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Article

Renewable Energy Potential for Micro-Grid at Hvide Sande

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Abstract: Decarbonization of ports is a major goal to reduce their global carbon footprint. The port of Hvide Sande is located on the coast of the North Sea in Denmark and it has the potential to utilize various renewable energy sources. Wind and solar thermal parks are already installed there. Wave energy is an alternative to solar and wind energies and its advantage is the spatial concentration, predictability, and persistence. Heat to the town is provided by Hvide Sande Fjernvarme. In this work, it is investigated if the heat demand could be fully covered by renewable energies. Power profiles for each renewable energy resource were calculated using 30 years of re-analysis environmental data. Long, mid, and short term time series of power supply has been statistically and quantitatively examined. Considering the heat demand of Hvide Sande, the lowest frequency of zero occurrence in power generation can be ensured by the combination of wind, solar energy and wave. The article also estimated the capacity for Lithium-ion batteries. The optimal size of the battery is found by the bisection method. Finally, different combinations of renewable energy and demand as well as batteries are evaluated. The lowest zero occurrences in power production is met by the mix of three renewable energies. Also, the mix of three renewable energies significantly reduces the value of energy, required from the battery.

Keywords: wave energy; wind energy; solar energy; low-carbon ports; battery; renewable sources

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1. Introduction

Ports emit a substantial amount of greenhouse-gases. The estimation for CO_2 are dozens million tonnes [1]. The European Union (EU) in particular finances projects focused on means to conduct the reduction of carbon emissions via renewable energy sources (RESs). One such EU project is DUAL Ports project [2]. The main goal of DUAL Ports is to achieve sustainable use of locally available resources for electrification. The project unites ports, local authorities, entrepreneurs, business partners, and universities to conduct pilots on new products, and processes. These initiatives are expected to be implemented in the ports' infrastructure. The targeted partners are the ports of the North Sea, such as Oostende, Vordingborg, Skagen, Niedersachsen, and Hvide Sande [2].

The port of Hvide Sande is successfully utilizing its local potential of various RESs. A wind park has been operating in the area since 2012, as well as a solar thermal plant [3] (Figure 1a and 1b respectively). The energy from two RESs is used to produce heat for the means of the town via Hvide Sande Fjernvarme (HSF) [4], and the heat demand is especially high during the cold times of the year. The connection to the main grid guarantees the power flow to fill the demand gaps when it is needed or to deliver energy for other destinations [2].

Wave energy technology is developing into a variety of engineering solutions. Some of the concepts are more advanced and tested than others. The classification by Falcao [5] is as follows: (1) oscillating water columns, overtopping devices and oscillating bodies [6,7];

(2) point absorbers, attenuators, and terminators [8,9]; (3) other technologies [10]. Seabased industry [11] is one of the partners of the DUAL Ports project. It supplies wave energy converters (WECs) of point absorber type (Figure 1c). Such a concept is known for small, relative to the wavelength size of the buoy. The generator is encapsulated in a protective case and is fixed on the bottom of the sea. These WECs use linear generator power take-off with direct drive [12] to reduce intermediate energy conversion. Therefore, the potential and kinetic energy of the wave is absorbed by the buoy and then converted from mechanical to electrical energy. Several WECs can be combined to form a wave park. Such a wave park could contribute to the installed RESs in Hvide Sande. Before that, the wave power potential should be explored at the site.

Most sea waves are generated from the action of the winds, causing swells when they act on the water for long distances [13]. When the wind stops, the waves keep going, losing energy along the way until reaching the shore. Due to this, the waves act as energy storage for the wind. Research on RESs integration [14] concluded that the wave resource enables better utilization due to the time delay compared to wind resources.

Wave energy has its advantages due to its spatial concentration, predictability, and persistence [15]. The potential for wave energy is enormous, but not yet exploited to the extent of wind and solar. The seasonality of wave power is much greater in the northern hemisphere, indicated as a disadvantage in Ref. [16]. Despite wave resources being of lower intensity in the summer months, a similar conclusion can be drawn for solar energy, as being a challenging resource in the long winter season.

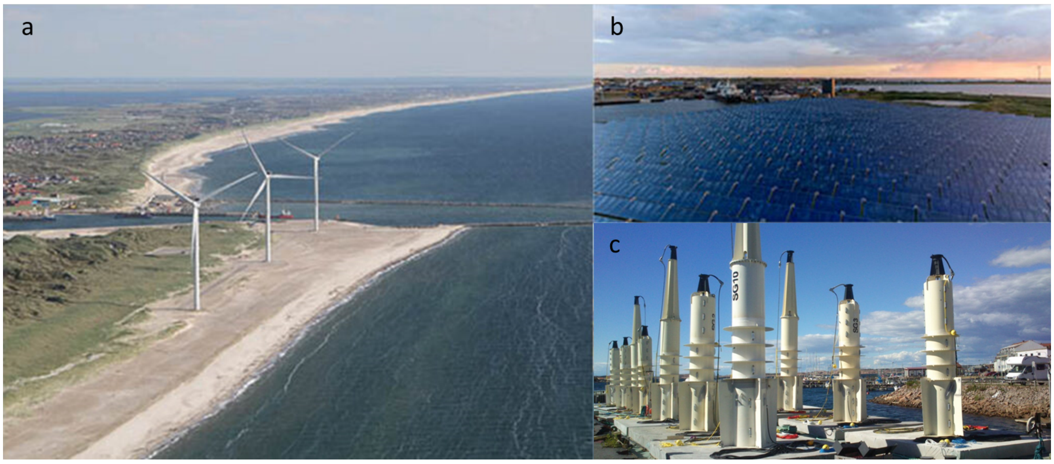


Figure 1. The RESs of Hvide Sande: (**a**) installed wind power park; (**b**) installed solar thermal park; (**c**) the wave energy converters used to form a wave power park.

Research on combinations of several renewable sources was completed for different locations, such as the Mediterranean Sea, Irish waters, and the North Sea near the UK coast [14]. High variability of the resources exists in a particular area of interest, therefore each site shall be examined carefully. There is much interest in wave energy in the North Sea [2]. Only the lack of knowledge and experience eliminates the use of wave energy converters efficiently, even in low energetic seas.

The netload variability of the wave, tidal, solar, and wind in the Nordic power system was presented in Ref. [17]. Intermittency urges for means, targeted to stable and reliable supplies, such as batteries. The use of batteries can be seen as lifting the penetration levels of intermittent renewable energies. An up-to-date comprehensive review of stationary energy storage systems [18] concludes that Lithium-ion batteries are still the best solution for RESs integration into the grid system, relative to other electrochemical energy storage technologies. In Ref. [19] it is pointed out, that in application with solar and wind, batteries replace diesel or gas generators, and even reduce the cost of RESs technologies.

