Estimation of critical CO_2 values when planning the power source in water desalination: The case of the small Aegean islands

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Abstract

Climate change is one of the most important issues our world faces today and it is responsible for a number of natural disasters that threaten human life and existence. Carbon dioxide, produced from almost every energy consuming activity, is the dominant greenhouse gas responsible for global warming. Water desalination is an energy intensive activity, and when it is powered by conventional energy sources, significant amounts of CO_2 are released. For every cubic metre of fresh water produced, there is a 2 kg of CO_2 reduction if renewable energy sources (RES) are used instead of electricity from the local grid. On the other hand, the cost of fresh water produced by desalination is much less if conventional sources of energy are used.

Making appropriate policy choices require information on both costs and benefits. So here we estimate the critical CO_2 cost, above which desalination units should use renewable energy instead of conventional energy sources. It was found that the critical CO_2 emissions cost can be close to the CO_2 capture cost and in many cases less than the penalties imposed by the European Commission. Several case studies of water desalination in the Aegean islands verify the conclusions.

Keywords: Desalination; renewables; carbon dioxide, Greece*

1. Introduction

In the late 1980s, interest was attracted to the issue of global climate change. Many studies focussed on the options for limiting emissions of greenhouse-related gases and managing the consequences of global warming and climate change.

The text of the Convention in Kyoto, ratified by the European Union Member States in 2002, promised to prevent "dangerous anthropogenic interference with the climate system" (UNFCCC, 1998). With this, EU countries agreed on reducing their collective emissions of six key greenhouse gases until 2012 by 8% with respect to the 1990 figures. Hence, there has been a turn to environmentally friendly sources of energy, because energy generation and use processes are among the most important greenhouse gases emission sources.

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Water desalination is an energy demanding process. Today, the most popular method for the desalination in small size units is reverse osmosis, a technique in which salty water (brackish or seawater) is forced through membranes in order to reduce its salinity. The amount of energy required for the production of one cubic metre of fresh water, sometimes called *specific energy consumption*, depends upon the salinity of the input water and the efficiency of the desalination unit.

Small desalination units have a fresh water output ranging from one to twenty m^3 per day, capable of meeting the drinking water and sanitary needs of a small village. A rough estimation of the energy required for the production of one cubic metre of fresh water is 4 kWh, therefore for the production of 10 m^3/day a desalination machine, operating continuously (powered e.g. by grid electricity) should have a power in the range of two to three kW after allowing for availability, efficiency and recovery factors.[1] Moreover, in case of desalination systems with higher production capacity, the specific energy consumption can be as low as 2.5 kWh/m^3 (SYCHEM, 2007). However more powerful desalination systems are needed when the energy is supplied by renewable sources such as the sun or the wind, because their operation is limited to the fraction of time that the energy resource is available. Besides, desalination units also need a water storage facility for balancing supply and demand and a brine disposal system, which adds to the cost of the required equipment. Figure 1 describes the basic structure of a desalination model.

