Generation expansion planning of Crete power system for high penetration of renewable energy sources

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Abstract. In this paper the Crete's Island power system, which is the largest isolated power system in Greece, is analyzed in two long term scenarios in order to estimate the corresponding costs and benefits associated with a significant high electricity production from renewable energy sources (RES) technologies in the period 2009-2020. In the first scenario, a 20% RES energy penetration in year 2020 is assumed, while in the second scenario the final RES energy penetration is increased to 50%, and it is achieved with the installation of hydro pumped storage systems. Long-range Energy Alternatives Planning (LEAP) software is used to develop the electricity demand model, as well as to estimate the gross electricity generation in Crete and the annual CO_2 equivalent emissions for the considered scenarios. This study demonstrates that substantial RES production till 2020 is technically feasible, and provides benefits in the forms of carbon emission reductions, energy adequacy and dependency.

Introduction

Isolated power systems, like the ones operating in large islands, face increased problems related to their operation and control. In most of these systems, the cost of electricity production is much higher than in interconnected systems due to the high operating costs of their thermal generating units, mainly diesel and gas turbines, and the import and transportation costs of the fuel used [1]. Renewable energy sources (RES) can often be used as a primary source of energy in such systems, as they are usually present in geographically remote areas.

Renewable energy technologies for electricity generation have several advantages over conventional generation technologies. Reduction of greenhouse gases (GHG) that contribute to global climate change and to local air quality is one of the major advantages of RES utilization. Additionally, they reduce the risk of fossil-fuel price fluctuations, and decrease the electricity-sector dependency. At the other side, the dispersion of RES installations and the variability of electricity production must be successfully managed by electricity grid. Though wind and sun reduces fossil-fuel usage, the total cost of RES projects must be careful investigated.

An isolated power system with increased RES techologies power penetration has significant differences from an interconnected power system. First, the isolated power system presents low minimum to maximum demand ratio and significantly larger frequency deviations with relatively small production or demand changes compared to an interconnected power system. Furthermore, quite often the installed thermal units have significant values of technical minimum that introduce problems in co-operation between thermal units and wind power making the operators disconnect some of the wind power production in order to avoid technical limits violations [2].

This paper analyzes the technical feasibility, impacts, costs, and benefits of high percentage electricity supply from RES technologies from 2009 till 2020 in Crete Island using LEAP software [3]. The Cretan power system is the largest isolated system in Greece, and due to its unique characteristics has been examined in a large number of studies [4]-[6]. Although the potential policy incentives for high levels of RES penetration in Crete Island have not been explored, the paper does intend to inform such discussions with credible analysis of the potential costs and benefits of such policies.

Crete possesses ample wind and solar resources, technically more than 1 GW that could be harnessed to produce electricity at reasonable cost, if control and management restrictions are excluded. In the developed model of the Cretan power system in LEAP software, numerous assumptions about the future mix and performance of conventional and renewable energy generation technologies, as well as transmission system operation and future energy demand have been implemented. For this study, generation capacity expansion is selected to achieve a cost-optimal generation mix over a 12-year planning horizon from 2009 to 2020.

Description of Crete's Island Power System

The Power System of Crete is the largest isolated system in Greece, with the highest rate of increase in energy and power demand nationwide. During 2006, the peak demand was 605 MW and the annual wind energy penetration was around 12%. The instantaneous wind power penetration has reached 39% during some valley hours in winter and early spring. Public Power Corporation (PPC) is the operator of this power system and has the obligation to buy at specific price (90% of the retail low voltage price) the energy produced by the wind park installations. This legal framework is beneficial for both the operator of the power system as well as the private sector investors that can timely payback their investments.

The installed wind power capacity on the island in 2006 was 105.9 MW in 12 wind parks, mainly at the Sitia region, on the eastern part of the island. The photovoltaic (PV) installed capacity is currently negligible, however it is expected to exceed 50 MW the following years, due to the attractive legislative framework that has been developed in Greece the last years. Moreover, as Table 1 shows, a large number of conventional units with different technology and response characteristics (diesel, gas turbines, steam turbines and one combined cycle unit) in three power plants with total installed capacity 743 MW have been installed. Table 1 also presents the percentage of annual energy production in 2006 for all installed units of the island (conventional and renewables). Two natural gas (NG) units of 250 MW each are expected to be installed in Crete the following years, replacing the steam turbines and a significant portion of existing diesel generators. In Fig. 1, the structure of the Cretan HV electricity network is depicted.

