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Metal hydride hydrogen compressors: Current developments & early markets

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ABSTRACT

Compression is one of the most critical issues related to almost all hydrogen storage methods and its subsequent usage. Hydrogen compression is only part of the so-called “Hydrogen Value Chain”, but it is crucial for overcoming the entry barriers for a “Hydrogen Economy”. It is widely accepted that there is a strong need for significant improvements in efficiency, durability and reliability of hydrogen compressors as well as for cost reductions, The basic scope of this work is to present the current developments on Metal Hydride Hydrogen Compressors (MH2C) and try to evaluate from both technical and economical point of view the potential integration of MH2C in real power systems comprising Renewable Energy Sources and Hydrogen technologies.

In this work, certain target markets for the MH2 compressor are identified, while all technical and financial issues of its integration in complete power systems have been assessed. Through a preliminary analysis of potential markets for the MH2 Compressor, it is shown that there are three major niche markets: (i) Chemical industry, by utilisation of waste industrial and/or available renewable heat; (ii) Hydrogen filling stations for vehicles and (iii) RES & H2 autonomous power systems for remote communities (e.g. off-grid islands).

A specific case study (the Greek island of Milos) is analysed in detail (using the HOMER software tool) with the aim of increasing RES penetration. A RES & hydrogen storage power supply system is proposed and examined from an economic, environmental and social perspective drawing the relevant conclusions.

1. Introduction

The intermittent nature of Renewable Energy Sources (RES), such as solar and wind, highlights the necessity for the integration of energy storage technologies both in public grid and in hybrid RES power systems. Energy storage can help deal with fluctuations in demand and generation by allowing excess electricity to be 'saved' for periods of higher electricity demand. From this point of view, energy storage technologies promote also higher RES penetration ensuring energy security. Hydrogen, an energy carrier that can deliver or store large amounts of energy, constitutes an attractive renewable energy storage means if it is produced in an environmentally friendly manner. In that respect, hydrogen production through an excess RES driven electrolyser, produced hydrogen compression and storage and hydrogen re-electrification through fuel cells compose a complete energy storage system with a potential for use in a broad range of applications across virtually all sectors - transportation, commercial, industrial, residential, and portable.

Compression is one of the most critical issues that associate with almost all storage methods for hydrogen and its subsequent usage. Hydrogen compression is only part of the so-called “Hydrogen Value Chain”, but it is crucial for overcoming the entry barriers for a “Hydrogen Economy”. It is widely accepted that there is a strong need for significant improvements in efficiency, durability and reliability of hydrogen compressors as well as for cost reductions, especially if the end-use is to be in vehicles or fuelling stations and

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is accompanied by request for high hydrogen purity in transportation and other industrial applications [1–4].

Efficient hydrogen compression is indeed a key component for a wide range of applications including different aspects (onsite storage, transport, dispensing) in the supply chain of hydrogen. Moreover, the development of lightweight high-pressure hydrogen storage vessels has led the working pressure to be much higher than it used to be. Hydrogen compressors currently used at fuelling stations are generally either diaphragm or reciprocating compressors. Poor reliability continues to plague forecourt hydrogen compressors because current standards for their design assume prolonged operation at peak pressure. This operating regime is not representative of the operating conditions to which forecourt hydrogen compressors are exposed. The operating and maintenance cost of in-service compressors is exacerbated by the on/off cycling of the compressors resulting from a lack of station demand. The capital cost of the commercial hardware remains high due to low production volumes. Identified activities to decrease the cost of hydrogen compression at the forecourt include research and development (R&D) to develop design standards and tests that accurately reflect operating conditions, development of high-temperature polymer and composites that are compatible with hydrogen, identification of high-strength metallic materials that are resistant to hydrogen embrittlement, improved compressor efficiency, and collection of compressor durability and reliability data to better understand the current mean time between failures and failure modes.

As a result, a need for efficient, safe, and low cost hydrogen compressors has begun to emerge. Hydrogen compression based on the reversible hydrogenation/dehydrogenation ability of metal hydrides (MH) has been proposed and investigated as a reliable process to compress hydrogen to high pressure without contamination and with relatively low energy costs. The method utilizes a reversible heat-driven interaction of a hydride-forming metal or alloy or intermetallic compound with hydrogen to form MH and offers an attractive alternative to conventional (mechanical) and other newly developed (electrochemical, ionic liquid pistons) concepts for hydrogen compression [5–7]. The advantages of MH compression include simplicity in design and operation, absence of moving parts, compactness, safety and reliability, and the possibility to utilize waste industrial heat and/or excess renewable energy (e.g. solar thermal) for the required heating of the MH tanks. This latter possibility (exploitation of waste industrial and/or excess renewable heat) constitutes a major argument in favour of MH based compression as it may lead to very significant operational cost reductions.

In summary, non-mechanical hydrogen compressors have several advantages over their mechanical counterparts, including smaller size, lower noise, lower operating and maintenance costs [8,9]. MH compressors are thermally powered systems that use the ability of reversible metal hydrides to compress hydrogen without any contamination [10]. They also provide the ability to connect them to the outlet of electrolysers [11]. Moreover, using available heat wastes or excess renewable energy to feed the chemical compressor enhances significantly the overall efficiency of system [12].

In general, a Metal Hydride Hydrogen compressor (MH2C) is a compressor that works by absorbing hydrogen at low pressure (<10 bar) and temperature (≤30 °C) and desorbing it at a higher pressure by raising the temperature (≥60 °C) with an external heat source like a heated water bath. Metal hydrides are special alloys like AB5-type (example, (La-Ce)(Ni-Al)5) or AB2-type (for example, (Ti-Zr)(Mn-Cr-Fe-Co-V)2) which can chemically store hydrogen in their metallic lattice [13].

This operating principle called thermal hydrogen compression system – based on the equilibrium pressure as a function of temperature and hydrogen content of the hydride – can offer an innovative economic alternative to traditional mechanical hydrogen compressors apart from the technical application for hydrogen storage in solid material. Fig. 1 depicts the basic principle.

In order to design and develop a MH2C, it is important to gather sufficient information about the selected metal hydride materials. It is necessary to obtain the enthalpy_ΔH and entropy_ΔS in order to predict the level of the plateau pressure P. This pressure is related to the temperature T by van't Hoff's law which states

$$\ln(P) = \Delta H/RT - \Delta S/R \tag{1}$$

where R is the ideal gas constant.

According to equation (1), the pressure increases exponentially with increasing temperature, and large pressure values can be obtained by moderate temperature changes. The metal hydride based hydrogen compressor can be tailored to cover a wide range of operating pressures and pressure ratios by selecting suitable alloys. To have a high outlet pressure, more hydride units can be serially connected, each unit with a different alloy and successively higher operating pressure. The most important properties of an alloy suitable for hydrogen compression are good hydrogen absorption - desorption rate, smaller process enthalpy, fast reaction kinetics, great structural stability during the cycles. For compression, metal hydrides with large pressure to temperature gradients are desired, especially in the range of low temperatures.

2. Background

HYSTORE Technologies Ltd. (with the assistance of other research partners) has already manufactured a small scale demonstrator, which was developed as a deliverable of a successfully completed under FP7 European research project (ATLAS-H2, PIAP-GA-2009-251562, FP7 Marie Curie/IAPP). The lab scale demonstrator, per se, is composed of 6 stages each utilizing a specific specialized metal hydride. It is capable of raising hydrogen gas pressure from <5 bar to more than 200 bar, utilizing water as heat exchange fluid and achieving a stable hydrogen flow of about 3 Nm^3/h. At each stage, specialized bleed valves can provide hydrogen at intermediate pressures, if required. Fig. 2 depicts a schematic illustration and real-life image of this lab demonstrator.

