more suited for *Bottom-up* energy models.
The high degree of technological detail makes *Bottom-up* models heavily dependent on credibility of data and assumptions on diffusion, cost and investment for future projections of technologies.
The approach adopted for this thesis work is *Bottom-up* due to the high degree of technological detail, that allow to represent the transient operations of fossil fuel power plants.

1.2 Unit commitment model

The *Bottom-up* approach can be adopted to model the unit commitment problem, that consists of scheduling of generating units in order to satisfy demand requirements, overcome possible losses and meet the energy system's constraints at least cost. This allow to assess the impact of *RES* and fossil fuel power plants generations on the problem of dispatch of electricity.
The unit commitment problem in electricity production deals with the fuel cost optimal scheduling of on/off decisions and output levels for generating units in a power system over a certain time horizon and typically involves technological and economic constraints. The unit commitment problem has been approached since long time: in 1994 *Sheble et al.* had reviewed different unit commitment problems [42] and one year later *Baldick* formulated the generalized version of the unit commitment problem [43].
Modeling the unit commitment and economic dispatch of a power system is not a trivial problem and advanced mathematical optimization software and techniques are used to determine the least cost production schedule. Possible constraints that can be introduced in the problem are: ramp limits, start-up costs, reserve constraints, transmission capacity limits, upper and lower limits on the generating units, power flow limits, generators' minimum up/down time, decay of efficiency at partial load.
Several optimization techniques have been applied to the solution of the unit commitment problem. Optimization problems can be conveniently formulated as the minimization or maximization of an objective function. The problem to solve is the optimal scheduling of generating units: the decision process selects units to be on or off, the type of fuel and the power generation levels for each unit respecting limits and constraints of the energy system. The objective function are operational costs that can be grouped into the following categories: fuel costs, *O&M* costs and start-up costs.
The implementation of certain constraints turns the unit commitment problem into a complex, non-linear, mixed-integer one. This is the case of this thesis work: the constraints implemented to represent the transient operation of fossil fuel power plants, transforms the unit commitment problem for the dispatch of electricity in a mixed-integer optimization problem.

1.2.1 Mixed-Integer Optimization

Mixed-Integer Optimization deals with mathematical optimization problems with two types of variables: variables taking values in an integer domain and variables taking values in a continuous domain.
The fact that Mixed Integer Optimization problems naturally appear in many contexts has led to an increased interest in the design of strong algorithms for

different variants of the problem.
In a Mixed-Integer Optimization, the unit commitment problem is solved by reducing the solution search space systematically through discarding the infeasible subsets.
The general solution concept is based on solving a linear program and checking for an integer solution. If the solution is not integer, linear problems or subproblems are continuously solved.
The adoption of integer variables in an optimization problem greatly increases the number of equations that can be implemented and solved [44].
A Mixed-Integer Optimization problem can be linear (*MILP*), convex or nonlinear depending on the constraints introduced.
Mixed-Integer Linear Optimization problems, or *MILPs*, are mixed-integer optimization problems involving only linear functions and finitely many variables.
An important and useful application of mixed-integer approach is the case of binary integer variables that are decision variables that are forced to be either 0 or 1 at the solution (boolean variables).
Such variables can be used to model yes/no decisions, such as whether to build a plant, buy a piece of equipment or start a power plant.
However, binary integer variables turn the optimization into a non-convex problem, and therefore far more difficult to solve.
Memory usage and computational time may rise exponentially or explode increasing the size of the problem or the number of binary integer variables introduced, because the number of combinations rise exponentially.
So a trade-off is needed between the size of the problem (number of units with constraints, number of time-steps) and the amount of constraints introduced in order to confine the complexity of the problem.

1.3 Transient operations of fossil fuel power plants

In last years modeling the unit commitment problem is becoming more challenging, due to higher complexity of electricity industry operations: thus the recent liberalization of many electricity markets, along with the rapid expansion of *RES*, in particular of *VRES*, such wind and *PV*, have resulted in drastic changes in how generation units are required to operate [4], increasing the frequency of fossil fuel power plants' transient operations. An increased penetration of *VRES*, due to their intermittent, variable and unpredictable nature, requires more flexible power generation units in order to counterbalance the fluctuations of these sources and maintain the system in balance. This required flexibility is usually provided by transient operations of fossil fuel power plants that are required to cycle and ramp up/down (ramping) in order to follow the load. Ramping refers to an increase or decrease of the power output between full and minimum levels in order to follow changes in generation demand. Therefore fossil fuel power plants are forced to cycle more frequently, inducing accelerated aging, lifetime reduction, components damages and significant increases in *Operation and Maintenance* costs (*O&M*), additional emissions and fuel consumptions that results from these inefficient off-design operations.
Improving the flexibility of generation units is becoming a very important issue: fast start-up and rapid load variations have become a priority objectives because they guarantee high profits in the short term, but provoke a lifetime reduction due to thermo-mechanical fatigue, creep and corrosion.
In this context of the electric power system, gas-fired power are gaining importance: the success of this technology has been motivated by, among other things, the shorter construction times, lower total investment costs and higher efficiency and flexibility in comparison to other thermal technologies such as coal or nuclear power plants.
Plant manufacturers have recognized changes to the way that large generators are scheduled, indeed the latest Combined-Cycle Gas Turbine (*CCGT*) units have been designed to operate efficiently and reliably under a wide range of conditions, without incurring damage [45].
The impact and the importance of these transient events could also be greater in future configurations of the energy system with higher *VRES* penetration. Many case studies show that the higher is the penetration of renewable energy sources, the higher are the transient operation of fossil fuel plants and so the associated costs.
Hermans et al. in [5], analyze the Spanish electricity system in the current and future configurations with higher VRES installed capacity, in order to evaluate how flexibility requirements impact on the operational regime of Combined-Cycle Gas Turbines (*CCGTs*).
This analysis is carried out implementing a unit commitment model that performs the dispatch of electricity, using an hourly time-step for a period of two

weeks and accounting for cycling costs of *CCGTs*.
The cycling costs considered are the long-term maintenance that are gaining importance as a result of increasingly flexible operating regimes: accrued damage and resulting maintenance costs are greatly affected by the required flexibility in terms of the start-up mode.
Two different start-up modes (Fast and Slow) are introduced in this model (Hermans et al.).
The simulation results show that the *CCGT* units adopt a high-cycling regime with increasing *VRES* penetration in both the Fast and the Slow start-up modes scenarios. Furthermore, the total system costs are slightly higher in the Fast scenario.

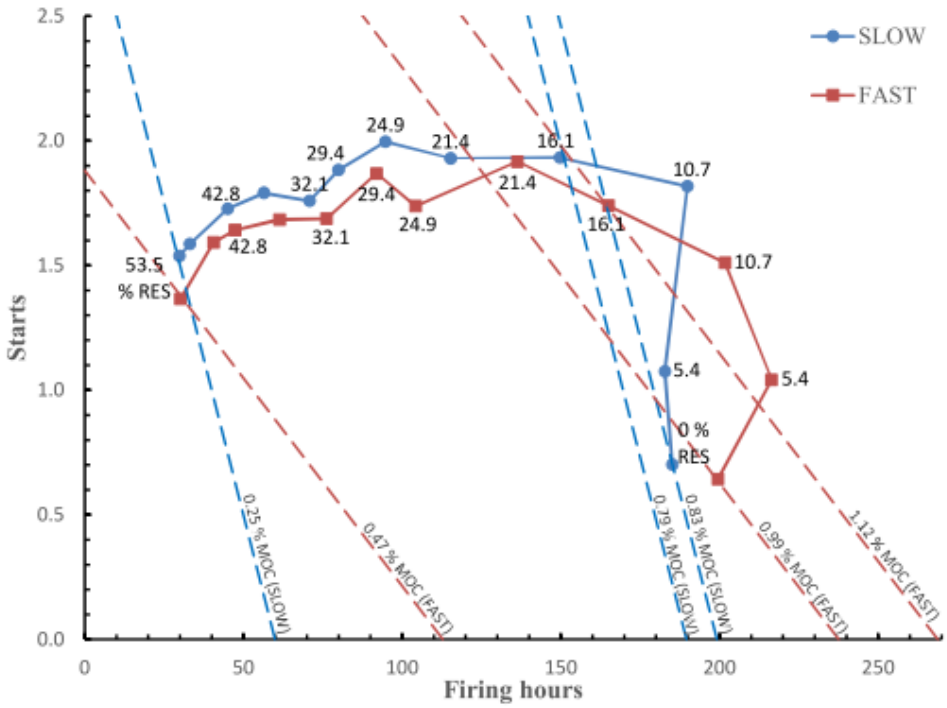

Figure 1.1: Cycling of CCGT in scenarios with various *VRES* penetration

[5]

In Figure 1.1 the average number of starts of *CCGTs* is plotted against the average number of firing hours in scenarios with different installed capacity of *PV* and wind (red and blue segmented lines) and considering both the start-up modes (Fast and Slow). As the installed capacity of wind and *PV* increases (moving counterclockwise on the red or blue lines) the trend exhibit is the following: the number of firing hours declines while the number of starts increases. In particular, in both the Fast and the Slow start-up modes scenarios,

the number of firing hours declines dramatically with increasing *RES* while the number of starts increases significantly.
Other authors, as [6] and [7], examine in their works (respectively [6] and [7]) the effects of an increasing penetration of *VRES* power on the operation of fossil fuel power plants, concluding that cycling operations (and so operative costs) of fossil fuel power plants rises as the electricity generation from *VRES* increases due to the fact that power plants are started-up more frequently and work longer at partial load.
They shown that cycling of fossil fuel units rises the overall costs of an energy system: additional Operations and Maintenance costs (*O&M*) resulting from deterioration of the components, start-up costs, inefficient fuel consumptions and higher specific emissions due to off-design operations.

1.3.1 Cycling

Cycling is defined by Lew et al. [1] as the range of operations in which a plant's output changes, including starting up and shutting down, ramping up and down, and operating at partial-load [1].
A similar definition is given by the National Renewable Energy Laboratory (*NREL*) [46], which defines cycling as "the operation of electric generating units at varying load levels, including on/off, load following, and minimum load operation, in response to changes in system load requirements".
Quantifying and identifying the costs related to cycling is particularly difficult given the wide range of elements involved and the fact that cycling related damage may not be immediately apparent.
Kumar et al. [26] divide the costs related to cycling in five distinct groups:

- Direct start-up costs: cost for fuel and auxiliary services during start-up.
- Indirect start costs: capital replacement costs and maintenance cost due to start-ups.
- Forced outage costs: cost of forced outages due to cycling, which is the opportunity cost of not generating during an outage
- Ramping costs: capital replacement costs and maintenance cost related to load following.
- Decay of efficiency costs: the cost of a decrease in efficiency due to cycling, that give rise to frequently partial load events.

1.4 Models available in literature

For the sake of this thesis work a deeper review has been performed over some of the models already present in literature. This analysis has been conducted on the most established bottom-up softwares, that provide an open documentation, in order to point out their working principles, strengths and weaknesses.
In the following subsection, a brief description of the reviewed models is presented. Table 1.1 reports a general overview of the investigated models.

OSeMOSYS

OSeMOSYS stands for *Open Source energy MOdeling SYStem* and its code was published firstly in 2008.*OSeMOSYS* was developed by *Royal Insitute of Technology (KTH)* of Stockholm and its ethics and working principles are presented by Howells in [8].
OSeMOSYS is a *bottom-up* (technology focused), partial equilibrium optimization model, which means that the quantities of the various fuels, the energy produced and other commodities are in equilibrium, (i.e. their quantities in each time period are such that the suppliers produce exactly the quantities demanded by the consumers). The model results consist in the configuration of the energy system that minimizes the *Net Present Costs (NPC)* in the time-horizon. These costs are obtained by summing and discounting the annualized costs of investment and the fixed and variable *Operation and Maintenance (O&M)* costs for each considered technology in each considered period, with the option of including carbon taxation.
The main advantages of *OSeMOSYS* are to be open-source (it's is possible to modify the code) and community-driven: the developer's goal is to extend energy modeling to a broader community, in order to benefit from this in terms of further development, reduce the barriers to entry by new users, as well as provide energy planning tools for those who are not experienced.
OSeMOSYS code is written in *GNU-MathProg* language (an open-source language for linear programming) and is publicly available, furthermore its "blocks" structure is designed to facilitate modifications and integrations with other softwares. The objective function is also the minimization of the *NPC*.
For what concerns time-discretization, *OSeMOSYS* uses a system of customizable time-slices and time-periods.
Transient analysis is not performed by *OSeMOSYS*, but the fact that is an open-source model gives the possibility to create new constraints and so to model transient events.
OSeMOSYS was not selected for this thesis work, because its poor time-discretization make not suitable the implementation of fossil fuel power plant transient events, as cycling and decay of performance in off-design conditions, that requires high temporal resolution to be modeled properly.

PLEXOS

PLEXOS [9] is a sophisticated power system modeling tool used for electricity market modeling and planning worldwide. It is a commercial software but is free for non-commercial research to academic institutions.
PLEXOS is a *bottom-up* model that optimize the power system over a variety of times scales: it minimizes the expected costs of the electricity dispatch considering various parameters and constraints.
Possible parameters and constraints are availability and operational characteristics of generating plants, licensing environmental limits, fuel costs, start-up costs, operator and transmission constraints, forced outage, maintenance schedules.
Forced outages are considered drawing on Monte Carlo simulation considering forced outage rates and mean time to repair. Maintenance schedules may be optimized considering exogenous maintenance schedules or, alternatively, average maintenance rates and mean times to repair.
Temporal resolutions are user defined and flexible, ranging from interval lengths of one minute to multiple hours in hourly, daily or weekly steps over the full problem horizon (typically one year or more).
The optimization problem is created using AMMO, a mathematical language written for PLEXOS. The problem is then optimized drawing on either of the CPLEX, Gurobi, MOSEK, or Xpress-MP solvers.
The transient analysis of fossil fuel power plants is performed in *PLEXOS* introducing start-up costs that are not time-dependent (they do not depend on the hours of stop of the plants).
PLEXOS does not allow to introduce in the optimization process new transient events of fossil fuel power plants different from the already implemented, because is not possible to add constraints and modify the core-code, thus *PLEXOS* is not open-source.
PLEXOS do not allow to improve the transient analysis of fossil fuel power plants adding new constraints such as ramp constraints, decay of efficiency during off-design operations or transforming the transient analysis in a time-dependent analysis introducing time-dependent constraints.

EPLANopt + CCGT _Model

EPLANopt + CCGT_Model model combine EnergyPLAN simulation model [10] with an optimization performed using *Genetic Algorithm (GA)* and a post-processing analysis on the cycling costs of *CCGT*.
The *EnergyPLAN* model has been developed since 1999 by H. Lund, from *Aalborg University* [10].
EnergyPLAN's is a *bottom-up* model that simulate the behavior of a given energy system (and costs and emissions related) along a single year.
According to the documentation [10], the main purpose of the model is to assist the design of national energy planning strategies on the basis of technical and economic analyses of the consequences of different national energy systems and investments, being able to perform technical analyses, market-exchange analyses or feasibility studies.
EnergyPLAN has a very good time-discretization, considering 8784 hourly time-slices along a leap year. This accuracy in time representation allows to better evaluate the behavior of technologies such as non-predictable *RES* and storage options, becoming particularly relevant when dealing with future, high renewable penetration scenarios.
A strength of EnergyPLAN is the user-friendly graphic interface, that allow an easy setting of any energy system that is intended to model, but can also be configured through specific input text files, very useful in case of large amount of data.
In EnergyPLAN the simulation of energy dispatching is performed through a system of priorities, aimed at reducing computational time and guaranteeing preferential treatment for *RES* and other low carbon technologies, similarly for example to what happens in most European electricity markets.
EnergyPLAN can easily be launched from any programming environment but is not open-source (although available for free) thus any modifications of the core-code are not possible (is not possible to implement new constraints).
Moreover, EnergyPLAN can only represent single-node systems, where all the energy suppliers and users are considered in the same macro-region and therefore no constraints on energy transmission are present.
EnergyPLAN is combined with a *Genetic Algorithm (GA)* to obtain *EPLANopt*.
EPLANopt (EnergyPLAN optimization) model [12] is a model for system optimization, developed at *EURAC Research*, Bolzano.
EPLANopt makes use of a *Genetic Algorithm (GA)* written in Python language, in order to evaluate, rank and optimize a large number of different EnergyPLAN configurations (obtained using EnergyPLAN as simulation tools), all based on the same reference scenario. The ranking is performed according to a double objective: minimization of the annual costs of the system (including annualized investments, fixed and variable *O&M* and eventual carbon pricing or electricity import) and of the annual *GHG* emissions. The results of an EPLANopt run, therefore, do not consist in a single optimal configuration (as in the case of

single objective solvers), but are represented by a Pareto front, composed of each least costly solution for any target *GHG* emission level.
EPLANopt is designed to provide the best set of configuration in order to reach a given target in terms of costs and annual *GHG* emissions.
On the results of the optimization of *EPLANopt* is performed a post-processing analysis on the electricity produced by *CCGT* power plants, in order to evaluate the cycling costs of these units. This post-processing analysis consists in a Python script (*CCGT_Model* that receives as input the hourly production from *CCGT* power plants during a year (that is a result of EnergyPLAN simulation), evaluates the working conditions of each power plants and calculate the cycling costs that consist in start-up costs and additional fuel consumption (and so costs) due to off-design operations. It is just a post-processing analysis on the electricity generated by *CCGT*, thus the cycling costs are not considered in the optimization of the electricity dispatch, but calculated a posteriori.

Oemof

Oemof [11] is an open source program written in Python programming language that has been developed starting from 2014 by the following institutions: Europa-Universitä at Flensburg (EUF), Flensburg University of Applied Sciences (HFL), Otto von Guericke University Magdeburg (OVGU), Reiner Lemoine Institut Berlin (RLI).
Oemof, that stands for *Open Energy Modeling Framework*, is a *bottom-up*, partial equilibrium model that allow to optimize the dispatch of electricity in an energy system with high temporal and spatial resolutions, being a multi-node model with an hourly time-step resolution.
Oemof consists in a framework, with a modular structure, containing several packages which communicate through well defined interfaces.
A detailed description of *Oemof* framework and its components is presented in the next chapter.
The *Oemof* framework is implemented using an object-oriented approach in the high-level programming language Python, where the focus is on capturing the structure and behavior of systems into small modules (object), that combines both data and process.
An implementation with programming language Python has the advantage of a rich set of external libraries and modules usable for scientific computing.
Oemof facilitate the modeling of complex energy systems providing a rich set of tools, (that include optimization libraries, tools to simulate feed-in from *RES* or local heat demand for a specific region), aimed to support current and future challenges in energy system modeling.
Oemof is a suitable tool to answer various questions concerning the transmission of the energy system.
The focus of these analyses may range from local to multinational and from sin-

gle sector to a coupling of power, heat and transport sectors; by combining and linking the various *Oemof* modules new energy system model can be modeled. *Oemof* is a community-driven, open-source model: it was conceived as a community project to take advantage of similar modeling activities and modifications of the core-code are possible (new features as constraints and components can be implemented).
Oemof features allow to properly implement the transient events of fossil fuel power plants: the high temporal and spatial resolutions enable to distinguish the transient operations of fossil fuel power plants, while the open-source feature gives the opportunity to implement new constraints in order to model the desired transient events.
For these reasons the analysis conduced in this thesis work is performed upgrading *Oemof* model.
In *Oemof* the only transient event considered is start-up of a power plants; this transient analysis in not time dependent, thus the costs related to the start-up do not depend on down-time of the plant (hour of stop).
Costs and emissions related to the decay of efficiency during off-design operations and ramp constraints of available power are not considered in *Oemof*.

Model	Open-Source	Scope	Spatial resolution	Temporal resolution	Transient analysis	Constraints for transient analysis	Critical aspects
OSeMOSYS	Yes	optimization	single node	time-slices	➢ no	➢ *no*	➢ *transient analysis is not implemented* ➢ *poor time-discretization*
PLEXOS	No	optimization	single node	user-defined	➢ integrated, ➢ not time-dependent	➢ *start-up costs*	➢ *transient analysis is not time-dependent* ➢ *ramp constraints are not implemented* ➢ *decay of efficiency is not implemented*
EPLANopt model + CCGT_Model	No	optimization	single node	hours	➢ post-processing	➢ *start-up costs* ➢ *ramp constraints* ➢ *decay of efficiency*	➢ *transient analysis is performed a posteriori (not included in the optimization process)*
Oemof	Yes	optimization	multi node	user-defined	➢ integrated, ➢ not time-dependent	➢ *start-up costs*	➢ *transient analysis is not time-dependent* ➢ *decay of efficiency is not implemented*

Table 1.1: Models available in literature

1.5 Novelty and scope of the thesis

The different *bottom-up* models reviewed in this chapter have highlighted various weakness and limitations in the analysis of transient events of fossil fuel power plants. In particular:

- *OSeMOSYS* does not perform any transient analysis; it is an open-source model, thus is possible to implement new constraint in order to reproduce the behavior of fossil fuel during transient operations, but this is not convenient due to the poor time-discretization that does not allow to characterize properly transient operations.

- *PLEXOS* considers only start-up as transient event; this transient analysis is not time-dependent, thus the start-up costs are not a function of the hours of stop of the plant. The implementation of new constraints to improve the transient analysis is not allowed because the model is not open-source and so no modification of the core-code are permitted.

- *EPLANopt + CCGT_Model* performs a post-processing analysis on the electricity produced by *CCGT* power plants, in order to evaluate the cycling costs due to transient operations that consists in start-up costs and decay of efficiency during off-design operations. It is just a post-processing analysis: the cycling costs are not considered in the optimization of the electricity dispatch, but calculated a posteriori. EnergyPLAN is not open-source, thus modifications of the core-code to introduce new constraints are not allowed.

- *Oemof* introduces only start-up as transient event; the costs related to the start-up does not depend on down-time of the plant (hour of stop), thus the transient analysis in not time dependent. *Oemof* is an open-source model, thus it is possible to implement new constraints. This feature along with the high temporal and spatial resolutions, allow to model the transient operations of fossil fuel power plants in detail introducing new constraints.

The aforementioned *bottom-up* models are not able to evaluate in a detailed way the impact of transient operations of fossil fuel power plants (cycling and ramping) on the optimization of electricity dispatch.
These transient operations are accruing importance in a world evolving toward a low-carbon energy sector: as the electricity generated from intermittent *VRES* increase, cycling operations of fossil fuel power plants rises because power plants are started-up more frequently and work longer at partial load in order maintain the whole energy system in balance and counterbalance the fluctuations of energy produced from *VRES*.

For this reason, the scope of this thesis work is to create a *bottom-up* model that is able to evaluate the impact of fossil fuel power plants transient operations on the optimization of the unit commitment problem (scheduling, over a period, of generating units in order to satisfy demand requirements and meet the energy system's constraints at least cost).
In order to represent the behavior of fossil fuel power plants in a detailed and realistic way, the model created for this thesis work performs a time-dependent analysis of fossil fuel power plants' transient operations: this means that the constraints implemented to perform this transient analysis introduces additional costs, emissions and ramp rate of available power that, for each instant of time, are a function of the hours of stop and of the power output of the plant.
The time-dependent transient analysis developed for this thesis work is performed enhancing *Oemof* model and leads to the creation of the denominated *Oemof_Transient* model.
Oemof_Transient is created using *Oemof* framework because is open-source and presents high spatial and temporal resolution (multi-node approach and hourly time-step) that allow to perform a detailed time-dependent transient analysis.
In particular in the following time-dependent constraints are implemented in *Oemof_Transient*: time-dependent start-up costs, time-dependent decay of efficiency and time-dependent ramp constraints.
The improvement of *Oemof_Transient* model with respect of the state-of-the-art (Table 1.2), is the time-dependent transient analysis that allow to evaluate with high accuracy the impact of fossil fuel power plants transient operations in the optimization of the electricity dispatch.
The methodology to build *Oemof_Transient* is presented in the next chapter, along with thorough description of the time-dependent constraints created.

Model	Open-Source	Scope	Spatial resolution	Temporal resolution	Transient analysis	Constraints for transient analysis	Critical aspects
OSeMOSYS	Yes	optimization	single node	time-slices	➢ no	➢ *no*	➢ *transient analysis is not implemented* ➢ *poor time-discretization*
PLEXOS	No	optimization	single node	user-defined	➢ integrated, ➢ not time-dependent	➢ *start-up costs*	➢ *transient analysis is not time-dependent* ➢ *ramp constraints are not implemented* ➢ *decay of efficiency is not implemented*
EPLANopt model + CCGT_Model	No	optimization	single node	hours	➢ post-processing	➢ *start-up costs* ➢ *ramp constraints* ➢ *decay of efficiency*	➢ *transient analysis is performed a posteriori (not included in the optimization process)*
Oemof	Yes	optimization	multi node	user-defined	➢ integrated, ➢ not time-dependent	➢ *start-up costs*	➢ *transient analysis is not time-dependent* ➢ *decay of efficiency is not implemented*
Oemof_Trasient	Yes	optimization	multi node	user-defined	➢ integrated ➢ time-dependent	➢ *time-dependent start-up costs* ➢ *time-dependent ramp constraints* ➢ *time-dependent decay of efficiency*	➢ *high computational burden*

Table 1.2: Models available in literature and *Oemof_Transient*

Chapter 2

Methods and Materials

In this chapter, the new methodology related to the creation of *Oemof_Transient* model is presented. This model has been developed to cope with the issues related to common bottom-up models presented in the previous chapter: no one of the models perform a detailed time-dependent analysis of transient operations of fossil fuel power plants.
Oemof_Transient is a unit commitment model that optimizes the dispatch of electricity performing a time-dependent analysis of fossil fuel power plants' transient operations. In *Oemof_Transient* the following constraints are implemented to represent the partial-load operations of power plants:

- **time-dependent start-up costs**: various start-up costs that depends on the hours of stop of the plant.

- **time-dependent ramp constraints**: various ramp constraints that depends on the hours of stop of the plant.

- **time-dependent decay of efficiency at partial load**: degradation of performances that is verified when power plants are not producing at full-load (nominal condition); it is implemented as an additional fuel consumption (and thus additional costs and emissions), respect to the ideal case where the efficiency remains constant and equal to the nominal value.

The transient time-dependent analysis is implemented using *Oemof* framework because is suited for this scope by being open-source (the core-code can be modified in order to implement new constraints), adaptable and time-step-flexible (temporal resolution and time discretization are user-defined); this allow to perform detailed technical analyses of energy systems, thus it is possible to set the time discretization in order to recognize the desired transient operation and implement new constraints to model it. In the next section a description of the structure of *Oemof* cosmos is provided.

2.1 *Oemof*

Oemof is a bottom-up, optimization model and is a very useful toolbox to build-up energy system models in high temporal and spatial resolution. In this section a more accurate explanation of *Oemof* structure and working principles is provided.

2.1.1 General structure

Oemof is an open source program written in Python programming language and has been developed starting from 2014 by the following institutions:

- Europa-Universitä at Flensburg (EUF)
- Flensburg University of Applied Sciences (HFL)
- Otto von Guericke University Magdeburg (OVGU)
- Reiner Lemoine Institut Berlin (RLI)

Oemof stands for *Open Energy Modeling Framework* and is a framework, with a modular structure, containing several packages which communicate through well defined interfaces. Due to the different research backgrounds of the collaborators, the framework was not designed for the scope of one particular application. Instead, the idea was to create a framework that can be used to build a variety of energy system models.
Oemof facilitate the modeling of complex energy systems providing a rich set of tools, (that include optimization libraries, tools to simulate feed-in from *RES* or local heat demand for a specific region), aimed to support current and future challenges in energy system modeling. The focus of these analyses may range from local to multinational and from single sector to a coupling of power, heat and transport sectors.
By linking different *Oemof* modules new energy system model can be designed. The *Oemof* framework is implemented using an object-oriented approach in the high-level programming language Python. In an object-oriented approach, the focus is on capturing the structure and behavior of systems into small modules (object), that combines both data and process.
An implementation within the high level programming language Python has the advantage of a rich set of external libraries usable for scientific computing; *Oemof* itself makes heavy use of external modules for optimization problem, data analysis, network analysis and additional packages for data processing and visualization can be included easily.

Oemof presents many useful characteristics, thus is:

- **Versatile and Adaptable**: It's possible to modify or create new units and constraints to an energy systems and adapt components to own scope and purpose.

- **Open Source**: modifications of the code are possible, thus new features as constraints and components can be implemented.

- **Modular**: It is possible to use the various Python packages (libraries) with well defined interfaces for modeling and optimization.

- **Cross-Sectoral**: Include and link heat, power and mobility sectors.

- **Time-step-flexible**: It is possible to choose the temporal resolution and the time discretization mostly suited for the model.

- **Multi-regional**: Multi-node approach can be adopted.

Oemof relies on a generic concept that constitutes the foundation of all libraries: an energy system is represented as a network consisting of nodes which are connected via flows.
Nodes and flow are the root elements of a network and are implemented in *Oemof* as Python's classes. Nodes are subdivided into Buses and Components, Buses are solely connected to Components and vice versa. Components are meant to represent actual producers and consumers of an energy system, while Buses are meant to represent how these components are tied together.
Flows are the directed edge between two nodes and represent the connection between a Bus and a Component object (are inputs/outputs of the various nodes in the network); all flows into and out of a Node are balanced.
An energy system that is represented in such a way can be approached mathematically using concepts from graph theory by looking at it as a bipartite graph, where Nodes are partitioned into Buses and Components while Flows act as the directed edges of the graph.
Oemof framework provides basic Components which can be used directly or is possible to implement new Components with different features.
An example of how to describe an energy system using this network structure is shown schematically in Figure 2.1.