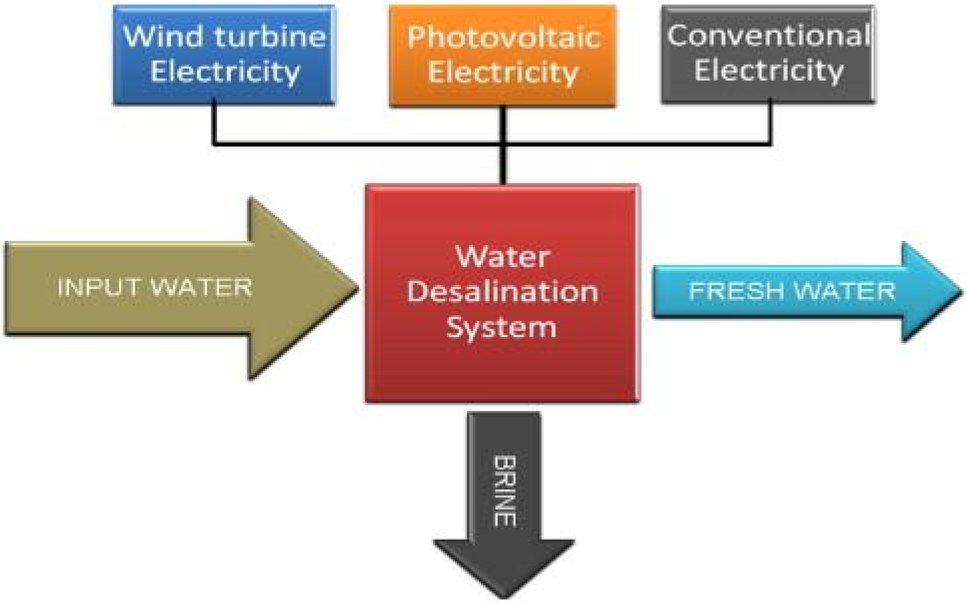

Figure 1: The desalination model

2. Review of current literature

Many studies have been published for the estimation of water desalination cost as well as the evaluation of the environmental impact of desalination processes, mainly focussing on the chemicals used and brine disposal. Calculations of water desalination cost for different valuations of CO_2 emissions, through imposed carbon tax, were also made (Agashichev and El-Nashar, 2005). Munoz and Fernandez-Alba compared two different desalination systems, one using brackish water and the other seawater. It was found that the one that uses

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[1] *The recovery factor is the ratio of fresh water output over the volume of water input.*

brackish water has significantly lower (almost 50%) environmental impact due to lower electricity requirements. (Munoz and Fernandez-Alba, 2008)

A number of Life Cycle Assessment studies have been used to evaluate the different impact of polluting categories and evaluation methods of different energy providing systems and desalination methods. Raluy et al. (Raluy et al., 2006; Raluy et al., 2005a, b; Raluy et al., 2004), compare the most commonly used desalination technologies (multi stage flash, multieffect evaporation and reverse osmosis) and draw three main conclusions. First, the environmental load associated to the operation stage is much higher than in the assembly and disposal stage, due to high energy requirements of desalination processes. Furthermore, reverse osmosis technology has a much lower environmental load due to higher efficiency and 5 to 6 times lower energy consumption. Finally, the airborne emissions obtained from an electricity production system based on renewable energy sources can be even 70 times lower than those obtained when the electricity production system is burning fossil fuels.

3. Methodology for the estimation of critical CO_2 emissions cost

Grid electricity generated mainly from coal or heavy fuel is the dominant energy source in Greece. Therefore the consumption of a marginal unit of grid electricity is associated with significant airborne emissions. On the other hand, grid electricity is practically uninterruptible and cheap in contrast with the intermittent electricity produced by photovoltaic cells and wind mills. The solution of *autonomous* desalination systems based on renewable energy is more expensive, but less harmful to the environment, and it is of interest to compare costs and benefits of different desalination methods by considering the environmental implications as well.

When comparing different energy supply sources for water desalination, it is necessary to internalise the cost of CO_2 emissions in cost-benefit calculations. One way of introducing CO_2 in the analysis is by adding the cost of pollution to the cost of desalination process as follows:

$$C_R + c_2 \times q_R < C_C + c_2 \times q_C$$

where:

C_R : Total fresh water desalination cost when only RES is used (€/m^3)
C_C : Total fresh water desalination cost when only conventional energy source is used (€/m^3)
c_2 : CO_2 cost valuation (€/t)
q_R : Quantity of CO_2 produced from the renewable source of energy, (t/m^3)
q_C : Quantity of CO_2 produced from the conventional source of energy, (t/m^3)

When both environmental and financial costs are considered, the shift from conventional to renewable energy sources is economically feasible if the inequality holds true.

Therefore, one may calculate the critical CO_2 value (c_2), above which RES is financially attractive, by solving the equation:

$$c_2 = \frac{C_R - C_C}{q_C - q_R} \tag{1}$$

The higher the cost or the amount of CO_2 generated by the conventional energy source, the more attractive the RES appears to be. When the cost differential of renewable to conventional systems is sufficiently small as compared to the difference of CO_2 generated quantities by the two systems, or when the value of CO_2 exceeds this ratio, RES-driven water desalination becomes economically viable.

The total annual cost of a conventional energy water desalination system consists of the cost of the unit itself (annual equivalent cost) plus the cost of electricity (or other form of energy) required for the desalination:

$$C_C = D_C \times a_{n,i}^{-1} + c_e \times q_e$$

where:

D_C : Purchase cost of the water desalination unit to be used with conventional energy source, net of any associated subsidy (€/m^3)

c_e : Electricity cost as charged to consumers ((€/kWh)

q_e : Specific energy consumption (kWh/m^3)

i : Interest rate

n : Number of years of the economic life of the desalination unit D

$a_{n,i}$: Annuity present value factor $\left(\frac{1-(1+i)^{-n}}{i} \right)$ for the estimation of the annual equivalent capital cost of the desalination unit.

