11

Criteria Assessment of Energy Carrier Systems Sustainability

Pedro Dinis Gaspar, Rui Pedro Mendes and Luís Carrilho Gonçalves
University of Beira Interior - Faculty of Engineering - Electromechanical Eng. Dept. Portugal

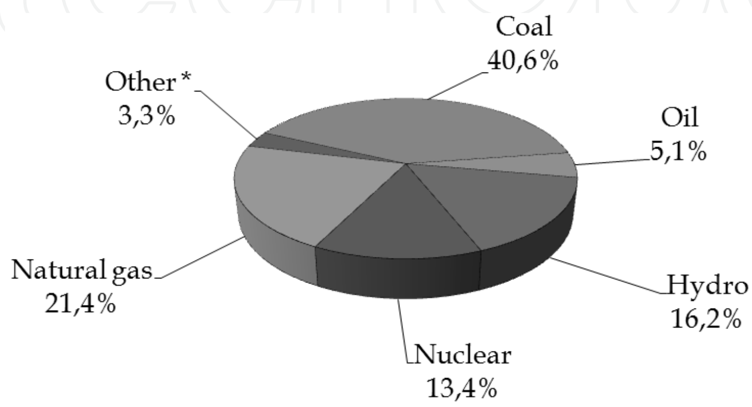
1. Introduction

Energy carrier systems of renewable sources have become widely used due to world's need to reduce the fossil fuel consumption and consequently greenhouse effect. However, the energy density of these systems is much lower than fossil fuels or nuclear fission. Besides, energy outlooks (IEA, 2011) show that energy demand around the world will continue its increasing trend. In turn, the wide scale construction of power plants based in fossil fuel cannot continue due to negative environmental effects. Also, the latest accident in reactor n.^{er} 3 of the Fukushima Daiichi Nuclear Power Station in Japan in consequence of the March 11 earthquake and tsunami increased the fear of radiation effects and the discussion about nuclear safety. Thus, it is relevant to provide an up-to-date assessment of the global sustainability of current and future energy carrier systems for electricity supply based on fossil fuel and renewable energy sources. It includes the analysis of energy carrier systems based on fossil fuels: coal, natural gas and oil and on renewable ones: wind, solar photovoltaic, geothermal, hydro, hydrogen, ocean (wave and tidal power), and nuclear.

The sustainability assessment of an energy conversion process into electrical energy is carried out in technological, economical, environmental and social dimensions. A solid basis for a state-of-the-art interdisciplinary assessment using data obtained from the literature supports the sustainability comparison. Thus, indicators that best describe the technologies and that are related to each of the abovementioned dimensions are defined to quantify the sustainability of energy carrier systems. These indicators are: efficiency of electricity generation, lifetime, energy payback time, capital cost, electricity generation cost, greenhouse gases emissions during full life cycle of the technology, land requirements, job creation and social acceptance. A criteria based on membership functions is exposed in order to determine a global sustainability index that quantifies how sustainable each energy carrier system is. The multi criteria analysis is performed considering different weighting functions applied to sustainability indexes in order to assess, today and in the near future, energy carrier systems that should be used in the mix of energy conversion systems to electricity. This work extends the research developed by Mendes et al. (2011a) and Mendes et al. (2011b).

2. Energy carrier systems

This section is devoted to describe the different types of energy carrier systems for conversion into electricity. The world energy source share of electricity generation in 2009 is shown in Fig. 1 (IEA, 2011a). Energy carrier systems are subdivided in renewable energy sources (wind, solar photovoltaic, geothermal, hydro, hydrogen and ocean) and fossil fuel (coal, natural gas and oil). Among these renewable energy sources, the wind and solar photovoltaic energies carrier systems are those with higher growth. Nowadays, nuclear energy can be considered as "an almost" renewable energy because new generation's nuclear plants can reuse uranium and its derivates. Thus, this energy carrier system is included into renewable section. Their advantages, disadvantages and capture technology are presented. The installed power, worldwide production and perspective of future increase are quantified for each energy carrier system.



*Other: wind, solar photovoltaic, geothermal,, biofuels and waste, and heat.

Fig. 1. 2009 World energy source share of electricity generation (IEA, 2011a).

2.1 Renewable energy

Renewable energy markets, investments, industries, and policies have experienced rapid changes in recent years. So, its status can't be assured without doubts. If the global economic recession, felt most acutely in Europe, that also strike the renewable energy sector due to incentive cuts announcement by several governments, is taken into account, the trend of these energy carrier systems installed capacity was supposed to decrease. However, if the three-month long oil spill in the Gulf of Mexico and the incident in nuclear power station in Japan are considered, the caused extensive damage and welfare of people in these regions led to rethink and promote the use of renewable energy carrier systems. In the following subsections, each of the renewable energy carrier systems is discussed.

2.1.1 Wind

Wind turbines are used for the conversion of wind's kinetic energy into mechanical energy and then into electricity. This form of energy produces no emissions or contamination during the system operation.

WWEA (2011) states that wind energy has reached 196.630 GW of worldwide installed capacity and 430 TWh of produced energy (2.5 % of the electricity global consumption). This sector shows a fast growth rate among the renewable energy carrier systems, but in 2010 has showed the lowest growth rate value (23.6 %) since 2004 due to the international economic situation. Although, the wind sector had a turnover of 40 billion Euro and employed 670 000 persons worldwide.

The distribution of the total installed capacity has changed since 2009, as China became number one in total installed capacity (44.7 GW), dethroning the United States of America (USA) with 40.2 GW. Also, China is now the centre of the international wind industry, adding 18.9 GW within one year, accounting for more than 50 % of the world market for new wind turbines. The growth rate in European countries shows stagnation in Western ones but a strong growth in a number of Eastern European countries (Romania, Bulgaria, Turkey). Nevertheless, Germany keeps its number one position in Europe for installed capacity with 27.2 GW, followed by Spain with 20.6 GW. The highest shares of wind power in electricity supply can be found in three European countries: Denmark (21 %), Portugal (18 %) and Spain (16 %).

WWEA predicts further substantial growth of wind sector in China, India, Europe and North America. Based on the current growth rates, this agency expects by 2015 a global wind capacity of 600 GW and more than 1 500 GW by the year 2020.

2.1.2 Solar photovoltaic

The solar photovoltaic (PV) technology is a method of converting solar radiation into electricity through the photovoltaic effect. It is an environmentally friendly energy carrier system by its ability to operate noiseless and emitting no greenhouse gases.

The PV sector showed a strong growth and investment, more than doubling in 2010 (REN21, 2011) as its capacity was added in more than 100 countries during that year, ensuring that PV remained the world's fastest growing power-generation technology.

The nominal worldwide installed capacity of PV systems in 2010 was about 40 GW – more than seven times the capacity in place five years earlier. Just only in 2010, 17 GW of capacity was added worldwide. This value represents an increase of 9.7 GW comparing with the installed PV power in 2009. The number of utility-scale PV plants continues to rise, accounting for almost 25 % of total global PV capacity.

Technology cost reductions in solar PV led to high growth rates in manufacturing and cell manufacturing continued its shift to Asia.

The PV market is dominated by the European Union (EU) countries (accounting for 80% of the world total) and particularly by Germany, which owns almost of half of global market (44 %) and installed more PV in 2010 (7.4 GW) than the entire world did the previous year. The rank is followed by Spain, Japan and Italy.

2.1.3 Geothermal

The geothermal energy source comes from the sub-soil heat, several hundred meters below the surface. For every 100 meters deep, the temperature increases about 3 °C. It is possible to reach the water boiling point temperature (100 ºC) at 3 km depth (Farret & Simões, 2006).

This energy can be used for direct heating or for electricity generation by producing steam to drive a turbine (Erdogmus et al., 2006). Only the latter process will be assessed in this work. In the past 25 years, the electricity production by geothermal resource has significantly grown, reaching in 2007 about 10 GW of worldwide installed capacity (Gallup, 2009). By the end of 2010, total global installations came to just over 11 GW, and geothermal plants generated about 67.2 TWh of electricity during the year (REN21, 2011). However, the availability of this energy carrier system becomes scarce due to the difficulty and costs associated with sub-soil drilling at depths that allow reaching temperatures values suited to operate a turbine.

2.1.4 Hydro

Hydropower is a clean, renewable and reliable energy carrier system, allowing for energy storage and subsequent use when needed, making it a highly available resource. The use of this renewable energy source is done by converting into electricity the kinetic energy contained in rivers and potential energy of water falls down a shaft. The energy conversion process requires directing the stored water to a hydraulic turbine in order to drive an electric generator (Varun et al., 2009). Hydro energy is a resource globally wide spread with an installed capacity of about 720 GW around the world in 2008 (Kaldellis, 2008). Since then, global hydropower production increased reaching an estimated 1010 GW. The top countries for hydro capacity are China, Brazil, the USA, Canada, and Russia, which account for 52% of total installed capacity. Brazil and Canada generate roughly 80% and 61%, respectively, of their electricity with hydropower, while many countries in Africa, likewise Norway produce close to 100% of their grid based electricity with hydro (REN21, 2011). World spread countries continue to develop hydropower on large to small scales as well as pumped storage systems.

2.1.5 Hydrogen

Hydrogen is an abundant substance on the planet due to its presence in the molecule of water that covers about 70% of the earth's surface. It is a clean energy that enables the production of electricity through hydrogen fuel cells. Fuel cells are available in units of 5 to 250 kW, being more suitable for decentralized electricity production. Two types of fuel cells will be considered in the analysis of hydrogen as a energy carrier system: the phosphoric acid and solid oxide (ceramic, zirconium oxide and yttrium oxide) fuel cells. The former represents the first generation of commercial fuel cells. However, despite its good performance, such cells showed low viability. The solid oxide fuel cells have become much more attractive. With units with capacities from 5 to 250 kW, these cells are accessible to small consumers becoming suitable for decentralized production (Afgan & Carvalho, 2004).

2.1.6 Ocean (wave and tidal)

This renewable energy carrier converts the kinetic and potential energy of ocean into electricity. Both technologies, wave and tidal, will be assessed together as one. It is a renewable energy resource with high energy potential, reaching around 320 GW along the European coast, which corresponds to 16% of the world total resource (Cruz & Sarmento, 2004, WavEC, 2004). However, both technologies used in the conversion of this energy are still in a development stage despite of the numerous devices and conversion techniques that are patented. Because they are in an emerging phase, there are only few technologies with commercial application and the information about its sustainability is still based on forecasts. Despite this fact, at 2010's end, an estimated total of 6 MW of wave (2 MW) and tidal stream (4 MW) capacity had been installed mostly off the coasts of Portugal and the United Kingdom. The world estimated power capacity of tidal barrage is around 500 MW and presently there are more than 100 ocean energy projects (exceeding 1 GW in cumulative capacity) in various phases of development (REN21, 2011).

2.1.7 Nuclear

Nuclear energy can be defined as the energy converted by the release of the binding energy of components, for example, protons and neutrons, from an atom nucleus. The source of nuclear energy is based on the well known Einstein's equation ($E = mc^2$). Thus, a small amount of mass can be transformed into a lot of energy.

The nuclear energy resource has been used along many decades and has a great potential for electricity production. Although, it usage has been always controversial due to social acceptance questions. Nuclear energy supplies about 13% (≈ 624 GW) of the world electric energy demand. The electricity generation through nuclear energy has reached a value of 2558 TWh in 2009 (WNA, 2010). The USA is the country with more electricity through nuclear power plants with 19% of the total consumption (EIA; 2010). In 2006, France has bet this value with 80% of consumed electricity produced by nuclear power plants (Beardsley, 2006). Among other countries with a remarkably steady increase in nuclear generation are China, the Czech Republic, Romania and Russia.

