Energy for Sustainable Development 27 (2015) 155–167

Contents lists available at ScienceDirect

Energy for Sustainable Development

The feasibility of the introduction of natural gas into the electricity production system in the island of Crete (Greece)

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ARTICLE INFO

Article history:
Received 28 December 2012
Revised 9 April 2015
Accepted 9 April 2015
Available online 3 July 2015

Keywords:
Natural gas
Thermal power plants
Isolated insular systems
Energy reserves exhaustion
Electricity production

ABSTRACT

This article examines the technical and economic feasibility for the introduction of natural gas for electricity generation in non-interconnected insular systems. In such systems, the introduction of natural gas constitutes a fundamental perspective towards the substitution of oil or coal, commonly used for electricity production. On the contrary, the expensive transportation of natural gas for long overseas distances, the required technical infrastructures and the expected limited consumption of natural gas in islands with low populations, constitute issues that can negatively affect the feasibility of the project.

The aforementioned tasks are examined in the present article for the island of Crete (Greece) chosen as a case study. The size of the island and its consequent electricity consumption create the fundamental prerequisites for the introduction of natural gas. The annual operation of the existing system and the new one, as it would be modified after the natural gas introduction, is simulated using all the required parameters and data as provided by the utility company. The annual production specific cost is calculated for both systems and the economic benefit from the substitution of oil with natural gas is evaluated. The CO_2 annual emissions are also calculated for both systems.

The annual electricity production cost in Crete with the introduction of natural gas is reduced 38%, while the CO_2 annual emissions are reduced 54%, compared to existing levels in 2013. The required investments exhibit a payback period above 3.5 years. On the other hand, the energy dependence of the island on imported energy sources remains.

Introduction

The existing situation in the electricity production sector in Crete

The electricity production in Crete is based on three thermal power plants and on a dispersed network of wind parks and photovoltaic stations (PV). The system is not interconnected.

The electricity generation system in Crete is characterised by several technical and economic inadequacies that can be summarized as follows (see also The existing electricity system in Crete and Results sections):

- the high installed power capacity of gas turbines compared to the installed power of the base thermal generators;
- the high annual consumption of expensive diesel oil by combined-cycle power plants and gas turbines;
- the frequent power interruptions during summer peak periods, whenever the power demand exceeds installed thermal generation capacity;
- the necessity to maintain thermal spinning reserve to improve the system's dynamic security, a procedure that implies the operation of the thermal generators close to their technical minima, with low efficiency;
- the dependence of electricity generation on imported fossil fuels with all the well known negative consequences (low energy security, increase of fuel prices);

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http://dx.doi.org/10.1016/j.esd.2015.04.009
0973-0826/

- the final electricity production cost higher than 20€/MWh, including all the involved components (fuel consumption, equipment maintenance, salaries, etc.);
- the emission of more than 1.5 million tonnes of CO_2 annually due to the consumption of heavy fuel oil and diesel oil.

It is obvious that the above features imply an operation of the electricity system in Crete far from the optimum one, which is determined by the secure and uninterrupted electricity production with a considerably reduced electricity production cost.

The rationalism of the electricity production system in Crete should aim at the following objectives:

1. The elimination of the dependence of the electricity supply on imported fossil fuels, which will strengthen the energy security of the island and enable the independence of the electricity production cost from the international variation (usually increase) of the fossil fuel prices.
2. The improvement of the system's dynamic security and competence, which will contribute towards the elimination of the occurred electrical contingencies and the improvement of the provided power quality.
3. The minimisation of the environmental effects of electricity generation.
4. The reduction of electricity production cost.

A considerable number of relevant studies (Mourelatos et al., 1998; Tsioliaridou et al., 2006; Tsoutsos et al., 2009; Giatrakos et al., 2009; Kaldellis et al., 2013) have been presented so far, examining different schemes for the secure and cost-effective electricity production in Crete. The proposed solutions can be summarized as follows:

1. Introduction of natural gas, a cheaper and environmentally friendlier fuel, as the main fuel in the thermal power plants, substituting the currently consumed heavy fuel oil and diesel.
2. The interconnection of the Cretan electricity system with the Greek mainland, which will enable the elimination of the expensive diesel oil consumption. The electricity generation cost will approach that of the mainland system and the greenhouse gas emissions in Crete will be reduced. Finally, the energy security of the power system will be considerably improved.
3. The maximization of Renewable Energy Sources (R.E.S.) penetration for electricity generation, combined with storage technologies, which will contribute to the reduction of the:
   a. dependence of the autonomous system on imported energy sources;
   b. greenhouse gas emissions;
   c. high electricity production cost, usually met in autonomous insular systems.

The present article examines the feasibility of the introduction of the natural gas in the electricity system in Crete, completely substituting liquid fuels that currently constitute the main energy sources for the electricity production. A design towards this target has been developed by the Power Production Corporation (P.P.C.), the national utility company in Greece. This design is adopted in this paper.

Natural gas — attributes and existing technologies

Natural Gas (NG) comprises one of the fundamental fossil fuels, exhibiting a 2.5% annual consumption global increase during the last decade. The annual NG production ($3.4 \cdot 10^9 Nm^3$) covered 23.9% of the global energy demand in 2012 (BP Statistical Review of World Energy, 2013). This percentage is expected to reach 50% until 2020 (Economides et al., 2000).

Compared to the liquid fossil fuels, NG exhibits the following advantages:

– the lower gaseous emissions from NG consumption in internal combustion engines (Papakonstantinou, 2008);
– the lower NG price;
– the NG reserves' longer life period.

On the other hand, the considerable CH_4 leakage throughout the NG production, transportation and consumption should be mentioned. This leakage may exceed 2% of the total NG annual production. The global warming potential (100 year time horizon) of methane is 28, according to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014).

Due to the geographic concentration of NG in specific areas on earth, the NG consumption requires a wide transportation network. The NG is transported either through pipelines (70%) or as Liquefied Natural Gas (LNG) with ships (30%). Recently, Compressed Natural Gas (CNG) has also been proposed for overseas transportation. It is less expensive to transport natural gas in a pipeline for larger demand volumes and shorter distances, while LNG is preferred for smaller demand and larger distances (Schwimmbeck, 2008).

LNG transportation requires the installation of large and expensive cooling, storing and regasification infrastructure (Marks' Standard Handbook for Mechanical Engineers, 2007). CNG shows lower production and storage cost compared to LNG as it does not require an expensive cooling process and cryogenic tanks (Dunlop and White, 2003). CNG requires a much larger volume to store gas equivalent compared to the respective gasoline or diesel.