Autonomous (RES driven) Desalination Systems

The cost of an *autonomous* (only renewable energy) system has no energy consumption cost component, but it is charged with the cost of a generally more powerful desalination equipment and the cost of the RES unit (*R*), which is required for the installation.

$$C_R = D_R \times a_{n,i}^{-1} + R \times a_{r,i}^{-1}$$

where:

D_R : Purchase cost of water desalination unit to be used with the RES, net of any associated subsidy (€/m^3)

R : Purchase cost of RES net of any associated subsidy (€/m^3)

n,r : Number of years of the economic life of the desalination (*n*) and the renewable energy (*r*) units respectively

An *autonomous* desalination system powered only by renewable source(s) will have to be more powerful than the corresponding conventional system, if it has to deliver similar amounts of fresh water per year. For example, if the RES is available 25% of the time, the desalination unit will have to be roughly four times more powerful than the unit in a similar grid electricity driven system.[2]

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[2] *The size of RES (solar PV or wind generator) depends upon solar and wind potential. Here, we assume an appropriate size to match the capacity of the desalination machine.*

Both autonomous and conventional desalination systems also have maintenance and "other" expenses, the difference of which is usually small and for simplicity are omitted here.[3]

Hybrid Desalination Systems

The case of adding an extra renewable energy source to a conventional energy driven desalination system is justified only if the cost of conventional energy saved, e.g. grid electricity, is sufficient to pay the capital cost of the renewable energy system. (This is true for any energy consuming application and it is not particularly related to water desalination).

$$R \times a_{r,i}^{-1} < c_e \times q_e \times r_e$$

and the total cost per m^3 for the case of a hybrid system (C_H) is:

$$C_H = D_C \times a_{n,i}^{-1} + R \times a_{r,i}^{-1} + c_e \times q_e \times (1 - r_e)$$

where:

r_e is the proportion of energy supplied by the renewable energy system and the capital cost of the desalination unit (D_C) is the purchase cost of the water desalination unit used with conventional energy source, net of any associated subsidy.

Note:

If the Public Power Corporation (PPC) is buying the renewable electricity produced at a price higher than its cost of production (by the RES unit), it pays to invest in large RES system and make profits by selling all surplus energy to the PPC. In the case of a renewable energy purchase price even higher than c_e, it is more profitable for the renewable energy generating system to sell all its production to the PPC and the desalination system to operate on (cheaper to buy) grid electricity. In Greece, today, PV generated electricity is purchased by the PPC at as high as 0.45 €/kWh (compared with average PPC consumer billing charge of 0.08 €/kWh), but this subsidisation is not expected to last long.

Usually, water desalination systems are installed in regions where the marginal cost of water is high enough to justify their introduction. For example, in many Greek islands, local water sources are insufficient and demand is satisfied by water imported at high cost. At the current state of technology seawater desalination is in many cases cost effective and, as a result, there is a large number of desalination stations of medium and large size around the world.

In order to examine the possibility of introducing desalination systems powered by RES, we consider the situation where the desalination system is expected to supply part of the water demand and that all water produced is consumed by the local community. In this case, the condition of economic viability of the renewable energy system as specified in (1) is:

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[3] *The reference is for similar desalinated water quantities and site installation. Hence, chemicals, membranes, filters, labor, insurance and any other maintenance costs may appear slight differences.*

$$c_2 > \frac{\left(D_R \times a_{n,i}^{-1} + R \times a_{r,i}^{-1}\right) - \left(D_C \times a_{n,i}^{-1} + c_e \times q_e\right)}{q_C - q_R} \tag{2}$$

and in the case of the hybrid system, where $D_R = D_C$,

$$c_2 > \frac{R \times a_{r,i}^{-1} - c_e \times q_e \times r_e}{q_C - q_R}$$

With the use of appropriate water desalination models, for example AUDESSY[4], it is possible to estimate the size of the required equipment, D_R, D_C and R as well as the energy needs of the systems for each case.

