AIR POLLUTANT EMISSIONS AT AN AEGEAN ISLAND PORT

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1. INTRODUCTION

Port emissions make up a small fraction of the overall emissions from shipping (USEPA, 2009). However, ports attract shipping traffic and form sources of concentrated exhaust emissions near populated areas. As a result the impacts of port emissions on public health are higher compared to the impacts of seagoing shipping (Corbet et al, 2007). The main pollutants emitted by ships are SO_2, because of the high sulfur content of marine bunkers, particulate matter (PM) and CO as a result of incomplete combustion of the low quality marine fuels and NOx that are emitted at the high temperatures and pressures in all internal combustion engines. Additionally, as in every hydrocarbon's combustion process, CO_2 is emitted, which does not cause acute toxic effects but contributes greatly to the greenhouse effect and global warming.

For this reason, global and regional organizations have adopted regulations to reduce pollutant emissions from shipping in ports and coastal areas. According to Annex VI of Marpol 73/78, the sulfur content of marine fuel in SECAs (Sulfur Emission Control Areas) should be 1% (m/m) till the end of 2014 and 0,1% (m/m) thereafter. General sulfur limits in other sea areas are 3,5% (m/m) and will be reduced to 0,5% (m/m) by 1st January 2020 (IMO, 2014) in case that the refinery industries can meet the demand, otherwise the reduction will be postponed to 2025. The EU (EU, 2005), issued the Directive 2005/33/EC that came into force on 1st January 2010 and requires the sulfur content of the marine fuels to reduce to 0,1% (m/m) while the ships are docked. The directive does not apply to ships in port for less than 2 hours and to vessels who "cold iron" i.e. change over to shore power in port. There are no explicit PM emission limits; however the reduction of sulfur in marine fuels results in reduction in PM emissions as a result of the refining of fuel and its better combustion.

As regards greenhouse gases, shipping has the lowest emissions of CO_2 per tkm or per pkm compared to other modes of transport and it is often recognized as an energy efficient and relatively environmentally friendly mode of transport (Chapman, 2007). Overall, shipping emitted 2,7% of global CO_2 emissions in 2007 (IMO, 2009). In spite of this, the CO_2 emissions by road transport have already been regulated (European Commission, 2014) and are gradually being reduced. In addition cargo shipping is estimated to treble by 2030 taking advantage from economies of scale (Chapman, 2007). Hence it is likely that in the future the fraction of emissions by shipping would be much higher and this would impair its competiveness. Thus recently (1st January 2013) IMO took some measures to reduce the CO_2 by ships introducing mandatory EEDI (Energy Efficiency Design Index) for new ships and SEEMP (Ship Energy Efficiency Management Plan) for all ships (IMO, 2014).

Greece's domestic short sea shipping links the numerous islands of the Greek archipelagos with each other and with the mainland. It is used by 20 million passengers per year and it is vital for the welfare of the islands. Overall, there are 1,500 daily links calling into 40 continental ports and 100 island ports (Observatory of Transport Policies and Strategies in Europe, 2013).

Lesvos is the third biggest (in terms of area) island of the Greek archipelagos. Its economy is mainly based on agriculture and stock breeding with high quality products such as olive oil, cheese and ouzo. Lesvos has a unique culture, tradition and physical environment so it has a great potential to develop sustainable tourism based on its natural and cultural heritage (Nijkamp and Verdonkschot, 1995).

In the municipality of the capital Mytilene, with a population of 37.881 inhabitants (ELSTAT, 2001), the port is located within the city limits (Figure 1). In earlier studies, it was found that in Mytilene air pollution episodes connected with the port do not last long and are related to the entry and exit of the ships to/from the port (Kotrikla et al, 2013). However, due to their concentrated nature, these episodes could create discomfort to the residents, especially those living around the harbor, and the tourists. Measures to reduce the effects of the port (and transport in general) will strengthen the green nature of the island making it more attractive to permanent residents and tourists.

The aim of this study was to estimate the quantities of particulate matter (PM10) and CO_2 emitted by the ships at the port of Mytilene and to discuss the potential of shore side electricity to reduce the emissions.

