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Is a 100% Renewable Energy Economy Possible in the Light of Wind Silence Occurrences?

ABSTRACT

This article is focused on analysing the present state of renewable electricity production and consumption coverage in Germany, concentrating on the intermittence of wind and solar energy production and considering the significance of the wind silence phenomenon. The development and promotion of renewable energy is a major goal set out by politicians of which one example is the German plan *"Energiewende"*.

The author examines wind and solar energy complementarity and attempts assessing the possibility of basing Germanys' electricity production on renewable energy sources, without significant advancements in technology and changes in consumer behaviour. Using the analysis based on hourly data of consumption and production by source of electricity in Germany in 2016, the research addresses the issues of renewable energy source effectiveness, intermittence and points to the critical matter of periodical unavailability of wind and solar energy.

KEYWORDS: renewable energy; wind; solar; intermittence; 100% RES; wind silence.

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ENERGY PRODUCTION STRATEGY

The development and promotion of renewable sources of energy production is one of the main topics within the discussion over the drive for the transition of many countries to a competitive, low-carbon and sustainable economy. Such a goal has been specifically addressed by the European Union, which has established an initial timeframe, in accordance with which by 2050 almost 97% of all consumed electricity is supposed to come from renewable energy sources (RES) combined with making electrical energy production practically a zero-emission sector (Communication of the EC, 2011). Having in mind the current state of energy mixes of the EU member states as well as the present level of technology of production and storage, it is not a trivial question, whether such a goal is achievable. Although EU policy makers have put forward a goal and a timeframe, as well as strongly promote the idea of a zero-carbon economy, there has been a significant lack of specific guidelines and suggested measures, that would lead the member states to achieve this goal.

One member state which did approve an internal and complex plan on achieving the goals set out within the EU is Germany, which adopted its' so called policy *Energiewende* (Jungjohann & Morris, 2014), which presumes i.a. the closing of all nuclear power plants by the year 2022 and supplying at least 80% of its electricity consumption from renewable sources in 2050 (BMU, 2010). This has been a topic for heated discussion, especially in the instance of Germany beating ever higher renewable energy production levels coming from wind and solar energy sources, which are the two most promoted renewable energy sources, often viewed as complementary means of production (Jurasz & Piasecki, 2016).

The aforementioned goals inevitably prompt questions considering the feasibility of this plan, especially whether renewable energy may be a source of safe and constant supplies of electricity. Although the achievement of this goal is claimed to be viable by policy makers, it has been subject of scrutiny. Existing research concerns not only Germany but a handful of other countries, and has been based on the examination of economies with different adjusted levels of interconnectedness to other markets (Akurua, Onukwubeb, Okoroc, Obea, 2017); (Child, Haukkala, Breyer, 2017); (Connolly, Lund, Mathiesen, 2016); (Krajac, Duic, Carvalho, 2011). Throughout the discussion, the feasibility of such a policy is often presumed to be attainable under the assumptions of a certain level of complementarity of the analysed renewable energy sources, significant advancements in the level of technology eg. energy storage technology, as well as changes in certain consumer patterns and habits (Sovacool & Hirsch, 2009). These assumptions considering especially the levels of future technology are uncertain, which therefore do not solve the biggest problem with renewable energy sources, which is their intermittence and the presence of intervals of very low combined renewable energy production. Thus the question is – is the achievement of a sustainable, zero-carbon economy based on renewable energy sources feasible, taking into account the current level of knowledge and technology?

This paper is focused on analysing the present state of renewable electricity production and consumption coverage in Germany, concentrating on the intermittence of energy production from wind and solar technology sources, as they are the two most heavily promoted and developed renewable energy sources. The goals of this paper are to examine, to what extent are wind and solar energy sources complementary and is there a realistic possibility of basing Germany's electricity production on a hybrid solar-wind system, without significant advancements in technology. The analysis is based on hourly data on consumption and production by source of electricity in Germany in 2016, giving a depiction of consumption coverage and correlated production throughout a 24h period in a 365 day timeframe on the basis of statistical analysis. The carried out research addresses the issues of renewable energy source effectiveness, intermittence of solar and wind power and focuses on the critical matter of periodical unavailability of wind and solar energy.

