sustainability

MDPI

Article

Energy Saving in Public Transport Using Renewable Energy

Vincenzo Franzitta *, Domenico Curto, Daniele Milone and Marco Trapanese

Department of Energy, Information engineering and Mathematical models (DEIM), University of Palermo (UNIPA), 90128 Palermo, Italy; domenico.curto@unipa.it (D.C.); daniele.milone@unipa.it (D.M.); marco.trapanese@unipa.it (M.T.)

* Correspondence: franzitta@dream.unipa.it; Tel.: +39-091-238-61941

Academic Editors: Francesco Asdrubali and Pietro Buzzini

Received: 24 September 2016; Accepted: 9 January 2017; Published: 13 January 2017

Abstract: Hydrogen produced by renewable sources represents an interesting way to reduce the energetic dependence on fossil fuels in the transportation sector. This paper shows a feasibility study for the production, storage and distribution of hydrogen in the western Sicilian context, using three different renewable sources: wind, biomass and sea wave. The objective of this study is the evaluation of the hydrogen demand, needed to replace all diesel supplied buses with electrical buses equipped with fuel cells. An economic analysis is presented with the evaluation of the avoidable greenhouse gas emissions. Four different scenarios correlate the hydrogen demand for urban transport to the renewable energy resources present in the territories and to the modern technologies available for the production of hydrogen. The study focuses on the possibility of tapping into the potential of renewable energies (wind, biomass and sea wave) for the production of hydrogen by electrolysis. The use of hydrogen would reduce significantly the emissions of particulate and greenhouse gases in the urban districts under analysis.

Keywords: hydrogen; wind; biomass; sea wave; mobility

1. Introduction

Among the actions that the Kyoto Protocol indicates in order to reduce CO_2 emissions, innovative technologies are promoted, in particular based on the exploitation of renewable energy sources (RES). All RES (expect geothermal) are related to solar radiation: annually the earth's surface receives about 885 billion GWh of solar energy. This huge amount of energy is equivalent to 6200 times the primary energy consumed by humankind in 2008 [1]. For this reason, the RES could theoretically satisfy the entire energy demand of human settlements. Nevertheless, the existing energy systems are dominated by technologies based on fossil fuels, producing the emissions of greenhouse gases and polluting the environment [2]. Within this economically managed part of the energy sector, renewable energy sources currently provide about 25% of the energy supplied [3]. Energy use and resource depletion does not, of course, constitute the primary goals of any society or individual within a society. For example, average Europeans or Japanese use about half as much energy as the average North American, but have a living standard similar to the North American citizens. This underlines the fact that the living standard and welfare depends on having primary (food, shelter, relations) as well as secondary standards of individual preference fulfilled and this can be done in different ways with different implications for energy use [3]. In the last years, the interest of research and policy has been focused on a new system able to exploit energy from nature or economical sources of energy.

Electricity generation from clean, safe and sustainable energy sources is nowadays a priority for many industrialized countries to meet increased energy demand and to reduce CO_2 emissions. The residential and industrial sector modified their fundamental structure, for example with the adoption of clean and sustainable improvements. In fact, another field that European Government studies with more attention is mobility. Numerous researches have demonstrated that the number of vehicles in the world is expected to double in the next 30 years, which could have serious negative consequences for energy security and the climate. The cause of this is the growing demand for cars in countries such as Brazil, China, India, South Korea, Mexico, Poland, Russia and Thailand as the people there seek to increase their individual mobility when they become more prosperous [4].

Figure 1 shows the correlation between the number of vehicles owned by people and the per capita income.

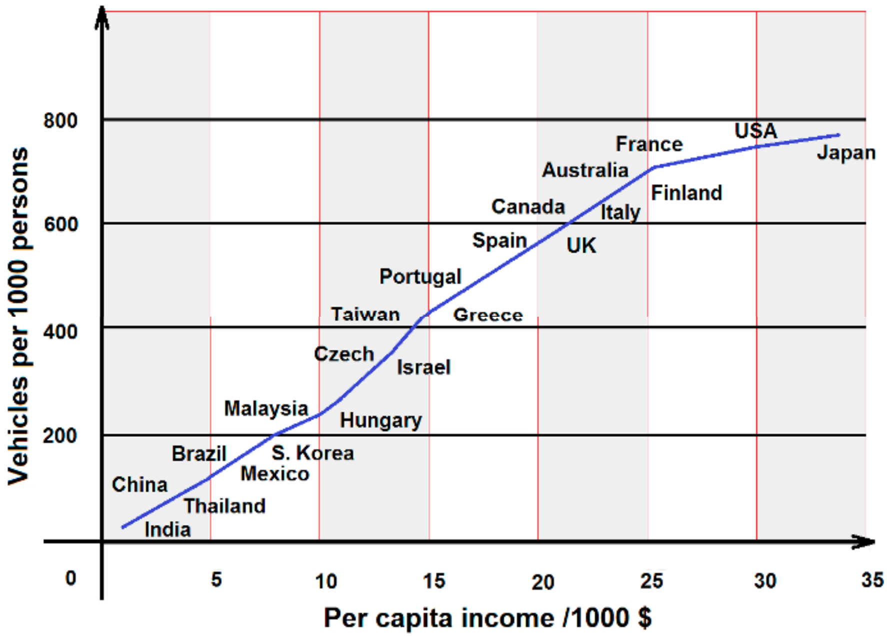

Figure 1. Correlation between the per capita income and the number of personal vehicles owned.

The most common effect of this above-mentioned amount is the increasing air pollution. Therefore, some new possible solutions should be investigated. Hydrogen is an energy carrier with great potential for clean, efficient power in stationary, portable and transport applications. It is envisaged as a significant element of the future fuel mix for transport, enhancing energy security, reducing oil dependency, greenhouse gas emissions and air pollution. Hydrogen allows a wide diversification of energy sources. In combination with fuel cells, it can also improve energy efficiency in transport and contribute strongly to mitigating climate change—especially when produced by renewable primary energy sources. Hydrogen and fuel cell technologies were identified amongst the new energy technologies needed to achieve a 60% to 80% reduction in greenhouse gases by 2050. Recent studies show the possible advantages of hydrogen's introduction on bus fleet. Shaheen et al. [5] showed that greater levels of exposure to hydrogen-fueled vehicles lead to higher levels of hydrogen acceptance and that early adopters tend to feel safer when using the technology, leading to significant improvements in public awareness. Langford et al. [6] presented Knoxville Area Transit (KAT) as a case study to support the transition of a medium sized transit agency to full conversion to hydrogen fuel, describing requirements for hydrogen bus fleets, production, storage, refueling and maintenance facilities. In the past decade, there have been several projects demonstrating the feasibility of hydrogen bus infrastructure, vehicles and operating procedures. Another interesting benefit regarding hydrogen's production, is that it can be obtained from a variety of sources, such as fossil fuels or water, etc. Technologies for the production of hydrogen from fossil fuels (steam reforming, partial oxidation, gasification) are, as mentioned, mature and widely used (more than 95% of the hydrogen produced today comes from these processes). As for its production from renewable sources, this comes from such sources as biomass or water. Currently, the European Parliament passed a law on hydrogen vehicles' homologation in an effort to protect the environment in urban centers.

The law applies not only to the development of fuel cell vehicles but also to the development of hydrogen filling stations and the necessity of producing hydrogen in sustainable ways [7]. Hydrogen can be produced from biomass through several thermochemical processes, such as gasification or pyrolysis and biological processes. One of the possible renewable energy sources to be used to produce hydrogen is water, through electrolysis or thermochemical processes. In this paper, we consider the hydrogen production based on the electrolysis process, since it requires only the electrical energy supply, that can be easily satisfied by using several renewable energy sources.

The following Section 2 analyzes the energy potential of wind, biomass and sea wave sources in the western Sicilian context. In order to exploit the wave source, an energy converter is presented. The Section 4 evaluates the hydrogen demand in order to replace the diesel-powered buses in Trapani with electrical buses equipped with fuel cells. The three different energy sources are considered for the hydrogen production. Finally, an economic and environmental evaluation is presented.