4. CO_2 emissions associated with different energy sources

Conventional electricity generating stations release CO_2 and other greenhouse gases not only during their usual operation, but they have also caused CO_2 releases during the stage of the production of their components and their transportation to the place they are located. Life cycle analysis methods are usually adopted for the estimation of total CO_2 or CO_2-eq[5] per unit of electricity generated. In the case of renewable energy generating systems (eg. PV or wind generators), which have no CO_2 related emissions in their operation, the environmental burden is caused during the construction and transport of their components. Table 1 summarizes the emissions from different energy sources.

4.1 Emissions from oil burning electricity generation stations

The lowest estimations for CO_2 emissions from oil-fired power generation stations are around 742 gCO_2/kWh (Hondo, 2005). However, others found that gas emissions for an oil plant can reach 880 gCO_2.eq/kWh (Jungbluth, 2005) and other calculations are indicating even higher values, reaching 942 gCO_2/kWh (Stoppato, 2008).

4.2 Emissions from photovoltaic panels

Life Cycle Photovoltaic (PV) CO_2 typically ranges from 21 to 43 gCO_2-eq/kWh depending on materials used (Fthenakis et al., 2008). Bernal-Agustin and Dufo-Lopez (2006) estimated that the CO_2 emissions during the life cycle of a PV system is 41.7g/kWh. Jungbluth (2005) estimated that GHG emissions from PV range from 39 to 110 gCO2-eq/kWh. Hondo, (2005) estimated a range from 26 to 53.4g CO_2/kWh due to different amounts of silicon used in the PV modules. Other estimations have showed that CO_2 emissions are about 20 times less when photovoltaics are used instead of diesel generators (Koroneos et al., 2006). Finally, one of the highest estimations is that of 104 gCO_2-eq/kWh from a p-Si system (Pehnt, 2006).

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[4] *AUDESSY is a decision support tool that can estimate with some precision the water desalination unit sizing and cost for systems using renewable energy sources. The software has been developed by Agricultural University of Athens, within the framework of the ADIRA project (partially funded by the EC).*

[5] *The CO_2-eq is calculated based on the global warming potential of greenhouse gases (GHG). The six GHG's considered by the UNFCC are CO_2, CH_4, N_20, HFCs, PFCs and SF_6.*

Table 1
Emissions from different energy sources

Technology	Emissions (gCO_2/kWh)	References
Oil burning electricity generation stations	742	(Hondo, 2005)
	880	(Jungbluth, 2005)
	942	(Stoppato, 2008)
Photovoltaic panels	21-43	(Fthenakis et al., 2008)
	41.7	(Bernal-Agustin and Dufo-Lopez, 2006)
	26-53.4	(Hondo, 2005)
	39-110	(Jungbluth, 2005)
	104	(Pehnt, 2006)
Wind turbines	2	(Lenzen and Wachsmann, 2004)
	9-11	(Pehnt, 2006)
	11-13	(Jungbluth et al., 2005)
	14.8	(Ardente et al., 2008)
	9.7-16.5	(Schleisner, 2000)
	29.5	(Hondo, 2005)
	7.9-123.7	(Lenzen and Munksgaard, 2002)
Coal burning stations	870	(Raghuvanshi et al., 2006)
	880	(Denny and O’Malley, 2009)
	975	(Hondo, 2005)
	850-1,000	(Franco and Diaz, 2009)
	1,000	(Stoppato, 2008)
	1,186	(Wang and Nakata, 2009)

4.3 Emissions from wind turbines

Lenzen and Munksgaard (2002) studied many different wind turbine installations and found that the emissions can vary between 7.9 and 123.7 gCO_2-eq/kWh, due to differences in parameters used such as lifetime, loadfactors and even differences in the fuel mix in the country of manufacture.

Jungbluth et al. (2005) found that the values of gas emissions were 13 gCO_2-eq/kWh for a 2 MW wind turbine while for a smaller 800 kW turbine it was 11 gCO_2-eq/kWh. Other researchers estimated the emissions in different wind farms to range between 9.7 and 16.5 gCO_2/kWh (Schleisner, 2000) and in other cases a little higher reaching 29.5 gCO_2/kWh (Hondo, 2005). In specific cases the environmental burden for the production and operation of wind turbines can be as low as 2 gCO_2-eq/kWh. (Lenzen and Wachsmann, 2004). Ardente estimated the emissions of a wind turbine farm at 14.8 gCO_2-eq/kWh (Ardente et al., 2008). Finally Pehnt (2006), for different cases of wind turbines (varying in size and installation site) estimated a range of 9-11 gCO_2-eq/kWh.

