Sustainable Energy Planning for Autonomous Power System of Crete

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Abstract: The autonomous power system of Crete has been selected as a representative model for long term energy planning estimation in case of significant high share in power and energy balance from renewable energy sources. A generation capacity expansion model selects from conventional electricity generation technologies such as thermal power units, combined cycle units, combustion turbines, and renewable energy technologies such as wind parks, photovoltaics and hybrid systems in order to supply the projected demand of the future years. At the same time, power system operation and control, special restrictions, performance projections, as well as generation expansion costs, should be comprehensively investigated. More precisely, this study analyses current system operation and demonstrates benefits and obstacles of a substantial share of Crete's projected load demand from renewable energy sources and hybrid systems by the end of 2020. The potential of high share is technically feasible, not cost-prohibitive, and provides advantages in the forms of carbon emission reductions, energy adequacy and dependency.

Keywords: Autonomous Power Systems, Energy Planning, Renewable Energy Sources

1. Short Overview

Renewable energy sources (RES) 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, spread the energy-mixture, and decrease the electricity-sector dependency.

At the other side, by their geographical and natural position, European Islands represent a key actor with specific characteristics into the implementation framework of a sustainable energy policy. More precisely, three main dimensions have been identified by the European Commission for a successful energy planning, which are security of supply, sustainability and competitiveness. Furthermore, several obstacles and technical restrictions are evident in island's the energy sector, such as higher total costs, fluctuations in the price and insecurity of supply. However, these disadvantages can be outweighed by inherent advantages, especially by utilization of renewable energy technologies, thanks to their relative high wind and sun exposure [Papadopoulos et al., 2008]. This potential should be better exploited in order to investigate the operation and planning limitations and estimate the possible solutions [Boulaxis et al., 2005].

The autonomous power system of Crete has been selected as a representative model for long term energy planning estimation in case of significant high share in power and energy balance from renewable sources [Zografakis, 2005]. Crete possesses ample wind [Katsaprakis, Christakis, 2004] and solar resources, technically more than 1.2 GW that could be harnessed to produce electricity at reasonable cost, if control and management restrictions are excluded. The dispersion of RES installations and the variability of electricity production must be successfully managed by electricity grid. Generally, the dispersed generation changes distribution networks from passive networks, with power flows from higher to lower voltage levels, into active networks with multi-directional power flows, [Strbac, 2002]. Furthermore, transmission and distribution infrastructures require specific economic regulations, [Stoft, 2002]. Although wind reduces fossil-fuel usage, the total cost of RES projects must be careful investigated.

This paper analyses the feasibility, and benefits of high percentage electricity supply from RES technologies till 2020 in Crete. Operation and statistical data of Crete's power system is used as a baseline input to this study that assess electricity generation capacity expansion for a cost-optimal generation mixture over a long-term planning horizon up to 2020, taking into consideration previous studies as [Tsioliaridou, et al. 2006], [Katsaprakakis, et al. 2008], [Tsoutsos, et al. 2009], [Kaldellis et al., 2009], and [Giatrakos, G.P., 2009].

2. Autonomous Power Systems

Autonomous or isolated power systems are all the small and medium size power systems where no interconnection exists with conterminous and/or continental systems. These power systems, like the ones operating in large islands, face increased problems related to their operation and control, [Smith, et al. 2006]. In most of these systems, dynamic performance is a major concern, since mismatches in generation and load and/or unstable system frequency control might lead to system failures, easier than in interconnected systems.

Renewable sources and especially wind power exploitation appear particularly attractive, [Doherty, O'Malley, 2006]. However, the integration of a substantial amount of wind power in isolated systems needs careful consideration, so as to maintain a high degree of reliability and security of the system operation, [Hatziargyriou, et al. 1998]. The main problems identified concern operational scheduling (mainly unit commitment) due to high production forecasting uncertainties, as well as steady state and dynamic operating problems [Thalassinakis, Dialynas, 2007]. These problems may considerably limit the amount of wind generation that can be connected to the island systems, increasing the complexity of their operation [Dialynas, Hatziargyriou, 2007]. Thus, next to the more common angle and voltage stability concerns, frequency stability [Karapidakis, Thalassinakis, 2006] must be ensured. This depends on the ability of the system to restore balance between generation and load following a severe system upset with minimum loss of load.