Table 1
Characteristics of Crete's electricity units

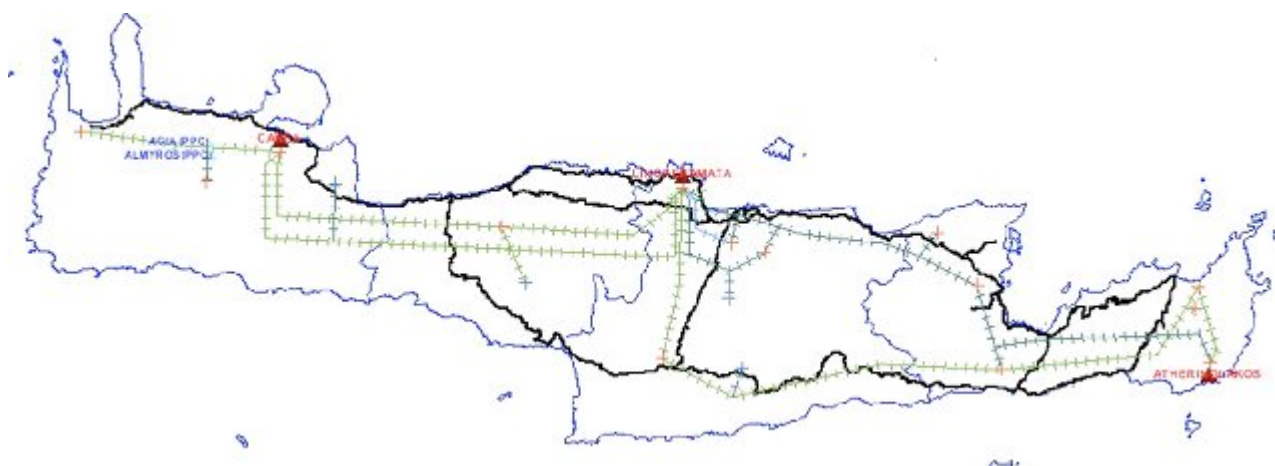| Technology	Fuel	Annual electricity production in 2006
Combined cycle (CC)	Diesel	19%
Diesel generator	Mazout	31.3%
Gas	Diesel	15.3%
Steam	Mazout	22.4%
Wind turbine	-	12%

Fig. 1. Electric network of Crete Island (HV transmission lines).

The Cretan power system presents all the typical characteristics of the isolated power systems. For the year 2006, the ratio of minimum to maximum demand was equal to 26%, and the annual load factor was equal to 55%. Fig. 2 depicts the load duration curve (red line), as well as the resultant annual load factor (yellow line) for the power system of Crete Island.
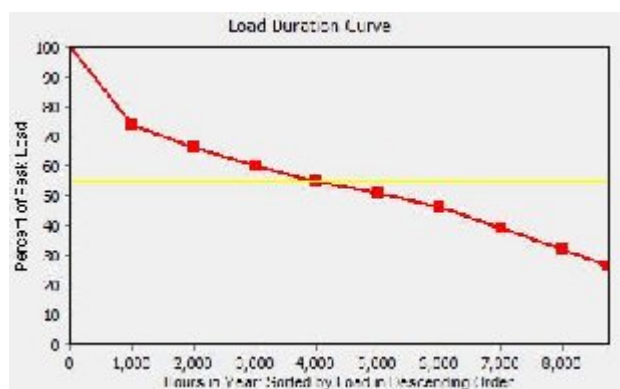

Fig. 2. Load duration curve and load factor for the isolated power system of Crete Island.