The benefits of combining two RESs have been stated in several research works. In Ref. [20] it is shown that the power generated by wind and waves is less variable than by separate RESs in California. The offshore combination of solar and wind potential is explored in Ref. [21], revealing synergy and a smoother total power output. In Ref. [22] an integration of onshore and offshore RESs, such as wind and wave with energy storage and a back-up diesel generator, is investigated. The integration of offshore RESs, such as wave and wind, reduces the visual impact [14]. Ref. [22] points out that the combination of wind turbines and WECs in a hybrid energy system can lead to large reduction of costs and emissions. Regarding the combination of three RESs, in Ref. [23], WECs were modelled along with solar and wind to estimate e-fuel production in the Maldives islands. The mixed scenario of wind, wave, and solar [24] was estimated to reduce the energy production from fossil fuels at the Aeolian Islands in the Tyrrhenian Sea (Italy) considering economic aspects. The proposed combination can cover 58.7% of the energy demand through the use of RES and can achieve annual economic savings of EUR 6.5 million. Another study was carried out for a real island network located on the Island of Pantelleria (Mediterranean Sea) when combining photovoltaic, wind, geothermal and wave sources. Due to favourable weather conditions, the mix of RES can become a near-zero energy island [25]. In Ref. [26], a comparative study of the Balearic Islands and Fiji was described, evaluating the association of wave, wind, and solar sources. The Balearic Islands can satisfy over 46% of the prevision of the annual electrical energy demand for 2025, while Fiji can reach 87% of the annual electrical energy demand by mixing the RES.

This work aims to provide insights into the potential of available RESs, such as wind, solar, and wave at the port of Hvide Sande. There is a lack of research publications on the mix of RESs for the Danish coast of the North Sea. Therefore, it is interesting if the local RESs could provide enough renewable power to supply the heat demand of the town. Another goal is to look at battery storage from the perspective of not storing most of the energy. Instead, the RESs power can be smoothened in the way to satisfy the demand. The optimal battery size can be found by using the bisection method. The results are organized in a way that the wind resource is used for comparison in the case of mixed RESs, already installed at Hvide Sande (wind and solar parks), and the possible addition of wave energy into the mix.

The paper is organized as follows. First, the data input from the re-analysis models is discussed for wind, solar, and wave resources. Then, a brief description of the method to obtain the RESs power profiles is given. The current installations at Hvide Sande are discussed along with the prospects for an additional wave energy park. A thorough statistical analysis of the 30 years of power data is performed for each resource and its mix. The results are presented for each case separately and summarized in the Discussion. Finally, it is concluded if the HSF could fully rely on RESs energy and what battery size would potentially suit the needs of the town.

2. Method

2.1. Cases

The wind resource is used as a comparison for other cases, due to its higher capacity relative to the solar thermal park. Then, a combination of two RESs is investigated, according to the installed wind and solar plants at Hvide Sande. Then, a mix of three RESs (wind, solar, and wave) is proposed to evaluate the combined local potential for Hvide Sande.

RESs data analysis has shown, that during two years (1993 and 1994), a low wind resource was recorded. Therefore, 1994 was picked for detailed analysis as an example of an extreme case. Other years have shown only a slight deviation in the RESs power profiles. A typical year, namely 2007, was chosen out of 30 years for detailed analysis of the selected period.

Different time intervals were considered: long term (one year); mid term (two weeks), and short term (24 h). One year of data represents the annual supply and trends during different months. Mid-term links between long and short term allows us to see the daily variation. The short term scale shows a detailed resolution via an hourly variation. Long, mid and short terms are essential to estimate the lack of RESs supply power. Long term analysis is used to determine the battery size.

The following cases are investigated:

1. Supply power to analyse the RESs potential;
2. Net load: how RESs potential covers HSF's needs to estimate the periods of negative energy;
3. Net load and battery to estimate the battery size needed to fully fulfil the HSF demand.

2.2. Environmental Data Input

Three different RESs are considered in this work: wave, wind, and solar. The environmental data for 30 years (1990–2019) was obtained by re-analysis models. An example of a dataset for 2007 is illustrated in Figure 2. It shows the characteristics of resources: solar (irradiance, outdoor temperature), wind (speed and direction), and wave (significant height and mean period).

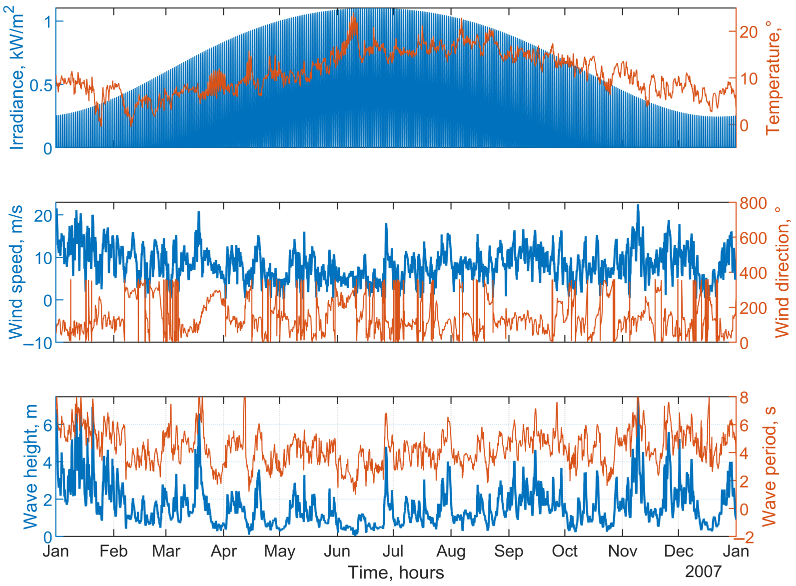


Figure 2. Example of the environmental data at Hvide Sande in 2007.

2.2.1. Solar Irradiance and Wind Data

For solar and wind, the primary data were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) [27], accessing the ERA5 data set [28]. The dataset uses a four-dimensional (4D) data assimilation method with an Integrated Forecasting System (IFS) based on the Cycle 41r2 [29]. ERA5 represents the state-of-the-art in climate re-analysis data, improving upon several previous iterations (i.e., ERA-Interim). Significant improvements have been made in database validation and by increasing the resolution with past databases. Another important element that makes ERA5 useful for preliminary analysis is the good temporal resolution (1 h) and the long duration of years that it covers. Offering 30 and more years of data ensures that any resource estimation and further power production analysis can be highly realistic [30,31]. Furthermore, ERA5 has been improved and has several parameters that are vital for renewable energies; this is evident in the derivation of atmospheric quantities useful for solar analysis. The typical irradiation values also represent, with accurate ambient temperatures, a parameter very important for the determination of photovoltaic power production.

2.2.2. Wave Data

Long term wave spectral data (significant wave height and mean energy period) were obtained by Simulating WAves Nearshore (SWAN) model. SWAN enables near-shore analysis for large water areas under the arbitrary wind, currents, and bathymetry conditions [32]. A description of the wind environmental data for the SWAN model is given in the previous subsection. The detailed description of the modelling, as well as the model validation against 8-years of buoy measurement data can be found in Ref. [33].

