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Article

Wind Energy Integration through District Heating. A Wind Resource Based Approach

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Abstract: The aim of this paper is to examine if the surplus of wind energy could be added to electricity-to-heat conversion systems when there is increased congestion in the grid or when there is wind power curtailment. In this way, the produced power can be utilized for contributing to the local district heating (DH) system needs. After examining scenarios, optimized energy distribution is recommended. A case study near Kozani, Greece with an onshore wind farm (WF) to be installed was thoroughly investigated exploring the options for increased wind energy integration analyzing thermal utilization possibilities based on the local DH needs. A wind resource assessment for the area was done, which optimizes the WF planning and links the DH system with the operation of the WF. The utilization rate between the electric and the DH grid was examined in order to describe the optimal way of the energy to be distributed reassuring profitability for the power producer and robust energy management for the system. It was found that the curtailed wind energy can be locally utilized in a DH system, by covering part of the demand that the diesel-based peak load boiler system does currently.

Keywords: district heating system; wind farm; curtailment; wind resource analysis; exergy; environmental sustainability

1. Introduction

The old fashioned way that electricity grids are structured cannot comply with the continuously increasing needs in modern grids. A totally different approach and in depth research in smart grids is required, aiming ultimately at unifying the electricity to the district heating (DH) grid focusing on improving wind energy integration.

In the city of Kozani, the DH system has been fully operational since 1993 and the main idea was to use the excess heat from the operating power plants in the wider area. Public Power Corporation S.A. (PPC) lignite fired generation plants Agios Dimitrios III, IV, and V generate 95% of the yearly heat demand (with 70% of the heat load) and a peak load boiler plant produces remaining 5% (30% of the heat load) [1]. Agios Dimitrios plants III, IV, and V are installed at a distance of 17 km from the city of Kozani and therefore there was a need for significant construction works for the supply transmission pipelines. The hot water is sent through a pipe system to the consumer's place and after utilization via return pipes back to the hot water generation unit [2].

The extensive use of renewables, such as biomass or geothermal systems, in DH systems has proven that there are not significant technical problems in achieving high penetration levels under commercial conditions. In general, DH systems can also provide demand response services that make it easier to integrate renewables into the local power system. Thermodynamically though, using electricity to produce heat is rather inefficient, but under some circumstances it can be a better economic option than wasting potential electricity from variable renewables, such as wind energy. At the same time, from an economic perspective, selling electricity at prices that thermal energy is offered is not highly profitable for the investor, however, such solutions in a competitive environment under liberated electricity, gas, and power markets with lower or even no feed-in-tariffs shall become imperative in increasing the project's rate of return.

What is known for Greece, is that there are a lot of potential applications for wind farm (WF) installations (more than 30,000 MW) [3]. The promising feed-in-tariff scheme gave the opportunity to many investors and independent power producers to submit their applications to the Regulatory Authority for Energy (RAE) and they are currently waiting for approval. However, the Greek financial crisis has created a fragile investment environment in the country in moving decisively forward to investment. Nevertheless, as Greece geographically is located near to countries/areas with significant electricity requirements, as it is "standing" among Europe, Asia, and Africa, and taking into account the prevailing winds from side to side in the country, it could be examined what could have happened without this funding scheme for wind. How can part of the produced electricity be used differently and what could be the consequences to investors and end-users from this change. The basic idea of this paper is to examine different scenarios and how the surplus or curtailed energy from the Transmission System Operator (TSO) can be used from the DH system, providing demand response and integration services to the TSO (curtailed wind, is when wind power was available, but the system operator for various reasons did not accept the wind power to be dispatched). The basic concept is based on the decision that the peak load boiler system may initiate immediately when there is an overproduction of wind energy, and at the same time, the motor producing electricity at the peak load boiler, which is based on using light fuel oil, can be turned off and therefore save fuel.

This paper is comprised of five sections. Section 2 focuses on knowledge gained so far from other studies; Section 3 describes the methodology; Section 4 focuses on the case study; and Section 5 on scenario planning and implementation presenting the results and summarizing.

2. Literature Review

Although there is a large body of literature on district heating and biomass or geothermal units, not much has been done so far on interaction between wind energy and DH grids. The fact that using electricity to produce heat is inefficient discourages researchers to study it as an alternative. However, the idea that curtailed wind power (surplus) can contribute towards that direction, or even can put the system into operational maintenance during summertime, offers another perspective to the whole concept.

Partly, this idea of increasing local renewable energy production in order to convert surplus electricity into thermal energy, was presented from Niemi *et al.* [4]. The analysis they did was based on multi-carrier urban energy systems. It was found that for the city of Helsinki wind power production could be increased by 40%–200% by adding the electricity-to-heat conversion option for using surplus wind energy into the heating network. Long *et al.* [5] tried to balance wind power variability using electric heat pumps and combined heat and power (CHP) units. Maegaard [6] presented the Danish example with increased integration of wind energy into the grid through the use of CHP facilities. Hong *et al.* [7] studied scenarios using EnergyPLAN on wind energy integration in parallel with the heat demand into the existing energy system of Jiangsu province, China. It was revealed that according to the needs of the province, the wind power production could range from 0% to 42% of the total energy demand. The EnergyPLAN model was also used in studies focused mainly in the Danish market aiming at maximizing renewables grid integration [8–10].

Fitzgerald *et al.* [11] tried to study how power system efficiency can be improved by integrating wind power through an intelligent electric water heating system.

