Technical Optimisation of the Greek Interconnected Energy System of 2020 using EnergyPLAN model

Sustainable Energy Planning and Management
Aalborg University - 3rd Semester Project
Nikolaos Alagialoglou

January 2011

The figure of the front page shows a Wind Farm 24MW in Antia (Karystia, Evia island).
No/type of wind turbines: 40 x Bonus 600KW MkIV. Connected to: PPC Substation in Livadi
In operation since: November 1999. The figure can be accessed from the webpage of “Invest in Greece Agency”
(http://www.investingreece.gov.gr/files/images/ROKAS_EVIA_ANTIA_1.jpg)

Aalborg University – Sustainable Energy Planning and Management, 3rd semester

Semester theme: Professional Development

Project title: "Technical Optimisation of the Greek Interconnected Energy System of 2020 using EnergyPLAN model."

Project period: 1st of September 2010 to 5th of January 2011

Project Group: SEPM3_2010-7

Author:

Nikolaos Alagialoglou

Supervisor: Brian Vad Mathiesen

Number of printed copies: 3

Pages: 70

Abstract

The point of departure of this report is how can the Greek Interconnected Energy System of 2020, as it is shaped by the plan for compliance with the 20-20-20 targets, be technically optimised aiming at a high wind penetration, with EnergyPLAN model. This problem is analysed by the formulation of a research question and four sub-questions, which support the approach of the overall research question.

All the necessary data for the modelling of the system are collected and formulated in order to be inserted to EnergyPLAN. The way that the operation of the units is technically regulated according to the optimisation process of EnergyPLAN is described and the outputs are compared with similar results obtained from CRES simulations. A sensitivity analysis is conducted so that the impact of various parameters can be unveiled, based on criteria such as the minimisation of excess electricity production, fuel consumption and CO2 emissions. Furthermore, the findings of the previous analysis are used to compose four different scenarios, so that the maximum wind penetration technically feasible for the system can be identified.

Based on the knowledge obtained from all the former analyses, conclusions concerning the technical optimisation of the Greek Interconnected Energy System of 2020 as well as the investigation of the technically optimum wind penetration are provided. In this way, a thorough answer in the Research Question of the project is achieved.

Faculties of Engineering, Science and Medicine
Department of Development and Planning
Sustainable Energy Planning and Management
Fibigerstræde 11-13
9220 Aalborg East
http://energyplanning.aau.dk

Preface

This report is written as a 3rd semester project at the Master of Science programme "Sustainable Energy Planning and Management", at Aalborg University. The theme of the semester is "Professional Development". Therefore, the project was conducted in the framework of my internship in the Centre of Renewable Energy Sources and Saving (CRES) in Greece. The duration of the internship was 3 months, beginning from 1st of September and ending to 30th of November. During this period, I had collaboration with the Energy Systems Analyses Laboratory which belongs to the Division for Energy Policy and Planning of CRES in order to accomplish the project that is described in the present report.

CRES is the Greek organisation for Renewable Energy Sources (RES), Rational Use of Energy (RUE) and Energy Saving (ES). Furthermore, CRES has been appointed as the national co-ordination centre in its areas of activity. Its main goal is the research and promotion of RES/RUE/ES applications at a national and international level, as well as the support of related activities taking into consideration the principles of sustainable development.

Within the recent activities of Energy Systems Analyses Laboratory was to contribute to the editing of the Greek National Renewable Energy Action Plan, as it is indicated by the DIRECTIVE 2009/28/EC of the European Parliament and of the Council. Therefore, the members of this Laboratory of CRES were responsible for doing all the modeling of the Greek Energy System in accordance with the binding targets set by the Directive and the relevant national laws.

Concerning my activity in CRES, after being accepted to have my internship there, it was agreed with the Head of the Laboratory, Dr. George Giannakidis, to work over a project for the optimisation of the Greek Energy System of 2020, as it is shaped by the plan for compliance with the targets of 20-20-20, using the Energy Systems Analysis model EnergyPLAN. It was decided from the beginning that emphasis should be placed on the effects of the high penetration of renewable energy sources and in particular wind. Also, the minimisation of the excess electricity production was among the initial main intentions of the project.

It is worth mentioning that the Chicago style is used for referencing.

I would like to give special thanks to the following persons for their help and the excellent cooperation, during my project work in CRES:

- Dr. George Giannakidis, Head of Energy Systems Analysis Lab.
- Mr. Kostas Tigas, Director of Division for Energy Policy and Planning
- Giannis Mantzaris, Member of Lab
- Nikolaos Sakellaridis, Member of Lab
- Christos Nakos, Member of Lab
- Phillip Siakkis, Member of Lab

Also I would like to give special thanks to Mr. George Markogiannakis for his meaningful advice as well as Ms. Fotini Karamani for sharing her office.

The author:
Nikolaos Alagialoglou
30/12/2010

Table of Contents

1 Introduction

As it is clearly stated by the European Commission, the foremost exponent of EU policy, energy constitutes the driving force of Europe. It is a necessity to put all the energy challenges such as: the climate change, the depletion of energy resources, the energy security, the decrease of dependency on imports and the guarantee of affordable energy for all consumers at the top of the list of priorities. Taking all these challenges as a point of departure, EU declares that is ready to follow an ambitious energy policy consisted of drastic changes to the full scale of the European energy systems. This “new industrial revolution”, as it is characterised, aims at leading to sustainable energy economies. Renewable Energy Sources (RES) as well as Energy Efficiency will have a key role to this energy shift. (EUROPA n.d.)

All the available types of RES such as solar power, wind power, hydroelectric power, biomass resources and geothermal energy it is possible to be utilized in order to replace the consumption of fossil fuels. Furthermore, the implementation of energy efficiency measures can contribute to the minimisation of energy consumption and energy losses. Therefore, both RES and energy efficiency, by increasing energy security, improving the national economies, stimulating employment and dealing with climate change, represent credible solutions to the energy challenges that Europe has to face. (European Commission 2010)

1.1 Subject background on EU level

In this framework, the European Union expressed its willing to transform its intentions, concerning energy issues, into tangible policy by adopting DIRECTIVE 2009/28/EC. As it is referred in the 1st Article of the Direction, its main scope is to encourage the promotion of the use of energy from renewable sources and set specific targets which will be mandatory for each Member State (DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL 2009).

Particularly, this Directive according to Article 3 §1 states that all the Member States should follow the national targets, as these are set in the Annexes of the Directive, so that EU will achieve at least a **RES share in the gross final consumption of the community up to 20% by 2020**. According to Article 4 §1, each Member State has to issue and adopt a National Renewable Energy Action Plan (NREAP). Each NREAP should set national targets binding for the Member States concerning the RES share consumed in all the energy sectors (electricity, transport, heating and cooling) up to 2020. Among others, a NREAP will also call for specific actions related to energy efficiency measures on final consumption as well as for collaboration of Member’s authorities in all levels. Directive 2009/28/EC should be put in action by Member States by December 2010. (DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL 2009)

It should be also mentioned that, at the end of 2006, EU had set another goal by adopting Directive 2006/32/EC. According to this, **EU has to reduce the annual primary energy consumption by 20% until 2020** (DIRECTIVE 2006/32/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL 2006). The aforementioned two goals along with a goal for **20% reduction of greenhouse gas emissions** (DIRECTIVE 2009/29/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL 2009) compose the triple target of the ‘20-20-20’ by 2020 (EUROPA 2009).

1.2 Subject background on national level

Under the harsh financial conditions that dominate Greece the last period, the triple target of ‘20-20-20’, apart from obligation, appears to be a chance for economical development and a unique opportunity to help the country to “pull through”, via the so-called green development. It is considered that the triple target is going to increase the energy security of the country, to attract capitals for investment and boost both the tourism and agricultural sector. (The Stability and Development Programme | Prime Minister’s speech 2010)

According to the Greek NREAP fundamental changes in the Greek energy system need to be implemented both in a technical and in a regulatory level, so that the specific targets set by the Directive 2009/28/EC can be met. Particularly for Greece, the targets indicate the reduction by 4% of the GHG emissions comparing to the emissions of 2005 and 18% RES penetration in the gross final consumption (DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL 2009). Considering these targets, in the electricity sector, which is the main focus of this project, a series of actions aiming at a higher RES penetration has been planned. Therefore, the full exploitation of RES potential by developing large scale RES plants, the gradual decommissioning of old and low-efficiency condensing power plants, the completion of the essential grid infrastructure and the planning of new distributed power units constitute such actions. (Ministry of Environment Energy & Climate Change n.d.)

The first step in order to put in action the aforementioned changes is to define the share of each renewable technology in the national energy mix. This can be done by taking into account various socio-economical parameters along with the installation costs of each renewable technology. Based on these factors, a number of scenarios for the evolution of the energy sector until 2030 were composed in the framework of the Greek NREAP (GNREAP). Furthermore, the GNREAP has to deal with barriers related to bureaucracy, time-consuming licensing processes and limited investment capitals in order to plan for a productive but at the same time realistic exploitation of RES. (Ministry of Environment Energy & Climate Change n.d.)

Summarizing the findings of the GNREAP, it is estimated that the share of RES plants in the power generation needs to be tripled and the full potential of all the available RES technologies need to be exploited so that the 20-20-20 targets can be achieved. Concerning the first stage of planning up to 2020, priority will be given to energy projects with substantial impact on the shift of the electricity generation which are already mature both technologically and investment wise.

Some indicative measures concerning the electricity production in the Greek Interconnected Energy System are the following:

- Carbon Capture and Storage technologies will be applied to lignite power plants which will be able to take advantage of biomass residues via co-firing
- A gradual decommissioning of the condensing power plants will take place according to their efficiency and levels of pollution
- Development of large-scale RES plants i.e. wind farms, hydro plants and CSP plants, together with medium & small scale RES plants based on photovoltaics, small hydro, biomass cogeneration, biogas, and geothermal
- Spreading of RES applications for electricity production in buildings of the residential and commercial sector
- Construction of new pump hydro plants, which are going to contribute to grid stabilization and reduced wind energy curtailment
- Addition of natural gas combined cycle plants and gas turbines (in a smaller extent)
- Development of CHP units

Furthermore, special emphasis will be put on the development of infrastructure related to smart grids, including monitoring and communication technologies. In this way a reduction of grid losses and an improvement in the demand-side management can be achieved (Ministry of Environment Energy & Climate Change n.d.).

According to the recent law L3851/2010, through which the targets set by the EU Directives are adopted by the national law system, the Greek government has set a target for 20% RES penetration (18% is what EU has set for Greece). Specific targets for 40% RES share in electricity production at least, 20% RES in heating/cooling and 10% RES in transportation have been also put in place. (Law 3851 2010) Finally, concerning the energy saving, Greece has already issued the first Energy Efficiency Action Plan (EEAP 2008) which calls for 9% energy saving in final consumption until 2016 according to Directive 2006/32/EC, while the target of 20% that has been set as an overall for EU has not been specified for each Member State individually (Tigas n.d.). In this framework, the energy mix for the electricity production of 2020 has been defined based on modeling calculation and considering all the targets which apply for Greece as they have been referred.

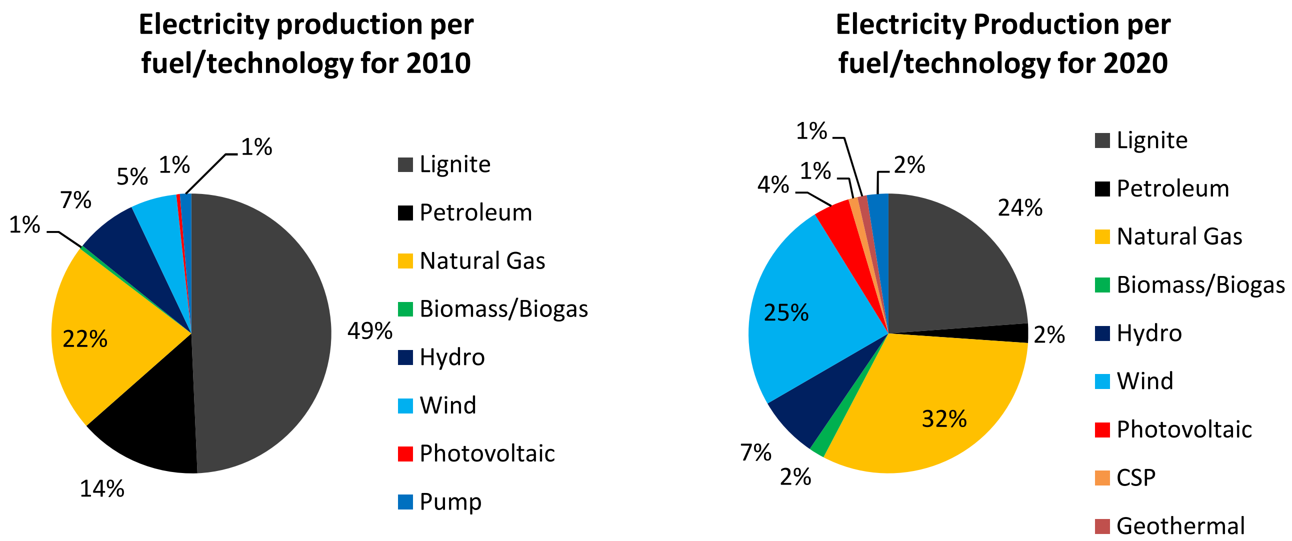

Figure 1.1: Estimated electricity production from the different technologies/fuels for 2010 and 2020 (Results Compliance Scenario 2010)

The contribution of RES to the national energy balance in 2010 is estimated approximately equal to 9% of gross final energy consumption. As for the electricity production from RES in 2010 is estimated equal to 13% in electricity production, including the production of large hydro power units but excluding the production from pumping. (Ministry of Environment Energy & Climate Change n.d.)

The development of the installed capacity that needs to be followed, according to the estimations of the Greek NREAP, in order to meet the triple target of 20-20-20 by 2020 can be seen in Figure 1.2.

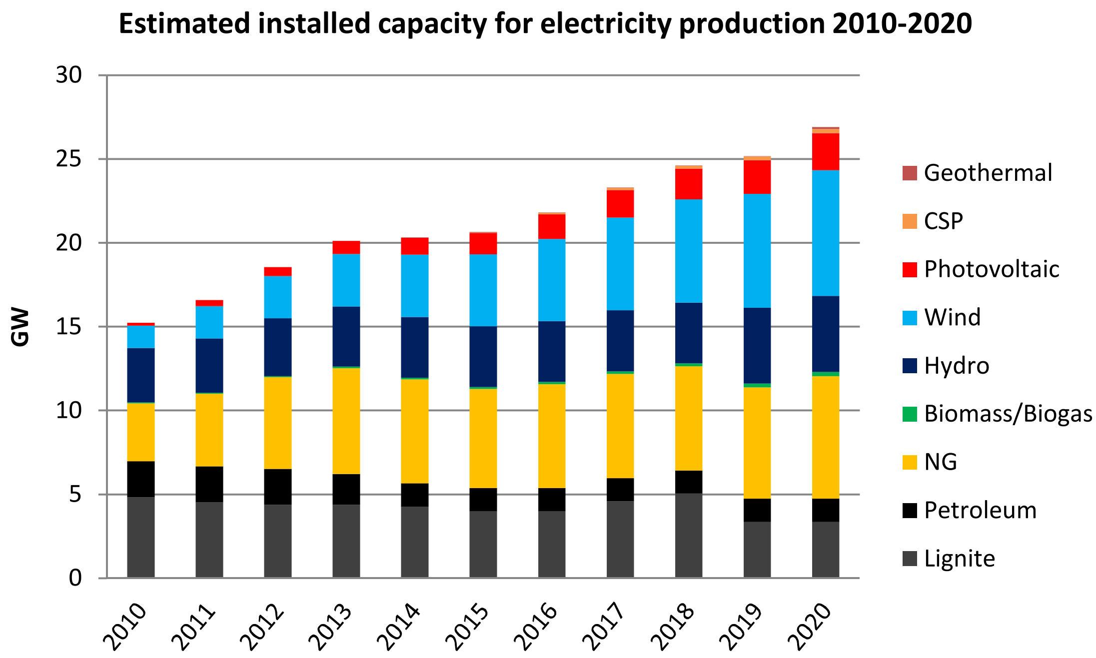

Figure 1.2: Estimated installed capacity of the different technologies for electricity production (Results Compliance Scenario 2010)

1.3 The core of the report and the Research Question

Taking as point of departure the triple target of '20-20-20' by 2020, as this has been set by the Directives of the European Union and has been transferred to the conditions of the Greek Energy System through the Greek NREAP, this project aims at investigating how the Greek Interconnected Energy System of 2020 can be technically optimised by using EnergyPLAN model, in order to accommodate a high RES penetration. Therefore, the Greek Interconnected Energy System, as it has been shaped according to the simulations of the host institute (CRES) for the scenario of compliance with the binding targets for 2020, is modelled with EnergyPLAN. The scope of the project is to identify how both the electricity and the heat generating units of the system should be regulated, considering all the technical requirements which are related to the operation of the units, based on three criteria:

- the minimisation of excess electricity production
- the minimisation of fuel consumption
- the minimisation of CO2 emissions

Special emphasis is put on the excess electricity production since the full potential of all the available RES technologies need to be exploited so that the 20-20-20 targets can be achieved, as it is clearly stated in the Greek NREAP. This means that all the components of the system need to be regulated in a way that the electricity produced is not wasted as excess but it is fully absorbed by the system.

Given that similar simulations have been conducted by CRES, using a combination of models such as MARKAL, WASP, COST and ENPEP, it is interesting to compare their outputs with those of EnergyPLAN mainly due to two reasons. The first one is that by comparing the results the validity of the findings of this project is being examined. The second reason is that by spotting the differences on the results of the two simulations useful conclusions concerning the logic behind the estimations of each simulation can be drawn.

Furthermore, various parameters which are involved in the optimisation process are determined and the impact of them in the behaviour of the system is evaluated according to the aforementioned criteria. In this way the project is able to provide with options which will contribute to a further minimisation of both the excess electricity production and the total fuel consumption. The positive impacts by implementing the proposed options can be scaled according to the findings of the project so that their influence can be prioritised.

Finally, various scenarios based on the combination of the parameters that proved to be crucial for the optimisation of the system are composed. These scenarios are used to investigate the optimum wind penetration considering the excess electricity production and the fuel consumption as a function of the installed wind capacity, which is increased continuously.

In this framework the Research Question along with the sub-questions, which govern the structure of the report, arise:

How can the Greek Interconnected Energy System of 2020, as it is shaped by the plan for compliance with the 20-20-20 targets, be technically optimised aiming at a high wind penetration with EnergyPLAN model?

- How can the operation of energy generating units be regulated so that the excess electricity production, the total fuel consumption and the CO2 emissions of the system can be minimised?

- What are the differences in the operation of the units and the general behaviour of the system between EnergyPLAN and the models used by the host institute?

- Which parameters, of those involved in the optimisation process, and to what extent can contribute to a further minimisation of the excess electricity production and the total fuel consumption of the system?

- What is the maximum feasible wind penetration on the 2020 Greek Interconnected energy system, as a function of the installed wind capacity, from a technical perspective?

1.4 Report's Structure

In this section the structure of the report will be presented, as this was composed in order to answer the sub-questions and the main Research Questions of the project (see Figure 1.3). Furthermore, the way that each chapter serves this scope and contributes to the coherence of the report will also be explained.

The 1st chapter is the Introduction of the report that provides the reader with all the information relevant to the subject of the project in order to introduce him to the core of the project. The core is summarised in the Research Question and it is further specified by the sub-questions.

In the 2nd chapter all the concepts as well as methods which were put in place both in the data collection and in the analysis stage of the project are mentioned. Moreover, the way that all these are used for the scopes of the project is explained.

Within the 3rd chapter the data that were inserted in EnergyPLAN are presented along with all the technical assumptions that were considered as well as some specifications concerning the way that they were formulated in order to match with the structure of the model.

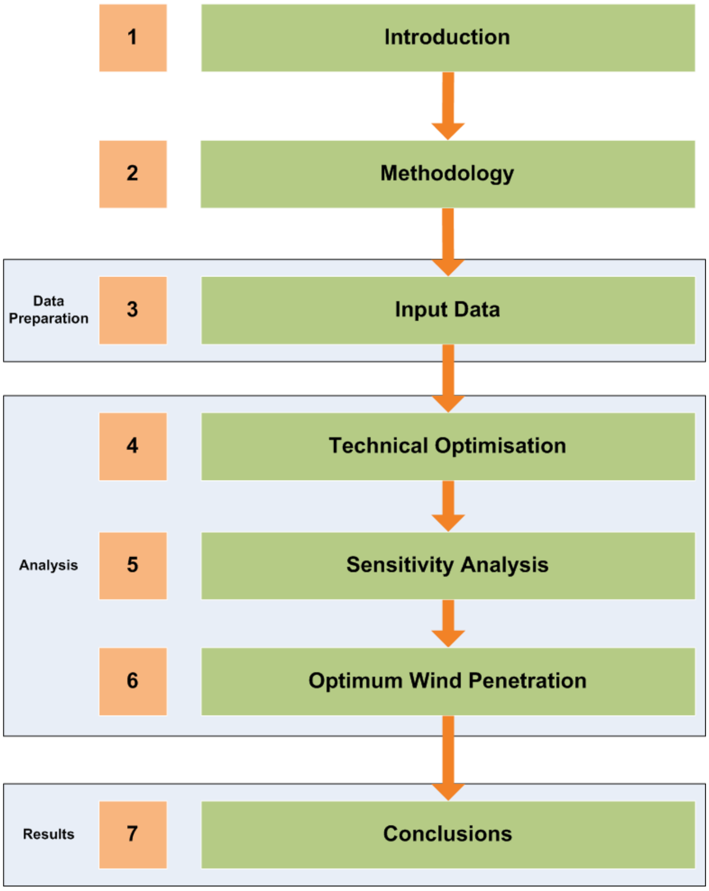

Figure 1.3: The structure of the report

The 4th Chapter constitutes the first chapter out of three which belongs to the analysis part of the present report. Based on the data described on Chapter 3 the reference system which represents the Greek Interconnected Energy System of 2020 is composed. This system is used to study how the operation of the units is regulated according to the optimisation process of EnergyPLAN. Moreover, the outputs of EnergyPLAN are compared with similar results obtained from CRES simulations.

