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Energy Meteorology

Assessment of the option "wind power to heat for buildings" with respect to meteorological conditions

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Abstract

For regions with a high wind-energy potential, the use of wind energy to power electrical heating devices can be considered as an option for the heating of buildings, or, in reverse, the heating of buildings in colder climates may offer a load that is well-matched to grids with a high wind penetration. Here, the feasibility of this option is assessed regarding the meteorological conditions at sites in Europe as given by information on the wind resource and the temperature conditions expressed by the heating degree days. From this, the seasonal balance of local supply and demand is analyzed, to identify regions well suited for the application of this combination. A case study based on a dataset of 10-min time resolution is additionally performed for a site in one of these regions for the identification of the appropriate system sizing, including requirements for the inclusion of storage facilities or auxiliary power sources.

Keywords: wind power, space heating; wind heating systems, regional climate

1 Introduction

For the heat supply of buildings based on volatile renewable sources, such as solar or wind power, the feasibility of the respective systems and their design is governed by the temporal patterns of both the heating requirements and the generation by the renewables. This issue is discussed here for the case of heating systems powered by wind turbines. While the different technical options for wind-powered heating systems (or short: wind-heating systems) and their basic economic performance have been discussed recently by CAO et al. (2018), this topic has been investigated for decades (see, e.g., DARKAZALLI and MCGOWAN, 1977; ØSTERGAARD, 2013; OKAZAKI et al., 2015; NITTO, 2016).

Currently there is an extensive discussion on the application of grid-tied wind-heating systems from the perspective of the benefits for grid stability by the management of the heating-system electricity requirements by adding to the flexibility of the load (see, e.g., XYDIS, 2015; ZHANG et al., 2016; ALAHÄIVÄLÄ et al., 2017; BLOESS et al., 2018). However, most of the studies mentioned analyze system performance for a specific case, without addressing the influence of the peculiarities of the meteorological conditions on system sizing and performance explicitly. While CAO et al. (2018) addressed the wind conditions, their discussion is limited to the annual conditions reflected in the capacity factor of the wind turbines. Dedicated studies relating the temporal pattern of the general electric load – influenced by the temperature conditions – and the wind characteristics are, for example, given by SINDEN (2007) and THORNTON et al. (2017), investigating the case of the British Isles. The underlying seasonal characteristics of wind speed and temperature are, for example, extracted by QU et al. (2012) for the seasurface conditions in the Northern Atlantic, showing that the wind speed peaks in winter and the temperature peaks in summer.

Here, the (cross)statistics of the pairs "ambient temperature and wind speed" and "heating load and generation by wind turbines" are analyzed using data from different sites in Europe. The main focus is the identification of a match of the pattern of the generation by wind turbines (or short: the wind generation) with the heating load. A good match should indicate the reduced requirements for the balancing of generation and load by storage or the requirements for inter-regional or international power exchange. For this, a basic assessment of the expected system performance is performed involving the issues of the site-specific temporal match of generation and heating load on different time scales and the demand for system oversizing or inclusion of storage for uninterrupted supply.

These issues will be discussed in two stages. First, the seasonal match of heating requirements and wind generation is analyzed using wind and temperature data of monthly resolution to gain a qualitative indication for the feasibility of this option in different regions in Europe. Second, a more detailed analysis of the system performance is done for a region identified as well suited for wind-heating systems. Based on local 10 min time series, the sizing of the windgeneration capacity and requirements for storage to gain self-sufficient systems will be discussed as a case study to give an impression of the required efforts connected to the realization of this option.

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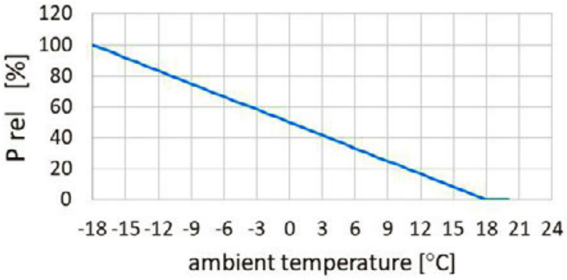

Figure 1: Chart shows the assumed simple characteristic of required heating power as function of ambient temperature. Power need P_{rel}, starting when ambient temperature falls below a limit temperature T_b is given as percentage of the rated power $P(T_c)$, defined for a critical ambient temperature T_c. Case shown here refers to $T_b = 18\,°\text{C}$ and $T_c = -18\,°\text{C}$.