Description of leap software

This paper uses a scenario-based energy-environment modelling platform called Long-range Energy Alternatives Planning (LEAP) system to estimate the impacts of different scenarios in Cretan Power System operation. LEAP is a bottom–up project analysis model developed by Stockholm Environment Institute (SEI) in 1997, which can make scenario analysis on future energy demand and environment development by designing different schemes. LEAP emphasizes the detailed evaluation of specific energy problems within the context of integrated energy and environmental planning for each 'what if' scenario or combinations of scenarios. LEAP model incorporates a full range of energy demand, conversion, transmission, distribution, and end-use. The model can simulate over existing as well as advanced technologies that may be deployed in the future. LEAP not only includes the Technology and Environmental Database (TED) that provides extensive information describing the current technical characteristics, costs and environmental impacts of energy technologies, but also enables the user to make projections of energy supply and demand over a long-term planning horizon. Four of the Energy Scenario programs address the main components of an integrated energy analysis relevant to mitigation analyses: energy demand analysis (Demand), energy conversion and resource assessment (Transformation), emission estimation (Environment), and the comparison of scenarios in terms of costs and physical impacts (Evaluation). LEAP can run under Windows environment and tree structure of input data is adopted,

two kinds of output types including table and figure can describe the model results and the output data can be easily selected according to the users' demand.

The best advantage of LEAP software is that the users can easily regulate the model structure and data framework according to the project's demand and the future tendency by using the way of ''what if''. With the environmental data base, LEAP can assess the pollution resulting from each stage of the fuel chain, including the reduction in airborne pollutant emissions from extraction, processing, distribution, and combustion activities that might result from more efficient use of electricity or other fuels. LEAP has been extensively used in energy demand, environmental impact, and economic evaluation [7]-[9].
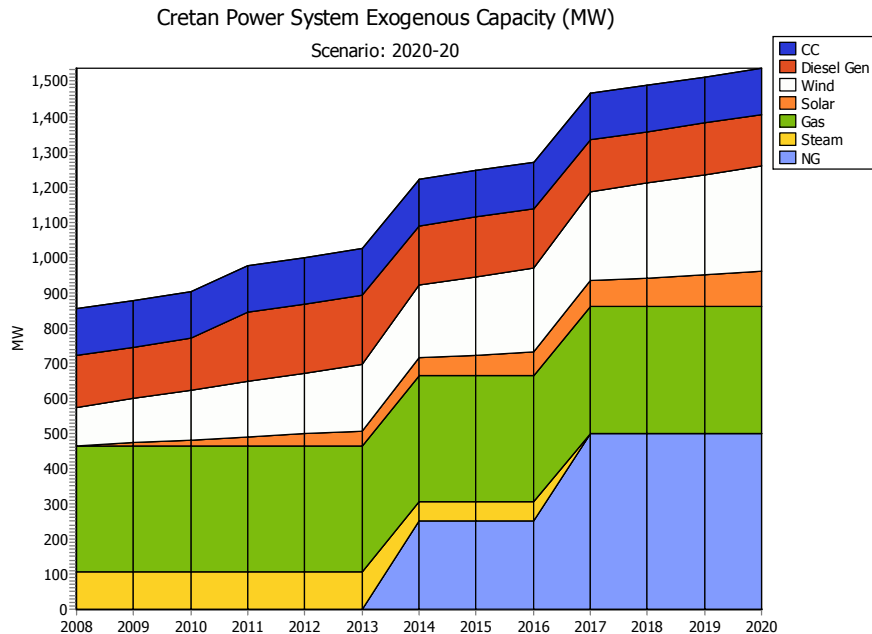

Fig. 3. Installed capacity evolution of different power generation technologies (2020-20 scenario).

Case study

In order to evaluate the effect of alternative approaches that are related to high penetration of renewable energy technologies (wind turbines (WTs) and PVs) in the isolated power system of Crete for the period 2009-2020, two basic scenarios have been developed in LEAP:

1. In the first scenario, named as 2020-20, the energy penetration of RES technologies will be increased linearly from 12% of total energy demand in year 2008 to 20% in year 2020. Considering 3% annual energy growth, this penetration can be achieved by setting a target for installed capacity in 2020 to 300 MW for WTs (which will produce the 16% of annual energy), and to 100 MW for PVs (which will produce the 4% of the annual energy).

