Optimal Power Grid Design for a Low Carbon Emission Future

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Title

Optimal Power Grid Design for a Low Carbon Emission Future

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Abstract

As we move towards a low carbon emission future, as a result of the increasing deployment of distributed generation, storage systems, and predominant usage of renewable energy sources, many new operational and planning challenges have appeared. In technical literature, one of the most studied problems which is called to deal with the challenge of obtaining an optimal grid design is the transmission expansion planning (TEP). It is a classical problem in power systems that aims at defining a network investment plan which decides what, where and when new equipment should be built in the transmission network. This problem has been adapting during the past decades in order to address questions related to the evolution of energy systems and supply future needs. On the other hand, the TEP is commonly addressed through reduction techniques to its search space, spatial, and temporal dimensions. Also, techniques related to uncertainties are usually considered in order to become it, a tractable problem.

Based on this, the thesis focuses on the modeling of the transmission network and reduction techniques aforementioned in the TEP; producing some contributions, presenting and testing sophisticated mathematical models to seek the optimal way the power grid will evolve.

The first contribution intended is related to the modeling of the network that considers a convex formulation of the AC power flow into the TEP problem. It offers good accuracy in network operation, which in turn improves investment decisions in the network; however, it has a high computation time that we will try to reduce based on the cycle approach. Besides, it is being considered the variable renewable energy (VRE), energy storage system (ESS), conventional network investment (CNI) such as transmission lines and transformers, and non-conventional network investment (NNI) such as phase-shifting transformers (PST), flexible alternating current transmission systems (FACTS) and switches to optimize the network topology. It implies to include chronological constraints (such as storage constraints, unit commitment, and switching constraints). Although the resultant problem is familiar with the TEP that considers switching and its mathematical formulations have been accepted as standards. Still, these might not be suitable in the context. Thus, a mathematical formulation is presented that includes the AC power flow based on the cycle approach and all equipment aforementioned.

The second contribution intended is related to reduction techniques, specifically in the extension of the snapshot selection technique, to represent chronological constraints. This technique aims at reducing the operational states into a reduced group of them that is selected that is representative of all the states that should influence investment decisions. Note that two main characteristics of the technique contrary to each other: computation time and the number of snapshots. The challenge is related to reduce the TEP with chronological constraints as well as possible while trying to preserve the solution of the TEP problem to be equal to the solution without reduction.

Finally, due to considering CNI and NNI, the search space is increased significantly. Thus, an application of reduction technique is needed; however, due to the inclusion of NNI, current techniques might not be suitable. Moreover, from the non-conventional investments side is considered PST, FACTS, and switches to increases the network flexibility. To deal with this, the proposed approach aims to obtain a small set of relevant conventional and non-conventional candidates from a large group to invest, taking care of the characteristics of candidates.

Keywords: AC power flow; network topology optimization; non-conventional investment; energy storage systems; renewable-based generation; transmission expansion planning.

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To my family, for their unconditional love and support.
A toda mi familia, por su amor y apoyo incondicional.

I solemnly swear that I am up to no good.
— J.K. Rowling, Harry Potter and the Prisoner of Azkaban.

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List of Abbreviations

BS	Battery system
DG	Distributed generator
DLR	Dynamic line rating
ESS	Energy storage system
FACTS	Flexible AC transmission system
FACTS	Linear programming
MILP	Mixed-integer linear programming
MINLP	Mixed-integer nonlinear programming
MISOC	Mixed-integer second-order conic
MNR	Modified Newton-Raphson
NLP	Nonlinear programming
OPF	Optimal power flow
PCC	Point of common couple
PDF	Probability Distribution Function
PTDF	Power Transmission Distribution Factor
QC	Quadratic convex
RES	Renewable energy sources
SOC	Second-order conic
SDP	Semidefinite relaxation
TSO	Transmission system operator
UC	Unit commitment
VRE	Variable renewable energy
VSS	Value of Stochastic Solution
WT	Wind turbine

1 Introduction

1.1 Background and Research Motivation

Driven by environmental awareness and supported by a convincing political agenda, the current electrical energy systems are faced with an increased deployment of renewable energy sources (RES). A large portion of these sources has been added since five years ago worldwide, and as proof of it, more than 200 gigawatts of it were installed at the end of 2019, as it is shown in Fig. 1.

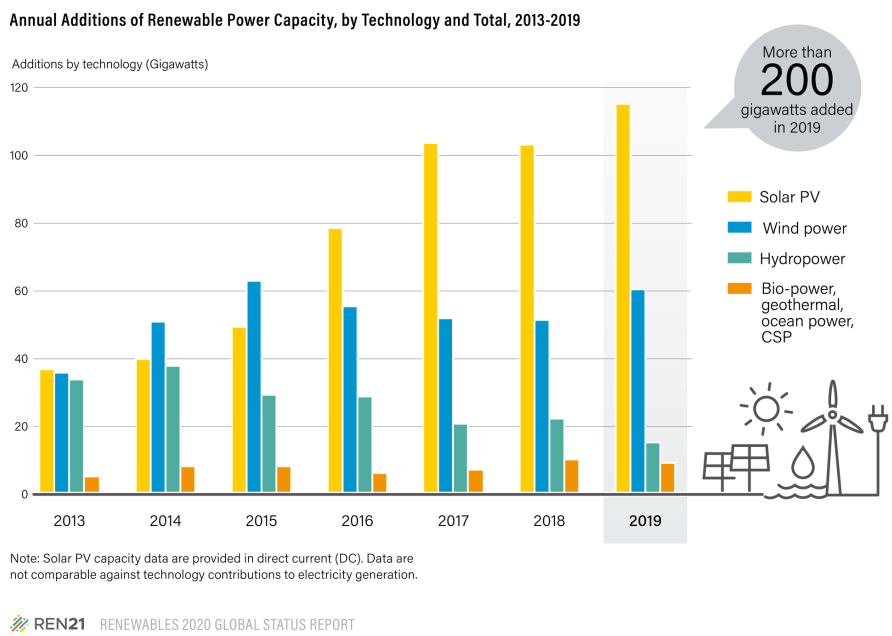

Figure 1 – Annual additions of renewable power capacity, by technology and Total, 2013-2019. [Source: Renewables 2020 Global Status Report [1]]