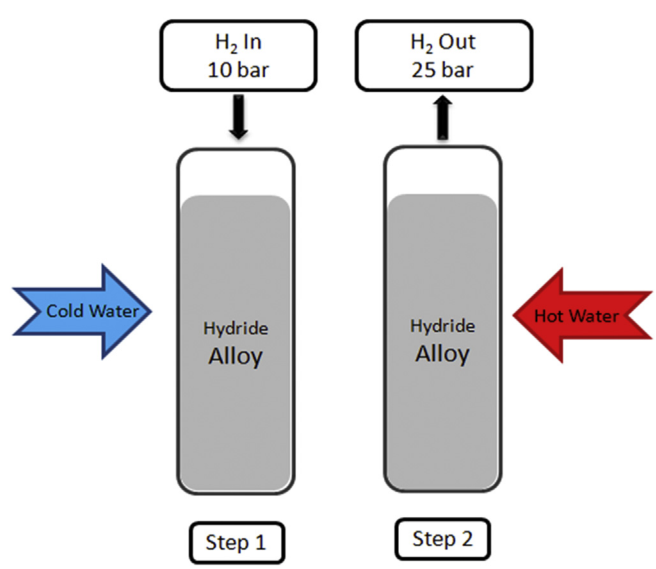

Fig. 1. Metal hydrides based compression principle.

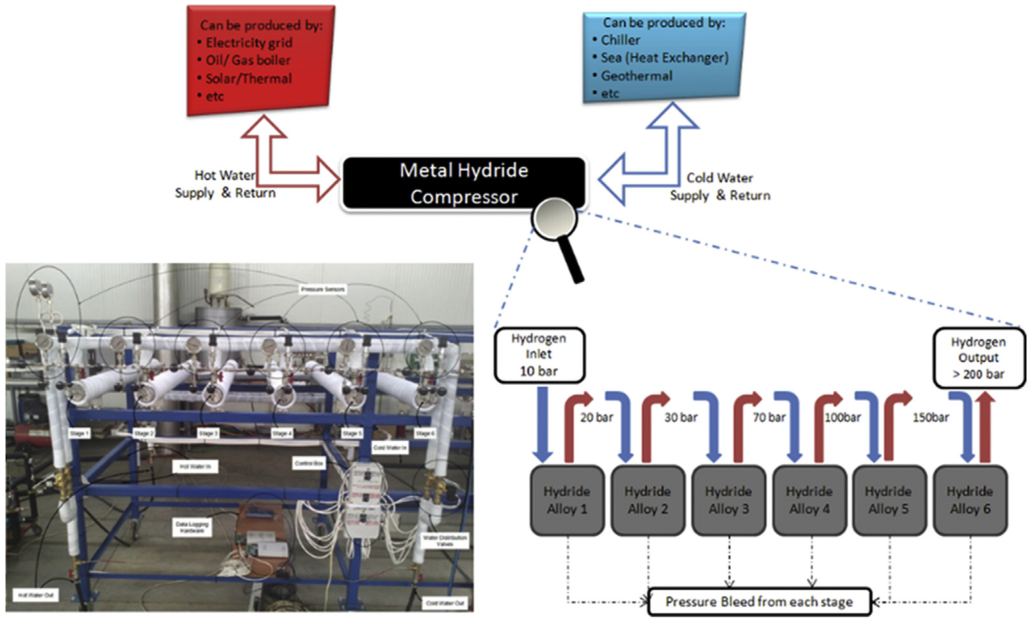

Fig. 2. MH2C demonstrator at HYSTORE premises.

Different possible sources of hot and cold water are listed in the upper part of the figure, such as solar heating, geothermal energy and other waste heat sources.

The potential to exploit such heat sources constitutes a significant competitive advantage over traditional mechanical hydrogen compressors. Preliminary modelling and simulation of a simple MH compressor has also taken place within the above FP7 project using commercial simulators [14].

Summary of the current operating conditions of the lab demonstrator [15]:

- Input Pressure: >2 bar
- Output Pressure: >220 bar
- Cold Water Inlet Temperature: 10–20 °C
- Hot Water Inlet Temperature: 70–80 °C
- Compression rate: >2.5 Nm^3H2/h

The metal hydride based hydrogen compressor developed under ATLAS-H2 is a first lab version of such a device with an output pressure >200 bar. The aim of the final version, which is under construction, is to go to pressures in the order of 350 bar. Large scale refuelling (e.g. for hydrogen passenger cars, bus and truck fleets, rail transport as well as maritime applications) is expected in the coming years to require hydrogen refuelling stations at pressure levels of 350 bar or 700 bar [16]. An up-scaled version of the metal hydride based hydrogen compressor with an output pressure of the order of 350 bar is currently under construction within the framework of the new ATLAS-MHC project (PIAP-GA-2013-612292).

The proposed compressor technology is benchmarked here against the mechanical compressor technology commercially available today in order to prove its merits (among others, higher reliability, with the potential of lower maintenance cost and less down time of compressor systems). This work also pays attention to the demonstration of MH2C potential applications and proposes paths for its market deployment and penetration. In general, the MH compressors can serve a number of markets such as traditional industry, renewable energy, emergency power, hydrogen fuel infrastructure as explained further below.

3. Identification of target markets

Table 1 bellow provides a comparison summary of Metal Hydride and Mechanical Hydrogen Compressors in order to identify the early markets of MH2C. The assumptions used in the economic comparison of thermal and mechanical compressors are the following:

- Operating Conditions: 56.63 Nm^3/h, Inlet P = 6.89 bar, Outlet P = 248.2 psia
- Capital costs: Mechanical compressor quotation; Thermal compressor detailed cost estimate.
- Operating Costs: Power @ € 0.10/kWh, Waste heat @ €0.00
- Maintenance Costs: Mechanical compressor annual rebuild; Thermal compressor valve replacement every other year
- It should be noted that Metal Hydride Compressors have an advantage over mechanical compressor when waste heat, especially from renewables (solar thermal, biogas etc.) is available on site.

From Table 1, it is evident that thermal MH2 Compressors offer significant advantages over mechanical compression for large scale hydrogen production from renewable resources:

- They present significantly lower weight and volume compared to mechanical compressors
- They have slightly lower capital cost
- They have significantly lower operation and maintenance costs
- They consume significantly lower energy to operate
- Waste heat from industry or renewable energy sources can be used in metal hydride compressors.

MH2 Compressors can serve a number of markets such as traditional industry, renewable energy, emergency power and hydrogen fuel infrastructure. While some of these emerging markets are still small, hydrogen can be readily used in a number of industrial processes already today [17]. As a first step, the authors have identified the following key business cases where MH2C can be directly introduced (early markets):

Table 1
Comparison of metal hydride hydrogen compressors and mechanical hydrogen compressors.

