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Regional economic and environmental impacts of wind power developments: A case study of a German region

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ABSTRACT

Wind power is an important technology in the transition towards a low carbon economy. This paper covers the regional impacts of wind power developments in a small German region. Wind power developments with a cumulative capacity of 63.1 MW which have been installed in 2017 in the Aachen region, generating 3901 GWh electricity from 2017 to 2037 lead to a regional value added of €50.8 million (or €805/kW). The avoided greenhouse gas emissions are 132,770 tCO_2-equivalents in 2017 and the total economic impacts of value added, avoided greenhouse gases and air pollution ranging from €20.9 to €24.6 million (€332–389 per kW or €107–126 per MWh electricity generated) in 2017. From an environmental economic view, the generation of wind power is the most beneficial electricity generation technology in comparison to PV and lignite.

1. Introduction

As acknowledged by most climate scientists, climate change, which has significant negative effects on the environment, is caused by the emission of greenhouse gases (GHG) such as carbon dioxide (CO_2) (NASA, 2017). Therefore, the avoidance of GHG, which has been adopted by international treaties such as the Kyoto Protocol and most recently by the Paris Agreement, is one of the main present and future societal targets and challenges (United Nations Framework Convention on Climate Change, 2014).

As most GHG gases are emitted by the energy sector (IPCC, 2014) there is especially a need to reduce emissions in this sector by the exploitation of renewable energy sources (RES).

In terms of installed capacities, wind power is, after hydro power, the most important renewable energy technology, whose significance is expected to increase in the future (REN21, 2018) and may therefore be regarded as a significant contributor to a lower carbon energy system.

However, the energy transition to a low carbon energy system has not only positive impacts. Critics point out for example job losses in conventional energy industries (dpa, 2014) and regions where conventional energy carriers play a significant role, such as the Rhenish lignite mining area (EEFA, 2010), are particularly affected. Nevertheless, there are opportunities for a more sustainable regional development that encompasses environmental and socioeconomic concerns (Hopwood et al., 2005), even in regions that historically relied heavily on fossil fuels. These chances should be quantified to realistically estimate future economic opportunities in regions such as the district of Aachen (German: Städteregion Aachen), which historically relied on coal, still mines lignite, and finds itself in a transformation process to a low carbon energy system. Indeed, studies of this sort have policy relevant implications, for instance in Germany, where the envisaged phasing out of lignite in 2035 is expected to impact all regions currently relying on fossil fuel industries (Kommission Wachstum, Strukturwandel und Beschäftigung, 2019). The region may, therefore, be representative for a region relying on fossil fuel industries. There are other regions in a similar situation and each one should be studied individually, due to the local situation.

The aim of the paper is therefore to comprehensively show the current regional economic and environmental effects of developing RES like wind power and comparing these to conventional energy generation technologies. While a number of studies have looked at the economic implications of wind power development at the regional level, only a few take into account both economic and environmental effects. Yet, illustrating both dimensions at the regional level is extremely important from a policy perspective, as in most countries, regional and local governments (e.g. states, provinces, or municipalities) are key decision makers in the energy transition. In more details, Jenniches and Worrell (2019) find that most studies covering regional economic impacts of renewable energies purely focus on economic effects and do not take into account further effects such as the positive impacts of avoided

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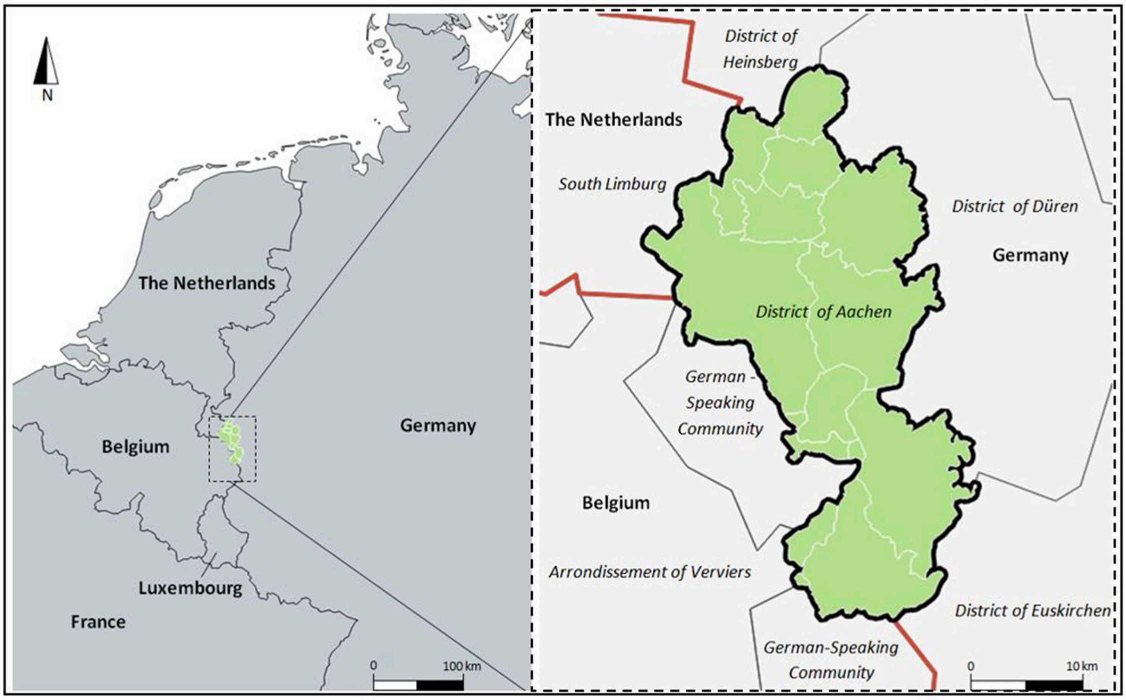

Fig. 1. Location of the district of Aachen in Europe (left) and neighbouring territorial units (right) on NUTS 3 level (Source: Jenniches and Worrell, 2019, modified; map data sources: Eurostat, s. 2018, a.b).

emissions (GHG or air pollution), which may be referred to as positive externalities. Exceptions are Madlener and Koller (2007), Stoddard et al. (2006), or Bost et al. (2012). Evaluations mostly conclude with a quantification of the emissions and a monetary valuation of effects is not integrated (an exception is Simons and Peterson, 2001). Most studies in the field, moreover, present a simple substitution of one energy carrier by wind power without taking into account the effects of the integration of wind power on the actual electricity generation mix (Novan, 2015). On the contrary, the positive externalities of renewable energy generation on avoided emissions should also be integrated as a contribution of a region to climate change mitigation. This is especially relevant in regions where fossil fuel generation takes place and a compensation of the negative effects of the transition is strongly required due to a regional responsibility (Chen and Chen, 2011; Kinzig and Kammen, 1998) and from a sustainable development perspective (Dincer, 2000). In fact, a valuation of these effects enables a hands-on quantification showing the positive aspects of RES for all regional stakeholders (e.g. politicians, end-users, and businesses) in comparison to fossil energy generation technologies.

Consistently, this paper presents a comprehensive analysis of the regional economic effects of wind power deployment, supplemented by the estimation of the monetised positive impacts of avoided emissions, based on the current energy mix. As the market evolves quite dynamically in terms of technological and economic development (Deutsche Windguard, 2015), an up-to-date assessment is carried out in the paper by evaluating developments for the most recent year (2017).

Moreover, the paper assesses the current benefits of wind power and PV compared to lignite. Such a comparison is at the center of recent discussions about the future of lignite in the German energy system, as regional stakeholders decide on developments in their regions (Schmidt-Mattern, 2018).

The paper is structured as follows: After the introduction (Section 1), the characteristics of the analysed region with a special emphasis on the energy system are introduced (Section 2). Section 3 introduces the method to evaluate the economic impacts of RES in regions, which is then applied to the Aachen region. Section 4 assesses the monetary value of environmental benefits of wind power developments, while the concluding Section discusses the findings and provides a comparison on the benefits of the renewable energy technologies wind power and PV to the fossil energy carrier lignite.

1.1. Characteristics of the region and wind power developments

The district of Aachen is situated in the West of Germany (Fig. 1) in the federal state North Rhine-Westphalia.

Regarding its historic development, energy is deeply rooted in the regions' 'socioeconomic DNA'.[1] In the North of the region, black coal was exploited until 1997, when the last coal mine was closed (Bergbaumuseum Grube Anna, s. a.). Mining and fossil energy carriers still play a significant role in the region, which is part of the Rhenish lignite mining area. There is for example the lignite mine Inden,[2] whose resources are exploited for the generation of electricity in the lignite power plant Weisweiler which is scheduled to close in 2030 (RWE Power AG, 2018). The work force of the lignite mine Inden and the power plant Weisweiler amounted to 2672 employees in 2009,[3] demonstrating the regional economic significance of the lignite industry.

In terms of renewable energy (RE) developments, the region can be considered an early mover. Indeed, the *'Aachen model'* (German: 'Aachener Modell') of cost covering feed-in tariffs for renewable energies, which has been introduced in the 1990s in the region, is considered as the predecessor to the German feed-in tariffs regulation of the Renewable Energies Act (EEG) (Solarenergieförderverein e.V. et al.,

[1] The following description of the historical and current role of energy in the region is based on Jenniches and Worrell (2019).

[2] The lignite mine is situated partly in the municipality of Eschweiler in the East of the region.

[3] Employment effects of RWE Power AG have been evaluated by multiplying the employees of RWE Power AG in the lignite mine Inden and the power plant Weisweiler (1600 employees according to RWE Power AG, 2009) by an average employment multiplier for the Rhenish lignite mining region (1.67 in 2009) according to EEFA (2010).

2018; Agentur für Erneuerbare Energien, 2014, 2017, 2018).

By the end of 2017, a cumulative capacity of 201 MW of wind power has been installed in the region (Fig. 2, left).