INTERMITTENCE OF RENEWABLE ENERGY SOURCES

The key issue with renewable energy sources is their intermittence, as in fluctuations in electricity production levels, which depend on the existing weather conditions. It should be pointed out that there are significant differences in this respect depending on the utilized technology. Broadly understood hydroelectricity and biomass-based energy production technologies will be more stable sources of electricity supply, stemming out of the basic principles of their operation, but for the purposes of this analysis they will be partially marginalized, since in reality Germany has so far focused in particular on developing the production of wind and solar energy, as it is in this area, that the largest increase in installed capacity is observable (BMWi, 2016).

According to data provided by the Bundesnetzagentur (German agency responsible i.a. for the transmission network) in 2016, Germany had 104.453 GW of installed capacity in renewable energy sources, which accounted for 49.3% of the total installed capacity in all sources, which amounted to 212.033 GW (Bundesnetzagentur, 2017). It should be noted that the installed capacity in wind energy amounted to 49.559 GW, which accounted for 47.5% of the installed capacity in renewable sources and 23.4% of the total installed capacity in all sources. The installed capacity in solar (or photovoltaic – PV) sources was 40,715 GW, which accounted for 39.0% of the installed RES capacity and 19.2% of the total installed capacity. For comparison, the installed capacity in hydroelectric power plants (excluding pumped storage power plants) and biomass combustion plants amounted to only 5.1% of the total installed capacity (10.3% of the installed capacity in RES).

However, the above percentages in installed capacity are not proportionally reflected in the share of electricity produced in 2016. According to aggregate data, a total of 600.3 TWh of electricity was generated in Germany in 2016, of which only 180.3 TWh came from RES, which accounted for 30.0% of total production. The disproportion between the share in the installed capacity and the share in the actual production amounted to as much as 19.3 pp. Thus it may be assumed that RES operated with approx. 60% efficiency in combination with the average production of all installed capacity[1]. Further disparities are noticeable when analysing individual sources.

In 2016 wind energy production reached a level of 77.0 TWh and was equivalent to 12.8% of total energy, which translates into a production efficiency at approx. 50% of the average production per unit of installed capacity from all sources. Solar energy has boasted even lower values in this respect, with a share in total energy production amounting to only 5.7%, which indicates an average efficiency of less than 30%. For comparison, energy based on biomass combustion was responsible for producing of ca. 41 TWh of energy, which accounted for 6.8% of total production in 2016, while the share of this industry in the total installed net power was less than 3.5%. Thus, the efficiency of using biomass combustion plants was almost twice as high as the average production efficiency of the whole sector, four times higher than wind power and almost seven times higher than solar power.

The aforementioned statistics point out a significant problem which is the effectiveness of the analysed technologies of renewable energy production. The low production efficiency may be

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[1] Efficiency of production in this part of the analysis is calculated as the ratio of the share of production from a given source in the total production of electricity from all sources to the share of installed capacity of a given source in the total installed capacity in all sources. This statistical measure is used for the purpose of giving a comparison between different energy sources in a real time functioning market.

directly associated with the high variability in production. In the case of photovoltaic technologies, the source of variability is quite obvious and dictated by the fact that it is impossible to produce solar energy during night hours. In addition, the production volume is positively correlated with the length of the day as shown in Figure 1. In 2016, the highest daily solar energy production was achieved in July, in which a total of 4,943 GWh of electricity was produced, while the lowest daily production level of 654 GWh was recorded in January. The daily efficiency of installed capacity adjusted to hours of daylight in a given month also shows significant volatility, reaching the maximum level of 23.4% in August and a minimum level of 5.2% in January, with the maximum hourly efficiency in PV energy production recorded throughout the whole year reaching approx. 64,0% of installed capacity.