In 2011, there were 437 nuclear reactors operating in the world and the International Atomic Energy Agency (IAEA) currently lists 64 reactors as "under construction" in 14 countries (Schneider et al., 2011). The world installed nuclear capacity has increased slowly, and despite of seven fewer units operating in 2011 compared to 2002, the capacity is still about 8 GW higher due to a combined effect of larger units replacing smaller ones and, mainly, technical alterations at existing plants, a process known as "uprating".

2.2 Fossil fuels

Oil and coal remain the most important primary energy sources since the 70's. Coal increased its share significantly since 2000. Growth slowed in 2005 and the total share of fossil fuels dropped from 86% in 1971 to 81% in 2004 (IPCC, 2007). In 2004, around 40 % of global primary energy was used as fuel to generate 17 408 TWh of electricity. Electricity generation has an average growth rate of 2.8 %/year and is expected to continue growing at a rate of 2.5 to 3.1 %/year until 2030 (IPCC, 2007). The electricity generation forecasts indicate that fossil fuels will to continue to support this energy carrier. Fossil energy resources remain abundant as proven and probable reserves of oil and gas are enough to last for decades and in the case of coal, centuries. Possible undiscovered resources (mainly in Artic) extend these projections even further.

2.2.1 Coal

Coal is the world's most abundant fossil fuel (IPCC, 2007). The fossil fuel coal here considered includes all coal, both primary (including hard coal and lignite) and derived fuels (including patent fuel, coke oven coke, gas coke, BKB, gas works gas, coke oven gas, blast furnace gas and other recovered gases). Peat is also included in this category.

Coal-fired electricity-generating plants technologies are of conventional subcritical pulverized fuel design, with typical efficiencies of about 35% for the more modern units.

Best plants with supercritical pulverized fuel design achieve efficiencies of almost 50% (IPCC; 2007). Improved efficiencies have reduced the amount of waste heat and CO_2 that would otherwise have been emitted to atmosphere.

In 2005, coal accounted for around 25% of total world energy consumption primarily in the electricity and industrial sectors. Although coal deposits are widely distributed, world's recoverable reserves are located in the USA (27 %), Russia (17 %) and China (13 %). Two thirds of the proven reserves are hard coal (anthracite and bituminous) and the remainder are sub-bituminous and lignite (IPCC, 2007). Global proven recoverable, probable and estimated additional possible reserves of all coal types are about 133 000 EJ (IPCC, 2007).

In 2009, 8119 TWh were generated in coal/peat-fired plants (IEA, 2011b). China leads world ranking for the electricity production through coal/peat fuel with 2 913 TWh. It is followed by the USA with a power of 1 893 TWh, and by India with 617 TWh (IEA; 2011). According to IPCC (2007), the demand for coal is expected to more than double by 2030 (4500 GW).

2.2.2 Natural gas

Natural gas production has been increasing in the Middle East and Asia–Oceania regions since the 1980s. During 2005, natural gas was obtained in the Middle East (11 %), Europe and Eurasia (38 %), and North America (27 %) (IPCC, 2007). Proven global reserves of natural gas are estimated to be 6500 EJ, of which almost three quarters are located in the Middle East (IPCC; 2007).

Natural gas-fired power generation has grown rapidly due to its relative superiority to other fossil-fuel technologies in terms of investment costs, fuel efficiency, operating flexibility, rapid deployment and environmental benefits. In 2009, 4301 TWh were generated in gas-fired plants (IEA, 2011). The ranking is composed by the USA (950 TWh), Russian (469 TWh) and Japan (285 TWh). Natural gas is forecast to continue to be the fastest-growing primary fossil fuel energy source worldwide. The share of natural gas used to generate electricity worldwide is projected to increase from 25 % in 2004 to 31 % in 2030 (IPCC, 2007).

2.2.3 Oil

Conventional oil products extracted from crude oil-well bores and processed by primary, secondary or tertiary methods represent about 37% of total world energy consumption with major resources concentrated in relatively few countries as two thirds of proven crude oil reserves are located in the Middle East and North Africa (IPCC, 2007). Oil comprises crude oil, natural gas liquids, refinery feedstocks and additives as well as other hydrocarbons such as oil products (refinery gas, ethane, LPG, aviation gasoline, motor gasoline, jet fuels, kerosene, gas/diesel oil, fuel oil, naphtha, white spirit, lubricants, bitumen, paraffin waxes, petroleum coke and other oil products). However, not all of these are suited as input of a oil-fired plant for electricity generation.

Similar to the operation of other conventional steam technologies, oil-fired conventional steam plants are used to generate electricity. Burning oil to generate electricity produces significant air pollution in the forms of nitrogen oxides, and, depending on the sulphur content of the oil, sulphur dioxide and particulates. Carbon dioxide and methane (as well as other greenhouse gases), heavy metals and volatile organic compounds all can come out of the smoke stack of an oil-burning power plant.

In 2009, 1027 TWh were generated in oil-fired plants (IEA, 2011). Saudi Arabia is the country with the highest production of electricity from oils that reachs 120 TWh. With electricity generated values rather low, the ranking is completed by Japan with 92 TWh and Iran with 52 TWh. Assessments of the ultimate extractable resource (proven + probable + possible reserves) have ranged between 11 500 to 17 000 EJ (IPCC; 2007). Considering that consumption rates will continue to rise (IEA; 2011b), a reasonable prediction for supply is limited between 30 to 40 years.

3. Sustainability indicators

To assess the sustainability of an energy conversion process, it is necessary to use status indicators that define and quantify the process subsystems. For properties of a system that are not directly measurable, assessment tools are used to obtain the indicators. From a sustainability point of view, indicators should quantify the technological (efficiency, lifetime and energy payback time), economical (capital cost and electricity generation cost), environmental (greenhouse gas emissions and land requirements) and social (job creation and social acceptance) performances.

3.1 Technological indicators

The technological indicators selected to quantify the sustainability of energy carriers systems into electricity were efficiency, lifetime and energy payback time. The maximum and minimum values for each one of these indicators are determined for the different energy carrier systems. The values assigned to each indicator, for each energy carrier were collected from relevant and up-to-date studies.

3.1.1 Efficiency

The efficiency of electricity generation of the selected energy conversion technologies is an indicator that quantifies the percentage of effective primary energy converted into electricity. A range of values for this indicator was acquired for each technology. The values for the respective efficiencies were collected from Hanjalic et al. (2008), Evans et al. (2009),. Roth et al. (2009), Brito & Huckerby (2010), Vob (2006), Evans et al. (2010), Graus et al. (2007) and Dones & Heck (2006). For ocean energy only one value has been considered (minimum value = maximum value) due to the lack of information on this technology. The range of values (minimum value - maximum value) of the power conversion efficiency for each technology is shown in Fig. 2.

3.1.2 Lifetime

The lifetime is an indicator that quantifies the technology durability, indicating the period of time that this energy carrier system is in full operation. The lifetime is given in years due to longevity associated to each technology. Fig. 3 shows the maximum e minimum values of lifetime for each technology based on Varun et al. (2009), Afgan & Carvalho (2004), Roth et al. (2009), Banerjee et al. (2006), Parker et al. (2007), PREGA (2005) and Wartmann et al. (2009).

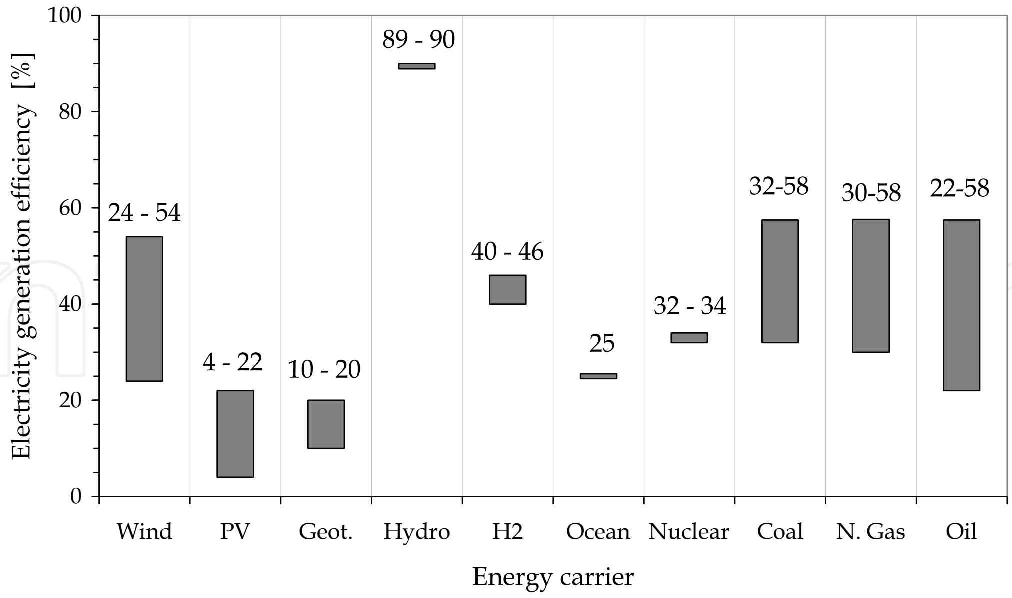


Fig. 2. Values range of electricity generation efficiency (%) for each energy carrier.

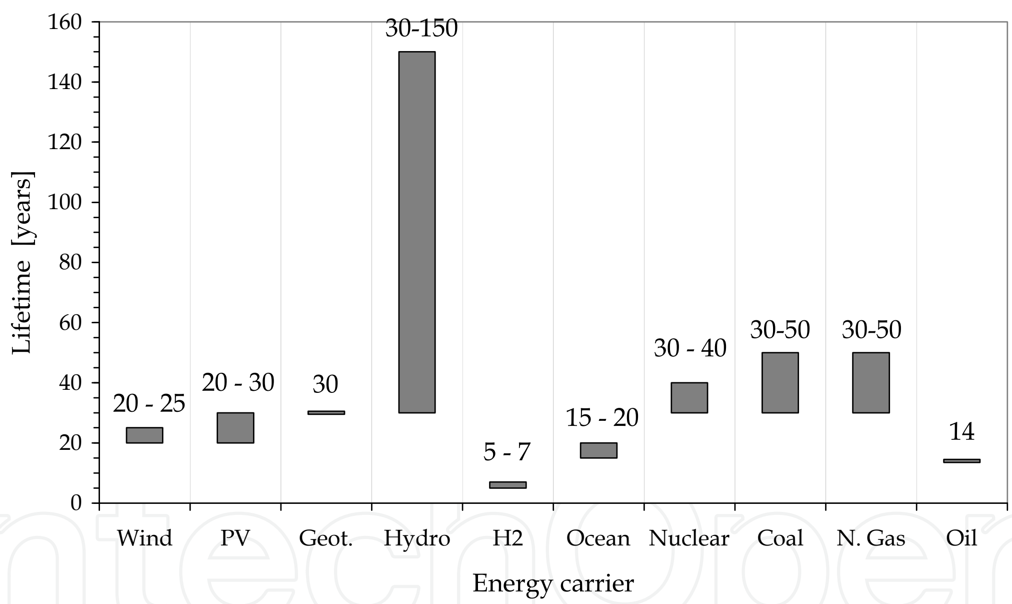


Fig. 3. Values range of lifetime (years) for each energy carrier.