3. Power System of Crete

Grete is the largest Greek island with approximately 8,500 km^2 and one of the largest in Mediterranean region. Its population is more than 600,000 inhabitants that triple in summer period. As well, it features a considerable annual increase of electricity demand approaching the 7% during the last decade, as it is clearly shown in Fig.1. As a result, the annual energy consumption during 2008 surpassed the 3TWh in comparison with the modest 280 GWh of year 1975.

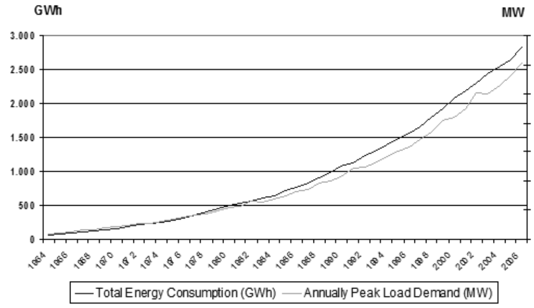

Fig.1 Load and Energy Consumption Time Evolution

Additionally, comparing the mean hourly load demand variation all year round, there is a considerable electricity generation diversification between months and seasons, as it is shown in Fig. 2.

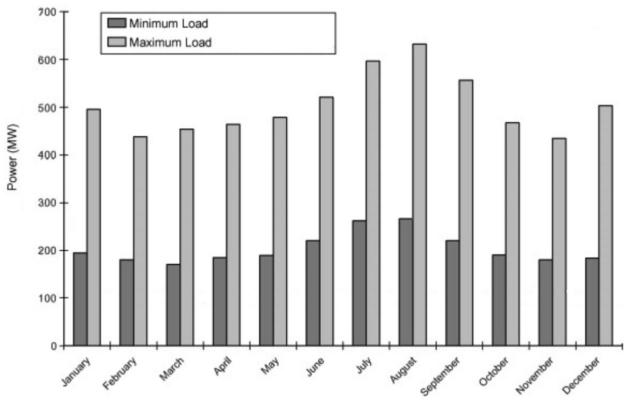

Fig. 2. Monthly variation of min and max load demand

However, even during the low consumption periods, minimum load demand is greater than current system technical minimum (approximately 120 MW). Island's electricity generation system is based mainly on three (3) oil-fired thermal power units, located as it is shown in Fig. 3. The nominal capacity of the local power plants is 742 MW in total, although the actual power is considered to be 721 MW for winter and 674 MW for summer operation, as it is described in the following Table 1.

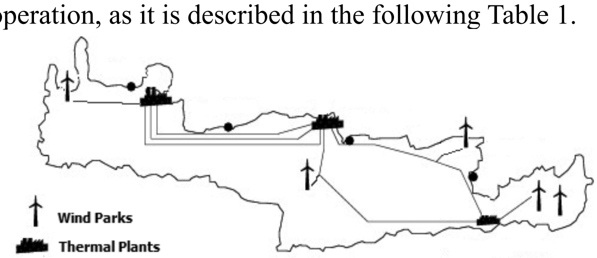

Fig. 3. Power plants and wind parks locations

The annual peak load demand occurs on a summer day, usually within August. Furthermore, the overnight loads can be assumed to be approximately equal to 25% of the corresponding daily peak loads. More precisely, Fig. 4 depicts the 24-hours load demand variation range.

Table 1 Conventional Installed Capacity

	Nominal Power	Actual Power (Winter)	Actual Power (Summer)
Power Plant 1			
STM 1	5,9	5,9	5,7
STM 2	14,3	14,3	13,2
STM 3	14,3	14,3	13,2
STM 4	23,5	23,5	23,0
STM 5	23,5	23,5	23,0
STM 6	23,5	23,5	23,0
DIESEL 1	11,0	11,0	10,8
DIESEL 2	11,0	11,0	10,8
DIESEL 3	11,0	11,0	10,8
DIESEL 4	11,0	11,0	10,8
GAS 1	15,0	15,0	12,8
GAS 2	15,0	15,0	12,8
GAS 3	42,7	42,7	41,0
GAS 4	13,5	13,5	12,8
GAS 5	27,6	27,6	25,0
Power Plant 2			
GAS 1	16,2	14,0	11,0
GAS 1	28,0	27,6	25,0
GAS 4	24,0	20,0	18,8
GAS 5	30,0	28,0	26,5
GAS 11	59,4	58,0	54,0
GAS 12	59,4	58,0	54,0
GAS 13	27,6	27,6	25,0
CC Unit	132,3	126,0	112,0
Power Plant 2			
DIESEL 1	51,1	49,7	49,5
DIESEL 2	51,1	49,7	49,5
	741,8	**721,2**	**674,0**