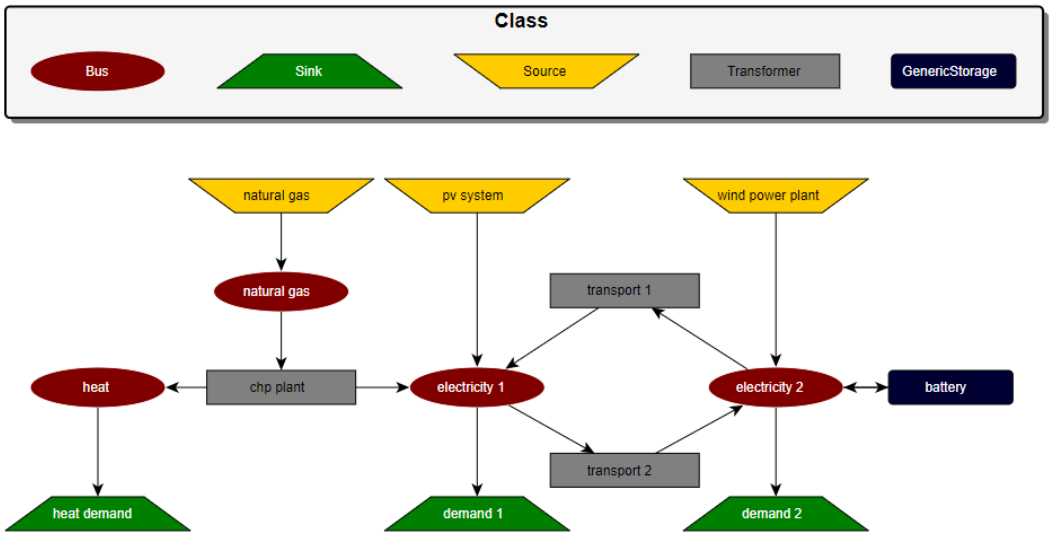

Figure 2.1: Schematic illustration of an energy system represented as a network

Depending on nature of the Flows (inflows or outflows), Components can be divided into three main subtypes representing different physical objects:

- **Transformers**: have inflows and outflows. Transformers can be used to model fossil fuel power plants (e.g. *GT*, *CCGT*, coal power plants), transmission lines or any kind of a transforming process (as electrolysis, a cooling device or a heat pump). It is possible to set only a constant efficiency for these components.

- **Sinks**: have inflows, but no outflows. Sinks can be used to model excess energy or energy consumptions as electricity or heat.

- **Sources**: have outflows, but no inflow. Sources can be used to model *RES* power plants (as *PV*, wind), import of energy, a reservoir that supply fuel to power plants.

- **Generic Storage**: have inflows and outflows. Generic Storage can be used to model any storage technology (e.g. *PHS* or batteries).

The modeling of energy supply systems and its variety of Components has a clearly structured approach within the *Oemof* framework. All basic energy system Components such as energy demands, *RES* and fossil power plants, can be modeled by means of these basic classes. For example *CCGT* can be implemented as a Transformer that consumes gas from a gas Bus and feeds electrical

energy into an electricity Bus. With additional information like parameters and transfer functions, the relation between inflows and outflows can be specified, (e.g. in a *CCGT* by setting the efficiency factor). For each component it is possible to set manually or generate (with demandlib, feedinlib libraries) the time series distributions of the power produced/consumed.
Node and Flow objects can be created step by step in the Python programming language, whereas large energy models can use their own functions to deal between data and parameter input and the creation of the nodes. One option provided by *Oemof*, to simplify the implementation of large energy models, is the adoption of a very useful function (*NodesFromCSV*): the elements (Nodes, Buses, Flows and various parameters) of an energy system are defined and described in a specially formatted CSV-file, that is used as input file for the simulation/optimization in *Oemof*.
With *Oemof-Solph* package is possible to create and solve linear programming (LP) and mixed-integer linear programming (MILP) optimization models. *Oemof-Solph* is a library based on Pyomo (a Python-based open-source optimization modeling language) and allows to model components with high technical details; it's possible to use the already implemented constraints, such as a mini/max power production, or to create new constraints that introduce new features, in order to make energy systems more similar to a real ones.
When implementing new constraints, only linear relations can be adopted and is not possible to use conditional statements (*if-else* conditions) on the optimization variables. The introduction of certain constraints turns the optimization problem from linear to mixed-integer linear: this occurs when the *status* variable is adopted in the constraints implementation (it is a binary integer variables that can be 0 or 1 depending if a power plant is up or down). A mixed-integer linear optimization problem is more complex and difficult to solve: memory usage and computational time rise (e.g using the *status* variable, the size of the problem increases because for each time-steps an additional variable is introduced).
There are various commercial (e.g. *Gurobi*, *Cplex*) and open-source (e.g. *CBC*, *GLPK*) solvers that can be used with *Oemof*, but no all of them are able to solve mixed-integer linear problems. Due to the mixed-integer nature of the constraints implemented in this thesis work to represent the transient operation of fossil fuel power plants, *Gurobi* [47] is selected as optimization solver because is able to solve mixed-integer problem and is also free for academic use.
The main feature of *Oemof* framework is that of separating the issue of describing an energy system's topology from the calculations: indeed after the implementation of the energy system topology (Bus, Components, Flow), is possible to choose the type of optimization. The typical optimization of for an energy system is the dispatch optimization, that is based on marginal costs and consists in the optimal use of the sources to satisfy demand at least costs; indeed it is possible to set variable and fixed costs for all nodes and flows and these costs do not have to be monetary costs but could be emissions or other variable units.

2.2 *Oemof_Transient*

In this section the methodology as well as the constraints implementation that lead to the creation of *Oemof_Transient* model are explained.
Oemof_Transient is a *Bottom-up* unit commitment model that performs an optimized dispatch of electricity based on costs, considering also the transient operations of fossil fuel power plants through a time-dependent analysis.
In *Bottom-up* modeling, usually the actual operational details of supply side (such as constraints and additional costs and emissions due to transient operations of fossil fuel power plants) are not considered in order to simplify the model, reduce computational time and memory usage.
Including the transient operations of fossil fuel power plant, allows to model an energy system in more realistic way and this issue is gaining a growing importance, due to recent transformations of energy systems.
The introduction of large amount of *RES*, due to their intermittent, variable and unpredictable nature, requires an increased flexibility from power generation units in order to counterbalance the fluctuations of these sources and maintain the system in balance. Nowadays, transient operations of fossil fuel power plants are the main source of operational flexibility for an energy system: indeed fossil fuel power plants are required to cycle and ramp-up/down (referred as cycling) more frequently in order to follow the load and compensate the intermittent generation from *VRES*. Additional costs (cycling costs) and emissions are associated to these transient operations.
The evaluation of fossil fuel power plants' transient operations is fundamental in the modeling of an energy system, in order to represent it in a more realistic and accurate way, do not underestimate the total system costs and optimize the production and schedule of fossil fuel power plants.
This is even more important when evaluating future configurations of the energy system with high *RES* penetration and so higher flexibility requirements.
Intensifying the cycling operations of power units increases the overall costs of an energy system: indeed power plants are started-up more frequently and work longer at partial-load , inducing additional start-up costs, inefficient fuel consumptions and higher specific emissions.
In this thesis work the impact of fossil fuel power plants' transient operations (and associated cycling costs) on the optimal dispatch of electricity, is evaluated creating a model (*Oemof_Transient*) that performs a time-dependent analysis of these events.
The time-dependent analysis is developed in *Oemof* framework, implementing new constraints for fossil fuel power plants that penalize their working conditions during transient operations.

2.2.1 Working principles

Oemof_Transient model performs an optimization of the electricity dispatch based on costs, considering also transient operations of fossil fuel power plants. *Oemof_Transient* model is implemented adopting a multi-node logic and it is possible to set the time resolution and the time discretization.
Oemof_Transient has been implemented enhancing the components already modeled in *Oemof* to define an energy system by introducing the time-dependent constraints described in the next subsection.
In order to run the optimization, the energy system is defined setting for each node the following components:

- **Electricity demand**:
  Electricity demand is modeled through Sink component (many inputs, no outputs) that consumes the electricity generated in the energy system. The electricity demand profiles are set before to run the optimization through time distributions that can be constant or variable in time and a fictitious value of installed capacity. The electricity dissipated at time t in each node of the energy system is obtained by multiplying the installed capacity by the value of time distribution in that time-step, as expressed in Equation (2.2). Equation (2.3) allow to evaluate the total electricity demand over the whole time horizon.

$$D_{\mathrm{n}}(t) = I_{\mathrm{n}} * distr_{\mathrm{n}}(t) \tag{2.1}$$

$$\tag{2.2}$$

where:

- $D_{n,u}(t)$: electricity demand at time t in node n. *[MW] (input data)*
- I_n: fictitious installed capacity of electricity demand in node n. *[MW] (input data)*
- $distr_u(t)$: value of the distribution at time t of electricity demand in node n. *[0 , 1] (input data)*

$$D_{\mathrm{tot}} = \sum_{n}^{nodes} \sum_{t}^{time} D_{\mathrm{n}}(t) \tag{2.3}$$

where:

- D_{tot}: total electricity demand. *[MWh]*
- $D_n(t)$: electricity demand at time t, in node n. *[MW] (input data)*

- ***RES***:
  Renewable energy sources *RES* are modeled through Source components (no inputs, many outputs), that generate electricity. Possible *RES* power units are *PV*, wind turbines, geothermal, biomass and hydroelectric power plants. For each power unit is possible to set the nominal installed capacity (maximum possible power output expressed in *MW*), the time profile (through distributions that can be constant or variable in time, defined before the optimization) and fixed/variable costs. Equation (2.5) allow to evaluate the total electricity generated by *RES* power plants, while with Equation (2.5) is calculated the electricity generated from a *RES* at time *t*, that is an input data.

$$RES_{\mathrm{n,u}}(t) = I_{\mathrm{n,u}} * distr_{\mathrm{n,u}}(t) \tag{2.4}$$

$$RES_{\mathrm{tot}} = \sum_{n}^{nodes} \sum_{u}^{unit} \sum_{t}^{time} RES_{\mathrm{n,u}}(t) \tag{2.5}$$

where:

- $RES_{n,u}(t)$: electricity generated by *RES* power plant u at time *t* in node n. *[MW] (input data)*
- $I_{n,u}$: installed capacity of *RES* power plant u in node n. *[MW] (input data)*
- $distr_u(t)$: value of the distribution at time *t* of *RES* power plant u in node n. *[0 , 1] (input data)*
- RES_{tot}: total electricity generated by *RES* power plants. *[MWh]*

- **Fossil fuel power plants**:
  Fossil fuel power plants are modeled through Transformer components (one input, one output), that receive fuel as input and produce electricity. *CCGT*, coal, oil and gas power plants can be implemented. For each fossil fuel power plant it is possible to set the nominal installed capacity (maximum possible power output expressed in *MW*), the time profile (through distributions that can be constant or variable in time, defined before the optimization), min/max power output, efficiency (constant) and fixed/variable costs. Equation (2.7) allow to evaluate the total electricity generated by fossil fuel power plants, while with Equation (2.6) is calculated the electricity generated from a fossil fuel power plant at time *t* staring from the the fuel consumed, that are optimization variables.

$$P_{\mathrm{n,u}}(t) = F_{\mathrm{n,u}}(t) * \eta_{nom,n,u} \tag{2.6}$$

$$P_{\mathrm{tot}} = \sum_{n}^{nodes} \sum_{u}^{unit} \sum_{t}^{time} P_{\mathrm{n,u}}(t) \tag{2.7}$$

where:

- $P_{n,u}(t)$: electricity generated by fossil fuel power plant u at time t in node n. *[MW] (optimization variable)*
- $F_{n,u}(t)$: fuel consumed by fossil fuel power plant u at time t in node n. *[MW] (optimization variable)*
- $\eta_{nom,n,u}$: nominal efficiency of plant u in node n. *[0 , 1] (input data)*
- P_{tot}: total electricity generated by fossil fuel power plants. *[MWh]*

- **Transmission lines**:
  Transmission lines are modeled to connect nodes of an energy system one to the other. Transmission lines are modeled using Transformer components (one input, one output), that transfer electricity from a node to the other. For each Transmission line is possible to set the nominal installed capacity (maximum amount of electricity that can be transferred) and the efficiency (to represent the network losses). Network losses depends on the electricity transferred from one node to the other and are calculated with Equation (2.9).

$$L_{\mathrm{network,a,b}}(t) = P_{\mathrm{a,b}}(t) * (1 - \eta_{network,a,b}) \tag{2.8}$$

$$L_{\mathrm{network,tot}} = \sum_{a}^{nodes} \sum_{b}^{nodes} \sum_{t}^{time} L_{\mathrm{network,a,b}}(t) \tag{2.9}$$

where:

- $L_{network,a,b}(t)$: network losses between node a and node b at time t. *[MW] (optimization variable)*
- $P_{a,b}(t)$: electricity transfered from node a to node b at time t. *[MW] (optimization variable)*
- $\eta_{network,a,b}$: transmission efficiency between node a and node b. *[0 , 1] (input data)*
- $L_{network,tot}$: total network losses of the energy system. *[MWh]*

- **Curtailment**:
  Curtailment is modeled through Sink component (many inputs, no outputs) and is introduced to dissipate the excess of electricity produced from *VRES*, when the storage is full, in order to balance the energy system and make the optimization problem feasible. Curtailment is an optimization variable and is calculated starting from the equations that describe the electricity balance of the energy system (Equation (2.15) instant balance, Equation (2.16) balance on the whole time-horizon); thus Equation (2.10) is obtained.

$$P_{\text{curt,tot}} = P_{\text{tot}} + RES_{\text{tot}} - L_{\text{storage,tot}} - L_{\text{network,tot}} - D_{\text{tot}} \tag{2.10}$$

where:

- $P_{curt,tot}$: total curtailment in the energy system. *[MWh]*
- P_{tot}: total electricity generated by fossil fuel power plants. *[MWh]*
- RES_{tot}: total electricity generated by *RES* power plants. *[MWh]*
- $L_{storage,tot}$: total storage losses of the energy system. *[MWh]*
- $L_{network,tot}$: total network losses of the energy system. *[MWh]*
- D_{tot}: total electricity demand of the energy system. *[MWh]*

Storage:
Storage technologies are modeled through Generic Storage components (one input, one output), that can store the excess of electricity generated by *VRES* power plants, when overproduction occurs and give it back to the grid when *VRES* are not producing. Possible storage technologies are batteries and Pumped-Hydro Storage (*PHS*). For each Storage technology is possible to set the nominal installed capacity(maximum amount of energy that can be stored expressed in *MWh*), inflow conversion factor, maximum power inflow to storage, outflow conversion factor, maximum power outflow from storage, capacity loss and fixed/variable costs. Equation (2.11) allow to evaluate the electricity stored, while Equation (2.12) the electricity produced from the storage; these quantities are optimization variables. The storage losses at time t are calculate with Equation (2.13), while the total storage losses with Equation (2.14)

$$S_{\text{charge,tot}} = \sum_{n}^{nodes} \sum_{u}^{unit} \sum_{t}^{time} S_{\text{charge,n,u}}(t) \tag{2.11}$$

$$S_{\text{disch,tot}} = \sum_{n}^{nodes} \sum_{u}^{unit} \sum_{t}^{time} S_{\text{disch,n,u}}(t) \tag{2.12}$$

$$\begin{aligned} L_{\text{storage,n,u}}(t) = S_{\text{charge,n,u}}(t) * [1 - \eta_{charge,n,u}] + \\ + S_{\text{disch,n,u}}(t) * \left[\frac{1}{\eta_{disch,n,u}} - 1\right] \end{aligned} \tag{2.13}$$

$$L_{\text{storage,tot}} = \sum_{n}^{nodes} \sum_{u}^{unit} \sum_{t}^{time} L_{\text{storage,n,u}}(t) \tag{2.14}$$

where:

- $S_{charge,n,u}(t)$: electricity stored by unit u at time t in node n. *[MWh] (optimization variable)*
- $S_{charge,tot}$: total electricity stored by unit u in node n. *[MWh]*
- $S_{disch,n,u}(t)$: electricity produced by storage unit u at time t in node n. *[MW] (optimization variable)*
- $S_{disch,tot}$: total electricity produced by storage unit u in node n. *[MWh]*
- $\eta_{charge,u,n}$: charge efficiency of storage unit u in node n. *[0 , 1] (input data)*
- $\eta_{disch,u,n}$: discharge efficiency of storage unit u in node n. *[0 , 1] (input data)*
- $L_{storage,n,u(t)}$: storage losses of unit u in node n at time t. *[MW] (optimization variable)*
- $L_{storage,tot}$: total storage losses of the energy system. *[MWh]*

In Figure 2.2 the structure of *Oemof_Transient* model is reported for a two-nodes energy system with the connections between the components.
The electricity is generated from Renewable Energy Sources (modeled as Source components in yellow) and Fossil Fuel Power Plants (modeled as Transformer components in gray) and is consumed as Electricity Demand (modeled as Sink component in green). The electricity produced can be transferred from one node to the other by Transmission Lines (modeled as Transformer components in gray) . If overproduction from Renewable Energy Sources occurs, the electricity excess can be stored with Storage technologies (modeled as Generic Storage components in blue),or if Storage is full, the electricity is dissipated leading to the so called curtailment.
Oemof_Transient model allow to introduce in the energy system many different power plants: PV, wind turbines, geothermal, biomass and hydroelectric power plants can be modeled using Renewable Energy Sources block, while $CCGT$, coal, oil and gas power plants can be added through Fossil Fuel Power Plants block.
The dispatch of electricity is performed in *Oemof_Transient* model taking as input data the electricity demand and the generation from RES and optimizing the production from fossil fuel power plant, the usage of storage technology and the electricity transferred from one node the the other, without overcoming the constraints and limits on the various components of the energy system.
The electricity produced and consumed in the energy system has to be in balance at each instant of time during the optimization, leading to the instant energy balance of Equation (2.15). The energy balance on the whole time-horizon is given by Equation (2.16).

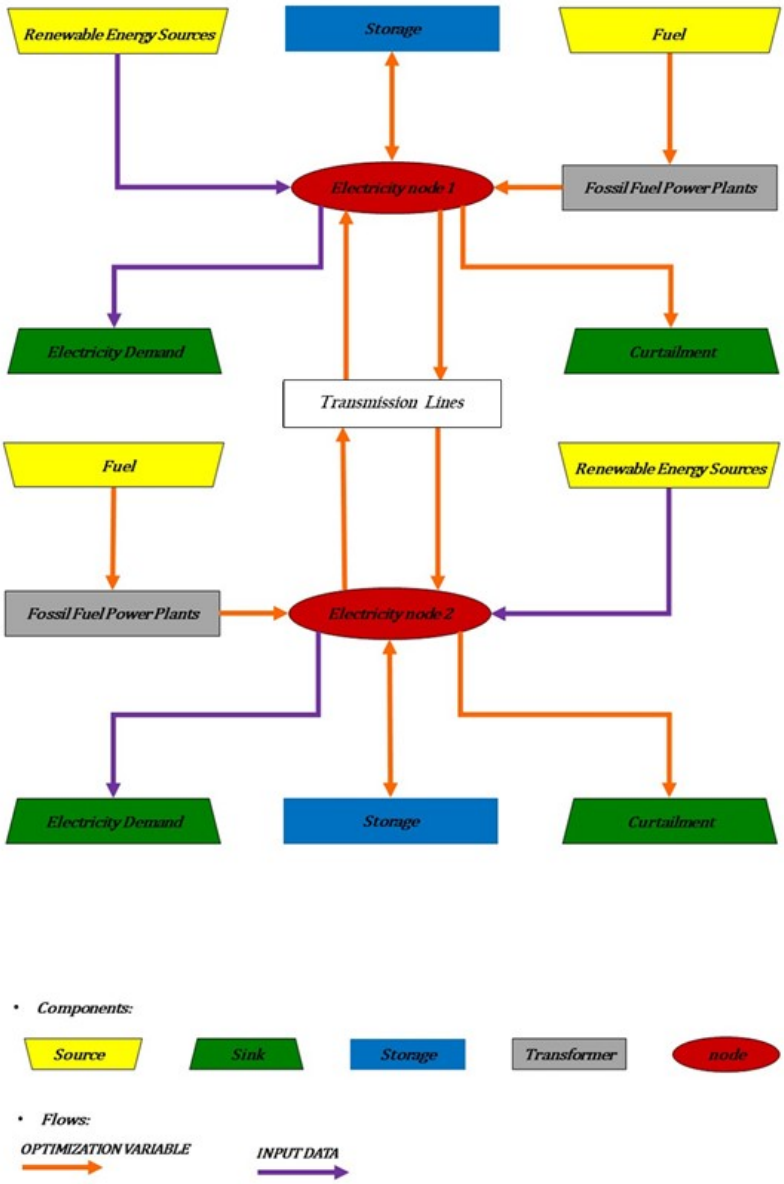

Figure 2.2: *Oemof_Transient* model structure for a two-nodes energy system

$$\sum_{n}^{nodes}\sum_{u}^{unit} P_{\mathrm{n,u}}(t) + \sum_{n}^{nodes}\sum_{u}^{unit} RES_{\mathrm{n,u}}(t) + \sum_{n}^{nodes}\sum_{u}^{unit} S_{\mathrm{disch,n,u}}(t) - \sum_{n}^{nodes}\sum_{u}^{unit} S_{\mathrm{charge,n,u}}(t) + \\ - \sum_{n}^{nodes}\sum_{u}^{unit} L_{\mathrm{storage,n,u}}(t) - \sum_{a}^{nodes}\sum_{b}^{nodes} L_{\mathrm{network,a,b}}(t) - \sum_{n}^{nodes} P_{\mathrm{curt,n}}(t) - \sum_{n}^{nodes} D_{\mathrm{n}}(t) = 0 \tag{2.15}$$

$$P_{\mathrm{tot}} + RES_{\mathrm{tot}} - L_{\mathrm{storage,tot}} - L_{\mathrm{network,tot}} - P_{\mathrm{curt,tot}} - D_{\mathrm{tot}} = 0 \tag{2.16}$$

where:

- $P_{n,u}(t)$: electricity generated by fossil fuel power plant u at time t in node n. *[MW] (optimization variable)*
- P_{tot}: total electricity generated by fossil fuel power plants. *[MWh]*
- $RES_{n,u}(t)$: electricity generated by *RES* power plant u at time t in node n. *[MW] (input data)*
- RES_{tot}: total electricity generated by *RES* power plants. *[MWh]*
- $S_{charge,n,u}(t)$: electricity stored by unit u at time t in node n. *[MW] (optimization variable)*
- $S_{disch,n,u}(t)$: electricity produced by storage unit u at time t in node n. *[MW] (optimization variable)*
- $L_{storage,n,u(t)}$: storage losses of unit u in node n at time t. *[MW] (optimization variable)*
- $L_{storage,tot}$: total storage losses of the energy system. *[MWh]*
- $L_{network,a,b}(t)$: network losses between node a and node b at time t. *[MW] (optimization variable)*
- $L_{network,tot}$: total network losses of the energy system. *[MWh]*
- $P_{curt,n}(t)$: curtailment that is verified in node n at time t. *[MW] (optimization variable)*
- $P_{curt,tot}$: total curtailment in the energy system. *[MWh]*
- $D_n(t)$: electricity demand at time t, in node n. *[MW] (input data)*
- D_{tot}: total electricity demand of the energy system. *[MWh]*

2.2.2 Time-dependent transient analysis: constraints implementation

An effective and useful way to consider and quantify these transient operations in energy system modeling, is the introduction of cycling costs, a parameter used to calculate the costs related to cycling operations of power plants.
Cycling costs are a result of both the number and type of starts-up and the operating regime of power plants; furthermore these costs present short-term and a long-term components.
Short-term cycling costs mainly consist of direct start-up costs, decay of efficiency costs and take place at moment of cycling and are easily determinable. Start-up costs are usually independent on the electricity produced after the start and depends on the installed capacity and the hour of stop of the plant.
Long-term cycling costs instead consist in maintenance costs due to accrued damage and occur over a long time horizon; these costs are hardly determinable, difficult to quantify and involve very complicated relations (non linear mathematical relations).

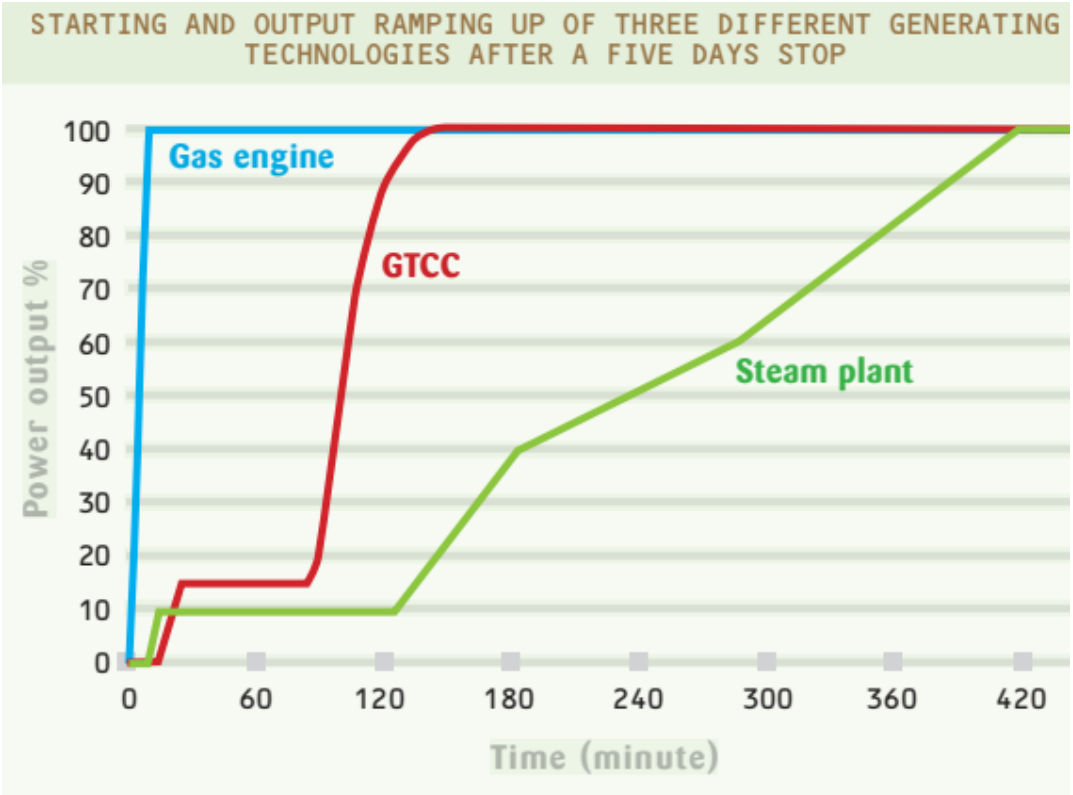

Figure 2.3: Ramp constraints of three different technologies, after a five days stop

[48]

Cycling and ramping of fossil fuel power plants are very common way to provide flexibility to an energy system; this capability is quantified by the ramp rate, defined as the rate of change in instantaneous output from a power plant. Fossil fuel power plants have ramp rate of available power during transient and during start-up (Figure 2.3), that depends on technology and the hours of stop of the plant.
Fossil fuel plants present different efficiencies depending on the load at which are working (Figure 2.4): if a power plant is not producing at full load, the efficiency is lower than the nominal value. This decay of efficiency during off-design working condition produces additional fuel consumptions and so additional costs and emissions.