Aim of the article

This article investigates the techno-economic feasibility for the introduction of NG for electricity generation in Crete, in favour of the P.P.C. The potential benefits for local communities are also examined. The feasibility of NG introduction in Crete is investigated under the following parameters:

- possible reduction of the annual electricity production cost;
- possible environmental benefits;
- energy supply security;
- other potential benefits for the local communities in Crete.

The existing electricity system in Crete

In the following subsections we present the power demand in Crete (Power demand section) and how this demand is met by thermal power plants (The existing thermal power plants, The dispatch order of thermal generators, and The thermal generators spinning reserve sections) and renewable power plants (Renewable energy power plants in Crete section).

Power demand

The P.P.C. provided the necessary data concerning the operation of the existing electricity system in Crete. The 2013 annual power demand time-series of mean hourly values is presented in Fig. 1. Characteristic features concerning the annual electricity consumption and power demand in Crete in 2013 are provided in Table 1.

Fig. 1 shows the seasonal variation in power demand, caused mainly by the increased tourism activities in summer. Table 1 shows that there was a considerable difference of more than 400 MW between the maximum and the minimum power demand in 2013. This power demand fluctuations lead the system to operate under significantly different conditions and renders the uninterrupted and secure power production a difficult task.

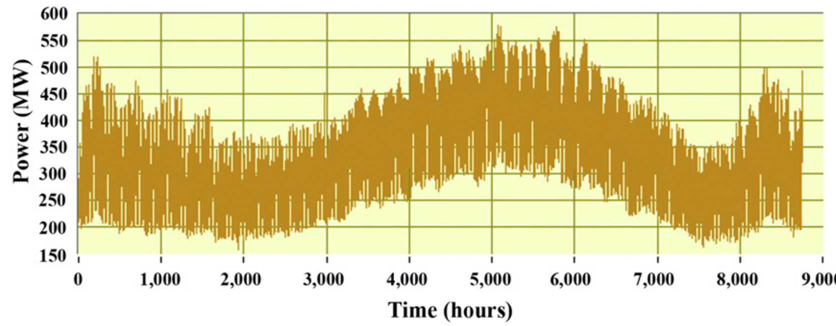

Fig. 1. Mean hourly electric power demand in Crete for year 2013.

The existing thermal power plants

The existing thermal power production system in Crete consists of three thermal power plants, located in Heraklion, Chania and Lasithi prefectures. The structure of these power plants at the end of 2013 is presented in Tables 2, 3 and 4 (Annual bulletin of exploitation of the Crete power production system for the year 2010 — P.P.C. S.A.).

As seen in these tables, Crete's thermal power plants comprise steam turbines, diesel engines, gas turbines and a combined cycle. The steam turbines and the diesel engines burn heavy fuel-oil, while the gas turbines and, consequently, the combined cycle, burn diesel oil.

The dispatch order of thermal generators

The dispatch order of thermal generators is determined by the following criteria (Annual bulletin of exploitation of the Crete power production system for the year 2010 — P.P.C. S.A.; Al et al., 2007):

- the power production system stability and security;
- the cost-effective operation of the power generation system.

The first criterion imposes the continuous operation of the generators with low response to the power demand variations and the slow switching on procedure, namely, the steam turbines and the combined-cycle power plant. This implies that the steam turbines and the combined-cycle power plant operate continuously. In cases of low power demand, these generators operate close to their technical minima, exhibiting low efficiency and high energy production specific cost, particularly due to the obligatory operation of the combined-cycle power plant that burns expensive diesel oil.

The aforementioned inefficient system operation cases are met during most of the year, especially in autumn and spring, when the power demand is low.

The second criterion depends on fuel prices and the efficiency of different types of power plants (see Table 5), which leads to the following dispatch order for thermal generators:

- diesel engines (since they are operated with less expensive heavy fuel oil in Crete);
- steam turbines (operating with heavy fuel oil);
- combined-cycle power plant (operating with more expensive diesel oil in Crete);
- gas turbines (also operating with diesel oil).

This order is kept when there are no other constraints imposed by the system stability. The steam turbines and the combined-cycle power plant operate continuously, at least at their technical minima, no matter what the thermal generator dispatch order may be.

All the thermal generators follow an annual maintenance schedule. The maintenance takes place from October to April (low power demand season). During this time period, all the thermal generators are set out of duty in turn. This maintenance schedule is embodied in the present simulation approach.

The thermal generators spinning reserve

The thermal generators' spinning reserve aims at the improvement of the system security. The fundamental rule is that the spinning reserve total power must be at least equal to the generator's maximum nominal power among the dispatch order of thermal generators.

Table 1
Characteristic features of the annual electricity consumption.

Year	Maximum annual power demand (MW)	Minimum annual power demand (MW)	Annual electricity consumption (MWh)	Mean daily electricity consumption (MWh)
2013	579	158	2,954,403	8094

Table 2
Thermal power plants in Heraklion.

Steam turbines	Technical minima (MW)	Nominal power (MW)	Diesel engines	Technical minima (MW)	Nominal power (MW)	Gas turbines	Technical minima (MW)	Nominal power (MW)
1	1.8	6.2	1	3.0	11.0	1	3.0	14.0
2	7.0	15.0	2	3.0	11.0	2	3.0	14.0
3	7.0	15.0	3	3.0	11.0	3	3.0	43.0
4	12.0	25.0	4	3.0	11.0	4	3.0	13.0
5	12.0	24.0				5	3.0	32.0
6	12.0	24.0						
Total	**51.8**	**109.2**		**12.0**	**44.0**		**15.0**	**116.0**

Table 3
Thermal power plants in Chania.

Gas turbines	Technical minima (MW)	Nominal power (MW)	Combined cycle	Technical minima (MW)	Nominal power (MW)
1	3.0	12.0	Gas turbine 6	10.0	37.0
4	3.0	13.0	Gas turbine 7	10.0	37.0
5	5.0	29.0	Steam turbine	20.0	36.6
11	8.0	55.0			
12	8.0	55.0			
13	3.0	32.0			
Total	**30.0**	**196.0**		**40.0**	**110.6**

Table 4
Thermal power plants in Lasithi.

Steam turbines	Technical minima (MW)	Nominal power (MW)	Diesel engines	Technical minima (MW)	Nominal power (MW)
1	17.0	50.0	1	12.0	51.0
2	17.0	50.0	2	12.0	51.0
Total	**34.0**	**100.0**		**24.0**	**102.0**

Renewable energy power plants in Crete

The total nominal power of the installed wind parks in Crete in 2013 reached 175 MW. The annual power production from the existing wind parks is calculated by taking into account the following:

- the installed wind power geographical distribution in Crete;
- the total installed wind power;
- the power curve of installed wind generator models;
- eleven (11) simultaneous wind velocity time series from the wind parks' installation sites or from neighboring areas.