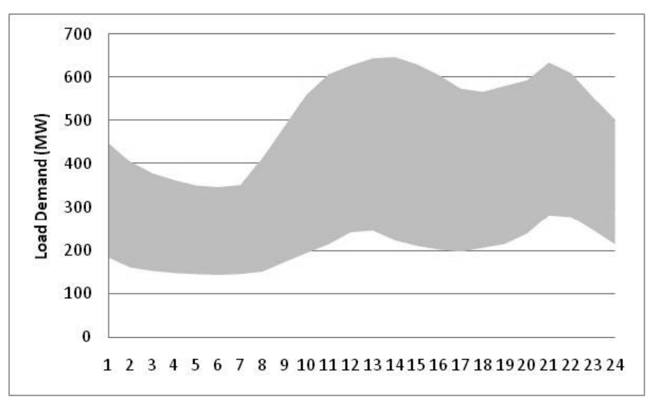

Fig. 4. Crete's 24-hours load demand variation range

The steam and diesel units mainly supply the base-load demand. The Gas turbines normally supply the daily peak load or the load that cannot be supplied by the other units in outage conditions. These units have a high running cost that increases significantly the average cost of the electricity being supplied. The annual duration curve is composed by each generation unit share, as it is presented in following Fig.5.

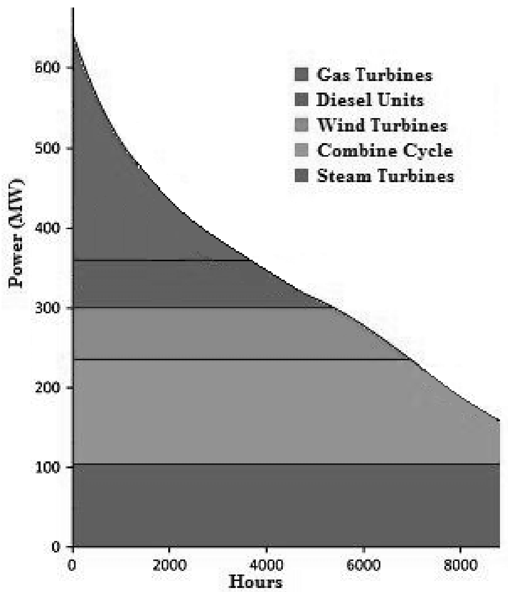

Fig.5 Crete's annual load duration curve

4. Current Status of RES in Crete

Currently, there are 30 wind parks installed with nominal power of 160.45MW in appropriate regions of the island. These WPs are connected to the grid through MV/HV substations of 20kV/150kV. The following Tables 2 and 3 present all the wind parks that are already installed and are planned to be installed in the near future respectively at the four prefectures of Crete island (Lasithi. Iraklio, Rethimno and Hania).

Table 2 Installed Wind Parks

	Prefecture	Plants	Percentage	Installed Power	Percentage
1	Lasithi	21	70%	98.90 MW	62%
2	Iraklio	6	20%	41.40 MW	26%
3	Rethimno	0	0%	0 MW	0%
4	Hania	3	10%	20.15 MW	13%
	Total	30	100%	160.45 MW	100%

Table 3 Wind Parks that will be installed shortly

	Prefecture	Plants	Percentage	Installed Power	Percentage
1	Lasithi	4	24%	8.22 MW	15%
2	Iraklio	2	12%	4.00 MW	7%
3	Rethimno	5	29%	24.30 MW	44%
4	Hania	6	35%	18.15 MW	33%
	Total	17	100%	54.67 MW	100%

The previously mentioned wind parks will be located almost all over Crete as it is depicted in Fig. 6, fact that wasn't met in previous years, where most of them were located in the eastern part of the island.