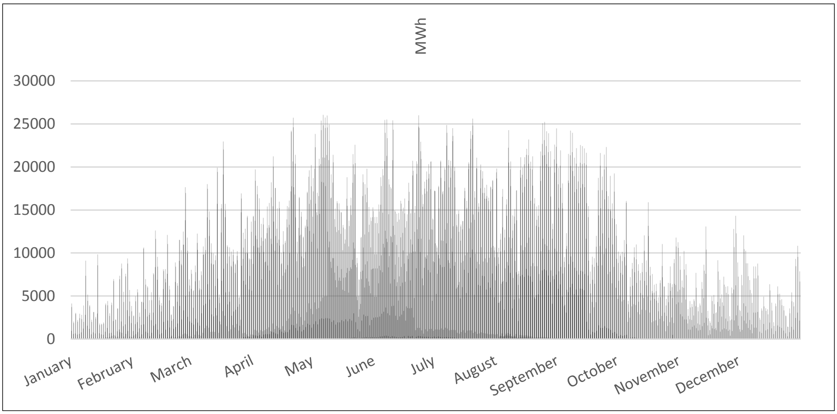

Figure 1. Hourly solar energy production in Germany in 2016

Data source: Bach P.F. *International time series 2006-2016*. Retrieved from: http://www.pfbach.dk/ (01.08.2018).

A less pronounced trend may be observed in the production of wind energy, which in turn is dependent on the occurrence of appropriate atmospheric conditions and is not limited in advance by a constant break in production at night. Technical literature indicates that the production of electricity in typical wind turbines takes place at wind speeds from approx. 3-4 m/s (about 10-14 km/h) to about 25 m/s (about 90 km/h), with the optimal conditions for achieving maximum efficiency being the wind speed of ca. 15 m/s (BWEA, 2005). Exploitation of turbines is limited to the cut-off wind speed level of over 25 m/s, which is equivalent to a storm with a strength of 10 degrees on the Beaufort scale.

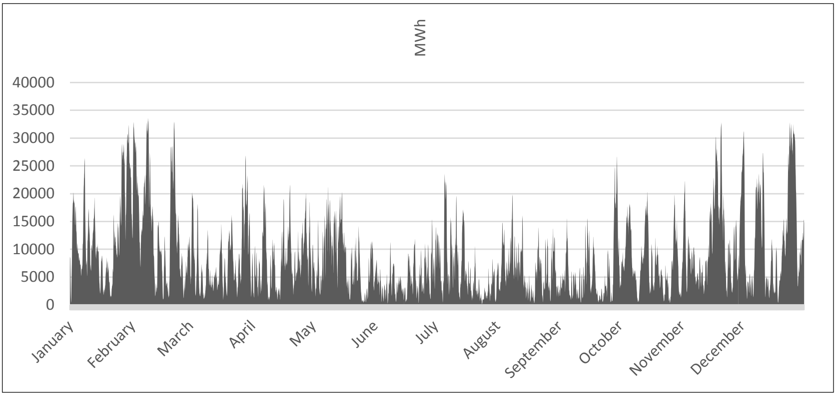

Figure 2. Hourly wind energy production in Germany in 2016

Data source: Bach P.F. *International time series 2006-2016*. Retrieved from: http://www.pfbach.dk/ (01.08.2018).

Figure 2 presents the production of wind energy in 2016, which shows higher daily volatility than production from PV installations and ranges from the lowest hourly production at 135 MWh to the peak production of 32,626 MWh. Thus the effective usage of installed capacity ranges from 0.27% up to 67.81%.

WIND SILENCE AND COMPLEMENTARITY OF SOURCES

One of the key issues in the context of the availability of electricity production from wind is the occurrence of the so-called wind silence phenomenon (Garbicz, 2015). This is a vague concept, used to describe a situation in which the production of electricity from wind practically disappears due to lack of wind or excessive wind, which inclines that the volume of electricity generation from this source is insignificant in the context of the entire energy system. For the purpose of this analysis, it was arbitrarily assumed that wind silence would practically occur when the current efficiency of the entire system would be below 10% of the average efficiency in the analysed year. In Germany the average hourly efficiency of wind turbines in 2016 was 17.7%[2]. Thus, the conditions in which the whole wind energy production sector produced only 1.7% of its potential power will be considered as wind silence. Although it may be argued that such a level still does not mean a complete lack of production, however there is no doubt, that an effective production level of only 1,7% may be interpreted as a practically irrelevant and close to zero. In 2016, 211 hours of such calculated wind silence were recorded in Germany.