In the framework of the 5th Chapter a Sensitivity Analysis is conducted so that the impact of various parameters considered by EnergyPLAN while optimising the units can be unveiled. The effects of those parameters are examined based on the criteria which have been already mentioned i.e. excess electricity production, fuel consumption, CO2 emissions.

In the 6th Chapter four different scenarios are constructed using the findings of the previous chapter so that the maximum wind penetration technically feasible can be defined for the system. This analysis is conducted based on two different approaches adding in this way one more interesting perspective on the project.

The last Chapter, the 7th one, lists all the conclusions which can be inferred from this project by answering the sub-questions one by one. In this way a thorough answer in the Research Question, which was initially placed, is given.

1.5 Delimitation

The Greek Energy System is divided into the National Interconnected System (see map in Appendix I) which covers the mainland and the non-Interconnected System which consists of the autonomous power systems of the islands (Regulatory Authority for Energy n.d.). One of the main limitations which apply to this project is that only the Interconnected Energy System of Greece is studied. This is done because the two systems must be modelled separately so that the optimisation can be more realistic. If the aggregated values which correspond to the quantities of both the Interconnected and the non-Interconnected were inserted, the model would have the option of replacing units of the one system with units of the other. Practically this is not possible.

Furthermore, a technical optimisation was considered from the very beginning as suitable to serve the scopes of the project, as these have been presented in section 1.3. This project focuses on the optimisation of the Greek Interconnected Energy System from a technical perspective considering only the technical parameters which are involved such as the grid stability requirements, the technical minimums of condensing units and the available transmission lines capacity based on technical criteria i.e. minimisation of excess electricity production, fuel consumption and CO2 emissions. This is why the project is delimited by conducting a market economic analysis in which all the economical conditions of the Greek Energy System, such as marginal production costs of the individual electricity production units and market prices, should be taken into account. It is quite important for the reader to keep in mind that all the outputs of the project which are presented in the following chapters are exclusively based on pure technical data and not any economical conditions are involved. Probably the outputs would be different in case of an economical optimisation but this is out of the question in the present project.

2 Methodology

This Chapter starts with the basic methods for data collection as well as the concepts which are used in the framework of the analysis' part of the project. Moreover, EnergyPLAN as an energy system analysis model is described. Finally, the models of the simulations of CRES for the Greek NREAP are briefly presented as well as their functionality in the context of the specific project.

Table 2.1: Methodological approach of sub-questions

Sub-question	Concept	Research tool	Chapter
1. How can the operation of energy generating units be regulated so that the excess electricity production, the total fuel consumption and the CO2 emissions of the system can be minimised?		- Document analysis - Literature studies - EnergyPLAN	4
2. What are the differences in the operation of the units and the general behaviour of the system between EnergyPLAN and the models used by the host institute?		- Document analysis	4
3. Which parameters, of those involved in the optimisation process, and to what extent can contribute to a further minimisation of the excess electricity production and the total fuel consumption of the system?	Sensitivity analysis	- Literature studies - EnergyPLAN	5
4. What is the maximum feasible wind penetration on the 2020 Greek Interconnected energy system, as a function of the installed wind capacity, from a technical perspective?	Scenario planning	- Literature studies - EnergyPLAN	6

In addition to the tools mentioned in the Table above, Excel is also used in various stages of the projects from the preparation of the data in order to be inserted in EnergyPLAN (Chapter 3) to the graphical solution for defining the optimum wind penetration for various scenarios (Chapter 6).

2.1 Document analysis and Literature studies

Document analysis and literature studies are the basic tools which were used several times throughout this project in accordance with the needs of each chapter. A wide range of scientific papers, reports and excel files with necessary data were studied and analysed during the period of running this project. However, some of them are not referenced in specific points of this report since most of the times they were just treated as incentives for inspiration. These sources are referenced in this section given that interesting information can be found there for future studies.

Sources such as (Energy Outlook of Greece 2009) and (Annual Report 2009), were used in the 3rd chapter in order to gain an overall insight of the Greek Energy System. Moreover, helpful sources which explain the way that the necessary data can be collected for the modelling of an energy system with EnergyPLAN are the following: (Connolly 2009), (Connolly, A User's Guide to EnergyPLAN Version 3 2010) and (Mathiesen 2010). Reports like (National Energy Data System | Manual 2010) appeared to be helpful for the interpretation of the available data. Many other documents edited by the Energy System Analysis Lab of the host institute, in the framework of producing the Greek NREAP and not only, were reviewed and they are referenced where it is applicable in the following chapters.

In the 4th Chapter for the needs of the first sub-question a series of scientific papers and articles was used as inspiration (Østergaard 2009), (Henrik Lund, Modelling of energy systems with a high percentage of CHP and wind power 2003), (Henrik Lund 2003). Furthermore, the background document of the Greek NREAP (Energy Scenarios Analysis of RES technologies' penetration in the Energy System and Achievement of 2020 National Targets using the models MARKAL, ENPEP, WASP and COST 2010) was reviewed in order to answer the second sub-question.

In the 5th and 6th Chapter, where various parameters of the reference system were investigated and they were combined in order to compose scenarios suitable for analysing the optimum wind penetration, various articles constituted excellent stimulants (Lund, Excess electricity diagrams and the integration of renewable energy 2003), (Lund, Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply 2005) and (Lund, Large-scale integration of wind power into different energy systems 2004).

2.2 Sensitivity Analysis

Sensitivity Analysis (SA) constitutes a research tool which is used in order to attribute variations that are observed in the outputs of a mathematical model to certain inputs of the model, either qualitatively or quantitatively (Saltelli 2008). Generally speaking, SA is a commonly used method for unveiling the correlation, if any, between models' inputs and outputs, by changing the values of the inputs and evaluating the impacts of the changes to the outputs. Usually, Sensitivity Analysis is utilized in order to examine the robustness of a study which is centred on a model, behind of which some mathematical logic lies. In this way, SA appears to be really beneficial for the developer of a model in the process of forming recommendations. Furthermore, conducting an SA can be useful for modellers since it facilitates their communication with people who make the decisions by increasing both the credibility and the understandability of their recommendations. Last but not least, through an SA potential errors in the model can be discovered contributing in this way to the improvement of it. (Pannell 1997)

2.3 Scenario planning

The scenario planning approach consists of a series of stories including "what-if" questions. In this way the user of a model or people who make the decisions are encouraged to think of various procedures as they have already occurred. This process of in depth thinking helps assumptions about the future to be identified. According to Peter Schwartz: "A scenario is a tool for ordering one's perceptions about the alternative future environments in which one's decisions might be played" (Schwartz 1998). Consequently, the scenarios do not constitute an attempt for predicting the future but preferably they are a way of preparing ourselves for different conditions in the future.

2.4 EnergyPLAN model

EnergyPLAN is an Energy Systems Analysis computer model which was first developed in 1999 and it is expanded continuously. EnergyPLAN is a user-friendly tool designed in a series of tab sheets and programmed in Delphi Pascal. A key feature of EnergyPLAN is that the analysis is conducted hour by hour for one year period on the basis of either technical optimisation strategies or market-economic strategies. The computation of 1 year needs just a few seconds in a normal computer to be conducted, since all the time consuming procedures are avoided. The model mainly aims at assisting the design of national energy planning strategies by analysing the outputs of different national energy systems and investments, either technically or economically. This is done by simulating the entire energy-system including heat, electricity, transport and industrial sectors. Special emphasis is put on the interaction between the production of cogeneration units and fluctuating renewable energy sources. Finally, it needs to be underlined that EnergyPLAN optimizes the operation of a given system instead of optimizing investments in the system, as many other tools. (D. Connolly 2009) (Lund, EnergyPLAN 2010)

EnergyPLAN is a deterministic input/output model with inputs such as demands, costs, RES, units' capacities, different regulation strategies for imports/exports and excess electricity production. The outputs can be hourly energy balances, annual productions, fuel balances and total costs. Suggestively, the available excess electricity production regulation strategies which can be implemented are the following seven:

1: Reducing RES1 and RES2

2: Reducing CHP production in group 2 (Replacing with boiler)

3: Reducing CHP production in group 3 (Replacing with boiler)

4: Replacing boiler production with electric heating in group 2.

5: Replacing boiler production with electric heating in group 3.

6: Reducing RES3

7: Reducing power plant production in combination with RES1, RES2, RES3 and RES4

The seven options are activated in a priority, either individually or in any possible combination.

Three different kinds of energy systems analysis can be conducted by EnergyPLAN:

1. A **technical analysis** of national energy system under various technical regulation strategies such as:

- Balancing heat demands
- Balancing both heat and electricity demands
- Balancing both heat and electricity demands while reducing CHP also when partly needed for grid stabilisation
- Balancing heat demand using triple tariff

Strategy 3 is similar with Strategy 2 apart from the fact that in 3 the model has the option of reducing the production of CHP when it is partly needed for grid stabilisation reasons. This means that in case of excess electricity production the model is able to reduce CHP and replace it with boilers for covering the given heat demand and even with condensing Power Plants for fulfilling the given grid stability requirements.

The technical analysis requires energy demands, production, efficiencies and capacities as well as energy sources for inputs. The outputs are annual energy balances, fuel consumptions and CO2 emissions.

2. A **market-economic analysis** of trade and exchanges in international electricity markets. Additional inputs for defining the prices on the market and estimating the response of the prices in import/export changes are required. Economical data for the marginal production cost of the units need also to be inserted. In this analysis each plant is optimised according to business-economic profits.

3. **Feasibility studies** can be conducted with EnergyPLAN by adding data for investment costs, operation and maintenance costs, lifetimes and interest rates. Moreover, the socio-economic impacts of the productions can be defined.

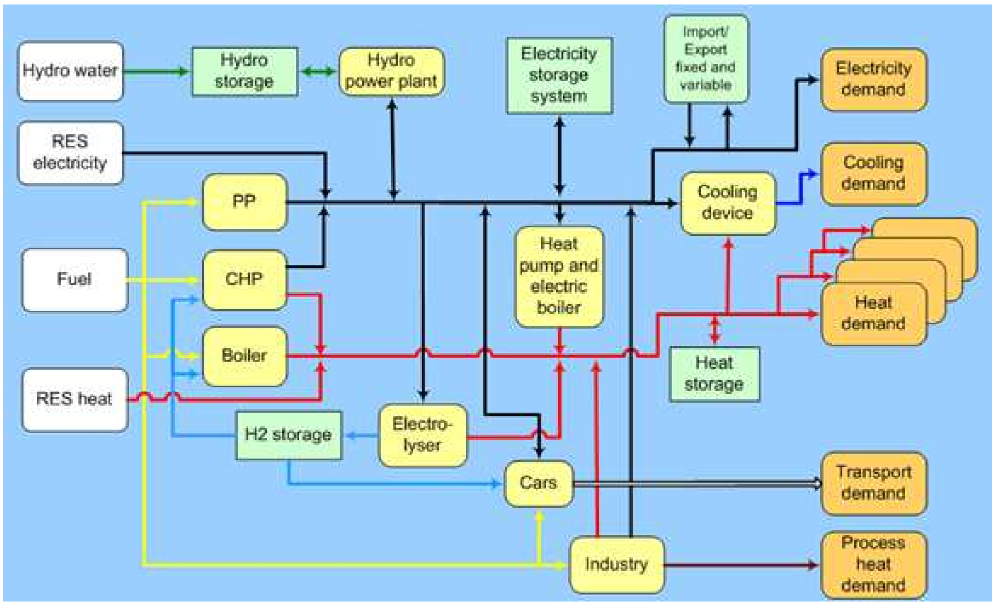

Figure 2.1: Energy system outline in the EnergyPLAN model. Front page view of the model downloadable from energy.plan.aau.dk

Basically, the model differentiates the technical regulation and the market-economic regulation, since only one of the two optimisation strategies can be selected. The technical optimisation minimises the import/export of electricity and aims at identifying the solution with the lowest possible fuel consumption. The market-economic optimisation identifies the solution with the lowest possible cost based on the business-economic costs of each production unit. (Lund, EnergyPLAN 2010) For the scope of this project, as it has been already mentioned in the Delimitation (Section 1.5), Technical Optimisation was selected.

2.5 CRES models

In the study that was conducted by the host institute, in the framework of the Greek NREAP, the possibilities of development of the national energy system under the light of the New European Policy concerning the RES penetration, the energy saving and the minimization of CO2 emissions have been analysed (triple target of 20-20-20). The accomplishment of the targets is examined with two energy models based on different logic: MARKAL, which is a technological bottom-up optimisation model, and ENPEP which is a hybrid simulation model. Therefore, two groups of scenarios were created, in order to conduct sensitivity analyses related to the cost of different technologies, the future penetration of lignite in the electricity production etc. In the qualitative analysis mathematical models such as WASP IV and COST took place also. (Tigas n.d.)

The elaboration of the first group of scenarios was accomplished by using MARKAL, WASP and COST with a specific sequence. Firstly, MARKAL provides a solution of the model, based on given assumptions for each scenario, defining in this way the development of electricity demand. The electricity demand of the Interconnected Energy System is used as input data in WASP model, in which the optimised electricity generation system is determined. After that, this solution is inserted in COST model in order to simulate the operation of the Interconnected System so that the excess wind power can be analytically identified and the correction of the corresponding capacity factor can be achieved. The solution of COST corrects the solution of WASP model and from this updated solution the outputs of MARKAL are also corrected. (Tigas n.d.)

The elaboration of the second group of scenarios is done with models BALANCE/ENPEP as well as a simplified version of WASP which is built in ENPEP. Given that ENPEP is not an optimisation model but a simulation one, the development of the technologies which comes as a result includes technologies and measures which are not strictly connected with the lowest cost solution. (Tigas n.d.)

It should be noted that the combination of models that were used in the simulations of CRES hereinafter often will be referred as “models’ set” or some times, for reasons of simplicity, “CRES model” or just “model” when CRES is implied.

3 Input Data

Whether to include this chapter or not was in doubt due to the extent limitations and the fact that all the points of the analysis part need to be brought forward and justified. However, it was considered that the description of the inputs make a study like this to be more concrete. Moreover, a rather high share of the time spent for the project was devoted to data collection and preparation. Therefore, all the data which were inserted in the model will be presented summarised in tables and graphs. Emphasis will be put on the data related to the electricity sector since the optimisation of it is the main focus of the project.

3.1 Electricity Demand

In Table 3.1 all the different types of electricity demands that were inserted in EnergyPLAN are listed. In the fixed value the total electricity demand of the final consumers of all sectors is included along with the electricity demand of the energy sector itself, since it constitutes a demand that needs to be covered by the electricity production of the system's units. Even the losses of the grid need to be included since they are a separate electricity demand.

Table 3.1: Various Electricity Demands inserted in Electricity Demand tab of EnergyPLAN

Electricity Demands	TWh/year
Fixed demand	50,09
Electric heating	3,94
Heat Pumps	1,08
Electric cooling	3,86
Flexible demand	0,52
Total	**59,5**

The distribution of the fixed electricity demand which is inserted in the model appears in Figure 3.1 as % percentage of the maximum electricity load (indexed values), which occurs during the summer period in the end of July, as it can be observed.

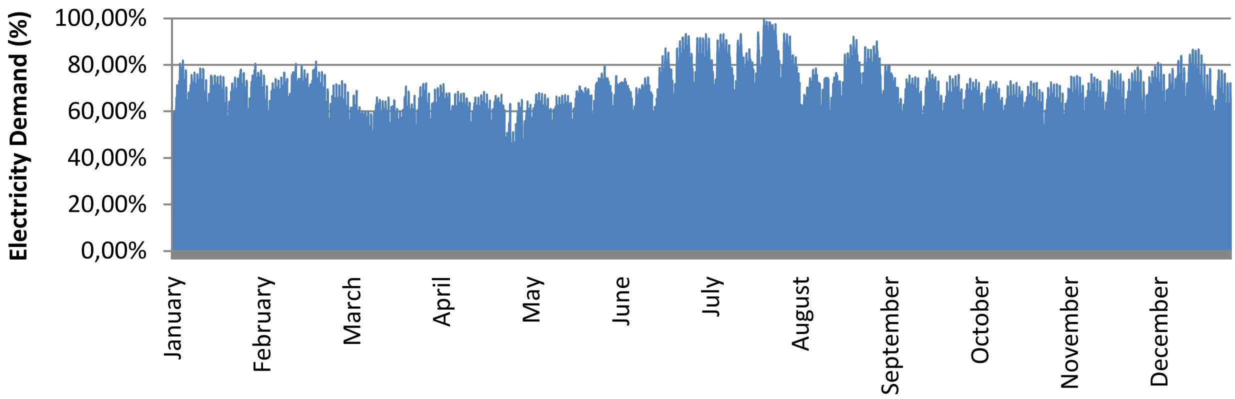

Figure 3.1: Annual hourly distribution of fixed electricity demand as a percentage of the maximum load

Electricity demands such as electric heating, heat pumps and electric cooling are described in the corresponding sections which follow.

A flexible demand of 0,52 TWh which represents the electricity consumption of electric vehicles in the transportation sector is also added. This demand is freely distributed over a 24-hour period according to the actual electricity balance. Therefore, there is the possibility of concentrating the demand at the actual peak hours for e.g. wind production. However, this requires a method of communicating this knowledge to the consumers, which is supposed to be existent here. The model also provides the option of flexible demands for one or four-week period. (Lund, EnergyPLAN 2010)

3.2 Condensing PP and CHP

All the data which are related to the operation of both the condensing Power Plants and the CHP units are inserted in the District Heating tab of EnergyPLAN. In this tab there are three different groups each one representing a separate DH category:

Group I: DH systems without CHP

In this group systems that use boilers, waste heat or some other form of heat supply other than CHP are included (Connolly, A User's Guide to EnergyPLAN Version 3 2010). In the Greek Energy System such systems do not exist since there are not autonomous heating plants.

Group II: DH systems based on small CHP-plants

Within the Greek Energy System there are not individual CHP plants which cover a specific DH demand. Individual industrial units constitute the only small CHP plants existent. These Industrial CHP plants produce electricity, a share of which is consumed by the industry itself, and heat which is used as process heat. Therefore, there is not heat produced to cover some DH demand but there is a share of the produced electricity equal to **4,974 TWh** which is fed to the electricity grid. This electricity production is placed in the Industry tab under the tag of Group 2. Since the industrial CHP in Greece is not subjected to any regulation, a constant distribution is used for Industrial CHP (included in the standard Distributions' file of EnergyPLAN as "const.txt"). This means that the output is considered to be simply constant which is the best proxy for modelling a production that cannot be controlled (Connolly, A User's Guide to EnergyPLAN Version 3 2010).

The fuel distribution of the Industry sector can be found in Table 4.13. The values in the table represent the total consumption of the Industry sector per fuel (fixed values). A share of these corresponds to the consumption of the small Industrial CHP plants.

Group III: DH systems based on large CHP extraction plants

In this group there should be included all the centralised CHP capacity. The determinant difference between group 3 and group 2 is the fact that for these plants it is not necessary to create heat while electricity is produced. They are able to remove the heat from their system by using water (usually from a river or the sea). (Connolly, A User's Guide to EnergyPLAN Version 3 2010)

In accordance with the conditions of the Greek Energy System, under this group data concerning the CHP part of large extraction plants (often referred as CHP3 units in this report), as well as data for the condensing Power Plants themselves have been inserted. Large Power Plants which are considered to constitute of a CHP part are the following: Agios Dimitrios units 3, 4 and 5 as well as the new plant in Florina (Evaluation of the National Potential for the Cogeneration of Electricity and Heat in Greece 2008).

The District Heating demand that needs to be covered by the CHP part is equal to 1,27 TWh. This value is the sum of the heat consumption of the Residential and the Commercial (or else Tertiary) sector (Results Compliance Scenario 2010).

Analytical data for CHP3 units were obtained from (Hellenic Association for the Cogeneration of Heat and Power - H.A.C.H.P. 2009), (Municipal Company for Water Supply and Sanitation of Kozani 2010) and (Pavlidis n.d.). The methodology which has been followed in order to define the capacities and efficiencies of CHP3 is explained thoroughly in (ΦΕΚ 8/A'/28-1-2009), (ΦΕΚ 1420/B'/15-7-2009 n.d.). According to this methodology, when the total efficiency (sum of electric and thermal efficiency) of the plants is lower than 0,8 which is the standard value for the specific cogeneration technology (condensing-extraction steam turbine with heat recovery) means that the plant is not operating fully in cogeneration mode but a share of electricity is produced without the simultaneous production of useful heat. In this case the unit is considered to be consisted of two parts: the CHP part and the non-CHP part.

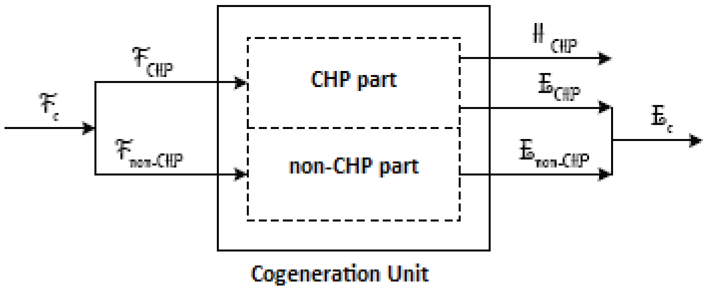

Figure 3.2: Separation of cogeneration unit in CHP part and non-CHP part (ΦΕΚ 1420/B'/15-7-2009 n.d.)