	MH2 Compressor	Mechanical Compressor
Hydrogen Flow	56.63 Nm^3/h	56.63 Nm3/h
Inlet Pressure	6.89 bar	6.89 bar
Outlet Pressure	248.2 psia	248.2 psia
Number of Stages	5	3
Weight	1000 kg	3600 kg
Volume	400 L	6000 L
Hot Water Flow (waste heat)	50 gpm @ 90 C	–
Heat Energy Required	240 kBTU/h	–
Cooling Water Flow	50 gpm @ 30 °C	20 gpm @ 30 °C
Electrical Power	500 W	20,000 W
Estimated Capital Cost	€ 130,000	€ 145,000
Annual Power Cost (2000 h/y, €0.10/kWh)	€100	€ 4000
Annual Maintenance Cost	€1000	€ 8000

i. Chemical industry, by utilisation of waste industrial heat; many industrial chemical processes generate large amounts of waste heat that can be fed back to a MH compressor. Thus, we observe a good match between traditional industry and thermally driven MH hydrogen compressors. Analysis of energy conversion performance using MH hydrogen compression in comparison with conventional organic Rankine cycle shows that MH compression is more promising, due to lower operation cost, higher exergy efficiency and thermal COP, higher output power and acceptable capital cost [18]. The advantages are especially pronounced in case of utilizing waste industrial heat.
ii. Hydrogen Refuelling Stations (HRS); Hydrogen refuelling infrastructure takes a significant part of the capital investments for the introduction of fuel cell powered vehicles and must be taken into account in the assessment of their economic viability. Indeed, such stations present high costs ranging between $500,000 and $5,000,000 per installation [19]. The most expensive H2 refuelling components originate from: (i) on-site hydrogen production and (ii) hydrogen compression (with a contribution of about 20% to the total cost of an HRS [20]). Cost performance optimisation of the H2 refuelling infrastructure can be achieved by the improvement of hydrogen compression technology (e.g. application of thermally-driven metal hydride hydrogen compressors) [21].
iii. RES storage in compressed hydrogen; hybrid RES/hydrogen storage in off-grid island applications for dynamic storage needs (business case study in the current work). It appears to be very promising to use MH2 compressors for large-scale hydrogen production from renewable energy sources for dynamic storage needs, including autonomous systems for isolated/remote communities like off-grid islands. Energy storage concepts enabling the maximum recovery of curtailed renewable electricity in a cost-effective way are needed. For example, MH2 Compressors combined with electrolysers can use curtailed electricity and efficiently store it in the form of hydrogen generating additional profit to the electricity suppliers as well as to potential hydrogen off takers. Moreover, one of the most important barriers for a successful introduction of hydrogen technologies in stationary power systems in general is their high cost. According to the European Roadmap for Hydrogen and Fuel Cells, as presented by the High Level Group of the European Commission one of the first real market applications will be small stationary power systems (<50 kW) based on low-temperature fuel cells. On the other hand, autonomous power systems already have a high energy cost, therefore it is predicted that this type of power system will be one of the first niche markets for hydrogen technologies and fuel cells [22]. Therefore, the identification of RES & H2 autonomous power systems as a first market target group is in agreement with the European H2 & FCs Roadmap.

A brief search has not yielded any results in terms of hydrogen compressor market size concerning sales volume for both units and capitalization. Similarly, we have not found any industry study to indicate trends or growth rates regarding H2 compressors. However, many publications indicate that “Hydrogen Economy” is expected to be developed in the next years; Mckincey's 2010 report ‘A portfolio of power-trains for Europe: a fact-based analysis’ [23], US′ National Renewable Energy Laboratory 2013 workshop about Hydrogen Infrastructure Market Readiness [24] and Toyota's announcement for a mass production hydrogen-fuelled car [25], are some among many. Consequently, it is safe to say that hydrogen compressors can be considered as a growing market that is expected to pick-up pace in the near future when their most promising application, the hydrogen refuelling infrastructure, will be expanded.

4. Techno-economical analysis of the integration of the metal hydride hydrogen compressor in real power systems

As described in the previous section, one of the most significant target market groups for MH2 Compressors is their integration in autonomous power systems driven by renewable energy sources and hydrogen technologies, especially in islands.

The main outcome of the techno-economic analysis is to identify barriers and potential benefits for the implementation of hydrogen-based autonomous power systems, giving emphasis on the metal hydride hydrogen compressor in the short to medium term. The analysis performed in this section is based on real technology and market parameters acquired during the operation of a selected autonomous power system rather than on theoretical assumptions.

An already existing autonomous power system, namely the power system of Milos Island in the Aegean Sea, currently based mainly on fossil fuels and a small percentage of renewable energy has been selected in order to assess the techno-economic impact of hydrogen technologies in a real case study. The system is redesigned and optimised as a hydrogen-based autonomous power system in order to meet the existing users' power demand at a minimum cost of energy. Load-profile data from the operation of the case study and cost data for different technology solutions are clearly necessary to successfully perform the techno-economic analysis. The methodology followed during this work is presented below.

4.1. Methodology and tools

The simulation and optimisation of the case study has been performed by employing the HOMER software tool, developed by the National Renewable Energy Laboratory, USA [26]. HOMER software incorporates a variety of energy component models including photovoltaics, generators running on diesel and other fuels, wind turbines, hydro, batteries, inverters and rectifiers, water electrolysers and reformers for hydrogen production, hydrogen storage tanks, fuel cells, etc.

To perform simulation and optimisation of the power system of Milos Island, using the HOMER tool, information and data on natural resources (such as wind and solar irradiance data), electric and thermal loads, economic constraints, current and future equipment costs, user behaviour and control strategies are required. The main purpose of the techno-economic analysis presented in this section was to investigate the impact of diesel generators and batteries replacement with hydrogen technologies, including electrolysers, metal hydride hydrogen compressors, and fuel cells both in technical and financial terms.

The first step in the analysis followed for the case study was to collect key data from the operation of each power system and simulate the existing autonomous power system based on conventional energy technologies. The purpose of these simulations was to record the operational characteristics and potential problems for each system and calculate the cost of energy produced by existing conventional autonomous power systems.

The second step was the optimisation of component sizes of the envisaged hydrogen-based autonomous power system, in which hydrogen energy technologies have replaced conventional components (mainly diesel generators and batteries). The optimisation performed considered mainly two aspects: i) the capability of the proposed hydrogen-based power system to meet existing user loads and ii) an effort to minimise the cost of energy produced by the envisaged hydrogen-based system.

The final step of the procedure taken over in the context of this section was to perform a techno-economic analysis of the optimum configuration for the proposed hydrogen-based autonomous power system in comparison to the existing conventional autonomous system, also taking into account future cost scenarios and cost targets for hydrogen energy technologies, including metal hydride hydrogen compressors. The analysis presented in this chapter aims to provide energy systems designers, power system installers and users with a useful tool in the planning of hydrogen-based autonomous power systems implementation. In the following section a detailed description of the case study of Milos Island power system is given.

4.2. Case study analysis

The hydrogen energy storage was examined as an energy storage option for the power system of the island of Milos in Greece. The storage system under examination includes a water electrolysis unit, a hydrogen compressor based on Metal Hydrides, a compressed hydrogen storage tank and a fuel cell. Electrolytic hydrogen is produced when excess energy generated by renewable electricity-generating technologies is available. Hydrogen is then compressed through the Metal Hydride Compressor, stored in gaseous form and can be used as a feedstock for the fuel cell in order to produce electricity when is needed.

For the island of Milos, HOMER was used to simulate and optimize the proposed RES & hydrogen-based power system. The optimal configuration is compared to the existing power system of the island in terms of cost of power generation, Renewable Energy (RE) penetration and locally produced emissions. The analysis presented in the following sections considers the financial and environmental parameters of the RES & hydrogen-based power system and their effects on the energy cost. Further, a sensitivity analysis is performed.