Additionally, PV with a total installed power of 89.885 MW had been installed in Crete at the end of 2013. The annual power production time series from the PV is calculated with the use of solar radiation annual measurements in Eastern Crete.

In non-interconnected power systems, such as the one in Crete, the wind and PV power penetration is limited, to ensure the system's stability and security (Annual bulletin of exploitation of the Crete power production system for the year 2010 — P.P.C. S.A.; Al et al., 2007; Kaldellis et al., 2004; Tande, 2000; Thiringer and Petersson, 2003; Boulaxis et al., 2002; Hatziargyriou et al., 2004; Larson, 2003; Thiringer et al., 1999; Ehnberg and Bollen, 2004; Caralis and Zervos, 2005). Practically, in the present simulation, the R.E.S. penetration is restricted whenever:

i. the total power production from the wind parks and PV is higher than 30% of the power demand;
ii. the thermal power reduction due to wind power and PV penetration imposes the dispatch thermal generators to produce lower power than their technical minima.

The introduction of electricity generation in Crete

Scope

In this section, the operation of the new electricity generation system in Crete after the introduction of NG is simulated. Specifically, the following tasks are analyzed:

Table 5
Consumed fuels and prices in the existing electricity system in Crete.

Fuel type	Fuel price (2013 annual averaged)
Heavy fuel oil	0.487€/kg
Diesel oil	0.991€/lt

- synthesis of the new thermal power plants in Crete;
- determination of the operation of the new system, dispatch order of the new thermal generators, spinning reserve, etc.

The new NG thermal power system in Crete

The synthesis of the new power system

According to a former study implemented by P.P.C. concerning the introduction of NG in Crete (Kardomateas, 2004; Prefecture of Crete, P.G.C. P.P.C., 2003), the configuration of the new system is described below:

1. A new thermal power plant will be constructed at the site of Korakia in Heraklion Prefecture, equipped with combined cycle units with a total nominal power of 320 MW and diesel engines with a total nominal power of 100 MW (Fig. 2).
2. Three existing gas turbines will be removed from the thermal power plant in Heraklion, modified into NG units and re-installed in the above mentioned new thermal power plant.
3. The existing gas turbines in Chania power plant will be modified into NG units.
4. The existing diesel engines in Lasithi thermal power plant will be modified into NG units and two new diesel engines of 100 MW total nominal power will be installed.

In synthesis, the total nominal power of the thermal generators in Korakia power plant will reach 564 MW. Additionally, 100 MW of new diesel engines will be installed in Lasithi thermal power plant. The total power of 956 MW (see Table 6) will be covered by the modifications of the existing thermal generators.

The configuration of the new power system, after NG introduction, is presented in Table 6 (Kardomateas, 2004; Prefecture of Crete, P.G.C. P.P.C., 2003). The new combined cycle units consist of a gas turbine and a steam turbine each.

The current thermal generators' (The existing thermal power plants section) total nominal power exceeds 40% the maximum annual power demand in 2013. The design of the new system aims to cover Crete's electricity demand until 2025. After this time point, additional thermal generators must be installed.

Fundamental assumptions for the system's operation

As in the existing thermal power system, the dispatch order of thermal generators in the new one is determined by the following criteria (Annual bulletin of exploitation of the Crete power production system for the year 2010 — P.P.C. S.A.; Al et al., 2007):

Fig. 2. The layout of projected NG distribution pipeline in Crete.

- the power production system's stability and security;
- the power production system cost-effective operation.

The dispatch order becomes:

1. combined cycles (now operating on NG);
2. diesel engines (now operating on NG);
3. gas turbines (now operating on NG).

The instant wind power and PV penetration percentage over the power demand is always kept below 30%.

As in the existing system, all the thermal generators follow an annual maintenance schedule, which is taken into account in the present simulation.

New efficiency curves for the new NG thermal generators, based on relevant technical data and bibliography (CRES and ZREU, 2001; Pappas, 2006), are introduced. As far as the thermal generators spinning reserve is concerned, the same procedure as with the existing system is applied.

Methodology

The methodology adopted for the evaluation of the NG introduction feasibility in Crete's power system is divided in the following steps:

- The annual operation of the existing and the new (with the NG introduction) electricity production system in Crete is simulated and the annual production cost is calculated for both systems.
- The required investments for the NG introduction in Crete are estimated.
- The economic feasibility for the NG introduction is then evaluated, based on the results of the previous two steps.
- The advantages of the NG compared to heavy gasoil and diesel, are evaluated, on the basis of the energy security and of any possible environmental positive impacts.
- Any secondary benefits for the local communities in Crete arising from the substitution of liquid fuels by NG are finally discussed.

Simulation

The simulation of the annual operation of the existing and the new (after the NG introduction) electricity production systems in Crete is based on the data and assumptions presented in The existing electricity system in Crete and The introduction of electricity generation in Crete sections. A new specialized software tool was developed for this specific purpose, namely the computational simulation for the operation of the existing and the new electricity production systems.

The data used for the system simulation are:

- the power demand annual time series of mean hourly values;
- the wind parks and PV power production annual time series of mean hourly values;

Table 6
The synthesis of the new thermal power system in Crete, after the introduction of NG.

Korakia power plant			Lasithi power plant		Chania power plant	
Combined cycles			Diesel engines		Gas turbines	
	Technical minima (MW)	Nominal power (MW)	Technical minima (MW)	Nominal power (MW)	Technical minima (MW)	Nominal power (MW)
Gas turbine	5.0	50.0	5.0	50.0	3.0	48.0
Steam turbine	2.0	14.0				
Units number	5		4		4	
Total	**35.0**	**320.0**	**20.0**	**200.0**	**12.0**	**192.0**
Diesel engines						
	5.0	50.0				
Units number	2					
Total	**10.0**	**100.0**				
Gas turbines						
	3.0	48.0				
Units number	3					
Total	**9.0**	**144.0**				
Total technical minima (MW)	**86.0**					
Total nominal power (MW)	**956.0**					

- the maximum wind power and PV penetration percentage;
- the characteristic features of the available thermal generators (efficiency curves, nominal power and technical minima, on-duty sequence);
- the consumed fossil fuels and their properties (thermal capacity, price).

The simulation is performed for an annual time period, following an hourly computational time step. For every hourly time step, given the current power demand, the software executes the following:

- calculates the wind power and PV penetration, according to the R.E.S. penetration restrictions described previously;
- determines the thermal generators that should be employed for the electricity production, given their on-duty sequence, their maintenance schedule and their power specifications (nominal power and technical minima);
- calculates the fossil fuel consumption from every thermal generator separately and in total, given the generators' efficiency power curves and the consumed fuels' thermal capacity.