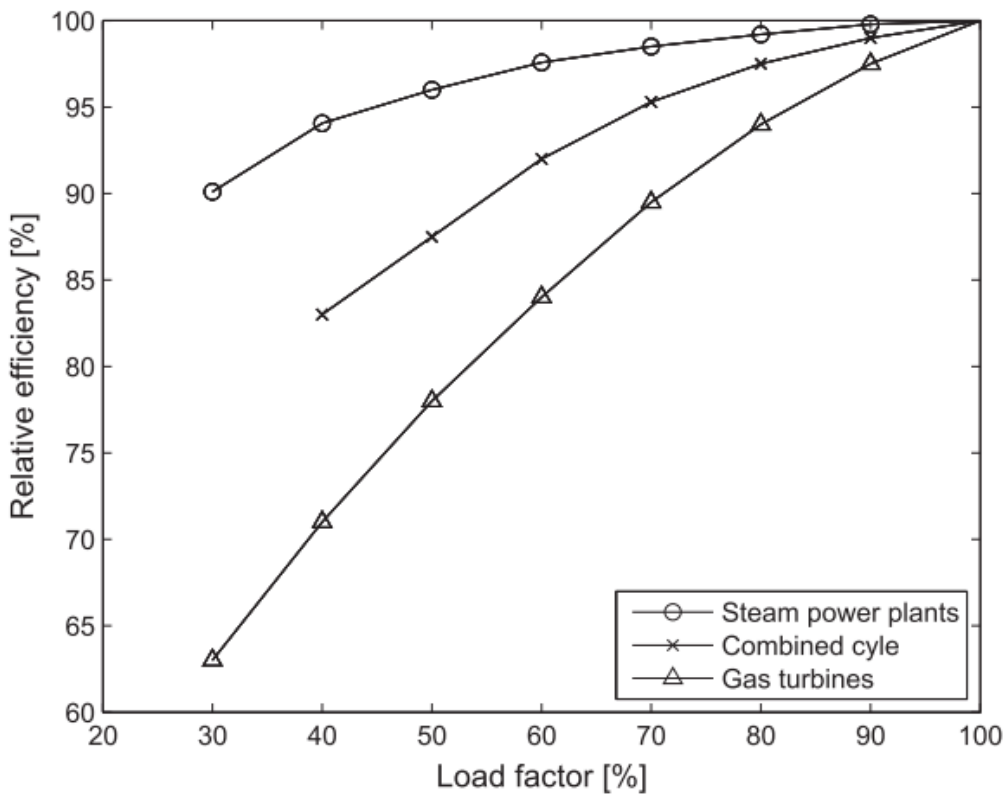

Figure 2.4: Decay of performance of fossil fuel power plant as function of the electricity generated

[49]

The analysis of the transient operations of fossil fuel power plants carried out in this thesis work is performed enhancing *Oemof* (version: Oemof v0.1.4). In *Oemof* power plants (Transformer element in *Oemof* framework) are modeled as fully-flexible (power output can vary from zero to the maximum in one time-step), the decay of performances during partial operations is not implemented and the only transient operations considered are starts-up with the associated costs. These costs do not depend on the hours of stop of the power plant, thus the transient analysis performed by *Oemof* is not time-dependent.
In order to evaluate with higher technological detail the impact of fossil fuel power plants' transient operations, new constraints have been developed in this thesis work, that leads to the creation of *Oemof_Transient* model.
In the analysis performed in this thesis work, only short-term cycling costs are considered (in particular start-up costs and decay of efficiency costs) because of their nature: indeed are easily determinable and is possible to model these costs using linear mathematical relations, that are the only one that are allowed in *Oemof* when modeling new constraints.
In particular in *Oemof_Transient*, the model created for this thesis work, the following constraints are introduced to perform a time-dependent analysis of power plants' transient operations: time-dependent start-up costs, time-dependent ramp constraints and time-dependent decay of efficiency at partial load.
Constraints are essentially sets of mathematical equations that are added to the model and can be implemented in *Oemof* with *Oemof-Solph* package (a library based on Pyomo language).
Oemof-Solph package has some limits: only linear relations can be introduced and is not possible to use conditional statements (*if-else* conditions) on the optimization variables.
In certain cases, in order to not overcome *Oemof-Solph*'s limits, rearrangements of the original problem have to be performed, one possibility is to introduce new variables and find equivalent mathematical reformulations of the problem that are allowed in *Oemof-Solph*.
A very useful variables in this context is *status(t)* variable, a binary (boolean) variable that can be either 0 or 1 depending if a power plant is up or down at time t.
The introduction of *status(t)* variables turn the optimization from a linear problem to mixed-integer linear one that is far more complex and difficult to solve: thus an additional binary variable is introduced in the model for each time-step and each constrained power plants, increasing size and complexity of the problem.
In the next subsections is given a detailed overview of the methodology adopted in this thesis work, to develop *Oemof_Transient* model: in particular are described the equations introduced and the Python's codes implemented to create the new constraints to perform a time-dependent analysis of fossil fuel power plants' transient operations.

Constraints for time-dependent start-up costs

When a power plant is started up, additional costs have to be considered. Start-up costs are usually independent on the electricity produced after the start and depends on the installed capacity (nominal power) and on hours of stop of the unit.
Starts can be classified according to the temperature of the metal in the turbine that depends on the down-time (hours of stop) of the plant.
In this thesis work various constraints are implemented to introduce time-dependent start-up costs in the optimization of the dispatch of electricity.
In particular three different types of start are introduced for fossil fuel power plants (Transformer components in *Oemof*):

- **hot start**
- **warm start**
- **cold start**

These different types of start are characterized by different costs and different down-times (hours of stop of the plant) that can be set in *Oemof_Transient* model depending on the technology adopted.
These time-dependent constraints relative to the different type of starts, have been created in *Oemof-Solph* library introducing one new variable (2.17) and one new Equation (2.18) each time-step, per constrained power plants and different types of start-up.
The introduction of these constraints turns the optimization in a mixed-integer problem (because the binary *status(t)* variable is adopted), that is more complex to solve, indeed higher computational time and memory usage are involved.
The variable (2.17) is created to recognize if a power plant has been down for an interval of time equal or higher than the down-time (Δt) that characterized the type of start-up.
This variable (2.17) is a binary (boolean) variable that return 1 if the power plant at time t has been down for an interval of time equal or higher than down-time (Δt), otherwise return 0; it is created starting from the already implemented boolean variable *status(t)*, that is 1 if the unit is up at time t, 0 if is down.
The start-up costs are introduced at each time-step and for the constrained power unit, using the Equation (2.18), where the boolean variable (2.17) is multiplied by the start-up cost ($C_{start\text{-}up,\Delta t}$) that can be set according to the down-time (Δt).
In Figure 2.5 it is reported the code created to reproduce the before mentioned relations ((2.18), (2.17)) in *Oemof-Solph* library.

In the implementation of these constraints some conditional statements (*if-else* conditions) are applied on variables that are predefined in the model (e.g. time t) and do not vary during the optimization process (are not optimization variables).
It is set the condition $t>=\Delta t$, otherwise the index of the summation in (2.17) is negative.
It is also considered the fact that when a cold start occurs, also the conditions for warm and hot starts are verified in the optimization (similarly when a warm start occur also hot start condition is verified).
The introduction in a model of these time-dependent constraints penalizes the cycling operations of power plants that are forced to be started-up less frequently, thus additional costs (that depends on the down-times) are introduced in the optimization, every time a unit is started-up.
The total cycling costs caused by starts-up of fossil fuel power plants can be computed with Equation (2.19).

```
def _startup_cold_rule(block,i,o,t):

    if t >= m.flows[i,o].binary.down_time_cold_start:
       expr = (self.startupcold[i,o,t] >= m.BinaryFlow.status[i,o,t] -
               sum(m.BinaryFlow.status[i,o,t-a] for a in
               range(1,int(m.flows[i,o].binary.down_time_cold_start) + 1)))
        return expr
    else:
        return (Constraint.Skip)

self.startupcold_constr = Constraint(self.STARTUPCOLDFLOWS,
                                     m.TIMESTEPS,
                                     rule=_startup_cold_rule)

if self.STARTUPCOLDFLOWS:
   startcoldcosts += sum(self.startupcold[i,o,t] * (
                     m.flows[i,o].binary.startup_cold_costs -
                     m.flows[i,o].binary.startup_warm_costs) *
                     m.flows[i,o].nominal_value for i,o in
                     self.STARTUPCOLDFLOWS for t in m.TIMESTEPS)
   self.startcoldcosts = Expression(expr=startcoldcosts)
```

Figure 2.5: Python code created for the implementation of time-dependent start-up costs using *Oemof-Soplh* library

$$X(t) = \begin{cases} 1 & \text{if} \quad status(t) > \sum_{i=t-\Delta t}^{t-1} status(i) \\ 0 & \text{otherwise} \end{cases} \tag{2.17}$$

$$C_{\text{start-up}}(t) = C_{\text{start-up},\Delta t} * P_{\text{nom}} * X(t) \tag{2.18}$$

where:

- t: time.
- $C_{start\text{-}up}(t)$: costs due to start-up at time t. *[€/MW] (optimization variable)*
- Δt: down-time (hours of stop). *[h] (input data)*
- $C_{start\text{-}up,\Delta t}$: specific start-up cost that depends on down-time Δt and nominal installed capacity P_{nom}. *[€/MW] (input data)*
- P_{nom}: nominal power. *[MW] (input data)*
- *status(t)*: boolean variable that return 1 if the power plant is up at time t and 0 if is down.
- *X(t)*: boolean variable that return 1 if the power plant at time t have been down for an interval of time equal or higher than down-time (Δt), otherwise return 0.

$$C_{start\text{-}up,tot} = \sum_{u}^{units} \sum_{start-up}^{starts} \sum_{t}^{time} C_{start\text{-}up,u}(t) \tag{2.19}$$

where:

- $C_{start\text{-}up,tot}$: total start-up costs of fossil fuel power plants. *[€]*
- *start-up*: type of start (hot start, warm start, cold start)
- $C_{start\text{-}up,u}(t)$: costs due to start-up of unit u at time t. *[€/MW] (optimization variable)*

Constraints for time-dependent ramp rate at start-up

Fossil fuel power plants have ramp rate (rate of change in instantaneous power output) of available power during transient and during start-up that depends on technology and the hours of stop of the plant(Figure 2.3); thus ramp constraints are introduced in *Oemof_Transient* to consider in the optimization that the available power from fossil fuel power plants is limited during start-up and during transient operations.
In this thesis work various constraints are implemented to introduce time-dependent ramp rate at start-up in the optimal dispatch of electricity.
In particular three different ramp rate of available power at start-up are implemented and characterized by different down-times (hours of stop of the plant) that can be set in *Oemof_Transient* model depending on the technology of the plant.
These time-dependent constraints have been created in *Oemof-Solph* library introducing one new system of Equations (2.20) each time-step, per constrained power plants and different types of start.
The introduction of these constraints turns the optimization in a mixed-integer problem (because the binary *status(t)* variable is introduced in the system of equations), that is more complex to solve, thus higher computational time and memory usage are required.
Oemof-Solph library imposes some limitations in the implementation of constraints (only linear relations and no conditional statements, *if-else* conditions, on the optimization variables). Thus equivalent mathematical expressions are developed to overcome *Oemof-Solph* limits, in order to replicate the desired conditional statements that involve optimization variables.
This is the case of the system of Equations (2.20), created to implement ramp constraints at start-up. This system of equations imposes that the available electricity generated by a power plant at start-up is a predefined value $P_{ramp,\Delta t}$ (ramp rate at startup), if the power plant was down for an interval of time equal or larger than Δt (hors of stop), otherwise the system of equation is always verified. It is possible to set different ramp rate of available power at start-up depending on the downtime of the plant.
The Python codes implemented to reproduce the before mentioned system of Equations (2.20) are reported in Figure 2.6 and Figure 2.7.
In the implementation of these constraints, some conditional statements (*if-else* conditions) are applied on variables that are predefined in the model (e.g. time t) and do not vary during the optimization process (are not optimization variables). It is set the condition $t>=\Delta t$, otherwise the index of the summation in (2.20) is negative.
The introduction of these time-dependent constraints in the optimization imposes ramp rate of available at start-up for fossil fuel power plants.

$$\begin{cases} P(t) >= \left[P_{ramp,\Delta t} * status(t) - \sum_{i=t-\Delta t}^{t-1} status(i) \right] * P_{nom} \\ \\ P(t) <= \left[P_{\text{ramp},\Delta t} * P_{nom} + \sum_{i=t-\Delta t}^{t-1} status(i) \right] * P_{nom} \end{cases} \tag{2.20}$$

where:

- t: time.
- *P(t)*: power generated at time t. *[MW] (optimization variable)*
- Δt: down-time (hours of stop). *[h] (input data)*
- $P_{ramp,\Delta t}$: ramp rate at start-up that depends on down-time Δt. *[MW] (input data)*
- *status(t)*: boolean variable that return 1 if the power plant is up at time t and 0 if is down.
- P_{nom}: nominal power. *[MW] (input data)*

```
def _cold_start_ramp_rule_part1(block,i,o,t):

    if t >= m.flows[i,o].binary.down_time_cold_start:
        expr=(m.flow[i,o,t] <=
              m.flows[i,o].binary.ramp_constraint_cold_start *
              m.flows[i,o].nominal_value +
              sum(m.BinaryFlow.status[i,o,t-a] for a in
              range(1,int(m.flows[i,o].binary.down_time_cold_start) + 1)) *
              m.flows[i,o].nominal_value)

        return expr
    else:
        return (Constraint.Skip)

self.coldstartramppart1_constr = Constraint(self.RAMPCONSTRAINTCOLDSTART,
                                            m.TIMESTEPS,
                                            rule=_cold_start_ramp_rule_part1)
```

Figure 2.6: Python code created for the implementation of time-dependent ramp constraints (part 1) using *Oemof-Soplh* library

```
def _cold_start_ramp_rule_part2(block,i,o,t):

    if t >= m.flows[i,o].binary.down_time_cold_start:
        expr=(m.flow[i,o,t] >=
              m.flows[i,o].binary.ramp_constraint_cold_start *
              m.flows[i,o].nominal_value * m.BinaryFlow.status[i,o,t] -
              sum(m.BinaryFlow.status[i,o,t-a] for a in
              range(1,int(m.flows[i,o].binary.down_time_cold_start) + 1)) *
              m.flows[i,o].nominal_value)

        return expr
    else:
        return (Constraint.Skip)

self.coldstartramppart2_constr = Constraint(self.RAMPCONSTRAINTCOLDSTART,
                                            m.TIMESTEPS,
                                            rule=_cold_start_ramp_rule_part2)
```

Figure 2.7: Python code created for the implementation of time-dependent ramp constraints (part 2) using *Oemof-Soplh* library

Constraints for time-dependent decay of efficiency at partial load

Fossil fuel plants have different efficiencies depending on the load at which are working (Figure 2.4). The efficiency assumes the maximum value when the power plant is producing in nominal condition (full load) and decreases as the electricity generated diminished, because fuel is consumed in a less efficient way. This decay of efficiency during off-design operations produces additional fuel consumptions and so additional costs and emissions.
The decay of efficiency is implemented in *Oemof_Transient* model in order to penalize partial load operations of fossil fuel power plants, introducing in the optimization additional costs and emissions every time a power plant is not producing at full load: one constraint is created to implement time-dependent decay of efficiency in the optimal dispatch of electricity.
This time-dependent constraint has been created using *Oemof-Solph* library, that imposes some limitations in the implementation of constraints, thus only linear relations can be modeled and no conditional statements(*if-else* conditions) on optimization variables can be adopted.
The decay of efficiency is considered in *Oemof_Transient* introducing additional costs and emission each time a power plant is not producing in nominal condition. These additional costs and emissions are modeled in the optimization as an additional flow of fuel ($\Delta F_{additional}(t)$) that is dissipated through a Sink component (Additional fuel consumption) without producing electricity, as depicted in Figure 2.8.

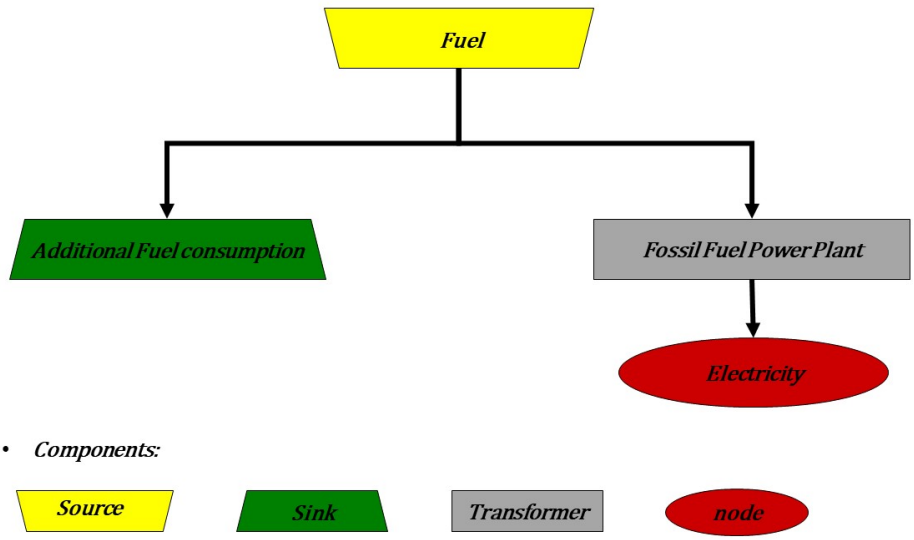

Figure 2.8: Schematic illustration of how decay of efficiency is implemented

The additional fuel consumption ($\Delta F_{additional}(t)$) is defined as the extra amount of fuel that is consumed at partial load due to decay of efficiency respect to the ideal case (no decay of efficiency) and is expressed by Equation (2.21); it is obtained by subtracting real fuel consumption (decay of efficiency at partial load considered) to ideal fuel consumption (efficiency considered constant and equal to the nominal value).
The amount of this additional fuel consumption ($\Delta F_{additional}(t)$) depends on the power output of the plant ($P(t)$) at each instant of time, because the decay of performance varies with the electricity produced, as depicted in Figure 2.4; thus a mathematical relation that links these quantities is needed. In order to not overcome *Oemof-Solph* limitations, only linear relations are introduced to model the decay of efficiency at partial load.
The decay of performance is modeled in *Oemof_Transient* introducing a mathematical equation that express the additional fuel consumption ($\Delta F_{additional}(t)$) as function of the relative power generated ($P_{\%}(t)$) and of the relative efficiency ($\eta_{\%}(t)$) due to decay of performance at partial load. Starting from the definition of additional fuel consumption (Equation (2.21)), it is possible to express real and ideal fuel consumptions ($F_{real}(t)$) and $F_{ideal}(t)$) as function of electricity generated (P(t)) and of decay of efficiency at partial load ($\eta(t)$), using Equation (2.22) and Equation (2.21); then the time-dependent quantities ($P(t)$, $\eta(t)$, $\Delta F_{additional}(t)$) are replaced with time-dependent relative quantities ($P_{\%}(t)$, $\eta_{\%}(t)$ and $\Delta F_{additional,\%}(t)$) adopting Equations (2.24), (2.25) and (2.26). Thus Equations (2.27) is obtained, where the relative additional fuel consumption ($\Delta F_{additional,\%}(t)$) is expressed as a non linear function of the relative power output ($P_{\%}(t)$) and the relative efficiency of the plant ($\eta_{\%}(t)$). Due to the non linearity of Equations (2.27), is not possible to introduce directly these expression in the model to replicate the decay of efficiency at partial load. In order to overcome this problem, starting from the point on the graph $\eta_{\%}(t)$ vs $P_{\%}(t)$ (Figure 2.4), the relative additional fuel consumption $\Delta F_{additional,\%}(t)$ is calculated with Equations (2.27) and the obtained points are plotted (in blue) as function of the relative power output ($P_{\%}(t)$), leading to Figure 2.9 for *CCGT* technology. The points of Figure 2.9 are then linearly interpolated, in order to obtain a linear mathematical expression that links the relative additional fuel consumption ($\Delta F_{additional,\%}(t)$) to the relative power produced from a power plant at each instant of time ($P_{\%}(t)$). Thus the red straight line of Figure 2.9 is obtained (for *CCGT*) and this line is forced to pass through the point (0;1) to account for no additional fuel consumption in nominal conditions, leading to m=-q, with m=slope and q=intercept.
The straight line of Figure 2.9 is expressed by the Equation (2.28), where m (slope) and q (intercept) are input data, while $\Delta F_{additional,\%}(t)$) and ($P_{\%}(t)$) are optimization variables.
In Figure 2.11 is reported the Python code created with *Oemof-Solph* library to model the time-dependent constraint that reproduce the decay of efficiency during partial load operation: this constraint is implemented introducing in

the optimization an additional flow of fuel ($\Delta F_{additional}$), that is expressed by Equation (2.29) and causes additional costs and emissions during partial load operations of fossil fuel power plants. The linear interpolation adopted to model the decay of efficiency, approximate with good precision the decay of performance of fossil fuel power plants during off-design operations, in fact the value of the coefficient of determination (R^2=0.958) is high.
In Figure 2.9 are reported for comparison the real decay of efficiency curve in blue (same of Figure 2.4 for $CCGT$) and the one adopted in this thesis work in red, where the relative efficiency ($\eta_{\%}(t)$) is obtained from Equation (2.27): $\Delta F_{additional,\%}(t)$ is calculated with Equation (2.28), knowing slope m and intercept q from the linear interpolation and providing arbitrary values to $P_{\%}(t)$; so $\eta_{\%}(t)$ is obtained from Equation (2.27) and the red curve is plotted. Figure 2.4 shows that the linear interpolation approximate with precision the decay of efficiency, since the two curves (red and blue one) are very similar.
The introduction of this time-dependent constraint to model the decay of efficiency at partial load, makes the optimization of the electricity dispatch a more complex problem: an additional flow of fuel ($\Delta F_{additional}(t)$) is introduced at each instant of time, in order to penalize the off-design operations of a power plant. This additional flow of fuel introduces additional costs and emissions, thus fossil fuel power plants are forced to work longer at full load.
The total cycling costs due to decay of efficiency during partial load operations of fossil fuel power plants can be computed with Equation (2.30).

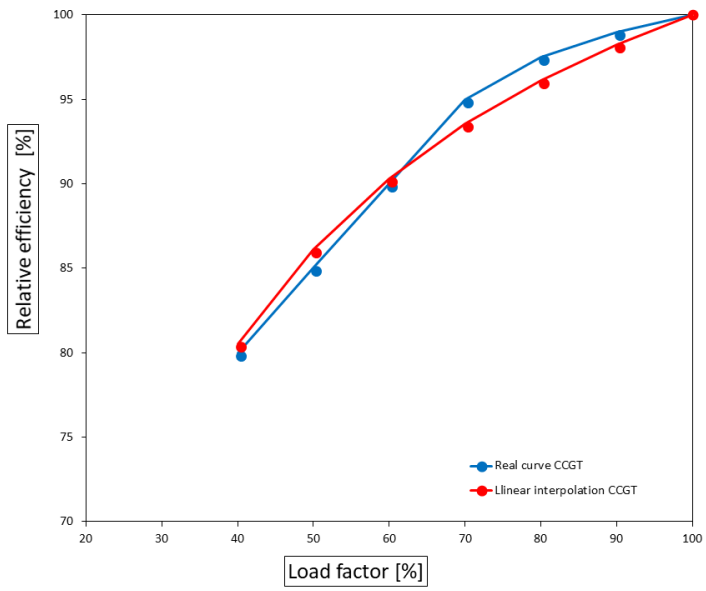

Figure 2.9: Linear interpolation of decay of performance of $CCGT$ as function of load

Elaboration of Figure 2.4

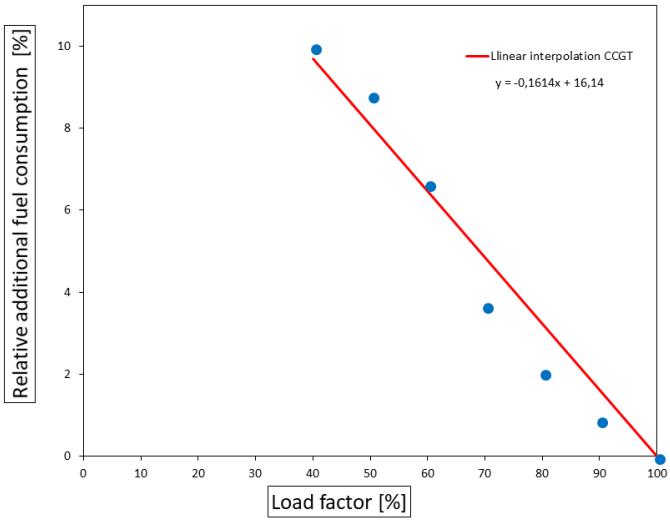

Figure 2.10: Additional fuel consumption of $CCGT$ as function of load

Elaboration of Figure 2.4

$$\Delta F_{additional}(t) = F_{real}(t) - F_{ideal}(t) \tag{2.21}$$

where:

- t: time.
- $\Delta F_{additional}(t)$: additional fuel consumption at time t due to decay of efficiency during partial load operations. *[MW]*
- $F_{real}(t)$: real fuel consumption at time t (considering decay of efficiency at partial load). *[MW]*
- $F_{ideal}(t)$: ideal fuel consumption at time t (not considering decay of efficiency at partial load). *[MW]*

$$F_{real}(t) = \frac{P(t)}{\eta(t)} \tag{2.22}$$

where:

- t: time.
- $F_{real}(t)$: real fuel consumption at time t (considering decay of efficiency at partial load). *[MW]*
- $P(t)$: power generated at time t. *[MW]*
- $\eta(t)$: efficiency at time t. *[0 , 1]*

$$F_{ideal}(t) = \frac{P(t)}{\eta_{nom}} \tag{2.23}$$

where:

- t: time.
- $F_{ideal}(t)$: ideal fuel consumption at time t (not considering decay of efficiency at partial load). *[MW]*
- $P(t)$: power generated at time t.
- η_{nom}: nominal efficiency. *[0 , 1]*

$$P_{\%}(t) = \frac{P(t)}{P_{nom}} \tag{2.24}$$

where:

- t: time.
- $P_{\%}(t)$: relative power generated at time t. *[0 , 1]*
- $P(t)$: power generated at time t. *[MW]*
- P_{nom}: nominal power. *[MW]*

$$\eta_{\%}(t) = \frac{\eta(t)}{\eta_{nom}} \tag{2.25}$$

where:

- t: time.
- $\eta_{\%}(t)$: relative efficiency at time t. *[0 , 1]*
- $\eta(t)$: efficiency at time t. *[0 , 1]*
- η_{nom}: nominal efficiency. *[0 , 1]*

$$\Delta F_{additional,\%}(t) = \frac{\Delta F_{additional}(t)}{F_{nom}} \tag{2.26}$$

where:

- t: time.
- $\Delta F_{additional,\%}(t)$: relative additional fuel consumption at time t due to decay of efficiency during partial load operations. *[0 , 1]*
- $\Delta F_{additional}(t)$: additional fuel consumption at time t due to decay of efficiency during partial load operations. *[MW]*
- F_{nom}: nominal fuel consumption. *[MW]*

$$\Delta F_{additional,\%}(t) = \left[\frac{1}{\eta_{\%}(t)} - 1\right] * P_{\%}(t) \tag{2.27}$$

where:

- t: time.
- $\Delta F_{additional,\%}(t)$: relative additional fuel consumption at time t, respect to nominal conditions, due to decay of efficiency during partial load operations. *[0 , 1]*
- $\eta_{\%}(t)$: relative efficiency at time t. *[0 , 1]*
- $P_{\%}(t)$: relative power generated at time t. *[0 , 1]*

$$\Delta F_{additional,\%}(t) = m * P_{\%}(t) + q \tag{2.28}$$

where:

- t: time.
- $\Delta F_{additional,\%}(t)$: relative additional fuel consumption at time t due to decay of efficiency during partial load operations. *[0 , 1] (optimization variable)*
- $P_{\%}(t)$: relative power generated at time t. *[0 , 1] (optimization variable)*
- m: slope of the straight line that interpolates linearly the points of the graph $\Delta F_{additional,\%}(t)$ versus $P_{\%}(t)$ (for *CCGT* Figure 2.10). *[-∞ , 0] (input data)*
- q: intercept of the straight line that interpolates linearly the points of the graph $\Delta F_{additional,\%}(t)$ versus $P_{\%}(t)$ (for *CCGT* Figure 2.10). *[0 , +∞] (input data)*

$$\Delta F_{additional}(t) = [m * P_{\%}(t) + q] * F_{\text{nom}} = \left[m * \frac{P(t)}{P_{nom}} + q\right] * \frac{P_{nom}}{\eta_{nom}} \quad (2.29)$$

where:

- t: time.
- $\Delta F_{additional}(t)$: additional fuel consumption at time t due to decay of efficiency during partial load operations. *[MW] (optimization variable)*
- $P_{\%}(t)$: relative power generated at time t. *[0 , 1] (optimization variable)*
- $P(t)$: power generated at time t. *[MW] (optimization variable)*
- P_{nom}: nominal power. *[MW] (input data)*
- F_{nom}: nominal fuel consumption. *[MW] (input data)*
- η_{nom}: nominal efficiency. *[0 , 1] (input data)*
- m: slope of the straight line that interpolates linearly the points of the graph $\Delta F_{additional,\%}(t)$ versus $P_{\%}(t)$ (for *CCGT* Figure 2.10). *[-∞ , 0] (input data)*
- q: intercept of the straight line that interpolates linearly the points of the graph $\Delta F_{additional,\%}(t)$ versus $P_{\%}(t)$ (for *CCGT* Figure 2.10). *[0 , +∞] (input data)*

$$C_{decay,tot} = \sum_{u}^{units} \sum_{t}^{time} [\Delta F_{additional,u}(t) * C_{fuel}] \quad (2.30)$$

where:

- $C_{decay,tot}$: total costs due to decay of efficiency during partial load operations of fossil fuel power plants. *[€]*
- $\Delta F_{additional,u}(t)$: additional fuel consumption of unit u at time t due to decay of efficiency. *[MW] (optimization variable)*
- C_{fuel}: specific fuel cost. *[€/MWh] (input data)*

```
def _decay_of_efficiency_rule(block,i,o,t):

    expr = (m.flow[m.es.groups[m.flows[i,o].binary.bus_additional_fuel_in],
            m.es.groups[m.flows[i,o].binary.bus_additional_fuel_consumed],t]
            == (m.flows[i,o].binary.angular_coeff_additional_fuel_rel *
            m.flow[i,o,t] / m.flows[i,o].nominal_value +
            m.flows[i,o].binary.intercept_additional_fuel_rel *
            m.BinaryFlow.status[i,o,t]) * m.flows[i,o].nominal_value /
            i.conversion_factors[o][t])

    return expr

self.decayofefficiency_constr = Constraint(self.DECAY_OF_EFFICIENCY_FLOWS,
                                           m.TIMESTEPS,
                                           rule=_decay_of_efficiency_rule)
```

Figure 2.11: Python code created for the implementation of time-dependent decay of efficiency at partial load using *Oemof-Soplh* library

2.2.3 Costs and emissions

In *Oemof_Transient* it is possible to set fixed and variable costs for all the various components.
In order to evaluate and analyze the impact of fossil fuel power plants' transient operations on electricity dispatch, the only costs introduced in the optimization are the variable costs of fossil power plants, so that the optimization is not influenced by other costs (e.g. investment costs) and the optimal schedule of these power plants is obtained as result.
Oemof_Transient model receives as input electricity demand, electricity production from *RES* power plants during the whole time-horizon and a portfolio of fossil fuel power plants that are schedule to generate electricity in order maintain the energy system in balance at each instant of time. The production of fossil fuel power plants is optimized so that the costs related to their operations are minimized.
The costs considered in the optimizations are: fuel costs (Equation (2.31)) and cycling costs (Equation (2.32)), due to transient operations (starts-up and decay of efficiency at partial load).
In the analysis performed in this thesis work only the transient operations of *CCGT* are considered , because nowadays, due to their characteristics, these power plants represent the main source of flexibility for an energy system, thus these units are required to cycle and ramp-up/down (cycling) in order to follow the load and compensate the intermittent generation from *VRES*; so the time-dependent constraints are applied only to this technology. The costs and the characteristics related to the different types of start of *CCGT* are difficult to define because depend on the model used for the calculations and the assumptions made. For these reasons in literature are reported different values; in Table 2.1 are listed the start-up costs for three different studies on *CCGT*: the optimistic scenario with lowest start-up costs [26] (named Best case), the scenario with medium start-up costs [27] (named Average case) and the pessimistic scenario with higher star-up costs [5] (named Worst case). These data along with the technical characteristics of *CCGT* reported in Table 2.2 are set as input for *Oemof_Transient* model.
The total variable costs of fossil fuel power plants are obtained by adding the fuel costs Equation (2.31) to cycling costs Equation (2.32), leading to Equation (2.33). The annual costs, related to investments and *O&M*, can be calculated with Equation (2.34) from the installed capacity and the annual production of each technology and thus the total annual costs of the energy system can be computed with Equation (2.35).
The specific costs related to fossil fuel power generation are calculated starting from total variable costs (Equation (2.33)) and electricity generated by these power plants. In particular the levelized cost of electricity (*LCOE*) is obtained, with Equation (2.36) by dividing total costs related to fossil fuel power plants (Equation (2.35)) by the electricity produced from these plants, while the specific

cycling costs are calculated with Equation (2.37), considering only cycling costs (Equation (2.32)). $LCOE$ is a measure of a power generation technology which attempts to compare different methods or conditions of electricity production. The CO_2 emissions of fossil fuel power plants are calculated with Equation (2.39) by multiplying the total fuel consumption (Equation (2.38)) by the carbon content of the fuel (emission factor).