3.1.3 Energy payback time

The Energy Pay Back Time (EPBT) is the time required for a technology to generate the same amount of energy needed for its manufacture and installation. This indicator is a measure of the return time. Once this period is completed, all the energy generated is profit (in energy terms). The values range of this indicator is shown in Fig. 4 is given in months. The values for E.P.B.T. were obtained by Varun et al. (2009), Banerjee et al. (2006), Parker et al. (2007), Soerensen et al. (2007), Vob (2006), WNA (2011), Randolph & Masters (2008), Mansure & Blankenship (2010), Voss (2001) and Biswas (2009).

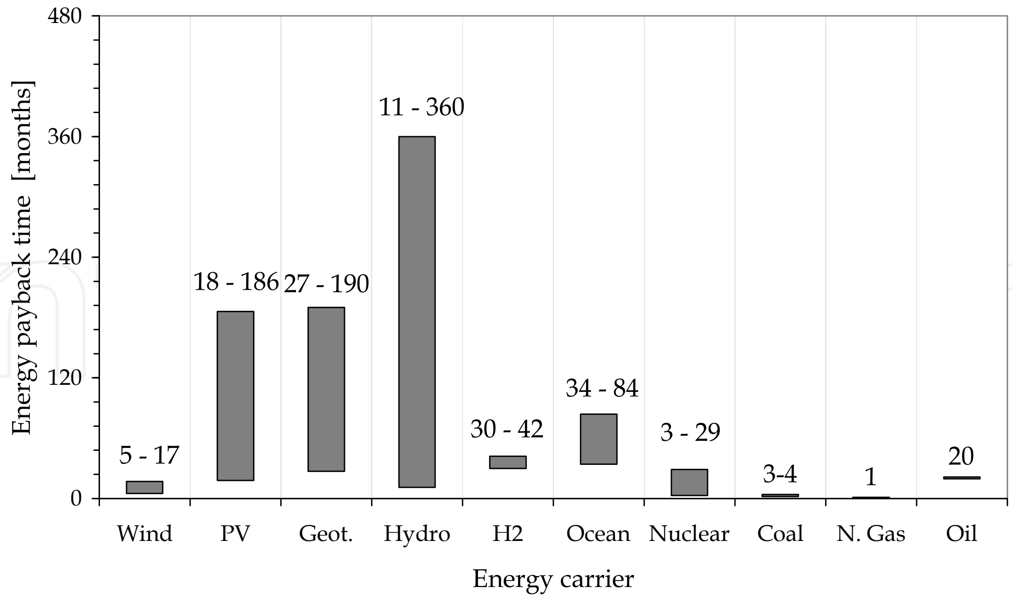


Fig. 4. Values range of energy payback time (months) for each energy carrier.

3.2 Economical indicators

The economical indicators selected to quantify the sustainability of energy carriers systems into electricity were capital cost and electricity generation cost. The maximum and minimum values for each one of these indicators are determined for the different energy carrier systems. The values assigned to each indicator, for each energy carrier were collected from relevant and up-to-date studies.

3.2.1 Capital cost

The capital cost is an economic indicator that measures the cost of installing technology for energy conversion considering its electricity generation capacity, i.e. its rated power. This indicator is given in €/MW. Fig. 5 shows the values range of this indicator for each technology. These values were obtained in Afgan & Carvalho (2004), Denny (2009), WNA (2011), Lako (2010), EIA (2010), Afgan & Carvalho (2002) and ESMAP (2007).

3.2.2 Electricity generation cost

This indicator quantifies the unit cost associated with the electricity production. It is given in the $€_{cent}$/kWh. The values were collected in Varun et al. (2009), Afgan & Carvalho (2004), Evans et al. (2009), Roth et al. (2009), Banerjee et al. (2006), Parker et al. (2007), Dalton et al. (2010), Dunnett & Wallace (2009), Allan et al. (2011), Lee et al. (2007), Evans et al. (2010) and PREGA (2005). Fig. 6 shows the range of values corresponding to this indicator.

3.3 Environmental indicators

The environmental indicators selected to quantify the sustainability of energy carriers systems into electricity were green house gas emissions and land requirements. The

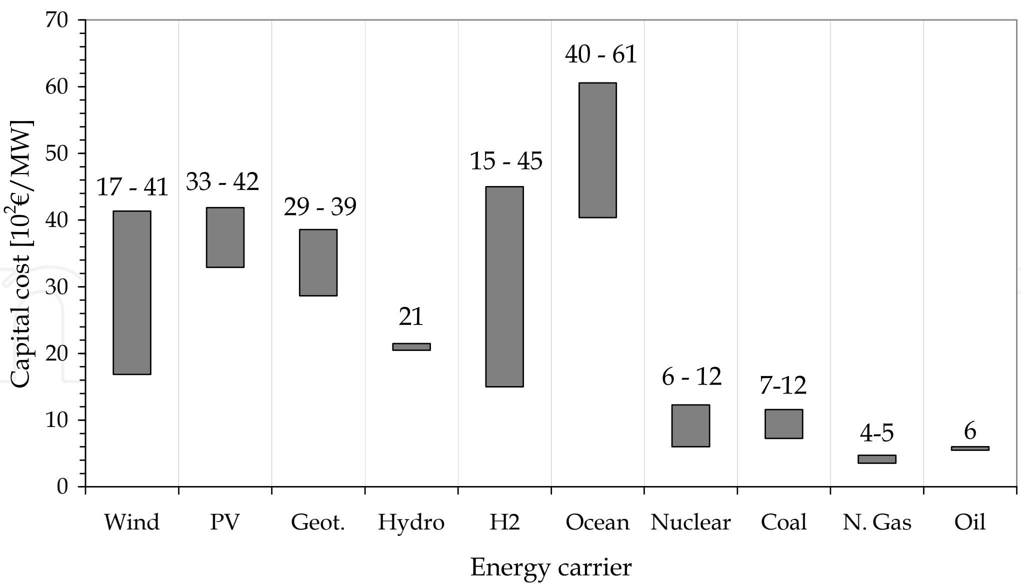


Fig. 5. Values range of capital cost (10²€/MW) for each energy carrier.

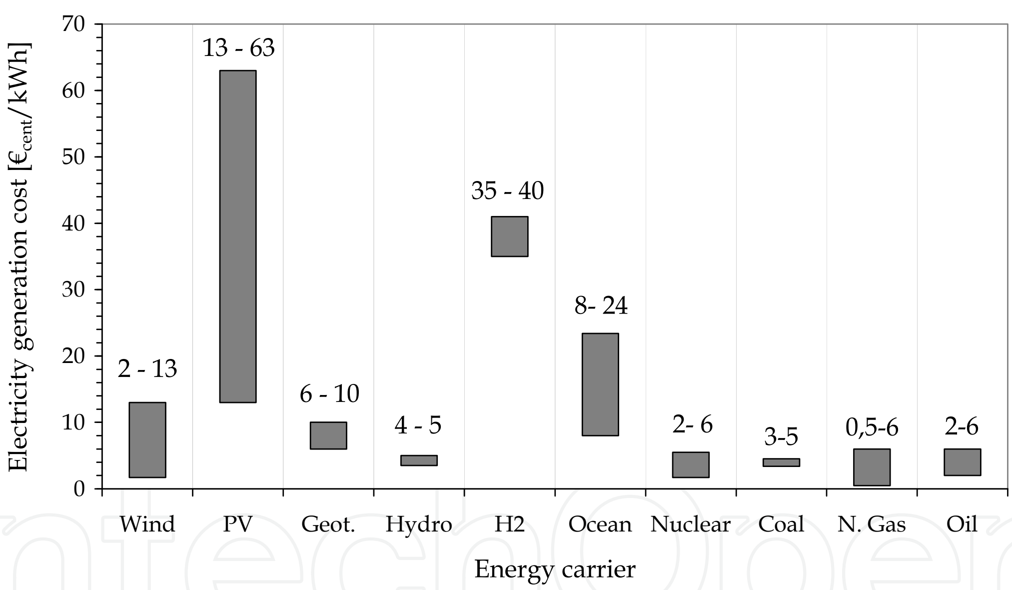


Fig. 6. Values range of electricity generation cost ($€_{cent}$/kWh) for each energy carrier.

maximum and minimum values for each one of these indicators are determined for the different energy carrier systems. The values assigned to each indicator, for each energy carrier were collected from relevant and up-to-date studies.

3.3.1 Greenhouse gas emissions (CO_2)

Greenhouse gases emissions have been the main reason why it became necessary to resort to the use of renewable energy. It is an indicator that quantifies the environmental impact of greenhouse gas emissions during the use of energy conversion devices. Sustainable energy carrier systems require minimal values of greenhouse gases emissions in order to not affect adversely the environment as it has been done by using fossil fuels combustion for electricity generation. There are several substances that are harmful greenhouse gases. However, carbon dioxide (CO_2) is the substance with more weight in the greenhouse gases composition, being the only one considered in this assessment. The CO_2 emissions are considered during the manufacturing and installation of the conversion technologies. This indicator is given in gCO_2/kWh of electricity generated and the values used to quantify it were obtained in Varun et al. (2009), Afgan & Carvalho (2004), Evans et al. (2009), Roth et al. (2009), Gagnon et al. (2002), Kannan et al. (2006), Sherwani et al. (2010), Varun et al. (2009), Raugei & Frankl (2009), Evans et al. (2010), ABB (2011), NEI (2011a) and Voss (2001). The values range of this indicator is shown in Fig. 7.

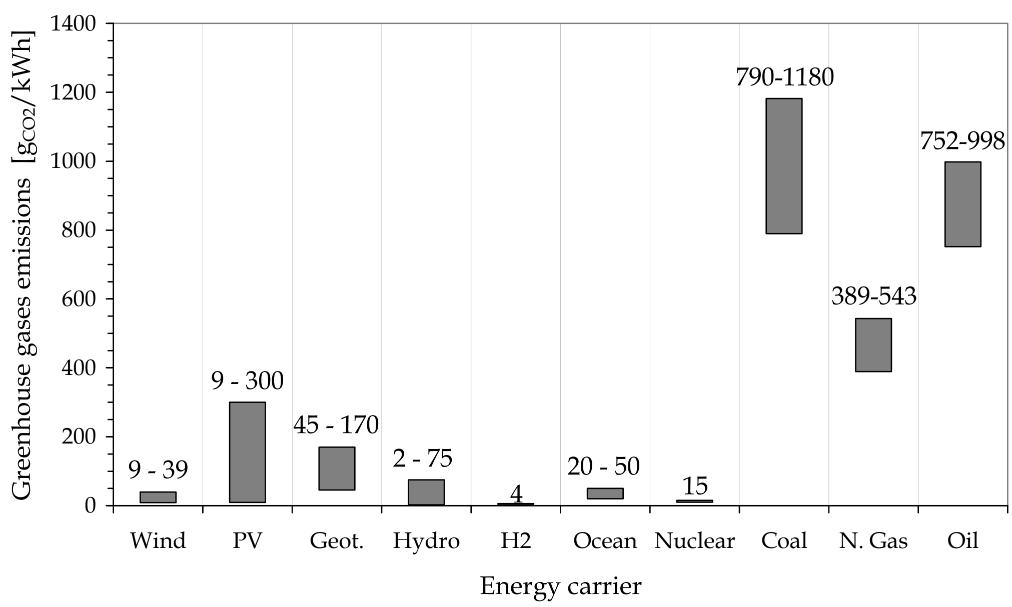


Fig. 7. Values range of greenhouse gases emissions (gCO_2/kWh) for each energy carrier.

3.3.2 Land requirements

This environmental indicator quantifies the area occupied by the installed technology. If the footprint is high, there may be harmful consequences on the environment due to the destruction of ecosystems. For this reason, the area occupied by the infrastructure of the energy conversion technology should be as small as possible. This indicator describes the area required to produce a given amount of energy per year.