2. Renewable Energy Sources in Trapani

2.1. Wind Source

Firstly, we analyze the wind resource. In Sicily, this source is characterized by high potential levels and the production of electrical energy from wind turbines represents [8] nowadays an important percentage of the overall electrical energy production in loco [9]. Wind source was accurately studied by CESI (Centro Elettrotecnico Sperimentale Italiano) and Physics Department of University of Genova. Thanks to these studies, the Italian Wind Atlas (Atlante Eolico Italiano) is now available [10]: it is a very useful online tool, that can be used to evaluate the theoretical electrical energy production from wind turbines. The web page reports a GIS (Geographic Information System) map, in which the average wind speed at different levels from the soil is expressed: 25 m, 50 m, 75 m, 100 m from the soil. In this work, we consider only the average wind speed at 50 m from the soil, because the particular type of wind turbine selected will be able to work at this distance. Greater distances involve the necessity to introduce a higher and more visible wind turbine, while shorter distances reduce the electrical energy production. Moreover, the authors focused their attention on the on-shore wind source in order to not use sea areas, which will be exploited with a Point Absorber, proposed in the Section 3. Moreover, the Italian laws are a serious obstacle for the potential installation of off-shore wind farms. Figure 2 shows the average wind speed in Sicily at 50 m above ground level.

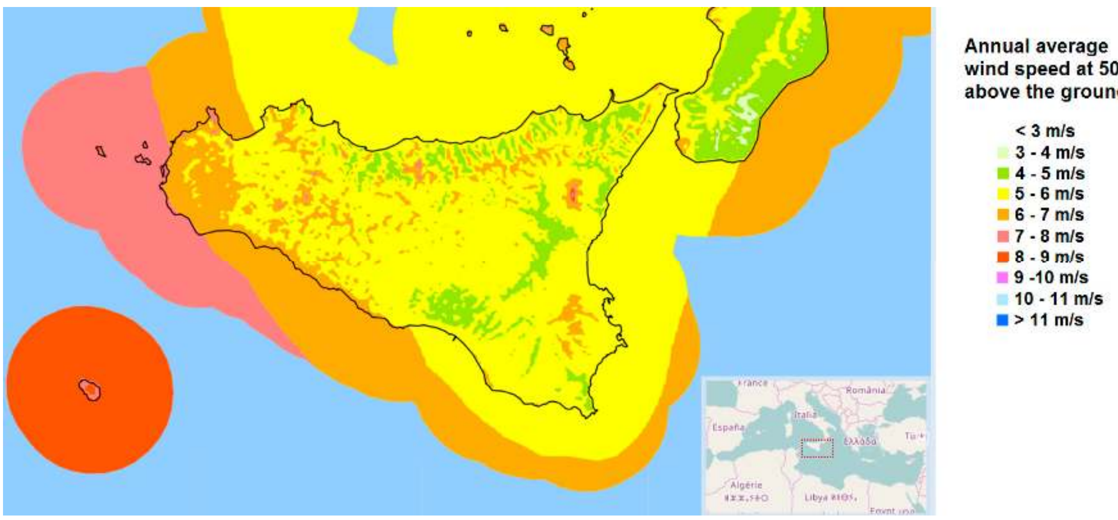

Figure 2. Average wind speed in Sicily at 50 m above ground level.

Particularly, most of the Sicilian lands are characterized by an average wind speed comprised between 5 and 6 m/s. Additionally, the province of Trapani presents higher values, comprised between 6 and 7 m/s, with a maximum of 8 m/s in the coastlines. This is due to the higher fetch in which the wind is able to blow. So, Trapani is an excellent place to adequately exploit the wind source.

Figure 3 shows the GIS map of the annual theoretical energy production by wind in Sicily. Most of Sicily shows an average production between 1500 and 2000 MWh/MW, while the values shown in the province of Trapani remain higher. It is marked by values comprised between 2000 and 2500 MWh/MW, with a maximum of 3000 MWh/MW in the coastlines. Prudently, an average value of 2000 MWh/MW is fixed in this text.

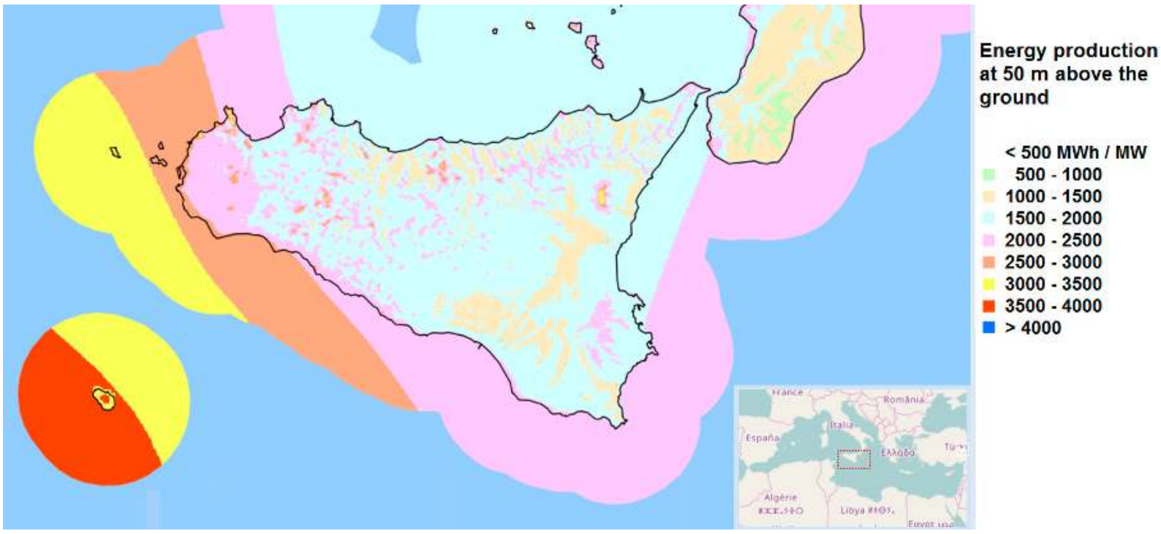

Figure 3. Energy production in Sicily at 50 m above ground level.

2.2. Biomass Source

As regards the biomass resource, we consider the installation of a power plant with a rated power of 1.2 MW (electrical output). The biomass power station is composed of eight small ORC (Organic Rankine Cycle) units, each one having a rated electrical output equal to 150 kW [11]. This kind of plant is able to use several types of biomass, for example straw, pruning residues of olives and vineyards. Before the use, the biomass is dried and converted into woodchips and pellets.

The annual biomass consumption of the power plant is estimated at about 13,600 t/year, considering a lower heating value (LHV) equal to 17 MJ/kg, an electrical efficiency fixed to 16% and a boiler efficiency fixed to 85% [11].

Based on the information given below, we will try to identify a suitable site for the installation of a biomass power plant, in the city of Trapani. The biomass catchment area is selected according to these conditions:

- collection of at least 50% of biomass from straw, sufficient to cover 30% of the biomass demand of the power plant;
- collection of at least 50% of biomass from pruning residues of olives and vineyards, sufficient to cover 70% of the biomass demand of the power plant.

The analysis firstly evaluates the territory of Trapani, having a surface of 3555 ha at the northern part of the town and 25,500 ha at the southern part. The following Figure 4 shows the land uses in the territory of Trapani. The greatest part of the territory is used for cultivation, in particular 42.8% for extensive farming and 31.8% for vineyards.

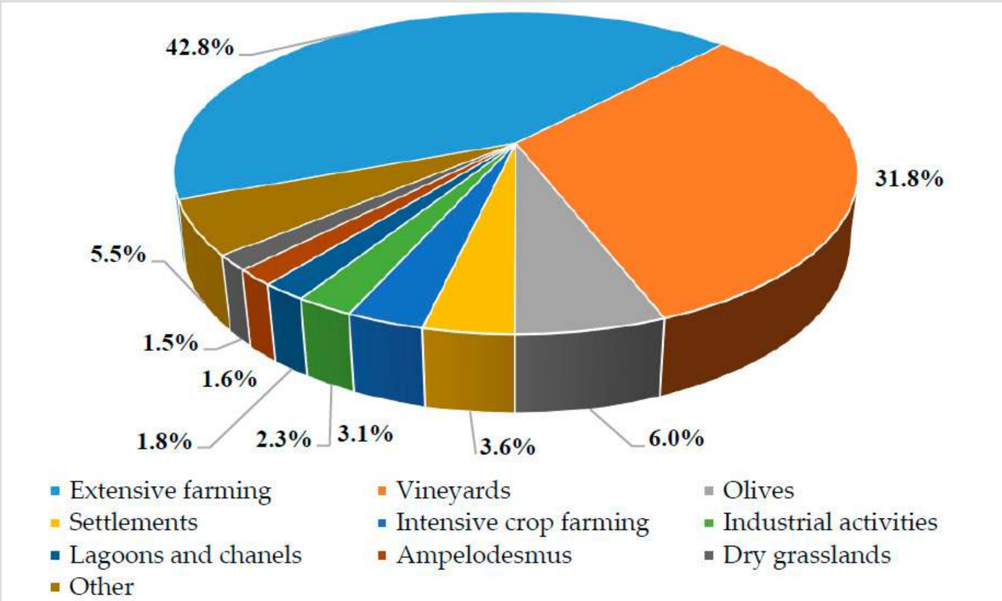

Figure 4. Land uses in Trapani city.