In general, there are few studies that confront the issue, despite the fact that in many cases, and in a great number of countries, the profitability of wind farms without the support of a scheme based on subsidization is questionable. Therefore, for this reason there were few studies in the literature linking the need for wind energy for DH networks to achieving greater integration shares. This paper is a unique case study since it connects a DH system in the city of Kozani, Greece, a detailed wind resource analysis, an annual energy production (AEP) forecast, and the local WF applications.

3. Proposed Methodology

3.1. Site Experimental Results

Accurate wind resource measurements are essential in order to identify areas with significant wind speeds at exploitable levels. For the evaluation of the winds in Kozani area, Geographic Information Systems (GIS) tools, the Wind Atlas Analysis and Application Program (WAsP) [12], and WindRose [13] tools were used as wind data assessment tools, and a wind map was created representing the wind speed at a height of 80 m above ground level (m.a.g.l.) in the wider area of the installed mast. Based on the analysis of these results, the primal outcome is an initial assessment of the area under examination. Wind profile measurements were carried out for specific periods using a meteorological mast. A satellite map of the area, including the wind mast, the location of the plants contributing mostly to the DH system, and the city of Kozani is shown in Figure 1.

Figure 1. A detailed satellite map of the area.

Mast coordinates, height in meters above ground level, period of measurement, average speed, and temperature are shown in Table 1.

Table 1. Main measured characteristics of the wind mast.

Latitude (°)	Longitude (°)	Mean Speed ($m{\cdot}s^{-1}$)	Period of Data Analysis	Height (m.a.g.l.)	Turbulence Intensity (T.I.) at 10m.
40°21'2" N	21°42'23" E	5.4 at 10 m	17 December 2006 to 17 December 2007	1093	11.19%

WindRose and WAsP tools were used for processing the experiments (yearly measurements) and generate estimates of speed/energy output. Vector Hellenic Wind Farms S.A. operates a certified wind measurements laboratory and the mast was under the laboratory's supervision. It is noticeable just by reviewing the wind rose (Figure 2) that the main directions were NW, WNW, and NNW.

The wind was studied for one year from 17 December 2006 to 17 December 2007. A 10 m mast was installed made out of steel in tubular form, which was kept in vertical position using tense wires. Anemometers and vanes were placed at ten meters. A data logger connected to the available sensors on the mast stored and sent the data to Vector Hellenic Wind Farms S.A. laboratory. The uncertainty of the measured wind speed for the mast was calculated using WindRose software and found to be quite high, at 0.187 m/s. The maximum 10-min average speed observed was 24.9 m/s and the maximum gust 33.9 m/s. The used data array was made up of the average (one value per second—600 values in 10 min) and maximum 10-min wind speed values in the site.

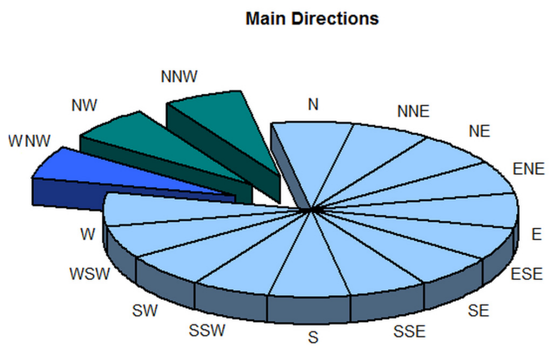
A preliminary statistical analysis of the measurements was useful for identifying the relationships among the examined variables. Weibull and Rayleigh probability density function analyses, which have an acceptable accuracy level of many wind resource studies in different locations [14–19], were used to identify the representation of the wind speed frequency curve. In Weibull distribution, the probability density function and the cumulative distribution indicate the variation in wind velocity. The probability density function $f_{Wei}(v)$ is given from the following Equation:

$$f_{Wei}(v) = \frac{k}{c} \cdot \left(\frac{v}{c}\right)^{k-1} \cdot e^{-(v/c)^k} \tag{1}$$

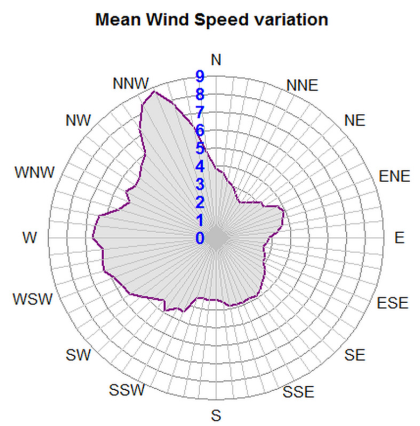
where k is the (dimensionless) shape parameter showing how peaked the wind distribution is, and c is the windy (dimensionless) scale parameter. Using the Weibull probability plotting paper method, k and c are calculated. The distribution function is transformed into a linear pattern using logarithmic scale and since the wind velocity is equal or lower than v, there is:

$$\ln\{-\ln[1 - f_{Wei}(v)]\} = k \cdot \ln(v) - k \cdot \ln c \tag{2}$$

If we plot the axes $\ln(v)$ for x and $\ln\{-\ln[1 - f_{Wei}(v)]\}$ for y, then the Weibull distribution is a straight line, with a slope of k and intersection $-k \cdot \ln c$. The real values of k and c can be found by producing the regression equation for the plotted line. It is known that for most wind conditions, k ranges from 1.5 to 3, while c ranges from 3 to 8 [20]. The results from the data and the Weibull distribution shown in Table 2 and in Figure 3, the Weibull shape and scale, the data distribution, the mean wind speed and the Turbulence Intensity (T.I.) at 10 m/s are shown for each direction.