Therefore, the total efficiency of the plant (η_{CHP}) should be considered as equal to 0,8 and the power to heat ratio (C) equal to 0,45. Based on the thermal output (H_{CHP})of the units in GWh and the power to heat ratio, the electricity output of the CHP part (E_{CHP}) can be found. The electricity output of the non-CHP part is equal to the difference between the total electricity output and the E_{CHP}. Based on E_{CHP}, H_{CHP} and η_{CHP} the fuel consumption of the CHP part is calculated. By deducting the fuel of the CHP part from the total fuel input the fuel consumed by the non-CHP part is estimated. Having all these data the calculation of the electric efficiency and the thermal efficiency of the CHP part as well as the efficiency of the non-CHP part can be easily calculated. Finally, the electric capacity both of the CHP and the non-CHP part can be defined. The aforementioned calculations are repeated for each one of the four plants and the values which are finally inserted in the model can be seen in Table 3.2.

Table 3.2: Capacities and efficiencies of various types of units in Group 3

Type of Units	Capacities (MW-e)	Efficiencies	
		Electric	Thermal
CHP	141	0,25	0,55
Boiler	127	--	0,85
Condensing PP	9344	0,46	--

It should be also noted that the total capacity of the thermal storage facilities in Power Plants with CHP part is up to 0,209 GWh (Municipal Company for Water Supply and Sanitation of Kozani 2010). The data related to the boilers which operate to cover the peak loads are obtained from (Pavlidis n.d.).

Moreover, a fixed boiler share, which represents a certain percentage of the DH demand that needs to be supplied from the boiler anyway, equal to 2% should be set. This is done because the CHP units are simulated as it was one single unit with an average production and efficiencies. Therefore, EnergyPLAN is not able to model situations in which one unit could be out of function due to breakdown or maintenance. According to studies 2% of fixed boiler share compensate this lack of the model properly. (Lund, EnergyPLAN 2010)

Table 3.3: Installed capacity, consumption and net electricity production of condensing PP per fuel (Results Compliance Scenario 2010)

Condensing PP	Installed Capacity for Electricity Production (MW)	Consumption for Electricity (TWh)	Net Electricity Production (TWh)
Coal (Lignite) Interconnected	3362	45,659[1]	16,329
NG Interconnected	5913	20,558	14,687
Biogas Interconnected	210	1,937	0,895
Total incl. CHP part	**9485**		**31,911**
CHP part	**141**		**0,652**
Total excl. CHP part	**9344**	**68,154**	**31,259**

All the values behind the data that were inserted in the model concerning the condensing PP are presented in Table 3.3.

3.3 Renewable Energy

The Renewable Energy Sources which are taken into account for the Greek Energy System are the following: Wind (RES1), Photovoltaics (RES2), Concentrated Solar Power – CSP (RES3) and River Hydro (RES4). All the relevant input data for each RES are presented in the next sections. It needs to be noticed that the available data for the distribution profiles of all RES were referring to 8760 hours. Given that EnergyPLAN asks for 8784 hourly values, the last 24 hours were double-counted. This is why minor differences in the production of RES can be observed when comparing the outputs of EnergyPLAN with those of CRES simulations. However, the variation which is caused is insignificant.

3.3.1 Wind

According to the estimations of CRES the Wind capacity for 2020 for the Greek Interconnected Energy System is equal to 6750 MW and the distribution profile appears in Figure 3.3 (NATIONAL RENEWABLE ENERGY ACTION PLAN | IN THE SCOPE OF DIRECTIVE 2009/28/EC n.d.).

[1] The lignite consumption which corresponds to the CHP part of condensing units has been deducted. All the condensing PP with CHP parts are running on lignite.

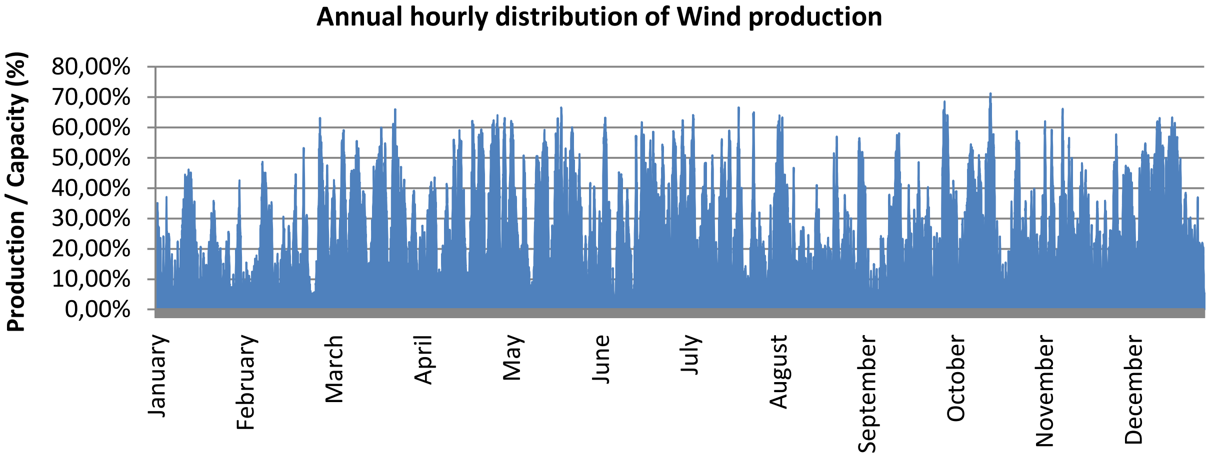

Figure 3.3: Annual hourly distribution of Wind production for Greek Interconnected Energy System of 2020

3.3.2 PV

The capacity of Photovoltaic installations in the Greek Interconnected Energy System by 2020 will be 1950 MW, according to the scenario for compliance with the triple target of '20-20-20' (NATIONAL RENEWABLE ENERGY ACTION PLAN | IN THE SCOPE OF DIRECTIVE 2009/28/EC n.d.).

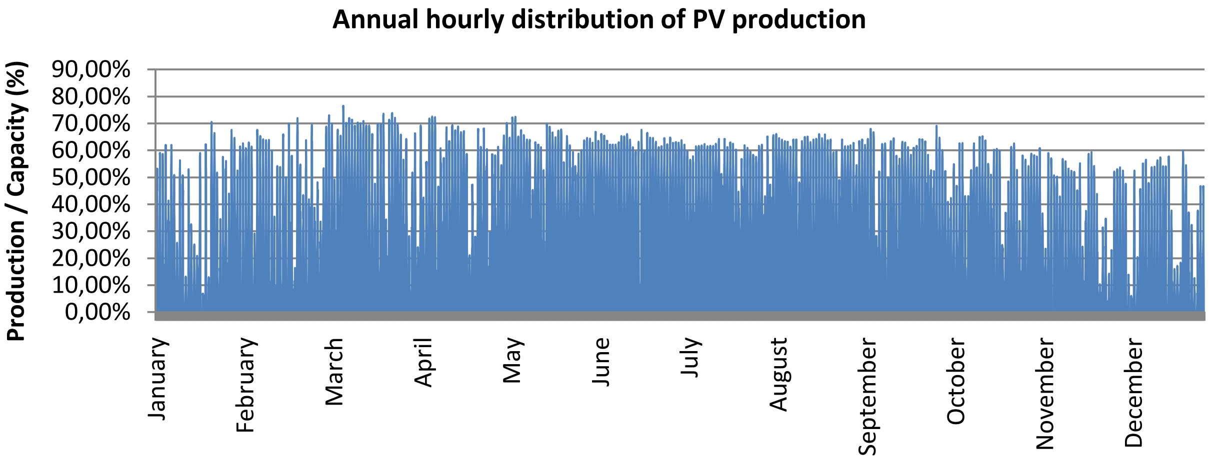

Figure 3.4: Annual hourly distribution of PV production for Greek Interconnected Energy System of 2020

3.3.3 CSP

The capacity of Concentrated Solar Power installations for electricity production reaches 100 MW by 2020 (NATIONAL RENEWABLE ENERGY ACTION PLAN | IN THE SCOPE OF DIRECTIVE 2009/28/EC n.d.). The hourly distribution is consisted of four different values depending on whether it is day or night, summer period or winter period. The figure with the distribution profile is not included in this report since the different values can not be represented properly due to space limits.

3.3.4 River Hydro (Small Hydro Power)

In this section all the data related to small hydroelectric plants (or else run of river installations) without the option of water storage are considered. The capacity of such plants for 2020 is equal to 254,9 MW (NATIONAL RENEWABLE ENERGY ACTION PLAN | IN THE SCOPE OF DIRECTIVE 2009/28/EC n.d.). The distribution, which is flat for each month, can be seen in the following Figure.

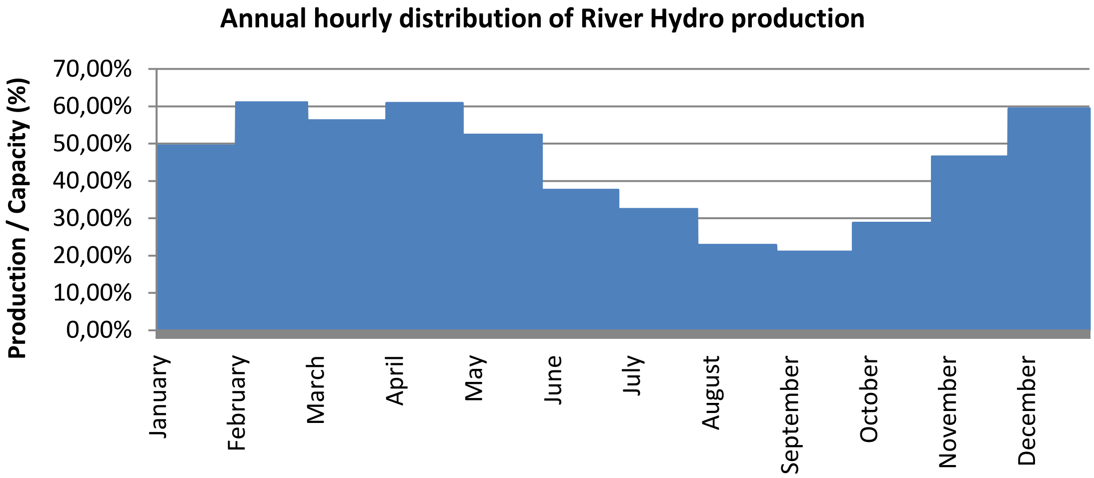

Figure 3.5: Annual hourly distribution of River Hydro production for Greek Interconnected Energy System of 2020

3.3.5 Large Hydro Power & Pump Hydro Power

The capacity of all the Hydro Power Plants in total is equal to 4286 MW of which 1579 MW is the capacity for pump hydro units (NATIONAL RENEWABLE ENERGY ACTION PLAN | IN THE SCOPE OF DIRECTIVE 2009/28/EC n.d.).

Table 3.4: Input Data for Hydro Power Plants

Capacity (MW-e)	4286
Efficiency	0,9
Storage (GWh)	4200
Annual Water Supply (TWh/year)	6,8

The distribution of the electricity production from Hydro Power is presented in the figure below, as flat monthly values.

Table 3.5: Input data for Pump Hydro units

	Capacity (MW)	Efficiency	Storage Capacity (GWh)
Pump/Compressor	1579	0,79	76
Turbine	1579	0,92	

It should be noted that the simultaneous use of the Turbine and the Pump is not allowed in the installations of the Greek Energy System, since the units do not have this option due to technical limitations (single penstock). These installations are not able to charge and discharge at the same time. In general, by using a double penstock-system, the pump storage facility introduces more flexibility in the energy system and hence it can contribute to the integration of more fluctuating renewable energy (Connolly, A User's Guide to EnergyPLAN Version 3 2010).

The values for the existing storage capacity both for Hydro Power units and Pump Hydro are obtained from (Argyrakis 2009). The data have been transformed to 2020 data according to the development of the capacity of the corresponding units which is known.

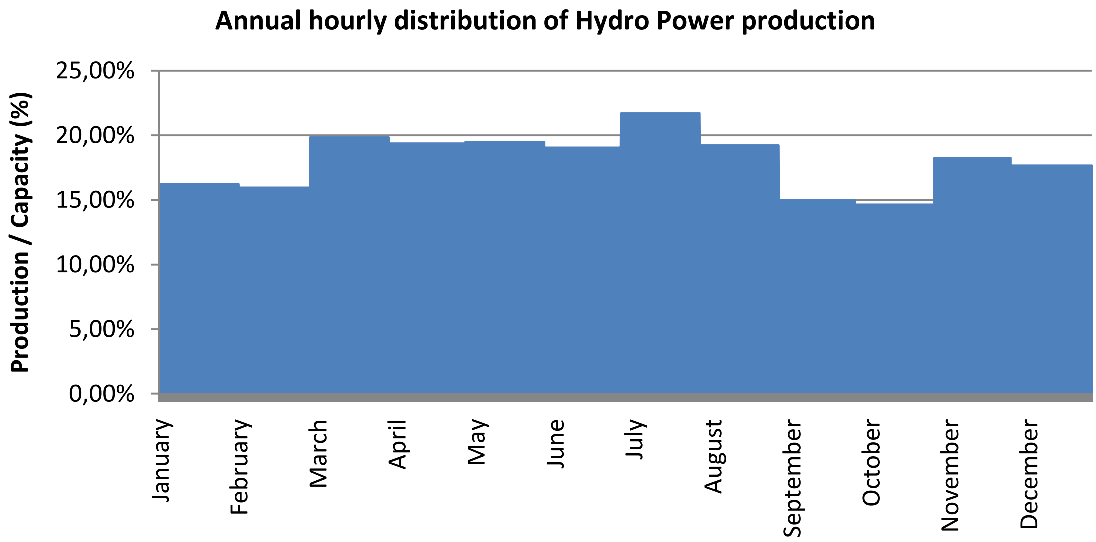

Figure 3.6: Annual hourly distribution of Hydro Power production for Greek Interconnected Energy System of 2020

3.3.6 Geothermal

The capacity of Geothermal plants is equal to 100 MW for the Interconnected System of 2020 and the distribution of it is considered as constant during the whole year.

3.4 Cooling

According to data retrieved from sources of CRES the cooling demand for Residential and Commercial sector is in total 15,44 TWh. Supposing that all the cooling units installed by 2020 will have a COP up to 4 the electricity consumption for covering the cooling demand becomes equal to 3,86 TWh (ΦΕΚ 407/Β'/9-4-2010).

The way that this electricity demand for cooling is distributed, is estimated based on a set of annual hourly temperatures of the outdoor environment for a typical year in Athens. Of course in this selection lies a margin of error, but Athens is considered to be a representative case for the whole country both because of the climatic conditions and due to the fact that the vast majority of consumers of electricity for cooling is gathered there. Therefore, taking also into account a base temperature of 26 °C and the duration of the cooling period between 1st of June and 30th of September (Technical Chamber of Greece 2010), degree-hours were calculated and the distribution is presented in Figure 3.7 by indexing the cooling demand for each hour to the maximum cooling demand that occurs (Connolly, Modelling the Irish Energy System | Data required for the EnergyPLAN Tool 2009).

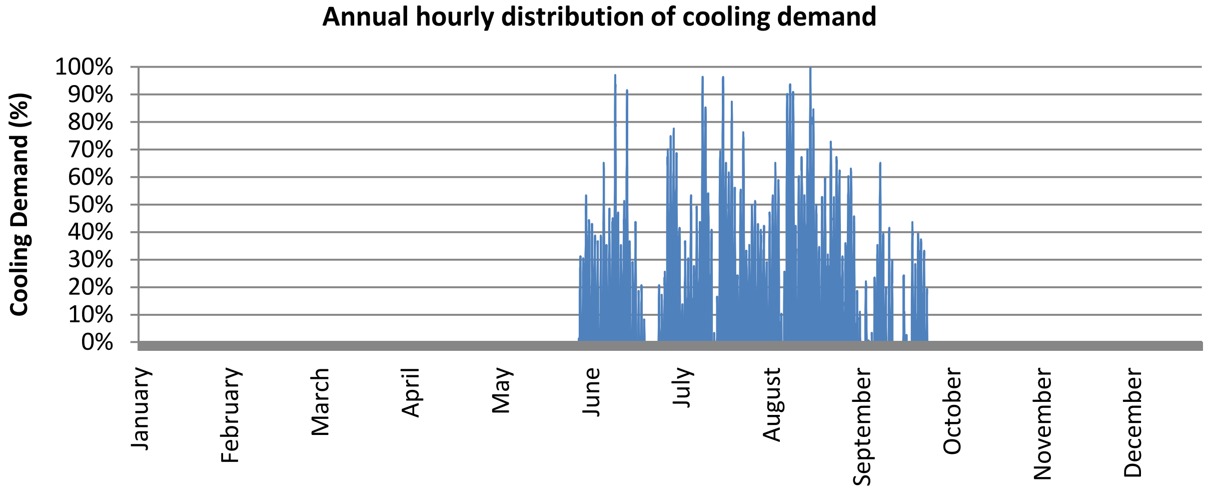

Figure 3.7: Annual hourly distribution of cooling demand indexed to maximum cooling demand

3.5 Individual (Residential & Commercial sector)

According to the data retrieved, the actual electricity consumption for electric heating in the Residential and Commercial sector is equal to 3,98 TWh. This is the right value that needs to be considered in the total electricity demand by the model in order to regulate properly the operation of the units. For this reason in the Individual tab, where the heat demand which corresponds to electric heating needs to be defined, a value equal to 7,1 TWh is set as heat demand so that after the contribution of solar thermal, in covering the given heat demand that was mentioned, the electricity demand for electric heating in the model matches with the actual value obtained from actual data i.e. 3,98 TWh. The way that this demand is distributed is presented in Figure 3.8.

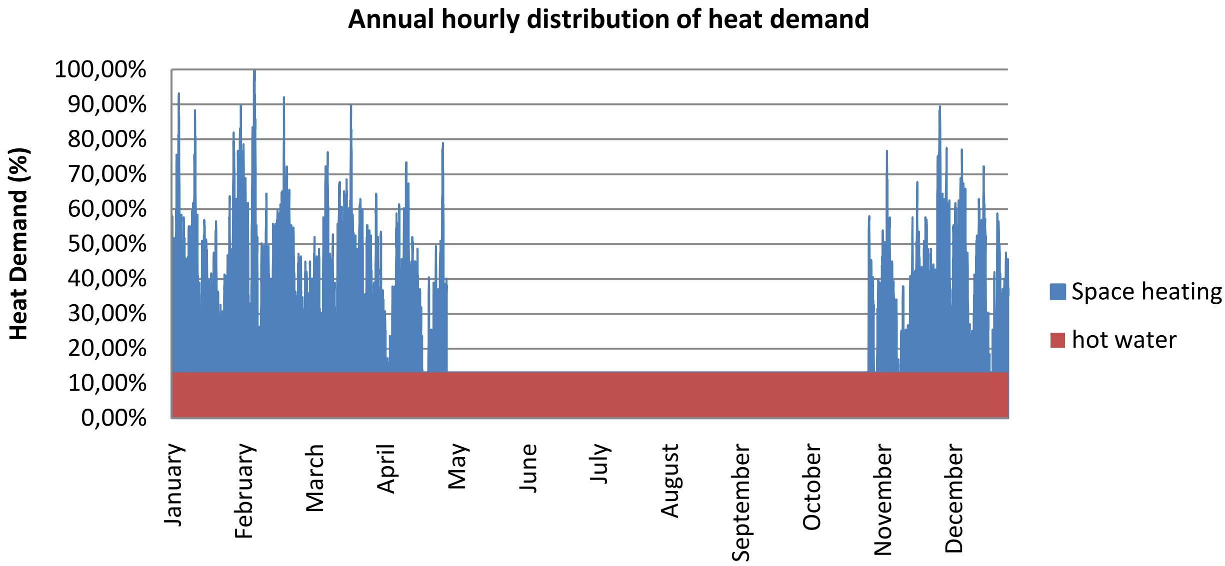

Figure 3.8: Annual hourly distribution of heat demand of Residential & Commercial sector

Similarly with the cooling distribution, this heat demand distribution has been created based on the same set of annual hourly temperatures of the outdoor environment for a typical year in Athens. The calculations in this case are a bit different comparing to the cooling demand distribution given that the heat demand is divided into space heat and hot water demand. According to analytical data obtained for space heat demand and hot water demand within the Interconnected Energy System of 2020, 87% of the total heat demand goes to space heating and 13% to hot water. Therefore, considering the base temperature equal to 18 °C, heating degree hours are calculated and then hourly values are indexed to the maximum value. Taking into consideration that space heat accounts for 87% the distribution of space heat demand is created and it its spread over the months of the heating period (between 1st of November and 30th of April). The hot water demand accounts for 13% and it is constant throughout the year. All these become easy to understand by observing the distribution in Figure 3.8. It should be noted that the same distribution is also used for the District Heating demand which is needed to be inserted in the DH tab.

One more key input for the Individual tab is the distribution of the solar thermal production. Therefore, the distribution of the energy production of a typical solar thermal installation in Greece was studied. Solar thermal in the Greek Energy System are mainly used for heating water in conjunction with electric heating installations. A typical solar thermal installation consists of 3,5 m2 collector's area, which is able to cover the needs for hot water of a typical four-member family (Bakos n.d.), with 0,7 collector's efficiency (Institut für Solartechnik SPF 2008). Based on these values and a set of annual hourly data for global horizontal radiation in Athens, the total useful solar thermal energy is calculated and the distribution of this appears in Figure 3.9.