4.3. Design of the hybrid system

The annual electricity demand of Milos Island is approximately 39,730 MWh with peak demand equal to 8.5 MW. In order to meet this demand, the existing power system includes 8 thermal generator sets with a total capacity of around 11.25 MW and a small wind park comprising 3 wind turbines with a total installed capacity of 2.05 MW. The simulations indicate that the existing power system delivers electricity at a cost equal to 113 €/MWh. According to the simulation results, the components of the proposed optimal RES & hydrogen-based power system when hydrogen is introduced as energy storage medium in the power system are shown in Table 2.

The cost of energy of the new proposed power system equals 112 €/MWh. This is the break-even point, meaning that this is the required subsidy rate in case of subsidies. The same goal could also be achieved via tax breaks; for example, the Greek Investment Law 4399/2016 foresees grants up to 40% or tax exemptions for hybrid power systems up to 5 MW in non-interconnected islands like Milos [27].

The cost of energy for the existing and the proposed power system have been derived assuming a 30% subsidy for renewable electricity-generating technologies, a 50% subsidy for hydrogen technologies and a cost of CO2 emission equal to 21 €/t. In the simulations, it was also assumed that waste heat from solar thermal installations can be used to heat the metal hydride compressor.

4.4. Costs

The costs of a project can be divided into the investment and the operational costs. The former include the initial and replacement costs and are presented in this section. Initial costs referred to as the first cost that usually includes cost elements that do not recur after an activity is initiated plus their installation cost. Generally, the initial cost is the major component of a renewable energy project and is usually higher than in non-renewable energy projects. The replacement costs involve the cost of equipment and installations procured during the operating phase of a project to maintain its original productive capacity. The investment costs of the proposed RES & Hydrogen-based power system for Milos are illustrated in Table 3. It should be noted that since HOMER does not contain specific models for hydrogen compressors, all technical and financial parameters of the Metal Hydride Hydrogen Compressor, have been incorporated and presented under the model of the

Table 2
The proposed RES & hydrogen-based power system for Milos Island.

Component	Type	Number	Size
Wind Turbine	V-52	28	850 kW (each)
	V-44	2	600 kW (each)
Thermal Generator	Sulger	2	1750 kW (each)
	MAN	2	700 kW (each)
	Rental	1	1032 kW
Fuel Cell	PEM	1	1 MW
Electrolyser	Alkaline	1	2 MW
Hydrogen Compressor	Metal Hydride	1	Up to 400 Nm3/h
Hydrogen storage tank	Compressed gas	1	4000 kg

Table 3
The investment costs of the proposed RES & hydrogen-based power system for Milos Island.

Technology	Type	Unit Cost [28]	Initial Cost	Replacement Cost
Wind Turbine	V-52	1200 €/kW	19,992,000 €	0 €
	V-44	1200 €/kW	1,008,000 €	0 €
Thermal Generator	Sulger	251 €/kW	880,000 €	88,000 €
	MAN	286 €/kW	400,000 €	40,000 €
	Rental	145 €/kW	150,000 €	0 €
Fuel Cell	PEM	3000 €/kW	1,500,000 €	450,000 €
Electrolyser + Hydrogen Compressor	Alkaline + Metal Hydride	2000 €/kW	2,000,000 €	0 €
Hydrogen storage tank	Compressed gas	800 €/kg	1,600,000 €	0 €
Total			27,530,000 €	

Electrolyser.

The initial costs shown in Table 3 are calculated by multiplying the unit cost of each technology with the number of necessary units shown in Table 2. The initial costs of the wind turbines and the hydrogen technologies are reduced, as a subsidy of 30% and 50% respectively has been included in the simulation. According to the simulation results, during the 20-year lifetime of the project 3 diesel generators and the fuel cell are replaced. The first diesel generator replacement takes place at the 12th year and is one of the Sulger generators. The MAN generators are both replaced, one during the 13th year and the other during the 19th year. The fuel cell is replaced twice during the project's lifetime during the 7th and the 14th year. Unlike investments costs, operational costs of RE projects are usually low. Operational costs include fixed and variable costs that recur continually over the lifetime of a project, including maintenance cost. The former remain relatively constant and are independent of the activities of the project while the latter vary with the level of operational activity. The operational costs for the proposed power system are given in Table 4.

As it can be seen in Table 4, a major contribution to the operational costs of the entire system is the cost of the fuels (57%) indicating the advantage of renewable electricity-generating technologies that use fuel of zero cost, such as wind or solar (with exception in the case of biomass). The investment and operational costs of all the necessary components of the proposed RES & Hydrogen-based power system were derived from previous studies [29,30], and from personal communications with equipment manufacturers.

4.5. Revenues

The revenues are derived from the sale of the electricity produced by the proposed power system. The proposed RES & Hydrogen power system is a hybrid system that contains both renewable energy technologies and conventional technologies. The price at which electricity is sold is different for different electricity-generating technologies. More specifically, for the proposed power system three different prices are considered. The first is the price of electricity that is generated from the wind turbines and is directly fed into the grid. The second is the electricity price for the energy produced by the diesel generators and the third is the price of the electricity that is fed into the grid from the storage system.

For the electricity of renewable and conventional energy sources the price is straightforward. According to the Greek Regulatory Authority of Energy (RAE), the price of wind-based electricity for non-interconnected islands is approximately 0.092 €/kWh. The price of electricity from conventional sources was considered around 0.1 €/kWh. The price of the electricity supplied from the storage system is more complicated. Usually, the pricing of electricity from the storage system of a hybrid system is case-specific and is done for each case distinctively. In this analysis, a price of 0.15 €/kWh was assumed based on the electricity prices of other hybrid systems in other islands. Generally, the price of electricity escalates every year and thus in the 20-year lifetime of the project a 3% annual increase is considered. In Greece, the municipality where a wind park is installed receives 3% of the revenues of the investor. This percentage is also included in the analysis. In Fig. 3, the annual electricity consumption and revenues for the 1st year are presented.

The total amount of electricity consumption is 791 GWh and the revenues over the lifetime of the project is 102.3 million €. It is worthwhile to mention that the wind turbines produce a considerably greater amount of energy than the amount that is absorbed by the grid. More specifically, the wind turbines produce annually 69,124,688 kWh out of which 7,352,470 kWh are fed into the electrolyser, 24,894,794 kWh go directly into the grid and 36,877,424 kWh are the surplus electricity that the system cannot use. So, the investor benefits only from 56% of the total annual amount of energy that the wind turbines produce (32,247,264 kWh). The effect of the excess electricity on the

Table 4
The operational costs of the proposed RES & hydrogen-based power system for Milos Island.

Parameter	Type	Unit Cost	Operational Cost
Wind Turbine	V-52	17,340 €/year	485,520 €/year
	V-44	12,240 €/year	24,480 €/year
Thermal Generator	Sulger	6.5 €/hour	44,948 €/year
	MAN	5.5 €/hour	36,636 €/year
	Rental	5.5 €/hour	5478 €/year
Fuel Cell	PEM	1.02 €/hour	4418 €/year
Electrolyser + Hydrogen Compressor	Alkaline + Metal Hydride	50,000 €/year	50,000 €/year
Hydrogen storage tank	Compressed gas	4000 €/year	4000 €/year
Fuel	Diesel	0.68 €/L	105,336 €/year
	Heavy oil	0.34 €/L	1,038,654 €/year
Emissions	CO_2	21 €/t	206,677 €/year
Total			2,006,147 €/year