In Europe, most countries are increasing the shares of RES in their final energy consumption [2], as can be noted in Fig. 2, during 2017 and 2018 to comply with the target for 2020. This target is part of the Climate strategies & targets of European Commission [3], where some targets are:

- For 2020:
  - 20% reduction in rehouse gas emissions compared to 1990
  - 20% renewable share on final energy consumption
  - 20% reduction in primary energy consumption
  - 20% electricity interconnection

- For 2030:
  - 40% reduction in rehouse gas emissions compared to 1990
  - 32% renewable share on final energy consumption
  - 32.5% reduction in primary energy consumption
  - 15% electricity interconnection

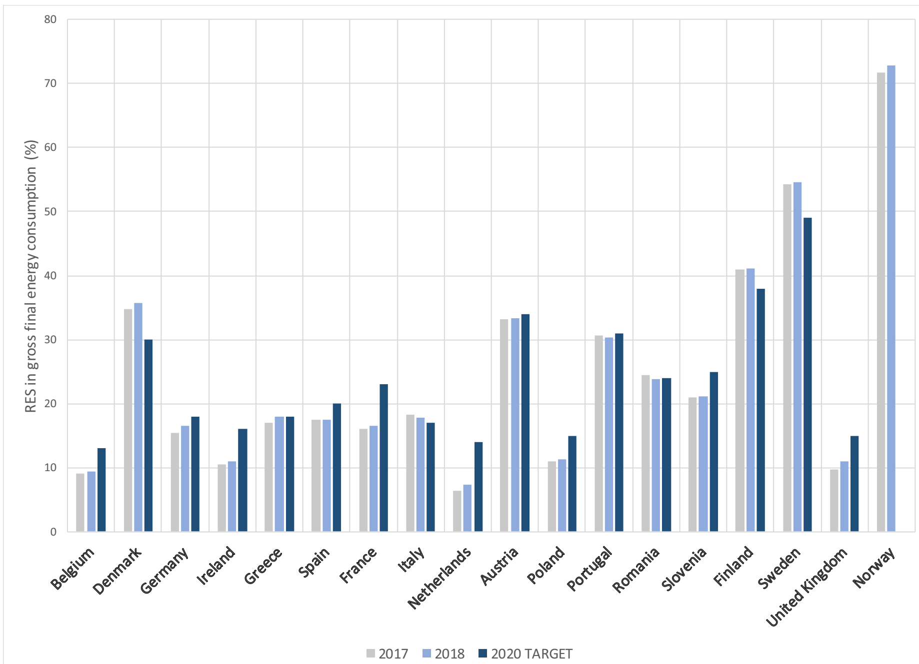

Figure 2 – Current status of share of RES in final energy consumption in Europe. [Source: Made by the author from [2]]

Moreover, Fig. 3 shows how RES can be deployed across Europe towards 2050 [4]. Many works like this try to explain and show different pathways to reach a low carbon emission future in 2050.

On the other hand, a significant part of these sources is composed of solar PV and wind power which are known as variable renewable energy (VRE) due to its difficulty in predicting and deliver a fluctuating power production. The integration of it into power systems are posing technical and economic challenges [5]; moreover, VRE is spatially distributed and not frequently correlated with load profiles. Thus, power systems planning and operation are suffering significant changes that mainly relate to the addition of uncertainty and variability of VRE. To deal with these changes, the power systems need to increase its flexibility [6–8].

As part of having a suitable integration of VRE, an increase in flexibility can be the key answer to this issue. The flexibility can be provided from operational strategies (energy curtailment [9] and generation control [10]), storage energy systems [11, 12], demand-side management [13–15], transmission network [16–18], and multi-energy systems [19–21].

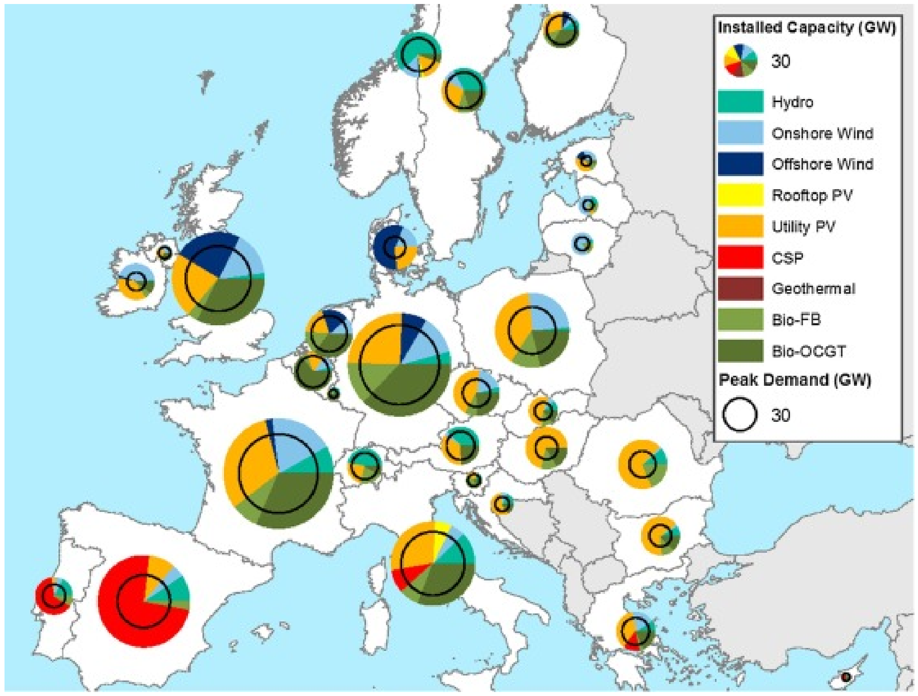

Figure 3 – Optimised generation capacity per technology in 2050 per country in Europe. [Source: [4]]

From these ways to increase the power system flexibility, the transmission network is considered as fixed and rigid equipment until now, which in most cases is active and only suffers topology changes in maintenance or fault periods. On the other hand, facing the future needs of the power systems, it is important to explore alternatives to increase its flexibility.