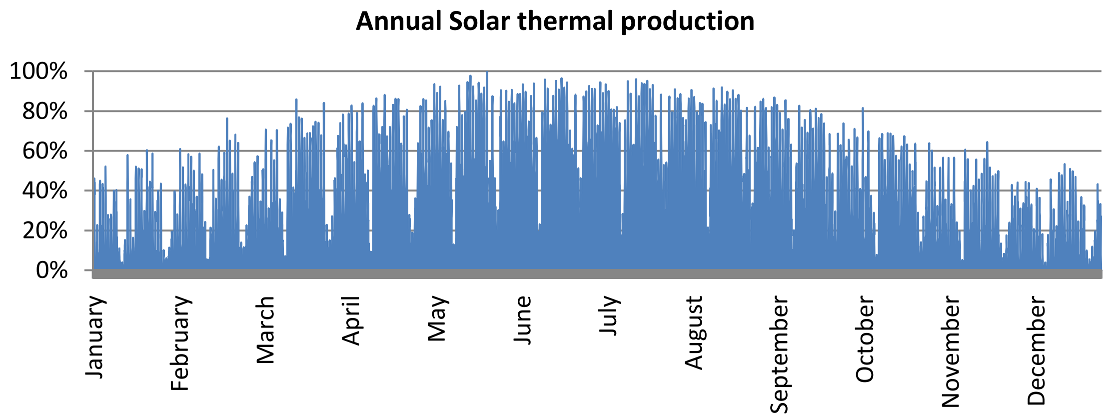

Figure 3.9: Annual hourly distribution of solar thermal production

The total solar thermal production from all the installations for 2020 is estimated equal to 5,7TWh/year (Greek Solar Industry Association n.d.). This production is divided to 4 TWh as solar thermal input in conjunction with electric heating installations and 1,7 TWh in conjunction with oil boilers. After adding the option of 2 days for heat storage (Bakos n.d.) the solar thermal output which represents the utilisable energy, is 4,86 TWh which matches more or less with the estimations of CRES for the total solar thermal consumption (NATIONAL RENEWABLE ENERGY ACTION PLAN | IN THE SCOPE OF DIRECTIVE 2009/28/EC n.d.)

Table 3.4: Input data for Individual Heat Supply

Type of individual heating installation	Fuel consumption Input (TWh)	Efficiency thermal	Heat Demand
Coal Boiler	0	0,7	--
Oil Boiler	35,332	0,75	--
NG boiler	9,369	0,9	--
Biomass boiler	6,466	0,7	--
NG micro CHP	--	0,55/0,34[2]	0,24
Heat Pump	--	4[3]	4,33
Electric heating	--	--	7,1

The data listed in Table 3.4 have been acquired by sources of the host institute.

3.6 CO2 emission factors

In Table 3.5 the CO2 emission factors are listed for each specific type of fuel. Weighted averages, based on the fuel consumption of each specific type of fuel, have been inserted in the model for Coal, Oil and NG (bold values).

Table 3.5: CO2 emission factors per fuel (Intergovernmental Panel for Climate Change n.d.)

Fuel	Sector	Type of fuel	CO2 emission factor (kg/GJ)	Consumption (TWh)
Coal	PP,CHP,CSHP,Industry	Coal (=lignite)	**123**	
Oil	CSHP, Industry	Heavy fuel Oil	78,5	14,79
	Individual heating	Diesel oil	74,1	35,332
	Transportation	Jet fuel	71,4	16,189
		Diesel	72,1	29,843
		Petrol	72	43,345
	Energy sector	Refinery feedstock	58,6	5,12
		Residual fuel oil	76	10,7
		Petcoke	101	1,94
	Weighted average of CO2 ef / Total consumption		**73,23**	157,259
NG	Electricity Production	NG	54,85	36,058
	Individual heating	NG	56,1	9,369
	Weighted average of CO2 ef / Total consumption		**55,11**	45,427

3.7 Transmission line capacity

The values that were considered in order to define the maximum export capacity of Greece and set a value to the Transmission Line Capacity in the Regulation tab of EnergyPLAN are listed in Table 3.6 (european network of transmission system operators for electricity n.d.) (Vaillati 2006). The interconnection between

2 The efficiency is electric in this case.
3 This is the value for the Coefficient of Performance (COP)

Greece and Turkey operated for first time at 18th of September of 2010; currently it is in testing mode for one year. After this period the interconnection will be available for electricity trade exchanges (Ministry of Environment Energy & Climate Change 2010).

Table 3.6: Export Capacity of Greece

Export Capacity		
from	**to**	**MW**
GR	IT	500
GR	AL	100
GR	FYROM	100
GR	BG	100
GR	TK	750
Total		**1550**

4 Technical optimisation

Chapter 4 brings forward the outputs of modelling with EnergyPLAN the Greek Interconnected Energy System of 2020, as this is represented by the inputs which were analytically described in Chapter 3. Firstly, the basic features which compose the reference system are presented as well as the reason why they were selected. Moreover, the optimisation process of the main units of the system that is followed by EnergyPLAN is briefly explained. Finally, the outputs of the technical optimisation are listed, providing in parallel the corresponding quantities which were estimated by the models of CRES, when this is applicable. In this way, Chapter 4 will answer the 1st sub-question: "How can the operation of energy generating units be regulated so that the excess electricity production, the total fuel consumption and the CO2 emissions of the system can be minimised?" as well as the 2nd one at the same time: "What are the differences in the operation of the units and the general behaviour of the system between EnergyPLAN and the models used by the host institute?"

4.1 Description of Reference System

As it has been already mentioned in the Introduction, the project is centred on the Greek Interconnected Energy System as this is shaped under the scenario for compliance with the targets of 20-20-20. Consequently, the characteristics of it compose the reference system which has been simulated with EnergyPLAN. The following Tables 4.1 – 4.6 summarise these basic characteristics, which were analytically explained in Chapter 3, in the form they were inserted in EnergyPLAN.

Table 4.1: Different types of Electricity Demands in TWh/year

Electricity Demands	TWh/year
Fixed demand	50,09
Electric heating	3,94
Heat Pumps	1,08
Electric cooling	3,86
Flexible demand	0,52
Total	**59,49**

Table 4.2: Installed capacity and Electricity Production of RES in the system

RES	Installed Capacity (MW)	Electricity Production (TWh/year)
Wind	6750	15,99
PV	1950	2,8
CSP	100	0,29
River Hydro	255	0,99
Large-scale Hydro	4286	8,89
Geothermal	100	0,61

It should be noted that the electricity productions for Wind, PV, CSP and River Hydro (see Table 4.2), are estimated by the model (in the stage of initial calculations not involving any electricity balancing) based on the installed capacity and the hourly distribution profile that are inserted in the model. As for Large-scale Hydro the estimated annual production in Table 4.2 includes also the potential production of Pump Hydro (or else Reversible Hydro) as it is initially calculated by the model (analytical explanations can be found in sub-Section 4.2.3). More detailed data behind these values can be found in Chapter 3.

Table 4.3: Characteristics of Pump Hydro storage components

Pump Hydro Storage Components	Capacity (MW)	Storage (GWh)	Efficiency
Hydro Pump	1579	76	0,79
Hydro Turbine	1579	--	0,90

Table 4.4: Basic characteristics of Electricity and/or DH generating units

Type of Unit	Capacity (MW)	Efficiency	
		Electric	Thermal
CHP Gr.2	836	0,34	0,55
Boiler Gr.2	600	-	0,85
CHP Gr.3	141	0,25	0,55
Boiler Gr.3	127	-	0,85
Condensing Power Plants	9344	0,46	-

In Table 4.5 all the fuel consumptions which are known and constitute inputs of the model are summarised.

Table 4.5: Annual Fuel Consumptions in TWh/year

Sector	Coal	Oil	NG	Biomass
Transport	0	89,38	1,15	7,18
Residential & Commercial	0	35,33	9,37	6,47
Industry	3,56	14,79	15,50	6,84
Various	0	41,64	0	0,45

Under the name “Various” the fuel consumptions of the Agricultural sector as well as those of the Energy sector itself are included.

The District Heating demand in Group 3 which is equal to 1,27 TWh and the electricity production of Industrial CHP units (or else CSHP) which is fed to the grid and it is equal to 4,97 TWh are also added to the model. Furthermore, inputs concerning the electric grid stabilisation requirements and in general the regulation of the reference system can be found in Table 4.6 below.

Table 4.6: Regulation characteristics of reference system

Technical Regulation Strategy	3
CEEP Regulation Strategy	0 (none)
Minimum Grid Stabilisation Production Share (MGSPS)	0,3
Stabilisation share of CHP2	0
Minimum CHP in Group 3	0 MW
Minimum PP	3500 MW
Transmission line capacity	0 MW

As it can be seen in Table 4.6 Technical Regulation Strategy 3 was selected for the reference system. Basically, the selection of a technical regulation strategy suitable for the reference system and in accordance with the scope of this project was based on the method of "reduction ad absurdum". Therefore, both Strategy 1 and 4 do not take into consideration neither the distribution of the electricity demand nor the RES power production. Consequently, by selecting one of these two strategies no action aiming at minimising CEEP is taken. Reversely, by selecting one of Strategies 2 and 3 the operation of the units is regulated in a way that seeks minimising CEEP. Moreover, it should be made clear that Strategy 3 was preferred over Strategy 2 since this is the strategy which leads to less excess electricity production while Strategy 2 should be selected if better efficiency in the system was the desired in this project (Lund, EnergyPLAN 2010). However, the effects of all the possible technical regulation strategies will be investigated in the following chapter.

Concerning the regulation of CEEP none of the available strategies was selected because one of the main scopes of the reference system is the calculation of the magnitude of CEEP without any attempt of minimising it. The effects on the system by applying different combinations of CEEP regulation strategies will be investigated at a later stage.

The Minimum Grid Stabilisation Production Share is set equal to 30% of the total electricity production as it is recommended in the manual of the model (Lund, EnergyPLAN 2010). An analysis based on different values of MGSPS will take place in Chapter 5.

No specific requirement has been set concerning the stabilisation share of CHP2. However, all the units that are included in Group 2 are industrial CHP units which are considered as stabilising units. (It has been observed that the operation of the system does not change at all even if the stabilisation share of CHP2 is set equal to 1, in the reference system, with or without CEEP regulation strategies applied.)

As for the minimum of CHP in Group 3 no minimum technical requirements have been set mainly due to lack of data availability. The only available data concerning minimum technical requirements of units referred to the overall operation of Condensing Power Plants (CHP units constitute just a part of them). The representation of the system could be more precise if minimum technical requirements which correspond to the CHP part of condensing PP could be set e.g. equal to 20% of max capacity as it is proposed in EnergyPLAN's manual (Lund, EnergyPLAN 2010). Therefore, the minimum CHP3 would be equal to 28 MW (20%*141 MW) which means that the differences in the operation of the system would be insignificant, since the average electricity production of CHP3 in the reference system is 79 MW (>28 MW). Of course the minimum value of electricity production of CHP3 is 5 MW (<28 MW) but this happens just a few hours during the year. Generally speaking, if the minimum technical requirements which correspond to CHP3 could be deducted from the total minimum for PP (which has been set equal to 3500 MW) then the CEEP would be even lower.

At this stage, the transmission line capacity is set equal to zero since the goal is to investigate the way that the model optimizes the system when there is no option for exporting electricity. Therefore, all the potential export is translated as Critical Excess Electricity Production (CEEP) in the reference system since there is no Exportable Excess Electricity Production (EEEP).

Last but not least, the simultaneous operation of the pump and the turbine in Pump Hydro units is not allowed in the reference system (for further explanation see 3.3.5).

4.2 The process of Technical Optimisation (from Inputs to Outputs)

Central aim of this Section is to provide the reader with a brief explanation of the optimisation process. This process is followed by the model in order to reach from the inputs composing the reference system (summarised in Section 4.1 and analytically described in Chapter 3) till the outputs (presented in Section 4.3). The focus will be put on specific parts of technical energy system analysis, in accordance with the scopes of this project, i.e. the operation of Condensing PP, CHP units, Hydro Power, Pump Hydro and Electricity Storage facilities. All the values in brackets correspond to quantities that either they have already mentioned as inputs of the reference system or they need to be calculated during the optimisation process. The equations, which are found in this section for giving a better understanding of what is described by the text, are taken from EnergyPLAN's manual (Lund, EnergyPLAN 2010) and have been modified according to the needs of the project.

4.2.1 Condensing PP, Exports, CEEP and EEEP

First of all, the steps followed for optimising the operation of condensing PP will be presented along with the calculation of potential Exports, CEEP (Critical Excess Electricity Production) and EEEP (Exportable Excess Electricity Production). At this point, it is necessary to be reminded that there is no chance for exporting excess electricity in the case of reference system, since the Transmission Capacity is 0, but this will change in the scenarios presented in Chapter 5. It is also worth mentioning that the aforementioned quantities are calculated continuously almost after each part of the technical optimisation (Lund, EnergyPLAN 2010).

1. Calculation of the total demand (d_{Total}) which is the sum of: constant electricity demand, cooling demand, heat pumps' demand, electric heating demand, hydro pump demand (see Table 4.1).

2. Calculation of the power production of all units apart from condensing PP (e_{Total}), which is the sum of: RES production (i.e. Wind, PV, CSP, River Hydro - see Table 4.2), micro CHP, Hydro (large-scale), Geothermal, Industrial CHP, CHP Group 3 and Hydro Pump (reversible hydro) power production (Lund, EnergyPLAN 2010).

3. Calculation of the power production of condensing PP which is considered as the higher value between:

- the total electricity demand (Step 1) reduced by the power production of the rest of the units (Step 2)

$$e_{PP} = d_{Total} - e_{Total}$$

- the necessary Condensing PP production to fulfil grid stability requirements (MGSPS = 30%). This is the result of the difference between the total power production that is needed to come from stabilizing units and the power production already coming from stabilizing units such as: CHP2, CHP3, Geothermal and Hydro.
- the minimum production on condensing PP due to technical requirements of the units themselves (min PP = 3500 MW)

4. Calculation of potential electricity export which is considered as the difference between the electricity (or else power) production of all the units including Condensing PP and the total electricity demand.

$$e_{Export} = e_{Total} + e_{PP} - d_{Total}$$

5. Calculation of CEEP that is equal to the export minus the Transmission line capacity. In the reference system, as it has been already referred in Section 4.1, the capacity of the Transmission line is considered as zero ($C_{Transmission} = 0$). This means that all the potential export is considered as Critical Excess Electricity Production and the Exportable Excess Electricity Production is zero.

$$e_{CEEP} = e_{Export} – C_{transmission} = e_{Export}$$

$$e_{EEEP} = C_{Transmission} = 0$$

4.2.2 CHP3 under Regulation Strategy 3

This section aims at giving an insight of the optimisation of CHP3 operation. Mainly, the operation of CHP3 units is optimised in a way that they can meet the District Heating demand (1,27 TWh) and at the same time meet the electricity demands while they are trying to minimise the production of Condensing PP by replacing them. The fulfilment of the heat demand is first priority in the operation of CHP3 units. As for CHP2 (CHP in Group 2), these are Industrial CHP units which feed the grid with the produced electricity (4,97 TWh see Section 4.1) and use the produced heat in their processes. This means that their energy production cannot be optimised since they operate according to the needs of the industry itself.

The operation of CHP3 units is affected by two different factors. Therefore, the electricity production of CHP3 (e_{CHP3}) for every single hour should be lower or equal to the maximum available capacity, C_{CHP}, (upper limit) and to the capacity which corresponds to the DH demand (lower limit). Within these limits it is considered as equal to the capacity which is needed due to grid stability requirements ($Stab_{total}$ = 30%) without relying on any effect from condensation power plants (Lund, EnergyPLAN 2010):

$$e_{CHP3} = (e_{Total} * Stab_{total} - e_{CHP2} * Stab_{CHP2} - e_{Geothermal} - e_{Hydro})$$

Furthermore, with Strategy 3 the model has the option of reducing the production of CHP. This means that in case of excess electricity production the model is able to reduce CHP and replace it with boilers for covering the given heat demand and even with condensing Power Plants for fulfilling the given grid stability requirements.

The boilers are responsible for covering peak loads this means that they simply supply the remaining demand after the optimisation of CHP3 operation. The only limit (upper limit) in their operation is set by the Thermal Capacity of boilers available (T_{B3}).

$$q_{B3} = h_{DH3} – q_{CHP3}$$
$$\textbf{If } q_{B3} > T_{B3} \textbf{ then } q_{B3} = T_{B3}$$

It should be noted that the heat demand referred here as h_{DH3} has been already reduced by the share that correspond to the heat produced from boilers ($q_{FixedBoiler3}$) due to the fixed boiler share that has been set equal to 2% ($FixedPercent_{B3}$) (Lund, EnergyPLAN 2010).

$$q_{FixedBoiler3} = H_{DH3} * FixedPercent_{B3} / 8784$$
$$h_{DH3} = h_{DH3} – q_{FixedBoiler3}$$

4.2.3 Hydro Power and Hydro Pump

A description of the whole process of optimisation of hydro production and the integration of hydro units will be attempted in the following lines, according to (Lund, EnergyPLAN 2010).

In general, a baseline hydro production is calculated which is then increased or decreased in order to maximise the total hydro production, taking into account limitations concerning storage and generator capacities, as well as minimise as first priority CEEP and then EEEP. It should be also noted that hydro power units contribute to grid stabilisation which also plays a role in the optimisation process.

The following steps give more clear and exact understanding of hydro power integration:

1. The potential hydro power production is calculated based on the water supply to the water reservoirs (6,8 TWh/year) and the efficiency of hydro turbines (0,9) as an average hourly value. The result is the baseline production.

When the distribution of flexible demand is defined all the various demand are reduced by this baseline hydro power production before the distribution of flexible demand is defined. Moreover, when the power production of all the other units is to be defined this baseline hydro production is included (for all technical regulation strategies 1-4). Therefore the hydro production that is used in the first calculation of PP production is the baseline hydro power production.

2. Hydro power production is calculated again in order to replace condensing units so that CEEP and EEEP (prioritised) can be decreased. The only limitation here is the capacity of hydro (4286 MW). If the capacity is higher than the baseline production (from Step 1) then it means that there is a margin for increasing the hydro production. If the resulting potential increase is higher than the PP production then the increase is kept equal to PP production because otherwise hydro would increase CEEP instead of decreasing it (Lund, EnergyPLAN 2010).

$$e_{Hydro\text{-}Inc} = \mathrm{MIN}\ [e_{PP}\ ,\ (C_{Hydro} - e_{Hydro})]$$

3. When there is CEEP the hydro production should be decreased and the extent of this decrease is considered as equal to the lowest value of either the CEEP or the baseline hydro production. Of course hydro production cannot be lower than it is needed for grid stability reasons.

$$e_{Hydro\text{-}Dec\text{-}CEEP} = \mathrm{MIN}\ (e_{CEEP}\ ,\ e_{Hydro})$$

$$e_{Hydro\text{-}Dec\text{-}CEEP} <= e_{Hydro} - e_{Hydro\text{-}Min\text{-}Grid\text{-}Stab}$$

4. If CEEP still exists (usually hours with high wind production) then the pump hydro units can decrease further the CEEP. This potential is considered as equal to the lowest value between CEEP (minus the share calculated in Step 3), the pump capacity and the energy content of the lower water storage (Lund, EnergyPLAN 2010).

$$e_{Hydro\text{-}Pump\text{-}Dec\text{-}CEEP} = \mathrm{MIN}\ [(e_{CEEP} - e_{Hydro\text{-}Dec\text{-}CEEP})\ ,\ C_{Hydro\text{-}PUMP}\ ,\ (s_{Hydro\text{-}PUMP} / \mu_{Hydro\text{-}PUMP})\ ]$$

The annual Hydro pump production, after the optimization as described above, is equal to **3,89 TWh/year**.

5. A balance for the hydro power production is calculated based on the potentials of increasing and decreasing it, as they have been defined in Steps 2 and 3. First priority is given to the reduction of CEEP and

then follows the reduction of EEEP. The balanced hydro power production is based on the following equity (Lund, EnergyPLAN 2010):

$$\Sigma\, e_{Hydro\text{-}Inc} = \Sigma\, e_{Hydro\text{-}Dec\text{-}CEEP} + \Sigma\, e_{Hydro\text{-}Dec\text{-}EEEP}$$

6. Fluctuations in the storage content are taken into account and the hour by hour modelling is repeated. The way that the storage capacity, the distribution of the water inflow and the generator capacity modify the hydro power production presented here:

$$\text{Hydro-storage-content of hour “x”= Hydro-storage content of hour “x-1”+ } w_{Hydro}$$

$$e_{Hydro\text{-}Input} = e_{Hydro} + e_{Hydro\text{-}Inc} - e_{Hydro\text{-}Dec\text{-}CEEP} - e_{Hydro\text{-}Dec\text{-}EEEP}$$

$$e_{Hydro\text{-}Input} <= (\text{Hydro-storage-content} - S_{Hydro})^* \mu_{Hydro}$$

$$e_{Hydro\text{-}Input} <= C_{Hydro}$$

This calculation aims at identifying a solution in which the final storage content is the same with the initial. In this way a better representation of the system is achieved. It should be also noted that the storage content in the beginning is considered equal to the half of the storage capacity (4286 MW/2 = 2143 MW) (Lund, EnergyPLAN 2010).

After this iterative process the annual balanced hydro power production, as calculated by the model, is equal to **8,89 TWh/year**.

4.2.4 Electricity Storage

Pump storage is the one and only electricity storage option available within the Greek Energy System. The operation of it is regulated so that CEEP can be minimised. The way that pump storage is regulated can be described through the regulation of the pump (charging unit) and the regulation of the turbine (discharging unit).