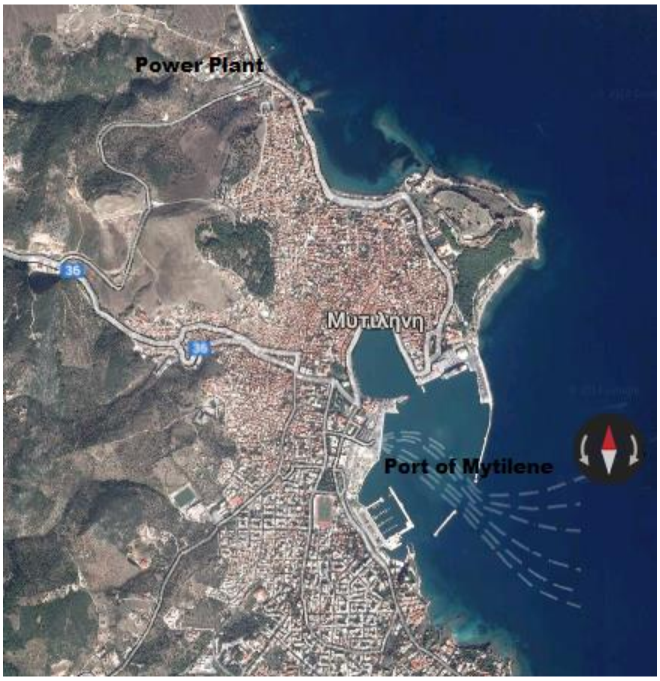


Figure 1. The port of Mytilene

2. METHODOLOGY

2.1 Calculation of the emissions

In this study the emissions of CO_2 and PM_{10} of the ships approaching the port of Mytilene were estimated for the period between 10 and 20 August 2012. Estimations of the shipping emissions were performed using a bottom-up methodology developed and applied to the Mediterranean Sea (CONCAWE, 2007). According to that, the emissions for a single trip of a vessel are determined using the following equation:

$$E_{trip,i,m} = \Sigma_p \left[t_p \left(P_e \times LF_e \times EF_{e,i,m,p} \right) \right] \quad (1)$$

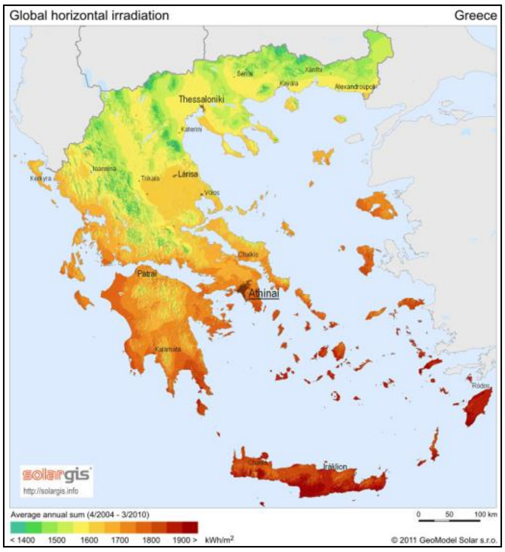
Here EF is the emission factor (kg/kWh) of CO_2 and/or PM_{10}, LF the engine load factor (%), P the engine nominal power (kW), and t time (hours). Subscript e refer to the different engine category (main, auxiliary), i to the engine type (slow-, medium-, and high-speed diesel), m to the fuel type (Residual Oil – RO, Marine Distillate-MD), and p to the different phases of the trip (berthing, maneuvering). Regarding the different phases of the trip, maneuvering refers to the slow movement of the ship between the port's breakwater (entry/exit) and point of berth, whereas berthing refers to the dockside mooring of the ship. The total inventory is the sum over all trips of all vessels during the period we investigated.

Details of the ships (IMO number, type of ship, gross tonnage, engine model, engine speed and power, type of fuel) were obtained from free internet data bases (Marine Traffic, 2012; Equasis, 2012), Greek Shipping Directory (2006), the Port Authority of Mytilene and from the personnel of the ships. Ship traffic data were obtained from the Port Authority of Mytilene. The time of maneuvering was obtained by observation of the ships' movements inside the port of Mytilene. The average load factors and emission factors of the main and auxiliary engines suggested by the study of CONCAWE (2007) were used in this study.

2.2 Renewable energy contribution simulation

In the Aegean Region both wind and solar energy is highly available. The following maps show the average solar radiation (in kWh/m_2) (Figure 2) and the average wind speed in meters per second (Figure 3) for Greece. From the maps it is apparent that both the solar and wind potential of Lesvos island is high. For this reason the use of renewable energy sources to reduce the dependence on fossil fuels and the air pollution is reasonable.