Table 1 reports the main data about the biomass production in the territory of Trapani. With the term "biomass equivalent", we consider a biomass having a lower heating value fixed to 17 MJ/kg.

Table 1. Agriculture residues in the territory of Trapani.

Type of Cultivation	Surface Occupied [ha]	Productivity [t/ha]	Moisture Fraction [%]	Lower Heating Value [MJ/kg]	Dry Residue [t/Year]
Extensive cultivation	11,545.60	3.0	-	14	34,636.80
Vineyard pruning	8592.73	2.8	50	17	12,029.82
Olive pruning	1631.93	2.1	40	17	2056.23
Total biomass equivalent	**21,770.26**		-	**17**	**42,610.48**

As shown in Table 1, the total available biomass is enough to satisfy the biomass demand of the power plant, in the case of complete interception. However, this hypothesis is unrealistic, in fact, the fraction of collected biomass generally does not exceed 50%. Furthermore, in order to reduce the volumes of biomass storage, the biomass input from extensive crops must be reasonably limited to 30% of the energy requirements of the power plant, due to the low calorific value and the low density of straw bales that increase the costs for the collection, transport and storage.

Table 2 shows the results of this first hypothesis: the available biomass from straw is abundant, while the biomass from the pruning of olives and vineyards is not enough to cover the demand of the power plant.

Table 2. Available biomass in the territory of Trapani and biomass required by power plant.

Type of Cultivation	Lower Heating Value [MJ/kg]	Available Biomass [t/Year]	Biomass Demand [t/Year]	Surplus [t/Year]
Extensive cultivation	14	17,318	4954	12,364
Vineyard pruning	17	6015	9520	−2477
Olive pruning	17	1028		

Figure 5 shows the distribution of several cultivations in the territory of Trapani. The map shows also that the territory of Trapani is contained in a range of 30 km from the ATM (Azienda Trasporti e

Mobilità) bus depot, so this location can be a potential site for the installation of the biomass power plant and hydrogen production.

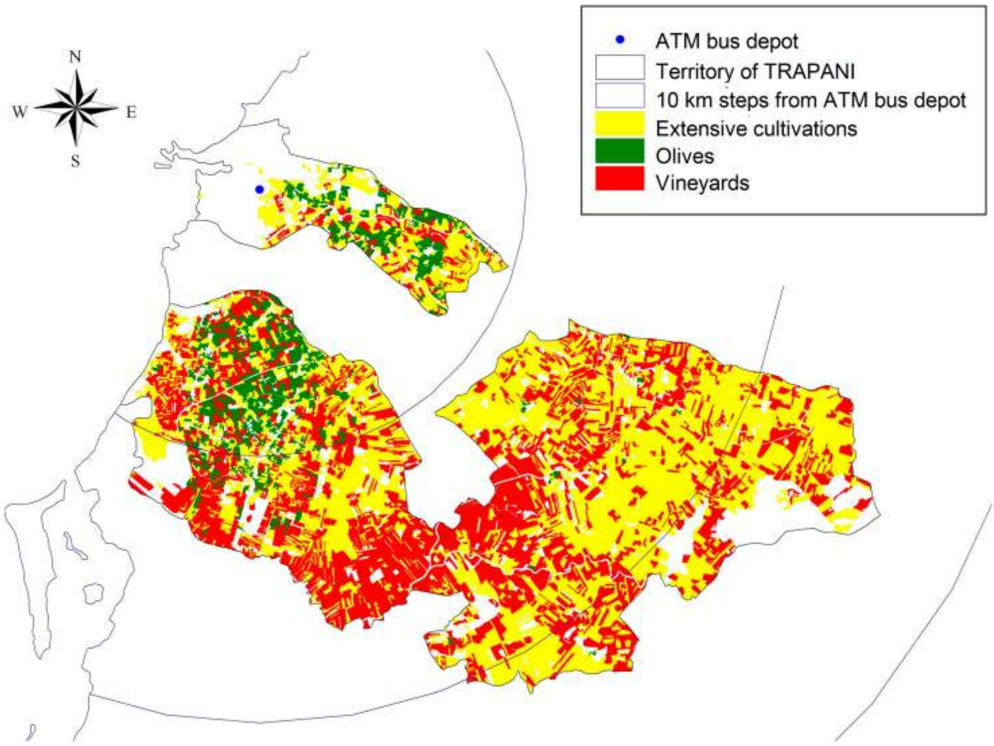

Figure 5. Culture distribution in the territory of Trapani.

However, since the availability of biomass in the Trapani area is not enough to cover the demand of the power plant, it will have to accept to increase the radius of the area of biomass interception. For this reason, the analysis is extended to the province of Trapani.

In order to respect the conditions for the identification of the biomass harvesting area and to contain the collection and transportation costs, the analysis is conducted considering the available resources in a radius not more than 70 km from the potential site of the power plant.

Table 3 reports the available dry biomass residue in the province of Trapani. This area is divided in concentric zones, with a step of 10 km and the center fixed in the location of the ATM bus depot, as shown in Figure 6. The map shows a heterogeneous mix of crops (olive, vineyard and straw) within a radius of 10 km, rather than vineyards and extensive cultivations that are more widespread. The major crops of olives are concentrated in the region having a radius ranging between 40 and 50 km.

Table 3. Available dry residues in Trapani province, by type of cultivation.

Distance [km]	Available Dry Biomass Residue [t/Year]		
	Extensive Cultivations	**Olives**	**Vineyards**
10	17,960.94	3419.84	3782.56
20	49,686.60	2232.81	17,312.36
30	50,465.28	2424.83	27,370.39
40	55,058.61	3308.38	35,798.84
50	33,338.85	12,020.64	20,569.28
60	10,155.51	1677.83	3940.85

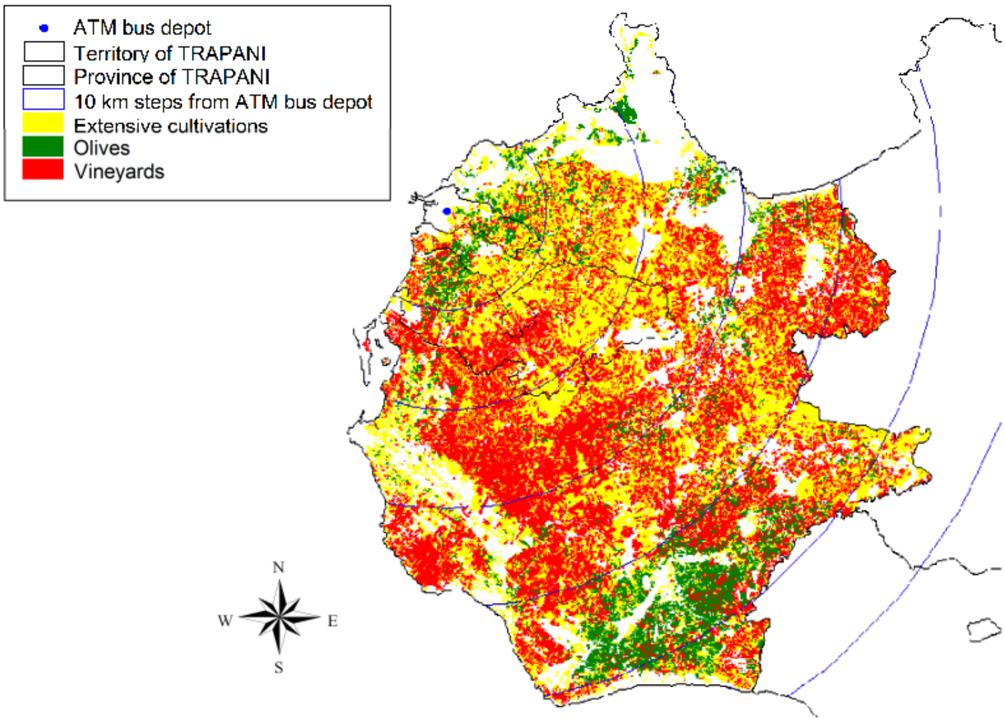

Figure 6. Culture distribution in Trapani province.

Figure 7 reports the available biomass resource as a function of the distance from the ATM bus depot. Fixing the fraction of collected biomass to 50%, the biomass demand from extensive cultivation can be satisfied with a collection radius ranging between 5 and 10 km, while the biomass demand from olives and vineyards cropping can be satisfied with a collecting radius ranging between 15 and 20 km, as shown in Figure 8.