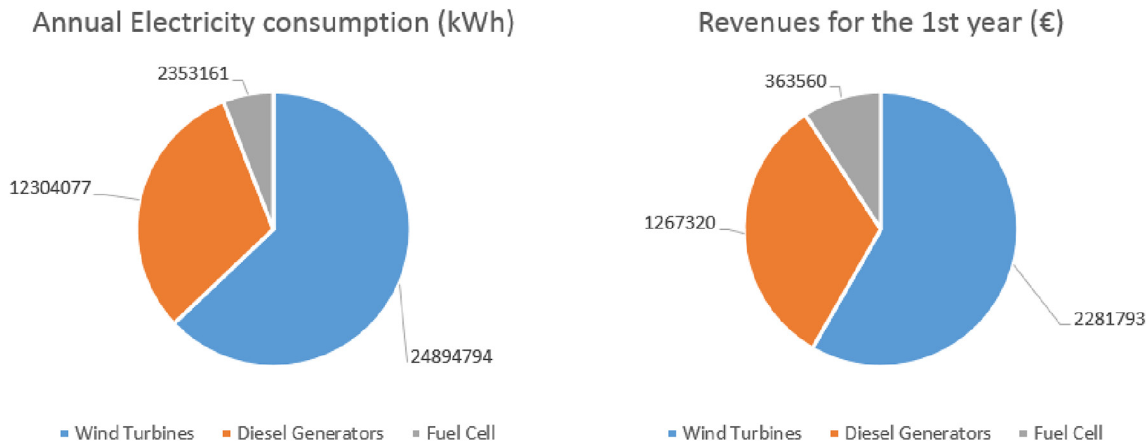

Fig. 3. Annual electricity consumption and revenues for the 1st year of the RES & Hydrogen-based power system.

economic attractiveness of the project is shown in the nextt section.

4.6. Financial analysis

The financial analysis is primarily focused on money aspects of a project, rewards and profitability to the potential investors. In order to evaluate the financial attractiveness of a project there is a number of appraisal techniques that can be used. The most commonly used techniques to evaluate investments are the Net Present Value (NPV) and the Internal Rate of Return (IRR). Both techniques emphasize the central importance of the concept of the time value of money and are regarded as more complete than other techniques, such as the payback period and the accounting rate of return.

In order to calculate the NPV it is necessary to use a discounted cash flow. The latter includes the annual inflows and outflows over the 20-year time horizon, which was considered the lifetime of the investment. The outflows referred to the initial capital cost, the O&M costs and the replacement costs. Thus, NPV can ve easily calculated according to the following equation:

$$\mathrm{NPV} = -C_0 \sum_{i=1}^{T} \frac{C_i}{(1+r)^i} \tag{2}$$

where, $-C_0$ = Initial Investment

C = Cash Flow
r = Discount Rate
T = Time

Table 5 shows the discounted cash flow for the RES & Hydrogen-based power system.

For the calculations of the NPV, a discount rate of 6% has been used. As Table 4 shows the project has a positive NPV. According to the NPV decision rules, a positive NPV demonstrates the financial viability of the project. However, the results of the NPV method, and in general of all the project appraisal methods, can be quite relative because, although the NPV in this case is positive, the value taking into account the initial investment is not sufficiently high. More specifically, on a €27,5 m investment the surplus generated beyond the opportunity cost of the investor is approximately €4 m. Thus, by implementing the proposed system, the investor would increase his wealth by this amount. So, a general conclusion that can be drawn is that the project's profitability is marginal.

From the results of the NPV method the effect of the excess electricity on the project's financial viability can be seen. The excess electricity is responsible for a 44% reduction in the revenues of the investor. So, although the investor purchases equipment for the production of 83,781,928 kWh/yr, only 46,904,136kWh/yr are sold. If the excess electricity was significantly smaller the NPV of the project would have been considerably greater making the investment more economically attractive. An option to increase the profitability of the investment is to use the excess energy for the production of hydrogen in order to be used locally as a fuel in the transport sector. This would be an additional application, where Metal Hydride Hydrogen Compressors could be used, creating an extra market opportunity for the newly developed product (MH2C). Another option is the use of this energy for heating purposes. In both cases the investor would have an additional source of revenues making the investment more profitable.

The financial viability of the proposed system was also examined by the IRR technique. The IRR describes by how much the cash inflows exceed the cash outflows on an annualized percentage basis, taking into account the timing of those cash flows. IRR is the rate of return, r, that equates the discounted future cash outflows with initial inflow:

Table 5
NPV of RES & Hydrogen-based power system for Milos Island.

Year	Cash flows	Discount factor	Present values
0	−27,530,000 €	1	- 27,530,000 €
1	−2,006,147 € + 3,798,715 €	0.943	+1,690,391 €
2	−2,006,147 € + 3,912,676 €	0.890	+1,696,811 €
3	−2,006,147 € + 4,030,057 €	0.840	+1,700,084 €
4	−2,006,147 € + 4,150,958 €	0.792	+1,698,690 €
5	−2,006,147 € + 4,275,487 €	0.747	+1,695,197 €
6	−2,006,147 € + 4,403,752 €	0.705	+1,690,311 €
7	−2,456,147 € + 4,535,864 €	0.665	+1,383,012 €
8	−2,006,147 € + 4,671,940 €	0.627	+1,671,452 €
9	−2,006,147 € + 4,812,098 €	0.592	+1,661,123 €
10	−2,006,147 € + 4,956,461 €	0.558	+1,646,275 €
11	−2,006,147 € + 5,105,155 €	0.527	+1,633,177 €
12	−2,094,147 € + 5,258,310 €	0.497	+1,572,589 €
13	−2,046,147 € + 5,416,059 €	0.469	+1,580,489 €
14	- 2,456,147 € + 5,578,541 €	0.442	+1,380,098 €
15	- 2,006,147 € + 5,745,897 €	0.417	+1,559,476 €
16	- 2,006,147 € + 5,918,274 €	0.394	+1,541,378 €
17	- 2,006,147 € + 6,095,822 €	0.371	+1,517,269 €
18	- 2,006,147 € + 6,278,697 €	0.350	+1,495,392 €
19	- 2,046,147 € + 6,467,058 €	0.331	+1,463,321 €
20	- 2,006,147 € + 6,661,069 €	0.312	+1,452,336 €
NPV			+4,198,873 €

$$\sum_{n=1}^{n}\frac{F_n}{(1+r)^n}+F_0=0 \tag{3}$$

where F_0 = cash flow at time zero (t_0),

F_n = cash flow at year n (t_n),
r = IRR, and
n = number of years

The IRR for the proposed RES & Hydrogen-based power system is 1%. According to the IRR decision rules, when the opportunity cost of capital is greater than the IRR on a project then the investor is better not to implement the project. Thus, under the IRR method the investment is found not to be financially viable.

The results of the financial analysis have produced conflicting decision outcomes, which depend on the project appraisal method employed. Based on the NPV method the investment should be accepted, while based on the IRR method the investment should be rejected. A reasonable question that may arise at this point is which method should be preferred. To answer that question it should be firstly pointed out that the results of both methods are not absolutely contradicting each other. According to both methods, the investment is not quite profitable. This is evident directly based on the 1% IRR, which characterizes the investment financially non-viable, and indirectly based on a positive yet small NPV that indicates that the investor would not lose any money but also would not increase greatly his capital. So, the general conclusion that the investment would not return most to the investor can be drawn from both methods. However, the NPV has the advantage of showing that although the profitability of the project is not satisfactory the investor would not actually lose any money. NPV is the better decision-making technique because it measures on absolute amounts of money. It gives the increase in investor's wealth by accepting a project. In contrast, IRR expresses its return as a percentage which may result in an inferior low-scale project being preferred to a higher-scale project.