In order to calculate the effect of renewable energy sources, 'Homer Energy' microgrid simulation software has been used (Homer, 2014). 'Homer Energy' software also provides information on solar radiation from the geographic coordinates of the installation place. In Mytilene area, the total annual sum of solar radiation was estimated to 1700 kWh/m_2, which is in accordance with other estimations (Figure 2). Wind map of the Aegean region shows that there are places with high wind speed on Lesvos Island with average wind speeds above 8m/sec. In the simulation an average wind speed of 7m/sec was considered as the wind resource. In the simulation software an electric model was created in order to measure energy from renewable energy and potential emissions reduction using combinations of photovoltaic systems of 500 kW and 5000 kW together with 1 to 4 wind turbines of 1.5 MW.



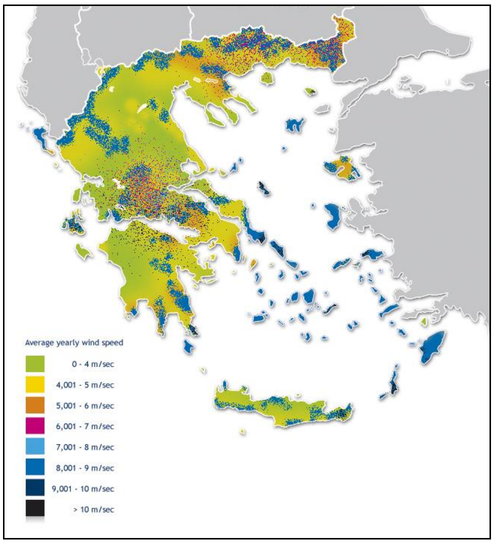


Figure 2. Average annual sum of solar radiation in Greece (4/2004-3/2010)
Source: http://solargis.info/doc/_pics/freemaps/1000px/ghi/SolarGIS-Solar-map-Greece-en.png

Figure 3. Average wind speed in Greece
Source: www.cres.gr

Although there are places with high average wind speeds near Mytilene city, installing wind turbines further away provides an additional advantage. Between distant places wind becomes less correlated, so wind energy production will differ from wind in the city (Stoutenburg et al, 2010). This is particularly important because higher pollutant concentrations exist when the wind speed in the city is low. Photovoltaics also have a similar advantage, which is that they are more effective on summer days without wind when the pollutant emissions do not disperse so they are more concentrated.

3. RESULTS AND DISCUSSION

3.1 Estimation of the emissions from the ships

During the period of interest (i.e. from 10 to 20 August 2012) there were 40 arrivals/departures of passenger ships, tankers and bulk carriers at the port of Mytilene. The total emissions from the activity during the whole period were 441 kg of PM_{10} and 282 tones of CO_2. The types of ships that arrive at the port of Mytilene were mainly passenger ships (6 ships, 35 arrivals/departures). There were also 3 tankers and 2 cargo ships. The passenger ships emitted in total 391 kg of PM_{10} (89% of the total emissions) and 254 tones of CO_2 (90%), whereas the rest of the ships accounted for the remaining emissions.

All ships have main engines (ME) for propelling and auxiliary engines (AE) providing energy for hoteling (lighting, heating, ventilation, air-conditioning, cold storage, cooking) and on-board cranes and pumps used for loading and unloading the freight. According to CONCAVE (2007) the average per vessel ratio of AE/ME total power for the Mediterranean passenger fleet is 0,27. In this study this ratio ranged between 0,10-0,21 for the specific vessels of the study.

The engines are used in certain loadings depending on whether the ships are cruising, maneuvering, or being at berth. Total PM10 emissions from all the ships during maneuvering were 164 kg (or 37% of the total emissions) and at berth 277 kg (63%). As regards CO_2 total emissions from all the ships during maneuvering were 66 tones (23%) and at berth 216,2 tones (77%). The mean time of maneuvering was 20 min and the time at berth 5.3 h. On average, the ships use their main engines during maneuvering at around 20% and the auxiliary engines at 50% of their maximum load. At berth, the main engines are operated at 20% of their maximum load for almost 5% of the berthing time. For tankers there is greater uncertainty since some of them (especially those not using diesel electric propulsion) will not run MEs in port but rely on AE power, and others will operate in port but with engine loads > 20%. A load factor of 20% have thus been chosen in an attempt bring the results to a reasonable approximation (CONCAWE, 2007). The auxiliary engines operate at 40-60% of their maximum load, providing energy for hoteling and loading/unloading the freight (CONCAWE, 2007). In our study, the ships remain at berth for an average time of 5.3 h hours per call and have a maneuvering time of 20 min. Therefore their emissions at berth overwhelm the emissions of the maneuvering.