The occupied land is referred to the field area used by the technology structure expressed in km^2/TWh/year. The values range for this indicator shown in Fig. 8 were collected from Afgan & Carvalho (2004), Evans et al. (2009), Gagnon et al. (2002), Evrendilek & Ertekin (2003), Rourke et al. (2010), NRC (2011), ESMAP (2007) and Wackernagel & Monfreda (2004).

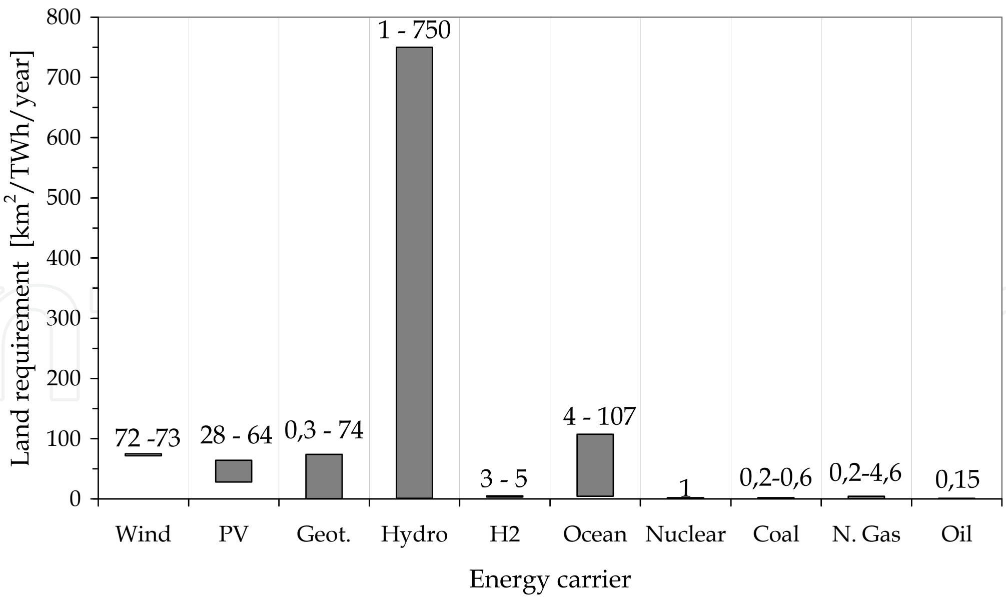


Fig. 8. Values range of land requirements (km^2/TWh/year) for each energy carrier.

3.4 Social indicators

The social indicators selected to quantify the sustainability of energy carriers systems into electricity were job creation and social acceptance. The maximum and minimum values for each one of these indicators are determined for the different energy carrier systems. The values assigned to each indicator, for each energy carrier were collected from relevant and up-to-date studies.

3.4.1 Job creation

Job creation is a social indicator that quantifies the number of jobs created by the construction of a technological system of energy conversion. The energy carrier systems impact in society is of significant importance for their sustainability, since its operation can be blocked by the population if the conversion technology is not socially advantageous. Thus, job creation becomes a good indicator to assess the social impact as indicates the capacity of employment of each installed technology. Its unit is Jobs $n.^{er}$/MW. The used values for this indicator are from Dalton & Lewis (2011), Rinebold et al. (2009), Peters (2010), Plowman (2004), NEI (2011b) and EFL (2011). The values range for this indicator is shown in Fig. 9.

3.4.2 Social acceptance

Social acceptance of any energy source involves both the general attitude towards the technology to capture energy as well as systems deployment decisions at local, regional or even national levels. In this context appears the latest formulation of "energy social acceptance" concept, named "triangle model". This model identifies three key dimensions of social acceptance: the socio-political acceptance, community acceptance and market acceptance (EWEA, 2009). The socio-political acceptance refers to the energy conversion technology acceptance and policies to a more general level. This component is not limited to levels of acceptance by the public in general, but includes the acceptance by stakeholders

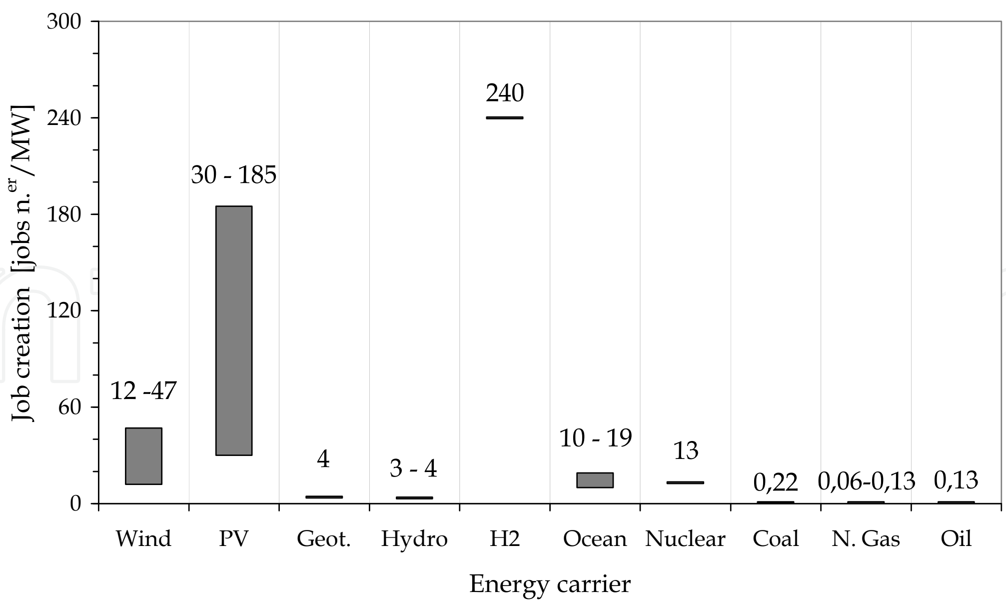


Fig. 9. Values range of job creation (Jobs n.er/MW) for each energy carrier.

and policy makers. The various political and private agents involved in the discussion are crucial in planning and promoting local initiatives. The community acceptance refers to the acceptance of specific projects at the site of potentially affected populations, of the main local stakeholders and local authorities. It is this part where the social debate around energy capture system suitable for a particular region emerges and develops. Market acceptance refers to the process by which commercial parties adopt and support (or not) an implementation of a particular technological system of energy capture.

The values range is divided into the percentage of individuals in favour (minimum value) and the sum of individuals in favour and undecided (maximum value) concerning the installation of the technological system to capture a particular energy source. It considers the public support levels for different types of energy sources obtained through polls and attitude surveys conducted by the Survey Standard Eurobarometer (EB) on the population of the European Union (EU) (EC, 2006, 2007). In the case of geothermal energy, Ungemach (2007) indicates that this energy source has a low social acceptance. So, it is considered a value of 40%, which does not affect or benefit the index. By other side, van Bree & Bunzeck (2010) indicate that the hydrogen energy conversion systems have a high social acceptance, because it is a clean energy source without any kind of controversy, although it is reported a low level of knowledge about the hydrogen technology. In this sense, is considered a value of 60% of global acceptance, that it will neither detriment nor benefit this energy capture system.

Globally, the social acceptance indicates the population approval to install and explore a certain technology power plant. This indicator encompasses the social-politic, community and market approval. This indicator quantification relies on statistical studies which were provided by EWEA (2009), Ungemach (2007), van Bree & Bunzeck (2010), Evans et al. (2010).

The values range for this indicator is shown in Fig. 10.

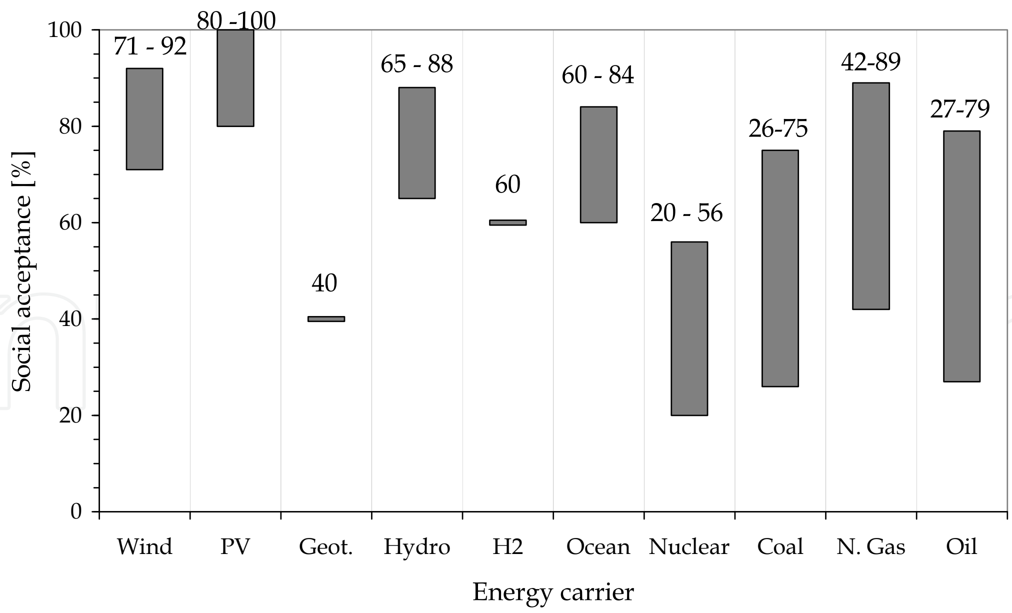


Fig. 10. Values range of social acceptance (%) for each energy carrier.

4. Sustainability assessment

The sustainability assessment is performed through a mathematical formulation that non-dimensional indicators, within the maximum and minimum values of all energy carriers. This procedure is performed for all the indicators, technological, economical, environmental and social ones. This mathematical formulation allows quantifying the sustainability indicators within the maximum variation range among all energy carriers. Two global sustainability indexes will be determined, a maximum and a minimum one. The former uses the maximum values among all energy carrier systems to obtain the non-dimensional relation. This procedure is made for each indicator. Afterwards, weighting functions are applied to perform a multi-criteria decision analysis. This procedure is performed likewise using the minimum values among all energy carrier systems within each indicator. This sensitivity analysis allows verifying which are the most relevant indicators to assess energy carriers sustainability.

4.1 Mathematical formulation

After choosing the indicators, an index is formulated to quantify the sustainability of each energy carrier system. It is necessary to relate them so they can be expressed by a quantifiable single value. This relationship is obtained through mathematical expressions that use a membership function for each indicator. The procedure is performed for the minimum and maximum values of each indicator in order to obtain of values range for the global sustainability index.

For each indicator:

- Select the maximum, $max(x_i)$, and minimum, $min(x_i)$, for each indicator separately for minimum and maximum values ranges.
- Evaluate whether the function $q(x_i)$ increases or decreases with the increase of x_i. Depending on the variation of function $q(x_i)$, select the proper expression.