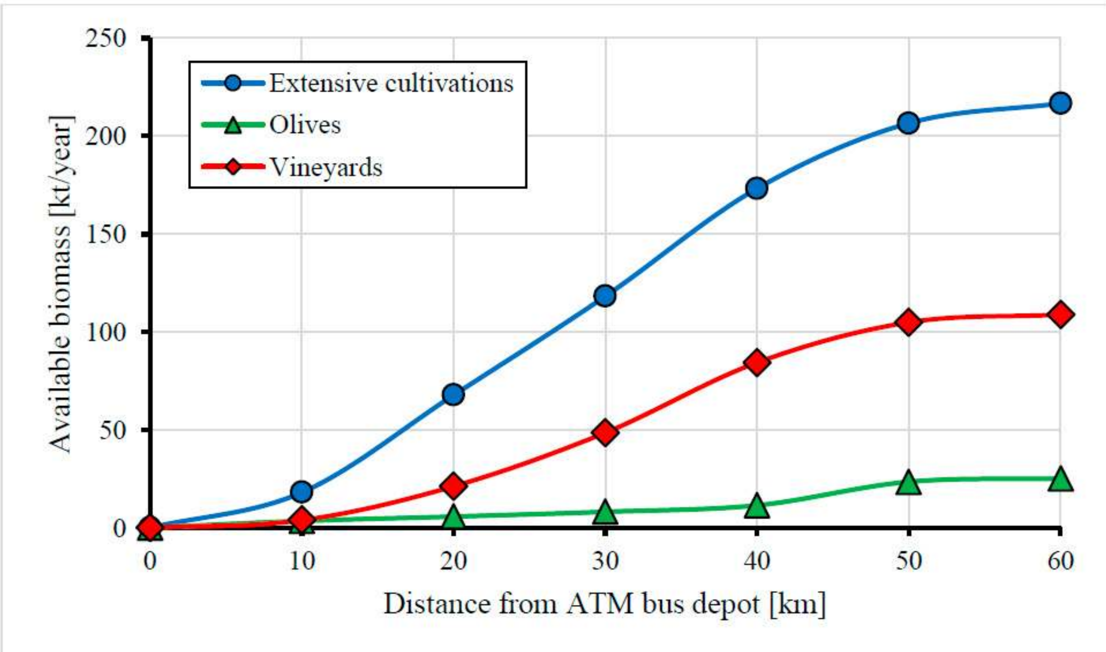

Figure 7. Available biomass in the province of Trapani, as a function of the distance from the ATM bus depot.

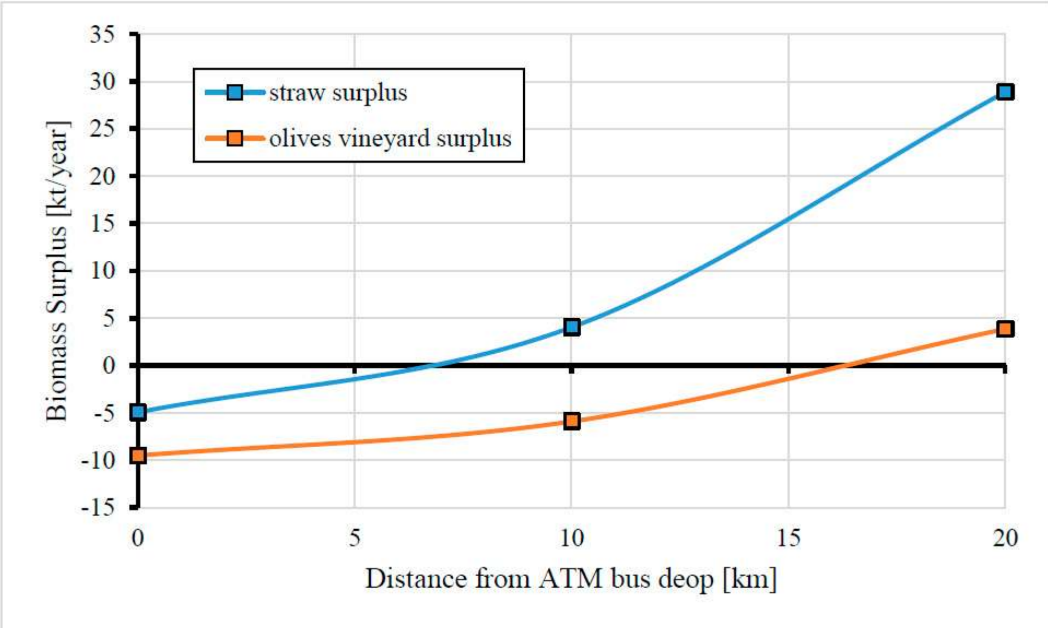

Figure 8. Biomass surplus as a function of the distance of the ATM bus depot, in the province of Trapani.

2.3. Sea Wave Source

Sea wave source represents nowadays an unused renewable source, despite the high levels of exploitable energy [12]. This consideration assumes greater importance, especially in this case study of the province of Trapani. In fact, as exposed in [12], the higher levels of wave energy in the Mediterranean Sea are identified in the western coasts of Sardinia and Sicily, with an average off-shore wave power greater than 5 kW/m [13]. So, these particular sites are the best ones along the Italian coastline in order to use the new conversion device here proposed. The main parameters through which wave energy is defined are significant wave height H_s (measured in meters); peak period T_p (measured in seconds); and main direction D_p. The first one represents the average height of the highest third of waves, while the second one is highest value of the period measured in the recording time. These parameters were collected thanks to the wave buoys of the Rete Ondametrica Nazionale (RON), which operated from 1989. Additionally, the data obtained through the wave buoys were used to confirm the values carried out by simulating software, which used wind data as input. In this way, it was possible to describe wave energy potential along the Sicilian coastline in more detail. Furthermore, the use of GIS technology (see Figure 9) is able to identify simultaneously the wave source and the restricted areas in which this source will not be exploited (for example, due to the presence of particular environmental and maritime constraints). Particularly, Figure 9 shows the presence of maritime constraints along the islands of Favignana, Marettimo and Levanzo. According to the average wave potential, the coastlines of the province of Trapani can be divided into two parts: the northern and the southern part. The first one is globally characterized by a wave power comprised between 5 and 6 kW/m, while the second one is characterized by values comprised between 6 and 7 kW/m. In this text, an annual wave power of 5 kW/m is cautiously fixed for the northern part of the coastlines and 6 kW/m for the southern part.

Moreover, the main wave direction is north-west [12], thanks to the exposition to the wider fetch. The correct position of the wave buoys array will have to consider this characteristic, in order to avoid interference phenomena. Finally, wave source appears to be higher during the winter season and lower during the summer season. The issue connected to the variability of this source can be overridden through the use of appropriate storage tanks.

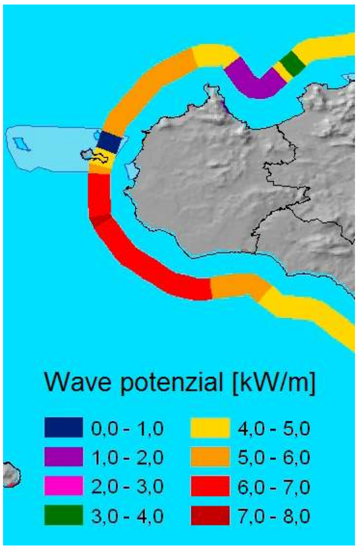

Figure 9. Average power (measured in kW/m) in the western coastlines of Sicily.

3. The Point Absorber for the Exploitation of Sea Wave Source

The Point Absorber here proposed is an innovative wave energy converter designed and developed by the Department of Energy, Information engineering and Mathematical models (DEIM) of the University of Palermo. This machine is able to directly convert wave energy into electrical output without the use of intermediate devices [14], such as toothed wheels, transmission belts or pressurized fluids (water or oils). Moreover, it will be able to convert wave energy independently from its propagation direction. This new technology is based on an innovative small-scale prototype of a linear generator projected and realized at the DEIM laboratory. The Wave Energy Converter (WEC) is shown in Figure 10. It is fundamentally composed of two floating buoys. The external buoy (yellow one) is the capture device, because it intercepts the continuous alternate wave motion. This motion is transferred inside the central buoy (green in the picture), which contains the linear generators, thanks to a connecting rod (blue rod). The external buoy has a nominal diameter of 10 m, while the internal one has a nominal diameter of 2 m. The working stroke of the linear generators is about 4 m: so, the WEC will produce electrical energy [15] also in bad weather conditions (which usually represents the most energetic sea state). Additionally, most of the conversion device is under the sea level in order to avoid a significant visual impact. The presence of a red light in the upper part of the WEC, at different heights in meters, makes it visible up to several nautical miles away. Each of the eight linear generators presents a nominal power of 10 kW, for a total nominal power of 80 kW. The particular size of the conversion device has been chosen in order to optimize the electrical energy production according to the wave climate along the western coast of Sicily. The greater inertia of the inner buoy and the presence of a hemispherical weight in its lower part guarantee the correct vertical positioning of the conversion device.