Figure 4 shows the variation of the daily average emissions of PM from the shipping activity during the period we investigated. There is a peak on the 11th of August 2012, and another one on the 17th of August coinciding with the movement of people for their summer vacation. In particular, the period from 10 to 20 August coincides with the most important religious fest that attracts many people to the island, and the peak of the touristic season of the year. A similar emission pattern with time was observed for CO_2.

3.2 Discussing the abatement of emissions

Taking into account that the port of Mytilene is adjacent to the center of the city, it would benefit the air quality of the city to take measures to reduce the emissions of the ships while at berth.

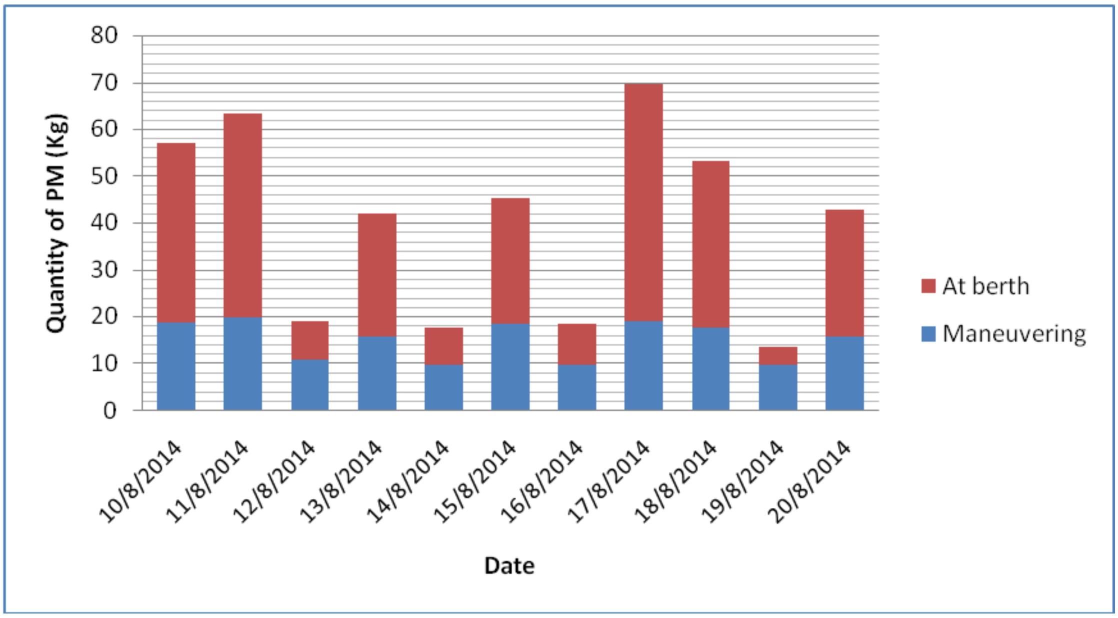


Figure 4. Daily emissions of PM from the shipping activity at the city of Mytilene from 10 to 20 August 2012

One measure is to provide electricity to the ships from the electric grid instead of producing electricity by ship auxiliary engines (European Commission, 2005). In general, the national grids in Europe are likely to have lower emission factors per MWh of electricity, either because of the type of electricity production process (e.g. wind, hydro, nuclear etc) or the stringent emission controls imposed on land based power plants (European Commission, 2005). The average CO2 emissions from electricity production across the EU can be estimated at around 330 g/kWh (European Commission, 2005). Also the average PM emission factors for EU25 electricity production are estimated around 0,03 g/kWh (European Commission, 2005).

The Greek islands are not connected to the mainland for their electricity needs and have low penetration of renewable energy. The electricity generation infrastructure of Lesvos Island comprises of one diesel power plant and two wind parks. The power plant consists of 10 electric generating sets that mainly use mazut (heavy fuel oil) and has an installed power of 66,464 kW. It is quite old since it first came into operation during the late 1970s, although the diesel engines have been replaced by new ones throughout the years as the energy demand increased (Giannoulis and Haralambopoulos, 2011). There is no pollution abatement system to the power plant. There are two wind parks that constitute the renewable energy production part of the island with an installed power of 11 MW combined. (Giannoulis and Haralambopoulos, 2011).