Best case	Hot start	[€/MWh]	32.4
	Warm start	[€/MWh]	51.0
	Cold start	[€/MWh]	73.2
Average case	Hot start	[€/MWh]	45
	Warm start	[€/MWh]	70
	Cold start	[€/MWh]	110
Worst case	Hot start	[€/MWh]	156
	Warm start	[€/MWh]	211
	Cold start	[€/MWh]	393

Table 2.1: Start-up costs of $CCGT$

Best case [26],Average case [27],Worst case [5]

Types of start	Hot start	[h]	$<=8$
	Warm start	[h]	$>8 \wedge <24$
	Cold start	[h]	$>=24$
Ramp rate	Hot start	[MW/min]	14
	Warm start	[MW/min]	7
	Cold start	[MW/min]	4
Nominal efficiency	[%]	55	
Decay of efficiency	Linear interpolation	Figure 2.9	
Technical minimum	[%]	25	
Fuel	Natural gas		
Cost	[€/MWh]	24.9	
CO_2 emission factor	[kg/MWh]	204.8	

Table 2.2: Technical characteristics and constraints of $CCGT$

[5, 22, 23, 26, 27, 49–51]

$$C_{fuel,tot} = \sum_{u}^{units} \sum_{t}^{time} [F_{ideal,u}(t) * C_{fuel}] \tag{2.31}$$

where:

- $C_{fuel,tot}$: total ideal fuel costs of fossil fuel power plants (not considering decay of efficiency at partial load). *[€]*
- $F_{ideal,u}(t)$: ideal fuel consumption of unit u at time t (not considering decay of efficiency at partial load).*[MW] (optimization variable)*
- C_{fuel}: specific fuel cost. *[€/MWh] (input data)*

$$C_{cycling,tot} = C_{decay,tot} + C_{start\text{-}up,tot} \tag{2.32}$$

where:

- $C_{cycling,tot}$: total costs due to cycling of fossil fuel power plant. *[€]*
- $C_{decay,tot}$: total costs due to decay of efficiency in partial load operations. *[€]*
- $C_{start\text{-}up,tot}$: total start-up costs of fossil fuel power plants. *[€]*

$$C_{tot,variable} = C_{fuel,tot} + C_{cycling,tot} \tag{2.33}$$

where:

- $C_{tot,variable}$: total variable costs of fossil fuel power plants. *[€]*
- $C_{fuel,tot}$: total ideal fuel costs of fossil fuel power plants (not considering decay of efficiency at partial load). *[€]*
- $C_{cycling,tot}$: total costs due to cycling of fossil fuel power plant. *[€]*

$$C_{\text{annual}} = \sum_{k}^{techs} \left[inv_k * \ I_k * \ \frac{i}{1-(1+i)^{-n_k}} + O\&M_k \ * I_k + F_k \right] \tag{2.34}$$

where:

- t: time.
- inv_k: specific investment costs for the technology k.
- $O\&M_k$: Operation and Maintenance costs for the technology k.
- F_k: fuel costs for the technology k.
- I_k : installed capacity of technology k.
- i: interest rate.
- n_k: life-cycle of technology k.
- $P_k(t)$: electricity produced at time t from technology k.

$$C_{tot} = C_{fuel,tot} + C_{cycling,tot} + C_{\text{annual,fossil}} \tag{2.35}$$

where:

- C_{tot}: total costs of fossil fuel power plants. *[€]*
- $C_{fuel,tot}$: total ideal fuel costs of fossil fuel power plants (not considering decay of efficiency at partial load). *[€]*
- $C_{cycling,tot}$: total costs due to cycling of fossil fuel power plant. *[€]*
- $C_{annual,fossil}$: total annual costs of fossil fuel power plants. *[€]*

$$LCOE = \frac{C_{tot}}{P_{tot}} \tag{2.36}$$

where:

- $LCOE$: levelized cost of electricity. *[€/MWh]*
- C_{tot}: total costs of fossil fuel power plants. *[€]*
- P_{tot}: total electricity generated by fossil fuel power plants. *[MWh]*

$$C_{cycling,specific} = \frac{C_{cycling,tot}}{P_{tot}} \tag{2.37}$$

where:

- $C_{cycling,specific}$: specific cycling costs of fossil fuel power plants. *[€/MWh]*
- $C_{cycling,tot}$: total costs due to cycling of fossil fuel power plant. *[€]*
- P_{tot}: total electricity generated by fossil fuel power plants. *[MWh]*

$$F_{tot} = \sum_{u}^{units} \sum_{t}^{time} [F_{ideal,u}(t) + F_{\text{additional,u}}(t)] \tag{2.38}$$

where:

- F_{tot}: total fuel consumed by fossil fuel power plants.*[MWh]*
- $F_{ideal}(t)$: ideal fuel consumption at time t (not considering decay of efficiency at partial load).*[MW]*
- $\Delta F_{additional,u}(t)$: additional fuel consumption of unit u at time t due to decay of efficiency. *[MW]*

$$E_{CO_2} = F_{tot} * emis \tag{2.39}$$

where:

- E_{CO_2}: total CO*2* emission of fossil fuel power plants. *[Kg]*
- F_{tot}: total fuel consumed by fossil fuel power plants.*[MWh]*
- *emis*: CO*2* emission factor of fuel (carbon content of fuel). *[kg/MWh]*

Chapter 3

Italian case-study

The objective of this thesis work is to develop an optimization-dispatch model that performs a time-dependent analysis of fossil fuel power plant transient operations in a multi-node energy system.
In order to demonstrate the validity of the methodology presented in the last chapter to build the model and to evaluate the impact of fossil fuel power plants transient operations on optimal electricity dispatch , the time-dependent transient analysis created in *Oemof_Transient* model has been applied to an Italian case-study. In particular the impact of these transient events is quantified by cycling costs and the Italian energy system is analyzed considering the situation at 2014 and possible future scenarios at 2050, with higher *VRES* installed capacity.
The situation at 2014 is analyzed to validate the model and quantify the impact of cycling costs on the actual Italian energy system, indeed the configuration at 2014 is very similar to the actual one; at 2014 two scenarios are considered (*Italy_2014* and *Italy_2014_CCGT*): *Italy_2014* is representative of the real configuration of the Italian electricity sector, where all the different technology of fossil fuel power plants are introduced in the model and the other scenario (*Italy_2014_CCGT*), where fossil fuel power plants are modeled only by *CCGT*; this scenario is created for comparison with scenarios at 2050, because it is assumed that in future configuration of the energy system, in order to reduce *GHG* emissions and provide flexibility to generation side, the only technology adopted for fossil fuel power plants is *CCGT*. This assumption is in accordance with the national strategy for future development of the Italian energy system: thus the official reference document, *Strategia Energetica Nazionale (SEN)* [14] (last version published in 2017), explains the plans of the Ministry of Economic Development for the energy transition until 2030, analyzing the possible scenarios and suggesting options in order to reach the targets set by the European Union; the general picture that emerges is a push to solar and wind power and is also stated the possibility of a complete phase-out from coal fueled power plants.
The scenarios at 2050 (*Italy_2050*) created for *Oemof_Transient* model, are

obtained considering different penetration of *VRES* and allow to quantify the higher importance of fossil fuel power plants transient operations in configuration of the energy system with growing *VRES* installed capacity. These scenarios have been developed evaluating the potentialities of variable renewable energy sources such as PV and wind power in terms of new installations and overall installed power.
The Italian case is extremely peculiar since the energy system has occurred several changes in the last decade. The high availability of RES such as sun and hydro-power, as well as the incentives granted to solar PV and wind turbines in the years after 2010, have converted Italy in one of the leading countries in the European Union for renewable energy. This increase of production from *VRES* (PV and wind turbines) has represented a structural change for the balance of the Italian energy system. Variable renewable energy sources (*VRES*) have always contributed in negligible percentages on the national electric balance. The incentives introduced starting from 2010 resulted in a strong increase of production from these renewable sources characterized by an intermittent, unpredictable behavior and their integration in the national electric system is a problem that is not completely solved. The energy strategies for the development of *VRES* gave incentives for the installation and priority of production. *VRES* power plants participate in the formation of price of electricity on the market, but they generate it at zero price so their offer is always under the price of electricity formed on the market. This fact had an enormous impact on fossil fuel power plants, that are designed to work at regime for the optimization of fuel consumptions and to preserve the mechanical components that are manufactured for this working conditions. The start-up of a thermoelectric plant involves stress on mechanical components and a certain amount of time before reaching the nominal power. The introduction of fluctuating *VRES* leads to an intermittent use of the thermoelectric plants with a lot of starts and production at partial load during the year, increasing the costs of production and penalizing the competitiveness of those types of plants on the market. In the last years the transition to a low-carbon energy system has slowed down, mainly due to a reduction of public incentives. However, a large share of the country's renewable potential is still unexploited.
The application of *Oemof_Transient* model to the Italian case-study has required a certain number of assumptions, as well as a thorough investigation to gather data on the current status of the Italian energy system and about the maximum potential of *VRES* installed capacity.
These assumptions and data have been adopted in order to build-up in *Oemof_Transient* model the scenarios at 2014 and to provide informations about the future scenarios at 2050. The input data and the assumptions for the various scenarios (*Italy_2014*, *Italy_2014_CCGT* and *Italy_2050*) are presented in this chapter. It is also provided an overview of fossil fuel power plants on the Italian territory.

Italian energy system: fossil fuel power plants

Historically the production of electricity in Italy has been provided mainly by fossil fuel plants: steam power plants fueled by coal in the past and Combined Cycles Gas Turbine (*CCGT*) in recent years. In the early years of this century (2000 - 2008), many steam plants were revamped and upgraded to *CCGT* power plants and new plants with this technology were built. *CCGT* power plants became by far the most common technology in the country, with benefits in term of *GHG* emissions, fuel consumption and flexibility of the generation side. The situation of fossil fuel power plants at 2014 is reported in Figure 3.1, where single power plants are shown, considering geographical position, technology adopted and installed capacity and in Figure 3.2, where the installed capacity of *CCGT* and of fossil units is reported in the various regions.
In order to perform the time-dependent analysis of fossil fuel power plants transient operations, is fundamental to gather data on the installed capacity and the spatial distributions along the Italian territory of these power units. The data are collected from *Terna* and *GSE* (Gestore dei Servizi Energetici) and are set as input for *Oemof_Transient* model.
In Table 3.1 the installed capacity of fossil fuel power plants is reported along the Italian territory divided per macro-region and per technology. It is possible to notice that the majority of installed capacity consist of *CCGT* power plants. The results obtained with the optimizations performed by *Oemof_Transient* model, that consist in the optimal schedule of fossil fuel power plants considering also transient operations, have to be consistent with the real production from these power units in order to validate the model and obtain affordable results: thus data on the yearly electricity generated and the equivalent hours are collected and reported in Table 3.2 and Figure 3.3. It is possible to notice that the electricity generated from *CCGT* is over half of the total electricity produced by fossil fuel power plants.
The validation of *Oemof_Transient* model is obtained comparing the results of the optimization at 2014, in particular CO_2 emissions and electricity yearly balance, with the values of these quantities provided by *Terna* and by *ISPRA* (Istituto Superiore per la Protezione e la Ricerca Ambientale).

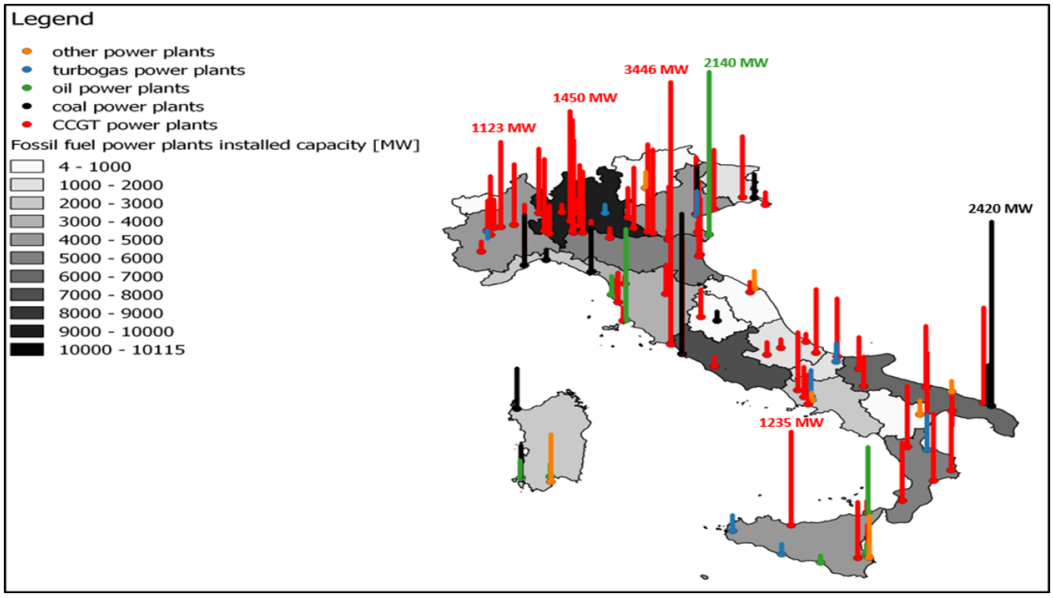

Figure 3.1: Installed capacity of fossil fuel power plants at 2014, considering single power units

Elaboration of Terna data [13]

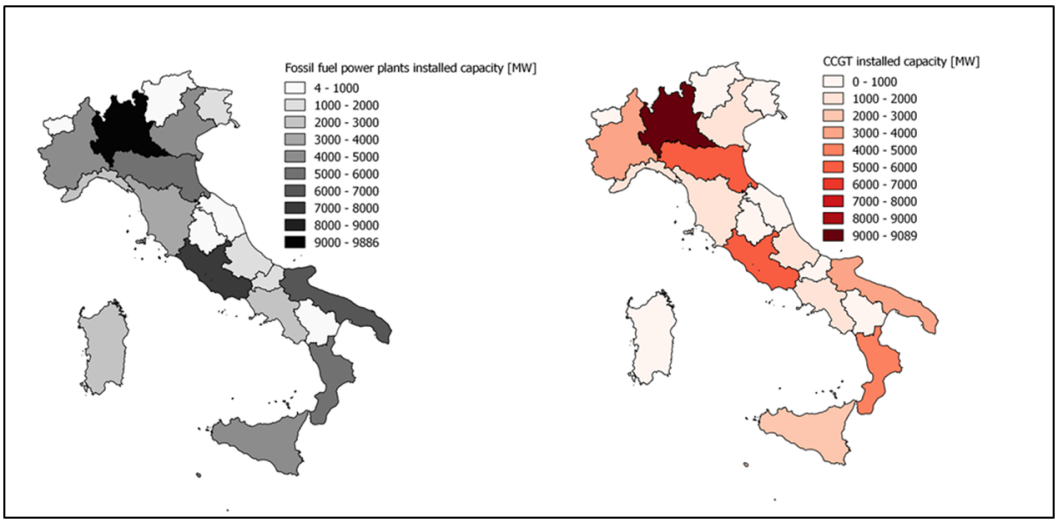

Figure 3.2: Installed capacity of fossil fuel power plants at 2014

Elaboration of Terna data [13]

Zone	CCGT	Gas power plants	Coal power plants	Oil power plants	Other power plants	tot
	[GW]	*[GW]*	*[GW]*	*[GW]*	*[GW]*	*[GW]*
NORTH	21.5	1.7	2.4	2.1	1.6	29.3
CNORTH	2.2	0	0.1	1.5	0.2	4.0
CSOUTH	8.7	0.4	1.8	0	0.1	11.0
SOUTH	8.6	1.0	2.9	0	0.6	13.1
SARDINIA	0	0	1.0	0.4	0.6	2.0
SICILY	2.6	0.4	0	1.1	0.6	4.6
tot	43.5	3.5	8.2	5.1	3.7	64

Table 3.1: Installed capacity of fossil fuel power plants per macro-region at 2014

Terna [13]

Power plants	Electricity generated	Installed capacity	Equivalent hours
	[TWh]	*[GW]*	*[h]*
CCGT	89.9	43.5	2067
Gas power plants	16.4	3.5	4753
Coal power plants	39.3	8.2	4784
Oil power plants	2.6	5.1	499
Other power plants	10.1	3.7	2694
tot	158.2	64.0	2472

Table 3.2: Characteristics of fossil fuel power plants at 2014

Terna [13]

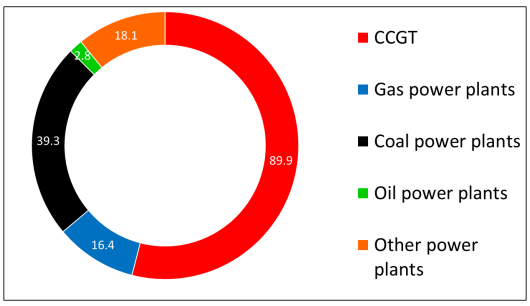

Figure 3.3: Electricity generated from fossil fuel power plants in 2014 *[TWh]*

Elaboration of Terna data [13]

3.1 *Oemof_Transient*: *Italy_2014* scenarios

The creation of *Italy_2014_CCGT* scenarios for *Oemof_Transient* model is the first step of the analysis performed in this thesis work and this scenarios are developed in order to validate the approach and assumptions and to evaluate the cycling costs in the actual configuration of the energy system.
In these scenarios is reported the configuration of the electricity sector for the Italian energy system at 2014; the data on electricity demand and production for every source are collected in the report of *GSE* (Gestore dei Servizi Energetici)[16–21], the managing authority of the energetic services, and *Terna*, the Italian transmission system operator (TSO), *Terna* [13, 15, 24, 25].
Table 3.3 summarizes the sources used in order to develop the scenarios in 2014.

Data	**Source**
Hourly distributions for *RES*	*Terna* [13, 15], *GSE*[16–21]
Installed capacity for *RES*	*Terna*[13, 15], *GSE*[21]
Installed capacity for fossil fuel power plants	*Terna* [13, 15, 24, 25]
Electricity demand	*Terna* [13]
Installed capacity for *PHS* technologies	*Terna* [13]

Table 3.3: Sources used for the development of *Italy_2014* scenarios for *Oemof_Transient* model

The structure of the electricity sector in *Oemof_Transient* model corresponds to the current configuration of Italian energy system: a multi-node approach is adopted, thus six macro-regions are implemented, that correspond to the actual configuration of the Italian electricity sector composed by six main zones defined by grid transmission capacities. Transmission losses are set equal to the 3% of the energy transferred from one node to the other.
The real configuration of the Italian electricity sector is reported in Figure 3.4, with transmission constraints in *[MW]*, and corresponds to the configuration adopted in *Oemof_Transient* to model the Italian electricity sector.
The multi-node approach is fundamental in order to do not underestimate cycling costs and curtailment from *VRES* (in scenarios at 2050) and do not overestimate the usage of storage technologies and thus obtain accurate and realistic results. These issues are particularly relevant for a territory like Italy, where the majority of the installed capacity of *VRES* is placed in the south while the *PHS* power plants are mainly located in the North. In the model are introduced the real regional distributions of *RES*, *PHS* installed capacities on Italian territory and grid transmission constraints
The scenarios for Italy at 2014 created for *Oemof_Transient* model are an accurate representation of the Italian electricity sector.

In *Oemof_Transient* the energy exchanges (import and export) with other nations are not considered, thus Italy is modeled as an isolate energy system and the total electricity demand is decreased by the value of annual import in order to obtain equivalent hours for fossil fuel power plants more similar to real ones. Import is not modeled because is difficult to associate value of CO_2 emissions to import of electricity, there are no hourly data available on import of electricity and the adoption of a constant distribution, would penalize renewable technologies that have a limited operating windows; indeed, the presence of a fixed amount of import, combined with the high production from *RES* in certain hours, would lead to high levels of excess electricity production.
In order to define the inputs for the electricity sector, the various technologies have to be distinguished: each technology requires specific parameters in order to be modeled in *Oemof*. For example, *VRES* plants are defined by their nominal capacity and their power output distribution, while fossil fuel power plants are defined by nominal capacity, efficiency, fuel consumed, constrains and so on.

Figure 3.4: Multi-node structure of Italian electricity sector in *Oemof_Transient*, with grid transmission constraints in *[MW]*

3.1.1 Renewable Energy Sources

RES are modeled in *Oemof_Transient* thought Source components (no inputs, many outputs), thus for each power unit is possible to set nominal installed capacity (maximum power output expressed in *[MW]*), time profile (through distributions that can be constant or variable in time) and fixed/variable costs. The costs of *RES* power plants are not set as optimization variable, but calculated a posteriori, so that the optimization is only affected by fossil fuel power plants costs and their optimal schedule is obtained as result. Equation (2.5) allow to evaluate the electricity generated from a *RES* at time t and is obtained multiplying the installed capacity by the value of time distribution at time t.
The plants exploiting *RES* considered for this work are: *PV* modules, wind turbines, run-off-river hydro, geothermal, hydro-reservoir and biomass power plants.
In order to define these power plants presented, both data on yearly installed capacity and hourly production for each source have been investigated. Data on installed capacity and the equivalent hours have been taken from the statistic report on renewable energy in Italy [16–21] published by *GSE*, the main authority in the country for themes such as renewable energy. Hourly data for production from *RES*, used to create the distribution profile of electricity production from the various sources, are obtained from *Terna*, Italian grid operator, which provides a web-available transparency report [13], where excel files containing hourly power generation from each source in the various regions are published each day.
However, in order use this data to create the time distribution used as input for *Oemof_Transient* model, the database downloaded from *Terna*'s website has to undergo some fixes. These data are not complete: one day, the 11th of June, is missing, thus to overcome this problem, the production of the previous day has been copied. Furthermore the clock changes in autumn and spring provoke error in the data, in particular on March, 29th the data from 2 A.M. to 3 A.M. are missing (the problem has been fixed by copying the production of the previous hour) and on October, 25th, the hour between 2 A.M. and 3 A.M. includes data on two hours instead of one (the problem has been solved by halving the electricity produced from each source in that hour). The approximations introduced by this operations should not impact the modeling much, given that in these hours electricity production and consumption are usually quite low.
The values of time distributions, which represent the available electricity production in each hour of the year from the various *RES*, are set as input for the model and consist in array with 8760 values contained between 0 (*RES* not available) and 1 (full production), depending on percentage of the power output respect to the installed capacity (nominal power).
The time distributions are calculated combining the data on hourly electricity generation from each *RES* [13], with data on installed capacity [15] and equivalent hours [16–21].

To find the distribution values that are the expressions only of the availability of the sources, the hourly data from *Terna*[13] are modified to consider that the installed capacity of *RES* increase during the year; thus a linear increase of the installed capacity for each source has been assumed, starting from the values related to the end of 2013 and arriving to the ones at the end of 2014. These data are provided by the *GSE* reports [20][21]. The value of installed capacity in each hourly time-step t has then been computed with the following equation (3.1):

$$I(t) = I(t-1) + t \cdot \frac{I(2014) - I(2013)}{8760} \tag{3.1}$$

The production from each source in each hour has then been rescaled to take into account of such increase in installed capacity (Equation 3.2):

$$Prod(t)^{fixed} = Prod(t)^{raw} \cdot \frac{I(2014)}{I(t)} \tag{3.2}$$

The obtained value of production is therefore equal to the equivalent power output that would have been produced in that hourly time-step by the total capacity installed at the end of the year. The value of hourly production is calculated considering a normalization over the installed power of 2014 and 2013. The result is a distribution consistent with the data of the national grid operator (*Terna*) and that represents the average availability of the renewable source over the year, considering the growth of installed power.
In order to obtain accurate distributions other calculations have to be implemented. *GSE* provides statistical reports about renewable energy every year [16–21], that gives detailed informations about the total annual production from renewable sources and in particular on the equivalent hours for each source. The data used in our model must be consistent with values of equivalent hours provided by *GSE*. The equivalent hours are the expression of how much energy can be obtained from a particular kind of plant with respect to the installed capacity of that plant: a value close to 8760 indicates that the plant has been able to produce at its nominal capacity for most of the time.

$$h_{eq} = \frac{\sum_{t=1}^{8760} Prod(t)}{I} \tag{3.3}$$

The method adopted to correct distributions for different values of equivalent hours is the one reported in EnergyPLAN documentation [10]. Such method, expressed in the Equation 3.4, is designed in order to ensure that the power output remains the same either at production equal to nominal capacity (i.e. full production) or at null production, while changing in the other hours according to a correction factor FAC_{RES}:

$$Prod_{(}t)^{fixed} = Prod(t)^{raw} \cdot \frac{1}{1 - FAC_{RES} \cdot (1 - Prod(t)^{raw})} \tag{3.4}$$

The correction factor FAC_{RES} has been determined in order to obtain a value of equivalent hours for the corrected distribution, calculated with Equation 3.3, equal to the values taken from *GSE* reports. In order to evaluate the functioning of *RES* over the year in the most accurate way, the value of equivalent hours for each renewable source used for the definition of the hourly production is not the value of equivalent hours of 2014, but the mean of the values of equivalent hours of 2014 and of the previous five years (from 2009 to 2014).
Once the on about hourly production have been handled and fixed accordingly to the above explanation, the hourly distribution for power output from *RES* can be easily obtained dividing the production data by the nominal installed capacity of each technology as expressed in Equation 3.5:

$$distr(t) = \frac{Prod(t)}{I(2014)} \tag{3.5}$$

In this way it is possible to obtain an array of 8760 elements for each *RES* power plants. This formulation allows to decouple the production from today capacity, and therefore to scale the distribution on any possible future value of installed capacity.

PhotoVoltaic panels

PV panels represent the most relevant *VRES* technology in the Italian energy system, with 18.61 *GW* of installed capacity in 2014 [21]. The values of installed capacity in the various macro-regions are reported in Table 3.4 and set as input for the model.
The high reliability of *PV* modules on the solar radiation leads to typical seasonal and daily profiles for power production, with null production during night, power output peaks in the middle of the day and generally higher output in summer than in winter.
The time distributions of *PV* in the six macro-region of the Italian multi-node energy system are reported in Figure 3.5. From the distribution, is possible to notice the fluctuating behavior of the source. The peak of production is in summer.
The time-distributions along with of installed capacity in various macro-region are the input data for the model.

Wind turbines

Wind turbines are the other *VRES* technology present in Italy, that in 2014 had 8.70 *GW* of on-shore wind power at its disposal, while offshore applications are still not employed in the country. The values of installed capacity in the various macro-regions are reported in Table 3.5 and set as input for the model. Figure 3.6 shows the time distributions for Wind turbines in the six macro-region of Italy. As it can be noticed, this kind of *RES* present a marked seasonal cycle which presents higher values in winter, opposite to the solar *PV* one.

Geothermal

Geothermal power plants present high value of equivalent hours thanks to the high availability of geothermal heat sources (where a gradient anomaly is present). The output of geothermal power plants is much more stable than the one of the other technologies afore-mentioned, and does not present any seasonal cycle; because of that the geothermal source is not a *VRES*.
Italy present 0.82 *GW* of installed capacity of Geothermal power plants in 2014, as reported in Table 3.6. These data are set as input for the model. As can be noticed this technology is only present in one macro-region, indeed the only power plants are located in Tuscany.