The analysis of the occurrence of the wind silence phenomenon is particularly important in the context of the complementarity in the production of wind and solar energy. As may be observed in Figure 1 and Figure 2, both sources do show a limited trend in seasonal substitutability, with more energy produced prom wind in the winter months followed by lower volumes in summer that coincide with the opposite pattern for the production of solar power, which is highest in summer.

The invariability of limitations in the production of electricity from PV at night is a reliable and predictable phenomenon,

[2] Calculated as the ratio of hourly production to installed capacity in wind turbines.

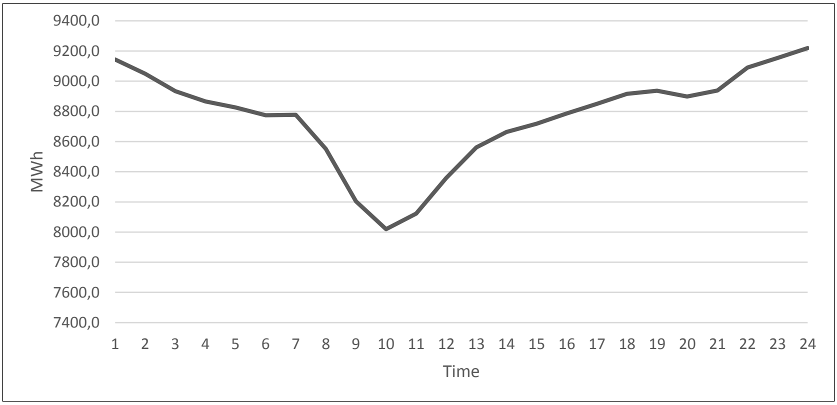

Figure 3. Average hourly energy production form wind turbines in 2016 in Germany.

Data source: Bach P.F. *International time series 2006-2016*. Retrieved from: http://www.pfbach.dk/ (01.08.2018).

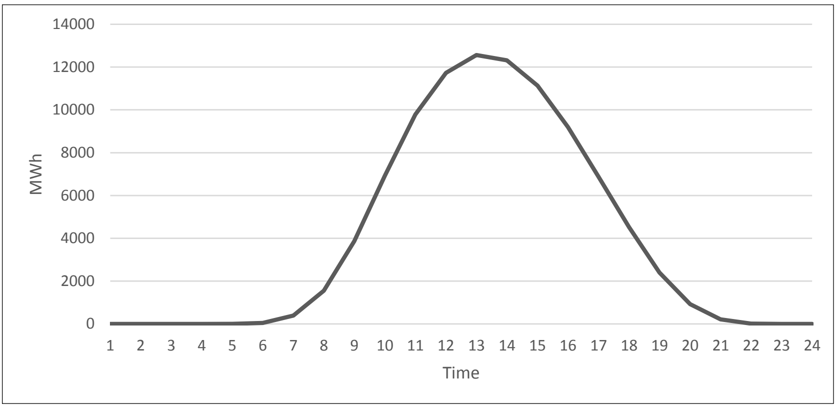

Figure 4. Average hourly solar energy production form in 2016 in Germany.

Data source: Bach P.F. *International time series 2006-2016*. Retrieved from: http://www.pfbach.dk/ (01.08.2018).

thus in the assumption of a hybrid model, wind energy should be a complementary source reliable enough as to compensate for the loss occurring form solar energy production in relation to the demand for electricity. By analysing average hour production of given renewable sources in a year, one may come to the conclusion that these sources may be acknowledged as substitutes, as on average more wind is produced during the night whereas solar energy production takes place exclusively during daytime hours.