Once the above described activities have been completed for the whole annual period (8760 hourly steps), the following annual totals are finally calculated:

- the fossil fuels annual consumption;
- the fossil fuels annual consumption cost;
- the total electricity production.

The above results lead to the calculation of the electricity production annual specific cost, as described below.

Methodology for the economic evaluation

The economic evaluation of the NG introduction in Crete is based on the:

- estimation of the required investment;
- the calculation of the annual production cost of both the examined and the new system, according to the above mentioned systems' simulations;
- the calculation of the annual production cost reduction, achieved with the NG introduction, which is considered as the investment's net profit.

Except for the fuel cost, the CO_2 emission costs and the thermal generators maintenance costs are also taken into account. These are presented in the following section. The remaining operation and maintenance costs (salaries, buildings, etc.) are not taken into account, since they are considered to remain the same for the two examined systems and, as a result, they do not affect the economic feasibility of the required investment.

The economic evaluation is integrated with the calculation of characteristic economic indexes for the total investment. A brief sensitivity analysis is also executed for the calculated economic indexes versus the NG price and the required investment.

Set-up cost estimation

Besides the installation of the new thermal power plant and the modification of the existing thermal generators (see The synthesis of the new power system section), the following works are required for the introduction of NG in the electricity production system in Crete:

1. The construction of a small harbour in the new thermal power plant in Korakia for the transportation of LNG.
2. The construction of LNG storage tanks in Korakia.
3. The installation of the gasification station in Korakia.
4. The installation of the NG distribution pipeline, with a total length of 280 km, from Korakia to Chania, Heraklion and Atherinolakos (Lasithi Prefecture) power plants (Fig. 2).

The construction of the new thermal power plant, the installation of the new thermal generators and the modification of the existing ones, described in The synthesis of the new power system section, will be undertaken by P.P.C. The above presented tasks 1 to 4, will be undertaken by P.G.C. The total set-up cost is divided respectively between the two companies.

A safe approach for the estimation of the set-up cost of the new thermal power plant and the modification of the existing thermal generators is retrieved from the relevant bibliographic sources (Marks' Standard Handbook for Mechanical Engineers, 2007). A characteristic set-up specific cost for a new thermal power plant is estimated at 1200€/kW of installed power, for conventional steam power plant of 500 MW capacity with natural gas[5] (Marks' Standard Handbook for Mechanical Engineers, 2007). For the existing thermal generators modifications into NG units, the cost of 50€/kW is given for the gas turbines and the cost of 100€/kW is given for the diesel engines.

The set-up cost components referring to tasks constructed by P.G.C. are found in a relevant former study (Kardomateas, 2004). The cost of the pipelines installation was calculated for a total tubes' length of 280 km, with X-65 and diameter of 16 in.

Operational cost estimation

The system's operational cost is configured from the following components:

1. fuel cost and energy purchased by wind parks and PV cost;
2. generators' maintenance;
3. staff salaries;
4. greenhouse gas emissions cost.

From the above costs, the fuel cost and the wind energy and PV cost are calculated by the systems' computational simulation.

The thermal generators maintenance cost is assumed to be 0.018 €/kWh_e (Marks' Standard Handbook for Mechanical Engineers, 2007) for heavy fuel or diesel oil generators, while for NG combined cycles it is given as equal to 0.009€/kWh_e (Marks' Standard Handbook for Mechanical Engineers, 2007).

With the introduction of the NG into the electricity production system in Crete, it is assumed that the same staff will be employed and therefore the salary cost will remain the same. Since the scope of this approach is to compare the two systems' operational cost, the salary cost calculation can be omitted.

The mean annual gases emissions specific cost is estimated at 0.0028 €/kWh_e for liquid fossil fuels and at 0.0013€/kWh_e for NG, by taking into account the following:

- A CO_2 emission rights' price equal to 5€/tn, as set in 2013 by the European Emission Allowances Auction (https://www.eex.com/en/market-data/emission-allowances/auction-market/european-emission-allowances-auction/european-emission-allowances-auction-download).
- The CO_2 emissions' coefficients, determined at 77.4 tn/TJ and 74.1 tn/TJ for heavy gasoil and diesel oil respectively and at 56.1 tn/TJ for NG by the 2004/156/EU directive (2004/156/EC). The lower heating values of heavy gasoil, diesel oil and natural gas are (Boundy et al., 2011):
  - heavy gasoil: 42.612 MJ/kg
  - diesel oil: 39.466 MJ/kg = 39.122 MJ/lt
  - natural gas: 47.141 MJ/kg = 38.113 MJ/Nm^3.

  Given the heating values of the involved fossil fuels, the above CO_2

[5] Marks' Standard Handbook for Mechanical Engineers (2007) (Table 17.5.1, pages 17–33) gives investment of 900–1000$/kW for 2003 prices for conventional thermal steam power plant of 500 MW capacity with natural gas. We have increased the value to take into account inflation and certain items not included in the above estimate.

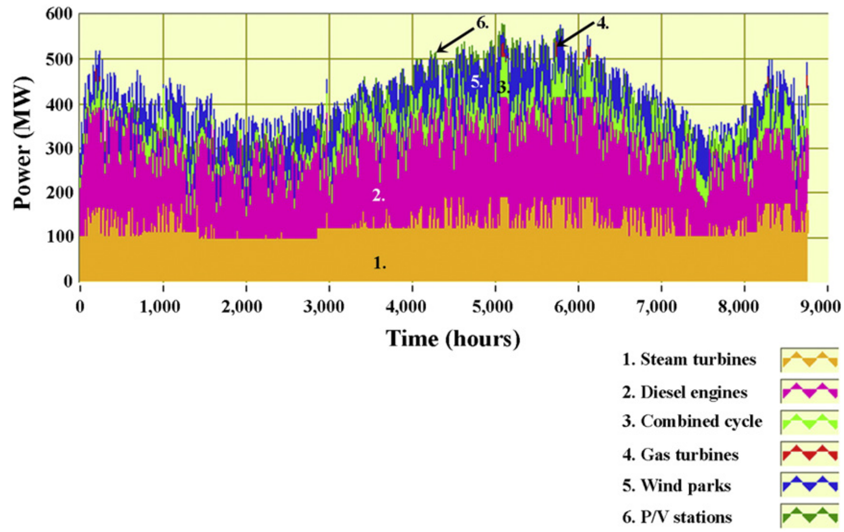

Fig. 3. Annual power production synthesis in Crete in 2013 with the existing power system.

emissions coefficients can be calculated per unit of consumed fuel (kg, lt or Nm^3):

- heavy gasoil: 3.298 kg CO_2/kg of consumed heavy gasoil;
- diesel oil: 2.899 kg CO_2/lt of consumed diesel oil;
- natural gas: 2.138 kg CO_2/Nm^3 of consumed natural gas.