For this, there are some non-conventional ways such as the switching which has been exhaustive studied in the Optimal Transmission Switching (OTS) problem [22], and changing the transmission topology considered in the Network Topology Optimization (NTO) problem [23]. However, the inclusion of these approaches to modify the transmission network topology in the power system operation might lead to a great challenge, even more significant if it is introduced in the transmission expansion planning (TEP), even though it should be tested.

Thus, studying all of these approaches of flexibility in the TEP firstly to make the decision-making process of investing in the transmission network (considering potential operating maneuvers and changes in the topology) could be lead us to deal challenges and opportunities to improve the transmission network and supply the future needs.

1.2 Literature Review

As a first step it is so relevant to set up the optimal power flow (OPF) as the core of the TEP. There is vast literature about OPF since it was proposed in [24] (1960's), and the common practice is the use of linearizations or approximations until now. As a result, we use linear models easier to solve that can guarantee the optimality; however, the solutions obtained from this models can be not feasible with respect to the original non-convex and non-linear problem.

Reason why the OPF problem has attracted considerable research interest for many years and also are broad range for applications [25], [26]. Currently, there two main ideas (which rules the contributions) in order to deal with non-convexity of power flows: the use of convex relaxations and Newton methods for solving the OPF.

This thesis is focused on the use of convex relaxations to solve the TEP. For this, a relaxation concept is presented as follows: The function $f(x)$ resembles the objective function of non-convex and non-linear OPF that may have several local minimums beyond the global minimum in Fig. 4. Using a convex relaxation technique, this function is transformed into a convex function, i.e. $\widetilde{f}_1(x)$ or $\widetilde{f}_2(x)$ as possible convex relaxations of the original function $f(x)$. The term relaxation is used so that the constraints of the original problem are relaxed or omitted. As a consequence, the possible solution space is increased and the solution for the convex relaxation is always a lower limit of the original non-convex problem. The term relaxation gap denotes the difference between the minimum of the convex relaxation and the global minimum of the non-convex original problem. A relaxation is tight if the relaxation gap is small. A relaxation is accurate, if the relaxation gap is zero, i. e., The gap equal to zero is reached if the minimum of the convex relaxation corresponds to the global minimum of the original non-convex and non-linear original problem.

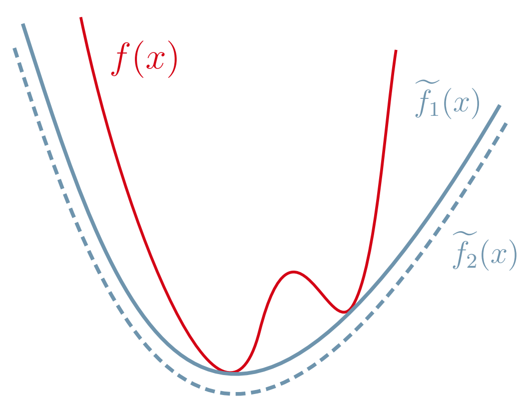

Figure 4 – Representation of the convex relaxation concept.
[Source: made by the author]

1.2.1 Transmission Expansion Planning

The transmission expansion planning (TEP) problem is based on the OPF and it is a combinatorial known problem and difficult to solve that frequently have several assumptions and approximations that significantly impact in the quality of the solution. The TEP aims at determining the location, number, and timing of investment in transmission lines, transformers, and other devices to be added to the transmission network in order to properly meet future power demand with minimum investment cost [27–29], an example of it is shown in Fig 5. This figure presents a multi-stage plan to invest in lines and var sources for the IEEE 118-bus system, more details can be found in [30].

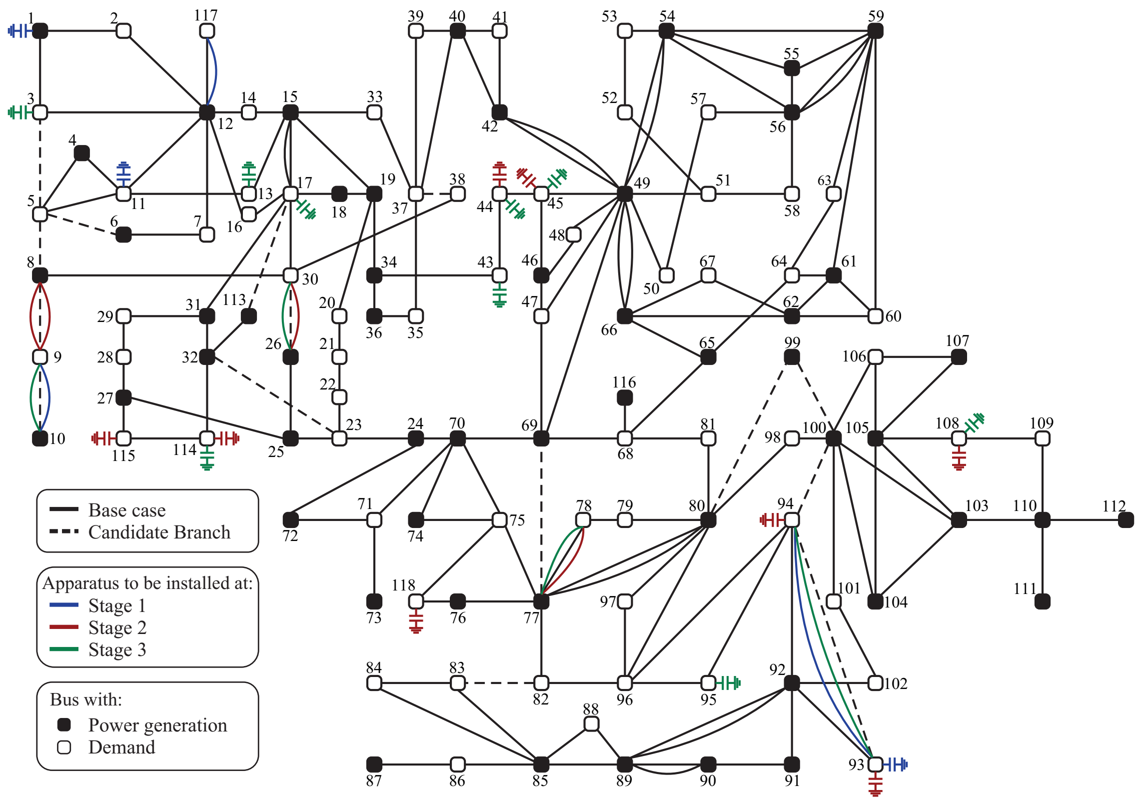

Figure 5 – Investment plan (lines and var sources) for the IEEE 118-Bus System.
[Source: [30]]