2. In the second scenario, named as HPS, the energy penetration of RES technologies will be increased linearly from 12% of total energy demand in year 2008 to 50% in year 2020. In order to be able to achieve technically such a high penetration, RES technologies have to be combined with hydro pumped storage (HPS) systems. Using HPS systems, the thermoelectric machines production is minimised and the RES penetration may exceed 90% [10]. Considering 3% annual energy growth, this penetration can be achieved by setting a target for installed capacity in 2020 to 900 MW for WTs (which will produce the 42% of annual energy), and to 200 MW for PVs (which will produce the 8% of the annual energy).

In Fig. 3, the installed capacity evolution of the power generation technologies for the 2020-20 scenario is depicted. The steam units and a large portion of diesel generators are considered to be replaced by the two 250 MW NG units in the years 2014 and 2017. Moreover, the simulation of

Cretan power system showed that the installation of an additional 50 MW diesel generator in year 2011 is crucial for the reliable operation of the system.

For each one of the examined scenarios and for each year of the examined period, the annual energy production from each type of electricity generation technology is calculated, as well as the corresponding annual CO_2 eq. emissions. Moreover, a sensitivity analysis of CO_2 eq. emissions considering different rates of annual energy growth (2% and 4%, respectively) is implemented.

Results

2020-20 scenario. Fig. 4 shows the annual energy contribution of each power generation technology, while Fig. 5 shows the annual CO_2 eq. emissions of conventional generators. Although the annual energy consumption is increased with a growth rate of 3%, the high RES technologies penetration, combined with the installation of the NG units after year 2014, results almost constant CO_2 eq. emissions. The new NG units are used as base-load, while the penetration of peak-load gas units is slightly decreased.
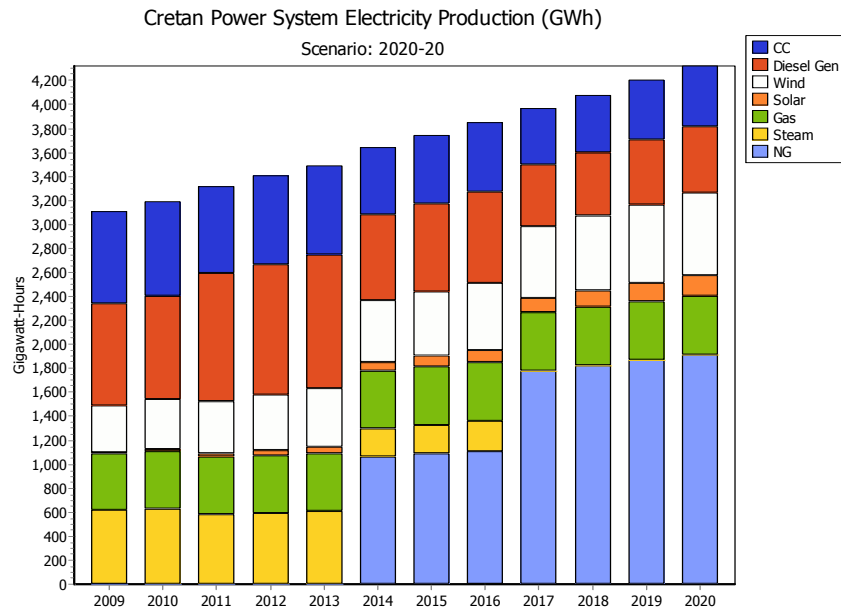

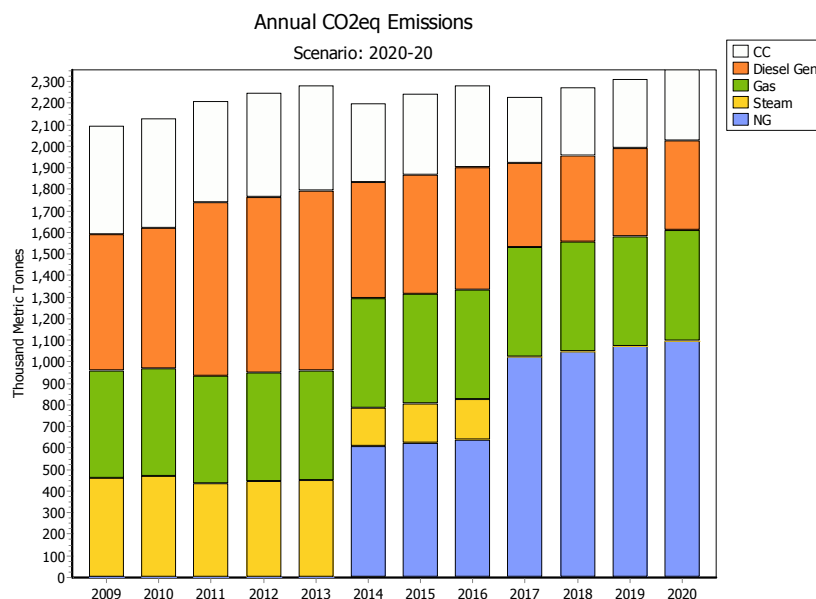Fig. 4. Annual electricity production for the period 2009-2020 (2020-20 scenario).