• The efficiencies for the existing and the new system's thermal generators, as calculated from the simulation of the systems for every time calculation step.

Methodology for the environmental evaluation

The main environmental benefit arising from the introduction of NG in the electricity sector in Crete is the reduction of the greenhouse gas emissions, mainly CO_2 emissions, compared to those of the existing thermal generators. The CO_2 emissions estimation is based on the calculation of the fossil fuel annual consumption, executed with the computational simulation of the annual operation of the existing and the new system.

The evaluation of the contribution of the NG introduction on the energy security supply in Crete is based on the existing experience and data from the consumption of imported fossil fuels by the thermal power plants in the insular systems in Greek.

Results

Simulation results

Existing system

The simulation of the annual operation of the existing electricity production system in Crete is based on the data and assumptions presented in The existing electricity system in Crete section. Characteristic power production synthesis graphs are presented in Figs. 3, 4 and 5.

In Table 7, a summary of the simulation results is presented, such as the electricity production, the fuel consumptions and the fuels' costs.

Finally in Table 8, the total annual electricity production analysis cost is presented. The selling price of the produced electricity from the wind parks and the PV in 2013 is set 0.085€/kWh and 0.260€/kWh respectively.

The annual CO_2 emissions, calculated on the basis of the annual fossil fuels consumptions, are presented in Table 9.

The new system with the introduction of NG

The evaluation of the new system's operation is performed considering demand for the year 2013, implying that all the thermal generators consume exclusively NG and the existing wind parks and PV in Crete are included, while the power demand remains the same.

The simulation of the annual operation of the new electricity production system in Crete was based on the data and assumptions presented in The introduction of electricity generation in Crete section. Characteristic power production synthesis graphs are presented in Figs. 6, 7 and 8.

In Table 10, a summary of the simulation results is presented, such as the electricity production, the fuel consumptions and the fuels costs. For the NG cost calculation, the price of 0.0367€/kWh_{th} was adopted, according to the mean annual market price in Greece.[6]

Finally in Table 11 the total annual electricity production cost analysis is presented.

The annual CO_2 emissions are calculated on the basis of the specific CO_2 emissions determined in Operational cost estimation section, according to the 2004/156/EU directive (2004/156/EC). Based on the above assumptions and taking into account the annual calculated NG consumption (365.065 Mm^3), the annual CO_2 emissions are calculated to be 780,570 tCO_2.

Synopsis of the simulation results from the new and the existing system operation

The main conclusions arising from the analysis of the simulation results for the existing and the new power system in Crete are summarized below:

• The mean annual production specific cost reduces from 0.1284€/kWh in the existing system to 0.0814€/kWh in the new NG system, giving a specific cost reduction equal to 0.0470€/kWh, that corresponds to 36.60% of the existing specific cost. Recall that the above specific costs depend on fossil fuel prices, as well as the wind and PV energy purchase costs. The remaining operation and maintenance costs (salaries, buildings, etc.) are not taken into account, since they are considered to remain the same for the two examined systems and, as a result, they do not affect the economic feasibility of the required investment (see also Methodology for the economic evaluation section).
• The annual CO_2 emissions would fall from 1,686,004 tn with the existing system to 780,570 tn with the new NG one. A total annual CO_2 emissions reduction would be 905,434 tn, that corresponds to 53.70% of the current emissions.
• The PV penetration is not affected with the introduction of NG in the electricity production system. The wind energy penetration is reduced by 7%.

[6] For the time being, mainland Greece is also provided with LNG. An onshore pipeline transportation network is under construction.

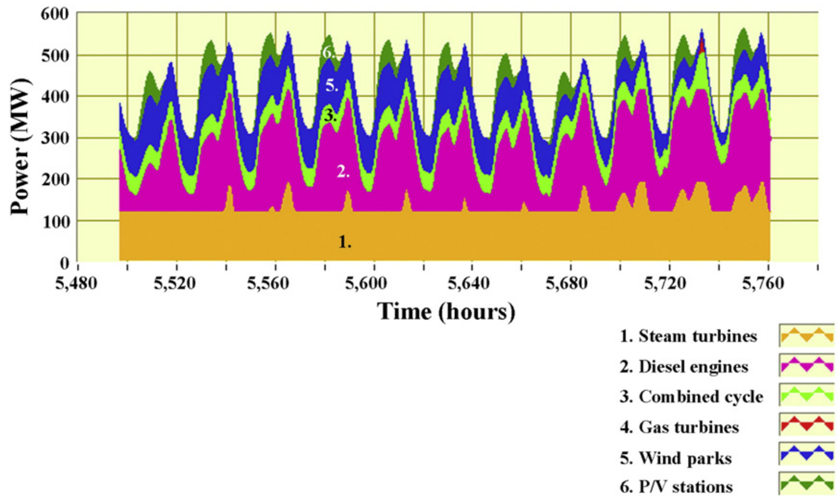

Fig. 4. Power production synthesis in Crete from 18-8-2013 to 28-8-2013 with the existing power system.

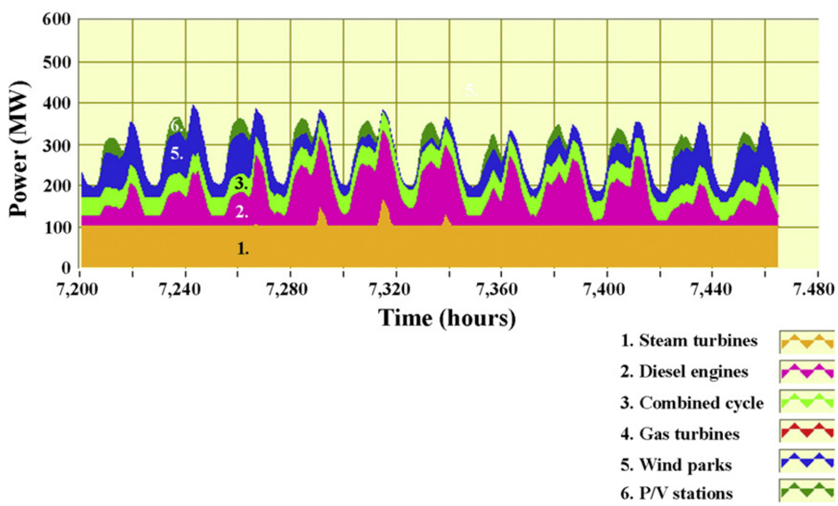

Fig. 5. Power production synthesis in Crete from 28-10-2013 to 7-11-2013 with the existing power system.