Furthermore, a jumper buoy (blue one) connects the lower part of the inner buoy to the weights located in the seabed, through heavy chains. The role of this jumper buoy is very important: in fact, it is able to maintain the four lower chains in vertical position, avoiding the damage of the seabed and its precious flora and fauna. Two springs are located in the upper and lower part of the inner case, avoiding any damage of the inner buoy due to bad weather, as shown in Figure 11. Each linear generator is composed of two parts: the stator and the translator. The first one represents the magnetic circuit, and it is composed of two plate packs steel. The copper coils are arranged in the hollows and present a three-phase connection, that is the connection of the national grid. The second one is composed of 132 neodymium–iron–boron permanent magnets fixed in a plate realized in a non-magnetic material, bakelite, which also has a high electrical resistance. Moreover, this particular type of magnet has been chosen thanks to its prominent features. In fact, neodymium–iron–boron magnets are able to produce a strong and long lasting magnetic field, without any electrical energy request. Obviously, the time variation of the magnetic field, due to the vertical alternate motion of the devices produced by the wave source, produces the electromotive forces in the electric circuit.

Figure 10. Graphic representation of a DEIM Point Absorber.

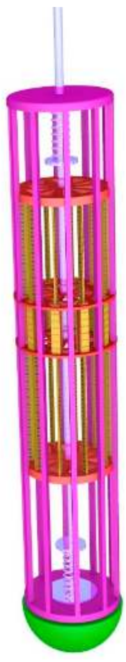

Figure 11. Cross section of the inner buoy of the DEIM Point Absorber.

Several tests have been realized on a small scale prototype at the DEIM laboratory, showing interesting results [16,17]. In particular, the electrical efficiency ranges from 50% to 75%, according to the values of the peak period and significant height of the sea wave.

Prudently, in this text, an overall efficiency of 50% is fixed, according to the experimental data obtained on the prototype, but it is clear that continuous studies about this WEC will be able to improve this percentage.

A DEIM Point Absorber can be used in multiple array in off-shore wave farms along the western coastline of the province of Trapani. In this way, it is possible to minimize the exploited areas and, at the same time, to increase significantly the installed power.

4. A Case Study: Replacing the Diesel Fleet of Urban Buses with Hydrogen Fuel

Urban buses represent one excellent example for the introduction of hydrogen fuel into urban mobility. We could find some benefit of this choice, such as the centralization of supply systems; regular paths; weight reduction compared to vehicles for private transport. In general, all manufacturers have focused on the polymer electrolyte cell (PEMFC, Proton Exchange Membrane Fuel Cell), that meets the requirements for use in road vehicles. Low temperature PEMFCs are characterized by a conversion efficiency of about 50%–60%, even at sizes of a few kilowatts [18,19]. Greater conversion efficiency can be realized with high temperature PEMFC, however this technology shows difficulties in a vehicular application, in particular the fuel cell must be firstly heated to the nominal temperature range in order to work properly. For this reason, a cold start of high temperature PEMFCs is not applicable [20]. PEMFCs have zero pollutant emissions when fueled directly with hydrogen, produced by renewable energy sources. There are some advantages, such as the high power density, the lack of corrosive fluids, a simple structure. We present an adoption of this system (PEMFCs) to the urban bus of Trapani, that is a city on the west coast of Sicily in Italy. The Municipal territory is inhabited by little more than 70,000 people spread over a vast area of 271 square kilometers. The urban buses have a central role in its mobility. Table 4 shows data of the ATM (Transport Company) of Trapani.

Table 4. Comparison between theory and experiment.

Statistical Data	ATM Trapani	Traveled [km]
Diesel	44	1,274,350
Natural gas	0	-
Electrical	4	115,850
Total	48	1,390,200

The principal aim of this work is the gradual replacement of diesel with hydrogen produced by renewable sources, such as wind, biomass and sea wave (examples presented in this work). We will represent four different scenarios of the total annual kilometers of the urban fleet. The hydrogen demand will be satisfied by the electrical energy production from renewable sources. In the final part, we are going to evaluate the avoided emissions of hydrogen buses and an economic analysis.

4.1. Scenarios

The aim of this work is the replacement of diesel buses with hydrogen buses in the entire province of Trapani. Moreover, this important goal can be achieved thanks to the use of a renewable energy mix, including biomass, wind and sea wave sources. In particular, the last one can be useful, exploited with the innovative conversion device proposed by University of Palermo. Different scenarios will be proposed, in order to show the electrical energy requests to satisfy the production of hydrogen as the energy carrier. These scenarios comprise a penetration respectively of 25%, 50%, 75% and 100% of the total annual kilometers of the urban fleet. In this text, the diesel consumption in the urban areas has been set equal to 0.4 l/km, while the hydrogen one has been set equal to 0.25 kg/km [21]. Table 5 reports the overall annual distance covered by the hydrogen bus fleet, the corresponding hydrogen demand and the avoided diesel consumption, in the four scenarios.

Table 5. Distance covered by hydrogen fleet and fuel request in four hydrogen penetration scenarios.

Penetration Rate [%]	Distance Covered by Hydrogen Fleet [km]	Avoided Diesel Consumption [L/Year]	Hydrogen Request [kg/Year]
25	318,587	127,435	79,647
50	637,175	254,870	159,294
75	955,762	382,305	238,941
100	1,274,350	509,740	318,588

A compensatory approach will be proposed: the conversion devices will be installed in the best sites of Trapani's province without territorial or marine constraints, while the production and storage of hydrogen is useful to be realized near the transport company's venue. The presence of the storage tanks will be helpful to compensate the fluctuations of the electrical energy production and, in this way, the hydrogen generator will be able to work optimally.

The electrical energy request to produce 1 kg of H_2 has been set equal to 56.3 kWh [22], through the electrodialysis technology. Furthermore, the electrical energy consumption for the storage of 1 kg of H_2 in compressed form has been set equal to 3.35 kWh [23], for a global request of 59.65 kWh/kg of H_2. Table 6 reports the evaluation of the electrical energy demand related to the production and storage of hydrogen in the four different scenarios.

Table 6. Electrical energy demand in the four hydrogen penetration scenarios.

Penetration Rate [%]	Electrical Demand to Produce H_2 [GWh/Year]	Electrical Demand to Store H_2 [GWh/Year]	Total Electrical Demand [GWh/Year]
25	4.49	0.27	4.75
50	8.97	0.53	9.50
75	13.50	0.80	14.25
100	17.94	1.07	19.00

As shown before, in this study, we consider the following renewable energy sources: biomass, wind and sea wave. As regards the biomass source, we consider the installation of several ORC units, each one having a rated electrical power of 150 kW; in particular, in the 100% scenario, eight ORC units will be installed, with an overall installed power of 1.2 MW. In order to exploit the wind source, we selected wind turbines, having a rated power of 330 kW. The rotor has a horizontal axis, installed about 50 m from the ground. In the 100% scenario, 10 wind turbines will be required. Finally, as regards sea wave source, we consider the installation of a wave farm composed of 20 DEIM point absorbers. Figure 12 shows the electrical energy production by renewable source; Figure 13 shows the number of units by renewable source in the four hydrogen penetration scenarios.

In every scenario, we have a modest surplus of electrical energy, which can be sold on the electrical network. The sizing of the renewable energy plants is realized, with the hypothesis of annual balancing. During the year, of course, it is possible that the energy production by renewable sources could exceed the electrical energy demand of the hydrogen station or on the contrary the renewable production could be not enough to cover the energy demand. In every case, the role of balancing between electrical energy production and energy consumption by hydrogen station will be assigned to the electrical grid.