In a German-wide comparison, higher dynamics took place between the mid-1990s and 2003 in the district of Aachen. This may be explicable by the introduction of the feed-in tariff (Fig. 2, right). After 2003, the dynamics in the region are almost comparable to the dynamics in Germany. In 2017, the region became more dynamic once more, which is explained by a change in the compensation system that nudges operators to install wind turbines until the end of 2018 (Section 3).[4]

2. Regional economic impacts of wind power

2.1. Selection of an assessment methodology

According to Jenniches (2018), most regional economic impact assessments of RES u employment ratios, Input-Output (IO) models, or supply chain analyses.

While the first method is not suitable to explore other factors besides employment, an IO model is an overall economic impact assessment tool (Leontief, 1936, 1951). It demonstrates the interactions of different industries in an economic system, illustrated in direct economic effects due to economic activities in an industry and indirect effects on suppliers of that industry. One of the challenges is the amount of data used to create an IO model. Unfortunately, regional IO tables (RIOTs) are not available for regions in Germany and would have to be derived from higher level (for example national) data (DIW, 2014) or constructed by surveys (Coon et al., 1985). Nevertheless, statistical derivation from larger scale IO models lacks precision on a small regional scale (BMVBS, 2011).

Supply chain analyses also evaluate flows of goods and services, whereas the starting point of analysis is not the whole economic system, but a specific end product. For this product, the effects in different stages of the supply chain are evaluated.[5]

In this sense, a supply chain analysis meet the evaluation's needs.[6] Moreover, as Llera et al. (2013) state, the advantage of analytical methodologies like the value chain approach is that that they are more easily to reproduce than IO models because the effects of significant variables are more comprehensible. This supports the validity of the results and makes a comparison of results easier (Section 3.5).

The supply chain analysis approach, which has been used by Hirschl et al. (2010) and Finus et al. (2013) in similar studies, which this paper follows methodologically, may be categorised as a bottom-up method to assess regional economic impacts. A detailed overview about the calculations is presented in Section 3.3. For a comparable study concerning the procedure in the district of Aachen see Jenniches and Worrell (2019) for PV. By applying this method, the regional value added according to the definition of Hirschl et al. (2010) and Bröcker et al. (2014) is assessed consisting of the components post tax revenues of enterprises, net income of employees, and regionally (i.e. municipally) raised taxes. Moreover, the number of full-time employees in the different industries is assessed in person years.

2.2. Lifecycle analysis and estimation of economic activities carried out in the region

In a first step, the activities concerning wind power developments and the activities that may be realistically taken over by regional enterprises are estimated.

Llera et al. (2013), followed by Jenniches and Worrell (2019) use 5 subsequent life cycle stages for the economic impacts assessment of RES which may be referred to as research and development (R&D) (1), manufacturing (2), installation (3), operation and maintenance (O&M) (4), and decommissioning (5). Fig. 3 shows the activities in each lifecycle stage following literature in the field such as Bröcker et al. (2014), BMVBS (2011), or Deutsche Windguard (2013). Defining activities that can be taken over by regional enterprises is challenging because there is no statistical classification of the renewable energy industry (Statistisches Bundesamt, 2017).[7]

Dealing with this challenge, various industry statistics such as official and non-official sources (e.g. IHK Aachen, s. 2018.; Cylex International S.N.C., 2018) have been analysed to identify regional enterprises that are involved in the renewable energy industry. The analysis has been supported by an online survey (Jenniches and Worrell, 2019) and 21 enterprises involved in activities in the wind power market have been identified in the region.[8] As it is difficult to provide a conservative estimate of specifically wind power related revenues of R&D and component manufacturing companies that are active in other business areas as well, the paper focuses on installation, operation and maintenance activities of wind power developments in the region as minimum economic impacts, nevertheless acknowledging the regional economic benefits of the local wind power industry.

To quantify the economic effects that depend on wind power developments in the region only, activities that are realistically carried out by regional enterprises are taken into account using enterprises located in the region from the regional enterprise analysis as a precondition, combined with literature values and field interviews for specific activities. In the installation stage, infrastructure, and foundation may fully be taken over by regional enterprises (Türck-Hövener, 2016).

It has been found that 55% of installed wind turbines in the region are operated by regional grid service companies, which is therefore assumed also to be the regional share of the activity grid connection. As some planning companies and wind turbine operators are located in the region, it is estimated, that all wind turbines may be planned and operated by regional enterprises. Due to the fact that insurances may be taken out by an internet contract or by a local insurance broker, a share of 50% for insurances taken out by regional brokers is assumed. However, in case some activities may be taken over by external companies, an additional assessment with a 50% share of regional planning

[4] Nevertheless, large scale developments like the installation of numerous wind plants in a wind power park that have –especially in small scale regions-a significant impact on the development dynamics are installed in specific years and not developed constantly over time. Due to regulatory restrictions (zoning, availability of suitable space, etc.), the development dynamics of wind power evolve differently than other RES technologies like for example PV which develops quite linearly in the region (see Jenniches and Worrell, 2019).

[5] The costs of wind turbine maintenance during operation, for example, are interpreted as the material costs (or intermediate input) and the additional costs and benefits of the maintenance company. By applying industry specific statistics, it is possible to calculate the regional value added, generated by the activity maintenance. The costs of intermediate inputs are interpreted as material costs and as additional costs and benefits of the previous stage of the supply chain, which may be trading in this case. The material costs of trading are interpreted as the intermediate inputs, benefits and additional costs of component manufacturers and so on. For further explanation about supply chain analyses see Jenniches and Worrell (2019) or Hirschl et al. (2010).

[6] For an evaluation of various regional economic impact assessment instruments see Breitschopf et al. (2011) or Jenniches (2018).

[7] For example, component suppliers of 'the wind power industry' are classified as manufacturers of the product categories rubber and plastic products, metal products, mechanical engineering, and electrical equipment (DIW, 2014), whereas not every enterprise listed in, for example, the mechanical engineering industry is involved in the wind power market.

[8] Four enterprises only involved in the small wind turbine market were excluded. Enterprises which are able to fulfill the activities funding, foundation and infrastructure, and insurance are also excluded in order not to sophisticate the amount of enterprises in the wind power market because wind power is considered as being only a peripheral business of these enterprises.

enterprises and operators[9] and a zero share of regional insurance companies is calculated in order to provide a more conservative estimate and an idea of the impact of a change in the regional share on the economic effects (Section 3.4), which is also referred to in the discussion (Section 5).

Whereas land lease may be naturally taken over by regional land owners, the paper follows BMVBS (2011) and uses a share of 45% of local credit institutes based on the analysis of local funding for RE projects. Other sources assume a higher share (such as 50% by Bröcker et al., 2014).

As depicted in Fig. 3, the effects generated in the R&D stage are assumed to occur before the installation in 2017. Moreover, manufacturing and installation are assumed to take place in 2017 with the exception of manufacturing of O&M material, which takes place between 2017 and 2037. The operation and maintenance stage is assumed to last 20 years, which may be outlasted in single cases (Fraunhofer IWES, 2015). Decommissioning is therefore assumed to happen in 2037, whereas waste management and recycling may succeed 2037.

2.3. Calculation of effects

In 2017, one turbine with a capacity of 0.8 MW, four turbines in the power class between 2 and 3 MW with a capacity of 10.8 MW, and 16 turbine between 3 and 4 MW with a cumulative capacity of 51.5 MW respectively have been installed in the region. Therefore, the total installed capacity of the 21 wind turbines in 2017 is 63.1 MW (Fig. 4). The estimated amount of electricity generated, based on location specific estimations for each wind turbine (Bundesnetzagentur, 2018), between 2017 and 2037 will be 3901 GWh.[10]

The individual capacities and further wind turbine specific characteristics are essential for the analysis of costs in the installation stage (Section 3.3.1). Moreover, the operation stage is analysed (Section 3.3.2), with a special emphasis on electricity generation (Section 3.3.3).

2.4. Installation

As the regional value added of wind power developments depends on wind turbine specific characteristics, an exemplary evaluation is illustrated for a Senvion 3.2M114 turbine with a capacity of 3.2 MW and a hub height of 143 m that started operating in September 2017 in the region. These calculations have been made for every individual turbine in the region. Before calculating the regional economic impacts of wind power developments, a detailed cost analysis is elaborated. The installation costs are usually separated into the costs for the wind turbine and the additional wind turbine investment costs (e.g. planning, infrastructure). Costs for wind turbines depend on the power class and the hub height, whereas the latter is the main cost driver (Table 1). Turbine costs for the 3.2 MW turbine are €3,936,000 (with €1230/kW).

An estimation of the shares of sub components of the investment costs is depicted in Fig. 5.

As specific costs for 2017 were not available, costs of turbine that have been installed between 2009 and 2013 were used (see Table 2). The position 'other costs' include costs like nature compensatory measures which occur when wind turbines have an impact on ecosystems or the landscape (Hau, 2017; Fachagentur Windenergie an Land, 2016, 2018, 2017). As the amount of compensatory measures are project specific (BUND and NABU, 2017), the costs for these measures cannot be properly disaggregated.

The calculation of the regional value added is illustrated in Fig. 6 for 'foundation and infrastructure' for all wind turbines from 3 to 4 MW.