If membership function $q(x_i)$ increase with x_i indicator, their relationship is expressed by:

$$q(x_i)=\begin{cases}0 & \text{if } x_i \le \min(x_i)\\ \dfrac{x_i-\min(x_i)}{\max(x_i)-\min(x_i)} & \text{if } \min(x_i)<x_i<\max(x_i) \quad (1)\\ 1 & \text{if } x_i \ge \max(x_i)\end{cases} \tag{1}$$

If membership function $q(x_i)$ decreases with x_i indicator, their relationship is expressed by:

$$q(x_i)=\begin{cases}1 & \text{if } x_i \le \min(x_i)\\ 1-\dfrac{x_i-\min(x_i)}{\max(x_i)-\min(x_i)} & \text{if } \min(x_i)<x_i<\max(x_i) \quad (2)\\ 0 & \text{if } x_i \ge \max(x_i)\end{cases} \tag{2}$$

The global sustainability index (Q) is the sum of the various indicators taking into account the weight (w_i) that each one has in the mathematical expression of the index. Considering m indicators for the process characterization, the final mathematical expression is given by:

$$Q(q;w)=\sum_{i=1}^{m} w_i q_i \tag{3}$$

4.2 Multi-criteria decision analysis based on weighting function variation

The multi-criteria decision analysis is performed with the weighting function variation. Several case scenarios are developed considering different weights for each indicator. This condition allows the analysis of the most relevant indicators on the sustainability assessment.

According to values range obtained through extensive bibliographic review, two index values are calculated, one referred to minimum values and other to maximum ones. For the indicators that have just a single value, this one is used in both situations. Several case studies are performed. In first case scenario (CS#1), all indicators are considered of equal importance, i.e. having the same weight (w_i = 11 %).

Efficiency, energy payback time, capital cost, electricity generation cost, greenhouse gases emissions and social acceptance are decisive indicators in the quantification of energy carrier systems sustainability (Afgan & Carvalho, 2004). According to Afgan & Carvalho (2004) and Hanjalic et al. (2008), where similar studies are presented, the most important indicator's weight coefficient is within the range of 60-70%. The mean value will be considered, i.e., a 65% weight coefficient for the most important indicator in each case study. Thus, in CS#2 to CS#7, per case, one indicator is considered more important than the others. This indicator will have a higher weight (w_i = 65 %) and the remaining an equal lower weight coefficient (w_i = 4,375 %).

For last, CS#8 considers that decisive indicators most relevant than the remainders. So, these indicators will have a higher weight (w_i = 14 %) and the remaining an equal lower weight coefficient (w_i = 7,5 %).

The respective weights for case studies are shown in Table 1. The membership function given by Equation (1) or (2) is used depending on the energy carrier system sustainability increase or decrease with the indicator, respectively (see Table 2).

In expressions (1) and (2) are used as maximum and minimum, respectively the largest and smallest value found for this indicator, given the range of values corresponding to all energy carriers. Thus, each indicator will be represented by a membership function that varies between 0 and 1.

Indicator, q_i		Weight, w_i (%)							
		CS#1	CS#2	CS#3	CS#4	CS#5	CS#6	CS#7	CS#8
q_1	Efficiency	11,1	65	4,375	4,375	4,375	4,375	4,375	14
q_2	Electricity generation cost	11,1	4,375	65	4,375	4,375	4,375	4,375	14
q_3	Capital cost	11,1	4,375	4,375	65	4,375	4,375	4,375	7,5
q_4	Lifetime	11,1	4,375	4,375	4,375	4,375	4,375	4,375	7,5
q_5	Greenhouse gases emissions	11,1	4,375	4,375	4,375	65	4,375	4,375	14
q_6	Land requirement	11,1	4,375	4,375	4,375	4,375	4,375	4,375	7,5
q_7	Job creation	11,1	4,375	4,375	4,375	4,375	4,375	4,375	7,5
q_8	Energy payback time	11,1	4,375	4,375	4,375	4,375	65	4,375	14
q_9	Social acceptance	11,1	4,375	4,375	4,375	4,375	4,375	65	14

Table 1. Weight of each indicator for the case studies.

Indicator		Sustainability	Equation used
q_1	Efficiency	Increases	Equation 1
q_2	Electricity generation cost	Decreases	Equation 2
q_3	Capital cost		
q_4	Lifetime	Increases	Equation 1
q_5	Greenhouse gases emissions	Decreases	Equation 2
q_6	Land requirement		
q_7	Job creation	Increases	Equation 1
q_8	Energy payback time	Decreases	Equation 2
q_9	Social acceptance	Increases	Equation 1

Table 2. Sustainability variation with indicator's value.

5. Analysis and discussion of results

Based on the mathematical formulation results, where the maximum and minimum values for the global sustainability index are obtained for each test scenario, the most relevant indicators are defined as well as the mix of energy carrier systems that should be considered in the electricity supply portfolio. In the following sections the results obtained with the case studies are discussed.

5.1 Case scenario n.^{er} 1 (CS#1): equal weighting factors for indicators

The minimum and maximum values of the sustainability index for each energy carrier system when it is considered an equal weighting factor (w_i = 11,1 %) for all indicators is shown in Fig. 11. The following considerations can be highlighted:

1. The high efficiency and lifetime of hydro systems contribute significantly to its global sustainability index;
2. The reduced E.P.B.T. and low cost of electricity generation associated with wind and nuclear systems contribute to their overall levels of sustainability;
3. The capital cost needed to generate energy by photovoltaic systems, geothermal and ocean (wave and tidal) penalizes their sustainability indexes;
4. The reduced CO_2 emissions associated with wind systems, hydro, hydrogen and nuclear contribute to their sustainability indexes;
5. The reduced land requirements of geothermal, hydrogen, nuclear and ocean energy and all fossil fuels conversion systems also influence their global sustainability index;
6. The number of jobs generated by conversion systems of hydrogen into electricity and in a lesser extent by photovoltaic systems potentates their index;
7. Social acceptance is less controversial in the wind, photovoltaic and hydro systems;
8. The global sustainability indexes for fossil fuel energy carrier systems (coal, natural gas and oil) rely on the reduced electricity generation cost, capital cost and land requirements when compared with other technologies;
9. The lifetime of fossil fuel energy carrier infrastructures benefit their global sustainability indexes;
10. The land requirement for a fossil fuel-fired plant to generate electricity (without taking into account natural resources extraction) is lower comparing to renewable energy plant, which promotes its global sustainability index;
11. Among the fossil fuel energy carrier systems, those of natural gas emit lower quantity of greenhouse gases, which increases their indicator value;
12. The number of jobs created in a fossil fuel-fired plant is higher than in a renewable one, enlarging this indicator, and consequently, promoting the increase of global sustainability indexes of fossil fuel energy carrier systems.

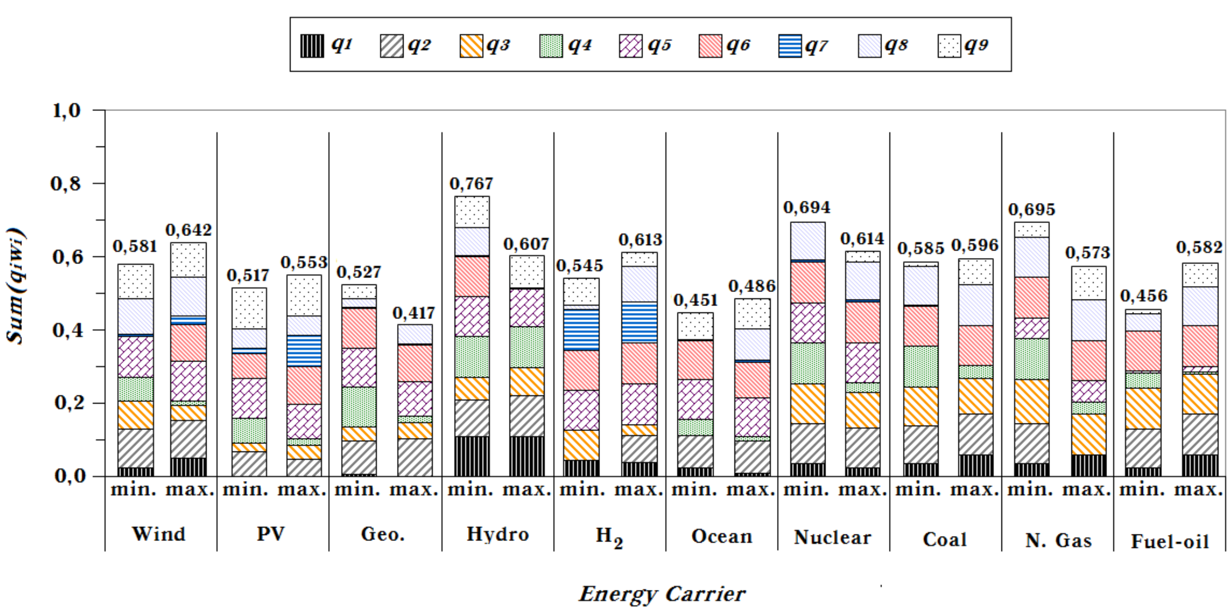


Fig. 11. Maximum and minimum values range of sustainability index for each energy carrier system - Case Scenario 1 (Equal weighting factors for indicators).

The analysis of this figure allows us to suggest a hierarchy of sustainability ranking of conversion technologies and propose a mix of technologies to convert energy into electricity. Thus, hydro, nuclear, natural gas and wind energy carrier systems are the ones which stand in front of a sustainable future for the electricity supply. Among these energy carrier systems, only one is based on fossil fuel, natural gas-fired plants. However, if nuclear energy is excluded from this comparison due to the controversy generated by this energy carrier system, coal and hydrogen conversion system are included in the front line of most sustainable energy conversion systems. Although fossil fuel-fired plants are a huge damage to ecology and its availability is very limited, natural gas and coal energy carriers are among those more globally sustainable due to the same weighting factor for all indicators.

Nevertheless, this analysis is refined considering the following case studies where the global sustainability is analysed from a single indicator view point. This kind of analysis is important to figure which are the indicators more significant on sustainability.

5.2 Case scenario n.er 2 (CS#2): highest weighting factor for efficiency indicator

Fig. 2 shows the sustainability index for each technology considering energy conversion efficiency as the core indicator (Case Scenario n.er 2: CS#2). The weighting factor for this indicator was considered as w_1 = 65 %. For this case scenario, hydro, natural gas and coal energy carrier systems are the most sustainable. The following renewable energy carrier systems most sustainable use hydrogen and wind as resource. By other hand, photovoltaic and geothermal energy carrier systems are the less sustainable.

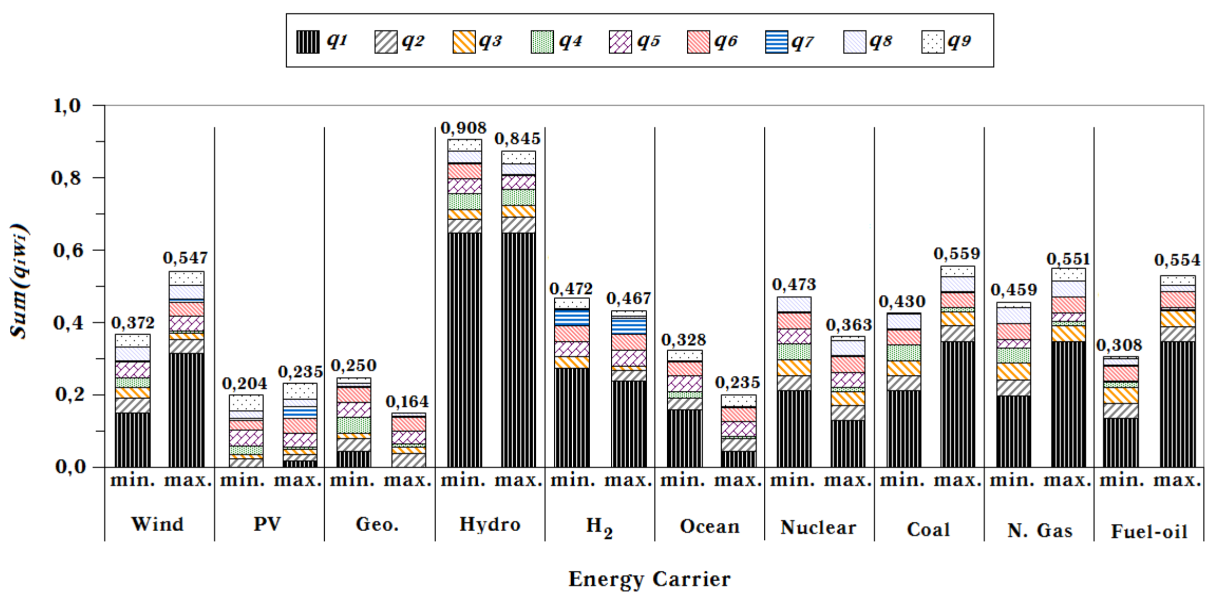


Fig. 12. Maximum and minimum values range of sustainability index for each energy carrier system - Case Scenario 2 (Highest weighting factor for efficiency indicator: q_1).