Fig.6. Geographical allocation of Wind parks in Crete

Collecting and analyzing all the relevant recorded data of the load demand and the corresponding wind production of the year 2008 few interesting figures are emerged. First, in Fig.7 the wind power production as a share of the overall power generation in a specific day (29/07/08) within 2008 is presented. In that day the daily energy supplied by wind parks was the annually highest and equal to 2,641.2 MWh. As well as the energy share of wind energy was 24% that is considered as a quite significant high share. Additionally, in that specific day the wind power penetration varied between 19% and 36% of the total power supply.

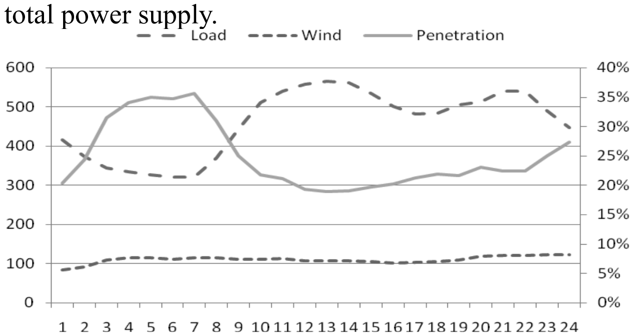

Fig. 7. Wind power penetration in power system of Crete

Furthermore, the day (25/10/08) with the highest share of wind energy in a daily base is depicted in Fig.8 where the wind energy production share was 32.6%. More precisely, that day the daily energy supplied by wind parks was equal to 2,359.1 MWh, while the wind power penetration varied between 29% and 38% of the total power supply without any significant operation difficulty. Consequently, these are considered as significant high RES penetration values, especially for an autonomous system such as Crete's network.

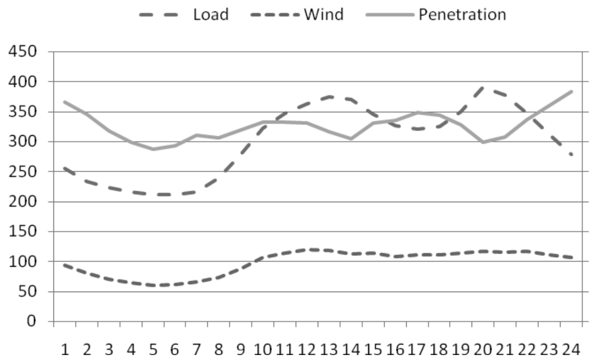

Fig. 8. Wind power penetration in power system of Crete

In the next Fig. 9 the hourly average values in daily base of the wind power and the corresponding penetration of the year 2008 are presented.

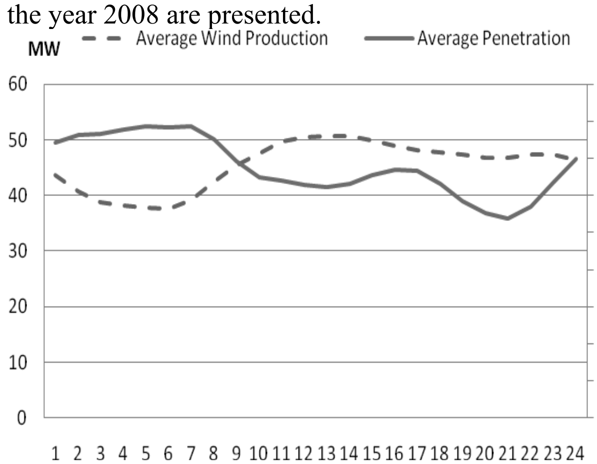

Fig. 9. Hourly average production of wind power

Another interesting parameter of Crete's power system operation for the year 2008 is that combining the highest recorded wind power production with the lowest recorded load demands, the possible maximum penetrations could be emerged. Of course in these cases, system operator should eliminate the wind power production to secure penetration values regarding the actual conditions, [Kaldellis, 2004]. However, this figure may give a nice picture of the corresponding upper limits of the current status.