The first step consists of multiplying the costs for foundation and infrastructure (Table 2) by the cumulative capacity of the wind turbines (1). Due to the fact, that these activities are usually taken over by regional enterprises (Fig. 3 and Türck-Hövener, 2016), a share of 100% of regional enterprises is assumed (2). These values are multiplied by the pre-tax profits as a share of the revenues of the construction industry, derived from industry specific statistics (Deutsche Bundesbank, 2018).[11] After subtracting trade taxes, corporate taxes, and the solidarity tax (4), one is able to calculate the net profits of regional construction companies as a first component of the regional value added (5).[12] The compensation of the employees is calculated by multiplying the revenues of the regional construction enterprises by an industry specific value (6). Integrating taxes (Bundesministerium der Finanzen, 2016) and social insurance costs (Bundesministerium der Justiz und für Verbraucherschutz, s. 2018, a,b,c,d,e,f,g, Bundesministerium für Arbeit und Soziales, 2016), the net income of employees can be illustrated (7). In a next step, regional taxes are evaluated, consisting of the regional share of the trade tax (8) and the share of the income tax of employees (9). To conclude, the total value added concerning the foundation and infrastructure of the 3–4 MW wind turbines in the district of Aachen is €1,072,036. The employment effects are calculated by dividing the net income for employees (Destatis, 2016,2017a, b), which yields 36 jobs in the construction industry in 2017 or 36 person years. These calculations have been processed for all activities in the installation stage (Table 5).

2.4.1. Operation and maintenance

For O&M costs, the latest data for Germany (Deutsche Windguard, 2013) is used. Because the costs vary during the first (year 1–10) and the second period (year 11–20) of operation due to different conditions (for instance maintenance costs are typically higher in the second term), average costs for the whole operation period (Table 3) are calculated. Regarding land lease, the paper follows Hirschl et al. (2010), who assumed a share of 80% of private landlords and 20% of the land owned by the municipality.

Funding conditions are based on Deutsche Windguard (2015), verified by an interview with the German Wind Energy Association (BWE). They assume a 2.5% interest rate and an 85% share of external capital. A 10 year credit period is considered, comparable to the conditions provided by KfW, the most important financial institution in the German renewable energy market (KfW, 2015; Papendieck, 2015).

Moreover, electricity marketing costs of €0.002/kWh (Deutsche Windguard, 2015) are included which results in operation costs of €0.02745/kWh. Following the method depicted in Fig. 6, one can estimate the regional value added for operation and maintenance activities generated between 2017 and 2037.

2.5. Electricity generation

Since the introduction of the EEG 2017, compensations for wind power electricity are determined by a tender process. However, in a transitional arrangement, turbines which have obtained planning permission before 2017 and start operating before the end of 2018, still have the right of a compensation by a general feed-in tariff (Bundesnetzagentur, 2017a). As the highest bid that awarded a contract in the second tender process in 2017 (4.29 c/kWh) has been below the

[9] In the calculation, the trade taxes of external operators flowing to the Aachen region, whose shares may vary in distinct cases (BWE, 2018), are not included in the calculation.

[10] For 18 of the 21 wind turbines, the amount of electricity generated was taken from publicly available(Bundesnetzagentur, 2018) reports which, for every plant to be built, provide the expected harvest of the plant by taking into account the specific geographic conditions (FGW, 2017a). For three plants without data, a regional average value has been used.

[11] For financial institutions in the O&M stage, statistics of Deutsche Bundesbank (s.a.a) are used.

[12] Solidarity tax was introduced in the 1990s to finance the German reunification (Ministerium für Inneres und Kommunales des Landes Nordrhein-Westfalen, 2015, 2017).

feed-in tariffs (Table 4), it is assumed that operators may make use of the transition arrangement (Bundesnetzagentur, 2017b).

The feed-in tariff for wind turbines in the transition arrangement consists of a higher feed-in tariff for the first five years of the operation period and a lower feed-in tariff for the last fifteen years of the operation time (Table 4).

The location specific harvest of a wind turbine has to be related to the harvest of that specific turbine type in a reference location, which may lead to an extension of the higher feed-in tariff period (FGW, 2017b). It is estimated that the exemplary 3.2 MW turbine generates 49.8 GWh in the first five years (Bundesnetzagentur, 2018) which is 92.8% of the harvest of the turbine in the reference location (Bundesnetzagentur, 2018).

The following formula is used to calculate the prolongation of the higher feed-in tariff period according the German renewable energy act (EEG). For a 92.8% reference location (x = 92.8), the higher feed-in tariff paid would be provided for 14.9 years in that case (Equation (1)).

$$[(130–x)/0.36 = t\ (\text{months})]/12 + [(100–x)/0.48 = t\ (\text{months})]/12 + 5\ (\text{years}) = t\ (\text{years}) \quad (1)$$

X = reference location.

(Source: Dağaşan et al., 2014, modified).

The average feed-in tariff for twenty years is calculated by using the following Equation (2), according to the EEG.

$$[(t_1/20) \times r_1\ (\text{c/kWh})] + [(t_2/20) \times r_2\ (\text{c/kWh})] = r_a\ (\text{c/kWh}) \quad (2)$$

(Source: BMU, 2013, modified).t_1 higher feed-in tariff period (in years).$t_2$lower feed-in tariff period.$r_1$feed-in tariff during the higher feed-in tariff period.$r_2$feed-in tariff during the lower feed-in tariff period.$r_a$average feed-in tariff.

Inserting the specific feed-in tariff periods (t_1 = 14.9, t_2 = 5.1) and the feed-in tariff (r_1 = 7.47, r_2 = 3.97) for the exemplary turbine, starting to operate in September 2017 in the district of Aachen, leads to an average feed-in tariff of 6.57 c/kWh during the 20 years of turbine operation.

Fig. 7 shows the calculation of regional profits and taxes of electricity generation for a 3.2 MW wind turbine resulting in revenues of €1,005,000 and regional taxes of €285,000.

As turbine operators will have to take part in the tender process from 2018 onwards, it is evaluated whether turbine operators in the Aachen region would be able to compete with a bid of compensation under 4.29 c/kWh which was the maximum bid in the second round in 2017. As the bid refers to a 100% reference location in the EEG 2017, the actual compensation is calculated by taking into account the location of the turbine. Following BWE (2016a, b), this leads to a compensation of 4.51 c/kWh.

Evaluating the profitability of investments for operators, the levelized cost of electricity (LCOE) is calculated following Kost et al. (2013) to evaluate the minimum bid for turbines in the Aachen region (Equation (3)).

$$\text{LCOE} = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{t,el}}{(1+i)^t}} \quad (3)$$

LCOE Levelized cost of electricity in €/kWh.I_0 Investment expenditures in €A_t Annual total costs in € in year t.$M_{t,el}$ Generated electricity in the respective year in kWh.i Interest rate (WACC) in %n Economic operational lifetime in years.t Year of lifetime (1, 2, …n).

Equation (3): Calculation of the LCOE (Source: Kost et al., 2013, modified).

Assuming that the interest rate is based on the Weighted Average Cost of Capital (WACC) to account for the operator's equity and debt. As the equity capital cost, a rate of 9% has been assumed (Kost et al., 2013). The LCOE and therefore the minimum bid for the turbine would be 6.36 c/kWh. To conclude, under these assumptions, wind turbines in the Aachen region cannot compete with bids in the tender process, considering future bids will be at a similar level as in 2017. However, the positive effects of wind power may still exceed other electricity generation sources as discussed in the conclusion (Section 5).

3. Results

Table 5 illustrates the final results for specific industries, including a scenario with a lower share of regional enterprises for the activities planning, insurance and electricity generation. In the assumed baseline scenario, all effects may be added up to €32,863,000 of profits, €10,362,000 of income, and €7,601,000 of taxes resulting in a value added of €50,825,000 and employment effects of 309 person years. Municipalities profit not only from taxes, but also from income from public land lease (€3,350,000), which yields €10,951,000 of municipal profits in total (Table 5). For 2017 only, the value added is €5.9 million.[13]

The total effects during the construction and installation stage are approximately €3,602,000 (€57,000/MW), whereas €734,000 are profits, €2,590,000 incomes and €278,000 municipal taxes. Employment effects are 90 jobs (1.4/MW) in 2017 (or 90 person years). In the operation stage (2017–2037), land lease, insurance, and financing lead to regional economic effects of €13,878,000 (€220,000/MW) and 19 person years (0.3/MW). The effects generated by electricity generation are €33,344,000 (€8.5 per MWh electricity generated) and 200 person years (0.05/GWh).

The effects of electricity generation account for 66% of the total effects. Land lease, making €12,508,000 or 25% of the total effects, are the second highest position although nearly three times smaller than the effects, generated by electricity generation. Other relatively high effects occur for planning and documentation (€2,020,000), funding (€1,245,000), and foundation and infrastructure (€1,312,000).

Most employment effects arise for wind turbine management in the activity electricity generation. Other relatively high effects account for planning (42 person years) and construction companies (44 person years). Even though planning companies' employees' income (€1,413,000) is significantly higher than incomes of the activity construction (€1,056,000), the employment effects are only slightly higher due to a higher average income in the planning industry.

Municipal taxes for wind power developments in 2017 are €645,000 in 2017 and amount to 0.13% of the total share of income and trade tax arising in the district of Aachen in 2016 (IT.NRW, 2018). It should be noted, however, that corporate taxes are not included. Total taxes of these wind turbines from 2017 to 2037 are €7,601,000 and provide for 1.5% of the regional income and trade tax in 2016.

The total effects of wind turbines installed in 2017 (309 person years) make 0.15% of total employees in the district of Aachen by the end of 2016 (Bundesagentur für Arbeit, 2018).

In the '*lower share of regional enterprises'* scenario, a 50% share of regional planning enterprises would lead to a reduced value added of €1,010,000 and a zero share of regional insurance companies to a reduction of €126,000. If only half of the wind power operators were situated in the Aachen district, this would imply a value added of only €16,672,000 for the activity electricity generation, and a 32% reduction of the total value added of wind power. The lower scenario would lead to a total value added of €33,017,000 and employment effects of 185 person years.