Based on the cash flow analysis the payback period can be derived. The simple payback period is around 11.5 years. As the analysis includes discounted cash flows, an improvement on the simple payback method that excludes discounted cash flows can be calculated taking into account the time value of money. The discounted payback period based on the present values of Table 4 for the RES & Hydrogen-based power system is approximately 17 years. However, the authors believe that this figure will be significantly improved in the near future as the cost of renewable energy sources (especially of the wind turbines) is expected to fall and the oil price to be increased and directly influence the final decision in favour of the investment.

4.7. Economic analysis including environmental and social impacts

In the preceding section the project has been financially evaluated from the perspective of the investor. However, the implementation of the project has also effects on the national economy and the environment. In this section an economic evaluation is carried out taking into account the environmental and social attributes of the project. The section begins with a qualitative description of the environmental and social impacts of the project followed by an attempt to quantify these impacts in order to assess the net economic impact on the environment and the society.

In the case study of Milos, part of the conventional energy technologies has been replaced with wind energy and hydrogen technologies. Wind energy is one of the most benign sources of energy. It has the major advantage of producing electricity without the emission of several greenhouse gases including carbon and sulphur dioxides. The prevention of harmful emissions assists in the amelioration of air quality that is damaged by the continuous use of fossil fuels.

Thus, from a social perspective, the use of wind energy and hydrogen technologies for the production of electricity provides a number of considerable benefits. The exploitation of wind energy for power purposes may assist in reducing imported fuel dependency and securing supply. These issues are of particular importance especially in the case of remote regions and islands that face problems with the supply of fuels due to a number of reasons, such as bad weather conditions. Since renewable energy sources are more evenly distributed among the world than conventional energy sources, their deployment secures the supply of electricity as a consumer good to isolated regions. Wind power, though, is an intermittent source of energy and its power output exhibits daily and seasonal fluctuations. The significant penetration of intermittent renewable energy sources may create problems in matching supply with demand and technical issues associated with weak grids. The introduction of hydrogen storage is one of the options that may ameliorate the incorporation of intermittent sources into power generation systems. Hydrogen storage has the benefits of providing a buffer between the grid and the unstable grid power, load levelling conventional power sources like diesel engine power and enabling the use of intermittent energy sources to supply power-on-demand.

The introduction of wind energy and hydrogen storage into the power system also entails employment benefits. During the manufacturing and installation of the technologies and the operation and maintenance phase of the project a number of temporary and permanent jobs may be created. The employment in manufacturing of wind turbines is generally concentrated in a few countries for instance in Europe Germany, Denmark and Spain account for more than 90%. Thus, in the case of Milos Island the effect on employment during installation, operation and maintenance was considered. The same approach was followed for hydrogen technologies. Apart from the direct work opportunities, indirect jobs may also be created as a result of the implementation of the RES & Hydrogen project. This effect is often described as the spin-off effect.

In terms of human safety hazards, wind energy industry involves similar risks with the building industry, such as the risk of falling from a high building during construction and maintenance. Normally, wind turbines are installed in sparsely populated areas and thus the risk of human incidents is small.

Tax revenues constitute an important source of revenues for the national economy. The introduction of wind energy and hydrogen storage into the power system results in a positive impact on this source of revenues. Apart from the environmental attributes of wind energy, local authorities can also economically benefit from wind energy developments as wind-based electricity producers are obliged to pay 3% of their revenues to the local authorities of the regions in which the wind parks are installed.

The following Table presents the cost of the technologies used in the RES & Hydrogen power system of Milos and the work opportunities during the purchase and installation phase of the project.

It has been considered that some equipment is imported from abroad and thus the cost of the equipment consists of two components, the domestic and the imported. Table 6 shows the percentage of the Greek participation for the purchase and installation cost. The imported cost of the investment has been multiplied by a shadow factor in order to incorporate the principle that it is preferred to utilize local suppliers and domestic expertise than to import goods and services. The subsequent Table shows the operation and maintenance cost the technologies of the RES &

Table 6
Cost and employment during purchase and installation phase of the RES & Hydrogen power system of Milos Island.

Technology	Cost	Greek Participation	Employment		
			Persons	Number	Days
Wind turbines	21,000,000€	30%	Engineers	8	365
			Technicians	7	730
			Operators	7	365
			Workers	16	365
Diesel generators	1,430,000 €	30%	Engineers	6	30
			Technicians	3	30
			Operators	3	30
			Workers	6	30
Storage system			Engineers	3	60
Electrolyser + Compressor	2,000,000 €	30%	Technicians	1	90
Hydrogen tank	1,600,000 €	100%	Operators	0	0
Fuel cell	1,500,000 €	30%	Workers	1	30
Total cost	27,530,000€				
Greek participation		34%			
Person-years (PY) engineers			8.99		
Person-years technicians			14.49		
Person-years operators			7.25		
Person-years workers			16.58		
Total Employment			47.3 (PY)		

Hydrogen power system of Milos and the ensuing work opportunities during this phase.

As it can be witnessed in Table 7, the impact on the employment has been calculated both for direct and indirect jobs. The creation of new jobs in a given sector may create new indirect jobs in other sectors and regions. This effect is known as the spin off effect. Table 8 presents the total O&M cost per year. Moreover, since some technologies are replaced during the lifetime of the project Table 8 also presents the total O&M costs of the years that a replacement had taken place. The derivation of the BC ratio has been based in a number of additional parameters. Table 8 shows these parameters along with their corresponding values. For the social parameters a number of assumptions have been made based on the experience of the authors.

The benefit from the avoided CO_2, SO_2, NOx and PM10 emissions caused by the proposed RES & Hydrogen power system are derived

Table 7
Cost and employment during operation and maintenance phase of the of the RES & Hydrogen power system of Milos.

Technology	Cost	Greek Participation	Employment		
			Persons	Number	Days
Wind turbines	510,000€/yr	80%	Engineers	1	365
			Technicians	4	365
			Operators	0	0
			Workers	0	0
Diesel generators (DG)	87,062 €/yr	90%	Engineers	1	365
			Technicians	2	365
			Operators	1	365
			Workers	0	0
Storage system			Engineers	1	365
Electrolyser + Compressor	50,000€/yr	60%	Technicians	2	365
Hydrogen tank	4000 €/yr	60%	Operators	0	0
Fuel cell (FC)	4418 €/yr	60%	Workers	0	0
Diesel fuel	105,336€/yr	100%			
Heavy oil fuel	1,038,654€/yr	100%			
CO_2 emissions	206,677€/yr	100%			
FC Replacement cost	450,000€/yr	40%			
DG 1750 kW Replacement cost	88,000€/yr	100%			
DG 700 kW Replacement cost	40,000€/yr	100%			
Total cost	2,006,147€/yr				
7th year	2,186,147 €				
12th year	2,094,147 €				
13th year	2,046,147 €				
14th year	2,186,147 €				
19th year	2,046,147 €				
PV of total cost	23,285,380€				
Greek participation		93%			
Permanent jobs for engineers			3		
Permanent jobs for technicians			8		
Permanent jobs for operators			1		
Permanents job for workers			0		
Total permanent jobs			12		
Spin off effect			33%		
Total Employment per year			15.96 (PY)		

Table 8
Parameters used in the derivation of the BC ratio.