In this sense, some dimensions that can characterize the TEP problem are presented as follows:

1. **Temporal representation:**
    - Static: It aims at obtaining an expansion plan towards a single year.
    - Dynamic: Most known as multi-year expansion planning, and that is why chronological constraints related to investments are considered.
    - Load levels: The complexity of the TEP problem in part is proportional related to the number of load levels, therefore many works only consider a couple of load levels.

2. **Network representation:**
   - **Case study:**
     - Test cases: Usually test cases from IEEE are used to test the TEP.
     - Real cases: Numerous attempts to represent real systems have been made; however, until now, these cases are approximations that can be appreciated in the number of nodes/bus-bars considered, but it could give us signals about the problems which real systems have to deal with.
   - **Nodes:** Or bus-bars. Depending on the number of it and transmission lines, the operational part of the TEP would be hard to solve.
   - **Transmission equipment:** According to the context, equipment directly impact on the TEP problem; for example, ESS might be change the conventional perspective of the operation. Main equipment considered are PST, FACTS, ESS, HVDC, and devices capable to modify the network topology.
   - **Power flow formulation:**
     - DC OPF: An approximated linear form of the AC power flow (NLP problem).
     - AC OPF: It is usually approximated into LP and relaxed into SOC, QC and SDP to solve it [31]. Beside sometimes, some meta-heuristics are using to solve it in its NLP form.
3. **Decision dimension:** In this dimension is common to try to reduce the search space. It leads to seeking promising candidates because including all possible investment candidates could lead us to an intractable problem in computational terms.
4. **Problem type:** As binary variables are included and depending of the OPF nature, the model can be a MILP, MISOCP, MIQC, MISDP or MINLP.

Then from Table 1, the predominant use of DC power flow can be appreciated; therefore almost all models to solve are of the MILP problem type. Another principal characteristic is related to temporal representation in which the single-stage toward to a specific year and hours clustered in blocks are frequently used. In addition, most models were tested using known IEEE test system which present known difficulties; however, there are some works proposed by authors in [32, 38, 40] that uses reduction techniques to cluster bus-bars into representative nodes and overcome the difficulty to use real systems in TEP problem. Also, almost no model considers at same time all technologies (VRE, ESS, DR, HVAC, HVDC, PST, FACTS, DLR, Double-bus bar, switches, etc) that could lead to interesting work about power grid design. Another common characteristic in TEP is the use of N-1 operating condition to assess the network reliability.

Table 1 – TEP models considering several technologies, reduction techniques, and uncertainties.

	Papers	[32]	[33]	[34]	[35]	[36]	[37]	[38]	[39]	[40]	[41]	[42]
Temporal Representation	Static or Dynamic?	Static	Dynamic	Static	Static	Static	Static	Static	Static	Dynamic	Static	Static
	Load levels	75 snpashots	1 block	1 block	4 days	5 blocks	1 block	8760 h	1350 h	4 blocks per year	1500 h	25 h
Network Representation	Case Study	Europe	IEEE118	RTS-24	RTS-72	Chile	RTS-24	Europe	RTS-24	1168-bus	IEEE300	RTS-72
	Nodes	1000	118	24	72	27	24	2088	24	1168	300	72
	ESS	-	-	-	Yes	Yes	-	-	-	-	-	-
	HVDC	Yes	-	-	-	-	-	Yes	-	-	-	-
	PST	-	-	-	-	-	-	-	-	-	-	Yes
	FACTS	-	-	-	-	-	-	-	-	-	-	Yes
	Network modification	-	-	Lines	Lines	-	Splitting of lines	-	-	Lines	-	-
	DC OPF	Cycles	-	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-
	AC OPF	-	Linear Branch Flow	-	-	-	-	-	-	-	-	Quadratic Convex Polar
Decision Dimension	Search space	-	-	-	-	-	-	Candidates' procedure	-	Candidates predefined	-	-
	Problem type	MILP	MILP	MILP	Trilevel & MILP	MILP	MILP	LP & MILP	MILP	MILP	Benders & MILP	NLP & MILP

[Source: made by the author]

Thus, the following research gaps can lead to potential contributions:

- **Power formulation:** Any improvement related to quality of solution that can be reached using AC power flow by SOC, QC or SDP formulation in TEP could easily lead to a contribution in TEP. On the other hand, to contribute using DC power flow by MILP needs many efforts because it was studied during the last decades. Besides, TEP needs a better network representation according to power system trends.

- **Technologies:** An assessment of a specific technology considering current trends with a better temporal and geographic representation can lead to a potential contribution. Besides of it, thinking ESS, VRE, and network topology optimization can lead to an exciting work because it will include the generation flexibility in TEP to optimize the network topology and potential maneuvers of it.

- **Reduction techniques:** According to all aforementioned, it is very interesting to add difficulties and technologies to the TEP; however, it can become the TEP into intractable problem.

Also from the technical point of view, the TEP presents the following main challenges related to the operation. Some of these challenges are associated with [36, 43, 44]:

- **Power flow formulation, AC vs DC:** An approximated DC formulation cannot not represent problem associated to voltage and reactive power. These problems are occurring more frequently due to the predominant use of RES. Also, the generation-consumption power balance, which might be even more different from the real ones.

- **Energy storage and transmission expansion planning:** substitutes or complements?.