(**a**)



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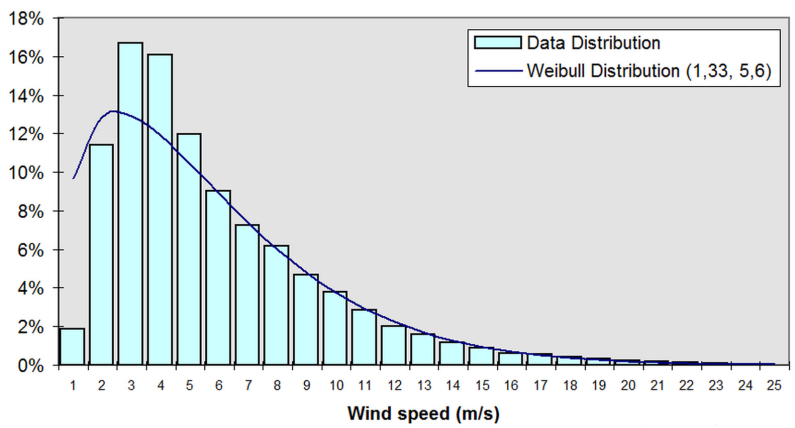


(**c**)

Figure 2. (**a**) Wind rose of the mast of Kozani area; (**b**) data and (**c**) Weibull distribution.

Table 2. Weibull distribution analysis of Kozani area mast.

Direction	Angles (°)	Weibull Shape	Weibull Scale	Data Distrib	Mean Wind Speed (m/s)	T.I. at 10 m/s
NNE	11.25–33.75	1.24	2.48	1.29%	2.8	9.9
NE	33.75–56.25	1.16	2.47	1.24%	2.8	11.2
ENE	56.25–78.75	1.9	4.29	2.41%	3.7	12.3
E	78.75–101.25	1.39	2.82	2.27%	3	13.3
ESE	101.25–123.75	1.4	2.55	3.18%	2.8	15
SE	123.75–146.25	1.78	3.55	6.95%	3.6	16.8
SSE	146.25–168.75	1.43	3.51	10.00%	3.8	13
S	168.75–191.25	0.87	2.17	6.06%	3.5	13.1
SSW	191.25–213.75	1.3	4.16	4.79%	4.2	12.8
SW	213.75–236.25	1.26	4.95	5.48%	4.9	12.6
WSW	236.25–258.75	1.64	6.65	5.34%	5.9	13.2
W	258.75–281.25	1.69	7.23	4.09%	6.4	11.4
WNW	281.25–303.75	1.58	5.68	11.61%	5.2	11.3
NW	303.75–326.25	1.68	6.6	9.38%	6	9.6
NNW	326.25–348.75	2.01	9.24	22.10%	8.2	10.8
N	348.75–11.25	1.28	4.68	3.81%	4.6	11.2

3.2. Wind Resource Analysis and Planning

The total number of valid data used was 52,345 (missing data 0.7%) and the included number of calm measurements (<2 m/s) was 6954. WAsP software was used to produce a wind map of the area; the estimated wind speed is visualized and different sites for wind turbines (WT) can be selected and proposed to be developed (Figure 3).

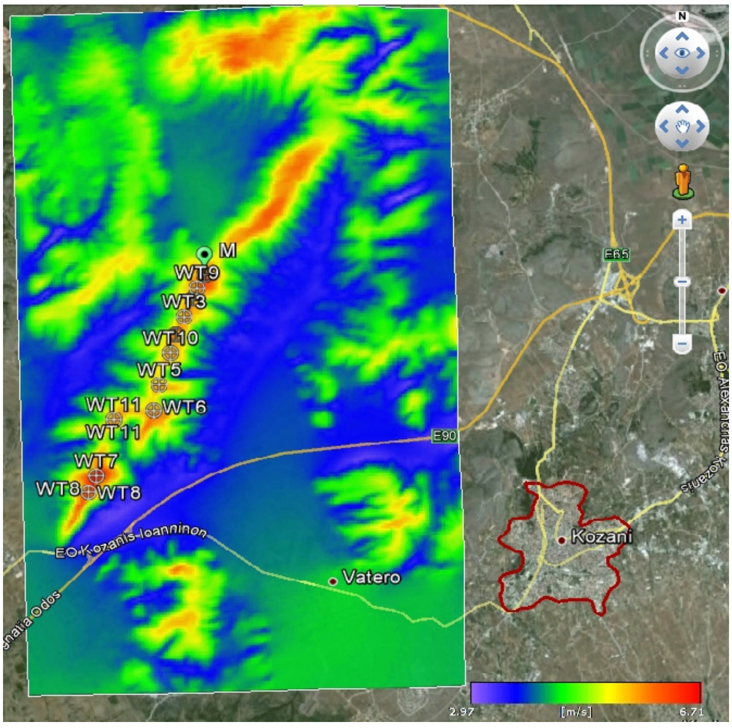


Figure 3. Wind resource analysis in the area.

From the wind analysis implemented in the area, the results show that the lowest average wind speed is 3.36 m/s and the highest is 6.74 m/s, extrapolated at 78 m from the ground. What can be easily observed is that the company developing the WF did not optimize the planning. However, there are more constraints, such as construction restrictions or environmental restrictions, *etc*. that ought to be taken into account in construction. In this specific case, the promising areas on the north side of the current planning were left out because there were other applicants for WF installation in the area. Based on RAE's licensing application files for new projects for power production [21] and the wind turbine spatial distribution limits per municipality, 2400 MW have been authorized and submitted to be installed in the prefecture (Table 3) [22].

Table 3. WT installation upper limits in Kozani Prefecture.