In cases of power plants that work with stationary, internal combustion engines, one benefit can be provided from the improved load factor of engines managed by electricity provider compared to the load factors of the marine engines when the ship is at berth (the latter typically at the range of 40%). Load factor of auxiliary engines is important as specific fuel consumption (and emissions) per kWh can increase significantly at low load factors. In the following indicative graph of common diesel engines (Figure 5) it can be shown that load factor variation can increase the fuel consumption per kWh produced more than 30%. There are cases where the reported load factors of marine auxiliary engines differ from the actual values measured during different operations (Nicewicz and Arnapowicz, 2012). Towards the same target of improving load factor to reduce emission, one option would be to use shore connection as emergency and backup and operate ships auxiliary engines at optimum load factor. Though this solution may have some technical implementation difficulties, emissions are reduced. Additionally, in this way grid load does not increase significantly, which is important at high season.

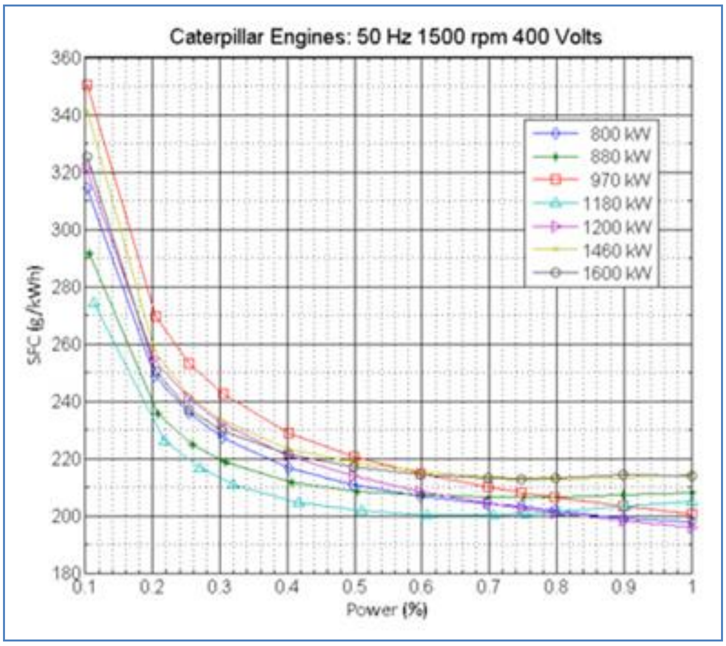


Figure 5. Efficiency of diesel generators versus load factor

Table 1. Emission factors for ship's AE at berth, g/kWh of electricity

	CO_2 (g/kWh)	PM[1] (g/kWh)
Marine Distillate (MD)	690	0,3
Residual Oil (RO)	722	0,8

[1]Total PM. Source: CONCAWE, 2007

Taking into account the specific characteristics of the island, if we assume that the heavy fuel oil used in Lesvos's power plant has similar properties with marine fuels, e.g. carbon content of 86,7% (CONCAWE 2007) this corresponds to a CO_2 emission factor of 3.179 kg/tonne of fuel. From data of fuel consumption and the generated electric energy given by the Lesvos' Power Plant for the study period (excluding the wind parks), it was calculated that the specific fuel consumption was on average 0,214 tonnes/MWh. Therefore the emission factor for CO_2 was 680 g/kWh, which is similar to the emission factor of the ship engines used in this study (Table 1), meaning that the potential of CO2 reduction by connecting the ships to the grid of Lesvos island is low.

On the other hand, for the emissions of PM there are indices from the literature that the emission factors are considerably lower in the power plants using petroleum products compared to the ships with the same fuel (Tables 1 and 2) meaning that the potential of PM reduction by connecting the ships to the existing grid of Lesvos island could be considerable and could be further explored.

Nonetheless, even if we have emission reduction by connecting the ships to the main grid that uses conventional energy sources, the location of the power plant in regard to the city (Figure 1) and the prevailing winds in the area (Figure 6) indicate that in many cases at low wind speeds the emissions would be dispersed in the direction of the city.