Fig. 5. Annual CO_2 eq. emissions for the period 2009-2020 (2020-20 scenario).

HPS scenario. The annual energy contribution of each power generation technology, as well as the annual CO_2 eq. emissions of conventional generators for the HPS scenario, are presented in Fig. 6 and Fig. 7, respectively. The large penetration of RES technologies, which achieves 50% in year 2020, results significant decrease of CO_2 eq. emissions, especially after the installation of the NG units. The energy production of the combined cycle and the gas units, which consume expensive diesel fuel is also decreased, while the NG units are used for base-load requirements.
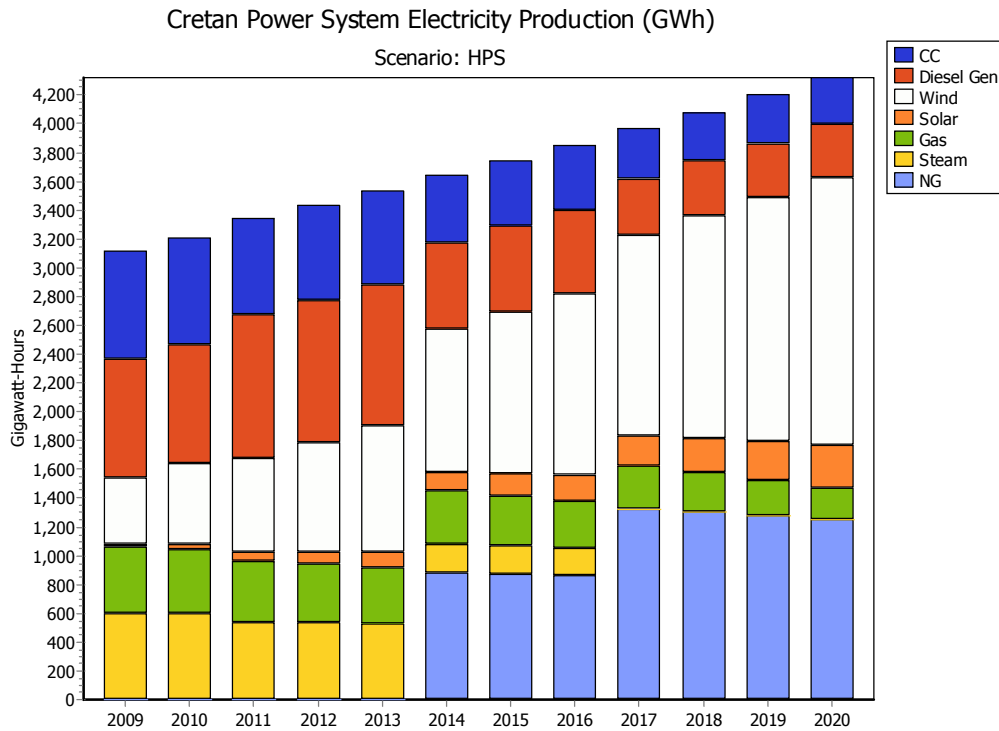