2.3. Energy Infrastructure

At the port of Hvide Sande, there is an installed wind park. It consists of three wind turbines, each with a 3.6 MW installed capacity (Vestas offshore [34]). They are pitch-type with active yaw and three-blade rotor. There is also a solar thermal park. It has a total capacity of 7 MW. The renewable power from wind and solar thermal parks is delivered to HSF. From HSF, heat via hot water is carried to the town. The grid compensates for the net load when needed. In this work, the thermal solar plant, providing hot water to HSF is simplified into a solar PV park, connected directly to the DC bus.

In an outlook, a wave energy park could contribute to the renewable power supply. The capacity of the potential wave park is up to 12 MW, comprising an alternative to the wind park.

2.3.1. RESs Supply Power

Power production for each power park was calculated using the 30 years of environmental data for wind, solar irradiation, and wave resources.

The hybrid optimal energy mix method used was developed by Seabased. The method can be explained as follows. Assuming that the locations of technology deployment are already identified, the data referent to each energy resource is selected. The present study considered wind speed, significant wave height, wave energy period, and solar irradiation as the resource input parameters. This is then put in iteration in time and frequency domains with the performance datasets that characterise the renewable energy converters. In this case, the power curves of the wind turbine (the model of the wind turbine), Seabased WEC, and solar PV panels (model of solar PV panel) are used to estimate the energy production. Here, two variables emerge as an object of relevance, namely the baseload and its temporal variability. The optimal point in which the baseload variability is lowest is found by defining the best iteration between each renewable energy resource in the mix, which can be done by adding or subtracting the installed capacities.

The power values are normalized to the wind peak power, such that the normalized power is equal to P/P_0, where P is the RESs power and P_0 is the wind park capacity, equal to 10.8 MW.

The averaged power during different seasons for 30 years with denoted maximum power production is shown in Figure 3. Despite each resource producing variable power profiles relative to each other, their combined averaged power stays at about 1.4 normalized power.

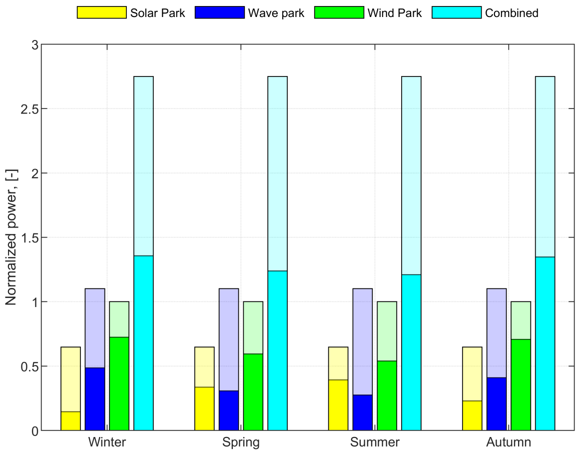


Figure 3. Averaged power for wind, solar, and wave parks separately and combined for 30 years, grouped by seasons. The maximum production is denoted by the higher transparency bar.

A boxplot representation of the RESs power profiles within 30 years is shown in Figure 4a. Solar has its full capacity within three months, such as May–August, and reduced average capacity for the rest of the year. The period of October–February is identified as zero average power per month due to the short day–time at the north location. For the wave and wind RESs, two main features can be noticed: the reduced resources between March–September and the higher performance during October–February.

Figure 4b presents an example of solar, wind, and wave power profiles during two weeks in January and July 2007. There is low power by the solar park, and high wind and wave resources are available in January. In July, the solar is at its maximum capacity, while there is a variation of wave and wind power profiles.

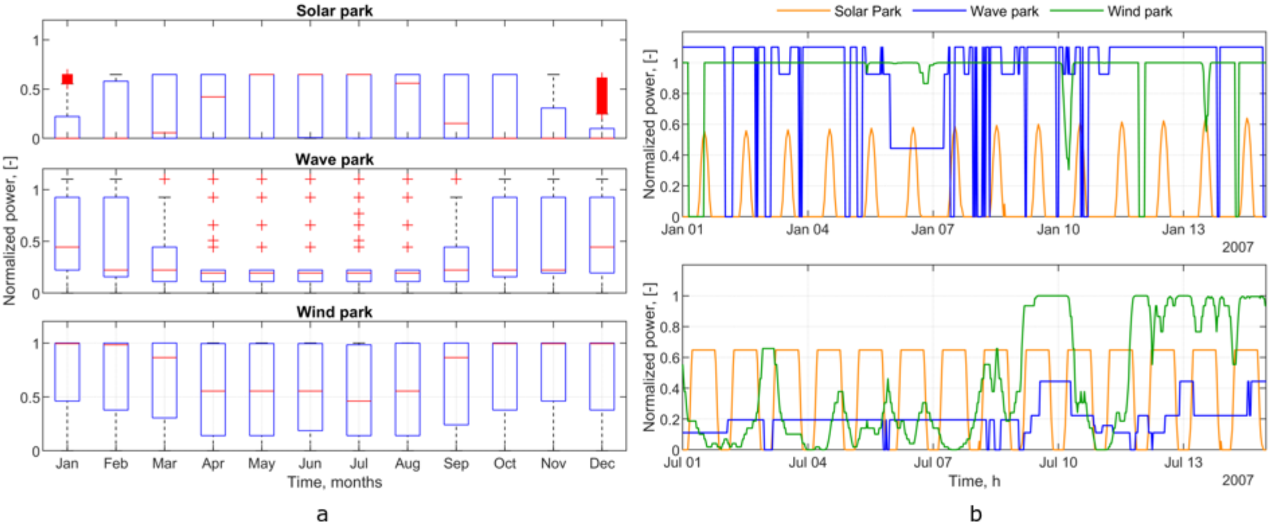


Figure 4. RESs normalized power profiles (solar, wind, and wave): (**a**) averaged by months for 30 years; (**b**) for 2 weeks in January and July 2007.

The Pearson correlation coefficient was calculated for different combinations of the RES (Table 1). When the value is close to 1, the correlation is stronger, which indicates that the two variables are correlated. By the lower and upper bound of the 95% confident interval, it can be seen that the relative error is low, about 0.002–0.003. It shows some positive correlation between wave and wind RES, while wave/wind with solar is uncorrelated. It means that the behaviour of 30 years data of wind/wave and solar is random relative to each other. Negative correlation stands for peaks and troughs overlapping.

The classic correlation analysis does not provide a desirable representation of the real characteristics of these energy sources. For extended analysis, long, mid, and short term time scales are looked into.

Table 1. Pearson correlation, lower and upper bounds for a 95% confidence interval.

RESs	Correlation Coefficient	Lower Bound	Upper Bound
Wave and Wind	0.402	0.3997	0.404
Wave and Solar	−0.09	−0.093	−0.087
Solar and Wind	−0.082	−0.084	−0.079

2.3.2. The Heat Demand

The heat demand data is provided by EMD-International [35] for three years (2018–2020). The raw data was originally sampled with 3 min intervals. The data contained solitary negative values and some data points were missing. The following data processing was carried out: (1) the negative values were replaced with zeroes; (2) the data for three years were averaged to obtain one year, if the missing point would be encountered in one of the three years, the average of the other two is taken for the resulting year. If only one data point is available, then it is taken as the only data point; (3) other solitary missing points were reconstructed by linear interpolation; (4) the sampling was resampled to 30 min interval to match the RESs power profiles. Figure 5 shows the processed and normalized heat demand for one year, sampled every 30 min and 24 h. The data have substantial seasonal variation, with lower values in the summer time.