The role of the Pump is to fill the storage when there is CEEP. The hourly operation of the pump is limited by the value of CEEP (e_{CEEP}), the available pump capacity (C_{Pump} = 1579 MW - see Table 4.3) and the available storage energy content. Therefore, the pump load is considered as equal to the lowest value between the above-mentioned (Lund, EnergyPLAN 2010):

$$e_{Pump} = \min [\, e_{CEEP}, (S_{Pump} - s_{Pump}) / \alpha_{Pump} , C_{pump} \,]$$

The role of the Turbine is to empty the storage in order to produce electricity which will replace the Condensing PP production. The hourly operation of the turbine is limited by the electricity production of condensing PP, the available turbine capacity ($C_{Turbine}$ = 1579 MW - see Table 4.3) and the available storage energy content. Therefore, the electricity production of the turbine is considered as equal to the lowest value between the aforementioned (Lund, EnergyPLAN 2010):

$$e_{Turbine} = \min [e_{PP}, (s_{Pump} * \mu_{Turbine}), C_{Turbine}]$$

4.3 Outputs of EnergyPLAN in comparison with outputs of CRES simulations

Main intention of this section is to present the outputs of EnergyPLAN model after the process of technical optimisation and compare them, when it is possible, with the corresponding results of the set of models used by the host institute (CRES). The data have been formulated in a way that they can be more comparable - without changing any of the main points. Additionally, the values of some quantities will be commented either for giving a better understanding of the optimisation procedure of EnergyPLAN or for the sake of comparison with the other set of models. It was considered more sensible to present the outputs of EnergyPLAN and compare them with the outputs of the other models' set at the same time in order to avoid repeating the first ones twice.

4.3.1 DH production

As it has been already mentioned in the previous sections the District Heating demand in the Greek Interconnected Energy System of 2020 is rather low and it is met by the operation of the CHP part of large Condensing Power Plants (Group 3). In Table 4.7 the cooperation of CHP with boilers, in order to meet the given annual DH demand, is presented through the values of their annual production.

Table 4.7: Annual DH demand and production in TWh/year

Demand (TWh/year)	**Production (TWh/year)**	
District Heating	CHP3	Boilers
1,27	1,20	0,06

It should be reminded that the operation of CHP3 is determined by the maximum available capacity (C_{CHP}) and the capacity which is needed due to the given grid stability requirements. Therefore, after the optimisation of the operation of CHP3 the remaining demand is met by the boilers, without exceeding in any hour the corresponding thermal capacity available. Apart from boilers' contribution in heat production which is appointed by the operation of CHP3, there is also a part of the production due to the fixed boiler share.

There are no available data indicative of the way that the CHP part of condensing PP and the boilers are cooperating, coming from the models' set of CRES. As it has been already mentioned the focus of the simulations accomplished by the host institute was on the electricity generation part of the Greek Energy System.

4.3.2 Electricity Demand and Production

In this section the outputs of EnergyPLAN concerning the electricity part of the reference system will be presented and compared with those coming from the simulations of the host institute (here referred as CRES models' set).

Electricity Demand

It should be noted that in order to define some of the inputs of EnergyPLAN the outputs of CRES models' set were used. In other words the data in the right column of Table 4.8 are outputs of CRES simulations -which aim at estimating the values of the corresponding quantities for year 2020- and inputs for EnergyPLAN model at the same time. In the left column of Table 4.8 are presented the different types of electricity demands as they were finally perceived by the model.

Table 4.8: Annual Electricity Demands in EnergyPLAN and in CRES simulations

Electricity Demands	EnergyPLAN (TWh/year)	CRES models' set (TWh/year)
Constant	50,09	50,064
Electric Heating	3,94	3,98
Electric Cooling	3,86	3,86
Flexible	0,52	0,52
Heat Pumps	1,08	1,08
Total excl. pump load	**59,5**	**59,5**
Hydro Pump	1,91	2,389
Total incl. pump load	**61,400**	**61,893**

Main intention concerning the electricity demands was to use exactly the same total electricity demand (excluding the pump load) in EnergyPLAN simulations with the one that was used in simulations of CRES. This is the only way to obtain outputs, concerning the operation of the power generation units, which are directly comparable. Therefore, it can be easily observed that the values in the two columns are identical (with a minor difference in Electric Heating demand - see Section 3.5 for explanation) apart from the hydro pump load.

Given that EnergyPLAN optimises the operation of hydro pump units (or else reversible hydro) so that CEEP can be minimised, the total annual pump load has been estimated equal to 1,91 TWh. In the calculation of this value parameters such as the available pump capacity and the available storage energy content, which is dependent on the pump storage capacity, have been taken into consideration.

In contrary to the way that the pump load is estimated in EnergyPLAN (output of the model), in simulations of CRES the pump load is considered to be fixed (input of the models' set). Therefore, the hydro pump units are subjected to forced operation instead of allowing the model to optimise their operation in a way which aims at minimising CEEP, as it happens with EnergyPLAN. Moreover, in the simulations of CRES it is not necessary to set the storage capacity of the hydro pump units. This is because the pump load does not depend on the pump storage capacity since the value of the pump load is fixed. As a consequence, the total electricity demand including the pump load has a difference up to 0,5 TWh between the two models. This is of utmost importance because the operation of all the power generation units is affected since they produce in order to meet a demand which is different between the two models.

Electricity Production

The outputs of EnergyPLAN concerning electricity production of all the power generating units are presented in Table 4.9. In the same table the corresponding values which constitute the results of the simulations carried out by CRES can be also found.

Table 4.9: Annual Electricity Production of all units in EnergyPLAN and in CRES simulations

Electricity production	EnergyPLAN	CRES models' set
RES	20,06	20,033
of which Wind	*15,99*	*15,97*
of which PV	*2,80*	*2,794*
of which CSP	*0,29*	*0,286*
of which River Hydro	*0,99*	*0,983*
Hydro Power incl. pump	6,36	5,593
of which Hydro Power	*5*	*3,889*
of which Pump Hydro	*1,36*	*1,703*
Geothermal	0,61	0,61
CSHP	4,97	4,97
CHP3	0,69	0,65
PP	31,87	31,259
Total	**64,56**	**63,122**

Starting from the electricity production of Renewable Energy technologies i.e. Wind, Photovoltaics, CSP and River Hydro minor differences are detected. The reason of the differences is that in EnergyPLAN 24 hours of production have been added in their hourly distribution profile, since all the distributions need to consist of 8784 hour values when they are inserted in EnergyPLAN. Apart from that, after the optimisation of the reference system with EnergyPLAN, it should be noticed that all RES including Geothermal are fully integrated in the system. The total of the available potential is exploited because no CEEP regulation strategy which could possibly reduce RES production is applied in the reference system at this stage.

Moreover, the electricity production of Industrial CHP units (CSHP) is identical in both cases. This is because the production of industrial units is not subjected in any regulation by the model.

On the contrary, the operation of Hydro Power units, CHP3 and condensing Power Plants are subjected in such a regulation so that the maximum possible minimisation of CEEP can be achieved. Of course this happens while all the limitations which determine the production of the aforementioned units are kept by the model.

Particularly, the electricity production of Hydro Power units appears considerable difference between the two models. Firstly, this is because pump hydro units operate under different logic in the two models. The pump units in CRES simulations are subjected to forced operation which is connected to the fixed pump load, whereas in EnergyPLAN the electricity production of pump hydro units is dependent on the electricity production of condensing PP, the available turbine capacity and the available storage energy content. Therefore, the operation of Hydro Power units is directly affected by the operation of Pump Hydro units since they are inextricably linked, given that in the reference system the simultaneous use of the turbine and the pump is not allowed. Secondly, the storage capacity of Hydro Power units is not taken into account in the simulations of CRES, whereas this limitation is determinant for the operation of Hydro in EnergyPLAN, as it has been already explained in sub-Section 4.2.3. Last but not least, in CRES simulations part of the operation of Pump Hydro units has been calculated based on economic conditions. Therefore, the operation of pumping units aims at minimising the cost of the electricity produced. Similarly, EnergyPLAN is able to identify the optimal business-economic solution concerning the operation of pumping units, when Market

Economic Optimisation has been selected as the basic optimisation strategy. However, as it has been made clear from the beginning of this report that Technical Optimisation Strategy has been selected for the scopes of this project, which means that no economic conditions are involved in the production of Pump Hydro units.

The annual electricity production of CHP3 units has been estimated up to 0,69 TWh by EnergyPLAN, given that technical regulation strategy 3 has been selected for the reference system. In comparison with CRES simulations the respective value appears to be just a bit increased. As it has been referred in 4.2.2, EnergyPLAN has calculated the electricity production of CHP3 taking into consideration the maximum available capacity (C_{CHP}), the capacity which corresponds to the DH demand and the capacity which is needed due to grid stability requirements ($Stab_{total}$ = 30%) without relying on any effect from condensation power plants.

The annual electricity production of Condensing Power Plants, which is calculated repeatedly after the optimisation of each power generating unit mentioned above, ends up to be equal to 31,87 TWh. This value represents the electricity which remains to meet the given electricity demand and fulfils the grid stability requirements at the same time. The respective value obtained from CRES simulations is equal to 31,26 TWh, which means that the models are really close concerning the operation of condensing PP. A possible cause of this minor variation is the fact that in CRES simulations limitations concerning the ramping of the units are taken into account whereas in EnergyPLAN there is not such an option. In Table 4.10 the hourly operation of Condensing PP, according to EnergyPLAN, is examined based on ramping and the magnitude of it.

Table 4.10: Evaluation of condensing PP based on ramping

Number of hours with:	>1000 MW	>500 & <1000 MW	>250 & <500 MW	<250 MW
ramp ups	45	103	131	230
ramp downs	3	160	204	266
no ramping	7641			

After all, there is a difference up to 1,44 TWh in the total annual electricity production between the two models. This difference along with the dissimilarity in the total electricity demand formulate the difference that can be observed in the CEEP as it has been estimated by the two models and presented in Table 4.11.

Table 4.11: CEEP in EnergyPLAN and in CRES simulations

CEEP	EnergyPLAN	CRES models' set
actual value	3,17	1,09
as % of Total Electricity Production	5%	2%

Therefore, it is observed a difference equal to 2,08 TWh, which is mainly caused by the difference in the operation of Hydro Power units which affects both the total electricity demand and the total electricity production.

Another output of EnergyPLAN which is worth to be examined is the "StabLoad", which expresses the extent in which the stabilisation requirements set in EnergyPLAN via the MGSPS (Minimum Grid Stabilisation Production Share) parameter are met, in % percentage. In Table 4.12 one can see three indicative values of StabLoad for the reference system.

Table 4.12: Min, max and average StabLoad of the reference system

Minimum	**Maximum**	**Average**
130 %	298 %	213 %

After the overall comparison of the outputs of EnergyPLAN and CRES models' set, which was conducted in sub-Sections 4.3.1 and 4.3.2, it is inferred that the outputs of the models are comparable, although they are not exactly similar they appear minor differences which are based on the different logic of the models and so they can be justified. This means that the two different simulations seem to be really close, something which increases the validity of EnergyPLAN outputs. Therefore, it is extrapolated that the Greek Interconnected Energy System has been represented quite precisely with EnergyPLAN. Consequently, the findings of the following Chapters, which will be based on the elaboration of the outputs presented until this point, gain added value.

4.3.3 Fuel Balance & CO2 emissions

In Table 4.13 the fuel balance divided by sector and fuel as this was estimated by EnergyPLAN for the reference system is presented. Basically, the first eight columns show the fuel consumption of the electricity generating unit. Therefore, all these units could be listed under the electricity generation sector.

Table 4.13: Fuel Balance of the reference system by EnergyPLAN

Sector / Fuel	Electricity generation								Solar Therm.	Transport	Individual	Industry	Various	Total
	CHP3	PP	Geoth.	Hydro	Wind	PV	CSP	River Hydro						
Coal	2,19	46,42										3,56		52,17
Oil										89,38	33,07	14,79	41,64	178,88
NG		20,9								1,15	9,81	15,5		47,36
Biomass		1,97								7,18	6,47	6,84	0,45	22,91
RES			4,39	5	15,99	2,8	0,29	0,99	4,86				0,58	34,9
Total	2,19	69,29	4,39	5	15,99	2,8	0,29	0,99	4,86	97,71	49,35	40,69	42,67	336,22

The only category of units which is not included is the Industrial units and that is because the fuel consumption of them is under the Industry sector. It should be also noted that in "Various" sector the fuels consumed by the Agricultural sector as well as the Energy sector itself are included. In the Various sector 0,58 TWh of RES, which represent the consumption of Geothermal of the Agricultural sector, have been added extra since there is not such an option in EnergyPLAN. Moreover, under the name of Biomass the consumptions of Biogas and Biofuels are also included. As for the Individual sector this contains the Residential and the Commercial sector. Something more that needs to be underlined is the fact that the values in Transport, Industry and Various refer to consumptions in the overall Greek Energy System i.e. Interconnected and Non-Interconnected.

Table 4.13 partly constitutes the image of Table 4.9, in which the electricity production of all units is represented, if the efficiency of the units is taken into account. The additional information is the consumption by fuel of sectors such as Transport, Individual, Industry, Agricultural and Energy. The fuel consumption of these sectors is standard values since is not subjected to any regulation from the model.

Based on the total fuel consumptions the CO2 emissions of each fuel as well as the overall emissions for the reference system are listed in Table 4.14 below.

Table 4.14: CO2 emissions of the reference system by EnergyPLAN

Fuel	CO2 emissions
Coal	23,11
Oil	47,16
NG	9,4
Biomass	0
Renewable	0
Total	**79,66**

The table which represents the fuel balance as this was estimated by CRES simulations was not considered as necessary to be included. This is because the comparison of the fuel balances of the two models would not lead to any additional findings. The points which come to light by observing the electricity production of all units according to EnergyPLAN and CRES models (see Table 4.9) would be simply reflected in the fuel balances.

5 Sensitivity Analysis (SA)

In this Chapter a Sensitivity Analysis will take place in order to investigate the effect of changing some parameters of the reference system (model inputs) on both the operation of system's units and on quantities indicative of the system's behaviour (model outputs). The effect of just one parameter will be analysed each time, therefore the SA will be divided into smaller parts. The main scope of this Chapter is to identify the parameters of the system which are crucial for its technical optimisation according to the criteria set from the beginning of this report. In this way the Chapter will answer the 3rd sub-question: "Which parameters, of those involved in the optimisation process, and to what extent can contribute to a further minimisation of the excess electricity production and the total fuel consumption of the system?"

The parameters under investigation in this sensitivity analysis are:

- the technical regulation strategy (see 5.1)
- the minimum grid stabilisation production share – MGSPS (see 5.2)
- the option of allowing or not the simultaneous use of turbine and pump, in pump hydro units (see 5.3)
- the pump storage capacity (see 5.4)
- the CEEP regulation strategy (see 5.5)
- the transmission line capacity (see 5.6)

In each part of the sensitivity analysis the value of both the parameter under investigation (in bold letters) and the rest parameters will be summarised in a Table in the beginning of the corresponding section. This helps the reader to have a better understanding of the conditions which apply to each separate analysis.

5.1 Regulation Strategies

As it has been already mentioned in Section 4.1, Technical Regulation Strategy 3 has been selected for the reference system out of the four available Strategies in EnergyPLAN. However, in this section some of the main outputs of the model after applying all the different strategies will be presented. The focus will be put on the quantities that vary by changing strategies.

Table 5.1: Inputs of the reference system for Regulation Strategies' SA

Technical Regulation Strategy	**1,2,3,4**
MGSPS	30%
Allow for simultaneous operation of turbine and pump	NO
Pump Storage	76 GWh
CEEP regulation	NONE
Transmission Line Capacity	0 MW

The way that the outputs of the reference system are affected by changing the Technical Regulation Strategy is depicted in the values of the quantities included in Table 5.2.

Table 5.2: Outputs of reference system for Regulation Strategies' SA

Technical Regulation Strategy	DH production (TWh/year)		Electricity consumption (TWh/year)	Electricity production (TWh/year)			CEEP (TWh/year)	Fuel consumption (TWh/year)	StabLoad (%)	CO2 Emissions (Mt)
	CHP	Boiler	Pump Hydro	Turbine	CHP	PP	total	total	min	total
Str1	1,2	0,06	1,89	1,35	0,7	31,87	3,18	331,28	131	79,66
Str2	1,2	0,06	1,89	1,35	0,7	31,87	3,17	331,28	131	79,66
Str3	1,2	0,06	1,91	1,36	0,69	31,87	3,17	331,28	130	79,66
Str4	1,2	0,06	1,91	1,35	0,7	31,87	3,17	331,28	130	79,66

It can be easily observed that either there are no variations or there are variations in the operation of units such as the pump hydro and CHP which are insignificant. Therefore, quantities indicative of the behaviour of the reference system such as the CEEP, the total annual fuel consumption and the total CO2 emissions are not affected by changing the regulation strategy. Obviously this is due to the fact that the district heating demand of the reference system is rather low so that the behaviour of the system is not affected whether the heat demand is the only demand which determines the operation of the units (Strategy 1) or the electricity demand is also involved (Strategy 2). Another reason is that there is no high margin for reducing the production of CHP3 (Strategy 3), since its production is already low given the low capacity of CHP3 units in the reference system. However, the theoretical selection of Strategy 3, which took place in Section 4.1, is now confirmed by the sensitivity analysis of regulation strategies. Technical Regulation Strategy 3 combines the minimum CEEP and the maximum operation of pumping hydro something that may have significant effects for higher wind penetration scenarios that will be analysed later on.

5.2 Minimum Grid Stabilisation Production Share (MGSPS)

The parameter under investigation in this section is the regulation requirement of minimum grid stabilisation production share. The effect of varying the value of MGSPS from 20% up to 60% on the system's behaviour will be detected.

Table 5.3: Inputs of the reference system for MGSPS SA

Technical Regulation Strategy	3
MGSPS	**20%, 30%, 40%, 50%, 60%**
Allow for simultaneous operation of turbine and pump	NO
Pump Storage	76 GWh
CEEP regulation	NONE
Transmission Line Capacity	0 MW

In Table 5.4 the values of all the quantities which are affected by the variation of MGSPS are presented. The highlighted line contains the outputs of the reference system with 30% MGSPS as this has been defined from the beginning (see Table 4.6)

Table 5.4: Outputs of reference system for MGSPS SA

MGSPS	Electricity consumption (TWh/year)	Electricity production (TWh/year)			CEEP (TWh/year)	Fuel consumption (TWh/year)	StabLoad (%)			CO2 emissions (Mt)
	Pump Hydro	Turbine	Hydro	PP	total	total	average	max	min	Total
20%	1,89	1,35	5	31,87	3,17	331,28	320	447	195	79,66
(ref) 30%	1,91	1,36	5	31,87	3,17	331,28	213	298	130	79,66
40%	1,93	1,37	5	31,88	3,18	331,31	160	224	107	79,67
50%	1,99	1,41	4,88	32,27	3,43	332,04	129	179	100	79,97
60%	3,05	2,17	4,4	35,56	5,92	338,69	112	149	100	82,52

A comparison between the outputs for different values of MGSPS will lead to interesting findings concerning the behaviour of the system.

From 20% to 30% and 40%

By increasing the MGSPS from 20% to 30% (reference value) and then up to 40% the behaviour of the system is not affected considerably. The outputs are almost similar with minor variations in quantities such as CEEP, Total Fuel Consumption (or else PES) and CO2 emissions. This is explained by looking at the minimum value of StabLoad, which is the requirement inextricably linked with the MGSPS. Therefore, even with 30% or 40% MGSPS the minimum value for StabLoad is 130% and 107% (>100%) respectively, which means that the requirement of 30% or 40% does not set any additional limitation to the operation of the system, comparing to the case of 20% MGSPS. This is because, at this point, the MGSPS requirement is overlapped by the requirement of minimum PP. Consequently, the model does not make significant changes in the operation of the units within the system. It seems that both hydro and pumping units operate at maximum so they can counterbalance the stabilisation of the grid and the CEEP. What could be inferred from all the above, is that both 20% and 40% of MGSPS could be used as requirement instead of 30%, which is used in the reference system, without significant alterations in the outputs of the system.

From 40% to 50%

In this case we observe that the minimum value of StabLoad is 100% which means that the requirement of 50% MGSPS set limits to the operation of the system. Particularly, the operation of PP is increased so that the requirement of 50% is met, something which stimulates the increase of CEEP. This also explains why the hydro are reduced a bit (before they were operating at maximum possible according to their design parameters and water inflow) and the pumping hydro units are increased. It is obvious that the model attempts to optimise the operation of the units though a small increase to the fuel consumption and the total CO2 emissions cannot be avoided.

From 50% to 60%

The operation of the units keeps changing with the same tendency as in the previous case. Hydro are reduced further while pumping hydro are increased in a try of the model to keep as low as possible the CEEP which has been increased due to the increased operation of PP, which was stimulated by the requirement of 60% MGSPS.

5.3 Penstock

In this Section the Sensitivity Analysis will be based on whether the simultaneous operation of turbines and pump, in pump hydro units, is allowed or not. In other words, the effect of having single or double penstock, in pump hydro stations, on the outputs of the reference system will be examined.

Table 5.5: Inputs of the reference system for Penstock SA

Technical Regulation Strategy	3
MGSPS	30%
Allow for simultaneous operation of turbine and pump	**NO, YES**
Pump Storage	76 GWh
CEEP regulation	NONE
Transmission Line Capacity	0 MW

Following the same way of thinking with the previous parts of SA analysis, in Table 5.6 the operation of units, directly involved in this part of SA, as well as quantities characteristic for the behaviour of the system are summarised. In the reference system it is considered that the simultaneous operation is not allowed since all the 3 pump hydro units of the reference system considered to have single penstock.