It should be noted that the demand for electricity also varies depending on the time of day and season (see Figure 5 and Figure 6). The average daily demand for electricity shows higher levels in the autumn and winter, while in the daily dimension there is a clear decrease in the demand for electricity at night.

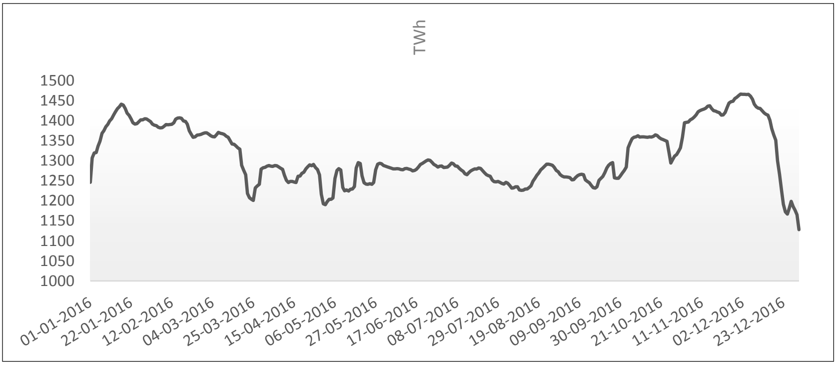

Figure 5. Rolling average of the daily demand for electricity in Germany in 2016.

Data source: Bach P.F. *International time series 2006-2016*. Retrieved from: http://www.pfbach.dk/ (01.08.2018).

Assuming the complementarity of both analysed sources, it would be expected that the average hourly total coverage of electricity demand from both sources should show to some extent relative stability and smaller deviations from the average than in the case of analysis of individual sources separately. Especially

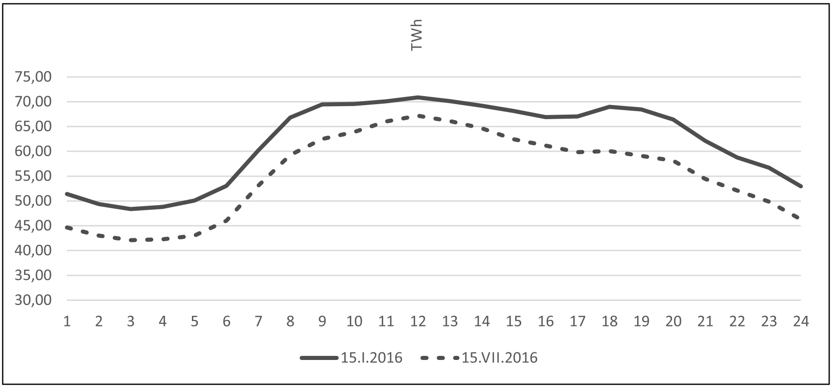

Figure 6. Hourly demand for electricity on selected days of 2016 in Germany.

Data source: Bach P.F. *International time series 2006-2016*. Retrieved from: http://www.pfbach.dk/ (01.08.2018).

basing analysis on average values concerning hourly production may give the illusion, that these two sources are substantially complementary to each other. The first manifestation of the lack of such complementarity results from the calculated correlation coefficient that takes a negative value (0.1604), which should be interpreted as statistically insignificant. For further analysis, it is most reasonable to use data concerning demand coverage, as this links production to the actual need for electricity produced.

Wind and solar energy in 2016 provided coverage of an average of 23% of the total electricity demand. Differences in levels between the analysed sources should be explained by the installed capacity at that time and average efficiency, which were discussed in the previous part of the analysis. It is the maximum values of energy production from RES that are at the centre of the public opinions attention and are used as arguments in favour of renewable energy. In 2016, the maximum total coverage of hourly demand by wind and solar energy reached a rate of almost 88%. In spite of obtaining such intervals of high production and demand

Table 1. The relation of electricity production from individual renewable energy sources to total demand.