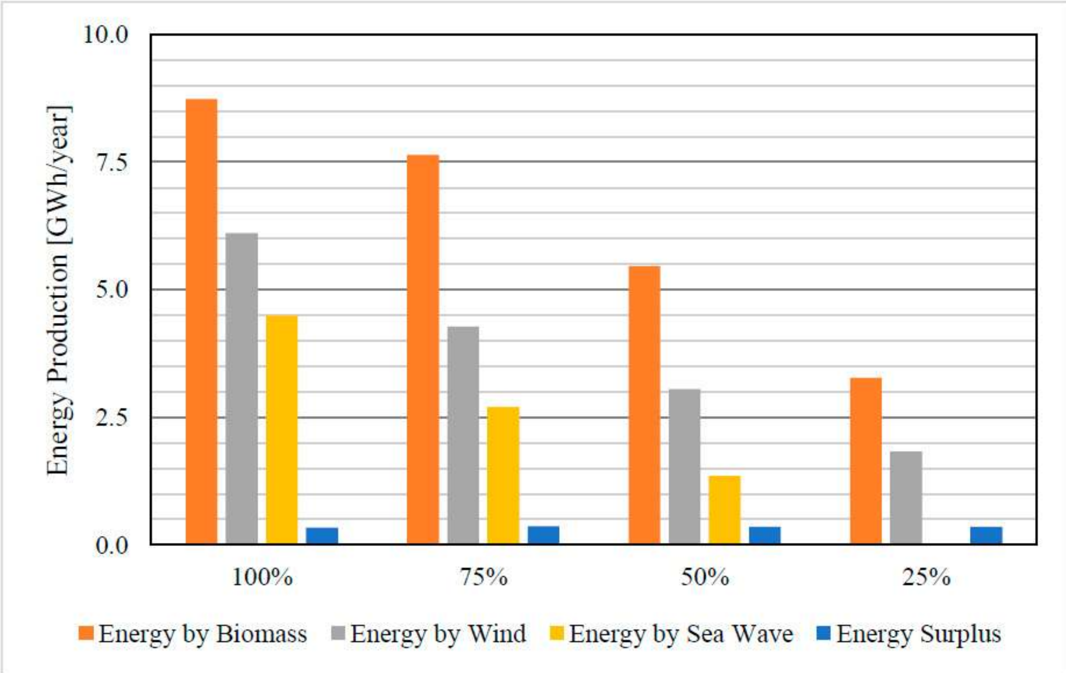

Figure 12. Electrical energy production to produce and store H_2, by renewable energies (biomass, wind and sea wave).

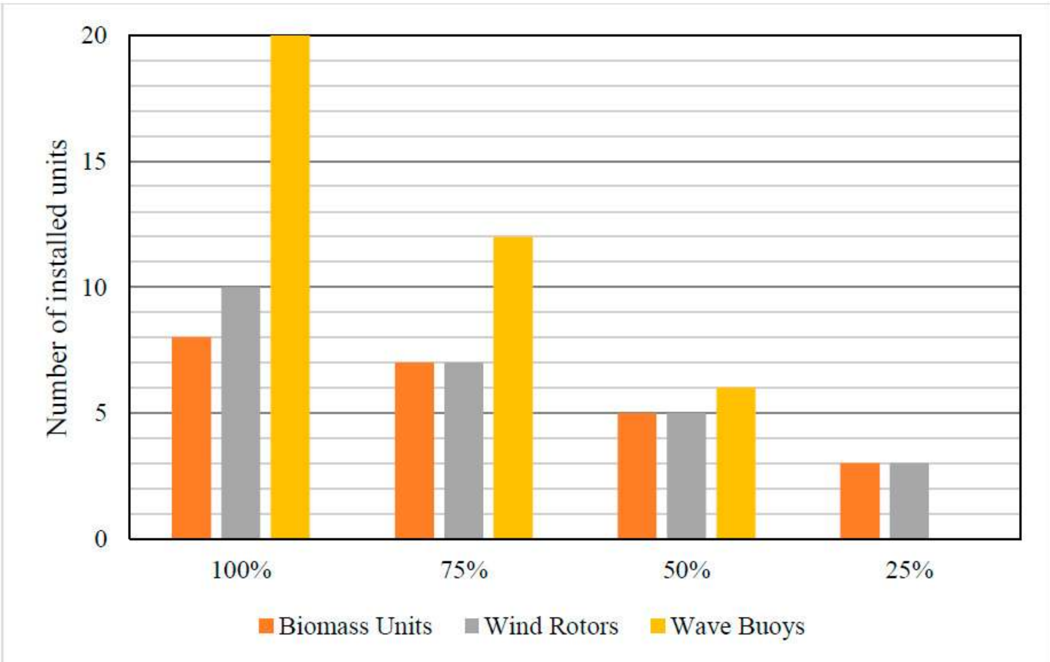

Figure 13. Number of units required to satisfy the electrical demand, by scenario.

4.2. Avoided Emissions

The replacement of diesel buses with hydrogen buses in the province of Trapani represents a big opportunity to reduce significantly the production of pollutants in urban areas, especially due to public transport. The centralization of the storage and the presence of specialized workers represent other important advantages. The emission factors used in this text are shown in Table 7 [17]. These are: CO_2, CO, PM_{10}, NMVOC and NO_x, expressed in g/km.

Table 7. Emission factors used for public transport in the province of Trapani.

Pollutants	Emission Factors [g/km]
CO_2	1132.797
CO	5.992
PM_{10}	0.879
NMVOC	1.642
NO_x	17.927

The avoided emissions are obtained by multiplying these emissions factors by the kilometers covered by the diesel buses in every scenario. Obviously, the biggest item is represented by CO_2, but the avoided emissions of the other pollutants have also an important role in order to reduce global warming [24].

Figure 14 shows the avoided emissions for the best scenario (penetration rate equal to 100%). In order to reach this prestigious goal, all three renewable resources are necessary, obtaining a variegated energy mix.

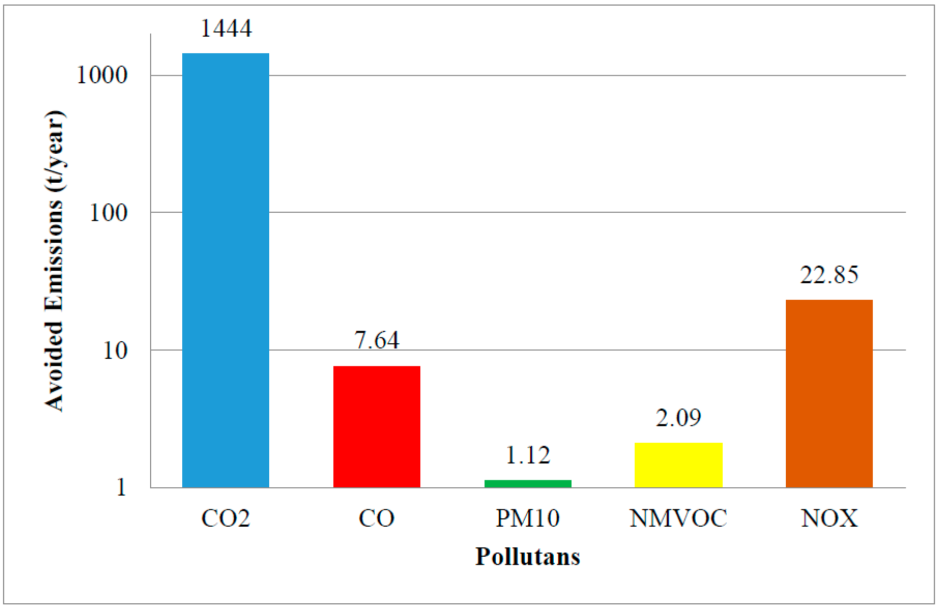

Figure 14. Avoided emissions in the best scenario (100% of hydrogen penetration rate).

Finally, the following Table 8 reports the avoided emission in the four different hydrogen penetration scenarios.

Table 8. Avoided emissions for public transport in the province of Trapani.

Penetration Rate Scenario [%]	Distance Covered by Hydrogen Fleet [km]	Avoided Emissions [t/Year]				
		CO_2	CO	PM_{10}	NMVOC	NO_x
25	318,587	361	1.91	0.28	0.52	5.71
50	637,175	722	3.82	0.56	1.05	11.42
75	955,762	1083	5.73	0.84	1.57	17.13
100	1,274,350	1444	7.64	1.12	2.09	22.85

4.3. Economic Analysis

In this section, we report the economic analysis in the 100% hydrogen penetration scenario. Except for the sea wave farm, in literature, much information about the items of investment, operative and maintenance costs can be found. The evaluation of the investment costs for hydrogen production can be easily realized, because all components are already used in the chemical industry.

In order to evaluate the economic viability, the discounted cash flow is calculated in two different hypotheses:

A. In this hypothesis, we take into account the initial investments of the biomass power plant, wind farm, wave farm, and hydrogen station. As virtual annual income, we consider the avoided purchase of fossil fuel.

B. In this hypothesis, we consider only the installation of the hydrogen station, run by purchasing electrical energy from the grid. Similarly, as virtual annual income, we consider the avoided purchase of fossil fuel.