Figure 6 shows the occurrence frequency for RESs power profiles of 30 years and heat demand for three years. The demand reaches the capacity of wind power park on a few rare occasions (1.2%).

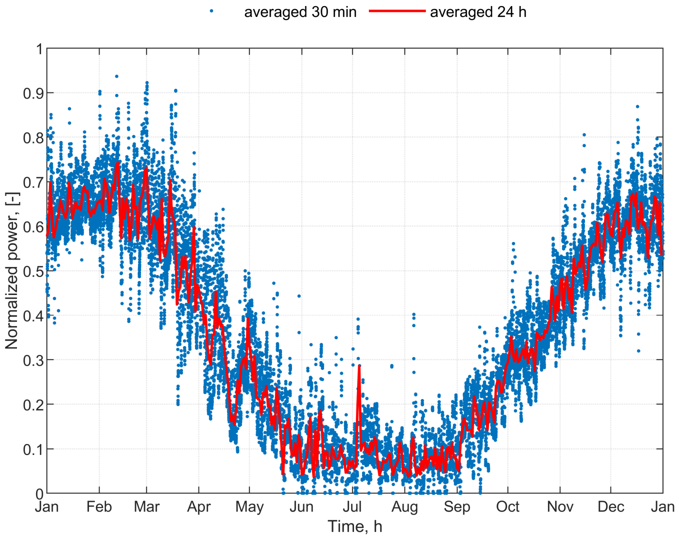


Figure 5. Normalized heat demand for 1 year with 30 min and 24 h sampling.

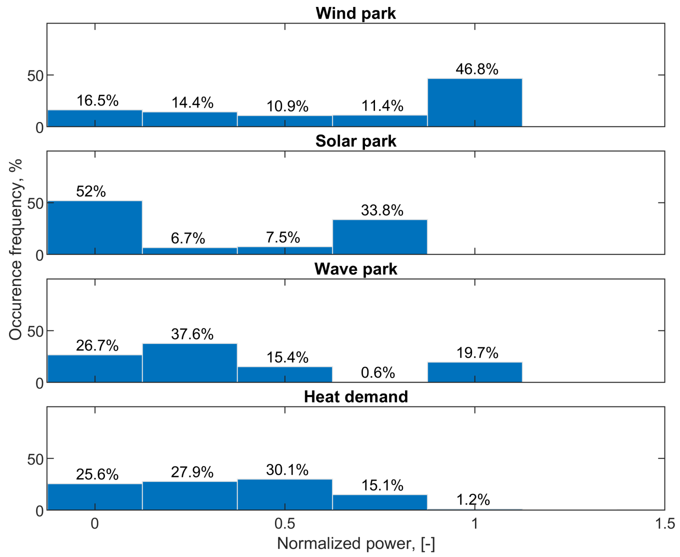


Figure 6. Occurrence frequency of RESs power profiles for 30 years and HSF demand for 3 years.

2.3.3. The Battery Model

The deficit/proficit of power or net load P_{net} can be found as follows:

$$P_{net} = P_{RESs} - P_d, \tag{1}$$

where P_{RESs} is the power by renewable energy sources; P_d is the demand power.

The battery manages peak shaving by balancing the excess energy and the demand. For stationary energy storage, the battery lifetime was raised from 8 to 10 years in 2015 to 15 years in 2020 [36]. Battery sizing stays an important issue. In this work, the aim is to study if the RESs power can fully fulfil the demand using batteries and to estimate its optimal size.

The battery capacity is within the interval $[a; b]$, where:

$$a = |E(t)_{min}|; \tag{2}$$

$$b = \sum_{t=1}^{t_{max}} E(t); \tag{3}$$

where a and b are the left border and the right border, respectively; $E(t)$ is the net energy, obtained by integration of the net power in the Equation (1).

If the left border fully satisfies heat demand, then the battery capacity can be found using Equation (3). Otherwise, the optimal battery size is found by the bisection method. If the RESs are not able to provide enough energy for the heat demand, the battery capacity is $b_{cap} = b$ and the rest of the demand shall be fulfilled by other means.

In this work, the minimum state of charge (soc_{min}) is 10% of its maximum capacity for long lasting exploitation. Initially, the battery is half charged. The diagram in Figure 7 describes the main steps in the computation of the battery capacity. Using the initial power/energy $E(t)$ and the given battery capacity x, a new power/energy $E^*(t)$ is computed for the time $[1 t_{max}]$. The battery energy is a non negative value, limited by RESs available energy. The accuracy of the computations is defined by $\epsilon = 10^{-3}$.

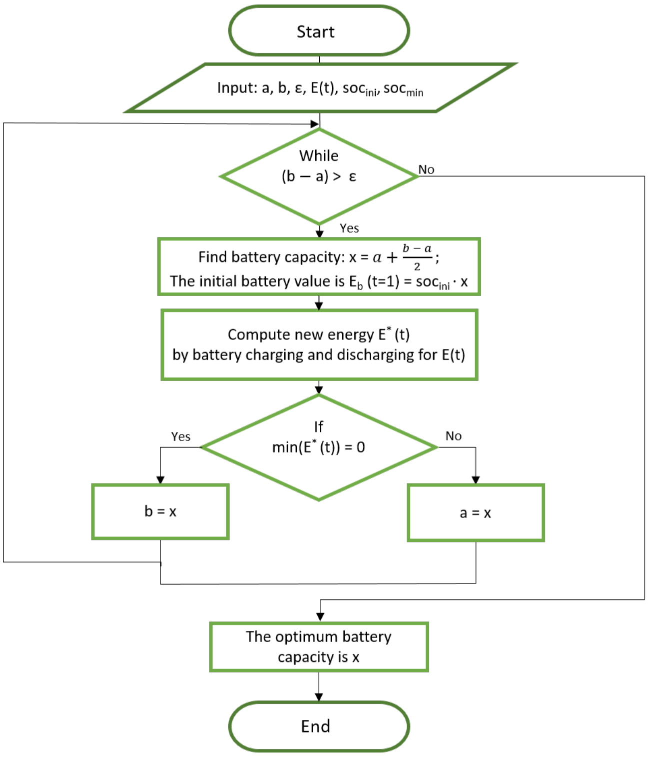


Figure 7. Diagram describing the computation of optimal battery capacity to fully fulfil the heat demand.