Table 5.6: Outputs of reference system for Penstock SA

Turbine & Pump simultaneous operation	Electricity consumption (TWh/year)	Electricity production (TWh/year)			CEEP (TWh/year)	Fuel consumption (TWh/year)	CO2 emissions (Mt)
	Hydro Pump	Turbine	Hydro	PP	total	total	total
(ref.) NO	1,91	1,36	5	31,87	3,17	331,28	79,66
YES	1,91	1,36	4,99	31,87	3,17	331,28	79,66

The behaviour of the system in both cases appears to be identical. The operation of Hydro Power is probably limited due to the minimum PP requirement (3500 MW), so that there is no big margin for additional operation of pumping units. Consequently the effect of the penstock is insignificant for the reference system.

It should be noted that this parameter had high effect in the system when a previous version of EnergyPLAN was used to simulate the reference system, in which there was not any requirement concerning minimum operation of Condensing PP.

5.4 Pump Storage Capacity

The parameter under investigation in this part of the analysis is the storage of pump hydro units. Therefore, the pump storage capacity comparing to the value of the reference system (76 GWh) becomes two times bigger, four times bigger and then theoretically infinite (99999 GWh).

Table 5.7: Inputs of the reference system for Penstock SA

Technical Regulation Strategy	3
MGSPS	30%
Allow for simultaneous operation of turbine and pump	NO
Pump Storage Capacity	**76, 152, 304 and 99999 GWh**
CEEP regulation	NONE
Transmission Line Capacity	0 MW

The comparison of the aforementioned cases leads to interesting findings about the correlation between the pump storage capacity and the outputs of EnergyPLAN, which are presented in Table 5.8. The corresponding values of CRES simulations have been also included in Table 5.8, since the different logic of the two models concerning the whole issue (see 4.3.2 under electricity production) of the operation of pump hydro units is of utmost importance.

Table 5.8: Outputs of reference system for Pump Storage SA

Pump Storage capacity (GWh)	Electricity consumption (TWh/year)	Electricity production (TWh/year)			CEEP (TWh/year)	Fuel consumption (TWh/year)	CO2 emissions (Mt)	StabLoad (%)
	Hydro Pump load	Turbine	Hydro	PP	total	total	total	min
(ref) 76	1,91	1,36	5	31,87	3,17	331,28	79,66	130
(x2) 152	2,13	1,51	4,99	31,73	2,97	330,98	79,56	130
(x4) 304	2,48	1,76	4,99	31,46	2,59	330,38	79,34	130
(∞) 99999	2,97	2,11	4,99	31,11	2,1	329,64	79,08	130
CRES	2,389	1,703	3,89	31,26	1,09	331,25	-	-

An attempt to describe and explain the reaction of the system will be made in the next few lines. While the pump storage capacity is gradually increased (x2/x4/infinite) the operation of hydro units remains stable at maximum level whereas the operation of pumping units is gradually increased. This means that the electricity production of pump hydro is increased and so does the pump load. At the same time the production of condensing PP gradually decreases since the continuously increasing total electricity demand is covered by pump hydro units. As a consequence the CEEP appears a considerable reduction while the reduction in the total fuel consumption and CO2 emissions is quite smooth.

As for the comparison with CRES simulations, it should be reminded that, a fixed value for pump load is set and that is the one and only limitation for the operation of the pump hydro units, there is no storage capacity set in CRES models. Looking at the Table 5.8 it is observed that when the reference storage becomes four times bigger, the electricity consumption of the pumps is almost the same as in CRES simulations (2,48 TWh/2,389 TWh).

The comparison between the CRES simulation and the case where the pump storage is four times the reference value shows that the electricity production from both pump hydro (turbine) and PP is almost the same. The difference between the two cases is that in CRES simulation the production of hydro is reduced and the CEEP is lower than in x4 case. Something more that can be inferred form this comparison, is that the fixed pump load, which is set in CRES simulations, seems to correspond to a pump storage capacity around 300 GWh, although the actual pump storage capacity as this has been estimated for the Greek Energy System for 2020 is around 76 GWh.

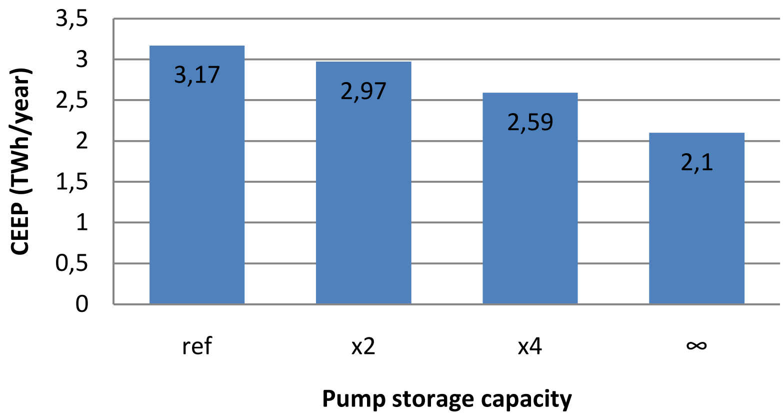

Figure 5.1: The effect of pump storage's capacity on the CEEP

Consequently, the increase of pump storage capacity can contribute significantly to the minimisation of Critical Excess Electricity Production, as it can be seen in Figure 5.1. Hence, it needs to be taken into account when a study which aims at minimising CEEP is conducted.

5.5 CEEP regulation strategies

This part of SA focuses on the effect of different CEEP regulation strategies provided by EnergyPLAN and aim at minimising CEEP by regulating properly the operation of the units of the reference system. Some strategies have been used alone and some of them have been combined so that the behaviour of the system can be improved further.

Table 5.9: Inputs of the reference system for CEEP reg. Strategies SA

Technical Regulation Strategy	3
MGSPS	30%
Allow for simultaneous operation of turbine and pump	NO
Pump Storage	76 GWh
CEEP regulation	**NONE, 1, 35, 7, 357**
Transmission Line Capacity	0 MW

As it can be seen in Table 5.9 the CEEP regulation strategies tested are the following:

- Strategy 1: Reducing the production from Wind power and Photovoltaics
- Strategies 3 and then 5: Firstly reducing the production of CHP3 by replacing with boiler and then replacing boiler with electric heating
- Strategy 7: Reducing the production from condensing PP in combination with all the RES
- Strategies 3 & 5 & 7: The actions described in the two previous bullets are combined sequentially

The operation of the units, which have been regulated by the model in each case, is presented in Table 5.10.

Table 5.10: Outputs of reference system for CEEP reg. Strategies SA

CEEP reg strategy	DH production (TWh/year)			Electricity Consumption (TWh/year)		Electricity production (TWh/year)					CEEP (TWh/year)	Fuel cons. (TWh/year)	CO2 em. (Mt)	Stab Load (%)
	CHP	boiler	EH	EH	Pump Hydro	Turbine	RES	Hydro	CHP	PP/ minPP	total	total	total	min
(ref)none	1,2	0,06	0	3,94	1,91	1,36	20,06	5	0,69	31,87/ 3500	3,17	331,28	79,66	130
1	1,2	0,06	0	3,94	1,9	1,35	16,9	5	0,69	31,87/ 3500	0	328,11	79,66	137
3,5	0,84	0,06	0,37	4,31	1,91	1,36	20,06	5	0,53	31,87/ 3500	2,63	330,61	79,37	130
7	1,2	0,06	0	3,94	1,9	1,35	17,85	4,99	0,69	30,92/ 1981	0	326,99	78,92	137
3,5,7	0,84	0,06	0,37	4,31	1,93	1,37	18,22	4,99	0,53	31,08/ 2013	0	327,06	78,76	136

In the first line of the table the reference case is included, in which none CEEP regulation strategy is applied to the reference system.

<u>1 vs reference:</u> The production of RES is decreased so that the CEEP becomes zero. The whole magnitude of CEEP (3,17 TWh in the reference case) is deducted mainly from the wind production (from 15,99 TWh/year goes to 12,87 TWh) and then from PV production (from 2,80 TWh/year goes to 2,76 TWh/year). The total annual fuel consumption is also reduced by 3,17 TWh. The operation of all the other units, apart from RES, is not affected so the CO2 emissions remain stable. The only parameter concerning the behaviour of the system that changes is the stabilisation of the grid which is increased due to the reduction of the RES share.

<u>35 vs reference:</u> By applying strategy 3 and then 5, the operation of CHP is regulated during hours with CEEP. Therefore, the electricity production of CHP is reduced in specific hours so that the CEEP can be minimised. The reduction in the electricity production means the simultaneous reduction in the heat production of CHP. For this reason the heat demand that was met by CHP, in the reference case, is now transferred to boilers (Strategy 3) and from boilers to electric heating (Strategy 5). In this way, a further reduction of CEEP is achieved, since with electric heating the heat demand is met by consuming electricity instead of producing electricity, as occurred in the reference case. As a consequence of this optimisation procedure, the operation of both condensing PP and RES units remains stable, comparing to the reference case.

The overall behaviour of the system is improved, given that the CEEP is considerably reduced and the total fuel consumption as well as the CO2 emissions are also reduced. Last but not least, the stabilisation of the grid seems to be the same as in the reference case. Probably, this happens because in the hours with CEEP the electricity demand is reduced due to electric heating so that the production of CHP3 (0,53 TWh) needed for stabilisation reasons is sufficient. In addition to this, the operation of condensing PP, which is forced by the requirement of minimum PP (3500 MW), is enough to meet the stabilisation requirements.

<u>7 vs reference/1:</u> In this case the total elimination of CEEP is achieved by reducing the production from all types of RES and the production of condensing PP simultaneously, even if there are some hours when the requirement of minimum PP (3500 MW) is not met. This means that the option to break the min PP

requirement is given to the model so that the elimination of CEEP can be achieved without reducing so much, in comparison with applying Strategy 1, the production of RES. This effect is reflected in the total annual fuel consumption and in the total annual CO2 emissions.

357 vs reference/7/1/35: By applying strategies 3, 5 and 7 sequentially the elimination of CEEP is achieved. At the same time a better balance between the production of PP and RES is achieved comparing to Strategy 7 and Strategy 1. This means that the production from RES is reduced comparing to the reference case but is reduced less comparing to strategy 7 (17,85 TWh/year) and strategy 1 (16,9 TWh/year). As for the operation of condensing PP it is increased comparing to strategy 7 because the RES share is increased and it is reduced comparing to strategy 1 because the min PP requirement is not met. The operation of CHP3 units is similar with this of Strategies 35. The fuel consumption and the CO2 emissions simply reflect the operation of the electricity generating units.

After this complicated explanation of the regulation of the units by applying different CEEP regulation strategies it becomes obvious that all the strategies have advantages and disadvantages. Consequently, it is a matter of priorities which strategy will be followed for the minimisation of CEEP. Therefore, if the elimination of CEEP is the one and only priority, then one of the strategies 1, 7 or 357 should be selected. In this case Strategy 1 would be preferred over the other two (7/357) if the requirement of minimum PP (3500 MW) needs to be met anyway, otherwise 357 would be prefered over 7 if a higher RES share is priority and 7 would be prefered over 357 if lower fuel consumption is priority. In case that the priority is to take fully advantage of the RES potential while minimising CEEP then Strategy 35 is the only option. However, if Strategy 35 it is not practically applicable and the highest possible RES penetration is top priority then the optimisation procedure of the reference case would be prefered, without applying any additional CEEP regulation strategy.

5.6 Exports

The main intention of this Section is to examine how the units are regulated when the option of exporting electricity is existent. The effect of including in the optimisation procedure the available Transmission Lines, with Capacity equal to 1550 MW (see Table 5.11), on the behaviour of the system will be investigated.

Table 5.11: Inputs of the reference system for NTC SA

Technical Regulation Strategy	3
MGSPS	30%
Allow for simultaneous operation of turbine and pump	NO
Pump Storage	76 GWh
CEEP regulation	NONE
Transmission Line Capacity	**0, 1550 MW**

At this point it should be reminded that EnergyPLAN considers three different kinds of excess electricity. The first one is the Excess Electricity Production (EEP) a quantity which expresses the potential electricity export (see also 4.2.1). EEP contains the other two kinds of excess which are the Critical Excess Electricity Production (CEEP) and the Exportable Excess Electricity Production (EEEP). EEEP corresponds to the share of EEP that can be exported given the available capacity of the transmission lines (C). When EEP exceeds this capacity then CEEP appears and it is equal to the difference between EEP and EEEP(Lund, EnergyPLAN 2010).

Therefore, by setting the transmission line capacity equal to 1550 MW, EEP increases comparing to the reference case and it is equal to 5,86 TWh/year (see Table 5.12). The exportable share (EEEP) is up to 5,55 TWh/year whereas in the reference case it was 0 since there was no option for exporting electricity. As a result, CEEP is equal to 0,31 TWh/year, which means that is significantly reduced in comparison with the reference case.

Table 5.12: Outputs of reference system for exports' SA

C (MW)	Electricity cons. (TWh)	Electricity production (TWh)				Excess EEP (TWh)	Critical CEEP (TWh)	Exportable EEEP (TWh)	Fuel consumption (TWh)		CO2 emissions (Mt)		Stab Load (%)
	Hydro Pump	Turbine	RES	Hydro	PP				Total	Dom.	Total	Dom.	min
(ref) 0	1,91	1,36	20,06	5	31,87	3,17	3,17	0	331,28	324,4	79,66	77,21	130
1550	0,62	0,44	20,06	5,79	33,4	5,86	0,31	5,55	335,39	322,66	80,85	76,31	126

The question that arises by observing the values of all types of excess electricity production listed in Table 5.12 is why EEP becomes greater, when there is the option of exports, than it was in the reference case. The answer will be given by explaining the way that the model regulates the operation of the units. Additionally, two figures will support this explanation. Both of them show the electricity balance during a day in March with rather high excess electricity production (which is due to the high wind potential), the one for the reference case (Figure 5.2) and the other for the case with 1550 MW transmission line capacity (Figure 5.3).

When C = 0 MW: The system is in a balanced state in which it takes fully advantage of the potential electricity production from RES and all the requirements (MGSPS, min PP) are met. As a result Critical Excess Electricity Production appears and can not be avoided.

When C = 1550 MW: In this case the option of exporting electricity is provided to the model so that CEEP can be minimised. Therefore, the maximum possible electricity is exported depending on the capacity of the transmission lines. The exported electricity comes from condensing PP where the fuel consumed is mainly Coal and NG and a small share of Biomass. At this point it should be underlined that the model prefers to export electricity produced from fossil fuels while electricity from RES is consumed domestically (within the country). When electricity is exported during a specific hour the balance of the system is disordered because the electricity production coming from stabilising units is reduced and the requirement of MGSPS equal to 30% is not met (StabLoad<100%). As a consequence, the model increases further the operation of both condensing PP and Hydro units so that the system comes to balance again (StabLoad ≥ 100%). This regulation stimulates the increase of EEP (see Figures 5.2 and 5.3 during hour 2010). However, the share of EEP which is exportable is rather high so that after the end of the optimisation procedure (8784 hours) the remaining excess which is critical (CEEP) is considerably lower than the CEEP of the reference case (where it was C=0MW).

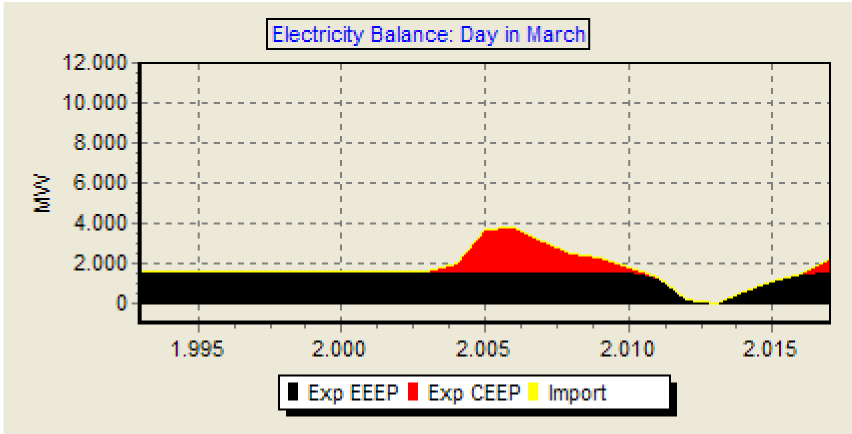

Figure 5.2: Electricity Balance during a day in March with C=1550 MW

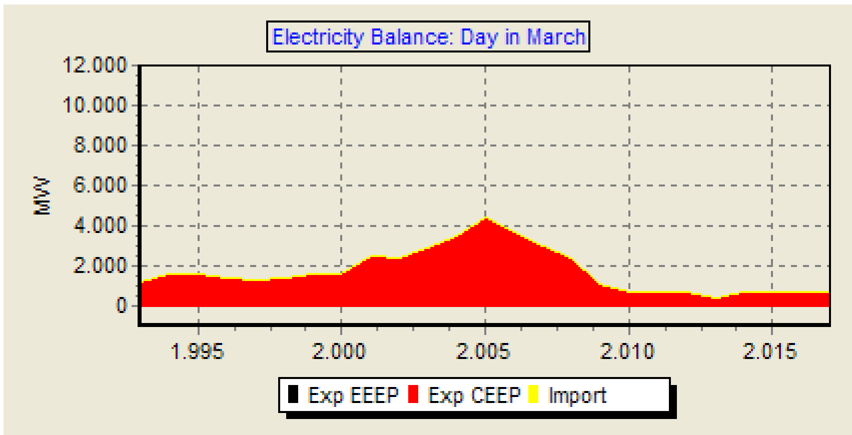

Figure 5.3: Electricity Balance during a day in March with C=0 MW

By having the option of export, the total fuel consumption (PES) and the total CO2 emissions are increased comparing to the reference case and this is due to the increased operation of condensing PP. However, the corresponding domestic values are reduced, since electricity is exported (domestic PES reduces) and it comes from fossil fuels (domestic CO2 emissions reduce).

6 Optimum wind penetration

In this chapter an analysis that aims at identifying the maximum wind penetration which is technically feasible will be conducted. Therefore, the investigation will be based on two criteria:

1. the minimisation of the primary energy consumed within the system and
2. the minimisation of the Critical Excess Electricity Produced (CEEP).

In this way the Chapter will answer the 4^{th} sub-question: "What is the maximum feasible wind penetration on the 2020 Greek Interconnected energy system, as a function of the installed wind capacity, from a technical perspective?"

In the framework of this investigation two approaches are adopted, according to the first one the balance between CEEP and total PES (PES_{total}) is the crucial factor for defining the maximum wind penetration technically feasible. While, the second approach is similar with the first one apart from the fact that the PES excluding Renewable Energy Sources including biomass ($PES_{excl.RES}$) is taken into account. It was considered as interesting to involve $PES_{excl.RES}$ in this analysis because the maximum feasible wind penetration would be defined from another point of view. Based on PES_{total} the minimisation of the total fuel consumed is considered as a positive impact on the system. However, in PES_{total} the amount of RES which is consumed is also included and the minimisation of RES consumption is not considered as positive according to the scopes of this project. This could be avoided by using $PES_{exclRES}$, since the minimisation of fossil fuels' consumption that can be achieved with high wind penetration, definitely is in accordance with the scopes of the project.

Particularly, the identification of the maximum wind penetration which is technically feasible will be graphic. The graphs will depict the rate of change of CEEP, PES_{total} and $PES_{exclRES}$ while the wind penetration will be gradually increasing. The spectrum of wind penetration extends from 0% to nearly 50%, these values correspond to 0 - 11750 MW wind capacity and 0 - 28 TWh annual electricity production from wind power. The whole procedure will be better explained in the following sections with specific data.

At this point, it should be mentioned that the maximum feasible wind penetration will be determined not only for the reference system but also for an alternative system. In the previous chapter the effect of each single parameter on the system was investigated by conducting a sensitivity analysis. Those parameters will be combined in order to compose the alternative system, taking advantage of the knowledge obtained from the findings of the sensitivity analysis.

The difference of the alternative system comparing to the reference one, is that the pump storage capacity is equal to 304 GWh (reference x4) and CEEP regulation strategies 3 and 5 are applied sequentially. The specific value for the capacity of the pump storage was selected because it leads to considerable CEEP reduction (see Table 5.8) and it is a realistic value. The last implies that such a pump storage capacity it is approachable given that one more pump hydro station has been planned to be included in the Greek Interconnected Energy System by 2020. Concerning CEEP regulation, strategies 3 and 5 have been selected because the SA proved that this combination keeps the RES share in the electricity production at maximum level, according to the RES potential available, and a considerable decrease of CEEP can be achieved (see Table 5.10).

Moreover, the option of exports will be investigated in combination with both the reference and the alternative system.

The four scenarios which come as a result of the above mentioned are:

- Reference closed
- Reference open
- Alternative closed
- Alternative open

The characteristic features of each scenario are listed in Table 6.1.

Table 6.1: Basic features of four scenarios

Basic features	Reference Closed	Reference Open	Alternative Closed	Alternative Open
Technical Regulation Strategy	3	3	3	3
MGSPS	30%	30%	30%	30%
Allow for simultaneous operation of turbine and pump	No	No	No	No
Minimum PP (MW)	3500	3500	3500	3500
Pump Storage (GWh)	76	76	304	304
CEEP regulation	None	None	35	35
Transmission Line Capacity (MW)	0	1550	0	1550

6.1 Reference Closed

The maximum technically feasible wind penetration will be defined in 3 steps. In the first step the lower limit is determined while in the second step the upper one, creating in this way a range. In the final step, within this range, the desirable percentage is defined. Of course, all the percentages mentioned below include a rather small error margin due to limited data resolution. However, each time they are representative of the case and their precision is satisfying for the scope of this study.

1st step: Defining the lower limit

In the following graph the values of CEEP, while the wind penetration is increasing, are presented. The lower limit of the maximum feasible wind penetration based on CEEP appears to be equal to 13%.