The next section starts with the basic scheme used here for modeling of the heating requirements and the wind generation on a monthly time scale, together with a presentation of the database used for this analysis. Section 3 discusses the emerging patterns of the seasonal match of load and generation for various locations in Europe. The scheme, database and the results of the 10 min resolved analysis are given in Section 4, followed by the conclusions and outlook in Section 5.

2 Modeling scheme and database

For the assessment of the characteristics of the heating load, a simple linear dependence from ambient temperature is assumed. Heating starts when the ambient temperature falls below a temperature threshold T_b, and the required power rises linearly with the actual difference to the value of T_b, with the rated power $P(T_c)$ of the heating system defined by the heating requirements for a worst-case temperature T_c. Fig. 1 gives an example for this simple type of load characteristic. This model neglects second-order effects, such as the increase of heating requirements with increasing wind speed (see, e.g., Wojdyga, 2008), whose inclusion would increase the correlation of the heating load and wind-power generation, giving more benefits for this combination.

The energetic requirements E resulting from the integral over the time series of power – or the sum for time steps Δt – can be expressed using the parameter heating degree days HDD [°C days] (see, e.g., Quayle and Diaz, 1980), which may be calculated as an annual or monthly value from the time series of the ambient temperature by

$$E = \left[\sum_i (\delta(T_b - T_a(t_i)))\Delta t\right] \frac{P(T_c)}{(T_b - T_c)},$$

where

$$\delta = \begin{cases} 0 & \text{if } T_a \geq T_b \\ 1 & \text{if } T_a < T_b \end{cases} \tag{2.1}$$

and

$$E = HDD \frac{P(T_c)}{(T_b - T_c)}.$$

The energetic requirements expressed here refer to the energy losses of the buildings that have to be counter-balanced by the heating system. The technical energy needed to drive the heating system depends on its technology, which may be higher due to system losses (all direct heating systems), or lower for systems using additional energy input from the environment (e.g., using heat pumps coupled to ground heat exchangers).

The basic temporal pattern of the energy need is mostly independent of the heating system selected, given that the systems can operate with a low variability of its coefficient of performance (COP, thermal energy provided/technical energy input). This condition is approximated by ground-coupled heat pumps, but not by heatpump systems using the ambient air as additional source. For those systems, the requirements for technical power are additionally influenced by the reduction of the system COP due to an increased difference of desired indoor temperature to ambient temperature. The following results will thus not be directly applicable for that kind of system.

For the calculation of the monthly turbine generation based on information of monthly average wind speeds wind speeds are scaled up from the measurement height – commonly 10 m above ground level – to 50 m above ground level, assuming a logarithmic profile according to a roughness length of 0.15 m. A monthly energy gain is calculated assuming Rayleigh distributed wind speeds using a power curve for a typical turbine with a power rating of 1 MW.

For the monthly-resolved analysis, the database included in the energysystem-modeling tool RETScreen (see Anonymous, 2018) is used, which offers site-specific monthly means of wind speed and heating degree days (together with other parameters, such as monthly means of ambient temperature and monthly irradiance sums), and is assembled from multi-year weather-station data collected in the period 1961 to 1990 (see, e.g., Whitlock et al., 2000). The assessment on this multi-year average monthly basis given in the next section is but a first qualitative indication on the system feasibility. However, detailed information on system design has to be based on data of high temporal resolution, as shown in Section 4.

3 Monthly heating requirements and monthly wind generation for various sites in Europe

To investigate the basic match of heating requirements with the wind generation for different sites, the site-specific heating requirements are scaled to be equal to the generation of a 1 MW rated turbine at the site under inspection on an annual basis. Table 1 gives the data for

Table 1: Annual mean wind speed and estimated annual generation of a 1 MW$_{\text{rated}}$ Wind turbine for the sites presented in Figs. 2–7. *Added values for the site Nólsoy, Faroe Islands, stemming from an analysis based on one year of 10 min averages of wind speed and ambient temperature (see chap. 4.)