4.4 Emissions from coal burning stations

There are estimations raising the environmental effect of coal burnt to around 870 gCO_2-eq/kWh (Raghuvanshi et al., 2006) and 880 gCO_2-eq/kWh (Denny and O'Malley, 2009). Other estimations are even higher reaching 975 gCO_2-eq/kWh (Hondo, 2005) or almost 1000 gCO_2-eq/kWh (Stoppato, 2008). Franco and Diaz (2009) put the environmental effect of coal burning in the range of 850 to 1000 gCO_2-eq/kWh. Finally, the highest estimate of emissions from coal are 1,186 gCO_2-eq/kWh (Wang and Nakata, 2009). Naturally, the type, purity and burning method of the coal play a very significant role in the determination of the pollution level.

5. CO_2 emissions calculated for desalination units in Greek Islands

The CO_2 values mentioned above do not include the environmental effect of the desalination unit itself. In order to present more accurate estimates, a life cycle assessment (LCA) of water desalination systems combined with different energy scenarios needs to be made. Furthermore, as these results present significant variation for different locations, it is necessary to make comparisons with previous research carried out for Greek islands.

Table 2

CO_2 emissions from a reverse osmosis desalination unit using several energy sources

Source: (Karagiannis and Freire, 2009)

Technology	CO_2 emissions (kg/kWh)
Desalination-Grid	0.913 - 0.940
Desalination-Wind	0.024
Desalination-PV	0.150

Karagiannis and Freire (2009), estimated the CO_2 emissions from a reverse osmosis desalination unit using several energy sources. Table 2 summarizes the results obtained from LCA for desalination systems in the Greek islands area.

In the case of grid electricity used, two different desalination systems with different electricity consumption are presented with small variations in CO_2-eq production (around 925 gCO_2/kWh). In case of photovoltaic panels used the emissions become much lower, at the level of 150 gCO_2/kWh. The desalination wind powered system presents the lowest specific emissions.

6. The CO_2 capture and storage (CCS) cost

According to IEA (2006), CCS is a 3-step process that includes:

1. CO_2 capture from power plants, industrial sources and natural gas wells with high CO_2 content
2. Transportation to the storage, usually via pipelines and
3. Geological storage in deep saline formations, depleted oil/gas fields, unmineable coal seams and enhanced oil or gas recovery sites. (IEA, 2006)

In 2005, the Intergovernmental Panel on Climate Change, a group of scientists that advises the United Nations Framework on Climate Change (UNFCC), estimated CO_2 avoided cost via CCS in a range from 14-91 $/t (IPCC, 2005). The International Energy Agency suggested that the CCS cost for the first big plants would be 30-90$/t, or even more, depending on technology, CO_2 purity and site (IEA, 2006). McKinsey's consultants have come up with an estimate of 60-90€/t of CO_2 avoided. However, this price is foreseen to be lower when the technology is mature and by 2030 the estimations given are for 30-45€/t (McKinsey & Company, 2008). A new study from the Belfer Center of Science and International Affairs, Harvard University, has shown that the initial cost for every tonne of CO_2 avoided could be around 150$ (Al-Juaied and Whitmore, 2009).

Other relevant articles have been published for this issue. Singh et al. compared two different CO_2 capture technologies. When CO_2 is separated from the products of combustion using conventional approaches, the capture cost is 53$/t of CO_2 avoided. In case of burning the coal with oxygen in an atmosphere of recycled flue gas the cost can be as low as 35$/t of CO_2 avoided (Singh et al., 2003).

Rubin et al. estimates the CCS cost at the range of 13-74$/t of CO_2 avoided for different type of plants before CO_2 transport and storage cost (Rubin et al., 2007). Others showed that CO_2 capture cost for a power plant can be as low as 33€/t of CO_2 (Abu-Zahra et al., 2007).