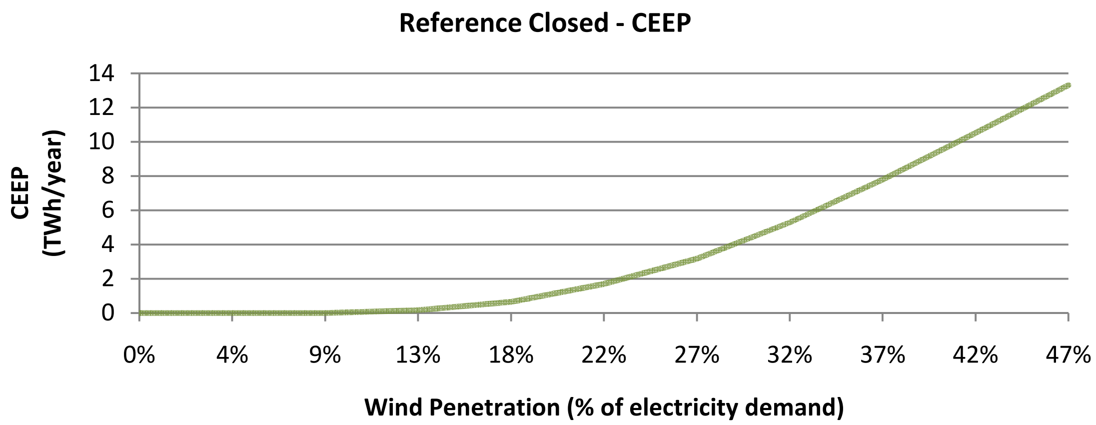

Figure 6.1: CEEP as a function of wind penetration for the Reference Closed scenario

This is the percentage of wind penetration for which CEEP becomes other than zero. This means that it does not worth to have a wind penetration lower than 13% given that the CEEP is zero until this point in any case.

<u>2^{nd} step: Defining the upper limit</u>

In the graph below the values of both the total PES and the PES excluding RES, for an increasing wind penetration, are depicted.

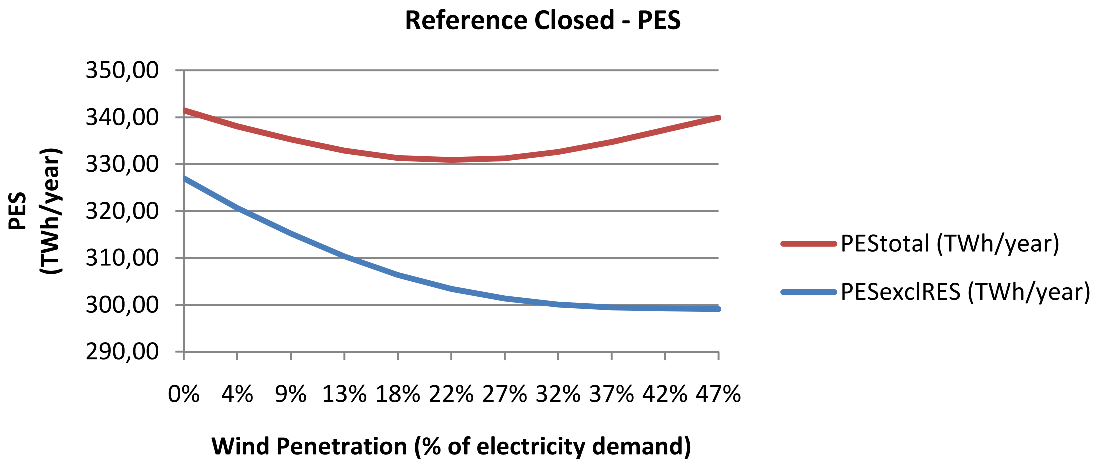

Figure 6.2: PES total and excluding RES as a function of wind penetration for Reference Closed scenario

According to the total PES the upper limit should be equal to 25%, since the curve of PES_{total} appears a gradual decline until this wind penetration. This means that, before this point, the RES which are added to the system are less than the fuel saving that can be achieved. On the contrary, after this point the PES_{total} appears gradual increase which means that the added RES exceed the fuel savings. The things look different by taking into account the curve of $PES_{exclRES}$. This appears a continuous decline until the wind penetration becomes equal to 32%, after this point $PES_{exclRES}$ remains stable.

<u>3^{rd} step: Defining the exact percentage</u>

In the following graph the rate of decrease of PES_{total} (ΔPES_{total}) and $PES_{exclRES}$ ($\Delta PES_{exclRES}$) and the rate of increase of CEEP (ΔCEEP) as a function of the increasing wind penetration are presented. It should be noted that the curve of ΔPES_{total} can even go down to the negatives. A negative rate of decrease means that the PES_{total} is increasing after one point, something which was also observed in Figure 6.2.

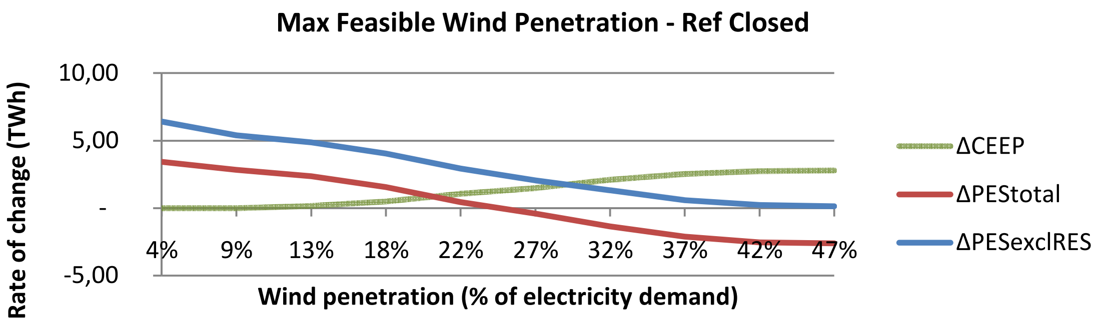

Figure 6.3: ΔPES_{total}, $\Delta PES_{exclRES}$ and ΔCEEP as a function of wind penetration for the Reference Closed

It is considered that the crossing points of each PES curve with the curve of CEEP give the percentage of the maximum feasible wind penetration for each approach. In this way, the definition of maximum wind penetration technically feasible is perceived as the penetration for which the decrease rate of PES (either total or excluding RES) is the same with the increase rate of CEEP. Particularly for the reference closed scenario, the maximum wind penetration is equal to **21% based on PES_{total}** and equal to **29% based on $PES_{exclRES}$**.

Therefore, for any lower penetration than 21%/29% the increase rate of CEEP is lower than the decrease rate of PES_{total}/$PES_{exclRES}$ so that it is worth moving to a higher penetration. Reversely, for any higher penetration than 21%/29% the increase rate of CEEP is greater than the decrease rate of PES_{total}/$PES_{exclRES}$ so that it is worth going back to a lower penetration. Consequently, the penetration determined by the crossing points expresses a balance between a positive impact such as the decrease of fuel consumption and a negative one such as the increase of CEEP.

6.2 Reference Open

Main intention of this section is to identify the maximum wind penetration which is technically feasible when the system has the option of exporting electricity. The same steps as in the previous section will be followed and the curves on the graphs are similar so the desirable percentages will be provided without repeating the same explanations but with just commenting new points that arise.

1st step: Defining the lower limit

In this scenario, in which the reference system is open, as CEEP is considered the difference between the Excess Electricity Production and the Exportable share of it.

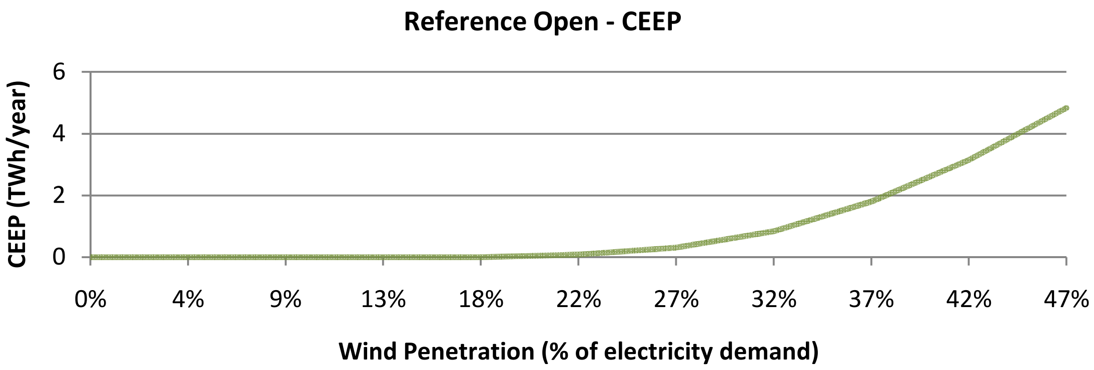

Figure 6.4: CEEP as a function of wind penetration for the Reference Open scenario

By looking at Figure 6.4 the lower limit seems to be equal to 22%, since before this point the CEEP is steadily zero.

2nd step: Defining the upper limit

In Figure 6.5 both PES_{total} and $PES_{exclRES}$ refer not only in the fuel which corresponds to electricity consumed domestically but the fuel which corresponds to the total electricity produced within the system. Even if some fuel is consumed to produce electricity which is exported, this fuel is consumed within the Geek Energy System so it needs to be included when the maximum penetration is defined.

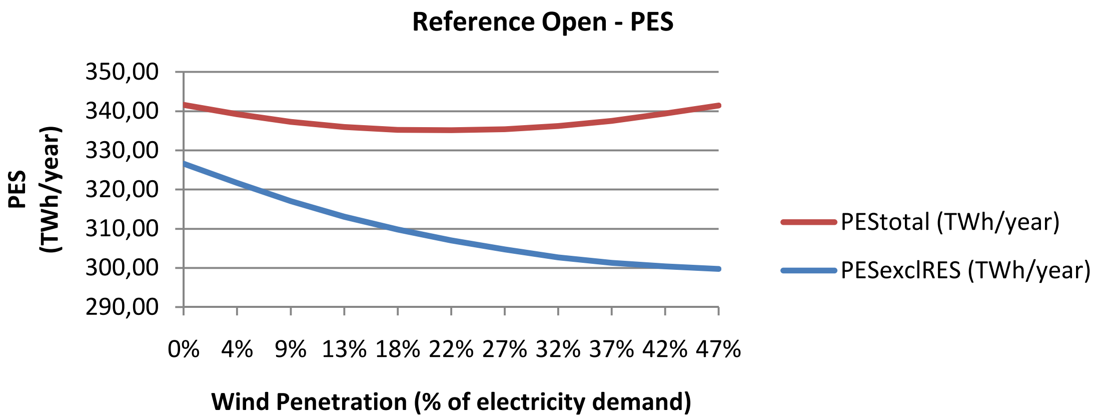

Figure 6.5: PES total and excluding RES as a function of wind penetration for Reference Open scenario

The upper limit appears to be around 23% based on PES_{total} and almost 42% based on $PES_{exclRES}$. The big difference between the two approaches is due to the fact that almost all the exported electricity is produced by fuels other than RES.

3rd step: Defining the exact percentage

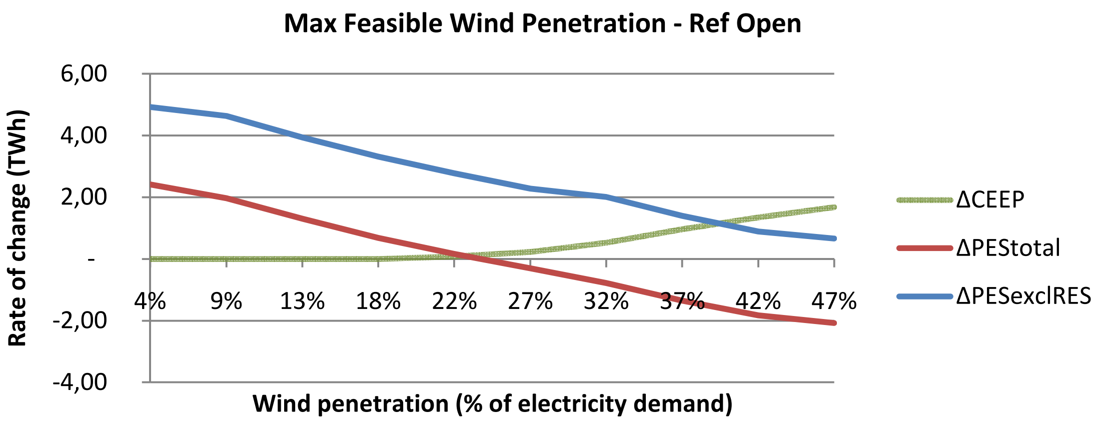

Figure 6.6: ΔPES_{total}, $\Delta PES_{exclRES}$ and ΔCEEP as a function of wind penetration for the Reference Open

The intersection points seem to be around 23% and 40% approximately. As a consequence, the **maximum wind penetration technically feasible** is equal to **23% based on PES_{total}** and equal to **40% based on $PES_{exclRES}$**. It should be noted that in the approach of PES_{total} the range that is created is too narrow and the resulted max wind penetration corresponds to zero CEEP and PES_{total} rates of change.

6.3 Alternative Closed

In the framework of this section, an estimation of the maximum wind penetration technically feasible for the alternative system, as this was defined in the beginning of the Chapter, will take place. Moreover, exporting electricity is not an option in this scenario.

1st step: Defining the lower limit

The lower limit as this is formulated by looking at the CEEP graph (Figure 6.7) for the alternative closed scenario is equal to 15% approximately.

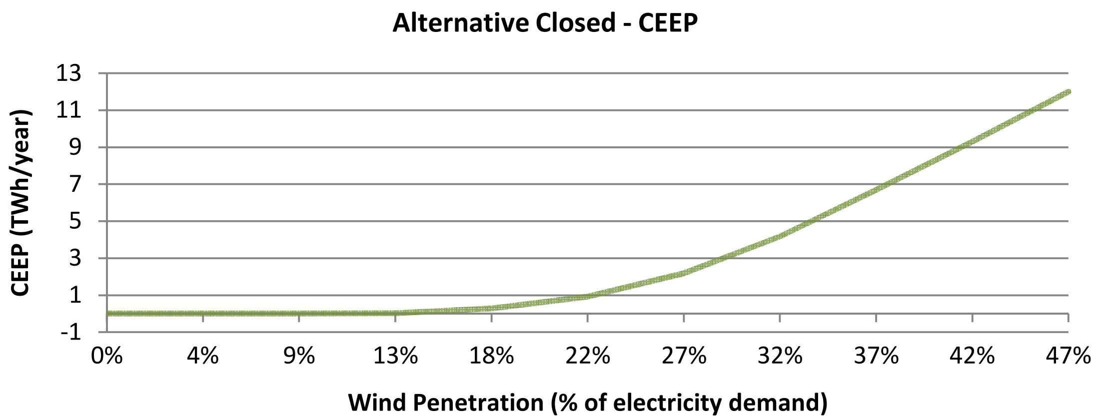

Figure 6.7: CEEP as a function of wind penetration for the Alternative Closed scenario

2nd step: Defining the upper limit

Based on PES_{total} the upper limit should be around 26%, since until this wind penetration the total fuel consumption is decreasing and after this point it starts to be increasing. By observing the $PES_{exclRES}$ curve the upper limit would be equal to 37% because after this point the curve seems to be stabilised.

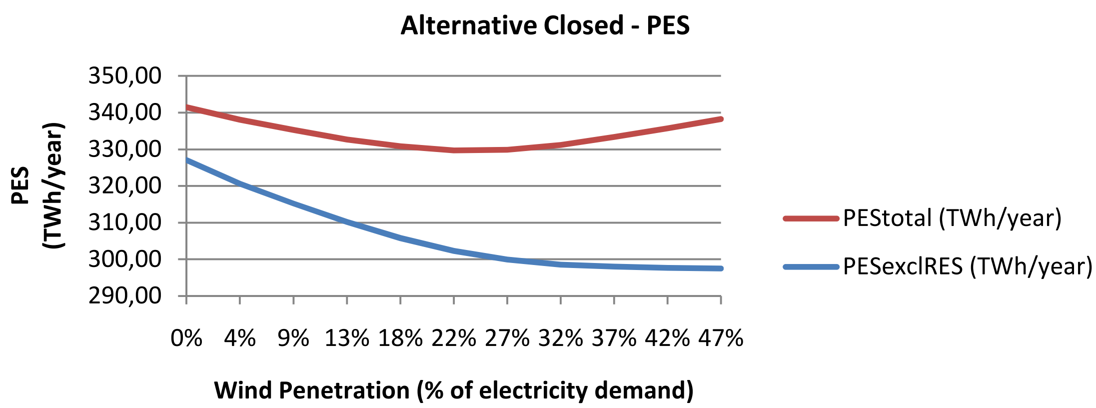

Figure 6.8: PES total and excluding RES as a function of wind penetration for Alternative Closed scenario

3rd step: Defining the exact percentage

The **technically optimum wind penetration** according to the decline rate of the total fuel consumption (**ΔPES_{total}**) is **23%**, whereas according to the decline rate of the fuel consumption excluding RES but including biomass (**$\Delta PES_{exclRES}$**) is **31%**.

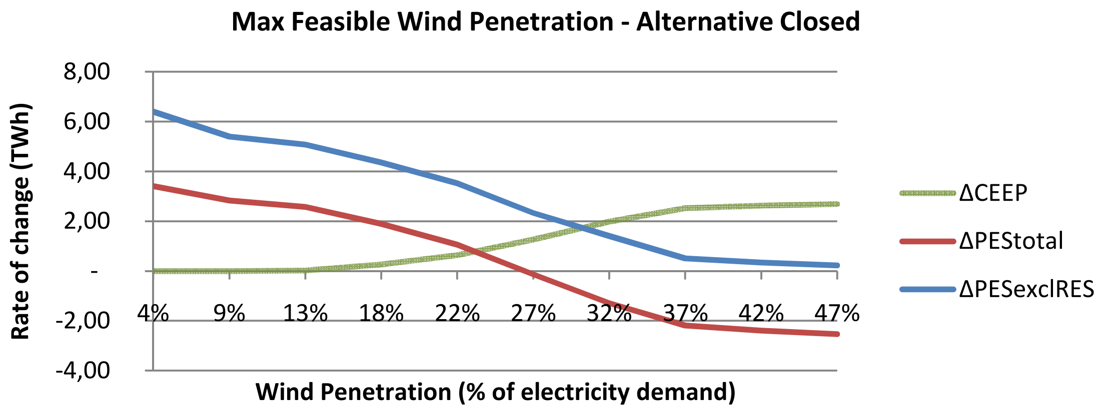

Figure 6.9: ΔPES_{total}, $\Delta PES_{exclRES}$ and ΔCEEP as a function of wind penetration for the Alternative Closed

6.4 Alternative Open

The system under investigation remains the alternative, as in the previous section, but the difference here is that the option of exporting electricity is added. Similarly with all the scenarios presented until now the three steps are also followed here.

<u>1st step: Defining the lower limit</u>

The lower limit will be defined equal to 22% because this is the wind penetration after which the values of CEEP are other than zero. In Figure 6.10 this is not clear due to the size of the graph but by looking at the data behind the graph this is the right percentage.

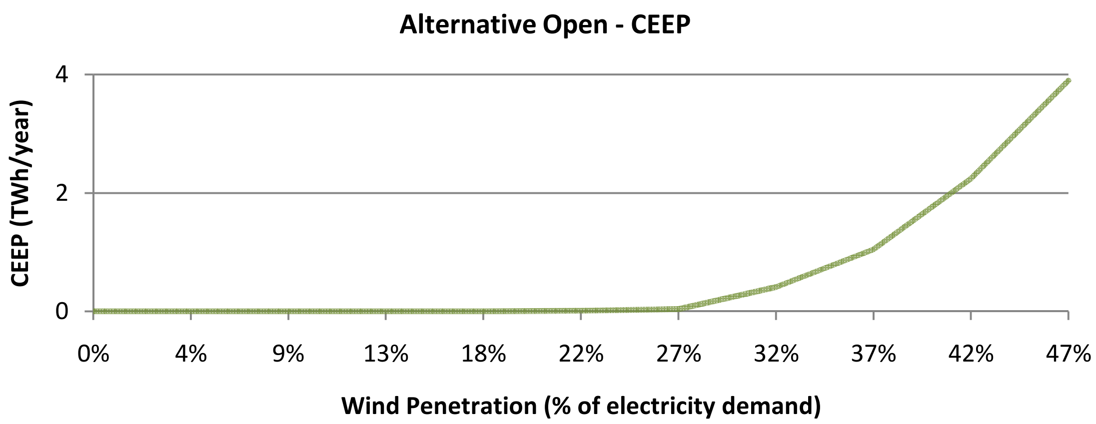

Figure 6.10: CEEP as a function of wind penetration for the Alternative Open scenario

<u>2nd step: Defining the upper limit</u>

The upper limit based on PES_{total} appears to be 27% and based on $PES_{exclRES}$ about 45%. Similarly with the Reference Open scenario, the big difference between the two percentages is due to the fact that almost all the exported electricity is produced by non-RES fuels.