Municipalities	Surface (km^2)	Max Allowed No. of WT	WT Licensed	WT Applications
Voiou	771.05	508.89	136.69	131.00
Eordeas	708.80	467.80	210.32	407.00
Kozanis	971.33	641.08	108.26	131.00
Servion–Velventou	548.10	361.74	23.74	49.00

Note: Typical size of WT: 2 MW.

It can be seen from Figure 4 that there is enough space for new applications/installations, except in the Eordeas municipality.

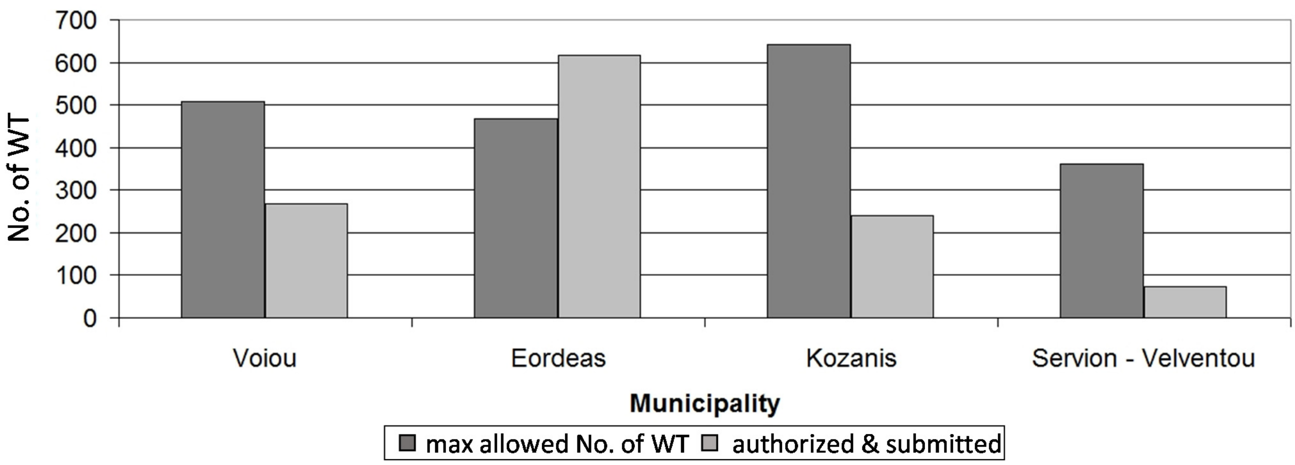
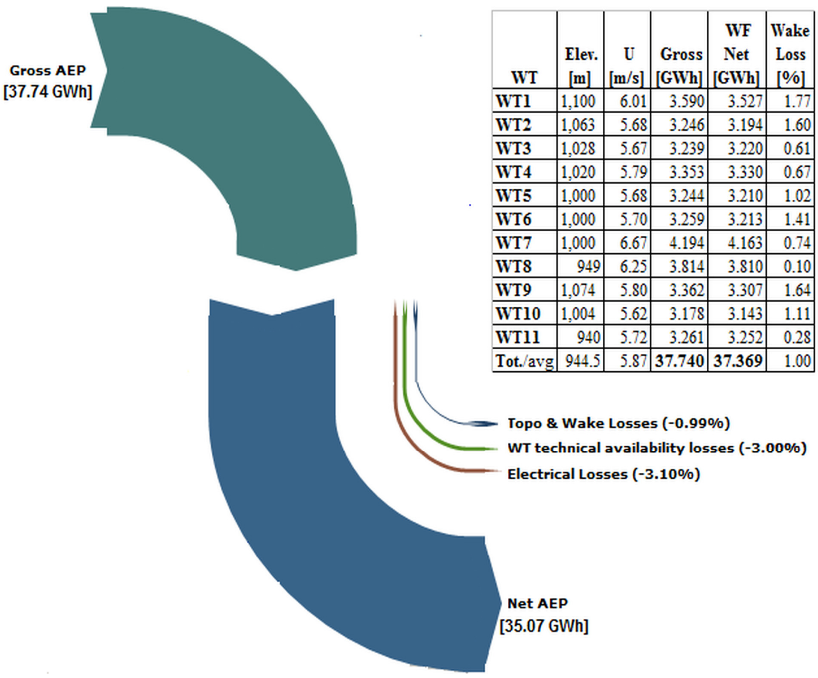


Figure 4. WT spatial distribution limits per municipality and WT authorized and submitted.

Based on these limits and applications, and since the load of the substations and the high voltage and medium voltage lines are not defined only from surface coverage constraints, it is rather possible that all WF may not secure interconnection terms with the grid. What is likely to occur is WFs interconnected, however, with high shares of curtailment. How can the curtailed energy be used differently in order: (a) to be effectively utilized and not wasted; (b) the profits of the investor to be secured; and (c) increase renewable energy sources integration?

4. Case Study in Kozani Region

The idea of smart utilization of the curtailed energy from wind (reducing peak demand and providing balancing loads) increasing at the same time the overall system's efficiency is improved was the drive for this research. Examining different scenarios with WF interconnection to the electricity grid and at the same time to the DH local grid will bring more options to the system. In general, it is known that the wind turbine is designed to operate under designed conditions, including constant air density. Thus, once the air density has changed, the output of wind turbine will certainly change. However, in this case, these calculations were included within the wind resource analysis. Adding up the electrical losses (internal interconnection medium voltage losses and transformer losses) and the wind turbine technical availability losses, a fixed percentage for the proposed wind farm, usually provided from the wind turbine manufacturer, it is possible to calculate the exergetic efficiency of the WF (Figure 5) [23–27].