Biomass

According to *Terna* [24] and *GSE* [21], the installed capacity of various kind of biomass power plants in 2014 in Italy was of 4.04 *GW*. The values of installed capacity in the various macro-regions are reported in Table 3.7 and set as input for the model.
Biomass power plants are modeled with a constant time distributions over the year, so that the yearly electricity produced correspond to the values present *GSE* report [21].

Run-off-river hydro

One big distinction when dealing with hydro-electricity is between reservoir plants and run-off-river plants (although many other categories are usually considered in between these two): a reservoir plants makes use of a basin in order to store water, that can be made flow through the turbine, while a run-off-river plant consists in turbines that exploit the river flow, and therefore its output can be controlled acting on the turbine itself. While reservoir plants implementation will be described in the next section, here the focus is on run-off-river plants, which are characterized by an intermittent power output.
GSE only provides data on hydro-electric plants as a whole, but *Terna* states in its 2014 annual capacity report that 5.06 *GW* of run-off-river plants were

available in Italy in that year [24]. The values of installed capacity in the various macro-regions are reported in Table 3.8 and set as input for the model.
In Figure 3.7 are reported the time distributions in the six macro-region of the Italian multi-node energy system. From the distribution, is possible to notice that the plants output is higher in spring than in the rest of the year.
The time-distributions along with the values of installed capacity in various macro-region are set as input for the model.

Hydro-reservoir

According to *Terna*, Italian energy system relies on 6.06 GW of hydro-reservoir plants, mainly located in the northern region. The values of installed capacity in the various macro-regions are reported in Table 3.9 and set as input for the model. These plants have represented the backbone of the national energy system for the first half of the 20th century.
Hydro reservoir plants are hydro power plants with the possibility of storage of water. This characteristic makes the production of this plants not intermittent, thus is possible to regulate the water flow employing storage of water under certain constraints.
Due to this characteristic hydro-reservoir power plants have been modeled setting installed capacity (Table 3.9) and maximum value of energy generated over a year equal to the value provided by *Terna*.

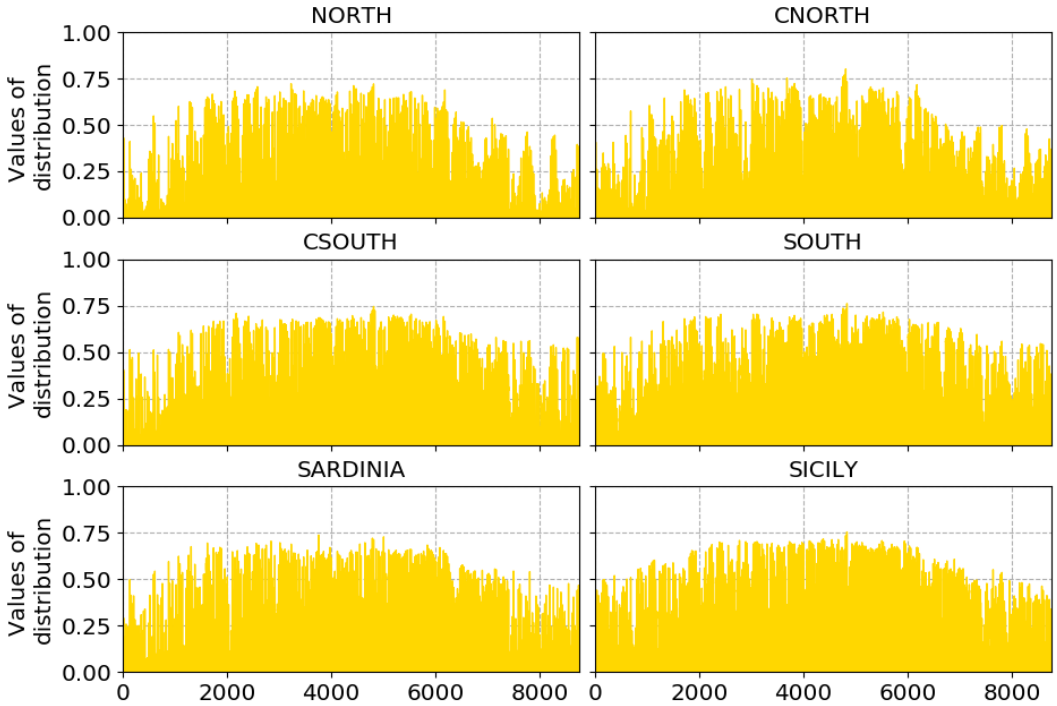

Figure 3.5: *PV* time distributions in the various macro-regions

Elaboration of *Terna* [13] and *GSE* [16–21] data

Zone	**PV**
	[GW]
NORTH	8.16
CNORTH	2.24
CSOUTH	2.61
SOUTH	3.59
SARDINIA	1.30
SICILY	0.72
tot	18.61

Table 3.4: Installed capacity of *PV* per macro-region in *Italy_2014* scenarios

GSE [21]

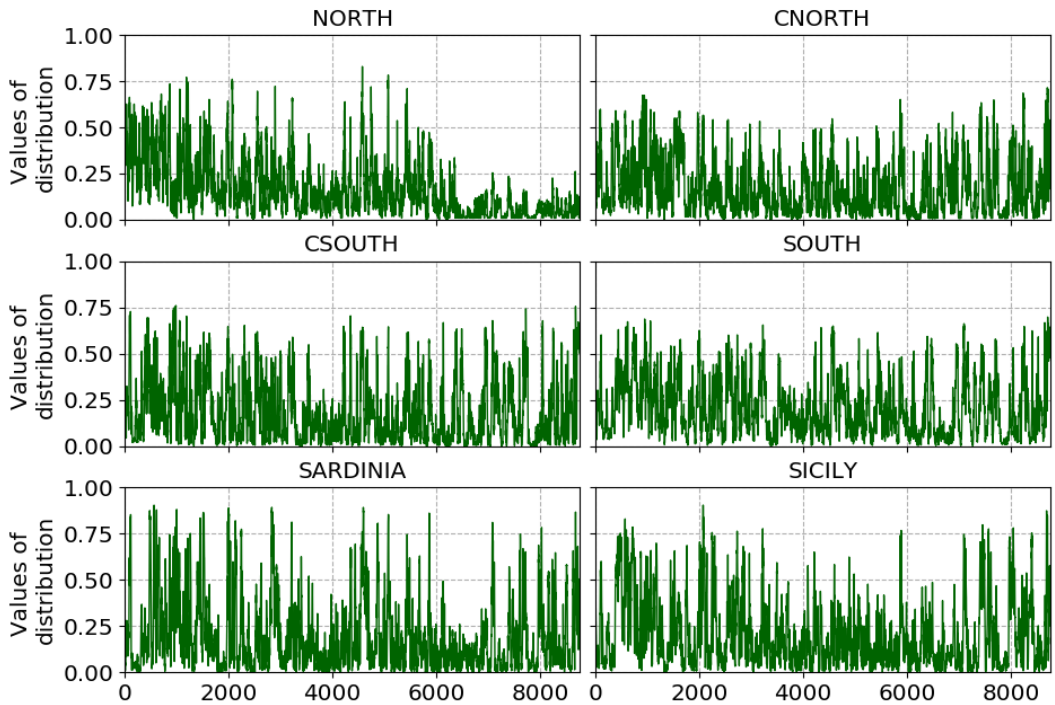

Figure 3.6: Wind turbines time distributions in the various macro-regions

Elaboration of *Terna* [13] and *GSE* [16–21] data

Zone	**Wind turbines**
	[GW]
NORTH	0.11
CNORTH	0.13
CSOUTH	1.53
SOUTH	4.18
SARDINIA	1.00
SICILY	1.75
tot	8.70

Table 3.5: Installed capacity of Wind turbines per macro-region in *Italy_2014* scenarios

GSE [21]

Zone	Geothermal
	[GW]
NORTH	0
CNORTH	0.82
CSOUTH	0
SOUTH	0
SARDINIA	0
SICILY	0
tot	0.82

Table 3.6: Installed capacity of Geothermal power plants per macro-region in *Italy_2014* scenarios

GSE [21]

Zone	Biomass
	[GW]
NORTH	2.51
CNORTH	0.28
CSOUTH	0.48
SOUTH	0.61
SARDINIA	0.09
SICILY	0.07
tot	4.04

Table 3.7: Installed capacity of Biomass power plants per macro-region in *Italy_2014* scenarios

GSE [21]

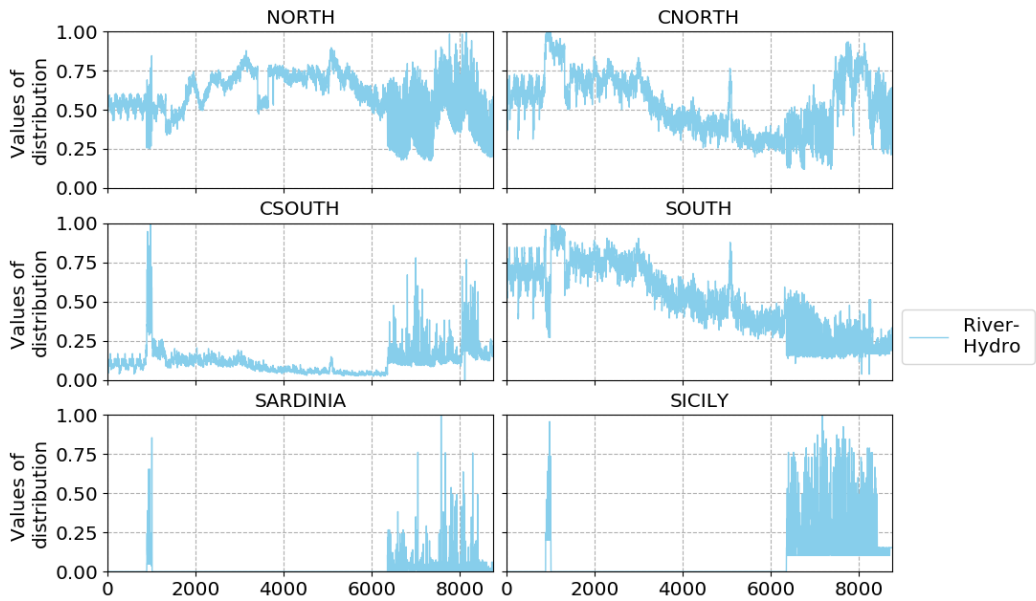

Figure 3.7: Run-off-river hydro time distributions in the various macro-regions

Elaboration of *Terna* [13] and *GSE* [16–21] data

Zone	**Run-off-river hydro**
	[GW]
NORTH	3.83
CNORTH	0.31
CSOUTH	0.49
SOUTH	0.26
SARDINIA	0.13
SICILY	0.04
tot	5.06

Table 3.8: Installed capacity of Run-off-river hydro per macro-region in *Italy_2014* scenarios

Terna [24]

Zone	**Hydro-reservoir**
	[GW]
NORTH	5.14
CNORTH	0.52
CSOUTH	0.21
SOUTH	0.11
SARDINIA	0.06
SICILY	0.02
tot	6.06

Table 3.9: Installed capacity of Hydro-reservoir per macro-region in *Italy_2014* scenarios

Terna [24]

3.1.2 Fossil fuel power plants

Thermoelectric power plants are dominated by *CCGT* technologies, that covers almost the 60% of the Italian conventional generation in 2014 [25], as is reported in Figure 3.3 . The remaining part is composed manly by oil and coal power plants, that are going to be decommissioned, according to the set plan, before 2030 [14].
In the analysis performed in this work, two different configurations of fossil fuel power units are considered for scenarios in 2014: one where fossil fuel power plants are modeled using different technologies (named *Italy_2014* scenario) and the other scenario where only *CCGT* power plants are introduced (this scenarios, named *Italy_2014_CCGT*) is created for comparison with *Italy_2050* scenarios, where a complete phase-out from coal fueled power plants is assumed and the other scenario, created to validate the model, where also other fossil fuel power plants are considered in addition to *CCGT*.

Combined cycle gas turbines

CCGT are modeled through Transformer components (one input, one output), that receive fuel as input and produce electricity. The following parameters are set as input for each *CCGT*: nominal installed capacity (maximum possible power output expressed in *MW*), technical minimum, nominal efficiency, natural gas cost and constraints for time-dependent transient analysis. *CCGT* power plants have to maintain the energy system in balance, by increasing/decreasing power output, in order to fill the gap between generation and consumption of electricity. The constraints applied to *CCGT* in order to characterize their transient operations are the ones described in the previous chapter: time-dependent ramp constraints at start-up, time-depended start-up costs and decay of efficiency out of nominal condition.
The strong assumption introduced in this analysis is that all the *CCGT* on the Italian territory are equal to a reference power plant. This is a simplification of the problem, but allows to evaluate costs and emissions related to the intermittent use of thermoelectric power plants in reasonable amount of time. Thus differentiating the *CCGT* would complicate the optimization problem leading to higher computational time. Technical characteristics and operative constraints of the *CCGT* selected as reference power plant, are reported in Table 2.2. This technology is equipped with the gas turbine *Mitsubishi M501G/fast*, an extremely flexible gas turbine able to adapt to intermittent working conditions and characterized by fast ramp rate at the start-up. The efficiency of the plant has been set at 55%, a more conservative value than the 59% presented in [50]. Three different types of start are defined by the hours of stop of the plant: cold start, warm start and hot start. Due to the hourly time-step resolution adopted in the optimization and given the ramp rate that characterized the different type of start-up of the reference *CCGT*, only one ramp constraint is introduced (cold start), because in case of a hot and warm start the maximum power is

available in one hour. The decay of efficiency during partial load operations is modeled introducing a linear interpolation (Figure 2.9).
The costs related to the different types of start of *CCGT* are difficult to define; they depend on: the model used for the calculations and the assumptions made. For these reasons in literature are reported different values; in Table 2.1 are listed the start-up costs introduced in the model that are the one reported in three different studies on *CCGT*: the optimistic scenario with lowest start-up costs [26] (named Best case), the scenario with medium start-up costs [27] (named Average case) and the pessimistic scenario with higher star-up costs [5] (named Worst case). Thus for each configuration of the energy system three different optimizations (one for each scenario) are performed changing start-up costs and leaving unchanged the other constraints and parameters.
The optimization of the dispatch of electricity on the Italian territory is performed considering only the cost of natural gas (Table 2.2) and the cycling costs introduced by the constraints created to represent transient operations of *CCGT* (Table 2.1), so that the optimal schedule of fossil fuel power plants is obtained as results. The costs related to the various technologies are not included in the optimization, but calculated a posteriori.
According to *Terna*, the Italian energy system relies on 43.5 *GW* of *CCGT* in 2014, mainly located in the northern region Table 3.1. The values of installed capacity and the number of power plants in the various macro-regions (input for the model), are obtained starting from the real value of installed capacity of *CCGT* (Table 3.1) and considering that the size of a single power plants is 400 *MW* (Table 2.2); thus in the model are introduced 110 *CCGT* power plants amounting to 44 *GW*, as reported in Table 3.10.

Zone	***CCGT***	**Number of *CCGT***
	[GW]	
NORTH	20.0	50
CNORTH	2.0	5
CSOUTH	8.8	22
SOUTH	8.8	22
SARDINIA	2.0	5
SICILY	2.4	6
tot	44	110

Table 3.10: Installed capacity and number of *CCGT* per macro-region in *Italy_2014* scenarios

Terna [13]

Other fossil fuel power plants

In *Italy_2014* scenario are introduced other technologies for fossil fuel power plants in addition to *CCGT*, in order to validate the results of the model at 2014.
Fossil fuel power plants are modeled through Transformer components (one input, one output), that receive fuel as input and produce electricity.
In this thesis work the analysis of transient operations is performed only for *CCGT*; power plants that use coal and oil are not included in this analysis. They require long time for start-up and are not suited for intermittent working conditions. Thus for these fossil fuel power plants is set a constant electricity production during the year.
For each fossil power unit is set as input the nominal installed capacity and a constant time distribution, so that the yearly electricity production in each macro-region is equal to the value provided by *Terna* [13] in 2014 (Table 3.2) for the various power plants reported in Table 3.11. For each fossil power unit is also set the nominal efficiency, that is calculated with Equation 3.6, as the weighted average of nominal efficiencies to yearly production of the different technologies, obtaining a nominal efficiency equal to 37%, as reported in Table 3.11. (Same procedure to calculate the average CO_2 emission factor).

$$\eta_{Average} = \frac{P_{Coal} * \eta_{Coal} + P_{Oil} * \eta_{Oil} + P_{Gas} * \eta_{Gas} + P_{Other} * \eta_{Other}}{P_{Coal} + P_{Oil} + P_{Gas} + P_{Other}} \tag{3.6}$$

Power plants	**Fuel**	**Efficiency**	**CO_2 emission factor**
		[%]	*[kg/MWh]*
Gas power plants	Natural Gas	36	204.8
Coal power plants	Coal	39	354.6
Oil power plants	Oil	35	262.2
Other power plants	Other	32	256.7
Average values		37	300.8

Table 3.11: CO_2 emission factor for the various technologies

[52]

3.1.3 Electricity demand

Electricity demand is modeled through Source components that dissipate part of the electricity generated in each node of the energy system. The electricity demand in each time-step during the year is set as input data for the model and is obtained with Equation (2.2) by multiplying the value of time distribution at time t by a fictitious value of installed capacity (Table 3.12). The time distribution for electricity demand are obtained with Equation 3.7 starting from *Terna* data [13]. The fictitious value of installed capacity (in Table 3.12) are calculated considering the time distribution and that the total electricity demand during a year is equal 263.8 TWh, value obtained by subtracting annual import from total electricity demand in 2014.

$$distr(t) = \frac{D(t)}{MAX\,(D(t))} \tag{3.7}$$

Zone	**Electricity demand**
	[GW]
NORTH	22.74
CNORTH	6.93
CSOUTH	8.53
SOUTH	8.53
SARDINIA	2.33
SICILY	3.28
tot	52.34

Table 3.12: Fictitious installed capacity of Electricity demand per macro-region in *Italy_2014* scenarios

Terna [24]

3.1.4 Storage

Storage technologies are introduced in the model in order to store the excess of electricity generated from *RES*.
These technologies are modeled in *Oemof_Transient* through Generic Storage components (one input, one output), that allow to store the excess of electricity. For each Storage technology is possible to set the nominal installed capacity(maximum amount of energy that can be stored expressed in *MWh*), inflow conversion factor, maximum power inflow to storage, outflow conversion factor, maximum power outflow from storage, capacity loss and fixed/variable costs. The costs related to these technologies are not set as optimization variables, but calculated after the optimization.
The storage technology introduced in the model for *Italy_2014* scenarios is *PHS* with the function of storing excess of electricity when overproduction from *RES* occurs and give it back when needed.

Pumped Hydro Storage

Pumped-hydro storage is a long-established technology for electricity storage and consists essentially in two water basins, located at different heights, connected by penstocks. Water can be pumped up the penstocks in the upper basin when overproduction from *VRES* is verified and then, when electricity is needed, the water is made flow through turbines back to the lower one, generating electricity.
For the strict requirements in terms of location, that has to be naturally suitable for the realization of the two basins, and for other issues related for example to landscape conservation, this kind of storage plants has stopped growing decades ago, having saturated their potential on Italian territory. New storage applications will have to employ different technologies. Still, pumped-hydro plants will play a more and more relevant role in a future dominated by intermittent *RES* technologies for power production.
In Italy, pumped-hydro storage capacity is equal to 700.76 *GWh*, with 6.18 *GW* of pumps and 7.82 *GW* of turbines installed. The values of installed storage capacity, inflow conversion factor, maximum power inflow to storage (pump), outflow conversion factor and maximum power outflow from storage (turbine) in the various macro-regions are reported in Table 3.13 and set as input for the model.

Zone	Storage capacity	Charge capacity (Pump)	Discharge capacity (Turbine)	Inflow conversion factor	Outflow conversion factor
	[GWh]	*[GW]*	*[GW]*	*[%]*	*[%]*
NORTH	446.7	3.94	4.98	85	90
CNORTH	25.7	0.23	0.29	85	90
CSOUTH	160.5	1.41	1.79	85	90
SOUTH	0	0	0	85	90
SARDINIA	22.0	0.19	0.25	85	90
SICILY	45.8	0.40	0.51	85	90
tot	700.76	6.18	7.82		

Table 3.13: Installed capacity and characteristics of Pumped Hydro Storage power plants per macro-region in *Italy_2014* scenarios

Terna [24], [53]

3.1.5 Validation of the model

The results of the optimizations performed by *Oemof_Transient* model for *Italy_2014* scenario have to be consistent with the data on Italian electricity sector, in order to prove the validity and the reliability of the methodology adopted in the analysis conduced in this thesis work.
Oemof_Transient model is validated by comparing the results of the optimization for 2014 with the actual values of CO_2 emissions and electricity generation provided by *Terna*, *ISPRA*, *IEA* and *World Bank*.
In Table 3.14 it is reported the energy balance provided by *Terna* for the Italian electricity sector in 2014 and the balance obtained as result of the optimization performed by *Oemof_Transient* on *Italy_2014* scenario. There are small differences between real data and optimization's results due to the hypothesis and approximations introduced in the implementation of the model: the electricity generation from *RES* are slightly different in the two cases because of the normalizations that have been introduced. Time distributions of renewable sources have been normalized in order to obtain values not influenced by the contingency of the conditions of the sources over the year and by the increase of installed power. The equivalent hours consider the mean of the values of equivalent hours of 2014 and of the previous five years (from 2009 to 2014). Moreover energy exchanges (import and export) with other nations are not implemented in the model (Italy is modeled as an isolate energy system). Considering the assumptions and approximation introduced, the results of the optimization are consistent with the data on the Italian energy system provided by *Terna*, thus the percentages values of electricity generation from the various sources (Figure 3.8 and Figure 3.9) are very similar.
The CO_2 emissions are connected to electricity generation from thermoelectric power plants, due to the content of carbon in the fuel. The annual CO_2 emissions for *Italy_2014* scenario are reported in Table 3.15 along with the data on Italian electricity sector for 2014 provided by *Terna* and *ISPRA*; these values are very close, so is possible to conclude that the results of the optimization are in accordance with the real data. In Table 3.15 are also reported the annual CO_2 emissions for the whole Italian energy system gathered from international agencies' database (*IEA* and *World Bank*), that are much than three times greater than the ones related to the electricity sector alone.
In Table 3.16 the characteristics of the generation from *CCGT* are reported for Italy in 2014: by comparing the data provided by *Terna* with the results of the model for *Italy_2014* scenario, it can be concluded that the production from *CCGT* obtained from the model is very similar to the real one. The number of starts per power plant per year is reasonable and corresponds to about one start-up every two days on average. In *Italy_2014_CCGT* scenario fossil fuel power plants are modeled only by *CCGT*, thus the equivalent hours are higher respect to *Italy_2014* scenario.

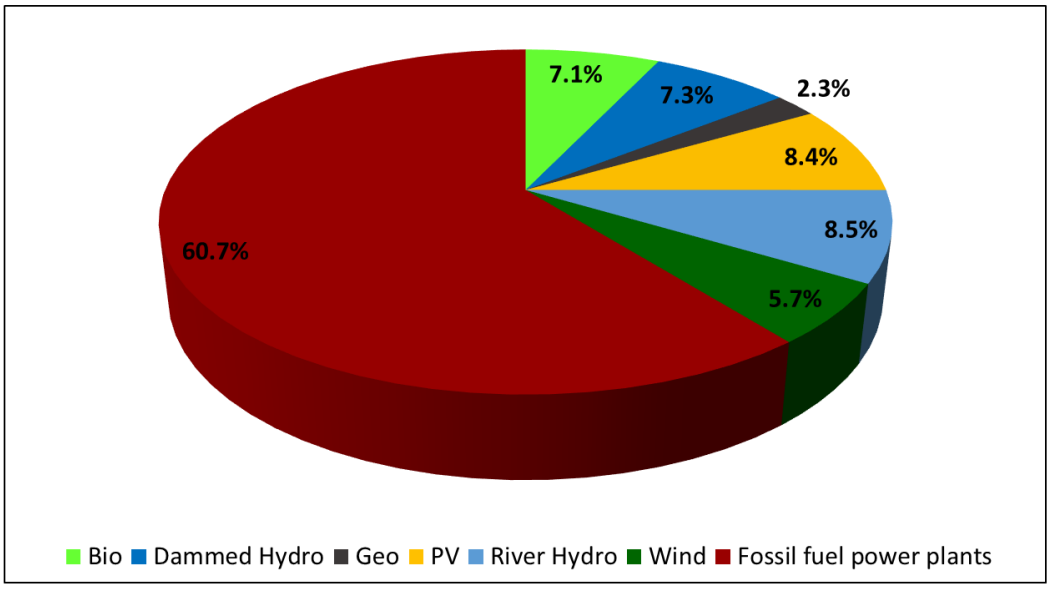

Figure 3.8: *Oemof_Transient* optimization results: annual electricity generation from the various technologies in *Italy_2014* scenario

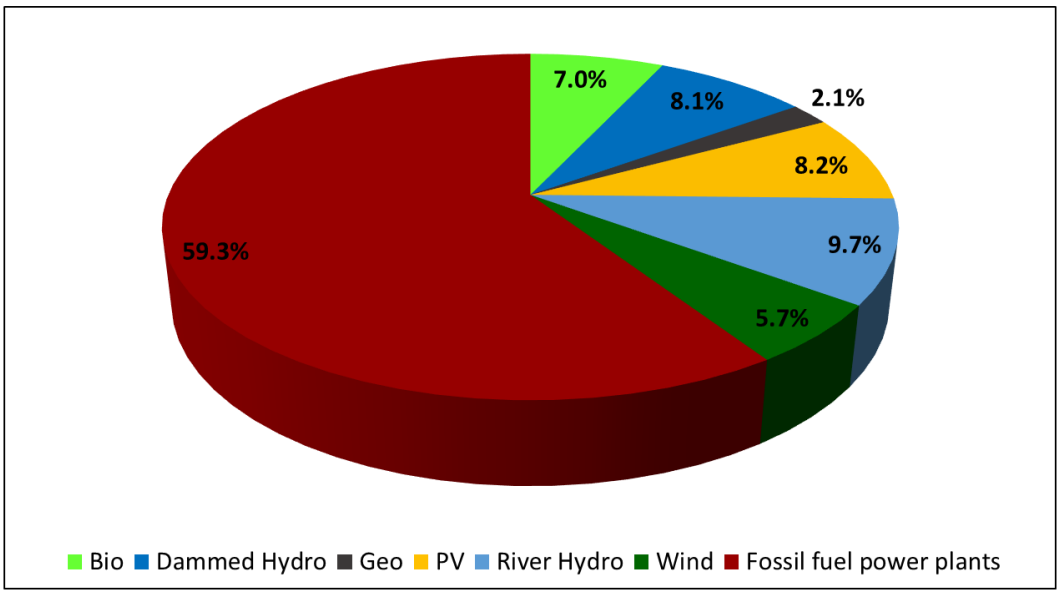

Figure 3.9: *Terna* data: annual electricity generation from the various technologies in 2014

Elaboration of *Terna* [13] data

	Terna *[TWh]*	***Oemof_Transient*: *Italy_2014* scenario** *[TWh]*
Electricity demand	**310.5**	**263.8**
Import	-46.8	0
tot	**263.8**	**263.8**
Biomass	18.7	18.7
Dammed Hydro	21.5	19.3
Geo	5.6	5.9
PV	21.8	22.1
River Hydro	25.9	22.5
Wind turbines	15.1	15.2
Fossil fuel power plants	158.2	160.4
tot	**266.8**	**264.1**
Export	-3.03	0
Transmission losses (model)		-0.3
tot	**263.8**	**263.8**

Table 3.14: Annual energy balances for Italy in 2014: *Oemof_Transient* results vs *Terna* data

[13]

	Annual CO_2 emissions *[Mt]*
Italian Energy system	
World Bank	320.4
Internal Energy Agency	319.8
Italian Electricity sector	
Terna	88.6
ISPRA	90.1
Oemof_Transient: *Italy_2014* scenario	89.7

Table 3.15: Annual CO_2 emissions for Italy in 2014: *Oemof_Transient* results vs *Terna*, *ISPRA*, World Bank and *IEA* data

Terna [13], *ISPRA* [54], World Bank [55], *IEA* [56]

Characteristics of *CCGT*		***Terna* 2014**	***Italy* *2014***	***Italy* *2014_CCGT***
Installed capacity	*[GW]*	43.5	44.0	44.0
Annual electricity generated	*[TWh]*	89.9	92.1	160.4
Equivalent hours	*[h]*	2067	2093	3645
Number of starts per power plant per year (Average case)	*[ ]*	150-200*	168	189

Table 3.16: Characteristics of the generation from *CCGT* for Italy in 2014: *Oemof_Transient* results for *Italy_2014* and *Italy_2014_CCGT* scenarios vs *Terna* [13].