3. Results

3.1. Case 1: RESs Potential

Figure 8 shows an analysis of the normalized power of RESs for 1994 and 2007. The results for 1994 show the following. The fraction of solar power exceeds the wind fraction. Mid term indicates two weeks in May with low wind and wave power profiles. Solar power provides a stable full capacity during day time. The short term indicates absence of power during several night hours. On the contrary, the wind fraction exceeds the solar fraction for 2007. The long term indicates nearly constant wind power with only several large gaps. Solar power has a noticeable seasonal lower trend in December and January. Wave power is less variable, compared to 1994. The mid term scale indicates power gaps, when the wind resource had a strong decline. Then, the short term shows that the solar and wave power profiles fill in the gaps.

Figure 9a illustrates the occurrence frequency for the RESs power profiles in 1994. For wind resource, the frequency of zero occurrences (FZO) is about 52%. This value reduces by half to 24% for the mix of two RESs. A mix of three RESs shows only 4% of FZO. The occurrence frequency of RESs power profiles in 2007 is presented in Figure 9b. Wind power has about 50% occurrence on its maximum capacity, with FZO equal to 14%. There is a noticeable reduction of FZO for the mix of two RESs (6%) and three RESs (0.3%). It can be noted that the variation of power increases for the mix of three resources.

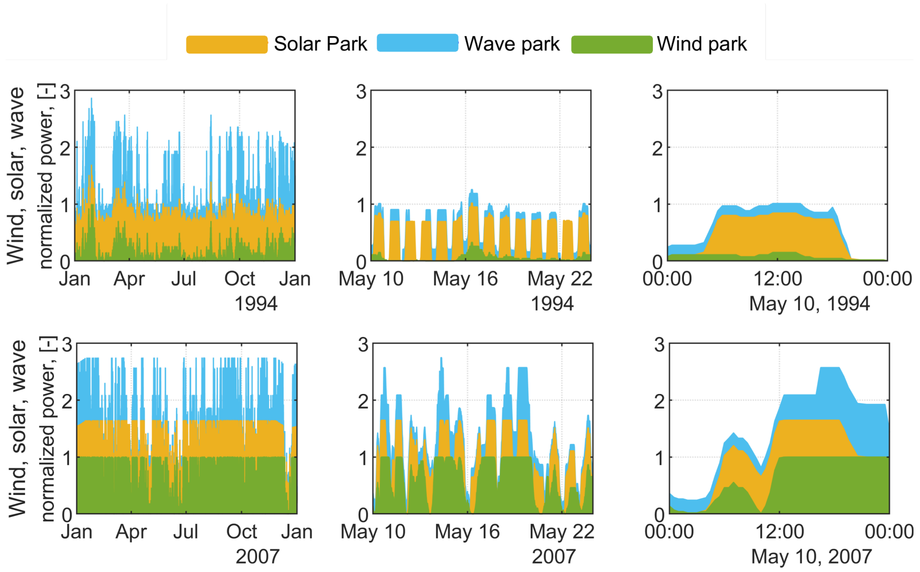


Figure 8. RESs supply in 1994 and 2007: long, mid, and short term (10th of May). Wind power is denoted by green colour, two RESs (solar and wind) by yellow, and three RESs (wave, solar, and wind) by blue.

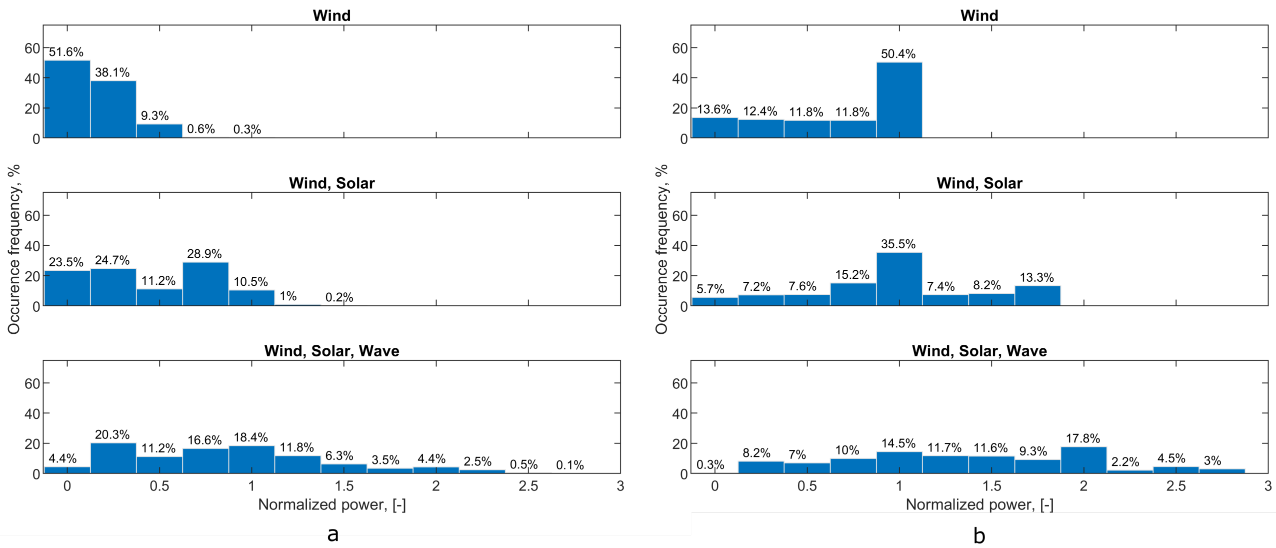


Figure 9. Occurrence frequency of RESs power during: (**a**) 1994; (**b**) 2007.

3.2. Case 2: Net Load

Taking into account the net load, the following can be seen. Figure 10 illustrates the net load in 1994 for short, mid, and long terms. On a long term scale, the reduction of negative net load is visible for a mix of three RESs. Only wind resource fulfils the summer demand. Mid term illustrates two weeks in February, when there is lack of RESs power. A mix of solar and wind partially fulfils the demand, primarily in day time, as it is illustrated by the short term scale. For the mix of three RESs, there are two continuous occurrences of negative values within 24 h. The negative net power value is reduced nearly twice for the mix of wave, solar, and wind compared to the solar and wind mix.

Figure 11 shows the net load in 2007. In long term analysis, a mix of three RESs essentially reduces the number of negative values. The mid term scale indicates dips during two weeks. Short term shows that a mismatch of heat demand and wind resource during the 15th of February is partially covered by solar power during the daytime. A mix of wave, wind, and solar slightly reduces the negative net load.

The occurrence frequency for net load in 1994 and 2007 is estimated in Figure 12a,b. It shows that the addition of wave power reduces the frequency of negative values occurrence (FNVO) from 6% for wind, to 3.7% for solar and wind and to 1.3% for three RESs in 1994. For a typical year, such as 2007, the FNVO is 1.3% for wind and 0.9% for a mix of solar and wind. The extremes of FNVO are eliminated for wave, wind, and solar. Due to the presence of negative values, a technical solution is required, such as a battery.