5.3 Case scenario n.er 3 (CS#3): highest weighting factor for electricity generation cost indicator

In this case scenario, the sustainability ranking is modified. Nuclear, hydro, coal and wind energy carrier systems are the most sustainable when electricity generation cost is considered the most relevant indicator to assess sustainability. Likewise in previous case scenarios, at least one fossil fuel energy carrier system is included among the most sustainable. Photovoltaic and hydrogen energy carrier systems are the less sustainable.

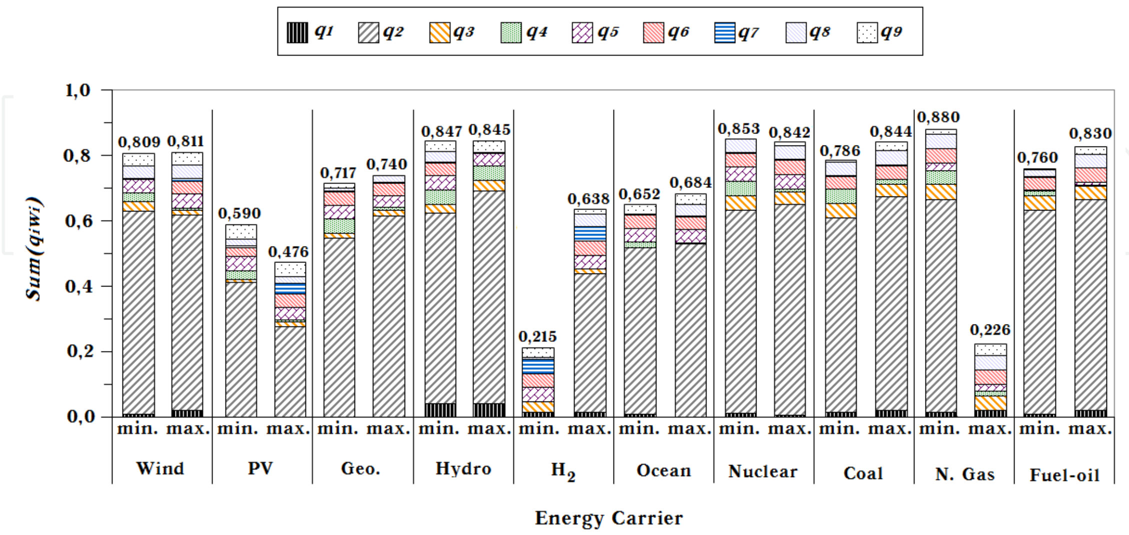


Fig. 13. Maximum and minimum values range of sustainability index for each energy carrier system - Case Scenario 3 (Highest weighting factor for electricity gen. cost indicator: q_2).

5.4 Case scenario n.^{er} 4 (CS#4): highest weighting for capital cost indicator

Considering case scenario n.^{er} 4 where capital cost is the most relevant indicator, the most relevant energy carrier systems are mainly based on fossil fuel resources (natural gas, nuclear, oil and coal). Following these systems appear the energy carrier systems based on renewable resources: hydro and wind. In this case study, ocean and photovoltaic energy conversion system are the less sustainable. These results mean that the capital cost for constructing and operating a fossil fuel-fired plant is less than a renewable one.

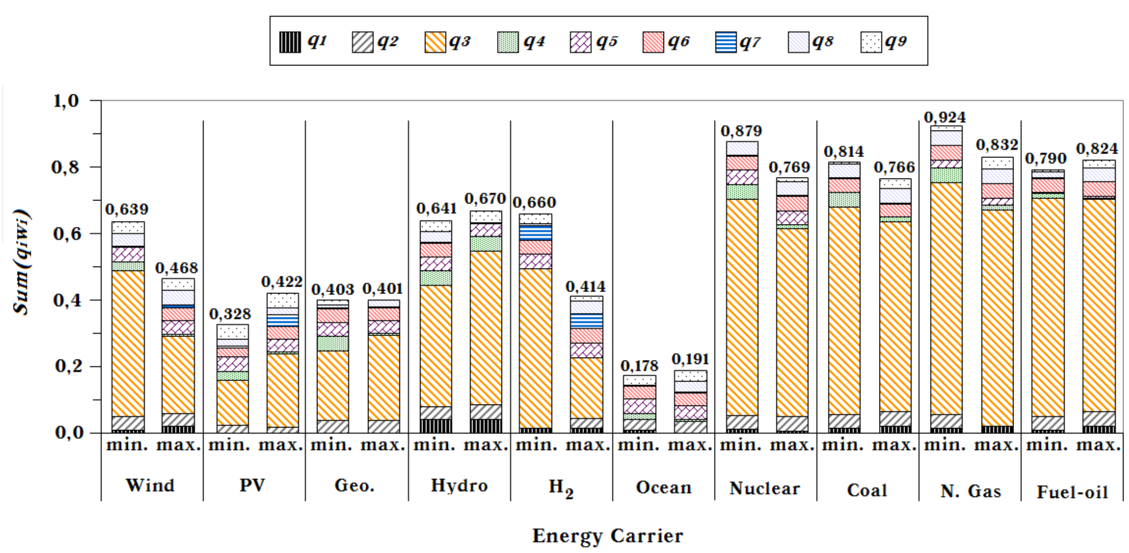


Fig. 14. Maximum and minimum values range of sustainability index for each energy carrier system - Case Scenario 4 (Highest weighting factor for capital cost indicator: q_3).

5.5 Case scenario n.er 5 (CS#5): highest weighting for greenhouse gases emissions indicator

For the case scenario where greenhouse gases (GHG) emissions is considered as the most relevant indicator (case scenario n.er 5), the ranking is composed by renewable energy carrier systems: nuclear, hydro and wind. All fossil fuel-fired power plants, i.e. natural gas, oil and coal energy carrier systems are the less sustainable. Due to the combustion emissions, these results were expected. Geothermal and photovoltaic energy conversion systems are the less sustainable among the renewable ones.

5.6 Case scenario n.er 6 (CS#6): highest weighting for energy payback time indicator

Case study n.er 6 considers E.P.B.T. as the core indicator. In this case, natural gas, nuclear and coal energy carrier systems are ahead in the ranking of most sustainable. Taking into account the results of previous case scenarios, fossil fuel-fired plants include the leader positions when economic and efficiency aspects are combined to define a mix for electricity supply. Geothermal and ocean energy conversion systems are the less sustainable.

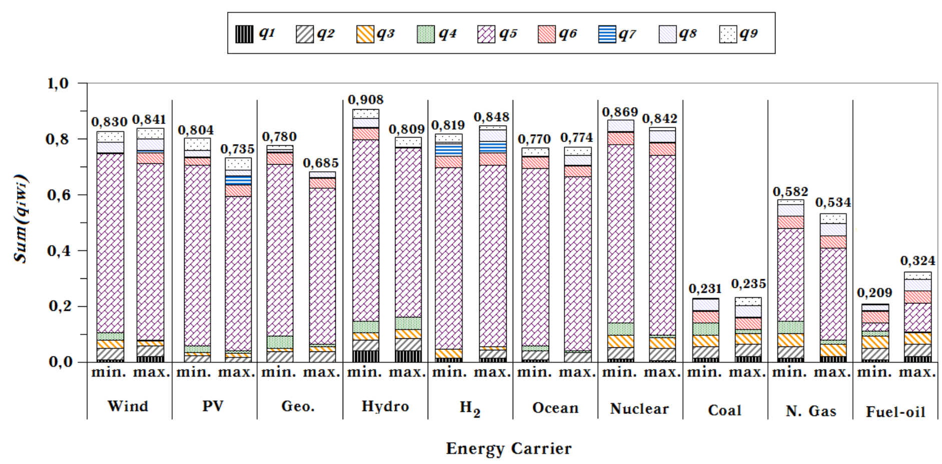


Fig. 15. Maximum and minimum values range of sustainability index for each energy carrier system - Case Scenario 5 (Highest weighting factor for GHG emissions indicator: q_5).

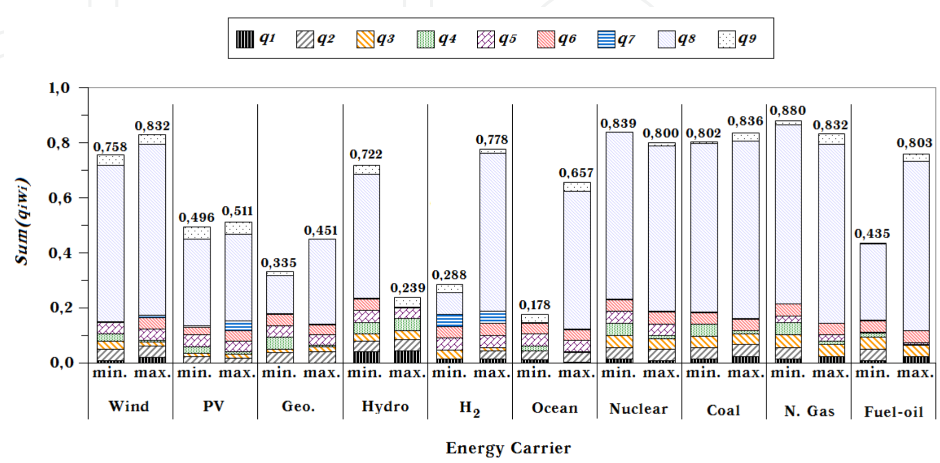


Fig. 16. Maximum and minimum values range of sustainability index for each energy carrier system - Case Scenario 6 (Highest weighting factor for energy payback time indicator: q_8).

5.7 Case scenario n.er 7 (CS#7): highest weighting for social acceptance indicator

Being social acceptance considered a meaningful indicator, there is a shift on leadership of the sustainability global index. Photovoltaic systems are considered now the most sustainable. Hydro and wind systems also include the leading group. Oil, nuclear and geothermal energy conversion systems are the less sustainable. The latter have reduced social acceptance due to the lack of reliable data. By other hand, nuclear and oil conversion systems possess low social acceptance worldwide due to the recent incidents.