Site	annual mean wind speed (50 m a.g.l.) [m(s]	annual generation of turbine P_{rated}: 1 MW [MWh]
Ålesund	9.39	3499
Tórshavn	8.94	3294
Bremen	6.18	1469
Lille	6.03	1376
Carcassonne	6.58	1737
Marseille	6.69	1811
Nólsoy Faroe Islands*	9.37	3605

the annual mean wind-generation at the sites inspected here, comprising locations in northern Europe, including the Atlantic Isles, north-west Europe, and the northern Mediterranean.

For the northern sites on islands or coastal locations, the prevailing pattern shows a requirement for heating in the whole year, including the summer months. Wind speeds and, thus, the peak in wind-turbine generation in winter yield a good match of the monthly data given here for the site Ålesund on the Norwegian west coast and Tórshavn on the Faroe Islands (Figs. 2 and 3, respectively). However, the load and generation show some shift, resulting in a lack of generation in spring, and a surplus in autumn, which reflects the North Atlantic wind and temperature conditions, as described in Qu et al. (2012). Similar patterns can also be identified for the Shetland isles and the north-western Scottish Islands. For sites in the interior of Norway, the general pattern is almost unchanged, but at a lower level due to the reduced wind speed.

For the locations in western continental Europe, the temporal pattern of the wind generation remains similar, where the heating requirements in summer are considerably reduced or disappear resulting in a remarkable surplus in generation for these months, as can be seen for the examples for the sites of Bremen, Germany and Lille, France (see Figs. 4 and 5, respectively). This pattern also arises for the coastal locations at the UK North Sea coast and the French Atlantic shore. For sites at some distance from the shore in Germany, northern France, Austria or Switzerland, both temporal patterns are active but with reduced wind speeds and prolonged periods without heating requirements found in summer.

For locations closer to the Mediterranean, the temporal pattern of the wind generation shows a less pronounced variation over the year, with peaks that may appear in late spring or summer. Figs. 6 and 7 give the examples for Carcassonne and Marseille, respectively, both in southern France. For these sites, the heating requirements tend to be anti-correlated to the wind generation, with a long period without heating requirements in summer. Thus, while the use of wind power to serve the heating requirements is not reasonable in this region the supply of cooling loads may be reasonable.

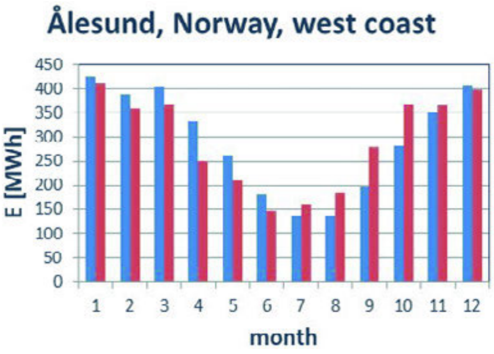

Figure 2: Monthly heating requirements (blue) and wind generation (red) for the site Ålesund (Norway). Wind generation refers to a wind turbine with 1 MW rated power, heating requirements refer to a building stock with an annual heating load equal to the annual wind generation. Annual mean wind speed and generation are given in Table 1.

Figure 3: Same presentation as Fig. 2, but for the site Torshavn, Faroe Islands.

The degree of mismatch of the series of monthly energy data may be quantified by the annual root mean square (RMS) of the monthly differences of generation and load, both normalized by their respective annual sums. Table 2 gives the respective values for an extended set of stations (all represented in the RETScreen dataset) in north-western Europe. In addition, this table contains a measure for the mismatch of the driving meteorological series that is extracted from the sets of monthly mean wind speeds and monthly HDD values. It is defined by the maximum difference of normalized monthly HDD values and wind speeds, both normalized by the mean values of the respective sets. Fig. 8 shows the relation of the measure for the energetic mismatch to the measure for the meteorological mismatch, illustrating a good correlation between the two datasets. Thus, the feasibility of wind-heating systems at a site can be pre-assessed by only inspecting the sets of monthly *HDD* values and wind speeds.