Table 2. Emission factors (g/kW) for PM_{10} by electric power generation and shipping recommended by different authors

Emission Factors (g/kWh)				
PM10	**Activity**	**Fuel/Technology**	**Comments**	**Reference**
0,065 (0,022-0,198)[1]	Power Generation	Heavy fuel oil/ -	Tier I. EFs based on fuel type, a mean of the range of combustion and abatement technologies	EMEP/EEA (2009)
0,011-0,144	Power Generation	Heavy fuel oil/	EFs based on level of technological sophistication	Visschedijk et al (2004)
0,007-0,018	Power Generation	Diesel/-	EFs based on level of technological sophistication	Visschedijk et al (2004)
0,096	Power Generation	Oil/Internal Combustion Engine	-	Cai et al (2012)
0,300	Shipping	MDO/MGO[1]/MSD[2]	Main Engines, Cruising	EMEP/EEA, 2009
0,900	Shipping	MDO/MGO[1]/MSD[2]	Main Engines, Manoeuvring, Hotelling	EMEP/EEA, 2009
0,504	Shipping	Heavy fuel oil/	-	Visschedijk et al, 2004
0,335	Shipping	Diesel/-	-	Visschedijk et al, 2004

[1]95% Confidence Levels

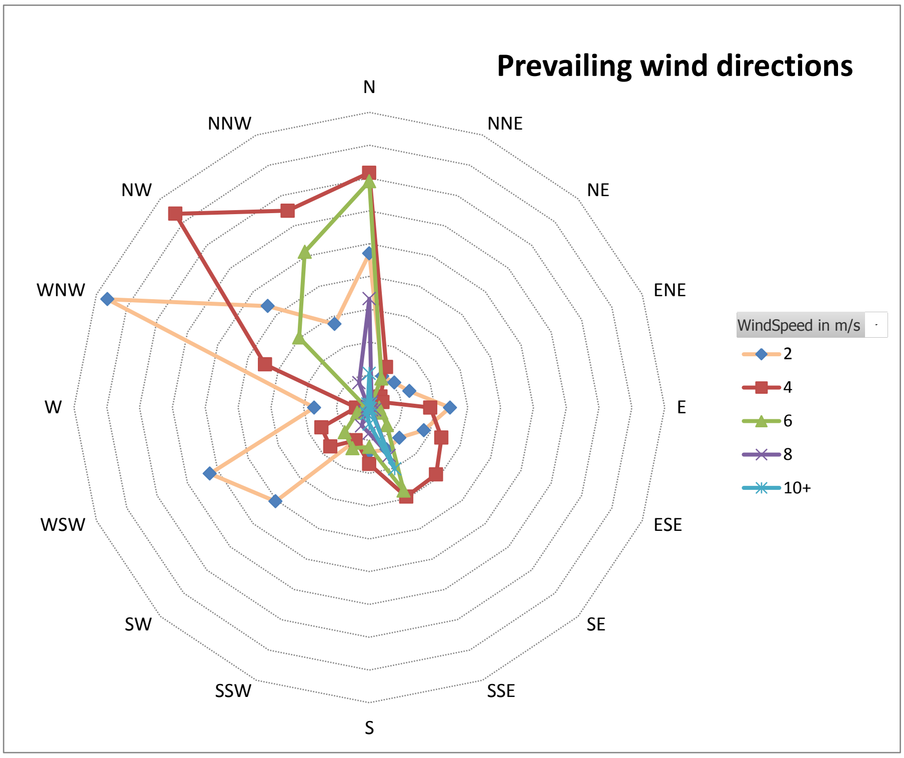


Figure 6. Rose chart of main wind directions at Mytilene airport during the study period

This influence of the power plant on the city has also been demonstrated using air pollution modeling (Kotrikla et al, 2013).

The above information indicates that cold ironing using the existing power plant infrastructure could provide some benefits but it will not completely solve the problem of pollution by the port in the city of Mytilene. A second option would be to combine cold ironing with renewable energy sources, which can provide a good solution for reducing emissions. Renewable energy sources can provide electric energy for the ship's load and for the power station. There are many different sizes of ship's auxiliary engines which vary from 200 kW up to 4 MW, therefore several simulations were examined in order to calculate the effect depending on the combination of ship engine and renewable sources size. In the simulation software, a simple AC (Alternative Current) bus electrical model has been created connecting renewable energy sources and load for cold ironing with the island's electricity grid. In the following Figure 7, the simulated power output of a photovoltaic array of 500 kW is given throughout the year. Similarly in Figure 8 the power output of 1.5 MW wind turbine with 77 meters rotor diameter and 65meters hub height is shown for the whole year.