WT	Elev. [m]	U [m/s]	Gross [GWh]	WF Net [GWh]	Wake Loss [%]
WT1	1,100	6.01	3.590	3.527	1.77
WT2	1,063	5.68	3.246	3.194	1.60
WT3	1,028	5.67	3.239	3.220	0.61
WT4	1,020	5.79	3.353	3.330	0.67
WT5	1,000	5.68	3.244	3.210	1.02
WT6	1,000	5.70	3.259	3.213	1.41
WT7	1,000	6.67	4.194	4.163	0.74
WT8	949	6.25	3.814	3.810	0.10
WT9	1,074	5.80	3.362	3.307	1.64
WT10	1,004	5.62	3.178	3.143	1.11
WT11	940	5.72	3.261	3.252	0.28
Tot./avg	944.5	5.87	**37.740**	**37.369**	1.00

Figure 5. Sankey flow diagram on the losses and the overall production of the WF.

The electrical losses were estimated taking into account the fact that the wind farm is planned to be 18.15 MW, and therefore the overall electrical losses will be specified from the medium voltage losses for the interconnection of the wind turbines and the distribution power station (20/150 kV 25 MVA transformer) losses. The average losses for each wind turbine of the internal Low Voltage/Medium Voltage (LV/MV) transformer are 0.6% and the wind farm MV/HV substation is 0.45% [28], the sum of the electrical losses is 3.1% for the proposed WF. Following the approach of Xydis [23] and of Hepbasli and Alsuhaibani [29], exergy efficiency of the proposed wind farm, including all losses can be estimated by using the Equation:

$$Exergy\ Efficiency = \frac{NetAEP}{8760\ \mathrm{C}_i} \cdot 100\% \tag{3}$$

where *NetAEP* is the Net Energy (MWh); 8760 h are the total hours within a year (365 days·24 h); and *Ci* the installed capacity of the wind farm (MW).

However in this case, exergetic efficiency may be increased. The amount of energy that would be wasted can be used on a different feed-in-tariff scheme and therefore increase the utilization rate of the generated electricity. The need to cover some of the needs of the peak load boiler, which produces 5% of the yearly required thermal load, as well as the PPC lignite plants when these are operating in the technical minimum. There is no need to maintain the operation of lignite plants at high levels just for covering the heating needs of the DH system. For the implementation of the concept, though, interconnection of the electricity with the DH grid is necessary.

It is obvious, though, that the profitability of such a project would be based on various offered prices to the end-users. The peak load boiler consists of three boilers of 10 MW_{th} and two of 27.5 MW_{th}, totaling 85 MW_{th}. Approximately 90% of the annual heat output comes from the central system (base load unit) and 10% from the peak boiler. The total district heating system is designed to serve the required demand with superheated water flow temperature, which vary seasonally between 90 °C and 120 °C. The building facilities allow return temperatures ranging (again based on the seasonal needs, e.g., the temperature is at its lowest during summer, when only hot service water is needed) between 55 °C and 70 °C.

The topography and hydraulic conditions of the network led to the design of a distribution network of 25 bar nominal pressure. The capacity of pumping stations was selected to ensure the supply of the outermost end-users. The distribution network consists of conductors insulated and installed directly on the ground. The conductors are insulated with polyurethane and polyethylene protective casing. Based on the data from Municipal Enterprise for water supply and sewerage of Kozani [1], it is calculated that on average the annual thermal energy production from the three PPC plants and the peak boiler is approx. 240,000 MWh_{th}. Therefore, as mentioned before, the peak load boiler plant produces 5% of the thermal needs for the city of Kozani and suburbs annually, which actually means 12,000 MWh_{th}. This exact amount of energy, which is covered from the boiler and uses oil as fuel, can be covered from the curtailed power. Currently, curtailment in the Greek mainland is taking place at low percentages, since it is something that it is mainly happening on islands, e.g., Crete Island [30]. However, it is something that will sway smart grids in the future. Based on a recent study of the National Technical University of Athens, founded from RAE and National Technical University of Athens, it was revealed that by the year 2025, when the Greek system is expected to have installed 5–8 GW of wind farms, it is expected that the average curtailment rate, for various reasons, to be from 0.8% to 4.3% [31]. Therefore there is:

$$Wind\ Curtailment = (0.8\% - 4.3\%) \cdot NetAEP \tag{4}$$

which means approximately from 280.5 to 1508 MWh_e yearly from this wind farm, taking into account the wind resource assessment and wind farm production forecasting that the NET Annual Energy Production is 35,070 MWh (Figure 5).

5. Results and Discussion

In reality, however, based on this analysis for the season 2006–2007, where all the wind and heat data come from, it was found that the possible annual contribution varies from 154.3 to 701.3 MWh per year. This is because only when the energy needed to run the peak load boiler the surplus of wind energy could be utilized. In this case, it was roughly assumed that conversion of wind electricity to heat can be achieved by adding an electric resistance to the peak boiler with a conversion efficiency of 100%, exactly as in the work of Niemi *et al.* [4].

Analyzing the profile of the average monthly and peak load fluctuation (Figure 6), it can be seen that different profiles occur every month and that the district heating system serves the customers from October until May.