- **Low-inertia:** It is due to the presence of renewable-based generation systems, connected to the system with electronic interfaces.
- **Robustness and reliability:** It is due to the uncertain nature of the variable renewable-based generation systems.

To overcome all of this, a suitable extension of the conventional OPF formulation based on AC power flow has been recently proposed by the authors in [45, 46] that can be applied to the TEP. The novelty in this OPF formulation is the consideration of the branch flow model for the analysis and optimization of transmission systems that includes mesh as well as radial networks. To accomplish this, the authors proved that the SOC relaxation of the branch flow model is exact for both mesh and radial networks. Thus, the formulation resultant leads a new approach to solving optimal power flow (OPF) considering the AC power flow with good accuracy. Table 2 shows the accuracy to use the branch flow model in TEP.

Thus, the contributions of the work in [33, 47] are considered as the cornerstone of this Ph.D. thesis (and many others recently published works, such as [48–51]), as it allowed the development of new mathematical formulations for the unit commitment and economic dispatch problem without the need of non-real technical assumptions because the branch flow model directly involves to voltage, current, active and reactive power flow, and the generation that is used in expression that can be easily transformed to relaxed expressions, as discussed ad proved in [45].

Moreover, the use of the OPF formulation based on branch flow model allows to make other assess as the integration of RES and ESS, joint expansion planning of generation and transmission as well as considering other technologies.

In this sense, the development of these models is an essential task in the research community, as there is not currently available a commercial tool, such as DIgSILENT or ETAP, that incorporates optimization tools referred.

On the other hand, although a good accuracy and modeling flexibility are reached by using the branch flow model in TEP as it can be appreciated in Table 2, the model resultant has a high computation time that forces to solve the TEP with very few load levels and scenarios, which leads to a sub-optimal solution. Based on this, the current TEP formulation with the AC branch flow model is faster in comparison to other TEP with AC power flow but not be suitable for large-scale and real systems yet.

Table 2 – Comparison of the results for the 118-bus system

Variable	$V_{i,t,\kappa'}$, [%]	$\theta_{i,t,\kappa'}$, [%]	$P_{ij,t,\kappa'}$, [%]	$Q_{ij,t,\kappa'}$, [%]
Max. error	0.140	1.363	1.340	1.452
Avg. error	0.003	0.192	0.097	0.055

[Source: [33]]

1.2.2 Generation and transmission expansion co-planning

Traditionally, the generation and transmission expansion planning problems have been solved separately. This is mainly since, in the liberalized context existing in most developed power systems, the expansion of generation is in the hands of private companies while that of transmission is in the hands of the system planners. Besides, the lack of computation resources has traditionally made the GTEP problem hard to solve. However, a vast amount of research works have focused on the coordination of the expansion of generation and transmission [52,53]. These are classified according to a) the solution techniques applied [54, 55], relating to whether generation and transmission investments are jointly, or iteratively, computed; b) the planning strategy considered, related to whether network investments are decided proactively or reactively [56]; c) the planning type (static or dynamic) [57,58]; d) if the market environment is considered or not [54,59]; e) the representation of the network, the generation and the transmission investments [54,60,61]; f) the representation made of the system operation in the time domain, considering, either load levels, or representative periods; and g) the representation made of uncertainty, whereby the planning problem can be deterministic, probabilistic or stochastic [54,57,58].

1.2.3 Unit commitment constraints within the planning problem

The unit commitment (UC) one is becoming more and more relevant due to the integration of VRE [62]. This is one main reason to consider unit commitment constraints in the expansion planning studies; works like [63] show that ignoring these constraints within the generation expansion planning (GEP) problem leads to a sub-optimal capacity mix resulting in higher operation cost, emissions, and the lack of achievement of climate targets. The authors in [64] show how these constraints affect the planning studies. According to them, in the presence of large amounts of VRE to integrate, the representation made of the UC constraints relevantly affects the effectiveness of the existing GEP models to achieve the objectives set for the system and the efficiency of the expansion planning solution computed. The authors also conclude that the ramping constraint has the largest impact on the former than other constraints like the minimum power limit, the startup, and the shutdown of a generation unit constraints. Additionally, the aforementioned work assesses to what extent considering network and UC constraints in the GEP problem are computationally feasible, making use of an Intel CoreTM i5-5200U with two processors clocking at 2.70 GHz and 4 GB of RAM, drawing the knowledge border.

1.2.4 Cycle-based Formulation

Previous works about it are presented as follows:

According to Table 3, the cycle-based formulation is an old and little known concept in

Table 3 – Paper works about cycle-based formulation

Paper	Year	power flow	Problem Type	Solver	Application
[65]	1988	DC	LP	Own algorithm	Optimal Power Flow
[66]	2016	DC	MIP & LP	Cplex	Optimization of transmission line configuration by solving the optimal transmission switching
[67]	2016	AC	SOC & SDP	Mosek	Optimal Power Flow
[68]	2017	DC	LP	Own algorithm	Computation of PTDFs
[69]	2018	DC	LP	Cplex	Optimal Power Flow
[32]	2020	DC	MILP	Gurobi	TEP

[Source: made by the author]

power system optimization. This concept is around the Kirchhoff Voltage Law (KVL) states that the sum of voltage angle differences across lines around all cycles in the network must sum to zero. It allows a reformulation of the linearized power flow equations, which circumvents the auxiliary voltage angle variables. By reformulating the OPF, it is possible to reduce the computation time. As an example of it and concordant with the focus of this thesis, a novel cycle-based reformulation for the TEP problem with DC OPF was proposed in [32]. This formulation was tested on a realistic generation and transmission expansion model of the European transmission system, and the cycle-based formulation solves up to 31 times faster for particular cases, while averaging at a speed-up of factor 4.

Then, as preliminary research, a first study will be carried out about an assessment of the TEP problem with AC power flow based on the branch flow model to include the cycle-based formulation for AC formulation proposed in [67]. This first step allows us to reduce the computation time of solving the TEP without reduction techniques.

1.2.5 Technologies considered in TEP

Until now, the literature review was focused on the power flow formulation in TEP. However, it is essential to consider the current trends and improve the TEP. That is why this section is focused on the technologies to increase network flexibility considering VRE, ESS operation, and UC.