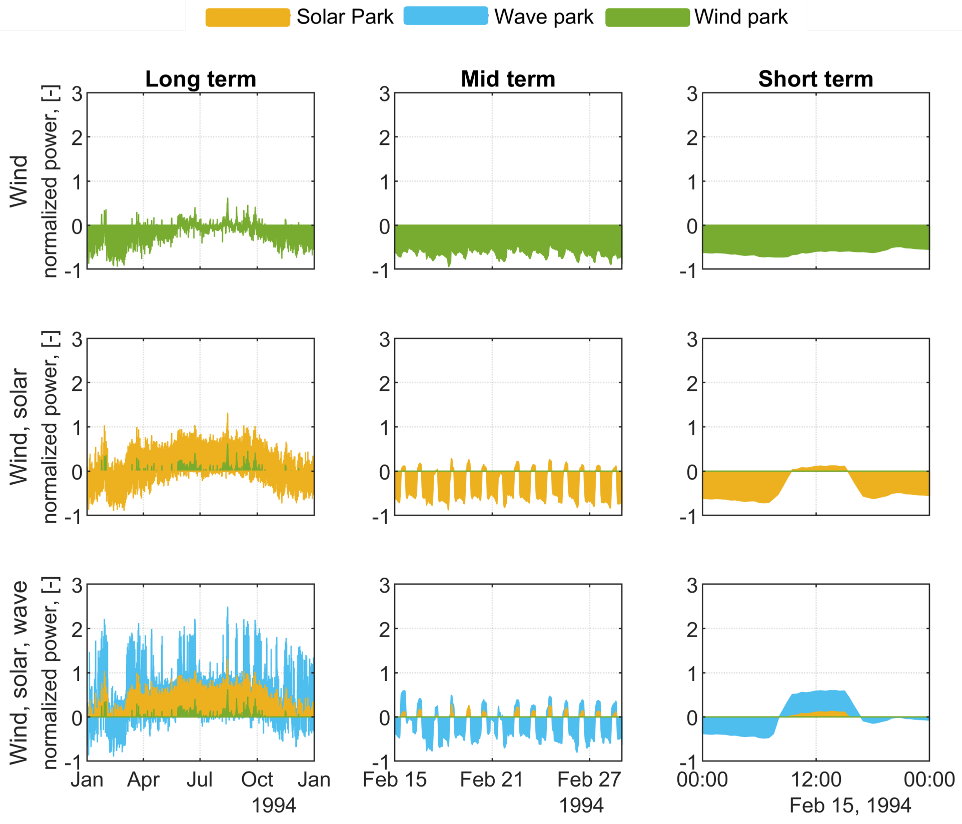


Figure 10. Net load in 1994: long, mid, and short (15th of February) term. Wind power is denoted by green colour, two RESs (solar and wind) by yellow, and three RESs (wave, solar and wind) by blue.

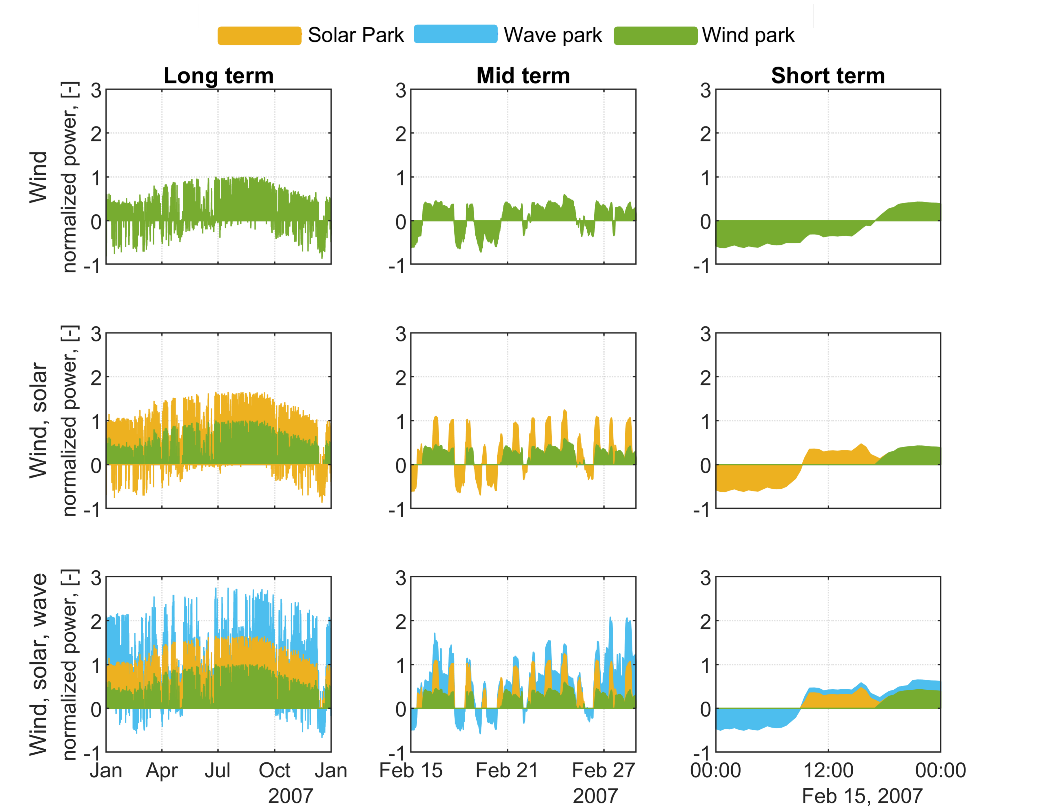
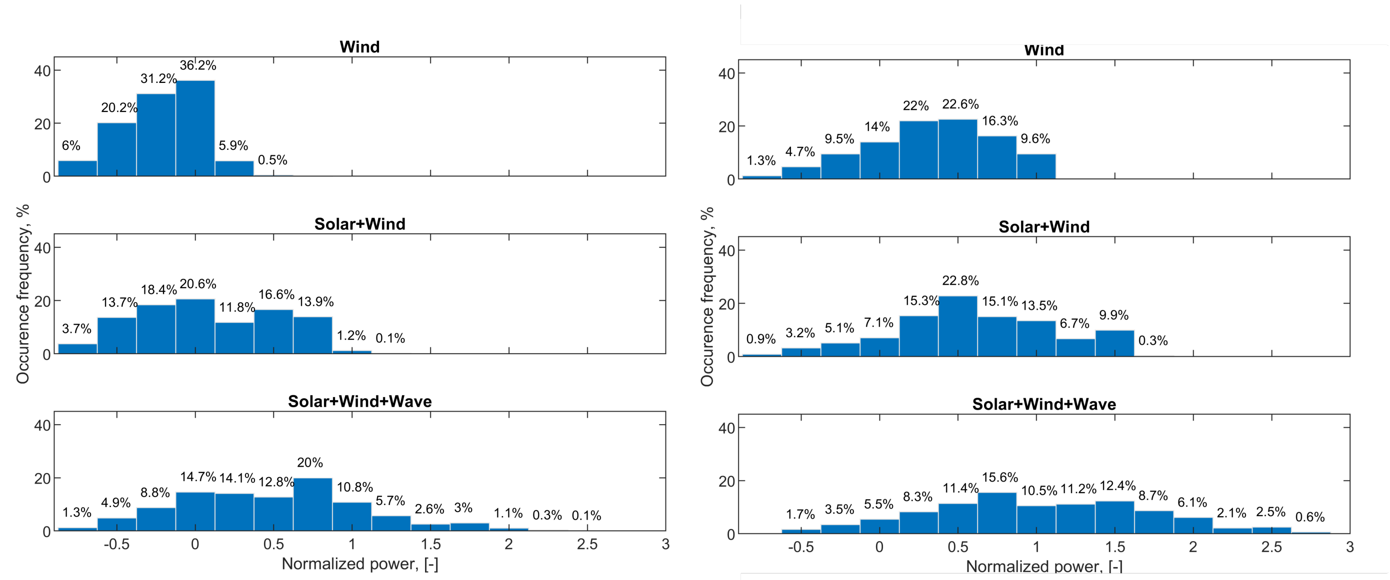