The system simulation provides information on the part of ship's load covered by renewable sources, the part covered by the grid and the excess renewable energy. This means that part of the energy required for the ships electricity comes from renewable sources and in cases when renewables provide higher power output than the ship's load, excess energy is fed back into the grid. In this way the renewable energy given to the grid reduces the emissions from the electricity power station. Since the excess energy can be given to the grid it was not necessary to study renewable electricity storing.

Next the required electrical energy for each ship is computed from auxiliary engines maximum power, average load factor and time at berth for the two busiest days (11th and 17th of August). Another simulation was run from 7:00am of 11th of August to 7:00am of next day, because a passenger ship with a power of 32.000 kW remained at berth during the night. From these calculations it was derived that on 11th of August 24.664 kWh of electric energy were required, on 17th of August 28.785 kWh and on 11th of August from 7:00am to 7:00am of next day 35.301 kWh. Simulation results for the 11th of August from 7:00am to 12th of August, 7:00am are shown in Table 3. The computed values for energy provided from photovoltaic (PV) array, wind turbines and conventional grid in order to cover the total load of 35.301 kWh of the ships in 24 hours are shown. The excess energy provided to the grid and the reduction of CO_2 ship's emissions and power station's CO_2 emissions are shown.

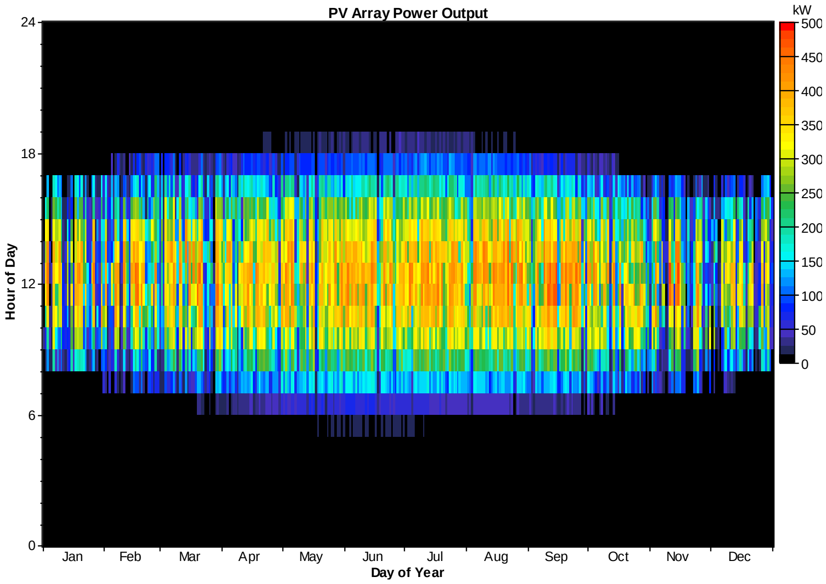


Figure 7. Simulated power output of a 500 kW Photovoltaic array in the area of Mytilene (without tracking system, with a 30^o slope)

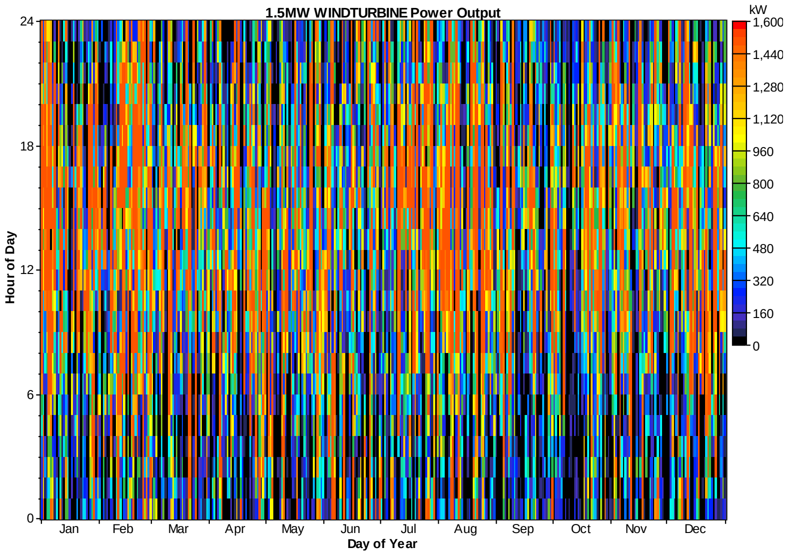


Figure 8. Simulated power output of a 1.5 MW wind turbine in the area of Mytilene