Parameter	Value	
Wind energy consumption	24,894,794 kWh/year	
Fuel cell energy consumption	2,353,161 kWh/year	
DG energy consumption	12,304,077 kWh/year	
Price of wind electricity	0.09174 €/kWh	
Price of fuel cell electricity	0.15 €/kWh	
Price of DG electricity	0.1 €/kWh	
Price of buying electricity	0.1 €/kWh	
Income Tax	20%	
Average period of unemployment	12 months	
Average unemployment allowance	430.75 €/month	
Average annual net salary	12240 €/year	
VAT	19%	
	Net	Gross
Engineer salary	19,600 €/year	27,048 €/year
Technician salary	10,800 €/year	15,012 €/year
Operator salary	10,000 €/year	13,900 €/year
Worker salary	8000 €/year	11,120 €/year

by applying the EcoSenceLE tool [31]. Table 9 displays the basic inputs, assumptions and the total external benefit from the avoided emissions due to the proposed power system in Milos.

The benefit-cost (BC) ratio is the most widely used indicator of the profitability of a project from a social or/and environmental point of view. The BC ratio is defined as the total benefits divided by the total costs of a project. When calculating the BC ratio the value 1 represents the threshold for an acceptable project. The benefits and costs of the proposed system are expressed in terms of equivalent money value. Moreover, the time value of money was also incorporated and thus the present values of the benefits and costs were included.

Based on the aforementioned data the BC ratio for the society and the environment has been calculated. Table 10 presents the social and environmental costs and benefits in monetary values and the BC ratio.

As it can be witnessed from Table 10, the BC ratio of the proposed RES & Hydrogen power system for Milos Island is greater than unity. This means that from a social perspective the proposed project is a profitable investment. Comparing the outcomes of the financial analysis for the investor, presented in earlier section, with the outcome of the cost-benefit analysis, it may be concluded that sometimes there is a considerable divergence between the financial and the social profitability indicating conflicts between private and social interests. Moreover, it can be argued from the results of the cost-benefit analysis that the subsidy for the implementation of the proposed power system in Milos is paid back to society because of the project's ensuing benefits.

Table 9
Avoided emissions due to the proposed RES & Hydrogen power system in Milos Island.

Milos proposed power system Avoided Emission values	
NOx	317,722 kg/year
SO_2	328,536 kg/year
PM_{10}	2684 kg/year
CO_2	17,120,117 kg/year
Assumptions	
Mortality value	75,000 €/Life Year Lost
Abatement cost per tonne of CO_2	19 €/t
Summary Results	
Human Health Mortality	629,000 €/year
Human Health Morbidity	332,000 €/year
Crops	293,000 €/year
Materials	44,500 €/year
CO_2	325,000 €/year
Total External Benefit	1,623,500 €/year
PV of total external benefit	18,621,417 €

Table 10
Socio-environmental BC ratio for the RES & Hydrogen power system of Milos Island.

Socio-environmental benefit or cost	Monetary value
Benefit from the purchase & installation phase	1,778,438 €
Benefit from the O&M phase	355,706 €/year
PV of benefit from the O&M phase	3,911,385 €
Benefit from the creation of new jobs	325,647 €
Benefit from public contributions	575,885 €
Benefit from the operation of the wind park	1,841,036 €/year
PV of the benefit from the operation of the wind park	997,690 €
Benefit from the production of electricity	3,955,203 €/year
PV of benefit from the production of electricity	45,365,869 €
Cost of domestic investment	9,360,200 €
Cost of imported investment	21,803,760 €
Cost of domestic O&M	1,872,136 €/year
PV of cost of domestic O&M	21,713,606 €
Cost of O&M imported	168,516 €/year
PV of cost of O&M imported	1,955,972 €
Total external benefit	1,623,500 €/year
PV of total external benefit	18,621,417 €
Total benefits	68,786,149 €
Total costs	54,833,538 €
Benefit-Cost Ratio	1.25

4.8. Sensitivity analysis

A sensitivity analysis has been conducted on a number of parameters that may affect the economic viability of the proposed RES & Hydrogen power system. Table 11 includes the parameters that have been varied over a range of values and have caused a large or small variation. The table presents the absolute and relative variation.

The results of the sensitivity analysis presented in this section include the effect on the cost of energy, NPV, IRR, Payback Period and BCR of the parameters that cause a significant variation. It should be stressed that during the sensitivity analysis, it was shown that the capital cost of the Metal Hydride Hydrogen Compressor did not significantly affect the cost of electricity produced by the system, neither IRR nor NPV of such a project.

4.8.1. Change in heavy oil price

Similar behaviour has been recorded for the variation of the heavy oil price. This price is proportional with the cost of energy and thus as the former increases the latter increases as well. It should be noted that although the variation of heavy oil price greatly affects the economics of the proposed system the variation of diesel price has a minor impact on the results. This may be explained considering that only one diesel generator, which operates only 6 months, runs on diesel while four generators use heavy oil as a fuel. The changes in the economics of the proposed system are shown in Figs. 4–6.

4.8.2. Change in fuel cell electricity price

In the financial analysis, the price the fuel cell-produced electricity is sold was assumed to be 0.15 €/kWh. This price is an assumption that was made based on the electricity prices of other hybrid systems in other Greek islands. As this value has not been known with absolute certainty and also the energy tariff scheme changes, the impact of the variation of the electricity price over a wide range has been studied. As the electricity price increases the NPV and IRR increase and the Payback Period decreases enhancing the financial viability of the investment. Figs. 7–9 show the results of the fuel cell electricity price variation.

Table 11
Parameters of sensitivity analysis and their range.

Parameter	Min.	Original	Max.
Fuel Cell capital cost	2000 €/kW	3000 €/kW	3000 €/kW
Electrolyser + Compressor capital cost	1500 €/kW	2000 €/kW	2000 €/kW
Diesel price	−20%	0.68 €/L	+30%
Heavy oil price	−20%	0.34 €/L	+30%
CO_2 emission trading allowance	−30%	21 €/t	+5%
Fuel cell electricity price	−20%	0.15 €/kWh	+20%

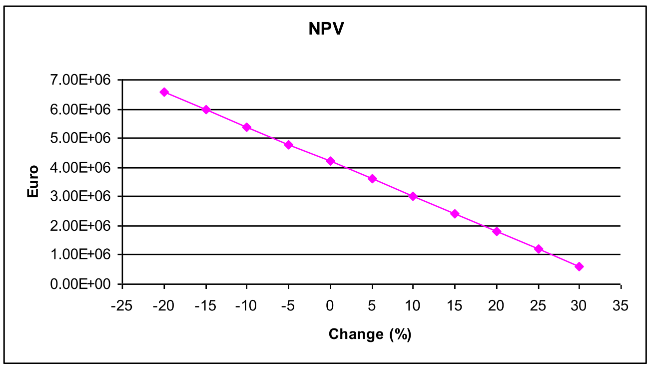

Fig. 4. Impact of heavy oil price on NPV.

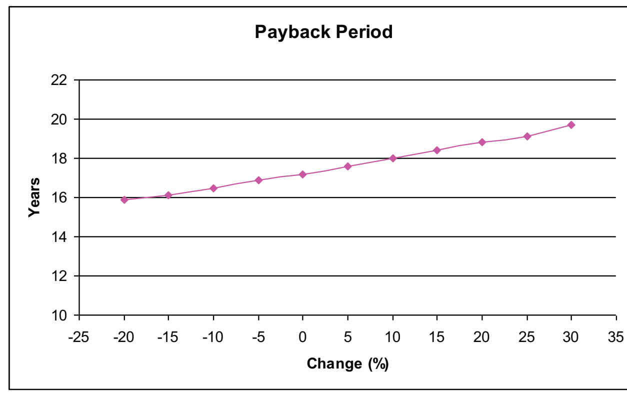

Fig. 6. Impact of heavy oil price on Payback Period.