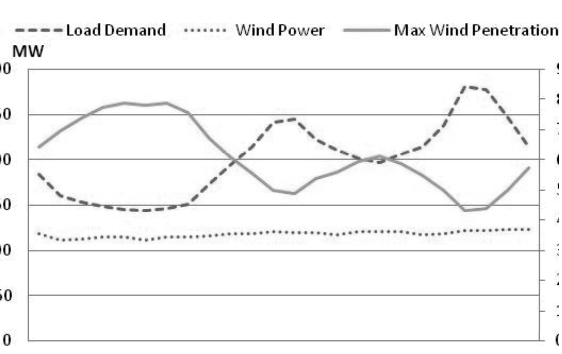

Fig. 10. Max recorded penetration in a 24-hours profile

Thus, according to the previous presentation of the current condition of wind parks and their operation for the year 2008, Crete deals even now with a significant dispersed generation and high RES penetration. This could be a fine baseline scenario for an even higher share of RES, taking into consideration the future prospects and the potential opportunities.

5. Future Prospects

The annual energy consumption in Crete for 2008 was 3.01 TWh. During the previous years the annual increase of electricity consumption was significant high, varying between 4% and 6%. In this study, two cases of the annual electricity demand evolution up to year 2020 have been considered, as they are depicted in Fig.11. These cases combine differently annual increase rates between 2% and 4%. The second and most moderate scenario of load demand augment, takes into account both the slight population growth, the financial crisis and the energy saving that might be achieved (EU directive 2006/32) at Crete till 2020.

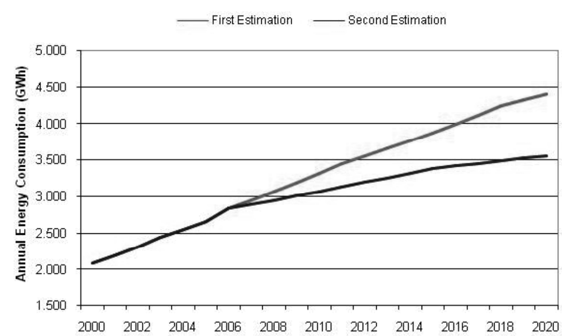

Fig. 11. Load demand evolution estimations

In addition to previous mentioned wind parks that are already installed or planned to, there are currently two more cases for extra 43.65 MW under license approval. This fact will lead shortly to even higher wind power equal to 258MW in the near future (Table 4). In this study two basic scenarios were investigated concerning wind power capacity till 2020. The first scenario follows the current trend that will lead to 258 MW wind power capacity till 2012 and estimates a capacity of 320 MW till 2020. The second scenario assumes a possible installation of pump storage systems [Kaldellis, et al. 2007] in Crete that will allow the expansion of wind power to 900 MW till 2020.

Table 4 Estimated wind power till 2012

	Prefecture	Plants	Percentage	Installed Power	Percentage
1	Lasithi	25	51%	107.12 MW	41%
2	Iraklio	10	20%	89.05 MW	34%
3	Rethimno	5	10%	24.30 MW	9%
4	Hania	9	18%	38.30 MW	15%
	Total	49	100%	258.77 MW	100%

Furthermore, the Greek Legislation (L.3468/2006) that promotes electricity production from RES and especially from PV introduces a program for a total installed capacity of at least 500MW in the interconnected system and at least 200MW in autonomous island systems till the end of 2020. As a result, a great interest for PV plants integration of 88.82 MW in Crete power system has been recorded. In the following Table 5 the share of each Crete's prefecture is presented, while in Fig.12 the geographical diversion of the corresponding PV plants are depicted. This fact will lead shortly to even higher RES generation and wider power dispersal.

Additionally, in this study two basic cases were investigated concerning PV power capacity till 2020. The first case assumes a moderate two steps increment, 88.2MW till 2012 and 120MW till 2020. The second case assumes final PV capacity of the second increment step up to 200MW till 2020.

Table 5 PV planned to be installed

	Prefecture	Plants	Percentage	Installed Power	Percentage
1	Lasithi	262	22%	19.90 MW	22%
2	Iraklio	501	42%	35.91 MW	40%
3	Rethimno	241	20%	18.26 MW	21%
4	Hania	200	17%	14.75 MW	17%
	Total	1204	100%	88.82 MW	100%

Fig. 12 Geographical dispersal of PV plants

Concluding, Cretan power system presents all the typical characteristics of an autonomous network and has been selected as a representative model for long term energy planning estimation, due to significant high share of RES and its expected future prospects.

5. Long-term Energy Planning

This paper uses a scenario-based energy-environment modeling platform called Long-range Energy Alternatives Planning [Heaps, 2002] system to estimate the impacts of different scenarios in Cretan Power System operation. Hence several scenario on future energy demand and environment development by designing different schemes have been investigated. 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. Constructed 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. The final platform not only includes the Technology and Environmental Database (TED) that provides extensive information of 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).