Economic feasibility of the introduction of NG in Crete's electricity system

Following the assumptions regarding the set-up cost estimation, as presented in Set-up cost estimation section, the analysis of the set-up cost is presented in Table 12.

Similarly, following the assumptions presented in Operational cost estimation section, the calculation of the total annual electricity production specific cost for both the existing and the introduced NG system is presented in Table 13. The annual money saving arising from the NG introduction is also provided in the same table.

Conclusively, given the results presented in Tables 12 and 13:

- the introduction of NG in electricity production sector in Crete requires the investment of 1.140 billion €
- the annual production cost reduction is estimated at 169.473 million € and concerns exclusively the P.P.C.

The results for the economic evaluation of the investment on behalf of P.P.C. (state company) are presented in Table 14. A mean discount rate of 6.5% is assumed for a time period of 20 years.

The above presented economic indices were calculated on the basis of the following assumptions:

- the price fluctuation during the examined time period is analogous for both the heavy fuel-oil, diesel and the NG, so as the annual money saving remains constant
- the efficiency of the new NG thermal generators does not fall with ageing
- the maintenance cost of the new NG thermal generators remains constant in time
- the annual electricity production from the existing Renewable Energy Sources (R.E.S.) technologies (wind parks, photovoltaics, hybrid stations) remains always between 10–15% over the annual electricity demand.

Table 7
Simulation results summary for the existing system operation in 2013.

Steam turbines	995,291	34.6	0.123	251,460	–	122.48	–
Diesel engines	938,208	46.4	0.092	176,568	–	86.00	–
Combined cycle	348,115	38.0	0.267	–	93,750	–	92.87
Gas turbines	688	22.4	0.452	–	314	–	0.31
Wind parks	548,795	–	0.085	–	–	–	–
PV	123,429	–	0.260	–	–	–	–
Thermal generators start up	–	–	–	476	14	0.23	0.01
Total	**2,954,526**	[a]**40.0**	**0.128**	**428,504**	**94,078**	**208.71**	**93.19**

[a] This is the total annual mean efficiency of the thermal power system.

Table 8
Total electricity production cost in Crete in 2013.

Total fossil fuels annual cost (M€)	301.91
Total wind parks annual cost (M€)	46.65
Total PV stations annual cost (M€)	30.86
Total production annual cost (M€)	[a]379.42
Total production annual specific cost (€/kWh)	[a]0.128

[a] Only the fossil fuels, the wind and PV energy costs are included. All the other costs (maintenance, salaries etc.) are considered negligible.

Table 9
Annual CO_2 emissions from the existing electricity production system in Crete in 2013.

Annual CO_2 emission due to heavy fuel consumption (tn)	1,413,279
Annual CO_2 emission due to diesel oil consumption (tn)	272,726
Total annual CO_2 emissions (tn)	1,686,004

In the sensitivity analysis graph presented in Fig. 9, the effect of the NG price on the annual production cost reduction and the P.P.C. set-up cost payback period are presented.

In Figs. 10 and 11 two more sensitivity analysis graphs are provided, regarding the P.P.C. set-up cost internal rate of return and net present value fluctuation in terms of the NG purchase price and the P.P.C. set-up cost.

From the above presented analysis it is revealed that the economic evaluation was implemented only for the works concerning the contribution of P.P.C. in the total project. The economic evaluation of this part of the project, on the one hand is related with the operation of the existing system, since it depends on the existing production cost reduction, and on the other hand refers to a state company, namely it concerns the Greek people. The economic evaluation of the works concerning the P.G.C. (private commercial company), namely the economic feasibility of the supply and the vending of NG in P.P.C., is beyond the scope of the present research.

Environmental evaluation

CO_2 emissions

The CO_2 emissions exclusively from the electricity production system in Crete have been calculated and presented in the previous sections for the year 2013 and for both the existing system and the new one. It is observed that a 54% reduction of the CO_2 annual emissions could be achieved by the substitution of heavy fuel and diesel oil with NG for the electricity production. Corresponding reduction for the remaining green house gases' emissions are also expected.

Furthermore, the EU's Emissions Trading System puts a cost on emitting CO_2. Therefore, the cost that is saved from the potential replacement of oil with NG for the system of Crete may be estimated at

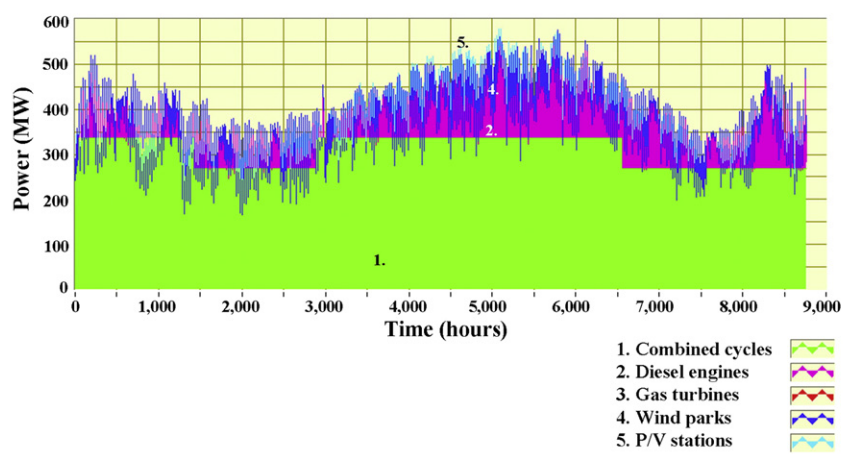

Fig. 6. Annual power production synthesis in Crete in 2013 based on the new thermal power system after the introduction of NG.

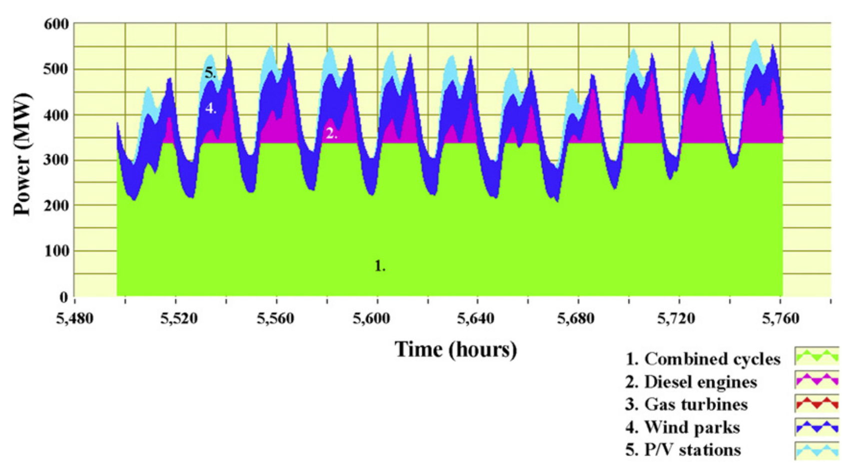

Fig. 7. Power production synthesis in Crete from 18-8-2013 to 28-8-2013 based on the NG new thermal power system.