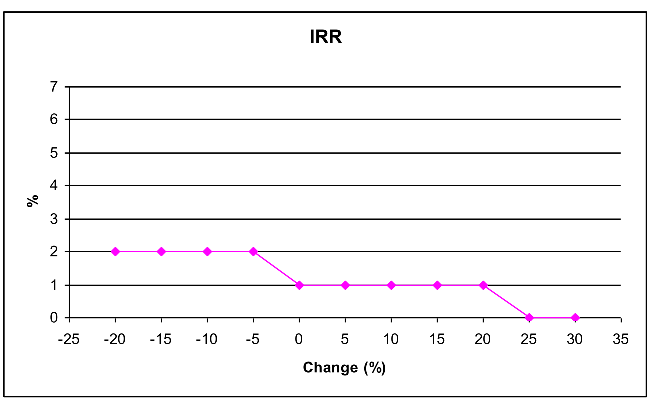

Fig. 5. Impact of heavy oil price on IRR.

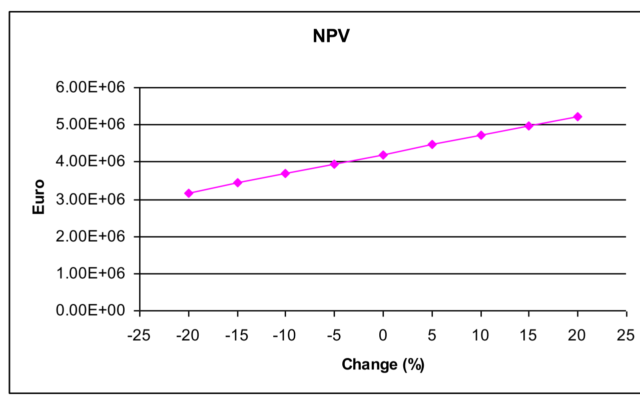

Fig. 7. Impact of fuel cell electricity price on NPV.

5. Conclusions

From the analysis presented above within the purposes of this study, it is evident that the Metal Hydride Hydrogen Compressor (MH2C) has good commercialization potential, provided that certain actions are taken in the near future. Both major target markets identified for the thermal compressors (i.e. i. Large – scale Hydrogen Production using excess energy from RES and ii. Hydrogen vehicle refuelling stations), show a rapid development. This is supported by the fact that due to the removal of nuclear plants in central Europe (especially Germany) the need of higher penetration of Renewables is becoming even more important. Higher penetration of large wind parks to the electricity grid can be achieved through the storage of excess energy in the form of hydrogen, which should be compressed in order to be used for re-electrification. Moreover the number of existing hydrogen vehicle refuelling stations in Europe is rapidly increasing and car industry has already introduced hydrogen vehicles in the market. Therefore, the emerging market for hydrogen compressors keeps growing and MH2Cs have a good opportunity to build upon their advantages over mechanical compressors in order to acquire a significant share of this market.

In order to increase RES penetration in the Greek island of Milos, a RES & hydrogen storage power supply system was proposed and examined from an economic, environmental and social perspective(using the HOMER software tool). The financial viability of the proposed system was investigated based on the NPV and IRR technique. According to both methods, the investment is not quite profitable as it has 1% IRR, which characterizes the investment financially non-viable, and a positive yet small NPV that indicates that the investor would not lose any money but also would not increase greatly his capital. The main reason rendering the proposed system financially non-viable is the excess electricity produced by the system. Excess electricity is responsible for a 44%

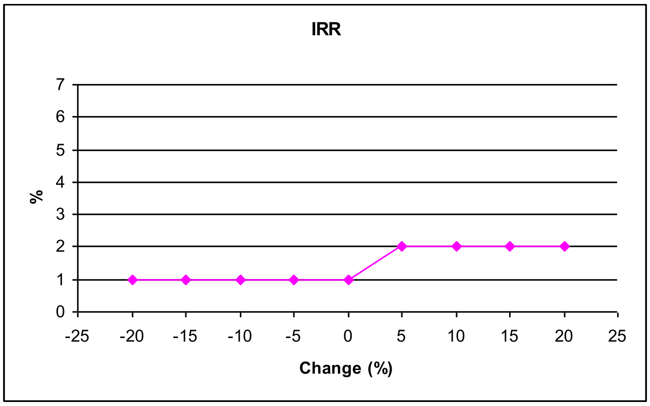

Fig. 8. Impact of fuel cell electricity price on IRR.

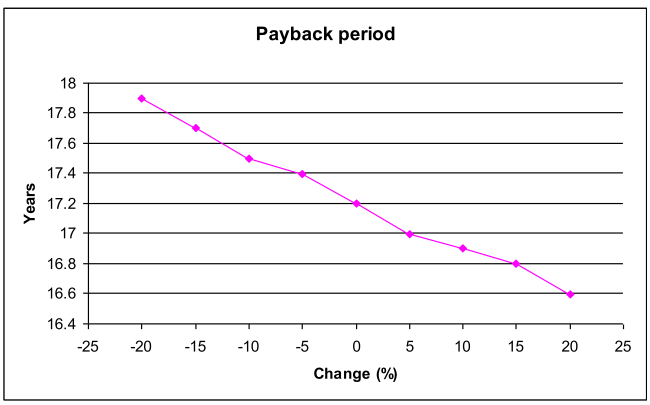

Fig. 9. Impact of fuel cell electricity price on Payback Period.

reduction in the revenues of the investor. If the excess electricity was significantly smaller, the investment would have been more economically attractive. It is worthwhile to mention that an option to increase the profitability of the investment is to use the excess energy for the production of hydrogen in order to be used locally as a fuel in the transport sector or for heating purposes.

Moreover, the proposed system was also examined in terms of its environmental and social implications. A CBA was carried out and the benefits and costs of the proposed system were identified aiming to calculate the net economic impact of the proposed system on the society as a whole. The benefits of the proposed system, such as the creation of new jobs and the reduction of harmful emissions outweighed the costs resulting in a BC ratio greater than unity that indicates that from a social perspective the proposed system is a profitable investment. Thus, although the proposed RES & hydrogen storage power system for Milos is not a clearly profitable investment from the investor's perspective, it shows social profitability as the society would benefit considerably from its implementation.

Even though, as shown by the sensitivity analysis of the Milos case study, the cost of hydrogen compressors does not have a significant impact on the techno-economic analysis of large-scale RES – Hydrogen power systems, a reduction of the order of 15–20% in the current cost of the thermal compressor would play a significant role in the commercialization of the product in small scale applications, such as autonomous, self-sufficient residences. Metal Hydride Hydrogen Compressors give the user the flexibility to utilize any source of heat such as, solar heating, waste heat, geothermal energy, etc., therefore minimizing the operating expenses (OPEX) and requiring lower maintenance (due to the absence of any moving parts).

A basic geopolitical barrier/obstacle for the proposed technology (common to all new hydrogen technologies) is the intention of public authorities and decision makers to support actively the promotion of a hydrogen-based economy and its associated technologies.

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List of Abbreviations

BC(R): Benefit-Cost (Ratio)
COP: Coefficient Of Performance
DG: Diesel Generator
FC: Fuel Cell
HRS: Hydrogen Refuelling Stations
IRR: Internal Rate of Return
MH: Metal Hydride
MH2C: Metal Hydride Hydrogen Compressor
NPV: Net Present Value
O&M: Operation & Maintenance
OPEX: Operating expenses
PEM: Proton Exchange Electrolyser
PY: Person-Years
PV: Photovoltaic
RES: Renewable Energy Sources
R&D: Research and Development