It is known that the intermittency of VRE raises many significant challenges to every aspect of power system operations, which generally are not taken into account in TEP. However, some works (like the proposal in [70]) show that benefits from network reconfiguration to minimize energy, spinning reserve, wind curtailment, and load shedding costs while accommodating transmission constraints. On the other hand, in [36], it is shown that ESS units may also act as complements of transmission lines; even some of its results show that, in some cases, incorporating ESS units promotes the installation of more new lines.

Moreover, from the security point, one of the critical challenges in resilient design is handling constraints associated with enforcing stability-related phase angle differences on power lines, which can be managed by introducing technologies, like FACTS and PST, for resilience purposes, as seen in [42]. Note that FACTS, PST, and switches (that optimize the network topology) are defined as non-conventional network investment (NNI) in TEP, which increase flexibility and optimize the topology of the network.

All technologies aforementioned implies to include chronological constraints (such as storage constraints, unit commitment, and switching constraints). Although the resultant problem is familiar with the TEP that considers switching and its mathematical formulation have been accepted as standard [22]. Still, these might not be suitable in the context of a low carbon emission future.

1.2.6 Efficient Reduction Techniques

Due to the complexity of the model resultant, reduction techniques are studied and tested to become the TEP to a tractable problem. Thus, two main reduction technique are presented:

1.2.6.1 Snapshot Selection Technique:

This technique is usually used to reduce the set of operational states which represent the power system operation. Typically, this type of technique uses the power demand, VRE, nodal prices, and network congestion patterns as clustering variables. Being the power demand through the load duration curve, the most used variable during the last decades [71]. However, a mix between power demand and VRE and k-means method to cluster it has been used in the previous years, as seen in [72, 73].

In [39], a novel procedure was proposed to make an efficient snapshot selection that uses the line benefit as a clustering variable. It is remarkable that this procedure achieves good accuracy (number of clusters needed to obtain the same solution as the non-reduced TEP problem) with only 15 clusters.

Currently, there are several efforts (like the proposal in [74] which present a procedure based on time-series aggregation) to make suitable representation when time-coupling constraints are considered, as an example of it are UC and ESS constraints. Nonetheless, there are not any consolidated procedure yet.

1.2.6.2 Search Space Technique:

In a regular TEP problem, the potential branches where a line can be installed is equal to the square number of bus bars. And, several lines can be installed in each branch. Also, if several types of equipment (PST, FACTS, etc.) are considered, the number is even more significant. That is why search space techniques are used to find the most promising candidates. Some criteria to identify the promising candidates are based on congested existing lines, nodal prices, overflows in lines, and candidates partially expand through the use of relaxed TEP problems. Being congested existing lines and nodal prices, the criterion most used in literature, as seen in [75–77]. However, a novel methodology was presented in [38], which is capable of having a good accuracy with few promising candidates. This set of candidates is found by solving a relaxed TEP problem iteratively.

Note that all of these methods to reduce the search space were thinking for candidate lines and that a simple extension of the technique for non-conventional candidates can lead to exciting works.

1.3 Document Outline

This document is organized in such a way that each chapter can be read independently, entirely understandable in terms of their scientific content. The structure is the following:

Chapter 2 presents the objectives to achieve PhD milestones.

Chapter 3 presents the problem definition, the resultant model that will be used, expected outputs and their potentials contributions.

Chapter 4 presents both the work done during the first year and how future tasks will be organized.

Finally, complementary and training activities are presented.

2 Objectives to achieve PhD milestones

2.1 Objectives

Based on the above-presented discussion, the main objective pursued in this thesis are related to:

- Contribute to the transmission expansion planning problem with novel theoretical and practical insights to reduce the computation time, by developing a state-of-the-art mathematical model, which must consider the technical and chronological operational constraints.
- Deal with the needs of a low carbon emission future, the planning of the operation and expansion of the network should be more accurate and flexible, while also being represented in a more compact way.

2.1.1 Sub-objectives

How these improvements can be addressed?

- Exploring the formulation of an AC power flow model considering cycle constraints in TEP,
- Integrating the operation of ESS and DR resources in the TEP problem
- Exploring the deployment of non-conventional network investments (PST, FACTS, and switchable elements) to increase network flexibility
- Identifying policy implications for the development and operation of regional systems through the application of the enhanced model to quantitative European scenarios [78] (optional)

3 PhD Thesis

3.1 Problem Definition and Mathematical Model

As it was discussed in section 1, this thesis aims at obtaining an optimal power grid design for a low carbon emission future by:

- Using an efficient TEP formulation with a suitable network representation,
- Considering high VRE shares, ESS, and UC constraints for a better representation of power system operation according to quantitative European scenarios [78],
- Increasing flexibility by network topology optimization to be carried out by installing PST, FACTS,
- Using reduction technique to obtain a solution in reasonable computation time.

Then, the thesis is focused in the TEP problem and possible ways to improve the quality of solution by having a reasonable computation time.

3.1.1 Leveraging the Power Grid with openTEPES

In order to study how to make an investment plan to obtain an optimal grid design, a TEP model will be used. For this, the model to be used is the *Open Generation and Transmission Operation and Expansion Planning Model with RES and ESS* (**openTEPES**) and it determines the investment plans of new facilities (generators, ESS and lines) for supplying the forecasted demand at minimum cost. Note that openTEPES was developed at IIT (Technological Research Institute)

In addition for this thesis, openTEPES will be used to make a tactical planning to concern with time horizons of 10-20 years (2030 and 2050). The expansion candidates are pre-defined, so the model determines the optimal decisions among those specified that satisfy simultaneously several attributes.

Its main characteristics are (**existing in black and future in blue**):

- **Static**: the scope of the model corresponds to a single year (2050) at a long-term horizon. It represents hierarchically the different time scopes to take decisions in an electric system:
  - Period: one year
  - Load Level: 8760 hours,
    from **2030-01-01T00:00:00+01:00** to **2030-12-30T23:00:00+01:00**

- Time-step: 1 hour

The time division allows a flexible representation of the periods for evaluating the system operation. For example, by a set of non-chronological isolated snapshots.