To summarize these examples, it can be stated that it is possible to identify regions well suited (or approx-

Table 2: Maximum difference of monthly, normalized HDD and normalized wind speed and root mean square of the monthly difference of normalized monthly load and production, as parameters quantifying the degree of match of the meteorological and energetic sets (see Fig. 8). *Added values for the site Nólsoy (see caption Table 1)

Site	RMS monthly energetic missmatch	max. monthly energetic missmatch
Akraberg, Faroe Islands	0.12	0.21
Torshavn, Faroe Islands	0.13	0.14
Lerwick, Shetlands	0.15	0.21
Aberdeen, Scotland	0.17	0.42
Ålesund, Norway Westcoast	0.17	0.25
Røros, Norway Interior	0.21	0.37
Brest, France, Bretagne	0.22	0.50
Plymouth, England Chanal Coast	0.28	0.46
Cardiff, Wales	0.35	0.52
Bremen, Northern Germany	0.39	0.69
Lille, Northern France	0.39	0.78
Dresden, Eastern Germany	0.44	0.88
Boulonge Seine, Northern France	0.47	0.75
Karlsruhe, South-Western Gernany	0.48	0.93
Nólsoy, Faroe Islands*	0.21	0.38

Figure 4: Same presentation as Fig. 2, but for the site Bremen, Northern Germany.

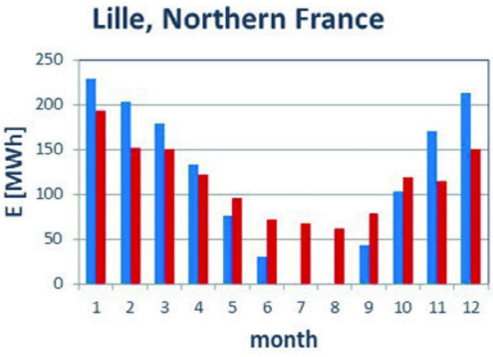

Figure 5: Same presentation as Fig. 2, but for the site Lille, Northern France.

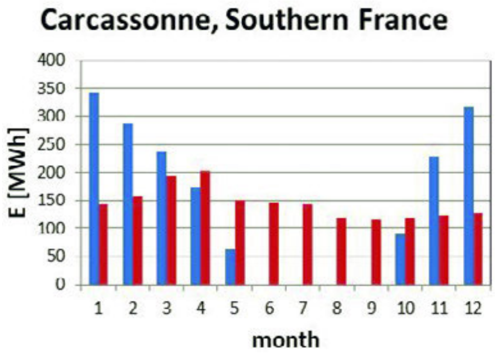

Figure 6: Same presentation as Fig. 2, but for the site Carcassonne, Southern France.

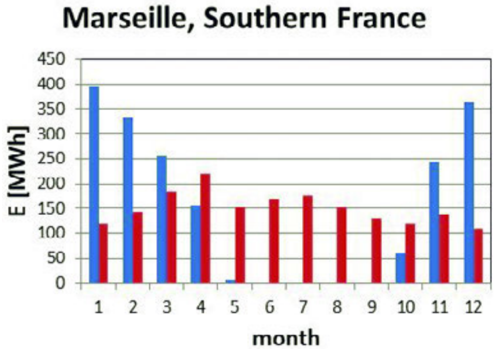

Figure 7: Same presentation as Fig. 2, but for the site Marseille, Southern France.

imately well suited) for basing the heating of houses on the local wind-turbine generation. For a more detailed analysis of this option, the system performance has to be analyzed with a higher time resolution, and thereby identifying the problems arising from the short-term variations of both wind speed and temperature.

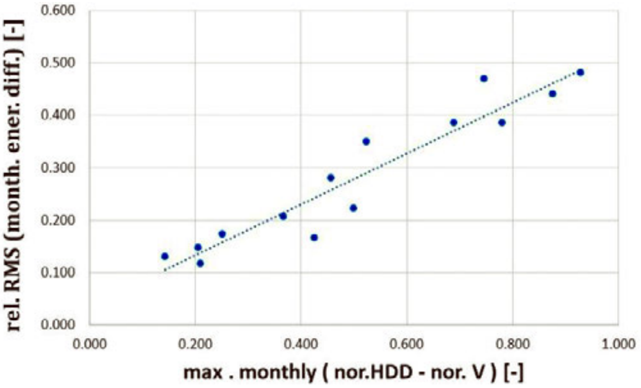

Figure 8: Relation of the root mean square of the monthly difference of normalized load and production – as measure of the energetic mismatch – to the maximum difference of monthly normalized HDD and normalized wind speed as measure of 'meteorological mismatch' (data see Table 2).