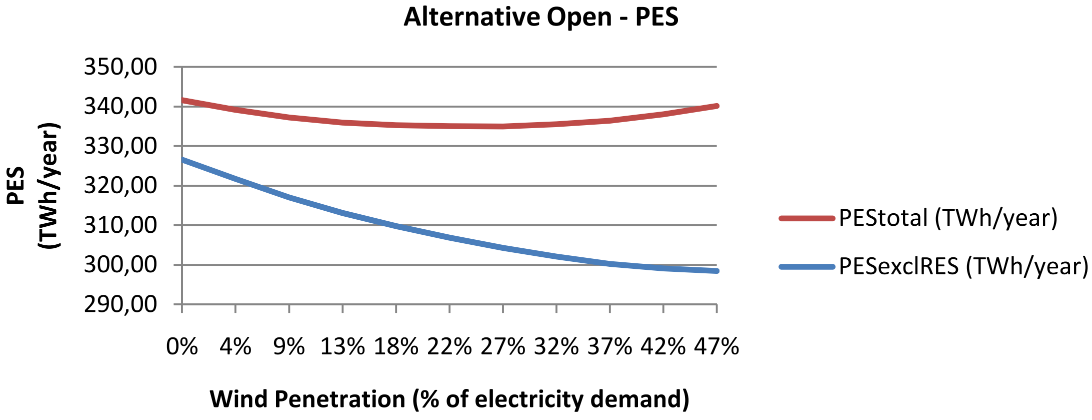

Figure 6.11: PES total and excluding RES as a function of wind penetration for Alternative Open scenario

<u>3rd step: Defining the exact percentage</u>

The optimum value for the wind penetration **based on PES_{total}** approach is estimated up to **27%**, whereas **based on $PES_{exclRES}$ is up to 42%**.

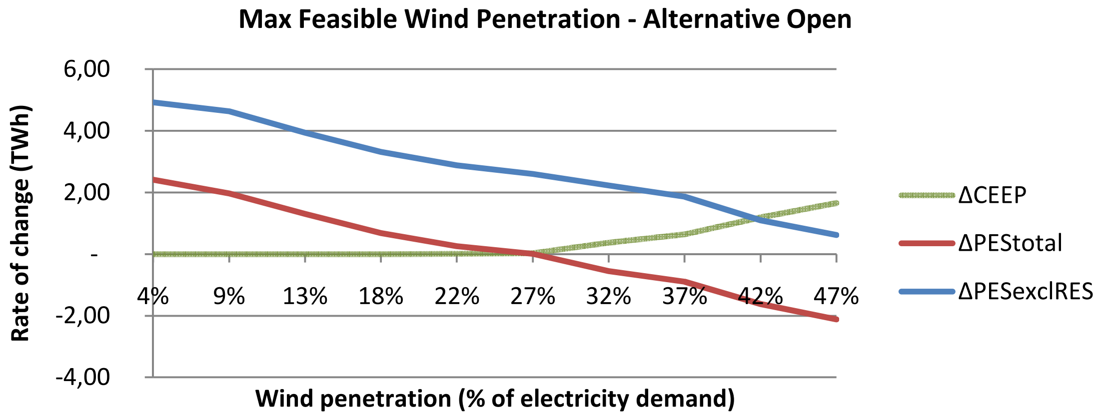

Figure 6.12: ΔPES_{total}, $\Delta PES_{exclRES}$ and ΔCEEP as a function of wind penetration for the Alternative Open

Similarly with the Reference Open scenario, in the approach of PES_{total} the resulted max wind penetration corresponds to zero CEEP and PES_{total} rates of change. Something which is explained by looking at Fig. 6.10 and Fig. 6.11 where both CEEP and PES_{total} curves appear to be stable (around 0 TWh and 335 TWh respectively).

7 Conclusions

Main intention of this Chapter is to provide the reader with a sufficient answer in the Research Question by answering all the sub-questions which flow from this and have been placed in the Introduction of this report. The answers will be based on an overview of the outputs of Chapters 4 and 5 in which constitute the analysis part of the project. Therefore, information and data, already presented until now, will be combined and reorganised in a way that is appropriate to give profound and coherent answers to the sub-questions and the Research Question of this project:

"How can the Greek Interconnected Energy System of 2020, as it is shaped by the plan for compliance with the 20-20-20 targets, be technically optimised aiming at a high wind penetration with EnergyPLAN model?"

Sub-question 1

How can the operation of energy generating units of the system be regulated so that the excess electricity production, the total fuel consumption and the CO2 emissions can be minimised?

- Condensing Power Plants should operate at the top of all the other electricity generating units and cover the remaining electricity demand. The way that this should be done is by operating at the minimum possible level, which is determined by the minimum technical requirements of the condensing units themselves and the grid stabilisation requirements.

- Hydro Power units operate based on a given water inflow. On the basis of this operation, their production should be increased in order to replace condensing units and decreased during specific hours when excess electricity appears by taking into account the grid stabilisation requirements at the same time. Of course this balanced production can not exceed the fluctuating potential energy content that is available in the storage, at any hour of the year.

- Pump Hydro units (reversible hydro) should operate depending on the available storage capacity during hours when excess electricity production still appears, after the regulation of hydro power units, and a further reduction of it is needed. Therefore, during these hours the pump should operate to fill the storage whereas the turbine should operate to replace the production of condensing units by emptying the storage.

- CHP units should operate in order to cover the district heating demand and fulfil the grid stabilisation requirements at the same time. Moreover, during hours with excess electricity production their operation should be replaced by boilers and condensing units.

- Boilers should operate supplementary to the CHP units in order to cover the remaining district heating demand.

- The operation of Industrial CHP units can not be regulated since no intervention can be made in the industrial processes. The electricity production of these units is fully used to cover part of the electricity demand.

- Renewable energy technologies i.e. Wind turbines, Photovoltaics, CSP, River Hydro and Geothermal should operate so that they can take full advantage of the available potential of RES.

Sub-question 2

What are the differences in the operation of the units and the general behaviour of the system between EnergyPLAN and the models used by the host institute?

- The outputs of the two different simulations appear to be really close. However, there are some minor differences between the outputs related to the electricity production of the units. The differences come from the different philosophy of the simulations in specific spots and result in slightly different excess electricity production.

- One vital difference is that in simulations of CRES economical data are taken into account whereas in the simulation with EnergyPLAN no economic conditions are involved in the optimisation process, given that it was used to conduct an optimisation study purely technical. This difference affects the outputs of the two models but it is difficult to define the extent of this impact.

- Another major difference in the outlook of the two simulations is that in EnergyPLAN the modelling and consequently the optimisation of all the sectors involved in the Greek Energy System (electricity, heat, transport, residential & commercial, industrial) are inextricably linked, whereas in simulations of CRES the modelling of the electricity and heat sector are segregated.

- The operation of Hydro Power units differentiates the two simulations in various points. The pump hydro units in CRES simulations are subjected to forced operation which is connected to a fixed pump load, whereas in EnergyPLAN the electricity production of pump hydro units is dependent on the electricity production of condensing PP, the available turbine capacity and the available storage energy content. Furthermore, no storage capacity is set in the simulations of CRES when hydro power units are modelled, whereas this is a determinant parameter for the optimisation of hydro power in EnergyPLAN. All these differences along with the dissimilarity of the two simulations concerning the economical data lead to variations in all electricity production and demands related to hydro power units.

- There is a difference in the total electricity demand between the two simulations due to the variation in the pump demand.

- In EnergyPLAN the regulation of condensing PP does not take into account any requirement related to the ramping of the units, since there is not such an option. On the contrary, this parameter is involved in the modelling of CRES.

- In CRES simulations, excess electricity production is eliminated by reducing the electricity production that comes from wind. Therefore, excess electricity becomes identical with the decrease of wind production that corresponds to zero excess electricity production for the overall system. Unlike CRES simulations, in EnergyPLAN these two quantities are not identical. This is because excess can be minimised (even eliminated) not only by decreasing the wind production exclusively but also by other means such as: by regulating the operation of CHP units, by reducing gradually RES production while regulating the operation of condensing units simultaneously, so that a share of excess is deducted by PP production, or by applying the aforementioned actions in parallel.

Sub-question 3

Which parameters, of those involved in the optimisation process, and to what extent can contribute to a further minimisation of the excess electricity production and the total fuel consumption of the system?

- None of the parameters under investigation affect the total fuel consumption considerably. The highest variation that is observed is equal to 1% (see Figure 7.1).

- The parameters which have significant effect on the minimisation of excess electricity production are mainly three: the pump storage capacity, the CEEP regulation strategy, the option of exports.

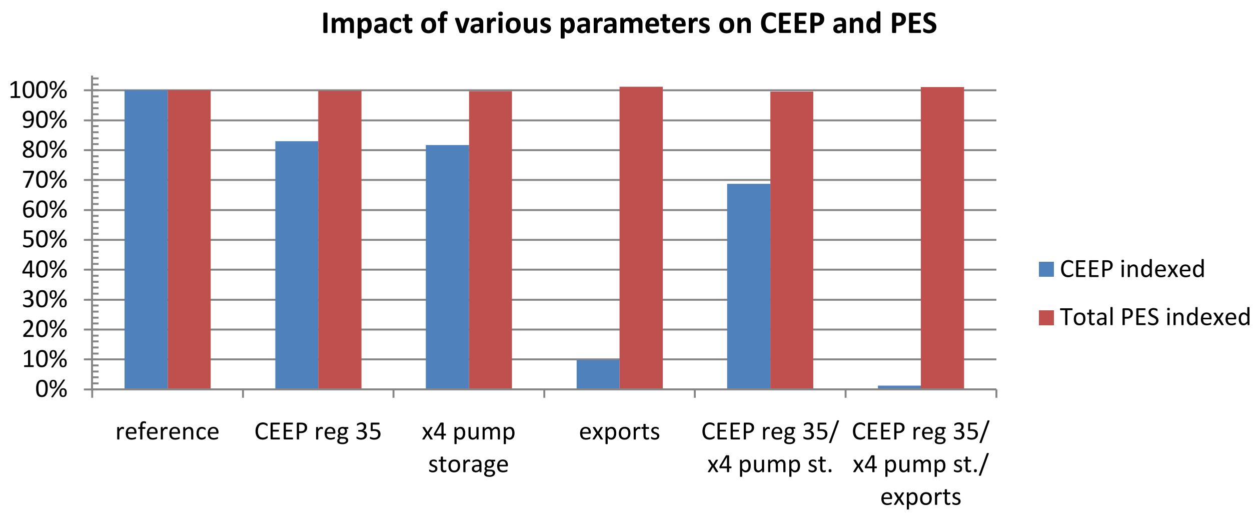

Figure 7.1: The impact of different parameters of the system on CEEP and PES

- Drastic increases of the pump storage capacity lead to significant reductions (up to 34% comparing to the reference case) of excess electricity. Particularly, by increasing the available capacity four times the excess electricity can be decreased by 18%.

- The excess electricity production can be reduced by 17%, comparing to the reference case, without decreasing the RES production but just by regulating the operation of CHP units. Otherwise, by decreasing the RES production around 9% and regulating the operation of CHP and condensing units a total elimination of the excess can be achieved.

- The option of exporting electricity can almost lead to the elimination of CEEP since it is reduced by 90%.

- Quite effective reduction of excess electricity can be achieved (up to 31%) by first quadrupling the pump storage capacity and then regulating the operation of CHP units, when the system is closed. By adding to these the option of exports (open system) the critical excess can be nearly eliminated, since the reduction is equal to 99%.

Sub-question 4

What is the maximum feasible wind penetration on the 2020 Greek Interconnected energy system, as a function of the installed wind capacity, from a technical perspective?

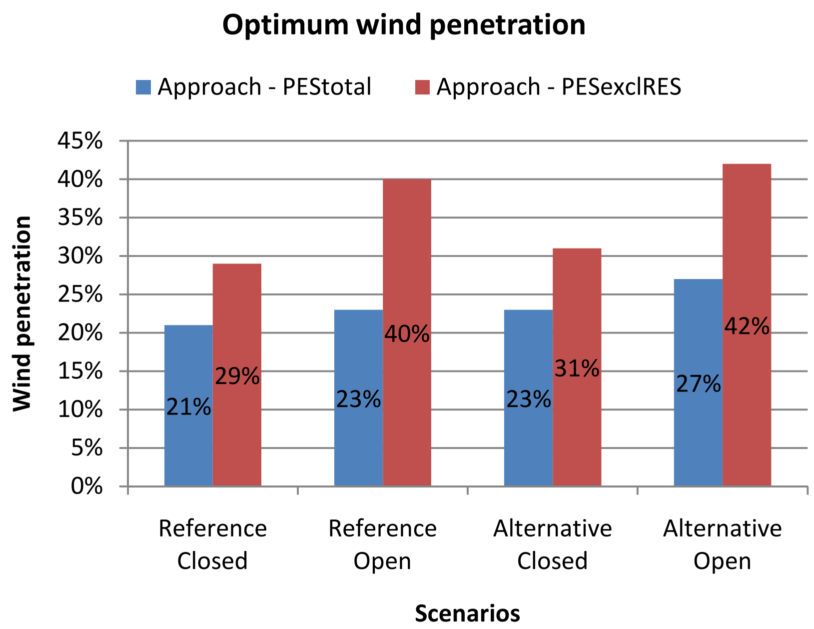

Figure 7.2: Optimum wind penetration under different scenarios

- The maximum wind penetration technically feasible, according to this study, mainly depends on 3 parameters.
    1. The approach adopted: whether PES_{total} or $PES_{exclRES}$ is used as criterion.
    2. The option of exporting: whether the system is considered as closed or open.
    3. The configuration of the system: whether the alternative configuration (CEEP reg. 35/x4 pump storage) of the system is considered or not.

- Based on PES_{total} approach optimum wind penetration varies from 21% to 27% depending on the other two parameters, whereas based on $PES_{exclRES}$ approach from 29% to 42%.

- When considering the system as closed, the maximum wind penetration fluctuates between 21% and 31%. By taking into account the option of exports the corresponding percentages go up to 23% and 42%.

- By implementing the proposed configuration of the alternative system to the Greek Interconnected Energy System the optimum wind penetration varies from 23% to 42%. Whereas by not implementing them the penetration is between 21% and 40%.

- The technically optimum wind penetration reaches an overall maximum up to 42% when the alternative system is considered as open and the analysis is based on the $PES_{exclRES}$ approach.

Perspectives

According to the Greek National Renewable Energy Action Plan, a rather high share of the existing hydro potential has been already exploited. However, the addition of one or two pump hydro units is under consideration since the operation of new hydroelectric pumped storage plants will contribute to grid stability and reduced wind energy curtailment. (NATIONAL RENEWABLE ENERGY ACTION PLAN | IN THE SCOPE OF DIRECTIVE 2009/28/EC n.d.) This study, among others, proves how important is the capacity of the storage of these units for the minimisation of excess electricity production. Therefore, a future study could deal with the optimisation of the capacity of this storage or to make it more general with the potential for further exploitation of the hydro storage as an option for electricity storage for the Greek Energy System.

Furthermore, this study accents a future perspective concerning the boost of connections between the heat and the electricity sector. This can be done by expanding the simultaneous heat and electricity production in CHP units. Preferably, CHP units should be decentralised so that they will be easily regulated contributing in this way to the minimization of excess electricity production, fuel consumption and CO2 emissions. Of course, this presupposes the increase of the existing district heating demand which requires the expansion of the corresponding infrastructure. Apart from cogeneration, another way to boost the connections between heat and electricity sectors is by expanding the installation of both large scale heat pumps in condensing Power Plants and individual heat pumps within the residential and commercial sector, the operation of which can be regulated.

The reinforcement of connections between other sectors such as the electricity and the transportation constitutes another interesting future perspective as well. Particularly, this can be done by the development of Electric Vehicles with smart charge, contributing in the integration of more renewable energy sources by increasing the flexible demand of the system.

Bibliography

Argyrakis, I. "The contribution of Hydro Power installations in the Energy Planning of the country." Public Power Corporation S.A., 2009.

Bakos, G. "Renewable Energy Sources." Xanthi: Democritus University of Thrace. 53.

Center for Renewable Energy Sources and Saving. *Annual Report.* Ministry of Environment Energy & Climate Change, 2009.

Center for Renewable Energy Sources and Saving. "Energy Scenarios Analysis of RES technologies' penetration in the Energy System and Achievement of 2020 National Targets using the models MARKAL, ENPEP, WASP and COST." NREAP Background document, 2010.

Center for Renewable Energy Sources and Saving. *Evaluation of the National Potential for the Cogeneration of Electricity and Heat in Greece.* Final Report | Study I, Athens: Ministry of Development, 2008.

Center for Renewable Energy Sources and Savings. *National Energy Data System | Manual.* Ministry of Environment Energy & Climate Change, 2010.

Connolly, David. *A User's Guide to EnergyPLAN Version 3.* University of Limerick, 2010.

Connolly, David. *Modelling the Irish Energy System | Data required for the EnergyPLAN Tool.* University of Limerick, 2009.

D. Connolly, H. Lund, B.V. Mathiesen, M. Leahy. "A review of computer tools for analysing the integration of renewable energy into various energy systems." *Applied Energy*, 25 October 2009: 1059-1082.

DIRECTIVE 2006/32/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL. Official Journal of the European Union, 2006.

DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL. Official Journal of the European Union, 2009.

DIRECTIVE 2009/29/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL. Official Journal of the European Union, 2009.

"EEAP." *Energy Efficiency Action Plan in the scope of Directive 2006/32/EC.* Athens, June 2008.

Energy Outlook of Greece. Ministry of Development, 2009.

EUROPA. http://europa.eu/legislation_summaries/energy/index_en.htm (accessed December 2010).

EUROPA. 29 March 2009. http://europa.eu/legislation_summaries/energy/energy_efficiency/en0002_en.htm (accessed December 2010).

European Commission. *Energy.* 4 November 2010. http://ec.europa.eu/energy/renewables/index_en.htm (accessed December 2010).

european network of transmission system operators for electricity. *Net Transfer Capacity map for season: Summer 2010.* https://www.entsoe.eu/index.php?id=70 (accessed November 2010).

"Executive Order for the Energy Performance of Buildings." 9 April 2010.

Greek Solar Industry Association. "Proposals of the Association for the Development of the Solar Thermal Market in Buildings." *Hot Water Production - Space heating/cooling.*

Hellenic Association for the Cogeneration of Heat and Power - H.A.C.H.P. 2009. http://hachp.gr/ (accessed November 2010).

Hellenic Transmission System Operator S.A. http://www.desmie.gr/content/index.asp?lang=2&parent_id=741 (accessed December 2010).

Henrik Lund, E. Munster. "Management of surplus electricity-production from a fluctuating renewable-energy source." *Applied Energy*, 4 January 2003: 65-74.

—. "Modelling of energy systems with a high percentage of CHP and wind power." *Renewable Energy*, 25 March 2003: 2179-2193.

Institut für Solartechnik SPF. "SPF Testing." *SCFv3.0en.* Switzerland, 9 December 2008.

Intergovernmental Panel for Climate Change. *Task Force on National Greenhouse Gas Inventories.* http://www.ipcc-nggip.iges.or.jp/EFDB/find_ef_s1.php (accessed November 2010).

"Law 3734." Promotion of cogeneration of two or more useful forms of energy, 2009.

"Law 3851." *Accelerating the development of Renewable Energy Sources to deal with climate change and other regulations addressing issues under the authority of the Ministry of Environmnent, Energy and Climate Change.* 4 June 2010.

Lund, Henrik. "Large-scale integration of wind power into different energy systems." *Energy*, 28 February 2004: 2402-2412.

—. "EnergyPLAN." Vers. 8. *Advanced Energy System Analysis Computer Model.* Aalborg University. February 2010. www.energyPLAN.eu (accessed December 2010).

—. "EnergyPLAN." *Advanced Energy System Analysis Computer Model.* February 2010. www.energyPLAN.eu (accessed December 2010).

—. "Excess electricity diagrams and the integration of renewable energy." *International Journal of Sustainable Energy*, 1 December 2003: 149-156.

—. "Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply." *Renewable Energy*, 1 June 2005: 503-515.

Mathiesen, Brian Vad. *Analyses of exchange with external electricity markets and 100% renewable energy systems design.* Aalborg, 15 February 2010.

Ministry of Environment Energy & Climate Change. 20 September 2010. http://www.ypeka.gr/Default.aspx?tabid=367&language=el-GR (accessed October 2010).

Ministry of Environment Energy & Climate Change. *NATIONAL RENEWABLE ENERGY ACTION PLAN | IN THE SCOPE OF DIRECTIVE 2009/28/EC.*

Municipal Company for Water Supply and Sanitation of Kozani. 2010. http://www.deyakozanis.gr/?page_id=7 (accessed October 2010).

Østergaard, Poul Alberg. "Reviewing optimisation criteria for energy systems analyses of renewable energy integration." *Energy*, 13 June 2009: 1236-1245.

Pannell, D. J. "Sensitivity analysis of normative economic models: Theoretical framework and practical strategies." *Agricultural Economics*, 1997: 139-152.

Pavlidis, Georgios. "16 Years of District Heating in Kozani."

Regulatory Authority for Energy. *The Energy System in Greece.* http://www.rae.gr/energysys/main.htm (accessed December 2010).

"Results Compliance Scenario." Centre for Renewable Energy Sources and Saving, 6 July 2010.

Saltelli, Ratto, Andres, Campolongo, Cariboni, Gatelli, Saisana, Tarantola. "Global Sensitivity Analysis." *The Primer*, 2008.

Schwartz, Peter. *The Art of the Long View: Planning for the Future in an Uncertain World.* 1998.

Technical Chamber of Greece. "Technical Directive of Technical Chamber of Greece." *Climate Data of Greek Districts.* Athens, June 2010.

The Stability and Development Programme | Prime Minister's speech. Athens, 22 March 2010.

Tigas, Giannakidis, Lalas, Mirasgentis, Saraphidis, Sakellaridis, Nakos, Mantzaris, Campouris. "Analysis of potental RES technologies penetration and Energy Saving in the Greek Energy System according to the European Energy Policy."

Vaillati, Ricardo. "Electricity corridors between European Union and neighbouring countries." Brussels: Cesi Ricerca, 12 December 2006.

"ΦΕΚ 1420/B'/15-7-2009." Definition of methodology for calculation of electricity produced by cogeneration and the efficiency of cogeneration.

Appendix I

Figure I.1: Map of the Greek Interconnected Energy System including International Connections (Hellenic Transmission System Operator S.A. n.d.)