* These values have been assumed

3.2 *Oemof_Transient*: *Italy_2050* scenarios

In order to evaluate the impact of fossil fuel power plants transient operations in configuration of the energy system with higher *VRES* installed capacity, new scenarios (named *Italy_2050*) for the Italian energy system are introduced.
The structure of the the Italian electricity sector in *Italy_2050* scenarios is the same adopted in *Italy_2014* scenarios (Figure 3.4): multi-node energy system (six macro-regions), grid transmission capacities, no exchange with other nations.
Italy_2050 scenarios are implemented starting from the scenario for Italy at 2014 and creating new scenarios varying the installed capacity of *VRES* technologies (*PV* and wind turbines) up to their maximum potential. These data on maximum potential of *VRES* installed capacity are obtained from two different studies: [22] for *PV* and [23] wind technologies.
In particular four scenarios are created (where '*%*' indicates the percentage of *VRES* installed capacity respect maximum potential): *VRES_25%*, *VRES_50%*, *VRES_75%* and *VRES_100%*.
In *Italy_2050* scenarios is assumed a complete phase-out from coal fueled power plants in order to reduce CO_2 emissions (as reported in [14]), thus only *CCGT* power plants are considered in the model.
The data on electricity demand and electricity generation from the various power plant are collected in the report of *GSE* (Gestore dei Servizi Energetici)[16–21], the managing authority of the energetic services, and *Terna*, Italian *TSO*, *Terna* [13, 15, 24, 25].
Table 3.17 summarizes the sources used in order to develop the *Italy_2050* scenarios, while in Table 3.18 are reported the configurations of the Italian energy system evaluated through the optimizations performed by *Oemof_Transient*.

Data	**Source**
Hourly distributions for *RES*	*Terna* [13, 15], *GSE*[16–21]
Installed capacity for *RES*	*Terna*[13, 15], *GSE*[21]
Maximum potential for *VRES* installed capacity	[22], [23]
Installed capacity for fossil fuel power plants	*Terna* [13, 15, 24, 25]
Electricity demand	*Terna* [13]
Installed capacity for *PHS* technologies	*Terna* [13]

Table 3.17: Sources used for the development of *Italy_2050* scenarios for *Oemof_Transient* model

Scenarios	***VRES* installed capacity**	**Fossil fuel power plants**
Italy_2014	*Terna*'s data in 2014	all technologies
Italy_2014_CCGT	*Terna*'s data in 2014	only *CCGT*
Italy_2050_VRES_25%	25% of $VRES_{\max}$	only *CCGT*
Italy_2050_VRES_50%	50% of $VRES_{\max}$	only *CCGT*
Italy_2050_VRES_75%	75% of $VRES_{\max}$	only *CCGT*
Italy_2050_VRES_100%	$VRES_{\max}$	only *CCGT*
$\boldsymbol{VRES_{\max}}$	***PV*** *[GW]* 121	**Wind** *[GW]* 49

Table 3.18: Configurations evaluated with *Oemof_Transient* model

3.2.1 Renewable Energy Sources

RES are introduced in the model adopting the same methodology described before for *Italy_2014* scenarios: these power units are modeled through Source components and the same data of *Italy_2014* scenarios are set as input, except for *VRES* (*PV* and wind) installed capacity.
Four different configurations of the energy system are introduced for *Italy_2050* scenarios: *VRES_25%*, *VRES_50%*, *VRES_75%* and *VRES_100%*. These configurations are obtained setting different values of *PV* and wind turbines installed capacity, on the basis of the percentage of *VRES* installed capacity respect to maximum potential.

Photo-Voltaic panels

In this analysis , the *PV* technology considered for *Italy_2050* scenarios is rooftop *PV*. Ground mounted *PV* presents problems related to the availability of space and consume of agricultural and urban land; these argumentations have convinced the Italian government to discourage the installations of ground mounted *PV* with the law decree #1, 2012 January, 24th [57].
The maximum available potential for rooftop *PV* application has been estimated by Taylor et al. [22] as 2 *kW* per capita; thus for Italy the maximum potential for *PV* technologies corresponds to 121.5 *GW*.
The values of *PV* installed capacity in the various macro-regions for *Italy_2050* scenarios are reported in Table 3.19 and set as input for the model. The time distributions of *PV* in the six macro-region of the Italian multi-node energy system are the same adopted in *Italy_2014* scenarios (Figure 3.5).

Wind turbines

The maximum potential for on-shore wind installation in Italy has been provided by Hoefnagels et al. [23], in the framework of the European project *RE-Shaping*, and it is equal to 49 *GW*. The assumption of the *Re-shaping* project is to replace existing turbines with larger ones, therefore the potential distribution reflects the current installed power distribution.
Off-shore wind turbines installations are not adopted in Italy and is difficult to define a potential for the maximum installed capacity.
In this analysis only on-shore installations are considered. The values of Wind turbines installed capacity in the various macro-regions for *Italy_2050* scenarios are reported in Table 3.20. The time distributions for Wind turbines are the same adopted in *Italy_2014* scenarios (Figure 3.6).

Geothermal

Modeled as in *Italy_2014* scenarios.

Biomass

Modeled as in *Italy_2014* scenarios.

Run-off-river hydro

Modeled as in *Italy_2014* scenarios.

Hydro-reservoir

Modeled as in *Italy_2014* scenarios.

Zone	***VRES 25%***	***VRES 50%***	***VRES 75%***	***VRES 100%***
	[GW]	*[GW]*	*[GW]*	*[GW]*
NORTH	13.89	27.78	41.67	55.56
CNORTH	3.10	6.20	9.30	12.40
CSOUTH	6.54	13.08	19.62	26.16
SOUTH	3.47	6.95	10.42	13.90
SARDINIA	0.83	1.66	2.49	3.33
SICILY	2.54	5.08	7.62	10.16
tot	30.38	60.75	91.13	121.51

Table 3.19: Installed capacity of *PV* per macro-region in *Italy_2050* scenarios

[22]

Zone	***VRES 25%***	***VRES 50%***	***VRES 75%***	***VRES 100%***
	[GW]	*[GW]*	*[GW]*	*[GW]*
NORTH	0.16	0.31	0.47	0.62
CNORTH	0.19	0.37	0.56	0.74
CSOUTH	2.16	4.31	6.47	8.63
SOUTH	5.89	11.78	17.67	23.56
SARDINIA	1.40	2.81	4.21	5.61
SICILY	2.46	4.92	7.38	9.84
tot	12.25	24.50	36.75	49

Table 3.20: Installed capacity of Wind turbines per macro-region in *Italy_2050* scenarios

[23]

3.2.2 Fossil fuel power plants

In *Italy_2050* scenarios is assumed a complete phase-out from coal fueled power plants, thus fossil fuel power plants are modeled only by *CCGT*.

CCGT

Modeled as in *Italy_2014* scenarios.

3.2.3 Electricity demand

Modeled as in *Italy_2014* scenarios.

3.2.4 Storage

Pumped Hydro Storage

Modeled as in *Italy_2014* scenarios.

3.3 Costs of technologies

The annual costs of technologies, that consist of annualized investment costs and *O&M*, are not considered in the optimization of the dispatch of electricity. Natural gas cost and cycling costs (decay of efficiency and start-up costs) are the only costs introduced in the optimization because the focus of the analysis performed in this thesis is on transient operations of fossil fuel power plants. The annual costs of technologies are calculated a posteriori with Equation (2.34) and the data in Table 3.21.

Technology	**Investment cost**	**Investment costs**	**Life-time**	**O&M costs**	**Interest rate**
	[€/kW]	*[€/kWh]*	*[years]*	*[%Inv]*	*[%]*
PV	1.8		25	2.1	3
Wind	1.3		20	3.1	3
Geothermal	4.6		30	3.5	3
River hydro	3.3		50	2.0	3
Hydro-reservoir	3.3		50	2.0	3
Biomass	2.1		35	3.3	3
CCGT	1.4		35	3.3	3
PHS pump	0.6		50	1.5	3
PHS		7.5	50	1.5	3
PHS turbine	0.6		50	1.5	3

Table 3.21: Costs of Technologies

[52]

3.4 Temporal resolution and time-horizon

In *Oemof_Transient* model is adopted an accurate temporal resolution, indeed the optimization of the dispatch of electricity is performed using an hourly time-step; this temporal resolution allow to evaluate with precision the behavior of technologies such as *VRES* and Storage and to adequately represent time-varying aspects of the energy system as transient operations of fossil fuel power plants. Adopting an hourly time-step in modeling of energy system with high generation from *VRES*, shows advantages over the approach in which the simulation of the year is created through characteristic days [58, 59].
With regard to the time-horizon (total number of time-steps of the optimization) a distinction is made: in the optimization without constraints on fossil fuel power plants the time-horizon is one year, in order to catch all the variability of *VRES* and only one optimization is performed, while in the case introducing time-dependent constraints on *CCGT* in the optimization, the time-horizon is reduced to one week due to computational time limitations and the year is composed performing different optimizations on selected weeks (four weeks to compose the year).
The implementation in *Oemof_Transient* model of time-dependent constraints (start-up costs, decay of efficiency and ramp constraints) to represent transient operations of fossil fuel power plants, turns the optimization in mixed-integer linear optimization problem, more complex to solve: memory usage and computational time rise exponentially, because for each time-steps additional variables are introduced, increasing the size of the problem. The computational time needed to performs an optimization depends on the size of the problem, that is a trade-off between technological details (number and complexity of constraints, number and size of power plants) and time characteristics (temporal resolution and time-horizon). High level of technological detail and of temporal resolution (or wide time-horizon) involves higher computational times, as reported in [58] and the two aspects are linked together; the constraints introduce new variables each time-step and thus as the total number of time-steps (time-horizon) increases, the number of variables introduced in the optimization is higher.
In the analysis performed in this thesis work, fossil fuel power plants are modeled with high technological detail: for each *CCGT* are set as input the characteristics of a reference power plant (Table 2.2, in particular the size of a single power plants is 400 MW and 110 *CCGT* are assumed for the Italian energy system) and different time-dependent constraints are introduced to correctly represent cycling operations. This high technological detail forces a reduction of the time-horizon in the optimizations with constraints on *CCGT*, in order to have reasonable computational times. So the time-horizon is reduced to one week and the year is composed performing four optimizations (one per season) on selected weeks.
The weeks have been selected so that the sum over the four weeks of the values

of electricity demand and production from the various technology best represent the year. In Table 3.22 are reported the results of the optimizations without constraints performed over the four selected weeks and over one year; in particular are highlighted the % errors respect to annual values introduced in the representation of the various technologies, that are lower than the 5%; these errors are calculated as percentage of annual values, with Equation (3.8) (where 'weeks' stands for the selected weeks and 'k' stands for the items in Table 3.22).

$$Error_{\mathrm{k,year,\%}} = \frac{\frac{365}{28} * \sum_{week}^{weeks} P_{\mathrm{k,week}} - P_{\mathrm{k,year}}}{P_{\mathrm{k,year}}} \tag{3.8}$$

Selected weeks	1/4 ÷ 8/4 1/7 ÷ 8/7 1/9 ÷ 8/9 1/12 ÷ 8/12			
	Electricity demand	***PV***	**Wind**	***CCGT***
Error respect annual values	2.54%	3.03%	-4.32%	3.22%

Table 3.22: Weeks selected for transient analysis

The optimizations with constraints on *CCGT* (time horizon reduced to one week and year composed by four weeks) are performed in order to evaluate the specific cycling costs of *CCGT* in the different configurations of the Italian energy system (*Italy_2014_CCGT* and *Italy_2050* scenarios) and is not possible to perform this analysis with a greater time horizon, due to computational time limitations.
The time-horizon of one week adopted in these optimizations allows to evaluate in an accurate way the specific cycling costs of *CCGT*, indeed by comparing the results of optimizations with different time horizons (one week and one month) the percentage change in specific cycling costs is lower than 1%, as reported in Table 3.23.

Time-horizons of optimization	**Specific cycling costs** [€/MWh]	**Specific decay of efficiency costs** [€/MWh]	**Specific start-up costs** [€/MWh]
1/7 ÷ 8/7	3.51	1.15	2.36
1/7 ÷ 1/8	3.48	1.14	2.34
Percentage change in specific cycling costs	0.85%	0.86%	0.85%

Table 3.23: Optimizations with different time-horizons for *Italy_2014_CCGT* scenario considering medium start-up costs (Average case)

Chapter 4

Optimizations results

In the previous chapter, assumptions and data required to design the Italian case-study have been presented. These information have been set as input for *Oemof_Transient* model. The model performs the optimal dispatch of electricity considering time-dependent constraints on fossil fuel power plants (start-up costs, decay of efficiency at partial load and ramp constraints), implemented in order to represent their transient operations.
The aim of the analysis performed in this thesis work is to evaluate the impact of fossil fuel power plants transient operations on electricity dispatch. In order to perform a complete analysis, different configurations of the Italian energy system are considered: *Italy_2014* and *Italy_2014_CCGT* scenarios, that are representative of the actual configuration of the Italian electricity sector and *Italy_2050* scenarios, where higher values of *VRES* installed capacity are introduced in the model. *Italy_2014* scenario is created to validate the model, thus all the different technology of fossil fuel power plants are considered; while in *Italy_2014_CCGT* scenario fossil fuel power plants are modeled only by *CCGT* and this scenario is developed for comparison with scenarios at 2050, where it assumed a complete phase-out from coal fueled power plants in order to reduce CO_2 emissions (as reported in [14]). In order to perform a complete analysis, the Italian energy system is evaluated also adopting a single node approach (without considering transmission losses and constraints) for the same configurations described above.
The next sections are organized as follow:

- **Impact of the time-dependent constraints created to model transient operations of fossil fuel power plant**: how the time-dependent constraints implemented in this thesis work affect the optimization dispatch problem.
- ***Italy_2014_CCGT* and *Italy_2050* scenarios**: comparison of the results for the various scenarios; in particular single node vs multi-node approach, CO_2 emissions, overproduction from *VRES* and cycling costs are analyzed in detail.

4.1 Impact of the time-dependent constraints created to model transient operations of fossil fuel power plants

Fossil fuel power plants are modeled in *Oemof* as fully-flexible units (power output can vary from zero to the maximum in one time-step) and the decay of performances during partial operations is not implemented.
In order to evaluate with higher technological detail the impact of fossil fuel power plants' transient operations on electricity dispatch, *Oemof* is enhanced; thus new constraints have been developed in this thesis work, that leads to the creation of *Oemof_Transient* model. The model created performs a time-dependent analysis of fossil fuel power plants' transient operations: this means that the constraints implemented introduce in the optimization additional costs, emissions and ramp rate of available power that, for each instant of time, are a function of the hours of stop and of the power output of the plant. In particular time-dependent start-up costs, time-dependent ramp constraints and decay of efficiency during partial load operations are introduced in the model. Start-up costs are set depending on the hours of stop of the plant (hot start, warm start and cold start are distinguished) and penalize the start-up of a unit; ramp constraints impose fixed amounts of available power at start-up based on the hours of stop of the plant, while the decay of efficiency at partial load penalizes the off-design working conditions by introducing in the optimization additional costs and emissions every time a power plant is not producing at full load (nominal power).
In Table 2.1 are reported the start-up costs introduced in the model: the optimistic scenario with low start-up costs [26] (named Best case), the scenario with medium start-up costs [27] (named Average case) and the pessimistic scenario with high start-up costs [5] (named Worst case). Thus for each configuration of the energy system three different optimizations (one for each scenario) are performed changing start-up costs and leaving unchanged the other constraints and parameters.
In Figure 4.1, 4.2, 4.3 and 4.4 (for a summer week in 2014) and Figure 4.5, 4.6, 4.7 and 4.8 (for a winter week in 2014) are reported the results of the optimizations for the three different scenarios (Best, Average and Worst case) considering the following constraints: three start-up costs (hot, warm and cold start), one ramp constraints and decay of efficiency at partial load. It is possible to notice from the graphs that changing the start-up costs, the constraints affect in different way the optimization dispatch problem: with low start-up costs (Best case) the constraint on the decay of efficiency at partial is the most influent, thus *CCGT* are forced to work at higher loads and so higher efficiency (Figure 4.4 for a summer week and Figure 4.8 for a winter week), the number of starts is higher and starts-up are more frequent (Figures 4.1, 4.2, 4.3 for a summer week and

Figures 4.5, 4.6, 4.7 for a winter week) respect to the other cases (Average and Worst); with high start-up costs (Worst case) the impact of the constraints on the optimization is different, in particular in this case the influence of start-up costs is higher respect to the decay of efficiency, thus the number of starts is reduced at minimum, $CCGT$ are started-up less frequently and only if strictly necessary and they works longer at lower loads; with medium start-up costs (Average case) the optimization results are more similar to the case with low start-up costs (Best case).

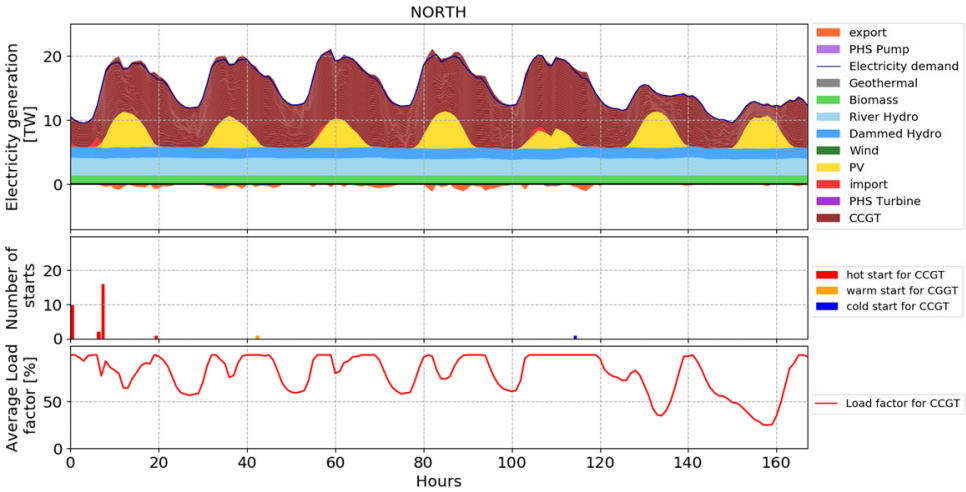

Figure 4.1: Results of the optimization with constraints on $CCGT$ considering high start-up costs (Worst case) for the first week of July in 2014 in the macro-region North: on the top matching between electricity demand and generation, in the center number of starts of $CCGT$ differentiated by start-up modes, while on the bottom Average Load factor (electricity produced from $CCGT$ at time t divided by the maximum amount of electricity that can be generated from the $CCGT$ that are turned on) as function of time.

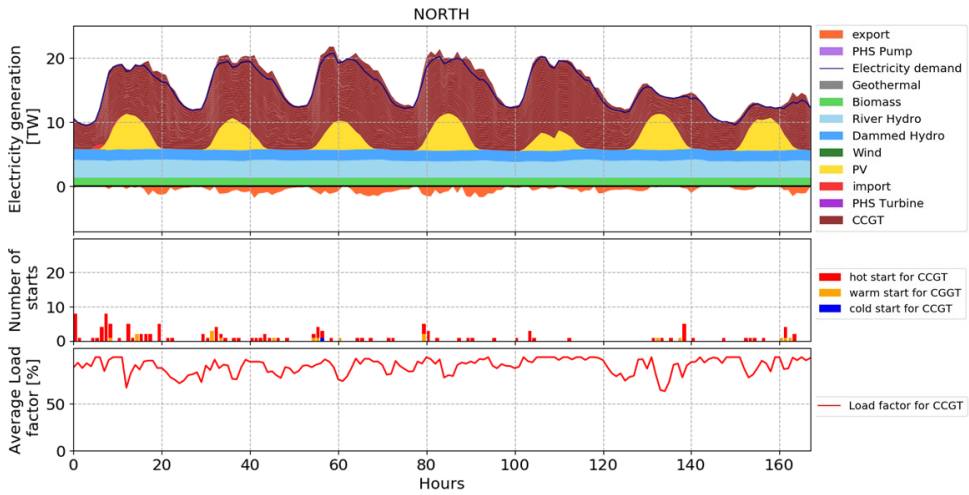

Figure 4.2: Results of the optimization with constraints on $CCGT$ considering medium start-up costs (Average case) for the first week of July in 2014 in the macro-region North: on the top matching between electricity demand and generation, in the center number of starts of $CCGT$ differentiated by start-up modes, while on the bottom Average Load factor (electricity produced from $CCGT$ at time t divided by the maximum amount of electricity that can be generated from the $CCGT$ that are turned on) as function of time.

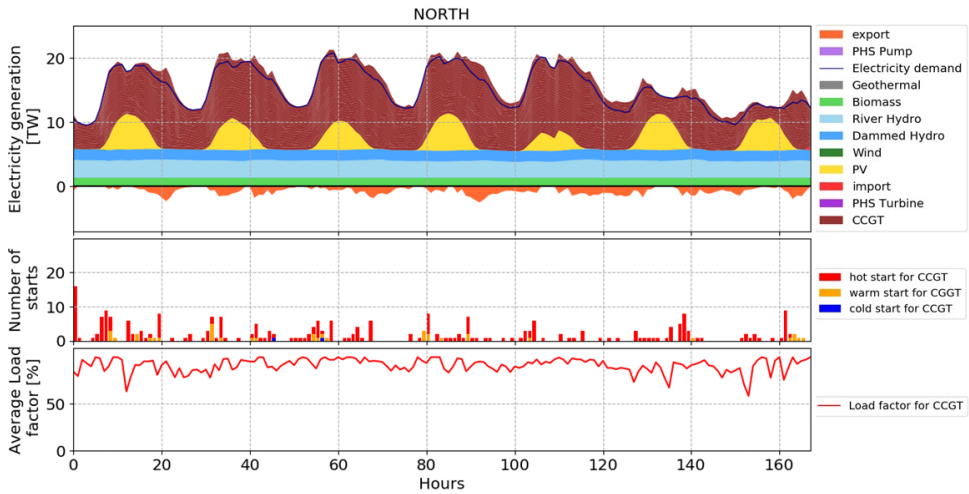

Figure 4.3: Results of the optimization with constraints on $CCGT$ considering low start-up costs (Best case) for the first week of July in 2014 in the macro-region North: on the top matching between electricity demand and generation, in the center number of starts of $CCGT$ differentiated by start-up modes, while on the bottom Average Load factor (electricity produced from $CCGT$ at time t divided by the maximum amount of electricity that can be generated from the $CCGT$ that are turned on) as function of time.

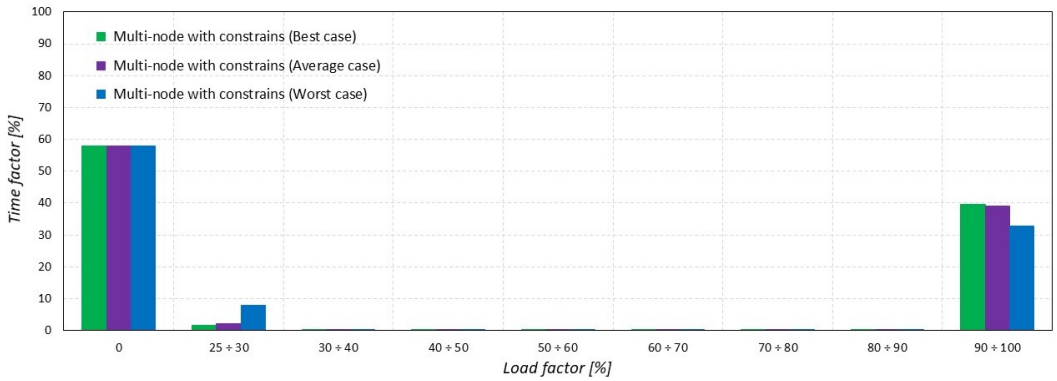

Figure 4.4: Results of the optimizations with constraints on *CCGT* for the first week of July in 2014 in the macro-region North: analysis of working conditions of *CCGT* considering various start-up costs (Best case, Average case and Worst case). *Time factor* (number of time-steps during which *CCGT* are generating a certain amount of electricity divided by the total number of time-steps) vs *Load factor* (percentage of electricity generated respect to nominal value).

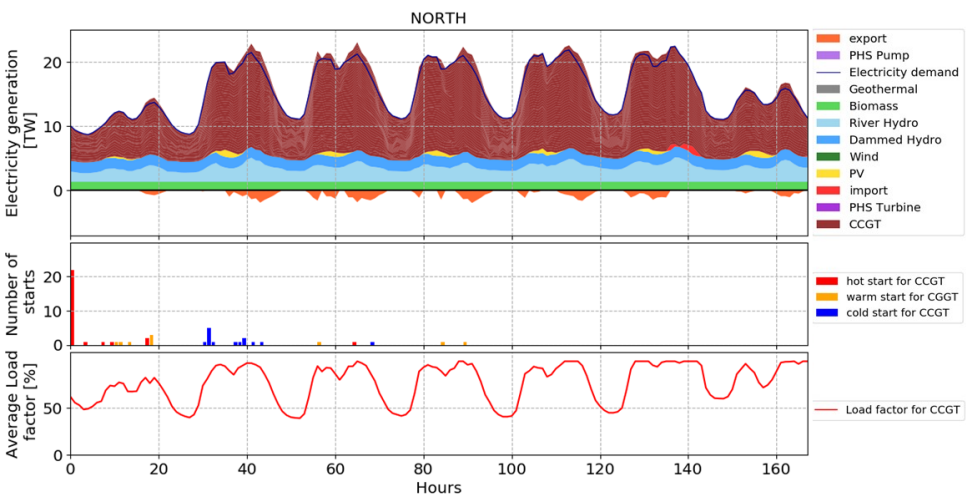

Figure 4.5: Results of the optimization with constraints on *CCGT* considering high start-up costs (Worst case) for the first week of December in 2014 in the macro-region North: on the top matching between electricity demand and generation, in the center number of starts of *CCGT* differentiated by start-up modes, while on the bottom Average Load factor (electricity produced from *CCGT* at time t divided by the maximum amount of electricity that can be generated from the *CCGT* that are turned on) as function of time.

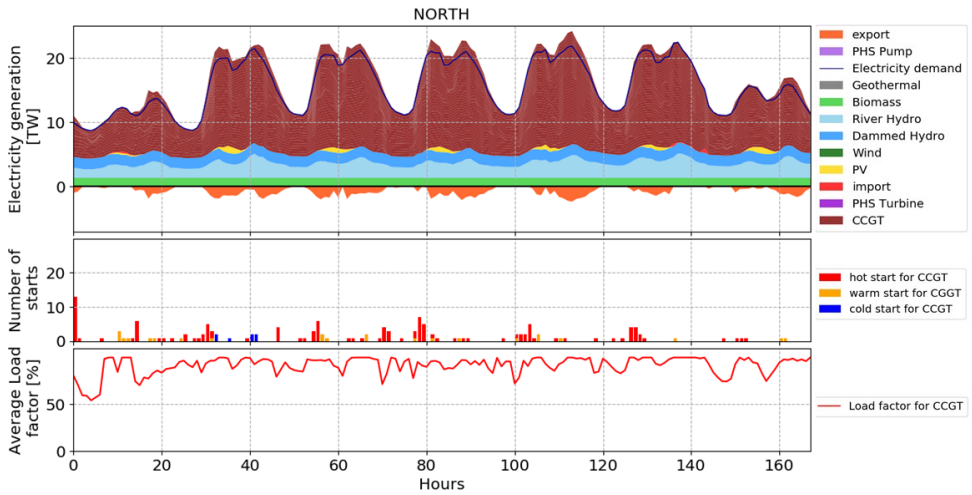

Figure 4.6: Results of the optimization with constraints on $CCGT$ considering medium start-up costs (Average case) for the first week of December in 2014 in the macro-region North: on the top matching between electricity demand and generation, in the center number of starts of $CCGT$ differentiated by start-up modes, while on the bottom Average Load factor (electricity produced from $CCGT$ at time t divided by the maximum amount of electricity that can be generated from the $CCGT$ that are turned on) as function of time.

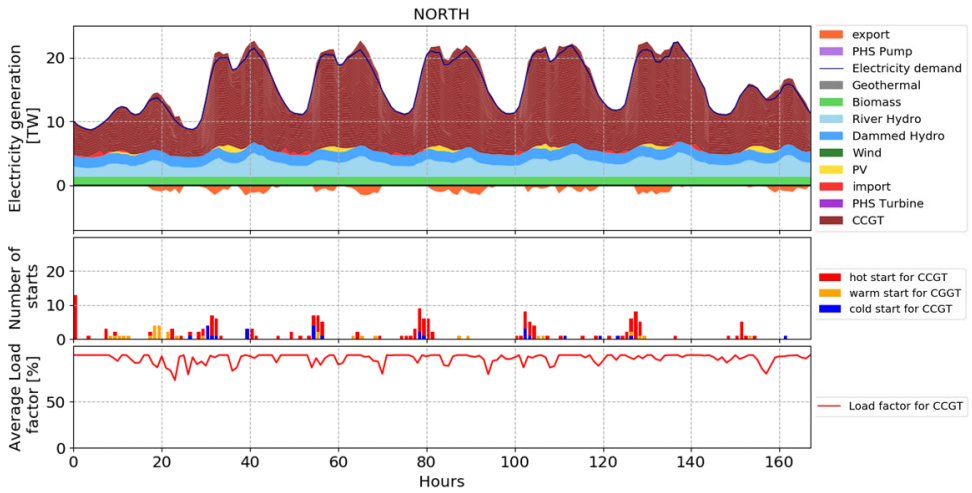

Figure 4.7: Results of the optimization with constraints on $CCGT$ considering low start-up costs (Best case) for the first week of December in 2014 in the macro-region North: on the top matching between electricity demand and generation, in the center number of starts of $CCGT$ differentiated by start-up modes, while on the bottom Average Load factor (electricity produced from $CCGT$ at time t divided by the maximum amount of electricity that can be generated from the $CCGT$ that are turned on) as function of time.