- **Deterministic**: All parameters that can influence the optimal transmission expansion decisions are predefined. Note that the operation is associated with VRE and electricity demand.
- **Multicriteria**: the objective function incorporates some of the main quantifiable objectives:
  - transmission investment cost (CAPEX) related to lines, transformers, reactive power sources, switches, PST and FACTS.
  - expected variable operation costs (including generation emission cost) (system OPEX)
- **Inputs**:
  - Demand: The demand is modeled as a chronological load curve. As the main goal is to have a realistic representation of large-scale European electrical system. Note that the demand is composed by its active and reactive part.
  - Thermal units: all existing thermal units are represented through their representative units. Thermal units are modeled considering fixed and variable operation costs, startup costs, active and reactive power limits, ramps and minimum startup/shutdown times.
  - VRE units (wind and solar) are modeled as thermal units with zero variable operation costs. Hourly Solar PV and Wind output are exogenous.
  - Synchronous condenser is modeled as thermal units with zero active power and variable operation costs.
  - Hydropower units are modeled as follows:
    * Conventional hydro unit: It is connected to a reservoir and supply energy according to water level on it.
    * Hydro-Pumped Storage (HPS): It is a hydro plant which has the same features as a conventional hydro unit but with the difference that it has the capability to pump water in order to fill its reservoir.
    * Pure HPS: Almost the same as the HPS unit with an exception that it is not subject to water inflows.
  - Transmission network is modeled as follows:
    * Transmission lines and power transformers have the following parameters: resistance, reactance, susceptance, capacity, TAP, and phase angle.
    * Capacitor or reactor bank have the following parameters: susceptance.

  - PST are modeled as following: reactance, susceptance, phase angle limits, and TAP.
  - FACTS are modeled as following: resistance, reactance, susceptance, phase angle limits, and TAP.

  Future improvements related to network topology modification using switches are planned to allow openTEPES optimize the topology.

- Search space reduction including PST, FACTS, and switchable equipment
- Identification and consideration of snapshots with chronological inter dependency – representation of inter-temporal constraints

The model formulates an optimization problem including network binary investment decisions and operation decisions.The operation model is a **network constrained unit commitment (NCUC)** based on a **tight and compact** formulation including operating reserves with a **AC power flow** based on the **branch flow model**. Also, the cycle-based formulation is applied to speed-up the computation time and the network topology can be optimized thorough switching maneuvers in bus-bars. It considers different **energy storage systems (ESS)**, e.g., pumped-storage hydro, battery, etc. It allows analyzing the impact of the use of storage capacity in the investment in transmission.

3.2 Expected Outputs

The main results of the model can be structured in these topics:

- **Performance**: Reduction of computation time (when AC power flow is considered in TEP)
- **Investment**: investment decisions and cost
- **Operation**: the output of different units and technologies (thermal, storage hydro, pumped-storage hydro, RES), RES curtailment, active and reactive power flows, active and reactive losses, voltage magnitudes, voltage angles
- **Others**: CO2 emissions and marginal costs per node

A careful implementation has been done to avoid numerical problems by scaling parameters, variables and equations allowing the model to be used for large-scale cases.

3.3 Potential Contributions

1. Network operation representation using AC power flow with cycle constraints
2. Search space reduction including PST, FACTS, and switchable equipment
3. Identification and consideration of snapshots with chronological inter-dependency – representation of inter-temporal constraints

4 Checkpoints

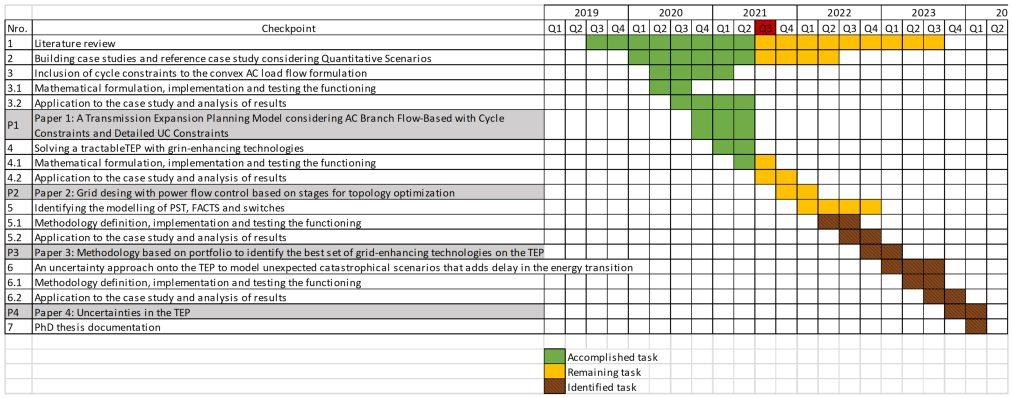

Figure 6 – Gantt diagram of the PhD thesis.
[Source: Made by the author]

4.1 First year work

4.1.1 Literature review

A literature review focusing on transmission expansion planning was performed to find the research gaps and presented in section 1.2.1. Since this thesis aims making an optimal grid design with the best network representation to improve the quality of the solution and computation time, the AC power flow formulation is chosen to represent it. Also, a brief review about cycle-based formulation was presented in section 1.2.4, which show a gap about the application of the cycles approach in TEP with AC power flow. On the other hand, technologies in TEP were presented in section 1.2.5. It shows the necessity of modelling technologies in TEP because impacts directly in TEP results. And, reduction techniques were presented in section 1.2.6. These techniques were widely studied but continue being relevant to the current context because the TEP formulation is getting harder and harder to solve.

4.1.2 Data

To test the TEP model resultant, a reference case will be used. Some characteristic of this case are presented as follows:

- Case: Large-scale European electrical system
- Nodes: > 200 bus-bars at voltage level > 220 kV
- Branches: > 200
- Time scope: 2050

As a first step to build the reference case of large-scale European electrical system, an extraction of data was made from:

- GridKit extraction of the ENTSO-E Transmission System Map. This kit model contains 6001 lines (alternating current lines at and above 220kV voltage level and all high voltage direct current lines) and 3657 substations.
- Electrical demand time series from the OPSD project.
- Open data of database powerplantmatching for power plants
- Time series related to VRE from ERA5 and SARAH, and assembled using the atlite tool.