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

1. In the first scenario, 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 approximately 3% annual energy growth, this penetration can be achieved by setting a target for WTs installed capacity of 258MW till 2012 and capacity of 320 MW till 2020, which will produce the 16% of annual energy. Concerning PVs this scenario assumes capacity of 88.8 till 2012 and capacity of 120 till 2012, which will produce the 4% of the annual energy.
2. In the second scenario, where hydro pumped storage (HPS) systems are constructed and used, the energy penetration of RES technologies will be increased linearly from 12% of total energy demand in year 2008 to 50% in year 2020. Using HPS systems, the conventional power units' generation will be frequently limited to their technical minima, while RES penetration may reaches 90%. Considering once again approximately 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. 13, the installed capacity evolution of the power generation technologies for the first scenario is depicted. The steam units that consume heavy oil are considered to be closed till 2017, while two 250 MW liquid natural gas (LNG) units are added in the years 2014 and 2017 respectively [Kapros, 2006]. 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.

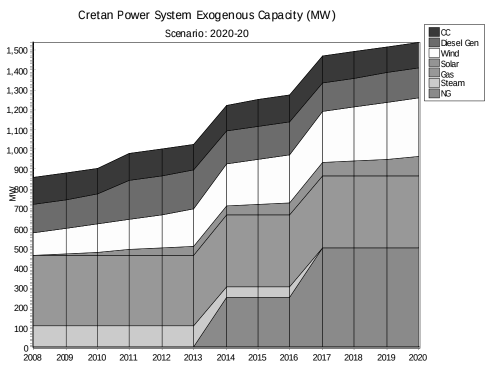

Fig. 13. Installed capacity evolution

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.

5.1 First Scenario Results

Fig. 14 shows the annual energy contribution of each power generation technology, while Fig. 15 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.

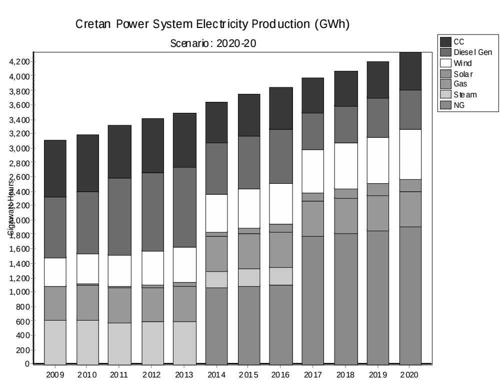

fig. 14. Annual electricity production

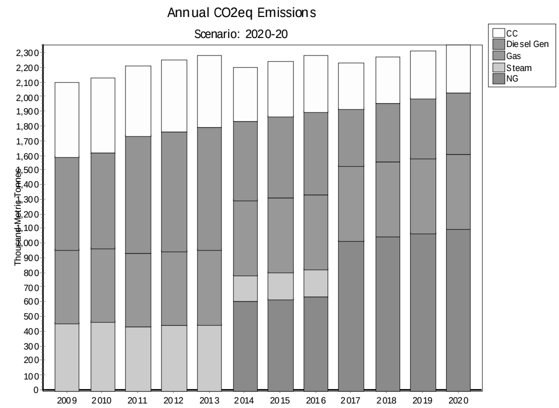

Fig. 15. Annual CO_2 eq. emissions

5.2 Second Scenario Results

The annual energy contribution of each power generation technology, as well as the annual CO_2 eq. emissions of conventional generators for the second scenario, are presented in Fig. 16 and Fig. 17, 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 that consume expensive diesel fuel is also decreased, while the NG units are used for base-load requirements.