	Hourly electricity demand coverage			
	Mean	Min.	Max.	Standard deviation
Combined production	23,14%	0,80%	87,88%	0,149
Wind energy	16,45%	0,28%	77,32%	0,131
Solar energy	6,70%	0,00%	55,51%	0,104

Data source: Bach P.F. *International time series 2006-2016*. Retrieved from: http://www.pfbach.dk/ (01.08.2018).

coverage by renewable energy, it is essential for the security of the power system to provide an appropriate and constant volume of electricity to cover the ongoing demand. In 2016, the minimum total coverage (by wind and solar generation) of demand was just slightly higher (in absolute values) than in the case of both sources considered separately, and was still at a level that implied the actual production from these sources was irrelevant in the means of the whole sector.

Applying the aforementioned concept of wind silence (Garbicz, 2015), that was previously used to present the efficiency of production, to the aspect of coverage of demand, the joint production on a level below 10% of the average supply from both sources (total coverage of less than 2.3% of demand) occurred in 2016 during a total of 106 hours. If analysing particular energy sources, singled out wind energy production boasted periods of demand coverage below 2.3% of the total demand amounting up to almost 484 hours in 2016. This means that solar energy was able to supplement wind energy production up to our critical level of 2.3% of total demand coverage for a length of 378 hours, which translates into 15 day and 18 hours. However this still leaves us with the critical problem of the aforementioned 106 hours during witch both sources were practically irrelevant in total production. Furthermore it must be held in mind, that these levels are still far from the volumes needed to guarantee the safe and continuous functioning of the whole energy system and economy in general.

Despite the fact that the above analysis is limited to calculations based on data from 2016, the results quite unequivocally indicate that the possibility to ensure a stable energy supply in Germany based only on a hybrid solar and wind energy model is limited, in the absence of truly significant innovation in energy production and storage technology. Despite Germany beating ever longer time and higher volume records of electricity supply from renewable energy, a form of conventional energy is still required to provide coverage for the base demand for electricity. If Germany were to achieve the volume of 80% of annual electricity demand coverage from renewable sources, which may be achievable by installing appropriate production capacity, it is questionable if this can be achieved with the simultaneous closing of conventional power plants, which will have to be kept operational in order to cover the intervals of time, where RES production levels did not meet the current demand. This puts a question mark on the possibility of Germany achieving the objectives of the adopted *Energiewende*, but also puts forward the overall balance of advantages of this programme, taking into account multiple variables eg. the carbon footprint (Messagie, Mertens, Oliveira, Rangaraju, Sanfelix, Coosemans, Mierlo, Macharis, 2014) or land-use requirements (Capellán-Pérez, Castrob, Artod, 2017) of solar panels.

RENEWABLE ENERGY BASED ECONOMY – CHALLENGES.

Germany's current energy security is ensured by the still functioning conventional coal and nuclear power plants. But in line with the low-emission economy presumptions, these safety buffers that supplement energy shortages from RES are to be gradually terminated. The question how to achieve the same level of safe an constant supply has been the subject of heated discussion. The most important claims of RES promoters are anticipated innovations and technological improvements, as well as diversification of sources of electricity production in geographical and technological terms. Furthermore it is often argued, that customer behaviour and habits will have to some extent alter in order to tailor demand to the current supply.

One of the problems faced by the energy sector in scope of RES is the efficiency and feasibility of storing electricity on a large scale with the use of currently available technology (Denholm & Hand, 2011). As an example, contemporary batteries act mainly as ancillary energy banks and the technology of home and car batteries is currently thriving, but a real technological revolution would be needed to ensure full levelling of the unavailability of energy form wind and solar sources, as the limitations considering the usage of the various kinds of available battery technology seriously restrict utilization of batteries on such a scale (Beaudin, Zareipour, Schellenberglabe, Rosehart, 2010) (Poullikkas, 2013).