[13] The value added of €5.9 million is 0.13% of the nationwide value added in 2012 (Hirschl et al., 2015). The employment effects in 2017 are 101 person years, accounting for 0.27% of total em-ployment in the German wind power industry (Hirschl et al., 2015). The 2012 data includes both onshore- and offshore wind power data as well as the economic effects of wind turbine manufacturing. Noted, however the installed capacity in Germany (2017) increased by 64% since 2012. Therefore the regional economic effects in 2017 may be lower in comparison to the national effects in Germany in 2012.

Due to the German and European merit-order effect[14] of wind power, a volatile energy carrier, substitutes mainly electricity generated by coal and gas (Section 4.2), as there are no large storage capacities. This has no significant impact on the regional energy system heavily relying on lignite, because no large coal or gas power plants are located in the region. However, as it is expected that lignite mine will be closed by 2030, the employment potentials of renewables should be compared to the fossil fuels in the region (Section 5).

3.1. Comparison of the results with existing studies

To analyse regional differences of economic impacts and to identify factors affecting the results of regional economic analyses, the results are compared to other German studies in the field that use a similar methodology (Table 6).[15] Enabling a comparison to international studies, economic effects of wind power developments outside of Germany are as well illustrated.

The German studies cover NUTS levels from local administrative units (LAU), which are municipalities, to NUTS 1 regions, which are federal states. The different sizes of regions affect the results because, for example, Bröcker et al. (2014) studied the impact of wind power on a federal state level where higher shares of taxes occur than on a municipal scale because of the German tax distribution scheme.

All wind turbines have the same lifetime of 20 years and capacities range from 1.6 to 3.2 MW. As most authors focus on a single power class, solely the effects of wind turbines with capacities between 3 and 4 MW as the predominantly installed power class are taken into account in the results for the Aachen district.

To overcome differences between calculations, data is aggregated making the results comparable to the results in the defined lifecycle stages in this paper, which is illustrated in the following.[16]

In the comparison of the value added of the installation stage, similar values are presented by Bröcker et al. (2014), and Hirschl et al. (2010). Differences to this paper are explicable first because of the installation which is taken over by regional enterprises in Bröcker et al. (2014) [17] and Hirschl et al. (2010). Moreover, Bröcker et al. (2014) asses the value added of other costs and costs for nature compensatory measures, whereas the latter is assessed by Hirschl et al. (2010) as well, which was not possible in this paper (Section 3.3.1). Hirschl et al. (2010) integrate the value added of logistics as well which partially explains higher results of Hirschl et al. (2010).

In summary, it can be concluded that the value added of the installation stage mostly depends on the activities and regional share of enterprises which are taken in the calculations into account.

The highest values in the operation stage are presented by Bröcker et al. (2014). This is mainly due to methodological differences, leading to a relatively high value added for the activity funding (more than 3 times higher than in Hirschl et al., 2010).

The results of Bröcker et al. (2014) and Hirschl et al. (2010) include the value added of maintenance activities, which and are fully carried out by regional enterprises.

Costs for land lease are approximately 1.5 times higher in Bröcker et al. (2014) than in Hirschl et al. (2010) because of higher benefits in the North German region Schleswig-Holstein with excellent potentials for wind power, whereas Hirschl et al. (2010) assess the overall situation in Germany.

Since BMVBS (2011) did not distinguish between profits of enterprises and income of employees, illustrating the sum of the two positions without taking other costs and taxes of enterprises into account and define the costs for borrowed capital directly as value added, which makes half of the value added in the operation stage, their values for operation are naturally higher than in Hirschl et al. (2010), where approximately 1/3 of the value added in the operation stage relies on funding. Therefore, BMVBS (2011) may overestimate the economic benefits of the operation stage.

The differences between Hirschl et al. (2010) and this paper's results are mainly due to the activities maintenance and disassembling that are taken over by regional enterprises in Hirschl et al. (2010), whereas in the Aachen region no regional enterprises involved in that activity has been identified. This is also the case for the position funding, where a 45% share of regional banks of has been assumed (Section 3.2). Secondly, a lower interest rate has been determined, whereas Hirschl et al. (2010) calculate the total regional potential by assuming a 100% share of regional banks and used different statistics calculating the value added for banks.

For the activity electricity generation, results range between €435 and €1175 per kW. These differences are partly explicable by geographical differences and wind potentials, ranging from 1936 full load hours (Trier in BMVBS, 2011) to 2780 h (Schleswig-Holstein in Bröcker et al., 2014), and 3072 h in the Aachen region.[18] Further determining factors are the decrease in feed-in tariffs, since the feed-in tariff for operators in the Aachen region is only 80% of the tariff in Schleswig-Holstein (Bröcker et al., 2014) in 2014 and a relatively high income tax rate for operators in this paper that can be regarded as a conservative estimation which may eventually underestimate the potential effects for operators.

In summary, along methodological differences, the availability of regional enterprises, the location which determines the electricity generation potentials, and decreasing feed-in tariffs for wind turbines can be rated as the significant variables influencing the impact assessment results.

In non-German studies, economic effects range from €19 to €95 per kW in the installation stage and from €37 to €172 per kW in the operation stage. Lower values in comparison to studies in Germany result mainly from methodological differences, since the studies use different costs and another definition and calculation of the regional value added as in this paper.[19] For example, annual land lease is calculated with €2263 per MW by Ratliff et al. (2010), whereas annual land lease in Schleswig-Holstein is more than six times higher (€14,400/MW) (Bröcker et al., 2014).

4. Impacts of wind power on GHG emissions and air pollution

4.1. Methodology to assess the impacts of wind power on GHG emissions and air pollution

When assessing the avoided GHG emissions for wind power, the emissions of a wind turbine during its whole lifetime should be

[14] The merit-order effect may be defined as: "The merit order of production ranks the available power plants in ascending order according to their marginal costs of production. The plants with the lowest marginal costs deliver power most of the time and are dispatched first. The higher the demand rises, the more expensive plants are utili[s]ed. Power price corresponds to the marginal costs of the last power plant that is still needed to cover demand" Böckers et al. (2013:2,3).

[15] A similar comparison has been conducted by Jenniches and Worrell (2019) for PV.

[16] For the installation stage, Bröcker et al. (2014) and Hirschl et al. (2010) present the aggregated costs of manufacturing and the assembly of the plant.

[17] This is especially characteristic for North German regions, where lots of enterprises of the German wind power industry are located (BWE, 2016b) (e.g. Enercon and Nordex which account for 51% of the installed capacity in the German wind power market according to BWE, 2015).

[18] The additional full load hours of plants in the Aachen region in comparison to plants in the coastal region Schleswig-Holstein are explicable by more efficient, modern power plants.

[19] Economic effects are not illustrated in value added, but in employee earnings only. In the operation stage, land owner benefits are also taken into account (an exception is Slattery et al., 2011).

included. Among the various approaches, a prominent method is a lifecycle assessment (LCA) which considers the emitted GHG during the whole lifecycle of wind power systems. Such lifecycle assessments “include impacts from extraction, processing and transportation of fuels, building of power plants and generation of electricity” (Gagnon et al., 2002).

LCAs for wind power have been applied by e.g. Crawford (2009), Tremeac and Meunier (2009), or Turconi et al. (2013). In evaluations of GHG emissions, some authors refer to CO_2 only, whereas other authors include other GHG like for example CH_4 or N_2O as well, transforming them into CO_2 equivalents (eq) (Wagner et al., 2007). In terms of comparability and transparency, it is opted for the latter assessment to consider other GHGs as well. According to the available literature reviews (Turconi et al., 2013; Weisser, 2007; Raadal et al., 2011), GHG emission values range from 3 to 55.4 gCO_2-eq/kWh. These values should be compared with the emitted GHG emissions of substituted energy technologies, in order to evaluate the avoided emissions due to wind power developments.

As the use of renewable energies is supposed to reduce air pollution significantly in comparison to conventional energy generation technologies such as coal (Jacobson, 2009), renewable energy developments have also a positive effect on human health. According to WHO (2014), approximately 13% of deaths worldwide were caused by air pollution in 2012, making it “the world's largest single environmental health risk” (WHO, 2014). For ambient air pollution, the number of deaths in 2016 is estimated in 4.2 million (WHO, 2018). According to Eurostat (2016), 13% of the most important acidifying gases and 8% of ozone precursors were emitted by electricity, gas, steam, and air conditioning supply in the EU-28 in 2014.

To enable methodological consistency, emission data which is used for GHG emissions is used for air pollution as well (Memmler et al., 2017). Specifically for air pollution, emission data of 2016 is used and an equal distribution of effects in the wind turbine lifetime is assumed to enable a calculation of net avoidance effects. In this regard, it is important to note that data should ideally be country specific and up-to date, taking into account the specific technology as well as the country specific energy system and substitution potentials.

4.2. Avoided GHG emissions

For the Aachen region it is referred to a study of the German Environment Agency (UBA) that evaluated the incurred and avoided emissions by generating electricity via renewable energy sources, on the basis of the principles of an LCA (Memmler et al., 2017). By wind power, electricity generated by black coal (61%) and gas power plants (39%) are substituted (Klobasa and Sensfuβ, 2016 in Memmler et al., 2017). Differently, electricity generation by lignite that is exploited in the region does not play role, due to the merit order of electricity generation technologies (Memmler et al., 2017). Since values for 2017 were not available, data for 2016 were used, under the assumption that all wind turbines were installed before the beginning of 2017 (Equation (4)).

$$\text{N (gCO2-eq/kWh) x } M_{el} \text{ (kWh) x V (€/kWh) = B (€)} \tag{4}$$

N net avoided emissions.M_{el} generated electricity.V monetised value of emissions.B monetised benefits of avoided emissions.