Figure 11. Net load in 2007: long, mid, and short (15th of February) term. Wind power is denoted by green colour, two RESs (solar and wind) by yellow, and three RESs (wave, solar, and wind) by blue.



a b

Figure 12. Occurrence frequency of net load during: (**a**) 1994; (**b**) 2007.

Duration of the negative net power profiles may be presented via net energy values. Figure 13 shows the negative net energy in terms of MWh for 2007. The minimum energy for wind is 104 MWh, 37 MWh for solar, and 17 MWh for the wave. Although the deficit is high for one resource (wind), it is of a low occurrence of below 1%, while for a mix of three RESs it is above 1%. The mean values of the energy are about −10, −3, and −2 MWh for the single REs and the mix of two and three RESs respectively.

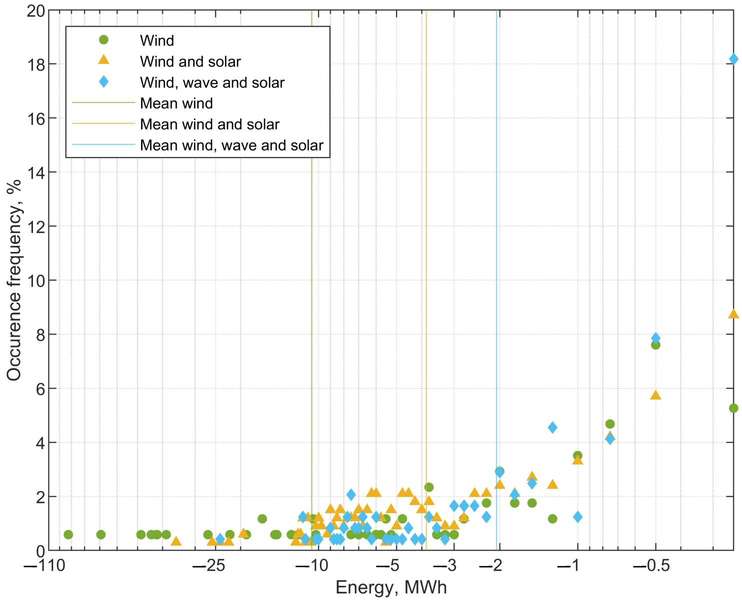


Figure 13. Deficit of energy in 2007.

3.3. Case 3: Net Load and Battery

The energy for battery capacity over the years is illustrated in Figure 14. Due to the low wind resource in 1993 and 1994, the maximum battery size is limited for only the wind case and the provided energy is not enough to fully fulfil the demand. This case is illustrated by the minimum required energy b_{min} exceeding the available maximum energy on the graph b_{max}. The optimal size b_{opt} is found, so that the negative load is balanced out by RESs via the battery.

Figure 15 shows battery capacity for different initial state of charge (soc_{ini}). For a mix of three RESs, the battery capacity for high ($soc_{ini} = 0.8$) and half of initial charge ($soc_{ini} = 0.5$) shows a minor difference. An initial charge of 0.2 shows higher required battery capacity to fulfil the heat demand by RESs.

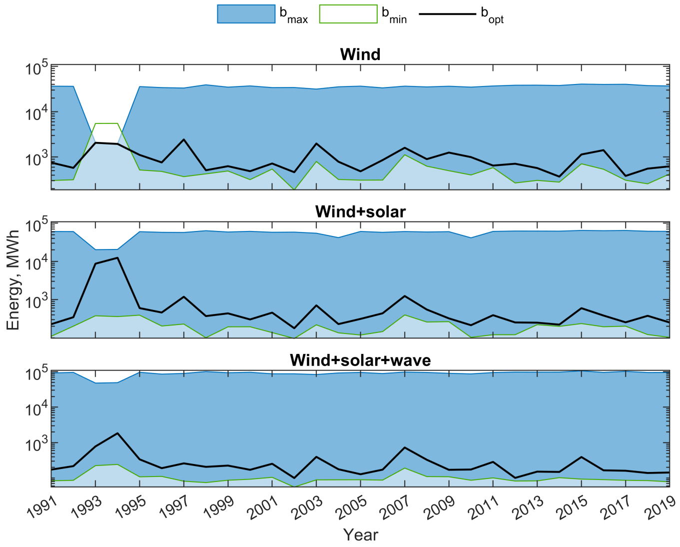


Figure 14. Maximum, optimal, and minimum battery capacity during the selected time.

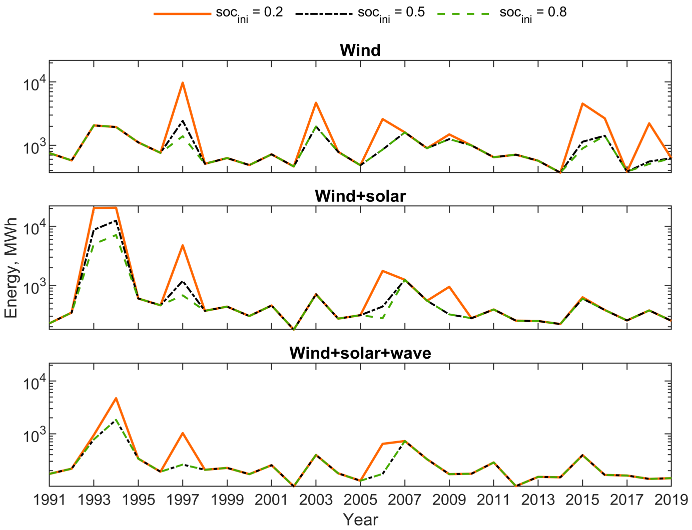


Figure 15. A variation of battery size during the selected time for different values of the initial charge.

Table 2 shows the calculated battery maximum capacity b_{max}, battery optimal capacity b_{opt}, and battery minimum capacity b_{min} for different years.

Table 2. Battery capacity.