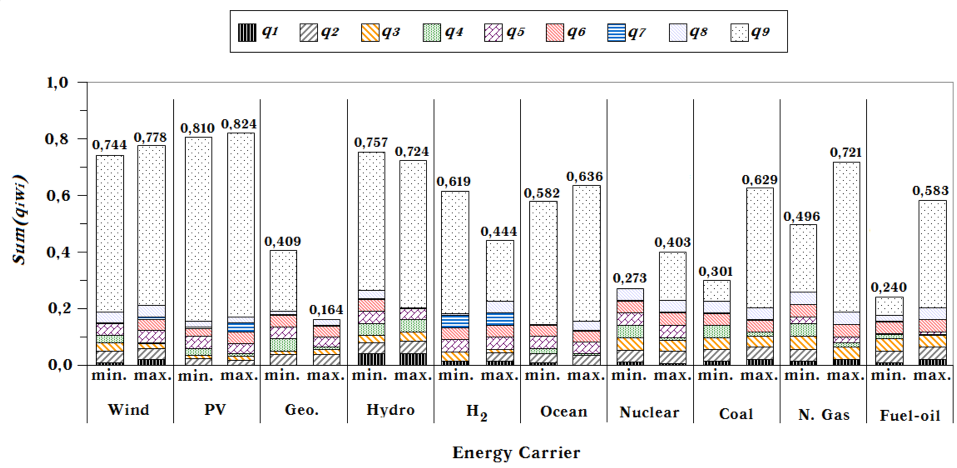


Fig. 17. Maximum and minimum values range of sustainability index for each energy carrier system - Case Scenario 7 (Highest weighting factor for social acceptance indicator: q_9).

5.8 Case scenario n.er 8 (CS#8): Higher weighting for selected indicators

A higher weighting factor is considered for selected indicators, i.e. efficiency, electricity generation cost, greenhouse gases emissions, energy payback time and social acceptance are considered as the relevant indicators to assess sustainability. Hydro, wind and nuclear energy carrier systems take the leadership for the mix on the electricity supply. Ocean, oil and geothermal energy carrier systems are the less sustainable assuming these conditions.

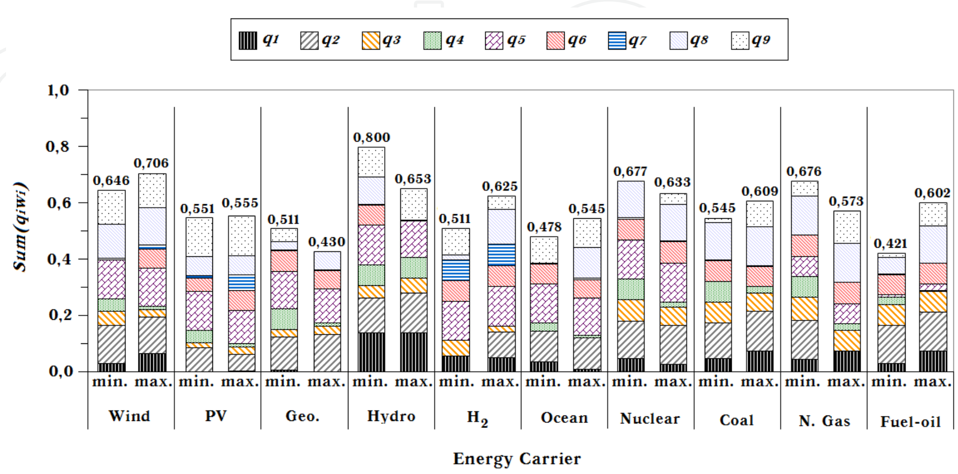


Fig. 18. Maximum and minimum values range of sustainability index for each energy carrier system - Case Scenario 8 (Highest weighting factor for selected indicators: q_1, q_2, q_5, q_8, q_9).

Table 3 includes a summary of the case scenarios. It is considered a ranking varying from 1 to 10 (equal to the number of the energy carrier systems assessed), corresponding respectively to an order from the less sustainable to the most sustainable. The sum of the global sustainability index for each energy conversion system, taking into account the case studies where one indicator is considered as the most relevant, provide an insight of the electricity supply portfolio mix more sustainable (see *total 1* in Table 3). Independently of the case study, analysing the different faces of a global sustainability, hydro, nuclear, wind and natural gas-fired power plants are those that should be considered as the most relevant on the electricity supply portfolio taking into account the individual significance of each indicator. It must be pointed out that among these four energy carrier systems, only one (natural gas) is of fossil fuel kind. Geothermal and ocean energy conversion systems are the opposite counterpart, i.e., are the less sustainable.

Case Scenario		Wind	PV	Geo.	Hydro	H2	Ocean	Nuclear	Coal	N.Gas	Oil
#1	Equal weight	**7**	4	2	**10**	5	1	**9**	6	**8**	3
#2	Efficiency	6	2	1	**10**	**7**	3	4	**8**	**9**	5
#3	Electricity gen. cost	**7**	2	5	**9**	1	4	**10**	**8**	3	6
#4	Capital cost	5	2	3	6	4	1	**9**	**7**	**10**	**8**
#5	GHG emissions	**8**	5	4	**9**	**7**	6	**10**	1	3	2
#6	E.P.B.T.	**7**	4	1	3	5	2	**9**	**8**	**10**	6
#7	Social acceptance	**8**	**10**	1	**9**	5	**7**	2	4	6	3
#8	Selected indicators	**9**	4	1	**10**	5	3	**8**	6	**7**	2
Total 1: $\sum_{i=2}^{7} Q(q;w)_{CS\#i}$		**41**	25	15	**46**	29	23	**44**	36	**41**	30
Total 2: $\sum_{i=1}^{8} Q(q;w)_{CS\#i}$		**57**	33	18	**66**	39	27	**61**	48	**56**	35

Table 3. Summary of global sustainability index variation.

Despite of the accordance between the ranking results on the energy carrier systems sustainability for electricity supply for the different case scenarios, it must be taken into account that all case scenarios were developed for a worldwide scale. For a particular national context, the results of the comparative assessment of energy supply options will be significantly different as some constrains would be considered. Examples of these constrains on a national level are described as follows:

- PV systems create the number of jobs depicted in Fig. 9 only in countries that do manufacture them, but not to the same extent in countries that import them;

- Social acceptance criteria is strongly locally dependent. For instance, Fig. 10 shows quite high acceptance for nuclear, but likewise other countries, it is known that in Germany the nuclear option is already abandoned. In the particular context of this country, the nuclear option must be neglected, i.e., the weighting factor must be zero;
- The possibility of using geothermal energy in large extend to supply electricity demand is also strongly locally dependent. In 1999, were identified 39 countries as having the potential to meet 100% of their electricity needs through domestic geothermal resources, although significant power production had been developed in only nine: Costa Rica, El Salvador, Guatemala, Iceland, Indonesia, Kenya, Nicaragua, Papua New Guinea, and the Philippines (Holm et al., 2010). Nowadays, geothermal plants around the world (in 24 countries) generated 0.33% (67.2 TWh) of the electricity demand (20 055 TWh). Based on this example, it must be pointed out that not all possible energy sources are uniformly distributed across all countries.

Many other constrains can be set for the indicators used to quantify sustainability. Although this can be seen as a limitation of the model, it is important to clarify that this comparative assessment of energy supply options can be developed in a national context, requiring precise values range of the indicators, null weighting values when a specific indicator can not be considered as well as the availability of the energy sources. Using these values, the energy carrier systems sustainability can be assessed in a national context, providing additional case scenarios to those that were developed along this chapter.

6. Summary

In a global sustainability context, now and near future electricity supply must be supported by an energy carrier systems mix that provide affordable, abundant, and reliable electricity while minimizing impacts on the environment. This chapter provides a road-map to develop sustainability analysis and the specific results for the energy carrier systems' context.

A wide range of indicators is used to characterize the technological, economical, environmental and social dimensions of current energy carrier conversion systems into electricity. Minimum and maximum values of selected indicators were collected from specialized and specific literature for each energy conversion system. Firstly, the same weight is given to all indicators in order to evaluate a global sustainability index from an equality point of view. Then, indicators are used separately to assess sustainability. For this evaluation, the weighting factor of a selected indicator is higher than the others. Finally, the weighting factors of indicators assumed as more relevant, are higher compared to the weighting factors of the remainder indicators.

A hierarchy ranking is outlined from the results of this multi-criteria analysis. Hydro, nuclear, wind and natural gas-fired power plants mix stand out for a sustainable future for the electricity supply. Notice that social acceptance of nuclear technology was based on data collected prior to the disaster in Fukushima power station. Nowadays, the social acceptance of this technology is probably lesser, affecting its overall level of sustainability.

In the opposite side, geothermal and ocean energy conversion systems are and will continue to be the less sustainable. This condition arises from the specific needs for the location of geothermal power plants as well as from the low values for each indicator when comparing with the others energy conversion systems. Ocean energy conversion system also includes this group mainly due to its technological infant stage. This energy conversion system still requires a lot of research and development to be competitive.

An update on variation range of different sustainability indicators is provided. The implementation of a particular system type over another change continuously, due to usual technology improvements. These improvements increase the energy conversion efficiency and reduce the greenhouse gases emissions, as well as the installation and operation costs. Additionally, these improvements can lead to changes in society mentality. However, is must be taken into account that all test scenarios were developed on a worldwide basis. In a particular national context, some constrains must be evaluated for each indicator. Additionally, the values range of each indicator must be determined locally.

This work aims to contribute on the debate on current and future electricity supply from energy carrier systems, taking into account that we will need to continue to use fossil fuel to supply the worldwide increasing demand on electricity.

7. References

ABB (2011). *Trends in global energy efficiency 2011*. Enerdata and Economist Intelligence Unit, The ABB Group.

Afgan, N. H. & Carvalho, M. G. (2002). Multi-criteria assessment of new and renewable energy power plants. *Energy*, Vol.27, No.8, pp. 739-755.

Afgan, N.H. & Carvalho, M.G. (2004). Sustainability assessment of hydrogen energy systems, *International Journal of Hydrogen Energy*, Vol.29, No.13, pp. 1327-1342.

Allan, G. et al. (2011). Levelised costs of Wave and Tidal energy in the UK: Cost competitiveness and the importance of "banded" Renewables Obligation Certificates, *Energy Policy*, Vol.39, pp. 23-39.

Banerjee, S., Duckers, L. J., Blanchard, R. & Choudhury, B. K. (2006). *Life Cycle Analysis of Selected Solar and Wave Energy Systems*, Advances in Energy Research, 2006.

Beardsley, E (2006). *France Presses Ahead with Nuclear Power*, NPR.

Biswas, P. (2009). Water Use and Re-Use in Energy Technologies in a Carbon Constrained World. *Proceedings of First National Expert and Stakeholder Workshop on Water Infrastructure Sustainability and Adaptation to Climate Change*, Arlington, Virginia, USA, January 6-7.

Brito, A. & Huckerby, J. (2010). *Implementing Agreement on Ocean Energy Systems - Annual Report*, International Energy Agency (IEA), Paris, France.

Cruz, J. & Sarmento A. (2004). *Energia das ondas: Introdução aos aspectos tecnológicos, económicos e ambientais*, Instituto do Ambiente. (in portuguese)

Dalton, G. J. & Lewis, T. (2011). Metrics for measuring job creation by renewable energy technologies, using Ireland as a case study, *Renewable and Sustainable Energy Reviews*, Vol.15, pp. 2123-2133.

Dalton, G. J. et al. (2010). Case study feasibility analysis of the Pelamis wave energy convertor in Ireland, Portugal and North America, *Renewable Energy*, Vol.35, pp. 443-455.

Denny, E. (2009). The economics of tidal energy, *Energy Policy*, Vol.37, No.5, pp. 1914-1924.

Dones, R. & Heck, T. (2006). LCA-Based evaluation of ecological impacts and external costs of current and new electricity and heating systems. *Proceedings of Materials Research Society Symposium*, Vol.895, pp. 37-50.

Dunnett, D. & Wallace, J. S. (2009). Electricity generation from wave power in Canada, *Renewable Energy*, Vol.34, pp. 179-195.