The following Table 4 provides a summary of simulation results for two days: 11th and 17th of August based on the total energy requirement from all ships at berth during these days. Table 4 also shows the relation between the energy produced from wind turbines and photovoltaic arrays compared to the remaining energy for the ship load that needs to be covered from diesel generators and depicts this percent for different ships.

Table 3. Simulation results for the 11th of August 7a.m. to 7a.m.

	1.5 MW WIND TURBINE	4 x 1.5MW WIND TURBINES	500 KW PV	5 MW PV	1.5 MW WIND TURBINE + 5 MW PV	4 x 1.5MW WIND TURBINES + 5 MW PV
PV array production (kWh/day)	0	0	2.707	27.073	27.073	27.073
Wind turbine production (kWh/day)	15.537	62.150	0	0	15.537	62.150
Energy by Power station to serve cold ironing (kWh/day)	19.882	11.087	32.594	21.224	13.135	7.917
Total load of the ships (kWh/day)	35.301	35.301	35.301	35.301	35.301	35.301
Excess PV-Wind energy fed into the grid (kWh/day)	118	37.936	0	12.996	20.444	61.839
Reduction of ships' CO_2 emissions (kg/day)	10.793	16.950	1.897	9.854	15.516	19.169
Reduction of power station's CO_2 emissions (kg/day)	82	25.798	0	8.840	13.904	42.052

Table 4. Simulation summary results for the 11th and 17th of August

Date/ Name of the Ship	Power Auxiliary Engines (KW)	Load Factor Auxiliary Engines	Average Power KW	Total energy requirement (kWh/day)	1.5 MW WIND TURBINE	4x1.5MW WIND TURBINES	500 KW PV	5 MW PV	1.5 MW WIND TURBINE + 5 MW PV	4x1.5MW WIND TURBINES + 5 MW PV
11 August			1.028	24.664	57%	90%	11%	65%	84%	95%
11 August (7am-7am)			1.471	35.301	44%	85%	8%	56%	76%	92%
17 August			1.199	28.785	51%	88%	9%	62%	81%	94%
ΕΙΡΗΝΗ Κ	205	0,4	82		98%	100%	71%	96%	99%	100%
EUROPEAN EXPRESS	3.300	0,4	1.320		48%	87%	9%	59%	79%	93%
ΠΕΛΑΓΙΤΗΣ	3.300	0,4	1.320		48%	87%	9%	59%	79%	93%
Blue Star Patmos	3.960	0,4	1584		41%	83%	7%	54%	74%	91%
ΜΥΤΙΛΗΝΗ	2.250	0,4	900		61%	92%	13%	69%	87%	96%
ΝΗΣΟΣ ΧΙΟΣ	3.078	0,4	1231		50%	88%	9%	61%	81%	94%

From the above Tables it is clear that cold ironing combined with renewable energy sources could be a solution to reduce fossil fuel consumption and emissions by the ships at the port of Mytilene. Even during low season periods when there are fewer ships at berth, renewable energy sources can supply the grid and still reduce emissions in the city from electricity production power station. Other considerations that influence the feasibility of the project such as cost and location of the photovoltaic arrays and wind turbines would be discussed in further work.

3.3 Conclusions

Passenger ships are the main polluters in the port of Mytilene. The pollution comes mainly from auxiliary engines (63-77%) and not from the main engines because the former are used throughout the duration of the stay of the ship in port. The emissions in the port could be reduced by connecting the ships at berth to the main electricity power grid. However, it is important to notice that if the main electricity system is provided by combustion of fossil fuels then the pollution in the ports is not totally abandoned but it is simply transferred to another area. For this reason, the use of alternative forms of energy (eg wind and photovoltaic) in the ports is proposed. The total energy requirements of the ships at the port of Mytilene could be covered by a hybrid system of four 1,5 MW wind turbines combined with a 5 MW photovoltaic system. The excess energy could feed into the grid so as not to require a storage system for the alternative energy. By this system there is a considerable reduction of the emissions at port but also some reduction at the power plant.

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