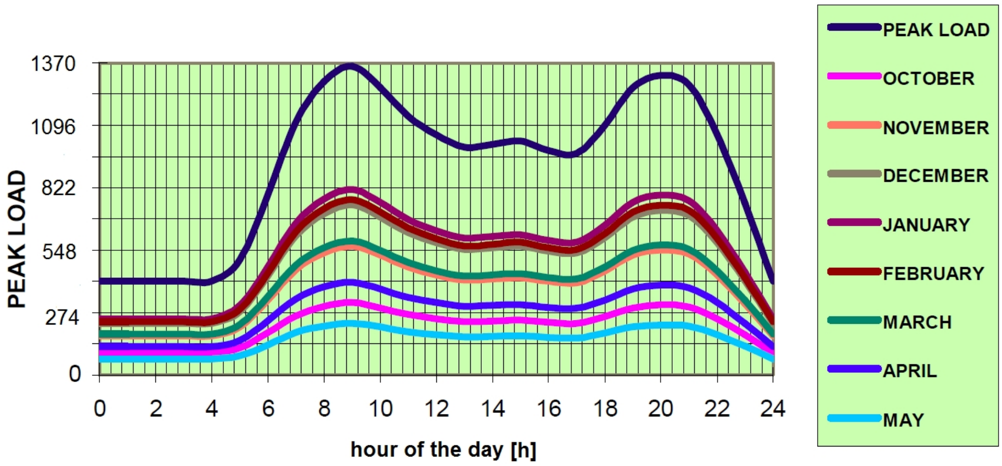


Figure 6. Average monthly and peak load daily demand [32].

It is acceptable that different load profiles happen because of different seasonal heating needs. Using WindRose tool, wind time series were used to produce average energy time series from the studied WF. Orography, wake, electrical, and WT availability losses were roughly introduced to the model and the results in Figure 7 were obtained.

Based on Figure 7 and Table A1 (Appendix), it can be seen:

(a). Regardless of the wind power curtailment rate, there is a realizable line (which represents what could happen in real life) that covers part of the needs of the peak load for every hour.
(b). At night and in the early morning, curtailed wind can cover higher amounts of heating needs.
(c). In May, the heating needs are so low that they can be almost totally covered from wind curtailment.

It should be clear, though the motive for the investor is to sell the rejected electricity from the system instead of only choosing curtailment as an option—and missing out on the associated remuneration. Based on the current law for renewables, Law 3851/2010, there is a provision for the compensation of the WF owner according to the occurred grid curtailment. At the end of each year, the TSO remunerates each WF owner additional payments, which are equal to a remuneration corresponding to 30% of the realized energy cuts imposed the previous year [33]. Therefore, the offered price from the WF owner to DEYAK should be higher than that. On the other hand, for DEYAK, the offered price should not be too expensive, however it should be cheaper compared to the current production cost of district heating. It has to be cheaper for DEYAK in order for this energy to be utilized instead of using the peak load boiler. A similar approach was followed in the recent study of Rezaie *et al.* [34].