One of the practically available large-scale and most common energy storage technologies are pumped storage power plants (Beaudin, Zareipour, Schellenberglabe, Rosehart, 2010). In 2016, Germany had 6 357 MW of installed capacity in pumped storage power plants, which represented approx. 3% of the total installed capacity. It should be noted however, that the production of electricity in pumped storage power plants does not take place without losses, reaching up to 30% on the net input-output of energy. As a supplement to these power plants, traditional hydroelectric power plants may be indicated as additional energy storages through their water reservoirs. However, the total installed capacity of all hydroelectric power plants in Germany in 2016 did not exceed 5% of the total installed capacity (total installed capacity of hydroelectric power plants was equal to 9,741 MW according to the data of the Bundesnetzagentur). Taking into account the maximum hourly electricity demand in 2016 amounting to 75,377 MWh, assuming the availability of all hydropower plants and their one hundred percent efficiency with zero losses on transmission, they would cover less than 13% of the total peak electricity demand. Thus in order to have an installed capacity capable to supplement the unavailability of energy from any other source, Germany would have to build an additional 65 TW of installed hydroelectric capacity (this is of course a hypothetical assumption, which does not take into account many key issues eg. limited hydropower efficiency etc.), which due to the geological conditions in Germany is arguably not feasible (Sinn, 2017). For comparison, one of the largest dams in the world – the Three Gorges Dam in China, with various estimates putting the construction cost as high as USD 37 billion (Graham-Harrison, 2009) and with a construction timeframe of almost 17 years upon reaching full production capacity in 2008, was fitted with 18.2 TW of installed capacity (Power Technology, 2018).

Appropriate diversification of renewable energy sources is the second aspect analysed in the pursuit of a hypothetical implementation of an economy based solely on RES (Connolly, Lund Mathiesen, 2016). The assumption would be to construct the entire production system in such a way that it could complement each other in the hierarchy from sources that are least dependent and stable (solar and wind energy) to sources that exhibit the least variability and are also the most controllable (hydroelectricity, biogas and biomass combustion). This strategy does however face limitations, of which the control is not readily possible. Given countries show different potential and efficiency for utilising given renewable energy technology. The use of hydroelectric power in Germany has a lower potential than in countries with more favourable topography and higher annual precipitation (eg. Norway (Indexmundi, 2014), where hydroelectric power in 2016 covered an average of 99.8% of electricity demand, with a minimum coverage level of 46.7%)[3], while the efficiency of photovoltaic generation will generally be higher in countries with a larger amount of average daytime hours.

This issue has significant meaning in achieving the desired structure of the electricity production sector in relation to a single, territorially limited country, especially when it comes to European countries that are relatively small without relatively significant geographical differences (excluding Russia). It should be noted however, that the problem of a given country could be solved by the internationalization of the electricity market and modelling of a renewable energy system not from the perspective of a single state, but a larger geographical area, thanks to which the "wind silence" effect could be mitigated. The adoption of a coherent policy by a larger number of countries that, due to their diverse topography and weather conditions would complement each other in terms of the effectiveness of a given source, could lead to implementing a fully renewable and independent of conventional technologies energy sector. In this respect, the European Union has a policy of integrating the entire EU energy market, supporting infrastructure projects and creating an international regulatory framework. Nevertheless, the feasibility of such a call to create a diversified international energy system based on renewable energy requires further extended analysis.

Further discussion should also focus i.a. on the educational aspect of changing consumer behaviour so as to achieve higher savings in electricity consumption and flexibility of demand to the current supply. Changes of peoples habits combined with higher awareness of the limitedness of resources put forward as one of the pillars of public education could make the goal of reaching

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[3] Calculated using data for Norway energy production and demand. Data source: Bach P.F. *International time series 2006-2016*. Retrieved from: http://www.pfbach.dk/ (01.08.2018).

the goal of a 100% RES economy more feasible, as the alteration of the demand level could further limit the effect of wind silence. The general public should not take for granted the problem of energy production, especially in the light of a growing demand for electricity. Thus a combination of advancements in technology and adjusted social attitudes are the main challenges of the nearest future, which if successfully implemented, may enable the world to become independent of fossil fuel energy production.

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