4 Case study of system performance on a 10 min time scale

A detailed study with a time resolution of 10 min is performed for the Faroe Islands, which is a region showing a good match on a monthly scale. This case refers to the island of Nólsoy, where a system incorporating a wind turbine to supply a small district heating system had been set up, with test operations analyzed in Thomsen et al. (2014). For the study presented here, wind-speed and temperature data measured onsite in 2008 by the Danish Meteorological Institute are applied. The measurements at 31 m above ground level show an annual mean wind speed of 9.37 m s^{-1}. These data are applied directly for the estimation of a time series of power output using the power characteristic as applied for the monthly analyses. The annual generation of a 1 MW rated turbine is estimated to be 3605 MWh. For the calculation of the 10 min heating load, the characteristic shown in Fig. 1 is used. The effects of the thermal inertia of the buildings are neglected. For the specific situation on the Faroe Islands where the building stock consists mostly of low-thermal-inertia wood construction, this should lead to negligible errors. In general, a detailed thermal modeling of the buildings must be applied to cope with the effects of the thermal inertia on the temporal evolution of the heating requirements (see, e.g., Lie et al., 2014).

Fig. 10 illustrates the system performance on a 10 min time scale, showing the accumulated energy balance of generation and load for a system with equal annual load and generation sums. Data are normalized by the annual mean of the daily load, i.e. the balance is given in days of load. From this curve, the size of a storage device necessary to assure the continuous operation of the load without the use of a back-up system can be deduced. It is, for the case of a balanced system as analyzed here, given by the difference of maximum and minimum accumulated balance. For more details on this method for storage sizing, including the handling of storage losses and oversized generation see, for example, Haas (1995). For the actual case, a storage size equivalent to about 46 days of average daily consumption is indicated. The need for storage is dominated here by a lack of generation in late spring/early summer. It has to be noted that the storage size indicated is based on the assumption that the previous year was equally balanced, i.e. the previous year gave a similar performance, and robust values have to be based on a multi-year analysis that includes all losses in the storage process.

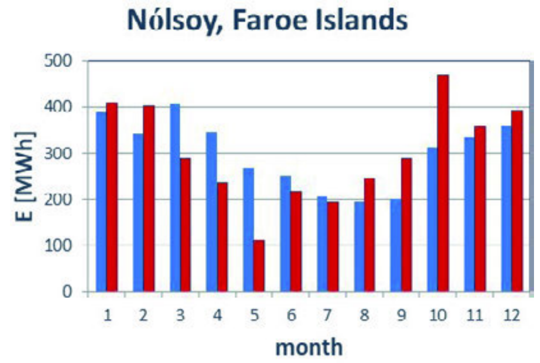

Figure 9: Same presentation as Fig. 2, but based on one year (2008) of measured data from the site Nólsoy, Faroe Islands and resulting from the analysis of 10 min time resolved data.

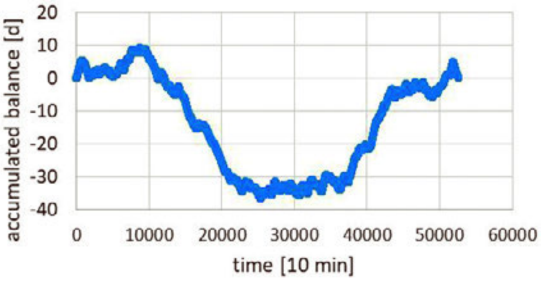

Figure 10: Trace of the accumulated balance of generation and load normalized to days of average load for a system at site Nólsoy, having equal annual generation and heating requirements. For this case of a matched system, the difference of maximum and minimum in the accumulated balance indicates the necessary size of a storage assuring continuous supply, assuming a loss-less storage.