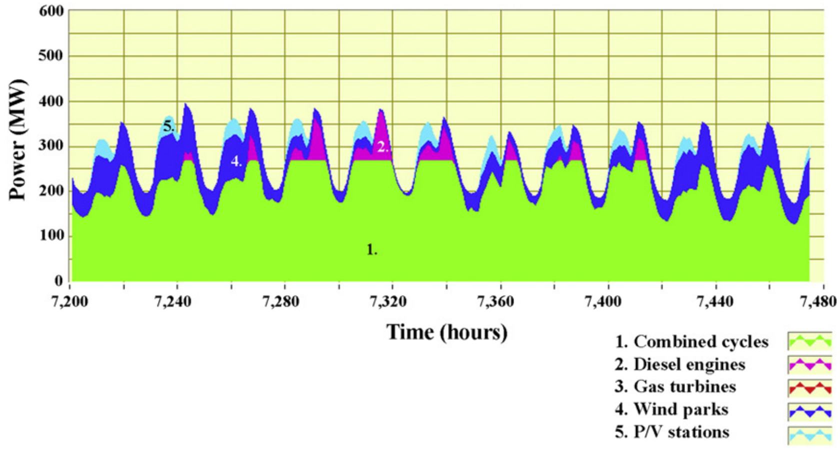

Fig. 8. Power production synthesis in Crete from 28-10-2013 to 7-11-2013 based on the NG new thermal power system.

Table 10
Simulation results summary for the NG new system operation for 2013 demand.

	Electricity production (MWh)	Efficiency (%)	Specific production cost (€/kWh)	NG consumption (Mm^3)	NG cost (M€)
Combined cycles	2,197,167	52.0	0.071	342.370	155.052
Diesel engines	127,997	45.7	0.080	22.687	10.274
Gas turbines	0	–	–	0	0
Wind parks	510,433	–	0.085	0	0
P/V stations	123,429	–	0.026	0	0
Thermal generators start-up	–	–	–	0.008	0.004
Total	**2,959,026**	[a]**51.7**	**0.081**	**365.065**	**165.330**

[a] This is the total annual mean efficiency of the thermal power system.

Table 11
Total electricity production cost in Crete in 2013 with the NG new power system.

Total NG annual cost (M€)	165.33
Total wind parks' annual energy cost (M€)	43.39
Total P/V stations' annual energy cost (M€)	32.09
Total production annual cost (M€)	[a]240.81
Total production annual specific cost (€/kWh)	[a]0.081

[a] Only the NG, the wind parks' and P/V stations' energy costs are included. All the other costs (maintenance, salaries etc.) are considered negligible.

4.527°10^6€ per year, as justified in Operational cost estimation section (assumed CO_2 emission rights' price 5€/tn) and presented in Table 13.

Energy security

Under the Greek Law, importers of crude oil or oil products destined for the domestic market, as well as large end-users (such as power plants), are required to hold oil stocks with a volume equal to 90 days oil consumption of their net imports in the previous year. As of December 2010, two main groups (Hellenic Petroleum and Motor Oil Hellas), one trader (Jet Oil) and one utility (P.P.C.) were obliged to hold oil stocks. Greece held 33.9 million barrels of oil stocks at the end of March 2011, equaling 109 days of 2010 net imports.

Similarly, during the Russia–Ukraine gas dispute in January 2009, Greece acquired three spot LNG cargoes in order to keep the natural gas demand in Greece under control.

According to the results of the above presented simulation, the NG requirements for power generation in Crete are of the order of 400 M Nm^3 in 2013. Applying the above rule analogously, a NG stock of around 100 M Nm^3 should be kept for energy security reasons.

Conclusively, as far as energy security is concerned, the introduction of NG in Crete does not negate the dependence of the Cretan community on imported energy sources. Hence, the energy supply in the island remains insecure and strongly affected by the global conditions on the energy sector.

Several other benefits

Regarding several other secondary potential benefits that can arise from the NG introduction in Crete, the following can be noted:

Table 12
Set-up cost analysis for the required works regarding the introduction of NG in the electricity production system in Crete.

No	Work's owner	Task description	Cost (M€)	Cost analysis		
				(M€)	(%) per company's cost	(%) over the total cost
1	P.P.C.	New thermal power plant construction in Korakia	630	600	95.24	52.63
2		Modification and transportation of the existing gas turbines in Heraklion		5	0.79	0.44
3		Modification of the existing gas turbines in Chania		13	2.06	1.14
4		Modification of the existing diesel engines in Lasithi		12	1.90	1.05
5	P.G.C.	New harbour construction in Korakia	510	15	2.94	1.32
6		Civil works in Korakia		470	92.16	41.23
7		L.N.G. tanks in Korakia				
8		L.N.G. gasification unit				
9		Pipelines installation		25	4.90	2.19
		Total cost	**1140**			

Table 13
Summary of the economic analysis results concerning the annual electricity production cost in Crete with the existing and the NG examined system.

	Existing system	NG system
Fossil fuels'/R.E.S. specific cost (€/kWh)	0.128	0.081
Thermal generators maintenance cost (€/kWh)	0.018	0.009
Gases emissions cost (€/kWh)	0.003	0.001
Total annual production specific cost (€/kWh)	**0.149**	**0.092**
Total annual electricity production (MWh)	2,954,526	2,959,026
Total annual electricity production cost (€·10^6)	440.815	271.343
Total annual CO_2 emissions (tn)	1,686,004	780,570
Total annual CO_2 emissions reduction (tn)	905,434	
Annual electricity production cost reduction (€·10^6)	169.473	
Cost including CO_2 annual emissions reduction (€·10^6)	4.527	

Table 14
Investment evaluation of the NG introduction in electricity sector in Crete, on behalf of P.P.C.

Investments accomplished by P.P.C. (€)	630,000,000
Annual money saving (€)	169,472,595
Payback period of the total set-up cost (years)	3.72
Discounted payback period of the total set-up cost (years)	4.40
Net present value (N.P.V.) of the total set-up cost (€)	1,161,816,917
Internal rate of return (I.R.R.) of the total set-up cost (%)	26.66

- The security and the stability of the electricity system are not affected, since the main electricity production will be based on thermal generators.
- Additional infrastructure works are not expected, beyond the ones at the new thermal power plant in Korakia (harbour, civil works) which, however, will be exclusively employed for the operation of the new plant.
- No upgrade is planned for the already existing electricity network (high and medium voltage lines).
- An important benefit is that the operation of the existing thermal power plant in Heraklion Prefecture, located only 10 km from the centre of the town of Heraklion will be terminated. On the other hand, the site in Korakia, a virgin area, with no human activities developed today, will be transformed in an industrial site.
- During the construction of the required works, a considerable number of employment positions will be created. Some of them can be covered with people living and working in the island of Crete.
- Few new permanent employment positions are expected to be created with the operation of the new system, mainly in favour of P.G.C. (operation of the new L.N.G. transportation premises and the gasification unit).