EFL (2011). *How Transitioning to Renewable Energy Can Create Jobs in the Dominican Republic*. Energy for Life (EFL), Milan, Italy.

EIA (2010). *Summary status for the US*, U.S. Energy Information Administration (EIA).

EIA (2010). *Updated Capital Cost Estimates for Electricity Generation Plants*, U.S. Energy Information Administration (EIA), U.S. Department of Energy, Washington, USA.

Erdogmus, B. et al. (2006). Economic assessment of geothermal district heating systems: A case study of Balcova-Narlidere, Turkey. *Energy and Buildings*, Vol.38, No.9, pp. 1053-1059.

ESMAP (2007). *Technical and economic assessment of off-grid, mini-grid and grid electrification technologies*. Energy Sector Management Assistance Program (ESMAP), Technical Paper 121/07, The International Bank for Reconstruction and Development (The World Bank), Washington, DC, USA.

Evans, A. et al. (2009). Assessment of sustainability indicators for renewable energy technologies. *Renewable and Sustainable Energy Reviews*, Vol.13, No.5, pp. 1082-1088.

Evans, A., Strezov, V. & Evans, T. (2010). Comparing the sustainability parameters of renewable, nuclear and fossil fuel electricity generation technologies. *Proceedings of 21st World Energy Congress - Montreal 2010*, Montreal, Canada, September 11 - 16.

Evrendilek, F. & Ertekin, C. (2003). Assessing the potential of renewable energy sources in Turkey. *Renewable Energy*, Vol.28, No.15, pp. 2303-2315.

EWEA (2009). *Wind Energy – The Facts: Chapter 6: Social acceptance of wind energy and wind farms.* European Wind Energy Association (EWEA), Earthscan Ltd., March.

Farret, F.A. & Simões, M. G. (2006). *Integration of alternative sources of energy*, Wiley-IEEE Press, 2006.

Frantzis, L. (2010). Job Creation Opportunities in Hydropower. National Hydropower Association Annual Conference.

Gagnon, L. et al. (2002). Life-cycle assessment of electricity generation options: The status of research in year 2001. *Energy Policy*, Vol.30, pp. 1267-1278.

Gallup, D. L. (2009). Production engineering in geothermal technology: A review, *Geothermics*, Vol.38, No.3, pp. 326-334.

Graus, W.H.J., Voogt, M. & Worrell, E. (2007). International comparison of energy efficiency of fossil power generation. *Energy Policy*, Vol.35, pp. 3936–3951.

Hanjalic, K., van de Krol, R. & Lekic, A. (2008). *Sustainable Energy Technologies, Options and Prospects*, Springer, 2008.

Holm, A., Blodgett, L. Jennejohn, D. & Gawell, K. (2010). *Geothermal Energy: International Market Update*, Geothermal Energy Association, May 2010.

IEA (2011a). *2011 Key World Energy Statistics*, Organisation for Economic Co-operation and Development (OECD)/International Energy Agency (IEA), Paris, France.

IEA (2011b). *World Energy Outlook 2011*, Organisation for Economic Co-operation and Development (OECD)/International Energy Agency (IEA), ISBN , Paris, France.

IPCC (2007). *IPCC Fourth Assessment Report: Climate Change 2007*. Working Group III - Intergovernmental Panel on Climate Change (IPCC), B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kaldellis, J. K. (2008). Critical evaluation of the hydropower applications in Greece, *Renewable and Sustainable Energy Reviews*, Vol.12, No.1, pp. 218-234.

Kannan, R. et al. (2006). Life cycle assessment study of solar PV systems: An example of a 2.7 kWp distributed solar PV system in Singapore. *Solar Energy*, Vol.80, pp. 555-563.

Lako, P. (2010). *Marine Energy*, International Energy Agency (IEA), Technology Brief E13 November 2010.

Lee, T. J. et al. (2007). Strategic environments for nuclear energy innovation in the next half century, *Progress in Nuclear Energy,* Vol.49, pp. 397-408.

Mansure, A. J. & Blankenship, D. A. (2010). Energy Return in Energy Investment, An Important Figure-Of-Merit For Assessing Energy Alternatives. *Proceedings of 25th Workshop on Geothermal Reservoir Engineering*, Standford University, California, USA, February 1-3, 2010.

Mendes, R. P., Gaspar, P. D. & Gonçalves, L. C. (2011b). Sustainability quantification of renewable energy conversion systems for electricity supply. *Proceedings of the International Conference on Engineering ICEUBI 2011*, University of Beira Interior, Covilhã, Portugal, November 28-30.

Mendes, R. P., Gonçalves, L. C. & Gaspar, P. D. (2011a). Comparação da sustentabilidade das tecnologias de conversão de energia a partir de fontes renováveis por indicadores tecnológicos, económicos, ambientais e sociais. *Proceedings of X Congresso Ibero - Americano em Engenharia Mecânica*, Porto, Portugal, September 4-7.

NEI (2011a). *Protecting the Environment*. Nuclear Energy Institute.

NEI (2011b). *New Nuclear Plants: An Engine for Job Creation, Economic Growth*. Nuclear Energy Institute (NEI).

NRC (2011). *Generic Environmental Impact Statement for License Renewal of Nuclear Plants*. U.S. Nuclear Regulatory Commission (NRC), Staff report NUREG-1437.

Parker, R. et al. (2007). Energy and carbon audit of an offshore wave energy converter, *Proceeding of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, Vol. 221, pp. 1119-1130, 2007.

Peters, N. (2010). *Promoting Solar Jobs: A policy framework for creating solar jobs in New Jersey*. New Jersey.

Plowman, C. (2004). *U.S. Job Creation Due to Nuclear Power Resurgence in United States*. U.S. Department of Energy.

PREGA (2006). *Fuel switching from oil to gas for power generation*. Promotion of Renewable Energy, Energy Efficiency and Greenhouse Gas Abatement (PREGA).

Randolph, J. & Masters, G. M. (2008). *Energy for Sustainability: Technology, Planning, Policy*, Island Press, 2008.

Raugei, M. & Frankl, P. (2009). Life cycle impacts and costs of photovoltaic systems: Current state of the art and future outlooks. *Energy*, Vol.34, No.3, pp. 392-399.

REN21 (2011). *Renewable 2011 - Global Status Report*, Renewable Energy Policy Network for the 21st Century, Paris, France.

Rinebold, J. M., Drajer, T. & Brzozowski, A. (2009). *A National "Green Energy" Economic Stimulus Plan Based in Investment in the Hydrogen and Fuel Cell Industry*. The Connecticut Center for Advance Technology, Inc.

Roth, S. et al. (2009). Sustainability of electricity supply technology portfolio. *Annals of Nuclear Energy*, Vol.36, No.3, pp. 409-416.

Rourke, F. O. et al. (2010). Tidal energy update 2009. *Applied Energy*, Vol.87, No.2, pp. 398-409.

Schneider, M., Froggatt, A. & Thomas, S. (2011). *The world nuclear industry status report 2010–2011: Nuclear Power in a Post-Fukushima World, 25 Years After the Chernobyl Accident*, Worldwatch Institute, Washington, D.C., U.S.A.

Sherwani, A. F. et al. (2010). Life cycle assessment of solar PV based electricity generation systems: A review. *Renewable and Sustainable Energy Reviews*, Vol.14, pp. 540-544.

Soerensen, H. C., Naef, S., Anderberg, S. & Hauschild, M. Z. (2007). Life Cycle Assessment of the Wave Energy Converter: Wave Dragon, *Proceedings of International Conference on Ocean Energy*, Bremerhaven, 2007.

Ungemach, P. (2007). Conclusions of the Workshop: Increasing policy makers awareness and public acceptance. *Proceedings of ENGINE Workshop 6 "Increasing policy makers 'awareness and the public acceptance", ENhanced Geothermal Innovative Network for Europe (ENGINE)*, Athens, Greece, September.

van Bree, B. & Bunzeck, I. (2010). WP6*: D6.1: Social acceptance of hydrogen demonstration projects*. NextHyLights Industry and Institute partners, Supporting Action of the Fuel Cell and Hydrogen Joint Undertaking (FCH JU), New Energy World JTI framework, European Commission, August.

Varun et al. (2009). Energy, economics and environmental impacts of renewable energy systems, *Renewable and Sustainable Energy Reviews*, Vol.13, No.9, pp. 2716-2721.

Varun, Bhat, I.K. & Prakash, R. (2009). LCA of renewable energy for electricity generation systems--A review. *Renewable and Sustainable Energy Reviews*, Vol.13, No.5, pp. 1067-1073.

Vob, A. (2006). A Comparative Assessment of Electricity Generation Options from an ecological and sustainability viewpoint," *Proceedings of the International Conference on Nuclear Power Plants for Poland* (NPPP), Warsaw, Poland, June 1-2, 2006.

Voss, A. (2001). LCA and External Costs in Comparative Assessment of Electricity Chains. Decision Support for Sustainable Electricity Provision? *Proceedings of IEA Conference - Energy Policy and Externalties: The Life Cycle Analysis Approach*, November 15-16.

Wackernagel, M. & Monfreda, C. (2004). Ecological Footprints and Energy. *Encyclopedia of Energy*, Vol.2., Elsevier Inc.

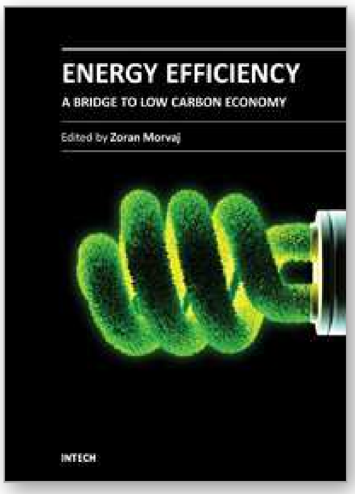
Wartmann, S., Jaworski, P., Klaus, S. & Beyer, S. (2009). *Scenarios on the introduction of co2 emission performance standards for the eu power sector*. Report commissioned by the European Climate Foundation. EcoFys Germany GmbH, Niederlassung Nürnberg, Germany.

WavEC (2004). *Potential and Strategy for the Development of Wave Energy in Portugal*, Wave Energy Centre (WavEC).

WNA (2010). *Another drop in nuclear generation*, World Nuclear Association (WNA) News.

WNA (2011). *Energy Analysis of Power Systems*, World Nuclear Association (WNA).

WNA (2011). *The Economics of Nuclear Power*, World Nuclear Association, url: http://www.world-nuclear.org/info/inf02.html acessed: [28-04-2011].
WWEA (2011). *World Wind Energy Report 2010*, World Wind Energy Association (WWEA), Bonn, Germany.



Energy Efficiency - A Bridge to Low Carbon Economy
Edited by Dr. Zoran Morvaj

ISBN 978-953-51-0340-0
Hard cover, 344 pages
Publisher InTech
Published online 16, March, 2012
Published in print edition March, 2012

Energy efficiency is finally a common sense term. Nowadays almost everyone knows that using energy more efficiently saves money, reduces the emissions of greenhouse gasses and lowers dependence on imported fossil fuels. We are living in a fossil age at the peak of its strength. Competition for securing resources for fuelling economic development is increasing, price of fuels will increase while availability of would gradually decline. Small nations will be first to suffer if caught unprepared in the midst of the struggle for resources among the large players. Here it is where energy efficiency has a potential to lead toward the natural next step - transition away from imported fossil fuels! Someone said that the only thing more harmful then fossil fuel is fossilized thinking. It is our sincere hope that some of chapters in this book will influence you to take a fresh look at the transition to low carbon economy and the role that energy efficiency can play in that process.