The discounted cash flow is evaluated by the following equation:

$$DCF = -I_0 - \sum_{i=1}^{n} \frac{I_i}{(1+\tau)^i} + \left(Fc_{fuel} - Ec_{energy}\right) \sum_{i=1}^{n} \left(\frac{1+\varepsilon}{1+\tau}\right)^i \quad (1)$$

Where I_0 is the initial investment, I_i the annual costs for operative and maintenance costs, F is the avoided annual diesel consumption, E is the annual energy required to produce hydrogen (this term is considered only in the hypothesis B), c_{fuel} and c_{energy} represent respectively the unitary costs of electrical fuel (1.40 €/L) and energy (170 €/MWh), τ is the discount rate and ε is the discount rate in the energy sector. According to [25,26], τ is fixed to 1% and ε to 3%.

Table 9 reports the main items of initial investments for the installation of the wind farm. In particular, the costs are evaluated considering the installation of 10 wind turbines, each one having a rated power of 330 kW [27,28]. The unitary costs are expressed in function of the installed power.

Table 9. Initial costs of the wind farm.

Item Cost	€/kW	€
Wind turbine	1652	5,451,600
Grid connection	354	1,168,200
Constructions	236	778,800
Others	118	389,400
Total	2360	7,778,000

Similarly, Table 10 reports the main items of initial investments for the installation of the biomass power plant. We consider the installation of eight ORC (Organic Rankine Cycle) units, each one having a rated electrical output of 150 kW [11,29].

Table 10. Initial costs of the biomass power plant.

Item Cost	€/kW	€
ORC unit	2440	2,928,000
Grid connection	150	180,000
Constructions	270	324,000
Others	50	60,000
Total	2910	3,492,000

Table 11 reports the initial costs for the installation of a wave farm, composed of 20 DEIM points absorber, each one having a rated power of 80 kW.

Table 11. Initial costs of the wave farm.

Item Cost	€/kW	€
On-shore transformers and grid	18	28,800
Cables	12	19,200
Mooring	75	120,000
Building/facilities	150	240,000
Installation work	35	56,000
Sea wave energy converters	2500	4,000,000
Total	2790	4,464,000

Finally, Table 12 reports the initial costs estimated for the realization of the hydrogen station. The unitary costs are expressed in function of daily production capability of hydrogen [30]. In particular, as reported in Table 5, the annual hydrogen demand estimated is equal to 318,588 kg/year. Fixing the annual availability to 0.97 and considering an increase in the total capacity of 20%, the hydrogen station has a rated capability of about 1080 kg/day.

Table 12. Initial costs of the hydrogen station.

Item Cost	€/kg Day	€
Building	310	334,740
Compressor	330	356,336
Electrolyzer	1320	1,425,345
Vessel	1050	1,133,797
Others	50	53,990
Total	3060	3,304,209

As regards the operative and maintenance costs, we consider the values reported in Table 13.

Table 13. Operative and maintenance costs.

	Unitary Costs	Annual Costs
Wave farm	55 €/(kW-year)	€181,500
Wind farm	47 €/(kW-year)	€155,100
Biomass power plant	98 €/(kW-year)	€117,600
Hydrogen station	48 €·day/(kg-year)	€52,068

Figure 15 shows two important results: the production of hydrogen by an own-power plant supplied by renewable sources is not economically viable (at least in the absence of incentives) because the avoided cost of diesel purchase does not pay the initial investment in a reasonable period; the hypothesis B shows that the purchase of electrical energy for the production of hydrogen is very high, in fact, in just five years the two different scenarios have the same discounted cash flow.

For these reasons, we simulate a third hypothesis, characterized by a greater power plant by renewable sources, in order to sell the electrical surplus and reduce the breakeven time of the project. In this hypothesis (C), we fixed the installed power by biomass (for reasons of availability of this resource) and increased the installed power by wind and sea wave. In particular, the power produced by wave and wind plants was doubled (6.6 MW for the wind farm and 3.2 MW for sea wave).

Thanks to the selling of the electrical energy surplus, in the last hypothesis, the breakeven time is about 14 years (see Figure 16). Of course, the breakeven time can be further reduced through the introduction of an incentive [31].

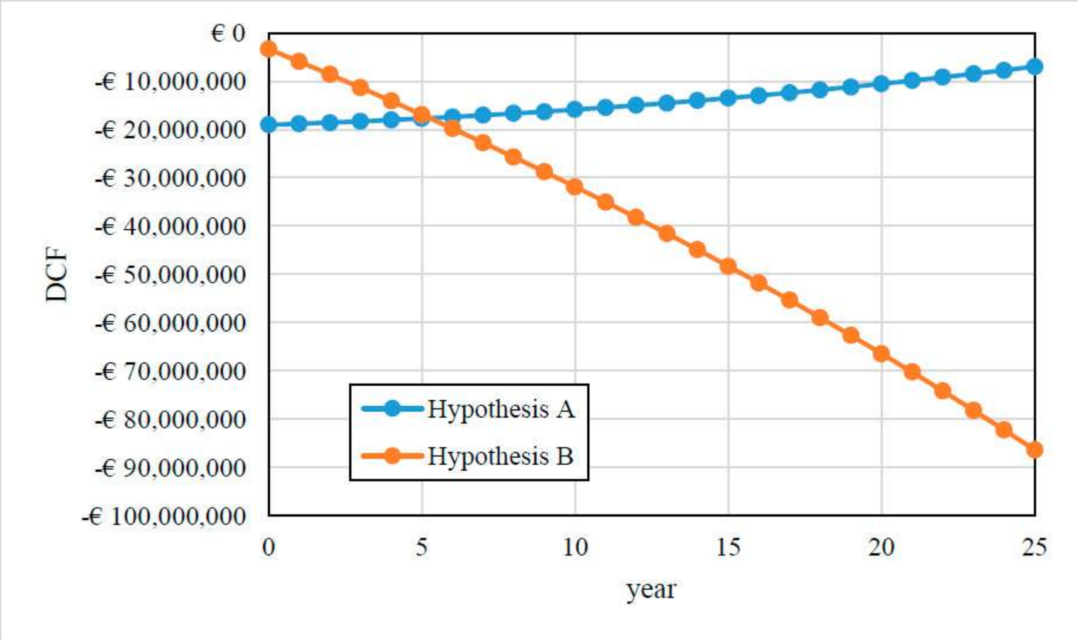

Figure 15. Discounted cash flow in the two different hypotheses.

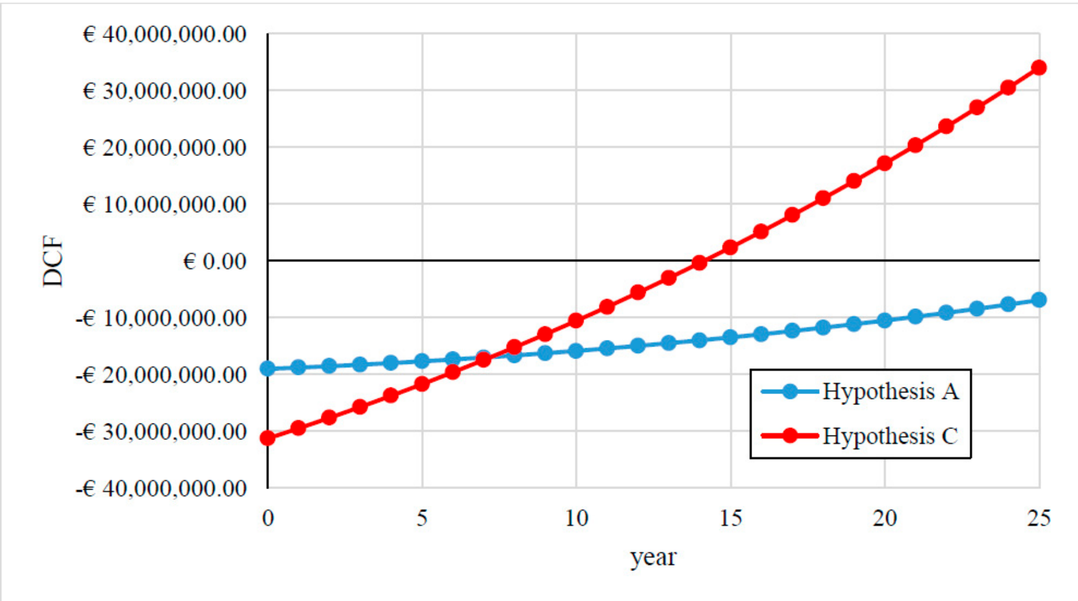

Figure 16. Discount cash flow in the hypotheses A and C.