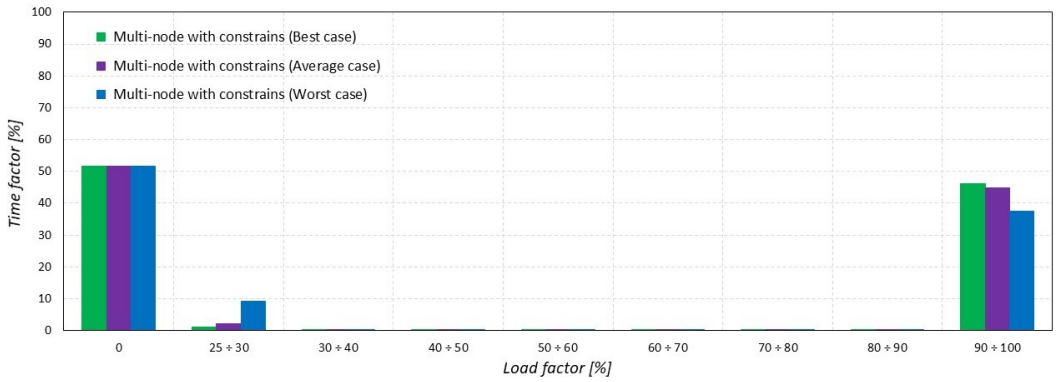

Figure 4.8: Results of the optimizations with constraints on *CCGT* for the first week of December in 2014 in the macro-region North: analysis of working conditions of *CCGT* considering various start-up costs (Best case, Average case and Worst case). *Time factor* (number of time-steps during which *CCGT* are generating a certain amount of electricity divided by the total number of time-steps) vs *Load factor* (percentage of electricity generated respect to nominal value).

4.2 *Italy_2014_CCGT* and *Italy_2050* scenarios

In order to evaluate the impact of the transient events of fossil fuel power plants on the actual configuration of the energy system and to estimate the growing influence of these events in future configurations of the energy system with higher penetration of *RES*, Italy is analyzed considering different configurations: *Italy_2014_CCGT* scenario that is representative of the actual configuration of the Italian electricity sector and *Italy_2050* scenarios, where higher values of *VRES* installed capacity are introduced in the model. In these scenarios is assumed a complete phase-out from coal fueled power plants (as reported in [14]). *Italy_2050* scenarios are implemented starting from the scenario for Italy at 2014 and adding the installed capacity of *VRES* technologies (*PV* and wind turbines) up to their maximum potential. In particular four scenarios are created (where '*%*' indicates the percentage of *VRES* installed capacity respect maximum potential): *VRES_25%*, *VRES_50%*, *VRES_75%* and *VRES_100%*. For each configuration of the Italian energy system, various constraints (time-dependent start-up costs, time-dependent ramp constraints and decay of efficiency during partial load operations) are introduced in the model and three different optimizations are performed changing start-up costs (Best case, Average case and Worst case) and keaping the other constraints and parameters.
In Figure 4.9 the penetration of *RES* is reported on the Italian territory as function of the relative *VRES* installed capacity respect to maximum potential; *Italy_2014* scenario corresponds to a 16% of maximum *VRES* installed capacity. From Figure 4.9 it is possible to notice that the *RES* penetration provided by *Terna* for the Italian electricity sector in 2014 is lower than the value obtained as result from optimizations because the electricity demand in the model is lower, as it is reduced by the value of electricity import; neglecting the electricity import, the value of *RES* penetration calculated with *Terna* data is very similar to the one for *Italy_2014* scenario. Figure 4.9 includes also the values of *RES* penetration for the optimizations performed with a single node approach, which are higher than the values for multi-node configurations because transmission losses are not introduced in the model and the absence of transmission constraints allow a better exploitation of *PHS*; it is too reported the case of perfect *RES* integration, where all the over-generation from *RES* is exploited (no curtailment).

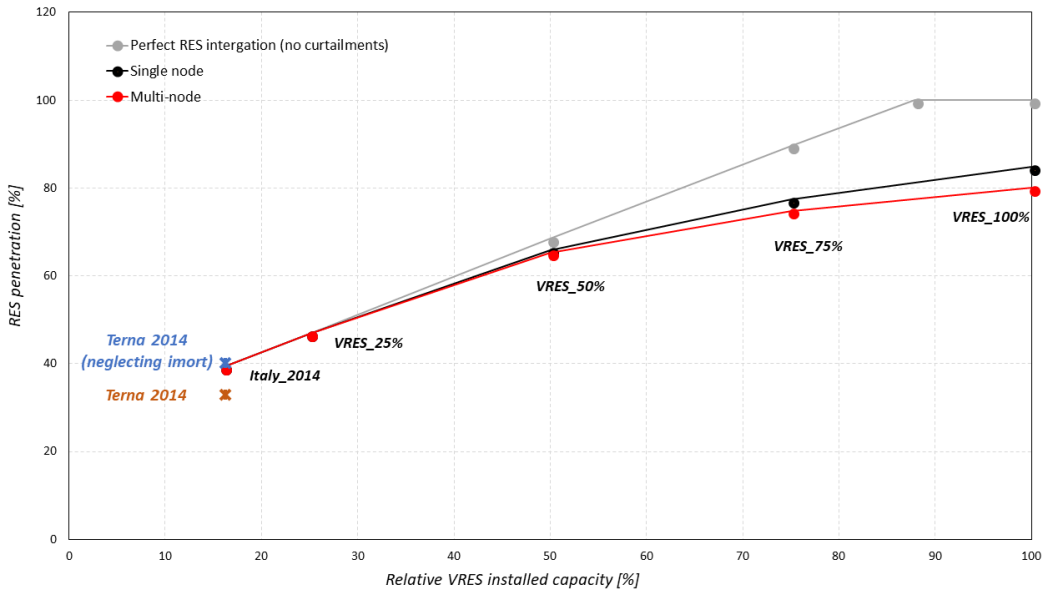

Figure 4.9: Results of the optimizations over one year for *Italy_ 2014_ CCGT* and *Italy_ 2050* scenarios considering single node and multi-node configurations: *RES penetration* (electricity generated from *RES* as percentage of total electricity consumptions) vs *Relative VRES installed capacity* (Nominal installed capacity of *VRES* respect to maximum potential). Comparison with *Terna* data [13].

The results of the optimizations have been compared to the targets on *GHG* emissions set by the Europe Union for 2020, 2030 and 2050:

- ***EU2020*** [28]: 20% reduction in *GHG* emissions (respect to 1990 levels).
- ***EU2030*** [29]: 40% reduction in *GHG* emissions (respect to 1990 levels).
- ***Energy Roadmap 2050*** [30]: 80% reduction in *GHG* emissions (respect to 1990 levels).

To evaluate the emissions targets for Italy, has been decided to simplify the analysis considering only CO_2 emissions in 1990. This value has been taken from *World Bank* database [55].
In Figure 4.10 the values of CO_2 emissions are reported for Italian energy system obtained as result from the optimizations. In *Oemof_ Transient* model only the electricity sector is analyzed, so the values of CO_2 emissions for the other sectors

are considered constants and equal to the values at 2014. By comparing the results of the optimizations on CO_2 emissions with the targets set by the Europe Union (Figure 4.10), it is possible to notice that the only target achieved is *EU2020*. It can be concluded that, it is not possible to act only on the electricity sector to obtain higher reductions in CO_2 emissions to meet the targets for 2030 (*EU2030*) and for 2050 (*Energy Roadmap 2050*).

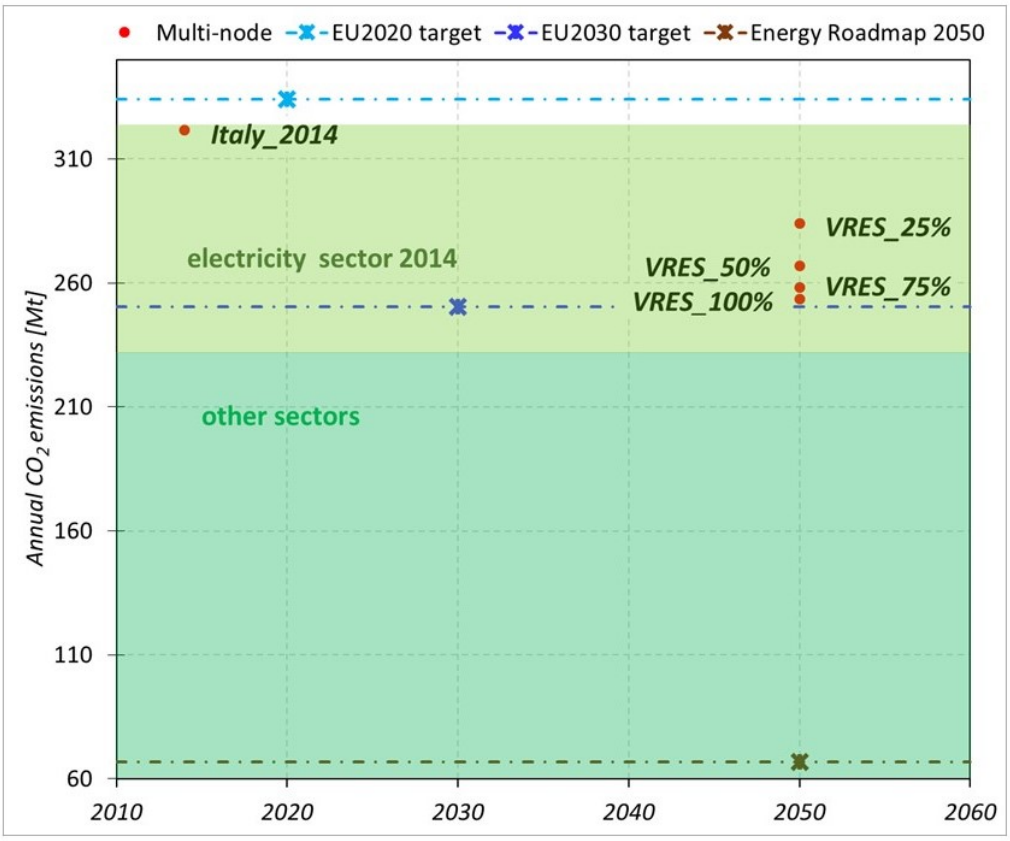

Figure 4.10: Results of the optimizations over one year for *Italy_ 2014_ CCGT* and *Italy_ 2050* scenarios considering multi-node configurations: Annual CO_2 emissions for the Italian energy system. Comparison with the targets set by European Commission (*EU2020* [28], *EU2030* [29], *EnergyRoadmap 2050* [30]).

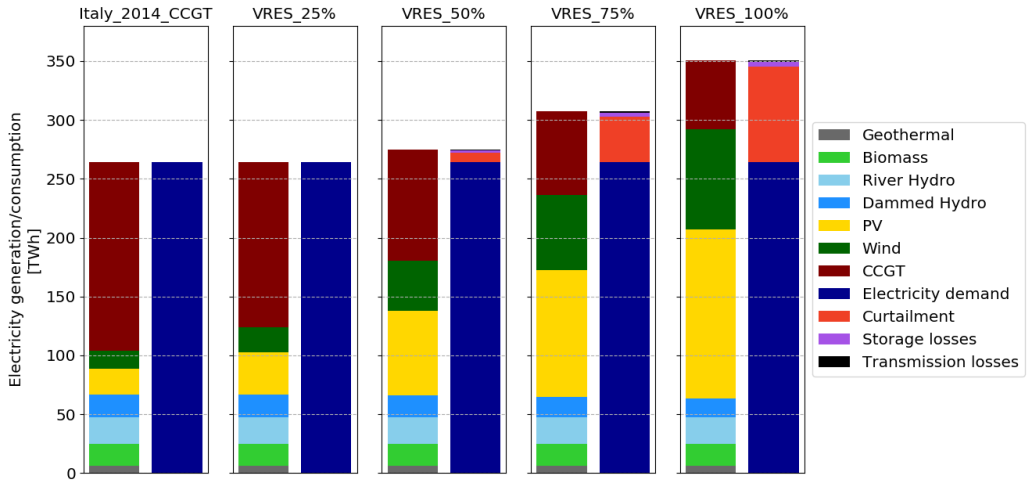

Figure 4.11: *Oemof_Transient* optimizations results: Annual electricity balance for *Italy_2014_CCGT* and *Italy_2050* scenarios

In Figure 4.11 the annual electricity balance are reported for the various configurations of the Italian energy system. It can be outlined that the electricity generation from fossil fuel power plants is reduced and the usage of *PHS* technologies is higher, as the installed capacity of *VRES* increase (passing from 2014 to 2050 scenarios). This is depicted in Figures 4.12, 4.13, 4.14, 4.15, 4.16 for a week summer: the usage of *PHS* technologies to store the overproduction from *VRES* starts to be significant in solutions where more than the 25% of the maximum potential of *VRES* installed capacity is exploited; thus the storage losses appear the first time in the annual electricity balance in *VRES_50%* scenario.
The results of the optimizations showed that the constraints related to the transmission and actual *PHS* installed capacity are not sufficient to absorb the over-generation from *VRES*, thus curtailment is verified in configurations of the energy system with high values of *VRES* installed capacity, as shown in Figure 4.11.
Under the current assumptions, it is not possible to obtain a 100% electric generation from *RES* in Italy, thus the production from *CCGT* is needed to balance the national energy system (Figure 4.11); a possibility to better exploit the over-production from *VRES* and to reduce the generation from fossil fuel power plants, is to increase the storage installed capacity by introducing new technologies in the model as electric batteries, *P2Y* strategies (where *'P'* stands for surplus renewable power and *'Y'* for the energy form or energy service to which this excess in converted to: thermal energy, hydrogen, gas and mobility) or to introduce seasonal storage.

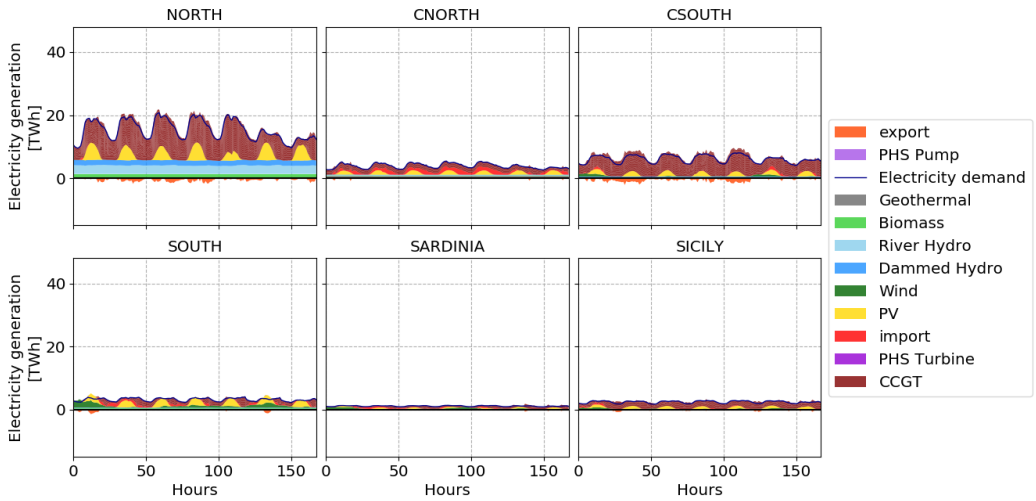

Figure 4.12: Results of the optimization with constraints on *CCGT* for *Italy_2014_CCGT* scenario considering medium start-up costs (Average case): matching between electricity demand and generation for the first week of July in 2014 in the various macro-regions.

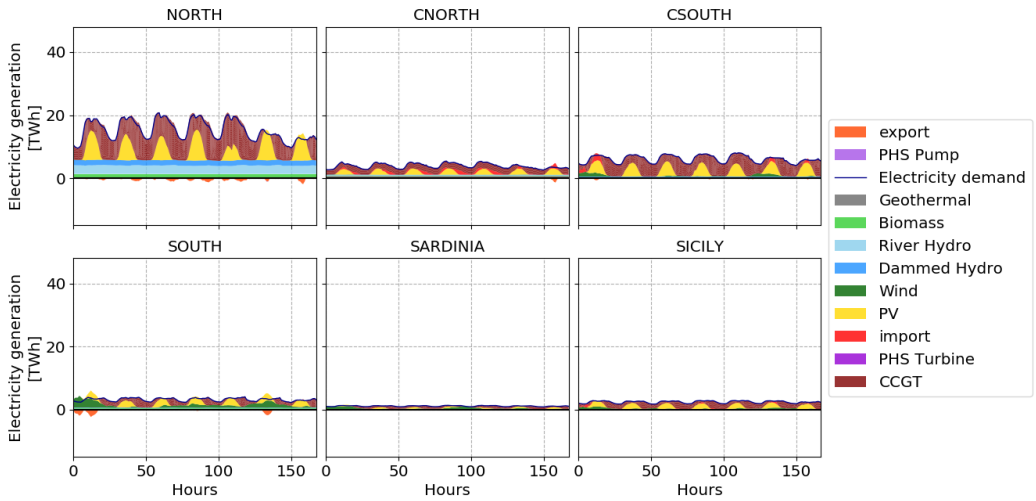

Figure 4.13: Results of the optimization with constraints on *CCGT* for *VRES_25%* scenario considering medium start-up costs (Average case): matching between electricity demand and generation for the first week of July in 2050 in the various macro-regions.

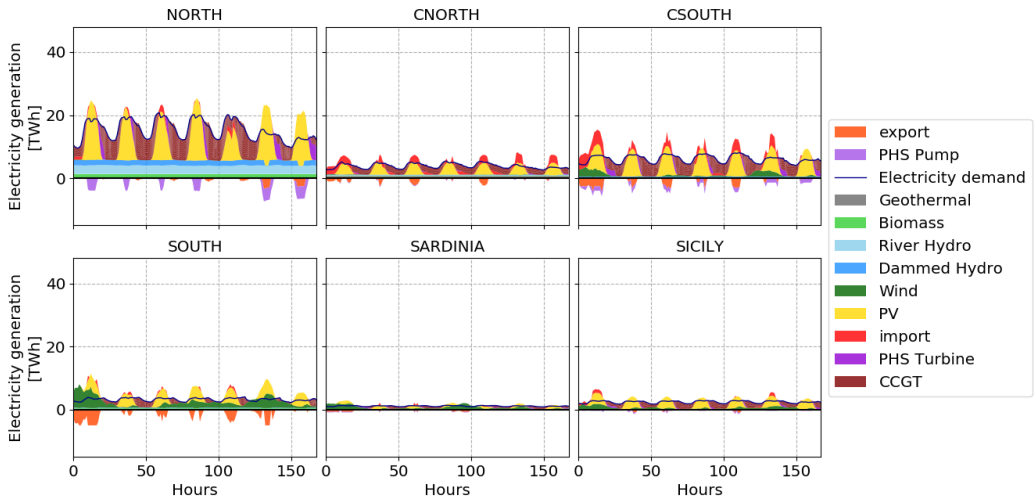

Figure 4.14: Results of the optimization with constraints on *CCGT* for *VRES_50%* scenario considering medium start-up costs (Average case): matching between electricity demand and generation for the first week of July in 2050 in the various macro-regions.

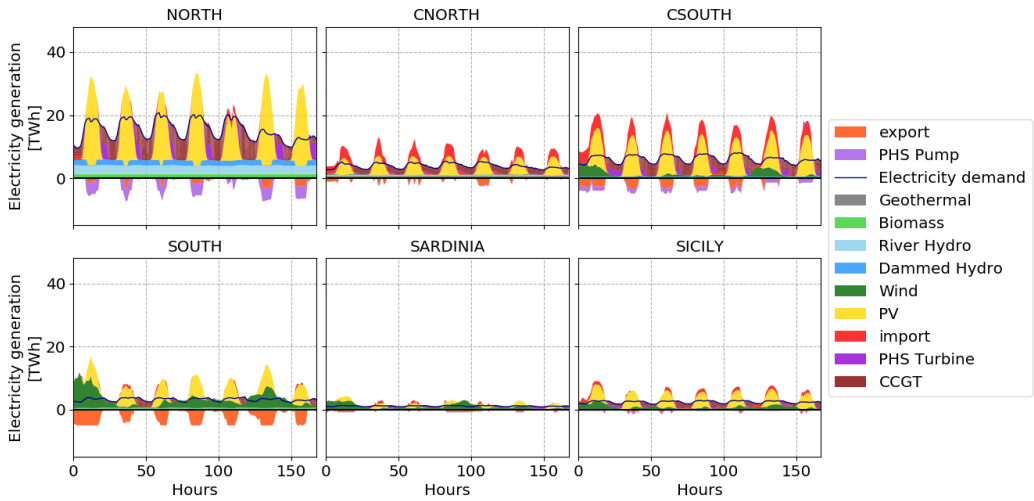

Figure 4.15: Results of the optimization with constraints on *CCGT* for *VRES_75%* scenario considering medium start-up costs (Average case): matching between electricity demand and generation for the first week of July in 2050 in the various macro-regions.

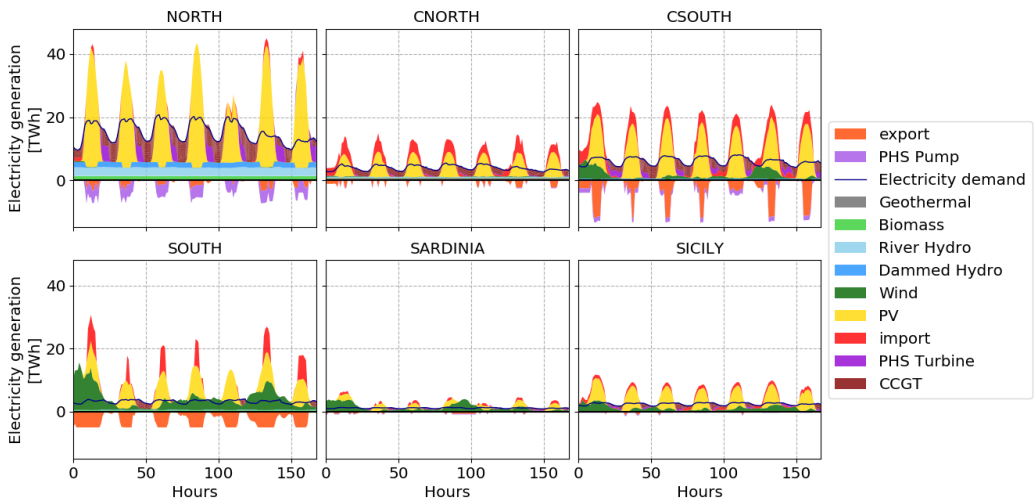

Figure 4.16: Results of the optimization with constraints on *CCGT* for *VRES_100%* scenario considering medium start-up costs (Average case): matching between electricity demand and generation for the first week of July in 2050 in the various macro-regions.

4.2.1 Costs and emissions

The growing installed capacity of *VRES* (passing from 2014 scenario to the ones for 2050) increases costs while reducing CO_2 emissions: thus the electricity generated from *CCGT* is reduced (as the associated costs and CO_2 emissions), because production from *VRES* rises. The savings due to the lower annual fuel consumptions does not compensate the annual costs associated to the higher values of *VRES* installed capacity and the higher specific cycling costs, as depicted in Figure 4.17, where is reported the relative increase in total annual costs as function of the relative decrease in annual CO_2 emissions respect to *Italy_2014_CCGT* scenario for the different configurations of the Italian energy system: from this figure it is possible to notice that as the *VRES* installed capacity increases, the total annual costs increase and the CO_2 emissions reduce; with the maximum value of *VRES* installed capacity (*VRES_100%* scenario) it is possible to obtain a reduction in CO_2 emissions higher than 60% for the multi-node configurations.
The total annual costs are associated to annualized investment costs, *O&M* costs, fuel costs and cycling costs, while CO_2 emissions depends on fuel consumptions (due to the amount of carbon in the fuel).
Looking at the figure it can be noted that the total annual cost and annual emissions rise when constraints on *CCGT* are introduced in the model (Best case, Average case and Worst Case) ; thus the transient operations of fossil fuel power plants, modeled by the constraints, introduce additional costs and emissions in the optimizations.
By comparing solutions obtained with multi-node approach , the single node

approach underestimates costs and emissions in configurations of the energy system with high values of *VRES* installed capacity (higher than 25% respect to maximum potential). In the multi-node configurations the transmission constraints are introduced in the optimizations and so, when over-production from *VRES* is verified the storage usage is limited, respect to single node, by maximum amounts of electricity that can be transferred from one node the other; in solutions with high values of *VRES* installed capacity, the multi-node approach present higher values of curtailment and the electricity produced from *CCGT* , so annual fuel consumptions increase as the associated costs and emissions respect to single node solutions.

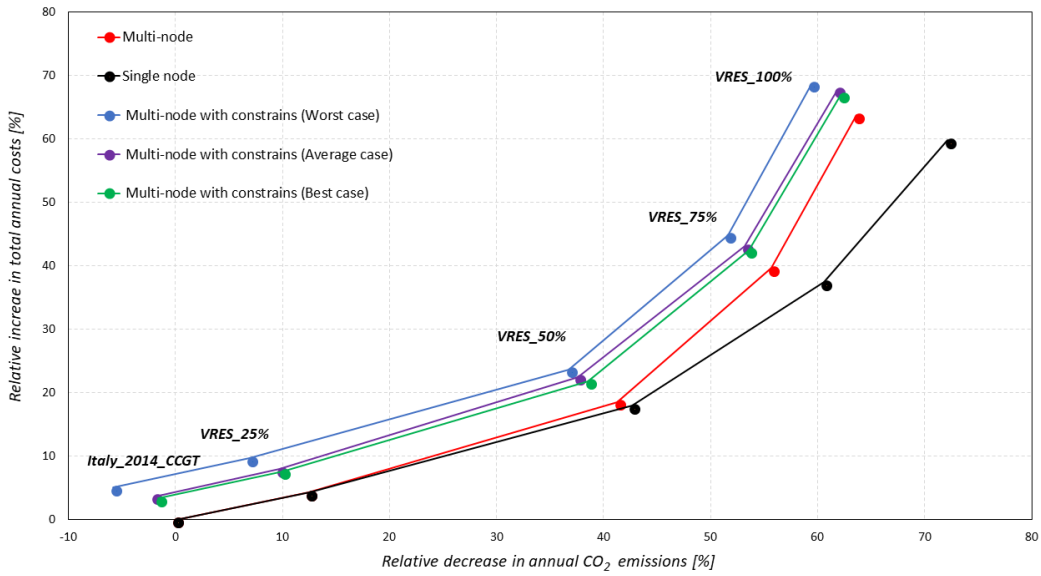

Figure 4.17: Results of the optimizations over one year for *Italy_ 2014_ CCGT* and *Italy_ 2050* scenarios considering single node, multi-node and multi-node with constraints on *CCGT* configurations: *Relative increase in total annual costs* vs *Relative decrease in annual CO_2 emissions*

4.2.2 Single node vs. Multi-node

The results have shown the importance of the multi-nodes versus single-node approach in energy system with high penetration of *VRES*; the multi-node approach is fundamental to not underestimate curtailment and CO_2 emissions and to not overestimate the usage of storage technologies obtaining more accurate and realistic results. The multi-node approach is particularly relevant for a territory like Italy, where the majority of the wind and *PV* installed capacity is located in the south while the *PHS* power plants are mainly located in the North. The optimizations results highlighted how the current transmission constraints and *PHS* installed capacity are not sufficient to absorb the whole over- generation from *VRES*, thus curtailment is verified in optimizations with high values of *VRES* installed capacity.
The single-node approach underestimates curtailment about 4% and an overestimates reduction in CO_2 emissions about 9% in the scenario with maximum *VRES* installed capacity (*VRES_100%*), while in *Italy_2014_CCGT* scenario the use of a single-node approach does not produce different results on curtailment if compared to the multi- nodes, because the limited *VRES* installed capacity allow to exploit the whole over-generation (Figure 4.18).

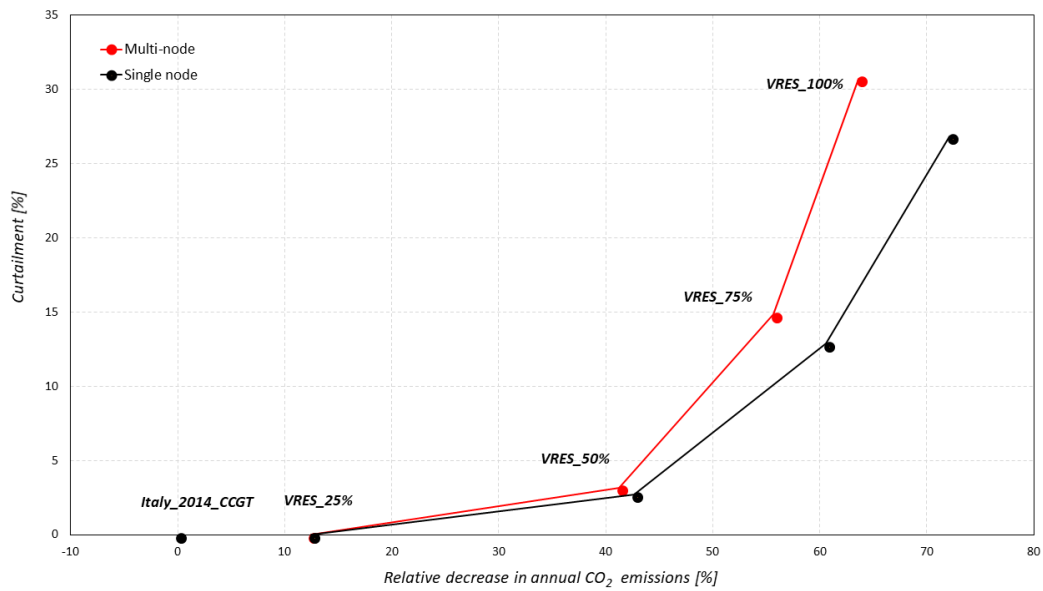

Figure 4.18: Results of the optimizations over one year for *Italy_2014_CCGT* and *Italy_2050* scenarios considering single node and multi-node configurations: *Curtailment* (calculated as percentage of total electricity consumptions) vs *Relative decrease in annual CO_2 emissions*

4.2.3 Curtailment

In Figure 4.19 it is reported the total curtailment that occurs in a year in the various macro-region for all the scenarios considered, while in Figure 4.20 curtailment is represented as function of time.
These figures highlight the over-generation problems as the *VRES* installed capacity increases; these problems are verified especially in south regions: in these regions peaks of over-generation higher than 20 GW occur, while the transmission constraints from south to northern regions is in the order of 3-4 GW and electricity demand and *PHS* installed capacity are low. Future developments could consider the possibility of extending transmission constraints to evaluate the impact on curtailments.