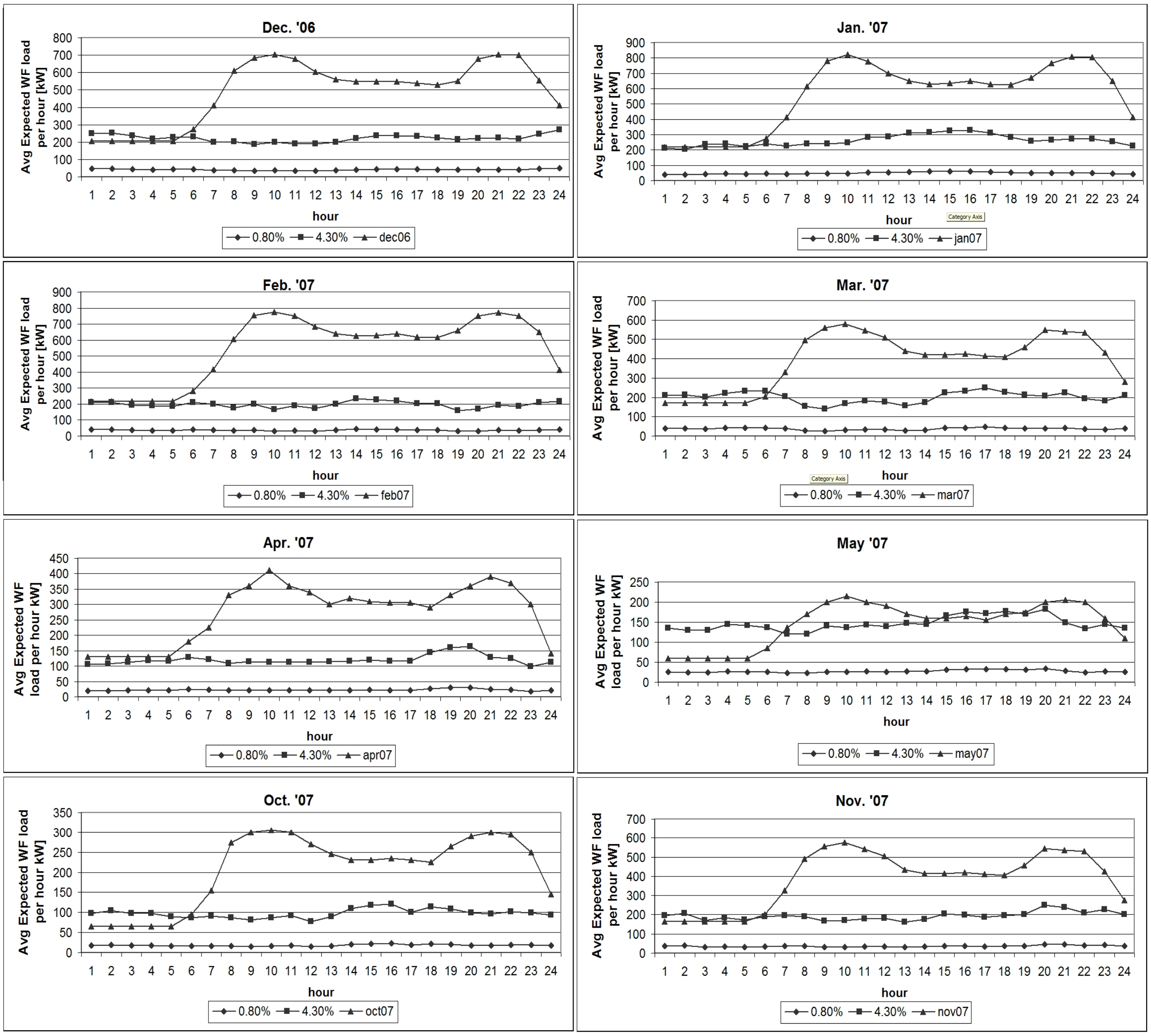


Figure 7. Average monthly load daily demand and average low (0.8%) and high (4.3%) wind power curtailment rate.

Based on the wind curtailment data and dividing the Feed-in-Tariff (FiT) by this 30% remuneration factor, the minimum of the FiT for the WF is found equal to 26.35 €/MWh. If the requested price falls below this number, then the WF owner has higher profits by receiving the government reimbursement from this 30%. According to the Law 3851/2010, this fraction can be increased up to 100%, so as the total compensation is equal to the smallest amount between: (a) the compensation to be received if operated with two thousand (2000) hours equivalent; and (b) the compensation to be received if operating without any curtailments. Therefore, for wind farms with low capacity factor (in the order of 20%–25%, such as in this region of Greece), which is about 2000 h, the compensation is usually 100%. Initially, the wind producer won't have any interest in selling his curtailments for heating at a lower price. However, under the EU Target Model, this is not effectively dealt—and the Renewables Directive simply says that renewables curtailment should be minimized via "appropriate grid and market-related operational measures" [35,36].

Therefore, a realistic approach was taken based on the discussions for the development of the energy commodity market in Greece and the curtailment was decided to be left out of the compensation according to the occurred curtailment, since, no physical power shall be offered to the grid. In order to minimize the investor's loss at the same time—based on the TSO's decisions on curtailment—it is assumed that the DH price to be offered can preserve part of the losses. The DH price offered to end-users remains steady over the past few years (52.46 €/MWh) despite the economic recession in Greece and the inconsistent oil prices. Therefore, if an assumed fixed price of 42 €/MWh can be offered from DEYAK to the WF owner when wind power can absorbed more from the heating system, and of course 26.35 €/MWh as a minimum, there are a number of scenarios that can be examined depending on the possible annual contribution (154.3–701.5 MWh). Based on the open source investment analysis tool (Cash Flow Model) that Xydis via [37] introduced through the author's personal company (www.xydis.gr/gx) website [38], three scenarios were examined for different integration schemes. Introducing to the model the Price per MWp (1325 €/kW), the total installed Capacity in MWp (18.15), the investment scheme (subsidy:equity:loan of 35%:25%:40%), the capital discount rate (7.48%), the estimated energy output (1932 kWh/kW), insurance, maintenance and operation costs and the selling price of produced kWh, the results can be seen in Table 4 under the initial scenario (no curtailed wind power utilized). Adding up the two extreme scenarios to that (1, delivering to the heating system 154.3 MWh with a price of 0.02635 €/kWh; and 2. delivering to the heating system 701.5 MWh with a price of 0.042 €/kWh), the results change slightly (Scenarios 1 and 2). It is estimated, based on the ECOHEATCOOL project [35], that CO_2 emissions reduction by using the curtailed wind energy in DH could reach up to 252 tn/yr (in the case of 701.5 MWh), while in the lower case of 154.3 MWh, CO_2 savings can at least reach 55 tn/yr.

Table 4. WF investment plan results.

	Initial Scenario	**Scenario 1**	**Scenario 2**	**Scenario 3**
Net Present Value (NPV) (T€)	16,399	16,439	16,688	16,760
Balance (T€)	10,386	10,426	10,676	10,748
Internal Rate of Return (IRR)	12.42%	12.47%	12.78%	12.87%
full repayment (yrs)	9	9	9	9

In any case, between these two scenarios the overall IRR of the project increases from 0.05% (scenario 1) to 0.36% (scenario 2) and the increase in the NPV value can be a maximum of 287,000 €. It is definitely not a profit that will play a crucial role in deciding to move on to an investment or not, but it can surely balance some of the losses not initially foreseen or some of the expenses needed to convert the peak load oil boiler to an electric boiler, such as adding the resistance equipment. In the extreme scenario of buying the wind curtailed power at 52.46 €/MWh, which is the price offered to consumers, the additional profit for the WF owner is 72,000 € yearly (Scenario 3—Table 4).

Assuming that the FiT scheme will change in Greece soon and major cuts are going to be put into force, since there is an increasing Annual Electricity Tariff Deficit, just as happened in Italy and in Spain recently [36,39], new modeling parameters shall be taken into account for the future energy system.

Finally, following Xydis approach [40] on accumulated capacity factors (ACF), this can be calculated from:

$$ACF = \frac{NetAEP + WPC}{8760 \cdot C_i} \tag{5}$$

where WPC is wind power curtailment and in real life can be anywhere between

$$154.3MWh \leq WPC \leq 701.5MWh \tag{6}$$

Something, which will determine the final ACF to:

$$22.15\% \leq ACF \leq 22.5\% \tag{7}$$

6. Conclusions

The basic aim of this research was to identify the difficulty for curtailed wind power to be integrated into the heating system minimizing the use of boilers that run on fossil fuels. Based on the case study for the city of Kozani examined here, it was found that curtailed wind can be utilized in a DH system thereby covering some of the needs that the peak load boiler would cover. It was found, an using energy time series, that the possible annual contribution could be from 154.3 to 701.5 MWh, far from the theoretical possible 1508 MWh yearly; this is because only when the energy is needed to run the peak load boiler can the surplus of wind power be utilized.