For a storage with the indicated capacity on a monthly scale, pumped hydro may be considered as option, but this realization has to respect the limits given by the geographical conditions. An assessment of this option for Faroe Islands was performed in the context of stabilizing the isolated grid on the isle of Suðuroy (Ludescher-Huber, 2013).

The requirement for storage may be reduced by the oversizing of the wind generation relative to the case of equal annual generation and load. Fig. 11 gives the oversizing necessary for autonomous operation as function of the storage size used. Fig. 11 gives the oversizing necessary for autonomous operation as function of the storage size used. As an example, a storage size of about a week requires to triple the wind generation as compared to the sizing for equal generation and load.

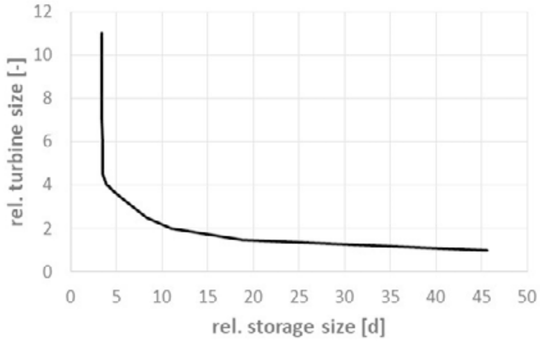

Figure 11: Combinations of relative turbine and storage size for systems assuring the continuous supply of the load based on the data set for the site Nólsoy, Faroe Islands. Turbine size is normalized by the size of the turbine assuring the annual match of production and load, the storage size is normalized to the annual average of the daily load.

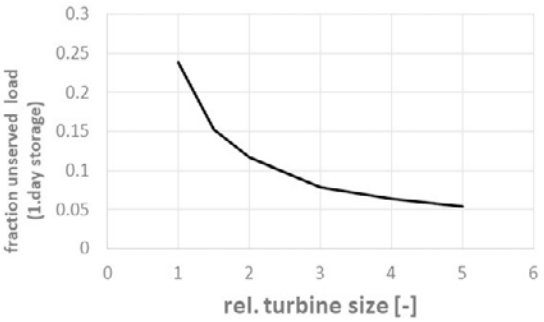

Figure 12: Fraction of unserved energy (normalized by the annual load) in systems using a storage to cover one day of load and various turbine sizes (database and normalization as for Fig. 11).

Another option for avoiding the need for large storage sizes is to allow either unserved needs or the use of a backup power source. Fig. 12 gives the fraction of unserved energy for systems with a 1-day storage and various turbine sizes. For a system with the turbine sized for an annual production to equal the annual load, the annual unserved load – or need for backup energy – amounts to ≈ 25 % of the annual consumption, which is consistent with the analysis of Thomsen et al. (2014) for the design of the test system. In that case, the storage included was "product storage" consisting of a hot water tank.

5 Conclusions and outlook

Various regions in Europe are demonstrated to offer optimal to reasonable conditions for the match of monthly generation of wind turbines with the heating requirements of buildings, with optimal conditions identified in the North Sea and Northern Atlantic regions, followed by the regions affected by "North Sea conditions" (windy and colder winters). As no information on the detailed site conditions are used here, this must be treated as a qualitative indication.

To identify the optimal scaling of regional systems designed in view of an enhanced regional self-sufficiency, analyses have to be performed with sub-hourly time resolution to cope with the short-term variability of the wind-turbine power generation. From this, the requirements for the power-generation capacity to be installed, and the need for the inclusion of storage devices, or the need for back-up energy/power exchange with the grid may be extracted.

As a still somewhat simplified example, a respective case study for a site on the Faroe Islands is given, finding that, even for a region with a good match of the monthly conditions, substantial efforts for the balancing of fluctuations on the sub-monthly time scale are necessary. In a broader context, the efforts connected to the realization of this option for the heat supply of buildings by renewable sources has to be valued in comparison with the other renewable options (e.g., solar and hydro) or hybrid solutions, relying on multiple renewable sources (see Beyer and Custodio, 2018 for a study on the wind/solar hybrid case for the Faroe Islands).

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