4.1.3 Modelling

- The formulation related to AC power flow based on branch flow model was made and include in openTEPES as module.
- The cycle-based formulation was applied to the AC power flow based on branch flow model and included in openTEPES as a module
- Building test case for TEP: RTS24 and RTS96.
- An interactive visualization was made in python, as it can be seen in Fig 7.

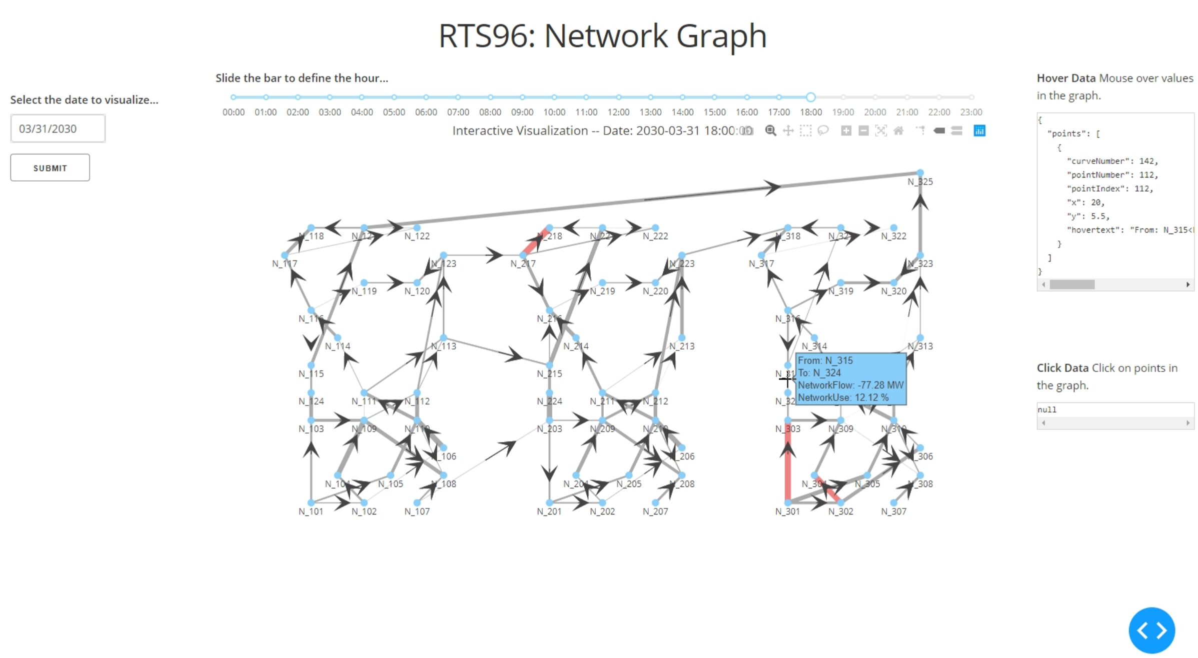

Figure 7 – Interactive visualization of the investment plan for the RTS72.
[Source: Made by the author]

4.2 Second year work

4.2.1 Literature review

A literature review about Generation & Transmission Expansion Planning was made and improved in section 1.2.2. Since this thesis is focused on an optimal grid design, it is important to take in account the generation & storage expansion planning to deal with the current trends.

4.2.2 Data

The RTS test system that is used as a system to validate results in this thesis was also updated using the recommendations presented in [79]. This test system was also modified to be used in expansion planning problems, and their parameters as installed capacities, demand profiles, energy profiles, and fixed costs were analyzed.

4.2.3 Modelling

- The openTEPES was packaged using the python standards in order to be found between all python packages published in the pypi web-page and it can be installed via pip. It can be found in the next url: `https://pypi.org/project/openTEPES/3.1.3/`
- The AC-OPF was improved as a second-order conic programming problem and included in openTEPES as an additional module
- A temporal reduction technique were designed and implemented to consider representative with hourly structure instead of the use of the hourly resolution to solve the expansion planning.
- The formulation of the optimal transmission switching (OTS) problem was also included in openTEPES as modules. The equation are also coordinated if candidate lines can make switching. Moreover, variables related to the switch-on & switch-off minimum time for staying in a on/off mode were implemented.
- In order to deal with the OTS into a TEP problem with hourly resolution in a year-planning, are being proposed switching stages. The definition of switching stages are performed by using line benefits and clusterization using kmedoids. The line benefits were performed in a methodology based on the PIN&TOOT approach with the difference that our approach can also consider existing lines.
- In the way take in account the demand response, an initial model for TSO & DSO coordination have been implemented. This model is being tested to measure its applicability in this thesis.

4.2.4 Publishing

A conference paper is almost submitted to the PSCC2022 – Power Systems Computation Conference. The title of this paper is: A Transmission Expansion Planning Model considering AC Branch Flow-Based with Cycle Constraints and Detailed UC Constraints

4.3 Remaining task

- Literature review
  - Integration of VRE and ESS, and demand response
  - Non-conventional network investments (switchable equipment, FACTS, and PST)
  - Search space reduction techniques
  - Snapshot selection techniques
- Data analysis
  - Electricity demand profiles
  - Operating reserves
  - Energy profile per hydro plant, ESS, wind farm and solar plant
  - Investment costs
  - Paper 1: Analysis related to topology optimization onto the expansion planning problem
  - Paper 2 & Paper 3
- Modelling
  - Non-conventional network investments: transmission line with DLR, FACTS, PST.
  - Search space reduction for non-conventional equipment

4.4 Complementary and Training Activities

Table 4 show the required activities to be done during the PhD program, in which the author has participated.

Table 4 – Activities in the PhD program

Training Activity	Required Hours	Current Status
Seminarios metodologicos	20h	Done
Seminarios de investigacion	20h	Done
Jornadas de doctorandos	8h	Done

[Source: made by the author]

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