Scenarios examined on wind curtailment to DH revealed that not only profits for the WF owner can be increased but also the IRR of the project by 0.36%. It was also shown that the ACF of the plant can be increased by almost 0.4%. In any case, based on this and similar research, it can be understood that, since there is a way to use part of the wasted energy for the heating systems, it should be a priority for heating and electricity systems to be integrated; mostly because there is an increasing need for the system operator to balance renewable energy sources and stabilize the system using various ways.

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Appendix

Table A1. Average monthly WF power output from power time series, low and high curtailment level, and heating needs per month.

December 2006																							
5804	5836	5505	5073	5301	5382	4652	4678	4344	4611	4392	4445	4662	5118	5489	5490	5453	5192	4970	5108	5245	5074	5744	6313
46	47	44	41	42	43	37	37	35	37	35	36	37	41	44	44	44	42	40	41	42	41	46	51
250	251	237	218	228	231	200	201	187	198	189	191	200	220	236	236	234	223	214	220	226	218	247	271
205	205	205	205	205	274	411	610	685	705	680	605	560	548	548	548	540	530	550	680	705	700	555	410
January 2007																							
4885	4752	5507	5555	5180	5583	5267	5547	5582	5771	6536	6649	7252	7282	7515	7605	7186	6568	6015	6189	6323	6310	5937	5234
39	38	44	44	41	45	42	44	45	46	52	53	58	58	60	61	57	53	48	50	51	50	47	42
210	204	237	239	223	240	226	239	240	248	281	286	312	313	323	327	309	282	259	266	272	271	255	225
218	218	218	218	218	277	414	613	780	822	775	700	650	630	635	650	630	625	670	765	810	805	650	414
February 2007																							
4916	4905	4521	4439	4308	4900	4628	4115	4613	3836	4377	3977	4675	5406	5263	5110	4721	4731	3731	3902	4522	4315	4855	5029
39	39	36	36	34	39	37	33	37	31	35	32	37	43	42	41	38	38	30	31	36	35	39	40
211	211	194	191	185	211	199	177	198	165	188	171	201	232	226	220	203	203	160	168	194	186	209	216
218	218	218	218	218	280	417	606	756	775	750	685	640	625	630	640	620	615	660	750	770	750	650	414
March 2007																							
4857	4955	4663	5155	5405	5393	4745	3550	3232	3921	4246	4091	3673	4014	5208	5412	5827	5293	4944	4809	5223	4469	4239	4882
39	40	37	41	43	43	38	28	26	31	34	33	29	32	42	43	47	42	40	38	42	36	34	39
209	213	201	222	232	232	204	153	139	169	183	176	158	173	224	233	251	228	213	207	225	192	182	210
170	170	170	170	170	205	330	495	560	580	545	510	440	420	420	425	415	410	460	550	540	535	430	280
April 2007																							
2453	2490	2617	2721	2717	3001	2816	2550	2671	2627	2615	2609	2640	2694	2796	2713	2713	3337	3709	3804	2996	2885	2301	2629
20	20	21	22	22	24	23	20	21	21	21	21	21	22	22	22	22	27	30	30	24	23	18	21
105	107	113	117	117	129	121	110	115	113	112	112	114	116	120	117	117	143	160	164	129	124	99	113
130	130	130	130	130	180	225	330	360	411	360	340	300	320	310	305	305	290	330	360	390	370	300	140

Table A1. *Cont.*

May 2007																							
3137	3029	3022	3373	3289	3162	2808	2805	3279	3189	3340	3252	3426	3375	3871	4070	3989	4131	3958	4237	3469	3100	3374	3140
25	24	24	27	26	25	22	22	26	26	27	26	27	27	31	33	32	33	32	34	28	25	27	25
135	130	130	145	141	136	121	121	141	137	144	140	147	145	166	175	172	178	170	182	149	133	145	135
60	60	60	60	60	85	137	170	200	215	200	190	170	160	160	165	155	170	175	200	205	200	160	110
October 2007																							
2259	2440	2276	2285	2093	2011	2117	2030	1897	2029	2148	1802	2069	2564	2735	2801	2327	2651	2529	2289	2244	2365	2319	2172
18	20	18	18	17	16	17	16	15	16	17	14	17	21	22	22	19	21	20	18	18	19	19	17
97	105	98	98	90	86	91	87	82	87	92	77	89	110	118	120	100	114	109	98	96	102	100	93
65	65	65	65	65	95	155	274	300	305	300	270	245	230	230	235	230	225	265	290	300	295	250	145
November 2007																							
4539	4842	3972	4265	4053	4407	4529	4432	3904	3966	4120	4191	3755	4092	4724	4610	4371	4530	4654	5823	5543	4907	5243	4664
36	39	32	34	32	35	36	35	31	32	33	34	30	33	38	37	35	36	37	47	44	39	42	37
195	208	171	183	174	189	195	191	168	171	177	180	161	176	203	198	188	195	200	250	238	211	225	201
165	165	165	165	165	200	325	490	555	575	540	505	435	415	415	420	410	405	455	545	535	530	425	275

Conflicts of Interest

The author declares no conflict of interest.

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