The emitted greenhouse gases for onshore wind turbines are 11 gCO_2-eq/kWh in 2016 (Memmler et al., 2017), which lays in the range of the values, provided by the reviews of Turconi et al. (2013), Weisser (2007), and Radaal et al. (2011). When multiplied by the estimated electricity generated in 2017 (195,073,000 kWh; Section 3.3.3), they result in 2086 tCO_2-eq. The gross avoided emissions are 691 gCO_2 -eq/kWh (Memmler et al., 2017) which corresponds to 134,856 tCO_2-eq. This leads to net avoided emissions of 132,770 tCO_2-eq (681 gCO2 -eq/kWh) for the Aachen region, which correspond to 0.29% of the avoided GHG emissions due to wind power in Germany in 2016 (Memmler et al., 2017).

Note that, in reality, that there is no equal distribution of effects over the wind turbine's lifetime since higher effects occur during manufacturing and construction (Weisser, 2007). However, in order to take into account all positive and negative effects, an equal distribution of effects over time was assumed.

As avoided emissions may be a quite abstract indicator for decision makers in the region, the economic benefits for avoided CO_2-eq emissions are calculated, following Jenniches and Worrell (2019), by assessing the social cost of carbon (SCC), which may be defined as the net present value of damage costs of mitigating an additional unit of carbon in a specific point in time (Tol, 2015). These damage costs are the product of the positive and negative impacts of climate change effects such as sea level rise, energy, agriculture, water supply, and health, etc. (Watkiss et al., 2006).

SCC varies among model assumptions in different studies. As reported by Isacs et al. (2016), SCC ranges from €6.3[20] to €734.4[21] per ton CO_2 in 2017.

In order not to underestimate climate change effects, a lower bound of €98.8 per ton CO_2 in 2017, as proposed by van den Bergh and Botzen (2014) and representing a conservative estimate, is used as a SCC value.[22] This leads to SCC of €13,117,715 (€0.07/kWh electricity generated) in 2017 that can be interpreted as the economic benefits of CO_2-eq mitigation due to wind power developments in 2017.

4.3. Avoided air pollution and its economic impact

Multiplying the electricity generated by each wind turbine in 2017 times the net emission reduction in tons per kWh of electricity generated by wind power in 2016 (Equation (4)) yields a reduction of 89.73t of nitrogen oxides (NO_x), 50.72t of sulphur dioxides (SO_2), 3.9t of non-methane volatile organic compounds (NMVOCs), 3.9t of dust, and (7.8t) of carbon monoxide (CO). Using the same source as for GHG emissions, it is possible to estimate that 0.29% of the national avoided air pollution related to wind power are due to wind power in the Aachen region (Memmler et al., 2017).

Due to geographic conditions such as population densities or the location of ecosystems as well as different atmospheric conditions that depend on the emitters’ location (EEA, 2014), damage costs vary spatially. Data of EEA (2014) is used, evaluating the damage costs due to air pollution by European industrial facilities from 2008 to 2012 on a country level.

The damage costs of air pollution on human health is measured by a value of a life year (VOLY) and a value of statistical life (VSL). The VOLY illustrates life expectancy decreases by considering the age of casualties whereas younger casualties are weighted higher than elder ones (EEA, 2014) and the VSL represents “individuals’ willingness to pay to secure a marginal reduction in the risk of premature death” (WHO, 2015:VIII). In the analysis, a VOLY of €68,000 and a VSL of €2,593,000 (both values in 2017 €[23]) are used, representing values for the European Union, based on evaluations of the NewExt research project (Hurley et al., 2005) and are values which are typically applied

[20] Isacs et al. (2016) illustrate a value of €6.1 per tCO_2 in 2015 which is based on Tol (2013) and Bateman et al. (2014). The value has been converted into 2017 € by including a damage growth rate of 2.3% p.a (Tol, 2013). and the inflation rate of Germany based on OECD (2018).

[21] Isacs et al. (2016) present costs of €724 per tCO_2 in 2015, based on Ackerman and Stanton (2012). The value has been converted into 2017 € by including a growth rate of damage costs per year (1.7%) and the inflation rate for Germany based on OECD (2018).

[22] The original value of $125 per tCO_2 of van den Bergh and Botzen (2014) has been converted into 2017 € by using an average exchange rate (Deutsche Bundesbank, 2018).

[23] Original vales are €57,000 (VOLY) and €2,200,000 (VSL). These values have been converted to 2017 € values using an inflation rate for Germany based on OECD (2018).

in projects on a European scale (Hein et al., 2016). In a comparison of values, Hein et al. (2016) find VOLY estimates ranging from €6200 to €150,000 and VSL estimates ranging from €0.5 to more than €6,000,000. Both values used can therefore be interpreted as slightly below the average value of existing studies in the field. However, the estimations are subject to uncertainty which should be taken into account when interpreting the results. Based on specific exposures to emissions, EEA (2014) provides country specific data for emitted pollutants (Table 7) where average values for Germany have been used.

The total economic value of avoided air pollution in 2017 ranges from €1,864,000 (€0.01/kWh electricity generated) (VOLY) to €5,480,000 (€0.03/kWh electricity generated) (VSL) because of wind power developments in the Aachen region in 2017 (Table 7).

Since the power grid is integrated it is difficult to evaluate the spatial distribution of air pollution reductions. Therefore, emission reductions take place inside as well as outside the region.

4.4. Comparison of the results with existing studies

Factors influencing the results of external costs of avoided emissions include different methods used, different emission amount values, and different external costs, which makes a comparison of results among studies quite challenging (Sundqvist, 2004; Novan, 2015). Krewitt (2002), therefore, states that a "validation of external cost estimates is not possible" (Krewitt, 2002:840) but sees merit in comparing the results as it illustrates differences in the assessments. While existing studies in the field are not specific to German regions, most authors compare electricity generation by wind to coal and gas, which are the same energy carriers substituted as in this paper.

In the studies where wind power replaces coal or gas (e.g. Munksgaard and Larsen, 1998; Sundqvist, 2004), avoided costs for wind substituting coal range from 3.7 to 8.5 c/kWh and are mostly higher than the avoided external costs for the substitution of gas (1.3–9.9 c/kWh) in the respective studies (e.g. McCubbin and Sovacool, 2013; Munksgaard and Larsen, 1998). This is due to a higher amount of emissions by electricity generation from coal than from gas (Table 8).

The most important cost parameter in most studies, disaggregating GHG and other emissions, are CO_2 emissions, which corresponds to the findings of our study.

The range of avoided costs (1.3–9.9 c/kWh) in McCubbin and Sovacool (2013) derives from the estimation of a low and a high impact scenario with different amounts of emissions. In their study, the site specifity of assessments becomes apparent as there are different amount of emissions due to the efficiency of substituted power plants in the region, where the specific wind turbines are installed.

Only a few studies take into account the actual energy mix substituted by wind power as stated by Novan (2015), who identified Cullen (2013) as the first paper studying "econometric estimates of the actual substitution pattern between wind generation and conventional generators" (Novan, 2015:296).

The outcome of our study for wind power substituting coal and gas ranges between 7.7 and 9.5 c/kWh. This result is a bit lower than in McCubbin and Sovacool (2013), mainly due to a lower CO_2 price (8 times lower than in our study in Cullen, 2013; 4 times lower than in this paper in Novan, 2015). To conclude, there is a high level of uncertainty and variety regarding emissions and estimated external costs, which should be made transparent and regarded in the interpretation of the results.

5. Conclusion and policy implications

The total regional value added effects of 63.1 MW wind power developments in 2017 in the district of Aachen are €50.8 million (€805/kW) consisting of profits of €32.9 million, net incomes of €10.4 million, taxes of €7.6 million, and employment effects of 309 person years (4.9 jobs per MW installed) (Table 5). Assuming a lower share of regional enterprises would lead to a value added of €33 million (€523/kW) and employment effects of 185 person years (2.9 jobs per MW installed), whereas the total regional value added highly depends on the electricity generation activity and implicitly on operators situated in the region. In fact, assuming only half of the operators being situated in the region would lead to a loss of total value added of 32%. Consequently, regions should actively promote electricity generation by regional operators.

In 2017 alone, value added is €5.9 million (€95/kW; €31/MWh electricity generated). Employment effects are 101 person years. In the scenario with a lower share of regional enterprises, the value added is €4.1 million (€65/kW; €21/MWh generated) and the employment effects are 75 person years (Table 9).

Further benefits of €13.1 million arise by 132,770t of avoided CO_2–eq emissions. The positive impacts of non-emitted air pollutants on human health range from €1.9 million to €5.5 million. Total benefits in 2017 range from €20.9- to €24.6 million (€332-€389/kW or €107–126/MWh electricity generated) in the baseline scenario and from €19.1 to €22.7 million in the lower scenario. Further benefits would occur if the amount of $PM_{2.5}$ and PM_{10} emitted would be integrated in the analysis, which has not been done by Memmler et al. (2017) and there is further research needed.

The supply chain approach is a valuable instrument for analysing economic impacts of RES, especially on a small regional scale, since there is no need for an economic model that is often not available on a local or small regional level. Moreover, the analysis is very illustrative and it allows assessing the parameters determining the impacts very precisely, which is a benefit for stakeholders in the wind power market.

An important question for stakeholders in the region are the benefits of wind power, compared to the second most important renewable energy generation technology PV (render, 2016) and the conventional energy generation technology lignite which are all generated in the region. By comparing the levelized cost of electricity (LCOE) which takes into account all costs for electricity generation of a technology, one sees that it would most economical to generate electricity by lignite (Table 10).

However, by integrating the external costs of GHG emissions and air pollution, wind power is the most economical electricity generation source, followed by PV, whereas the external costs of lignite make it the least economical option. The presented example is based on conservative assumptions as the lowest LCOE for lignite, which may -with an upper value of 7.98 c/kWh (Kost et al., 2018)- be well above the LCOE of wind power and PV, is chosen. Furthermore, the emissions of lignite electricity generation are assumed to be quite low,[24]which illustrates the superiority of renewable energy sources compared to lignite. Differently from other studies (e.g. Sims et al., 2003; Munksgaard and Larsen, 1998), the external costs of wind power generation are not considered zero, as emissions over the whole technology lifecycle (including plant manufacturing) are taken into account and not only energy generation, which makes the comparison more comprehensive.