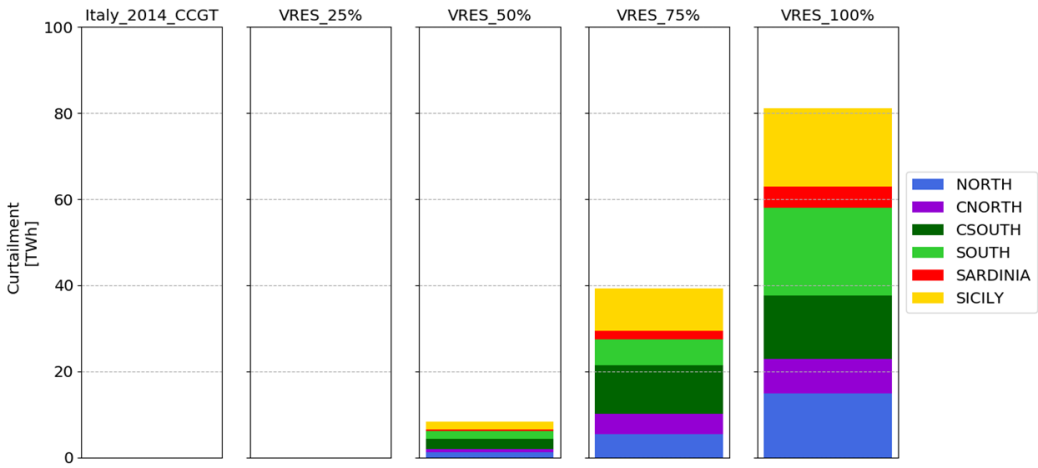

Figure 4.19: Results of the optimizations over one year for *Italy_2014_CCGT* and *Italy_2050* scenarios: annual Curtailments in the various macro-regions.

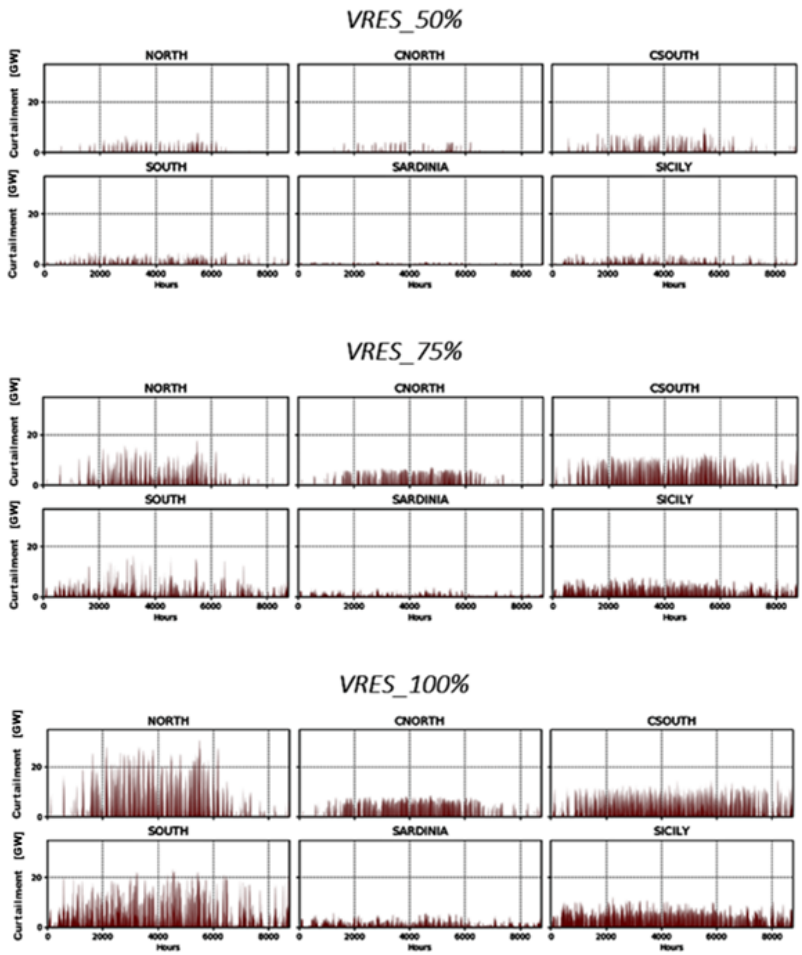

Figure 4.20: Results of the optimizations over one year for *Italy_ 2050* scenarios: Curtailments in the various macro-regions as function of time.

4.2.4 Impact of *CCGT* power plants transient operations on electricity dispatch

Many case studies ([5], [6], [7]) show that the higher is the penetration of renewable energy sources, the higher are the transient operation of fossil fuel plants and so the associated specific costs and emissions. This behavior is also experienced in the analysis conduced in this thesis work, thus from Figure 4.21 is possible to appreciate that as the *VRES* installed increases, specific cycling costs rise. The higher the production from variable renewable energy sources, the lower the electricity generated from *CCGT* and this together with a less constant hourly of production induce a rise in specific cycling costs.

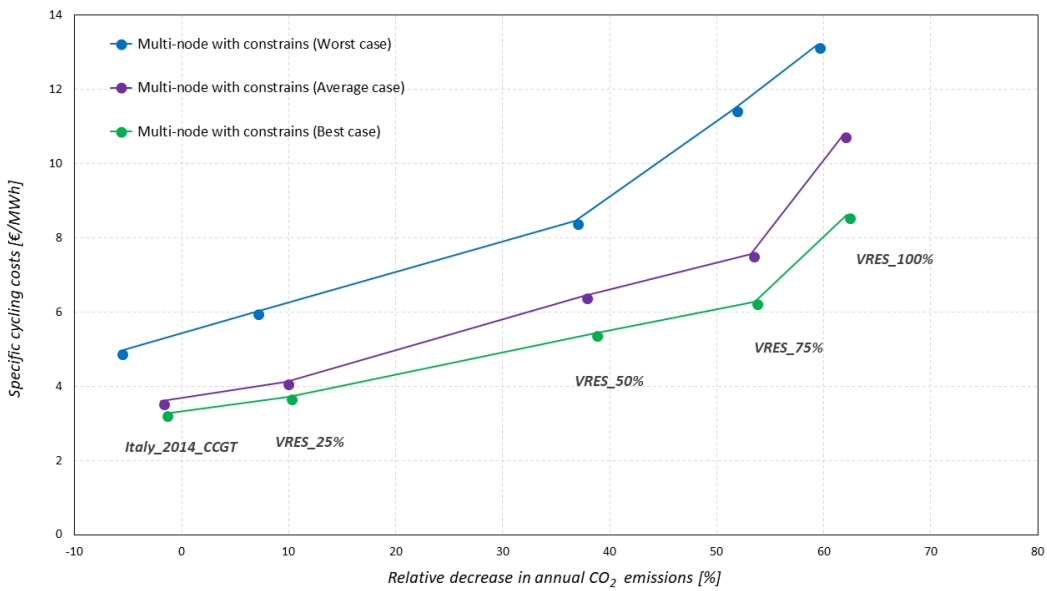

Figure 4.21: Results of the optimizations over one year for *Italy_ 2014_ CCGT* and *Italy_ 2050* scenarios considering multi-node configurations with constraints on *CCGT*: *Specific cycling costs* vs *Relative decrease in annual CO_2 emissions.*

Assuming different start-up costs (Best case, Average case and Worst case), the constraints affect in different ways the optimizations, as reported in Figure 4.21.
The impact of transient operations is evaluated with cycling costs, that are chosen as indicator, because quantify the effects of transient operations in monetary units. From Figure 4.22 is possible to appreciate the impact of the constraints implemented in this thesis work that lead to the creation of *Oemof_ Transient* model. The figure shows, for the different configurations analyzes, the relative increase in costs due to cycling as percentage of *CCGT* specific fuel costs, that is the only costs considered in optimization without constraints. Specific

cycling costs rise with *VRES* installed capacity (from *Italy_ 2014_ CCGT* to *VRES_ 100%* scenario); in particular in the scenarios with higher start-up costs (Worst case) the constraints affect the optimizations as follow: considering the actual configuration of the Italian energy system (*Italy_ 2014_ CCGT*) the optimization with constraints on *CCGT* presents costs higher than 10% , while for the scenario with maximum *VRES* installed capacity the impact of the constraints is higher, thus costs rise up to about 30%.

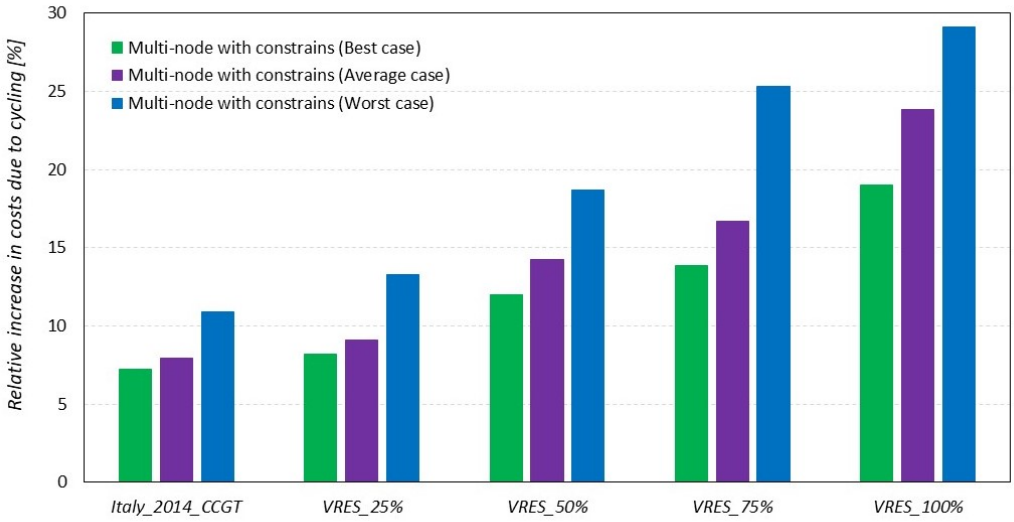

Figure 4.22: Results of the optimizations over one year for *Italy_ 2014_ CCGT* and *Italy_ 2050* scenarios considering multi-node configurations with constraints on *CCGT*: Specific cycling costs as percentage of *CCGT* specific fuel costs (the only costs considered in optimization without constraints).

The results show that the impact of transient operations of fossil fuel power plants is not negligible with a specific costs increase from 5% to about 30% , as depicted in Figure 4.22.
The lower specific cycling costs correspond to 3.3 €/*MWh* (Best case) and 4.9 €/*MWh* (Worst case) and are verified in *Italy_ 2014_ CCGT* scenarios, because the *VRES* installed capacity is the lowest and so the equivalent hours of *CCGT* are the highest, as depicted in Figure 4.23; the higher specific cycling costs are equal to 8.6 €/*MWh* (Best case) and 13.2 €/*MWh* (Worst case) and occur when the maximum *VRES* installed capacity is assumed (*VRES_ 100%* scenario), because the equivalent hours of *CCGT* are the lowest and the profile of production is more intermittent.

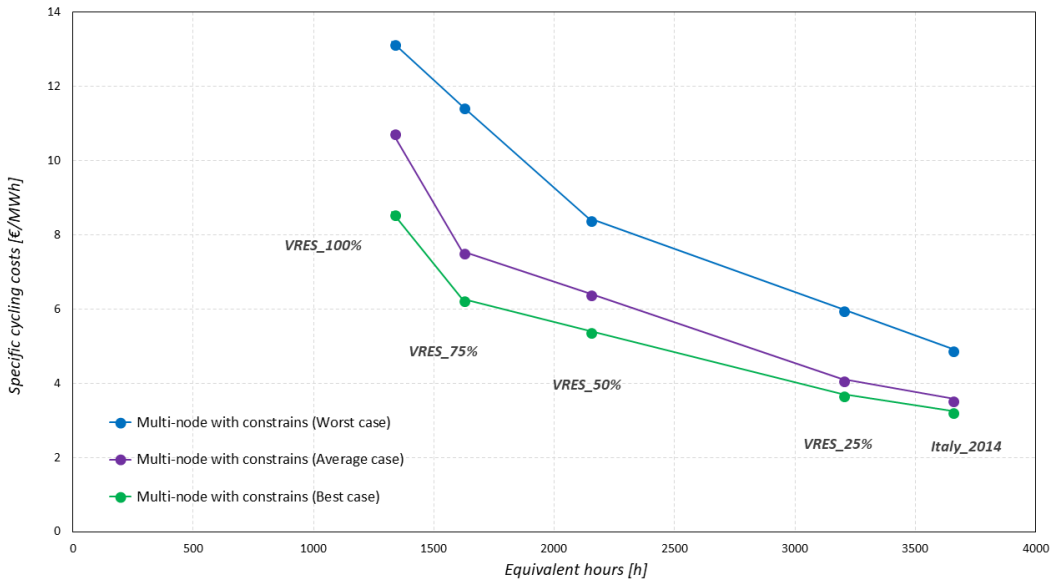

Figure 4.23: Results of the optimizations over one year for *Italy_ 2014_ CCGT* and *Italy_ 2050* scenarios considering multi-node configurations with constraints on *CCGT*: *Specific cycling costs* as function of the *Equivalent hours* of *CCGT*.

The absolute value of cycling costs varies in a narrow range as the *VRES* installed capacity increases, thus assuming low start-up costs (Best case) cycling costs are equal to 4-5 *M€* per *CCGT* per year, for the Average case correspond to about 5-6 *M€*, while assuming high start-up costs (Worst case) cycling costs amount to 7-8 *M€* per *CCGT* per year, as reported in Figure 4.24. The absolute value of cycling costs stays almost constant as the penetration of *VRES* increases, because the equivalent hours of *CCGT* are reduced (lower generation from *CCGT*) and the specific cycling costs rise.
In Figure 4.25, Figure 4.26 and Table 4.1 the characteristics of the transient operations of *CCGT* are reported for the different configurations of the Italian energy system analyzed assuming medium start-up costs (Average case). In particular specific CO_2 emissions and specific costs caused by the transient operations of *CCGT* are reported. Specific cycling costs are split into decay of efficiency costs and start-up costs. It is possible to notice that as the *VRES* installed capacity increases, the specific start-up costs are higher, thus *CCGT* are stared/stopped more frequently in order to follow the load and provide flexibility to the generation side. Specific decay of efficiency costs and specific CO_2 emissions show the same behavior, because *CCGT* work longer at lower loads (low efficiency) as *VRES* penetration increases.

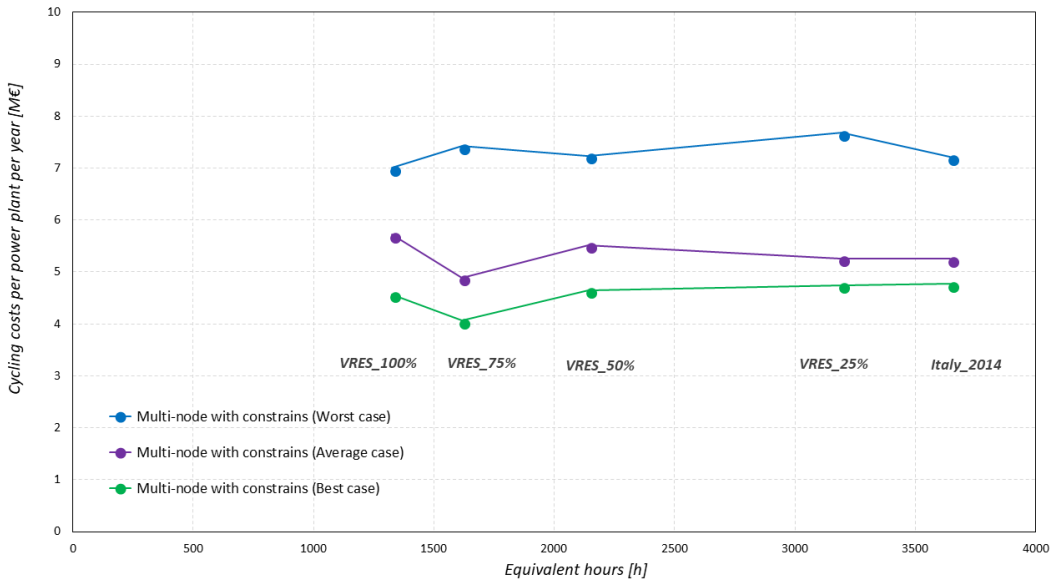

Figure 4.24: Results of the optimizations over one year for *Italy_2014_CCGT* and *Italy_2050* scenarios considering multi-node configurations with constraints on *CCGT*: yearly cycling costs of one *CCGT* as function of the *Equivalent hours*.

		Italy 2014	*VRES 25%*	*VRES 50%*	*VRES 75%*	*VRES 100%*
CO_2 emissions						
Specific fuel emissions	*[kg/MWh]*	372.4	372.4	372.4	372.4	372.4
Specific cycling emissions	*[kg/MWh]*	9.9	10.7	13.2	14	15.6
Specific emissions	*[kg/MWh]*	382.3	383.1	385.6	386.4	388
Increase in emissions due to cycling	*[%]*	2.6	2.9	3.5	3.8	4.2
Annual emissions	*[Mt]*	61.3	53.8	36.3	27.5	22.6
Characteristics						
Annual electricity generated	*[TWh]*	160.4	140.5	94.2	71.1	58.4
Equivalent hours	*[h]*	3645	3192	2141	1616	1326
Costs						
Specific fuel costs	*[€/MWh]*	45.3	45.3	45.3	45.3	45.3
Specific decay of efficiency costs	*[€/MWh]*	1.2	1.3	1.6	1.7	1.9
Specific start-up costs	*[€/MWh]*	2.4	2.8	4.8	5.9	8.9
Specific cycling costs	*[€/MWh]*	3.6	4.1	6.4	7.6	10.8
LCOE	*[€/MWh]*	48.9	49.4	51.7	52.9	56.1
Increase in LCOE due to cycling	*[%]*	7.9	9.1	14.1	16.8	23.8
Cycling costs per plant per year	*[M€]*	5.3	5.3	5.5	4.9	5.7

Table 4.1: *Oemof_Transient* optimizations results for *Italy_2014_CCGT* and *Italy_2050* scenarios considering multi-node configurations with constraints on *CCGT* (Average case).

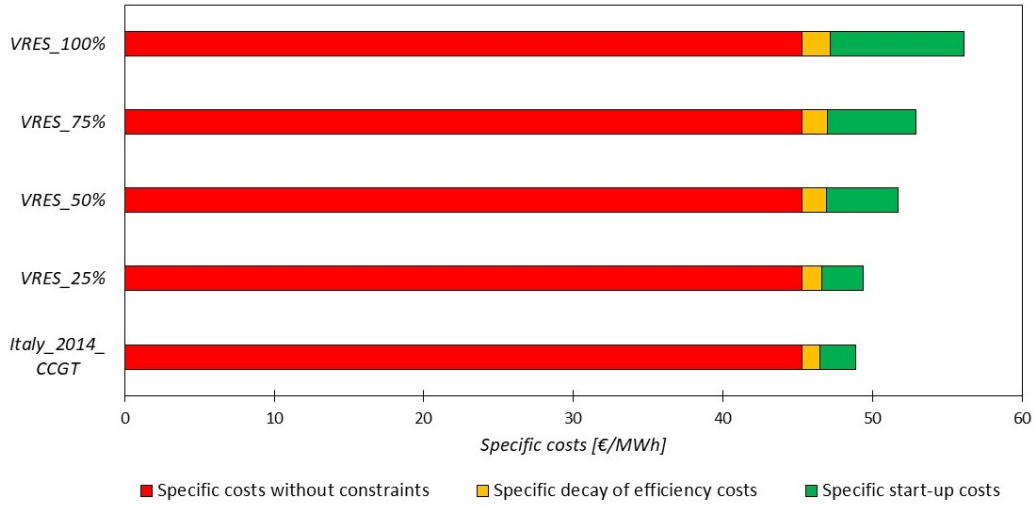

Figure 4.25: *Oemof_Transient* optimizations results for *Italy_2014_CCGT* and *Italy_2050* scenarios considering multi-node configurations with constraints on *CCGT* (Average case): *specific costs.*

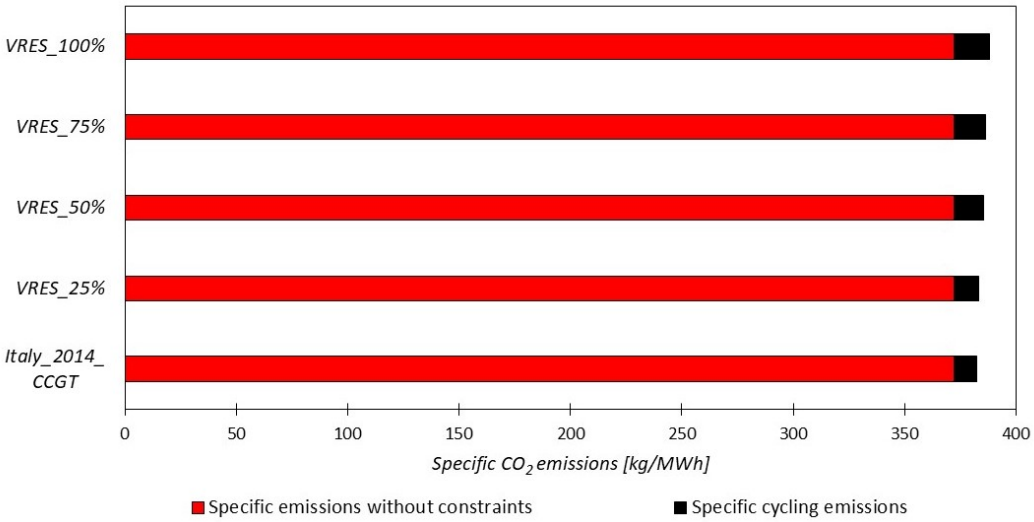

Figure 4.26: *Oemof_Transient* optimizations results for *Italy_2014_CCGT* and *Italy_2050* scenarios considering multi-node configurations with constraints on *CCGT* (Average case): *specific CO_2 emissions.*

Chapter 5

Conclusions

The model created in this work have been developed to improve the analysis of the transient operations of fossil fuel power plants in energy system modeling. This objective has been reached moving toward two different directions: high temporal resolution (hourly time-step) and high technological details (constraints on fossil fuel power plants) to model with precision and accuracy the role of *VRES*, the usage of storage and the transient operations of fossil fuel power plants in order to evaluate their impact in the optimization of the dispatch of electricity. Usually, in order to reduce the computational time, the transient operations of fossil fuel power plants are not considered in energy system modeling, however, these transient events can not be neglected, especially in configurations with high penetration of variable renewable energy sources (*VRES*), where the higher flexibility required to maintain the energy system in balance is provided by fossil fuel power plants.
The transient operations of fossil fuel power plants have been analyzed at different levels of integration of *VRES* and this analysis has been performed implementing new constraints in *Oemof* by taking advantage of its features; thus *Oemof* (Open Energy Modeling Framework) is a model written in python programming language that presents high temporal resolution (hourly time-step), high spatial resolution (multi-node) and is versatile and open source, so is possible to modify or add new components and constraints to an energy system. Fossil fuel power plants are modeled in *Oemof* as fully-flexible units (power output can vary from zero to the maximum in one time step) and decay of performances during partial operations is not considered. In order to improve the transient analysis present in *Oemof* and evaluate with higher technological detail the impact of fossil fuel power plants' transient operations, new constraints have been implemented in this thesis work. This leads to the creation of *Oemof_Transient* model, a *Bottom-up* (focus on technology) multi-node model that performs the optimization of the dispatch of electricity based on costs, considering also the transient operations of fossil fuel power plants. *Oemof_Transient* model takes as input data the electricity demand and the generation from *RES* and optimize the production from fossil fuel power

plant, the usage of storage technology and the electricity transferred from one node the other, without overcoming the constraints and limits on the various components of the energy system.
The constraints implemented in this thesis to model in a detailed and realistic way the transient operations of fossil fuel power plants are time-dependent: this means that the constraints introduces additional costs, emissions and ramp rate of available power that, for each instant of time, are a function of the hours of stop and the power output of the plant. In particular the time-dependent constraints are the following: time-dependent start-up costs (hot start, warm start and cold start), decay of efficiency at partial load and time-dependent ramp constraints.
The improvements of *Oemof_Transient* model with respect of the state-of-the-art of energy modeling are given by the multi-node modeling approach coupled to the hourly based dispatch optimization accounting for time-dependent constraints to model with accuracy the transient operations of fossil fuel power plants.
The model has been applied to the Italian case as it is characterized by a very high capacity and electricity production from combined cycle gas turbine (*CCGT*) systems. In the future, their role for modulating the load will even increase considering the planned coal phase out planned in Italy by 2030 [14].
The Italian energy system is analyzed considering the actual configuration (2014) and different configurations (2050) with higher values of *VRES* penetration up the the maximum capacity that can be installed, in order to estimate the growing influence of transient operations of *CCGT* as *VRES* penetration rises.
The results show that as *VRES* installed capacity increases (passing from 2014 scenario to 2050 scenarios), higher costs and higher reductions in CO_2 emissions are verified: thus the electricity generated from *CCGT* is reduced (as the associated costs and CO_2 emissions), because the savings due to the lower annual fuel consumption do not compensate the annual costs associated the higher values of *VRES* installed capacity and the increases in specific cycling costs. By comparing the CO_2 emissions for the scenario with maximum *VRES* installed capacity with the targets set by the Europe Union for 2030 (*EU2030*) and for 2050 (*Energy Roadmap 2050*), it can be concluded that is not possible to act only on the electricity sector to meet these targets.
The results of the optimizations highlighted how the current transmission constraints and *PHS* are not sufficient to absorb the over-generation from *VRES*, thus curtailment is verified in configurations of the energy system with high *VRES* penetration and under the hypothesis made, is not possible to obtain a 100% electric generation from *RES* in Italy, thus the production from *CCGT* is needed for the electricity balance of the national energy system.
The results have shown the importance of the multi-nodes versus single-node approach in energy system with high penetration of *VRES*; the multi-node approach is fundamental in order to do not underestimate curtailment and CO_2 emissions and do not overestimate the usage of storage technologies and thus

obtain more accurate and realistic results. The multi-node approach is particularly relevant for a territory like Italy, where the majority of the wind and *PV* installed capacity is located in the south while the PHS power plants are mainly located in the North. The single-node approach presents an underestimation of curtailment of about 4% and an underestimation of CO_2 emissions of about 9% in the scenario with maximum *VRES* installed capacity.
From the results of the optimizations is highlighted that the higher is the penetration of *VRES*, the higher are the transient operation of fossil fuel plants and so the associated specific costs and emissions, thus these units operate longer at partial load and have to be started-up or shut-down more frequently in order to provide flexibility and maintain the entire energy system in balance. The results show the importance of considering cycling costs costs of *CCGT*, thus with constraints on *CCGT*, specific costs increase from 5% to about 30%, that correspond to 3.3 €/*MWh* and 13.2 €/*MWh*.
The analysis performed in this thesis work highlights the importance to consider the transient operations of fossil fuel power plants in energy system with high *VRES* penetration. The model developed (*Oemof_Transient* model) analyzes in detail these transient operations, but high computational times are required to perform an optimization, thus the time-dependent constraints created increase the complexity of the problem.
Oemof_Transient model considers only the electricity sector, in order to obtain a complete analysis also transportation and thermal sector should be included in future developments.
The time-dependent transient analysis created opens up to model that evaluate the best solutions in terms of flexibility for an energy system by comparing cycling of fossil fuel power plants with other strategies that better exploit the over-production from *VRES* by storing (e.g. electric batteries) or converting in other forms of energy (e.g.: thermal energy, hydrogen obtained by electrolysis) this excess of electricity. Efforts should be made to allow an accurate integration of the intermittent *VRES*, since such technologies (*PV* modules and wind turbines) nowadays represent some of the best options available to face environmental (climate change) and energy security issues (security of supply).

Acronyms

PV	Photo-Voltaic
RES	Renewable Energy Source
VRES	Variable Renewable Energy Source
PHS	Pumped Hydro Storage
GHG	Green-House Gases
CCGT	Combined-Cycle Gas Turbine
HRSG	Heat Recovery Steam Generator
GT	Gas Turbine
BAU	Business as usual
TSO	Transmission system operator
O&M	Operation and Maintenance
MILP	Mixed-Integer linear programming
NPC	Net Present Cost

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