Gibbins and Chalmers calculate the CO_2 capture cost for gas fired plants between 58 and 112 $/t of CO_2 avoided, while for coal-fired plants it can be at the range of 23 to 36 $/t of CO_2 avoided, depending on the different capture technology. However, these costs are very site-specific and do not include storage and transport costs. (Gibbins and Chalmers, 2008)

There are large differences in CCS cost as estimated in several papers and reports. Some of the main reasons are the following:

- The different power plants in each case
- The different timescale that the plant is built
- The location
- The different equipment that might be used
- The different contracts, guaranties and infrastructure used
- The different cost calculations eg. in many studies CO_2 compression cost is included, but not CO_2 transport and storage costs, which are outside their scope

7. Critical CO_2 values when photovoltaic panels are used

Under Greek weather conditions, 10kWp of photovoltaic cells will generate an average of 15,000 kWh per year (EC, 2009). Taking into consideration that the energy requirement for the production of 1 m^3 is 4 kWh, the nominal amount of fresh water that can be produced is 15,000/4=3,750 m^3 or, allowing for breakage and availability, 3,500 m^3. In this case the required *autonomous* (RES only driven) desalination unit should have a capacity of producing at least 2.5 m^3/h. In case of a grid connected or hybrid desalination system, the same amount of water can be produced with a smaller desalination system, with capacity around $0.6 m^3/hr$, because in this case, the system may operate almost 24 hours a day. Table 3 shows the values used for the calculation of CO_2 emissions critical cost.

Table 3

Data used for the comparison of CO_2 emission values from desalination units powered by PV and grid electricity

		Symbols	Value	Source
Desalination unit	Desalination unit purchase & installation cost (2.5 m^3/hr) net of subsidies	D_R	35,000€	(AUDESSY, 2007)
	Desalination unit purchase & installation cost ($0.6m^3$/hr) net of subsidies	D_C	15,000€	(AUDESSY, 2007)
	Economic life of desalination systems	n	20 years	(AUDESSY, 2007)
	Specific energy consumption	q_e	4 kWh/m^3	(Karagiannis and Freire, 2009)
	Annual water production		3,500 m^3	
Power generating unit	10 kW Photovoltaic purchase & installation cost net of subsidies (40%)	R	50,000€	(AUDESSY, 2007)
	Economic life of photovoltaic cells	r	25 years	(AUDESSY, 2007)
Interest rate		i	5%	
Cost of grid electricity		c_e	0.27 €/kWh	(RAE, 2008)
Emissions from photovoltaic power generation life cycle		q_R	150 g CO_2-eq/kWh	(Karagiannis and Freire, 2009)
Grid electricity emissions *		q_C	925 g CO_2-eq/kWh	(Karagiannis and Freire, 2009)

G *such as those in the Greek islands*

Substituting the above values in the previous inequality (2), it is found that in order to operate profitably an energy autonomous system powered by photovoltaic cells instead of grid electricity, the value of CO_2 should be higher than 128 €/t.

This value is just higher than the financial penalty that European Commission imposes (100€/t) on each tonne of CO_2-eq that exceeds the annual sum of allowances (EC, 2003). It is also similar to CO_2 capture cost, according to the U.S. Department of Energy (2007), estimated in the order of 150$ per tonne of CO_2.

The Greek Regulatory Authority of Energy (RAE, 2008) quotes the cost of electricity production, transmission and distribution in 0.27 €/kWh with regard to local generation of small size islands. Other estimations for medium and small size islands are in the range of 0.15 and 0.40€/kWh (Kaldellis and Zafirakis, 2007). In order to explore different scenarios, the use of different parameters gives interesting results. Table 4 shows the variation in CO_2 emissions critical value when different costs of electricity and specific energy consumptions are considered.

Table 4

Critical values of CO_2 emissions of autonomous desalination PV-powered units at different costs of grid electricity

		SPECIFIC ENERGY CONSUMPTION (kWh/m^3)	
		3	*4*
Cost of grid electricity (€/kWh)	*0,150*	324,90	282,99
	0,270	170,06	128,15
	0,369	41,92	0,01
	0,402	-0,01	-41,92

In medium to large size Greek islands, where the cost of generating grid electricity is 0.15 €/kWh, the critical CO_2 emissions cost is 283 €/t. On the other hand for smaller islands with higher cost of power generation, 0.27 €/kWh, the CO_2 emissions critical values drop down to less than half (128€/t). At an electricity cost higher than 0.35 €/kWh, PV powered desalination is economic even without considering the benefit from the reduction of CO_2 emissions. The zero and negative values in both the specific energy consumption columns, highlight this point.