Comparing the employment effects, the effects of wind power enable approximately half of the effects of lignite. However, due to methodological specifics, the estimation of the regional employment effects of lignite is quite high and regions nearby are also considered, though the lignite mine (Section 2) is only partly situated in the Aachen district.

Most of the employment effects (nearly 4 times more than lignite)

[24] The costs of lignite range between 4.49 and 7.98 c/kWh depending on the full load hours and the carbon prices of the EU Emissions Trading System of lignite. To avoid double counting, the carbon costs are have been excluded by using an average carbon price value for 2017 (€5.58/t CO_2; European Energy Exchange AG, 2017). The GHG emissions of lignite, used by Memmler et al. (2017) are relatively low in comparison to other sources. Using the average value of the literature analysis by Wagner et al. (2007) would lead to emissions of 1083 g/kWh electricity generated, which would lead to GHG emission costs of 11 c/kWh.

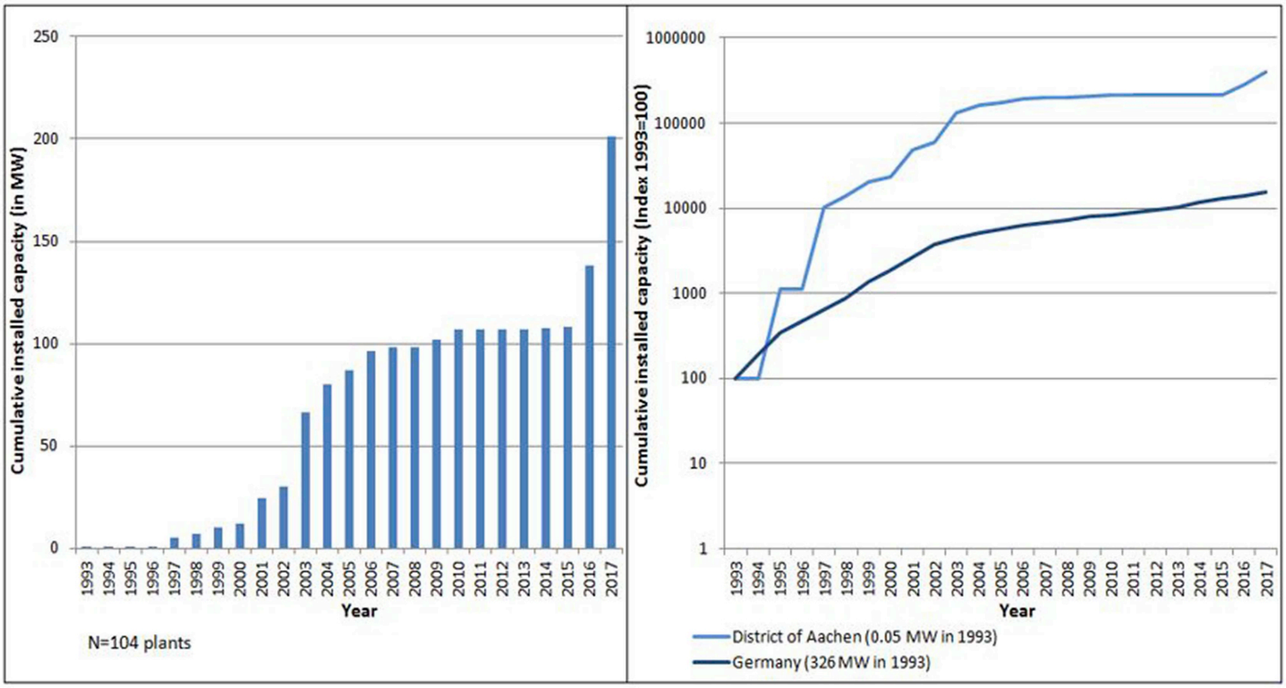

Fig. 2. Cumulative installed capacity of wind power in the district of Aachen from 1993 to 2017 (left) (Source: render, 2018; Bundesnetzagentur, 2018) and wind power developments in comparison to Germany from 1993-2017[25] (right) (Source: data compilation by BMWi, 2016; Deutsche Windguard, in BWE, 2017).

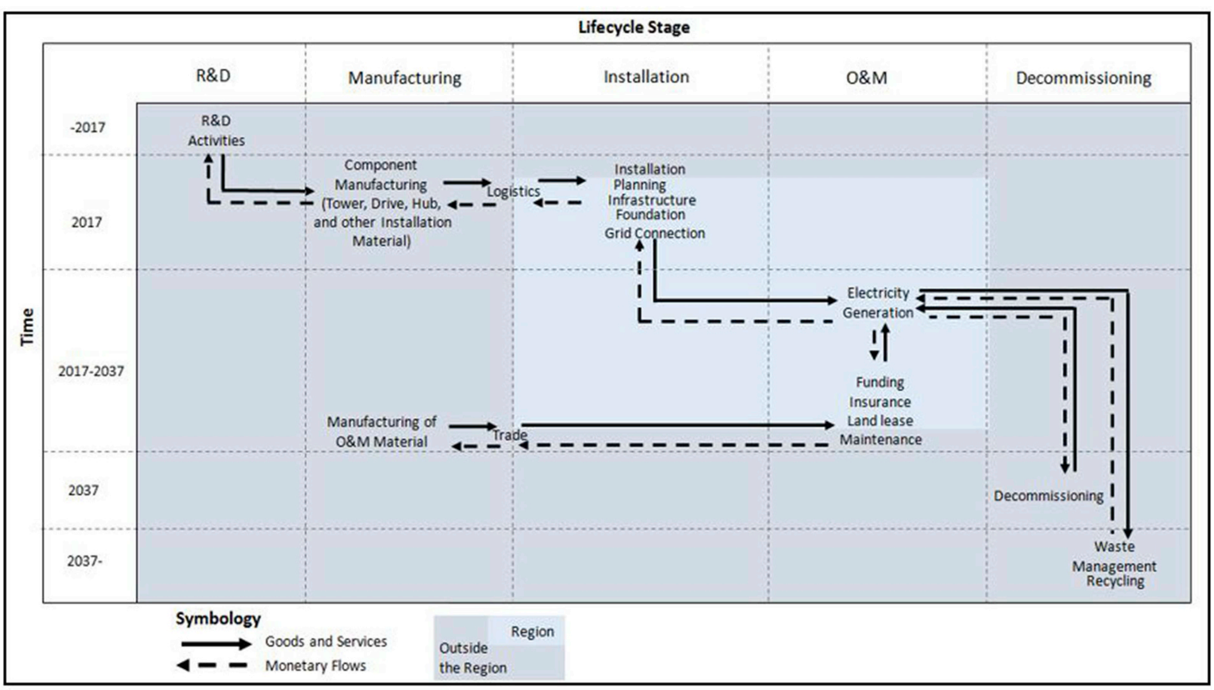

Fig. 3. Lifecycle stages, time periods, activities and their spatial distribution regarding wind power developments in the district of Aachen.

account for PV which is due to more regional PV enterprises in the region, whereas specialised enterprises for wind power are located in other regions.

Investing €1 million in wind, PV, or lignite allows a generation of 15.7 GWh of wind power, 14.9 GWh of PV and 21.8 GWh of wind power. However by taking into account the external costs, the same investment would lead to 15.4 GWh of wind power, 13.2 GWh of

[25] Due to issues of illustratability, a logarithmic scale has been used, which has to be taken into account when comparing the different developments in Germany and the district of Aachen. The plant installed in 1993 was a small plant of only 0.05 MW. Therefore, the changes from 1993 to 2017 occur much

(footnote continued)
higher than in the case of Germany in the illustrated Figure where an index has been used.

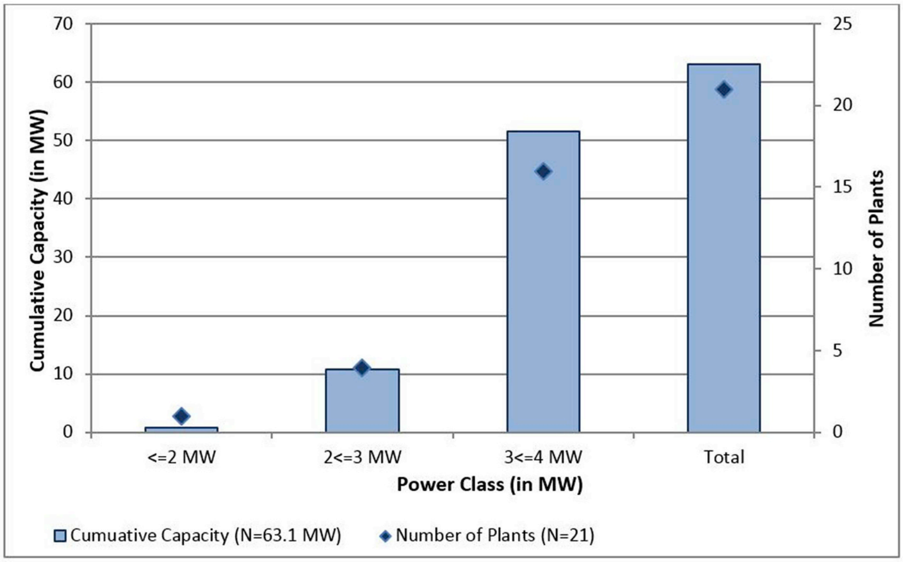

Fig. 4. Number of wind turbine and total installed capacity of turbines installed in 2017 in the district of Aachen (Source: own calculations based on Bundesnetzagentur, 2018).