5. Conclusions

The availability of biomass, wind and sea wave in the province of Trapani shows that the use of these resources for the electrolytic hydrogen production would allow the replacement of the entire fleet of urban buses powered by diesel with an equal number of hydrogen vehicles. From the environmental point of view, this project allows the abatement of several greenhouse gases, in particular, in the best scenario (100% replace of diesel buses), the annual avoided emissions are 1444 tons of CO_2, 7.64 tons of CO, 1.12 tons of PM_{10}, 2.1 tons of NMVOC and 22.85 tons of NO_x.

From the economic point of view, the project—in absence of an incentive—presents a very long breakeven time, incompatible with the lifetime of the plants. A possible solution is the oversizing of wind and sea wave power plants in relation to the electrical demand for hydrogen production, in order to sell the surplus of energy into the electrical grid. In this way, with a double installed power of wind and sea wave farms, the breakeven time is about 14 years. The introduction of an incentive related to the annual distance covered by hydrogen buses and/or the selling of electrical surplus can be a successful way to reduce the breakeven time, making this project feasible.

Author Contributions: All authors contributed to writing the article on equal terms. All authors read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. International Energy Agency IEA. *Solar Energy Perspectives*; OECD (Organisation for Economic Co-operation and Development) Publishing: Paris, France, 2011.
2. Boscaino, V.; Cipriani, G.; Curto, D.; Di Dio, V.; Franzitta, V.; Trapanese, M.; Viola, A. A small scale prototype of a wave energy conversion system for hydrogen production. In Proceedings of the IECON 2015-41st Annual Conference of the IEEE Industrial Electronics Society, Yokohama, Japan, 9–12 November 2015; pp. 003591–003596.
3. Sørensen, B. *Renewable Energy—Its Physics, Engineering, Environmental Impacts, Economics & Planning*, 3rd ed; Elsevier: Amsterdam, The Netherlands, 2004.
4. Winter, U.; Weidner, H. Hydrogen for the Mobility of the Future Results of GM/Opel's Well-to-Wheel Studies in North America and Europe. *Fuel Cells* **2003**, *3*, 76–83. [CrossRef]
5. Shaheen, S.; Martin, E.; Lipman, T. Dynamics in Behavioral Response to Fuel-Cell Vehicle Fleet and Hydrogen Fueling Infrastructure: An Exploratory Study. *Transp. Res. Rec. J. Transp. Res. Board* **2008**, *2058*, 155–162. [CrossRef]
6. Langford, B.C.; Cherry, C. Transitioning a bus transit fleet to hydrogen fuel: A case study of Knoxville Area Transit. *Int. J. Hydrogen Energy* **2012**, *37*, 2635–2643. [CrossRef]
7. Briguglio, N.; Andaloro, L.; Ferraro, M.; Di Blasi, A.; Dispenza, G.; Matteucci, F.; Breedveld, L.; Antonucci, V. Renewable energy for hydrogen production and sustainable urban mobility. *Int. J. Hydrog. Energy* **2010**, *35*, 9996–10003. [CrossRef]
8. Trapanese, M.; Franzitta, V.; Viola, A. A dynamic model for hysteresis in magnetostrictive devices. *J. Appl. Phys.* **2014**, *115*, 1–4. [CrossRef]
9. GSE (Gestore Servizi Energetici). Incentivazione delle Fonti Rinnovabili. Bollettino Aggiornato al 31 Giugno 2015. Available online: http://enerweb.casaccia.enea.it/enearegioni/UserFiles/GSE_FR_IISem2015.pdf (accessed on 10 January 2017).
10. RSE (Ricerca Sistema Energetico). Atlante Eolico Interattivo—RSE. Available online: http://atlanteeolico.rse-web.it/ (accessed on 19 October 2016).
11. Zuccato Energia. ZE 150 LT. Available online: http://www.zuccatoenergia.it/images/pdfs/DS_ZE150_IT.pdf? (accessed on 10 January 2017).
12. Sannino, G.; Bargagli, A.; Carillo, A.; Caiaffa, E.; Lombardi, E.; Monti, P.; Leuzzi, G. Valutazione del Potenziale Energetico del Moto Ondoso Lungo le Coste Italiane. Available online: http://www.enea.it/it/Ricerca_sviluppo/ documenti/ricerca-di-sistema-elettrico/correnti-marine/rds-151.pdf (accessed on 10 January 2017).
13. Franzitta, V.; Trapanese, M.; Giaconia, C.; Ferrara, P.; Viola, A. Design and experimental test of a low costweather buoy. In Proceedings of the 2013 MTS/IEEE OCEANS-Bergen, Bergen, Norway, 10–14 June 2013; pp. 1–5.
14. Franzitta, V.; Viola, A.; Trapanese, M. Design of a transverse flux machine for power generation from seawaves. *J. Appl. Phys.* **2014**, *115*, 17E712. [CrossRef]
15. Franzitta, V.; Milone, A.; Milone, D.; Trapanese, M.; Viola, A.; Pitruzzella, S. Experimental evidence on the thermal performance of opaque surfaces in Mediterranean climate. *Adv. Mater. Res.* **2014**, *860*, 1227–1231. [CrossRef]
16. Curto, D. *Ottimizzazione delle Performances Energetiche di un Innovativo Generatore di Energia Elettrica da Moto Ondoso*; Gruppo Editoriale L'Espresso: Rome, Italy, 2015.
17. Franzitta, V.; Curto, D.; Rao, D.; Milone, D. Near zero energy island with sea wave energy: The case study of Pantelleria in Mediterranean Sea. In Proceedings of the OCEANS 2016, Shanghai, China, 10–13 April 2016; pp. 1–5.

18. Shao, Y.; Yin, G.; Wang, Z.; Gao, Y. Proton exchange membrane fuel cell from low temperature to high temperature: Material challenges. *J. Power Sources* **2007**, *167*, 235–242. [CrossRef]
19. Song, C. Fuel processing for low-temperature and high-temperature fuel cells: Challenges, and opportunities for sustainable development in the 21st century. *Catal. Today* **2002**, *77*, 17–49. [CrossRef]
20. Feroldi, D.; Basualdo, M. Description of PEM Fuel Cells System. In *Green Energy and Technology*; Basualdo, M.S., Feroldi, D., Outbib, R., Eds.; Springer: London, UK, 2012; Volume 87, pp. 49–72.
21. Zoulias, E.; Varkaraki, E. A review on water electrolysis. *TCJST* **2004**, *4*, 41–71.
22. Beccali, M.; Brunone, S.; Galletto, J.M. Trasporto pubblico su gomma, penetrazione di mezzi ad idrogeno. Potenzialità della Sicilia occidentale. In Proceedingds of the 63 Congresso Nazionale ATI—"Energia per lo Sviluppo Sostenibile", Palermo, Italy, 23–26 September 2008; pp. 1–9.
23. Burke, A.; Gardnier, M. Hydrogen Storage Options: Technologies and Comparisons for Light-duty Vehicle Applications. Available online: https://escholarship.org/uc/item/7425173j (accessed on 10 January 2017).
24. Franzitta, V.; Milone, A.; Milone, D.; Trapanese, M.; Viola, A. A case study to evaluate the indoor global quality. *Adv. Mater. Res.* **2014**, *864*, 1054–1058. [CrossRef]
25. Tasso Bce. Available online: http://www.euribor.it/tasso-bce/ (accessed on 4 November 2016).
26. Steinbach, J.; Staniaszek, D. Discount Rates in Energy System Analysis Discussion Paper. Available online: http://bpie.eu/wp-content/uploads/2015/10/Discount_rates_in_energy_system-discussion_paper_2015_ISI_BPIE.pdf (accessed on 10 January 2017).
27. International Renewable Energy Agency (IRENA). *Wind Power*; IRENA: Masdar City, UAE, 2012.
28. Italtechwind. Il Primo Generatore Brevettato a Magneti Permanenti Multistadio—CATALOGO. Available online: http://www.italtechwind.it/it/utility/pdf/italtechwind_ita.pdf (accessed on 10 January 2017).
29. International Renewable Energy Agency (IRENA). Biomass for Power Generation. Available online: https://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-BIOMASS.pdf (accessed on 10 January 2017).
30. Melaina, M.; Penev, M. Hydrogen Station Cost Estimates. Available online: http://northcat.org/sites/default/files/file_uploads/NREL%20Hydrogen%20Station%20Cost%20Estimates%202013.pdf (accessed on 10 January 2017).
31. Franzitta, V.; Pitruzzella, S.; Milone, D.; Trapanese, M.; Viola, A. Energy savings through integration of the illumination natural and artificial, using a system of automatic dimming: Case study. *Appli. Mech. Mater.* **2013**, *372*, 253–258.