Conclusions

- Economic feasibility
  In a former study (Nikos et al., 1996) it is proved that the introduction of NG in Crete either exclusively for power production or for both power generation and domestic use, is not economically feasible. This fact has changed since 2011, when the prices of the imported fossil fuels have increased by almost 35%, due to a specific state tax. This oil price increase in Greece resulted in a considerable increase of the annual money savings from the substitution of oil with NG in Crete's

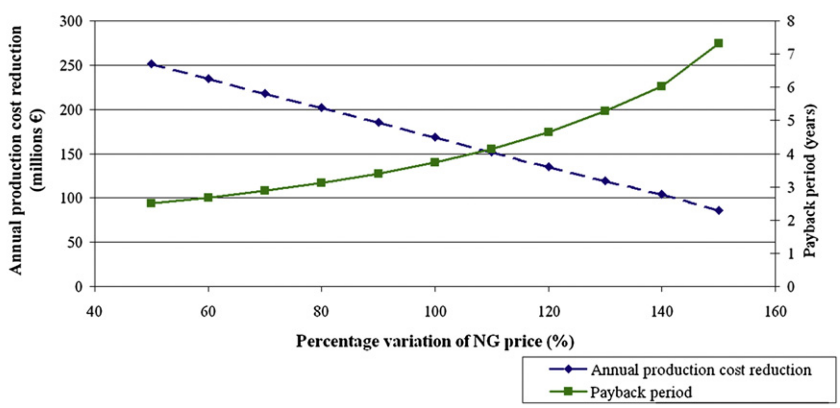

Fig. 9. Sensitivity analysis graph of the annual production cost reduction and the P.P.C. investment's set-up cost payback period versus the NG purchase price.

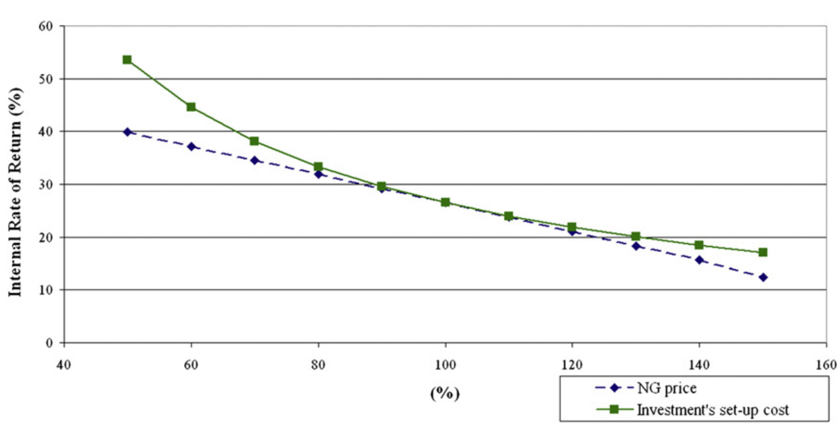

Fig. 10. Sensitivity analysis graph of the I.R.R. versus the NG purchase price and the set-up cost.

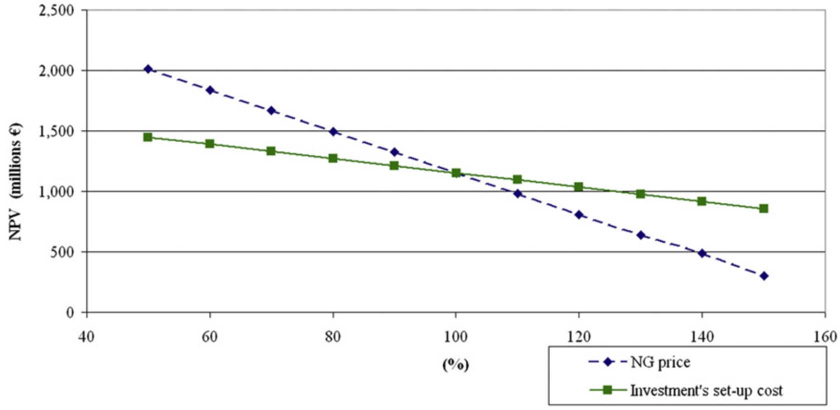

Fig. 11. Sensitivity analysis graph of the N.P.V. versus the NG purchase price and the P.P.C. set-up cost.

power production system. Consequently, despite the rather high set-up costs of the required works for the introduction of NG in Crete, the corresponding investments exhibit excellent economic indexes, mainly due to the high existing annual cost of the consumed oil.

- Environmental benefits
  The introduction of NG exclusively in Crete's power generation sector results in a significant reduction of the annual CO_2 emissions that reaches 54% compared to the ones from the existing thermal power plants in 2013. Corresponding reductions are also expected for the remaining GHG emissions. The CO_2 emissions' reduction results in annual money savings of approximately 4.5 million euros.
- Energy security
  Natural gas is a non-renewable energy source. Hence, the introduction of NG in Crete does not provide a permanent solution in the electricity supply of the island. The dependence of the Cretan community on imported energy sources remains. The only change is that the energy dependence of the Cretan community will have a different geographical origination, namely from the Middle East to North Africa. The energy supply in the island remains insecure and strongly affected by the global conditions on the energy sector.
- Other benefits
  Two additional benefits are expected for the island of Crete:

i. the abandonment of the Heraklion thermal power plant, and the development of a new industrial area in Korakia
ii. the creation of several employment positions, mainly during the construction of the works, rather than during the operation of the new system.

It seems that the only way for the non-interconnected insular communities to gain, at least partially, their energy independence, following a development plan aiming at sustainability, cost-effective and environmentally friendly energy production is the exploitation of their own energy sources, namely the exploitation of the Renewable Energy Sources (R.E.S.) that are plentiful in the majority of them. Characteristic integrations of power production plants based on R.E.S., introduced in insular non-interconnected systems can be found in former relevant articles.

Acknowledgment

The authors gratefully acknowledge:

- the Technical Chamber of Greece, Departments of Eastern and Western Crete, for funding of this research work.
- Dr. Gareth Owens and Dr. Fragoulis Krokos for their assistance.

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