Table 1
Costs and number of wind turbines (in brackets) in the Aachen district depending on hub heights and power classes.[a]
(Source: Deutsche Windguard, 2013; Deutsche Windguard, 2015; modified; nominal values)

Hub Height (HH)	Power Classes and Number of Wind Turbines		
	0 MW < P ≤ 2 MW	2 MW < P ≤ 3 MW	3 MW < P ≤ 4 MW
HH ≤ 100 m	€1090/kW (1)	€980/kW (1)	€990/kW (0)
100m < HH ≤ 120m	€1200/kW (0)	€1160/kW (0)	€1120/kW (0)
120 m < HH ≤ 140 m	–	€1280/kW (2)	€1180/kW (9)
140 m < HH	–	€1380/kW (1)	€1230/kW (7)

[a] For plants above 2 MW, data refers to plants installed in 2016 and 2017 following Deutsche Windguard (2015). For plants below 2 MW, data refers to plants installed 2009–2013 following Deutsche Windguard (2013).

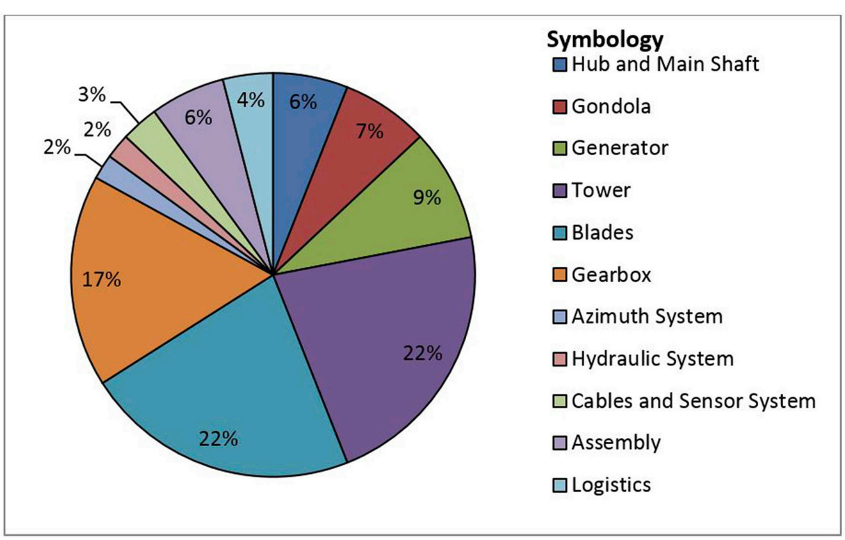

Fig. 5. Components of investment costs (Source: Hirschl et al., 2010, modified).

Table 2
Components of additional wind turbine investment costs.
(Source: Deutsche Windguard, 2013; modified; nominal values)

Component	in €/kW	in %
Foundation	67	18
Grid Connection	73	20
Infrastructure	41	11
Planning	95	25
Other Costs	97	26
Total	**373**	**100**

electricity by PV, and 10.7 GWh of lignite. The regional employment effects of the investment are 1 person year for wind, 9 for PV, and 4 person years for lignite.

In summary, from an environmental and economic perspective, the development of PV and wind power is preferable than investing in lignite electricity generation, where the generation costs of wind power are the lowest. From a socioeconomic perspective, PV is the preferable electricity generation technology. Regional decision makers should therefore always opt for developing PV over lignite. The decision between developing wind or lignite is based on a trade-off between environmental economic and socioeconomic concerns, whereas, from a global view, the long term negative effects of climate change may be more important than individual regional employment. Differently, a balanced deployment of PV and wind should consider technical issues,

Table 3
Nominal O&M costs, depending on time periods and components for wind turbines installed between 2009 and 2013.
(Source: Deutsche Windguard, 2013; modified)

Component	Year 1–10 €/MWh	Year 11–20 €/MWh	Year 1–20 €/MWh	Year 1–20 €/kWh
Maintenance	10.5	14.7	12.6	0.0126
Land Lease	5.3	5.1	5.2	0.0052
Operation and Management Costs	4.1	3.6	3.85	0.00385
Insurance	1.2	0.7	0.95	0.00095
Reserve Assets	1	1.4	1.2	0.0012
Other Costs	2	1.3	1.65	0.00165
Total	24.1	26.8	25.45	0.02545

Table 4
Feed-in tariff of wind turbines in the district of Aachen, starting to operate in September 2017.
(Source: Netztransparenz, 2018; nominal values)

Component of feed-in tariff	In c/kWh
Higher feed-in tariff (first 5 years)	7.47
Lower feed-in tariff (last 15 years)	3.97

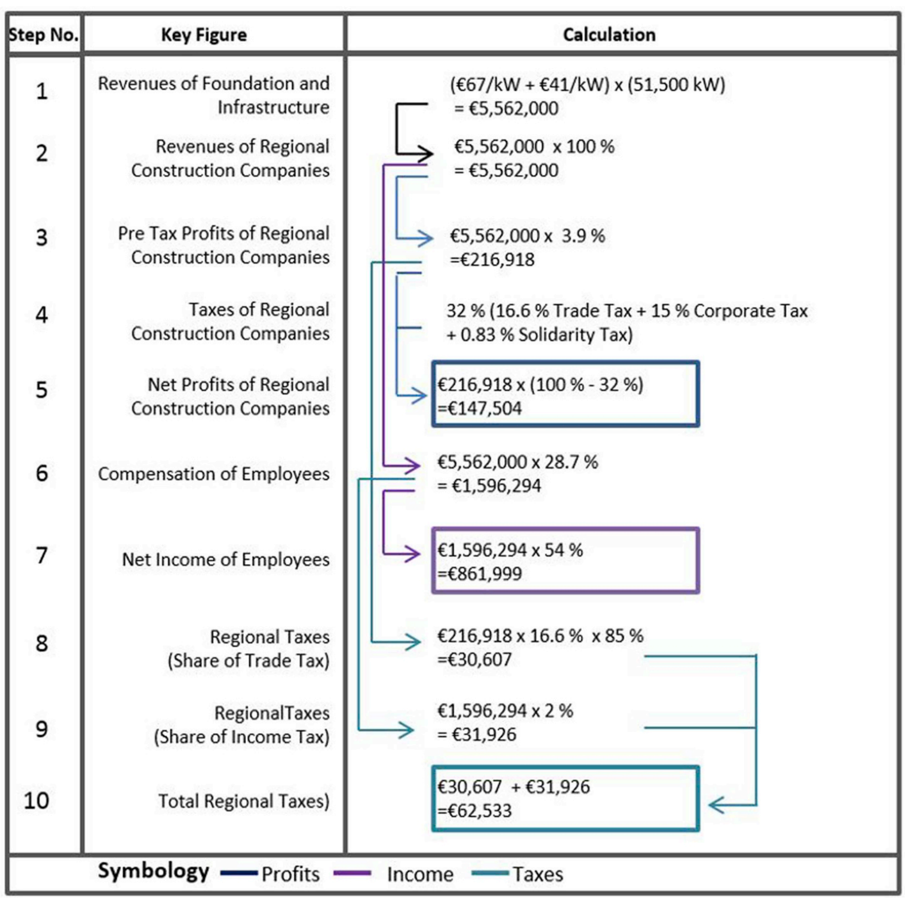

Fig. 6. Calculation of regional value added of foundation and infrastructure of wind turbines from 3 to 4 MW, installed in the Aachen district in 2017 (nominal values)[26].

[26] The results vary slightly from the results in Table 5 due to rounding effects.

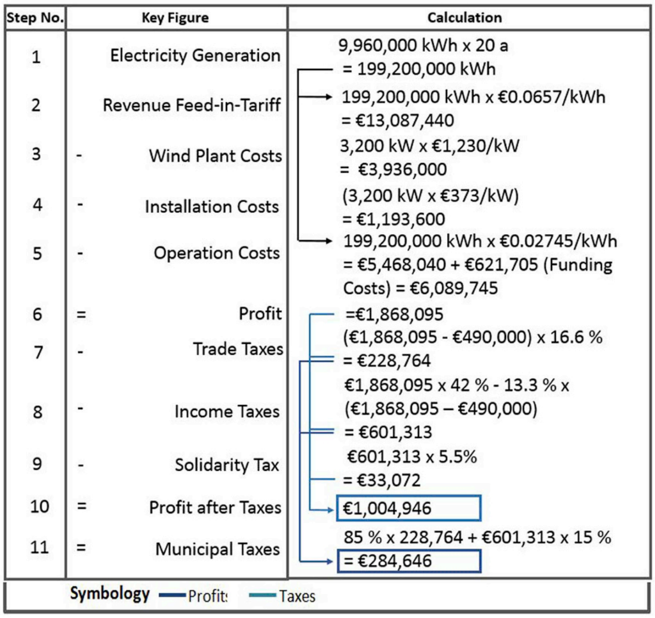

Fig. 7. Schematic illustration of the value added effects of electricity generation (excl. Income) of the exemplary 3.2 MW turbine installed in 2017 in the district of Aachen (nominal values).

in addition to environmental and (socio)economic aspects. From a regional employment perspective, the deployment of PV is more beneficial than wind power, although energy generation costs are slightly higher. In any case, to achieve a total electricity supply by renewable energies, wind power remains necessary: even by exploiting the whole PV potential in the region, the regional electricity demand could not be satisfied by PV alone (render, 2018).

In this regard, incentives are needed to foster the transformation to a low carbon energy system in fossil fuel regions and to steer regions towards a low carbon energy policy, as local governments might prefer to support local jobs rather than reducing emissions, which is a classic "tragedy of the commons" (Hardin, 1968:1245) challenge. This can be solved by fully taking into account the negative impacts of fossil energy generation. Internalising the external damage costs could be done by making emitters accountable or by re-warding operators or regions for their efforts to avoid GHG and air pollution.