8. Estimation of critical CO_2 value when wind turbines are used

Greek wind potential is significant. In the coastal areas average wind speed is usually around 4-5 m/s, while in many islands it can be over 7.5 m/s. (Kaldellis and Zafirakis, 2007). With the use of specialised software for the estimation of the amount of electricity that can be produced from the wind, it was found that the average electricity production at wind speeds around 4.5 m/s is about the same as that from photovoltaics, about 1,570 kWh per kW of installed capacity. (WindCad, 2000). Table 5 shows the values used for the calculation of CO_2 emissions critical cost.

Table 5

Data used for the comparison of CO_2 emission values from desalination units powered by wind turbines and grid electricity

		Symbols	Value	Source
Desalination unit	Desalination unit purchase & installation cost (capacity equal to 2.33m^3/hr)	D_R	35,000€	(AUDESSY, 2007)
	Desalination unit purchase & installation cost (capacity equal to 0.58m^3/hr)	D_C	15,000€	(AUDESSY, 2007)
	Economic life of desalination systems	n	20 years	(AUDESSY, 2007)
	Specific energy consumption	q_e	4 kWh/m^3	(Karagiannis and Freire, 2009)
	Annual water production		3,500 m^3	
Power generating unit	9 kW wind turbine purchase & installation cost	R	12,000€	(AUDESSY, 2007)
	Economic life of wind turbines	r	20 years	(AUDESSY, 2007)
	Yearly hours of operation		1476 hr	(WindCad, 2000)
Interest rate		i	5%	
Average wind speed			5.3 m/sec	(Kaldellis and Zafirakis, 2007)
Cost of grid electricity		c_e	0.27 €/kWh	(RAE, 2008)
Emissions from wind turbines life cycle		q_R	24 g CO_2-eq./kWh	(Karagiannis and Freire, 2009)
Grid electricity emissions		q_C	925 g CO_2-eq./kWh	(Karagiannis and Freire, 2009)

Application of formula (2) shows that the critical value of CO_2 is negative for all cases where the cost of electricity is higher than 0.17 €/kWh, indicating that wind turbines is already an economic proposition for electricity production even if we do not take into consideration the significant environmental gain. This can be attributed mainly to the low capital cost of wind turbines and is the reason why the majority of investments in renewable energy sources in Greece is highly destined to wind energy (Tsoutsos et al., 2008). At a cost of grid electricity generation as low as 0.15 €/kWh, the Wind turbine becomes economic if the value of CO_2 is greater than 23.27 €/t or 59.32 €/t depending upon the specific energy consumption. As already discussed in the case of PV powered desalination, this value is on the low side, since estimated values of CO_2 emissions are around 100 €/t. Table 6 shows the variation in CO_2 emissions value when different costs of electricity and specific energy consumptions are considered.

Table 6

Desalination Wind Powered Unit critical values of CO_2 emissions at different costs of electricity

		SPECIFIC ENERGY CONSUMPTION (kWh/m^3)	
		3	*4*
Cost of grid electricity (€/kWh)	*0,150*	59,32	23,27
	0,171	36,01	-0,04
	0,203	0,49	-35,56
	0,270	-73,87	-109,92

9. Conclusions

In order to substitute conventional sources of energy for the production of fresh water in Greek islands, the critical value of CO_2 emissions varies significantly for different costs of conventional electricity generation and the specific energy consumption. It was found that, due to lower electricity production cost, wind energy is preferable, not only because of the lower environmental impact, but also due to the fact that the cost of wind electricity production can be less than the electricity production cost from fossil fuels in most small and medium size islands.

There is only a relatively small number of water desalination units in the Greek islands today. Most of them operate on grid electricity, although wind generated electricity can be cheaper. This is probably due to the fact that the use of grid electricity is the “convenient” solution, because it does not require additional investment funds and there is always the possibility of adding a wind turbine at any time after installation. Besides, although the real cost of electricity produced by fossil fuels in small islands is fairly high, this is not reflected in grid electricity bills, because the PPC is subsidising the cost of electricity to local consumers, thus making wind electricity less financially attractive.

In the case of photovoltaic energy, the critical CO_2 emissions cost can be close to its price in the carbon market and less than the penalties imposed from the European Commission. In cases of high electricity production cost (more than 0.37€/kWh) as is the case in many Greek islands, the choice of renewable energy sources for the production of fresh water is obvious even before considering the environmental advantage.

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