Year/RESs	Wind			Wind, Solar			Wind, Solar, Wave		
	b_{min}, MWh	b_{opt}, MWh	b_{max}, MWh	b_{min}, MWh	b_{opt}, MWh	b_{max}, MWh	b_{min}, MWh	b_{opt}, MWh	b_{max}, MWh
1991	304	754	36,437	110	228	60,671	84	173	91,880
1992	316	577	36,167	202	347	60,462	86	217	95,097
1993	5493	2061	2061	378	8730	20,290	224	781	47,700
1994	5514	1944	1944	360	12,450	20,576	243	1836	48,924
1995	519	1113	35,666	393	601	60,039	109	337	96,072
1996	482	760	33,836	204	461	57,711	111	190	85,335
1997	370	2435	33,181	230	1189	57,229	82	260	89,138
1998	426	511	39,003	101	371	63,581	75	207	100,430
1999	492	628	34,666	195	437	58,888	87	225	93,161
2000	318	487	36,896	195	303	61,182	93	171	96,045
2001	544	720	33,873	138	457	57,898	105	253	86,974
2002	189	463	34,030	96	179	58,405	56	100	87,010
2003	797	1984	31,414	220	708	54,697	89	396	83,081
2004	320	788	35,262	160	274	58,994	89	177	92,045
2005	310	484	36,462	119	314	60,816	90	128	95,071
2006	311	856	33,389	146	439	57,677	88	173	88,588
2007	1123	1600	36,434	399	1244	60,531	191	727	97,447
2008	629	899	35,064	260	551	59,000	110	328	94,865
2009	500	1253	36,285	266	323	60,036	109	171	89,876
2010	403	996	34,712	141	279	58,655	87	174	86,456
2011	584	648	36,771	121	392	60,952	101	285	94,455
2012	268	711	38,190	121	253	62,459	83	101	97,409
2013	306	571	38,315	221	250	62,283	83	152	96,961
2014	280	370	37,724	200	222	62,001	103	149	97,205
2015	709	1139	40,497	237	598	64,625	93	392	105,190
2016	539	1417	39,778	195	384	63,612	90	165	95,196
2017	308	383	40,110	202	255	64,511	86	161	101,828
2018	257	555	37,487	122	378	61,599	85	139	94,488
2019	425	624	36,819	103	252	61,207	78	143	95,020

4. Discussion

The overall goal of the paper was to study the balance of the renewable energies and the heat demand of a town, such as Hvide Sande. There is always a chance for at least one quiet night during the year, when there are no wind and no waves. And therefore, there is no supply RESs power to balance the demand. By analysing the frequency of zero occurrences in power production, the regularity of such events can be estimated.

In [22] it is stated that combining wind and wave energy allows for a more stable energy supply, with less variation in energy production when taken individually. Another research on RESs integration [14] concluded that the wave resource enables better energy utilization due to the time delay compared to wind resources.

The long term data were analysed to detect similar patterns in energy production. Then, two different years were chosen for a detailed analysis. The first year is an example of low wind resources, shown by 1994. The second year represents a general year with strong wind resource and it is well illustrated by 2007. Years with low wind resource are about 7% of the selected time period.

The results show that the frequency of zero occurrences in power production is 52% in 1994 and 14% in 2007 for the wind power park. The mix of two resources shows a reduction of these values by half. The inclusion of waves into the renewable mix shows an even higher reduction of zero occurrences in power production: 11.8 and 5.5 times compared to wind power park and wind and solar mix, respectively, for 1994. For a general year, the mix of three resources leads to nearly fully eliminating zero power production.

The local heat demand data is valuable to account for when planning for battery capacity. The heat demand at Hvide Sande is seasonal. The boxplot (see Figure 4a) shows that the average values of wave and wind power profiles represent the trend of the demand curve. Then, the solar RES can be used as a backup solution to securely fill the gaps of net load in the daytime.

The battery's energy may still not be enough for the demand needs if the demand for energy exceeds the eventually available RESs' energy. The results show, that during 1993 and 1994, the low wind resource is not covering the demand even with a battery of maximum capacity. A mix of resources reduces the required battery capacity and enables enough energy to balance the demand. The years with low wind drastically affect the results due to the fact that the wind park is more mature than the wave technology and has higher capacity than the solar park.

The results show that the renewable energy mix leads to large overproduction. It could be solved by curtailment [37]. The low occurrence of high power production for three RESs could be curtailed due to the limited micro-grid capacity. For example, suggesting to curtail 3% of power per year (see Figure 9) would result in 2855 MWh lost energy per year. Another well-known alternative is to store the excess energy via a battery to release it during events of zero power production. Such battery capacity can be estimated, based on long term historical data. This work does not aim to assess the economic part of the project; this requires more in-depth estimates, which will potentially be investigated in a future study.

The results show that renewable energy provided only from the wind power park does not fulfil the heat demand during low wind years. The mixes of two and three resources provide enough energy to store and therefore to fulfil the demand, making it possible for the micro-grid at Hvide Sande to become fully renewable.

5. Conclusions

This paper investigated if the heat demand of Hvide Sande, Denmark could be fully covered by renewable energies. The required capacity of Lithium-ion batteries to fulfil the heat demand has been estimated for each year over a period of 30 years.

Currently, the heat demand is provided by wind and solar power plants. Wave power has high potential and it can be integrated into the existing wind and solar power production in Hvide Sande.

Analysis of the environmental data requires careful consideration: the expected power output depends on the energy infrastructure. Therefore, an analysis of calculated power in the area of interest gives insights into the potential of the renewable energy sources. Each resource has its benefits, such as higher power production in a specific year, season, or time of the day. Using historical data and determining such patterns help to find the best solution for a particular demand.

Long term analysis does not provide a complete representation of resource potential, as the minor variations occurring during shorter periods are becoming neglected. The mid term data analysis allows for a better understanding of the energy production dynamics over the days of a week. Temporal variations within the hours of a day are an important scale to assess due to the number of zero occurrences in power production, their maximum values, as well as the duration.

It has been shown that the mix of three renewable energy resources reduces the frequency of zero occurrences in power production sufficiently. The study is subject to limitations, such as the transmission losses being omitted. The model is simplified so that the energy lost during conversion steps is not accounted for.

There is a high potential for renewable energy resources at Hvide Sande. Despite this, it can be seen that some years lack wind energy. A mix of three resources reduces the reliance on wind and the required Lithium-ion battery capacity is less than that required for the mix of two resources.

Remaining knowledge gaps and areas for future research concern the cost evaluation of the whole system as well as the evaluation of the technical feasibility of the project.

The lowest frequency of zero occurrences in power production can be ensured by the combination of wind, solar energy, and wave resources, and it is therefore the most favourable choice for the future.

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Abbreviations

The following abbreviations are used in this manuscript:

EU	European Union
RESs	Renewable energy sources
HSF	Hvide Sande Fjernvarme
WECs	Wave energy converters
ECMWF	European Centre for Medium-Range Weather Forecasts
4D	4-dimensional
IFS	Integrated Forecasting System
SWAN	Simulating WAves Nearshore
PV	Photovoltaic

FZO	Frequency of zero occurrences
FNVO	Frequency of negative values occurrence
ERDF	European Regional Development Fund

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