However, regions relying on fossil fuels have to compensate structural employment market changes by providing alternative opportunities for employees in the fossil fuel industries. In this case, job training is necessary. Ultimately, the number of jobs depends on the ability of regions to attract RES industries as well as on the renewable energy generation potentials, which both support a sustainable economy in the long term.

Table 5
Detailed overview of regional economic effects of wind power developments installed in 2017 (in € nominal and person-years), including a lower share of regional enterprises scenario *(in italics)*.

Stage	Industries	Activities	Power Classes	Profits	Income	Taxes	Person-Years
Installation	Planning Companies	Planning	< = 2 MW (n = 1)	5546	17,914	2155	0.5
			2 MW < P ≤ 3 MW (n = 4)	74,873	241,838	29,095	7.3
			3 MW < P ≤ 4 MW (n = 16)	357,033	1,153,211	138,740	34.6
		Total		437,452	1,412,964	169,990	42.4
		Planning (50%)	*< = 2 MW < P ≤ 4 MW (n = 21)*	*218,726*	*706,482*	*84,995*	*21.2*
	Construction Companies	Foundation and Infrastructure	< = 2 MW (n = 1)	2277	13,390	971	0.6
			2 MW < P ≤ 3 MW (n = 4)	30,737	180,769	13,112	7.5
			3 MW < P ≤ 4 MW (n = 16)	146,571	861,999	62,527	36.0
		Total		179,586	1,056,158	76,610	44.1
	Grid Service Companies	Grid Connection	< = 2 MW (n = 1)	1485	1531	404	0.0
			2 MW < P ≤ 3 MW (n = 4)	20,041	20,665	5459	0.6
			3 MW < P ≤ 4 MW (n = 16)	95,566	98,544	26,032	2.8
		Total		117,091	120,740	31,896	3.4
O&M	Financial Institutions	Funding	< = 2 MW (n = 1)	5564	7400	1644	0.2
			2 MW < P ≤ 3 MW (n = 4)	83,016	110,402	24,532	2.9
			3 MW < P ≤ 4 MW (n = 16)	385,545	512,731	113,932	13.7
		Total		474,125	630,533	140,108	16.8
	Insurance Companies	Insurance	< = 2 MW (n = 1)	347	854	111	0.0
			2 MW < P ≤ 3 MW (n = 4)	6393	15,717	2045	0.4
			3 MW < P ≤ 4 MW (n = 16)	26,627	65,460	8516	1.7
		Total		33,367	82,031	10,672	2.2
		Insurance (0%)	*< = 2 MW < P ≤ 4 MW (n = 21)*	*0*	*0*	*0*	*0*
	Landlords	Land Lease	< =2 MW (private)	86,024	0	9344	0
			< =2 MW (n = 1) (public)	34,889	0	0	0
			2 MW < P ≤ 3 MW (private)	1,582,644	0	171,908	0
			2 MW < P ≤ 3 MW (public)	641,874	0	0	0
			3 MW < P ≤ 4 MW (private)	6,591,616	0	715,986	0
			3 MW < P ≤ 4 MW (public)	2,673,363	0	0	0
		Total		11,610,410	0	897,238	0
	Turbine Operators	Electricity Generation	< = 2 MW (n = 1)	154,443	73,521	22,008	2.1
			2 MW < P ≤ 3 MW (n = 4)	2,301,955	1,352,613	838,940	38.3
			3 MW < P ≤ 4 MW (n = 16)	17,554,087	5,633,548	5,413,246	159.4
		Total		20,010,486	7,059,682	6,274,194	199.7
		Electricity Generation (50%)	< =2 MW < P ≤ 4 MW (n = 21)	10,005,243	3,529,841	3,137,097	99.9
	Total			**32,862,517**	**10,362,107**	**7,600,708**	**308.7**
	Total (lower share of regional enterprises)			*22,605,181*	*6,043,753*	*4,367,944*	*185.4*

Table 6
Comparison of regional economic effects of wind power developments (nominal values)[a].

Country	Region	Spatial Level	Installation €/kW	Operation		Source
				Operation €/kW	Electricity Generation €/kW	
Germany	Trier	NUTS 2	–	684	435	BMVBS (2011)
Germany	Nordschwarzwald	Four aggregated NUTS 3 regions	–	684	435	BMVBS (2011)
Germany	Städteregion Aachen	NUTS 3	57	215	555	This Paper
Germany	Municipalities in Germany in general	LAU 2	121	388	700	Hirschl et al. (2010)
Germany	Hannover	NUTS 3	–	692	669	BMVBS (2011)
Germany	Friesland	NUTS 3	–	698	873	BMVBS (2011)
Germany	Schleswig-Holstein	NUTS 1	77	872	1175	Bröcker et al. (2014)
US	Texas	State	30	37	–	Slattery et al. (2011)
US	Washington	State	33	117	–	Heavner et al. (2003)
US	Utah	State	95	88	–	Ratliff et al. (2010)
US	Colorado	State	19	172	–	Madsen et al. (2002)
US	Livingston County	County	55	146	–	Loomis, (2018)

[a] Values have been converted into € by relying on Deutsche Bundesbank (2017).

Table 7
Avoided air pollution and economic valuation of wind power developments in 2017 (Source: own calculations based on Memmler et al. (2017) (emissions) and EEA (2014) (economic assessment[a]).

Substance	Net avoided air pollution (t)	VOLY (€/t)	VSL (€/t)	Economic value of avoided air pollution (€) (VOLY)	Economic value of avoided air pollution (€) (VSL)
SO_2	50.72	22,357	67,846	1,133,937	3,441,052
NO_x	89.73	8040	22,479	721,473	2,017,097
NMVOCs[b]	3.90	2230	5628	8701	21,958
Total				**1,864,111**	**5,480,108**

[a] The values of EEA (2014) were originally in 2005 €, which have been converted using an inflation rate for Germany based on OECD (2018).
[b] EEA (2014) include secondary organic aerosols (SOA) into NMVOCs as well, whereas it is not clear whether they are included in the calculations of Memmler et al. (2017).

Table 8
Avoided external costs of wind power generation in different studies in c/kWh.[a].

Authors	Wind replacing coal (c/kWh)	Wind replacing gas (c/kWh)	Wind replacing coal and gas (c/kWh)	Region
Munksgaard and Larsen (1998)	3.7–5.1	1.8–2.7	–	Denmark
Roth and Ambs (2004)	7.9	5.5	–	US
Sundqvist (2004)	8.5	3.7	–	Global Sample
McCubbin and Sovacool (2013)	–	1.5–9.9	–	Altamont (CA)/US
		1.3–6.9	–	Sawtooth (ID)/(US)
Cullen (2013)	–	–	0.8	Texas
Novan (2015)	–	–	2.2	Texas
This Paper	–	–	7.7–9.5	District of Aachen

[a] Values have been converted into 2017 € based on Deutsche Bundesbank (2018) and using an inflation rate for Germany based on OECD (2018). Net benefits have been calculated, following Timilsina et al. (2013). If several values were presented, a medium scenario has been chosen. In the evaluation of Novan (2015), nuclear energy and other not specified energy carriers are also taken into account. However, their impact has been considered negligible.

Table 9
Economic effects of wind turbines installed in 2017 in the Aachen region in € and in €/kW in 2017, including a lower share of regional enterprises scenario (in brackets).

Indicator	Category	Total (in €)	€/kW	€/MWh
Value added	Profits	(1,619,892) 2,340,549	(26) 37	(8) 12
	Income	(2,091,398) 2,978,473	(33) 47	(11) 15
	Taxes	(402,223) 644,606	(6) 10	(2) 3
Total value added		*5,963,629*	*95*	*31*
Avoided GHG	CO_2 -eq.	13,117,715	208	67
Avoided Air pollution	SO_2	1,133,937–3,441,052	18–55	6–18
	NO_X	721,473–2,017,097	11–32	4–10
	NMVOCs	8701–21,958	0.1–0.4	0.04–0.11
Total avoided air pollution		*1,864,111–5,480,108*	*30–87*	*10–28*
Total (lower scenario)		19,095,339–22,711,336	303–360	98–116
Total		**20,945,455–24,561,451**	**332–389**	**107–126**

Table 10
Costs and employment effects of electricity generation of wind power, PV, and lignite in the Aachen region.
(Sources: LOCE of wind: own calculation (Section 3.4); LCOE lignite and PV (average value for Germany for large rooftop plants): Kost et al. (2018, modified); GHG emissions and air pollution: Memmler et al. (2017), GHG prices: van den Bergh and Botzen (2017, modified) (see Section 4.1); cost of air pollution: EEA (2014, modified) (see Section 4.2); regional employment: wind power: own calculation (Section 3.4), lignite: own calculation based on employment and electricity generation of lignite (Section 2), PV: Jenniches and Worrell (2019).

LCOE (c/kWh)		Wind	PV (large rooftop)	Lignite
		6.36	6.71	4.59
LCOE excl. EU ETS carbon price (c/kWh)				4.36
GHG emissions (g/kWh)	*CO_2 - eq.*	*10.69*	*67.81*	*413.15*
Cost of emitted GHG (c/kWh)	CO_2 - eq.	0.11	0.67	4.08
Air pollution (g/kWh)	*SO_2*	*0.01*	*0.07*	*0.23*
	NO_x	*0.02*	*0.09*	*0.26*
Cost of emitted air pollution (VOLY) (c/kWh)[a]	SO_2	0.03	0.15	0.51
	NO_x	0.02	0.07	0.42
Costs of electricity generation (c/kWh)		**6.51**	**7.59**	**9.37**
Regional employment (person years/GWh)		**0.08**	**0.63**	**0.17****

[a] We have chosen the VOLY here to provide a single value, following Hein et al. (2016) who consider –among others-the VOLY as a superior indicator for measuring air quality as VSL.**The calculation of the employment effects of lignite is based on another methodology as for wind power and PV, which makes a comparison difficult.

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Appendix A. Supplementary data

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