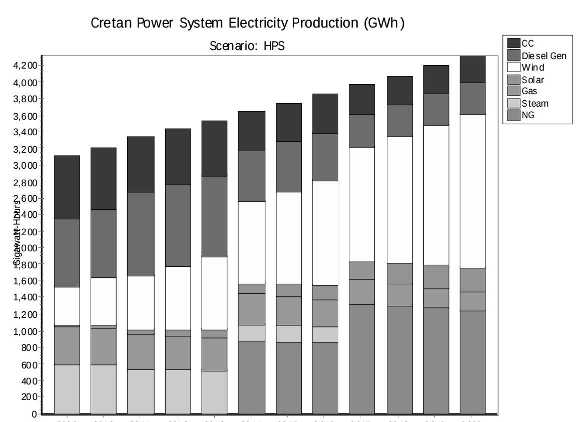

Fig. 16. Annual electricity production

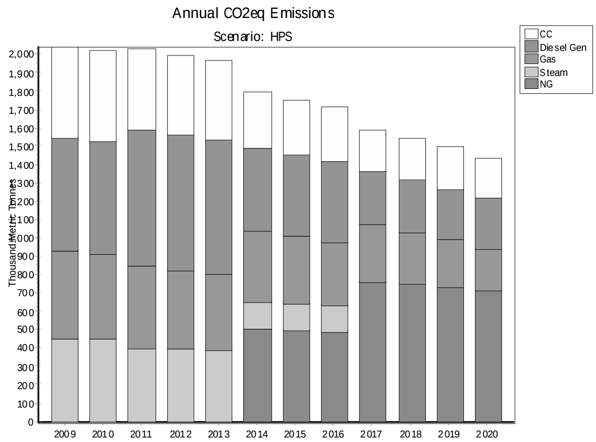

Fig. 17. Annual CO_2 eq. emissions

5.3 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 5. 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 the first scenario.

Table 6 Effect of different annual growth energy consumption rates in CO_2 eq. emissions at year 2020

Annual Energy increment	**Final CO_2 eq. Emissions (first scenario)**	**Final CO_2 eq. Emissions (second scenario)**
3% (base case)	$2355 \cdot 10^3$ tn	$1434 \cdot 10^3$ tn
2%	$2095 \cdot 10^3$ tn	$1275 \cdot 10^3$ tn
4%	$2644 \cdot 10^3$ tn	$1610 \cdot 10^3$ tn

7. Conclusions

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 and in case of higher load demand annually increment, the improvement by renewable energy sources cannot overcome the presumed 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.

In this study, the utilization of other renewable energy technologies and sources except wind turbines and photovoltaics didn't considered. This was due to low energy potential of them (geothermal energy, biomass, etc) in Cretan terrain and to lack of interest by investors. Therefore this study focused only to the wind parks and PV power plants evolution with or without the parallel construction of pump storage systems.

Additionally, this study didn't examine the possibility of Cretan power system interconnection with the continental power system of Greece. The implementation of such an interconnection will offer the opportunity for further wind and solar power exploitation, overcoming many current technical and operational limitations.

The analysis in this paper examines only technical aspects in each considered scenario. Methodological approach and paper's results could be considered as base case. Consequently, in a future work, the comparison of the two alternative approaches which will contain a combination of economic and technical criteria, should clarify which of the considered scenarios is superior, compared to the others.

Concluding, comprehensive studies for sustainable energy planning, which combines grid enhancement, advance operation control, wind and solar further exploitation in collaboration with pump storage systems, in parallel with successful energy and power saving, could lead to a realistic high RES share implementation scenario.

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Устойчивое Энергетическое Планирование для Независимой Энергосистемы Крита

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Резюме: Независимая энергосистема Крита была выбрана в качестве представительной модели для долгосрочной оценки энергетического планирования в случае значительно высокой доли в электроэнергии и энергетическом балансе от возобновляемых источников энергии. Модель расширения генерирующих мощностей выбирает из условных технологий электроэнергии, таких как установки тепловых энергоблоков, парогазовые установки, газовые турбины, а также технологии возобновляемых источников энергии, таких как ветропарки, фотоволтайки и гибридные системы для снабжения прогнозируемого спроса на будущие годы. В то же время, операция и контроль энергосистемы, специальные ограничения, исполнение проекций, а также затраты на расширение генера́ции электроэнергии, должны быть вразумительно исследованы. Точнее, это исследование анализирует текущую операцию системы и демонстрирует преимущества и препятствия значительной части прогнозируемой требуемой нагрузки Крита от возобновляемых источников энергии и гибридных систем к концу 2020 года. Потенциал высокой доли технически возможен, не запретительной стоимости, и предоставляет преимущества в виде снижения выбросов углерода, энергетической адекватности и зависимости.

Ключевые слова: Независимая Энергосистема, Энергетическое Планирование, Возобновляемые Источники Энергии