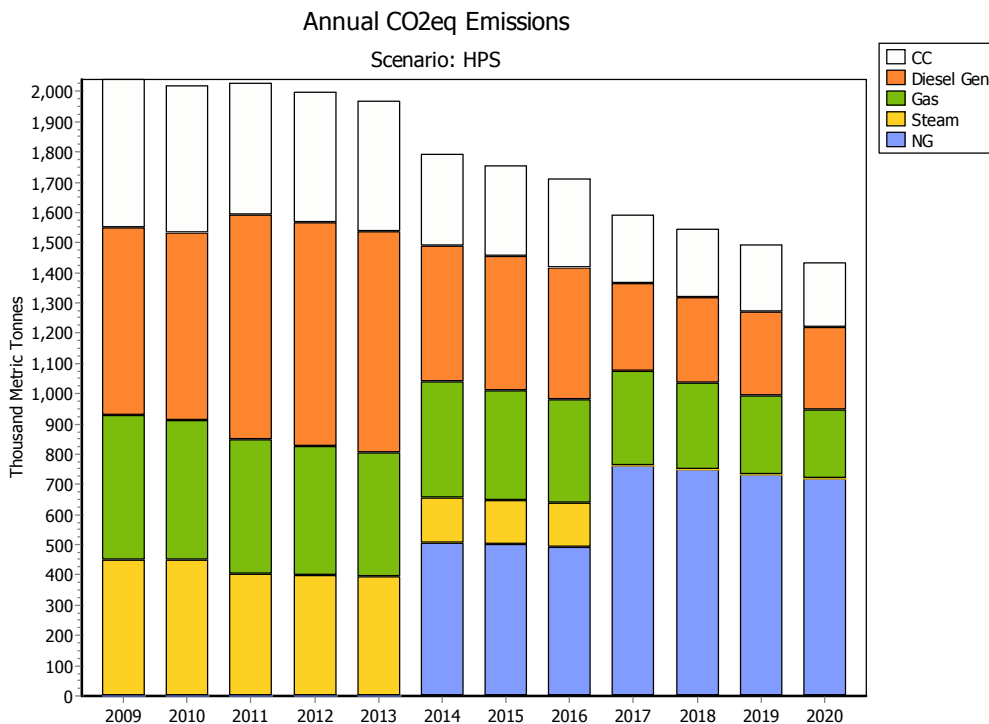Fig. 6. Annual electricity production for the period 2009-2020 (HPS scenario).

Fig. 7. Annual CO2 eq. emissions for the period 2009-2020 (HPS scenario).

Sensitivity analysis. The sensitivity analysis examines the effect of two different annual growth energy consumption rates (2% and 4%) in CO_2 eq. emissions at the last year of the examined period. The results are presented in Table 2. It can be concluded that the decrease of annual energy growth by 1% decreases 11% the final CO_2 eq. emissions for both scenarios, while the increase of annual energy growth by 1% increases 12% the final CO_2 eq. emissions for both scenarios. Moreover, the reduction of CO_2 eq. emissions in year 2020 in the HPS scenario is almost 40%, compared to 2020-20 scenario.

Table 2

Effect of different annual growth energy consumption rates in CO_2 eq. emissions at year 2020

Annual energy increase	Final CO_2 eq. emissions (tn) (2020-20 scenario)	Final CO_2 eq. emissions (tn) (HPS scenario)
3% (base case)	$2355 \cdot 10^3$	$1434 \cdot 10^3$
2%	$2095 \cdot 10^3$	$1275 \cdot 10^3$
4%	$2644 \cdot 10^3$	$1610 \cdot 10^3$

Conclusion

This paper examined the effect of two different high RES penetration scenarios in the electricity production and the total CO_2 eq. emissions of the Cretan isolated power system. The examined period was twelve years (from 2009 to 2020), and the analysis was implemented with the help of LEAP software. The first scenario assumes 20% RES penetration in year 2020, while in the second scenario the final RES penetration is increased to 50%, and it is achieved with the installation of hydro pumped storage systems.

The obtained results showed that in the first considered scenario, the improvement in renewable energy technologies cannot overcome the increase in annual energy demand, resulting almost constant CO_2 eq. emissions for the whole examined period. On the other hand, in the second considered scenario, the high penetration of renewable energy technologies overcomes the increase in annual energy demand, so the final CO_2 eq. emissions almost 40% lower, compared to the first scenario.

The analysis in this paper examines only technical aspects in each considered scenario. In a future work, the comparison of the two alternative approaches will contain a combination of economic and technical criteria, in order to clarify which of the considered scenarios is superior, compared to the others.

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