

Regional economic and environmental impacts of renewable energy developments: Solar PV in the Aachen Region

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ABSTRACT

The energy transition is a challenge that affects regions on various scales. This paper presents the economic chances of deploying the renewable energy technology solar photovoltaic in a German region. Total regional economic effects of 280 PV plants, installed in 2014 with a cumulative capacity of 3.7 MW, lead to a regional value added of approximately €3.8 million (€1019/kW installed, €57/MWh electricity generated) and employment effects of 42 full-time person years (11 person years/MW installed), occurring from 2014 to 2034. The avoided greenhouse gas emissions of these plants are 2365 tons CO₂ equivalents per year (0.7 kgCO₂-eq/kWh generated) and the avoided air pollution is 0.97 tSO₂ per year, 1.48 tNO_x per year, and 0.07 t NMVOCs per year in 2014. The total economic effects of regional value added, avoided CO₂ emissions, and avoided air pollution per year in 2014 range from €0.8 million - €1 million or (€208–€277 per kW installed, €231–€307 per MWh electricity generated).

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Introduction

One of the main characteristics of the 'German Energiewende' is the transformation of the energy system from large centralised energy generation systems, based on e.g. fossil or nuclear energy, to a more distributed, decentralised energy system, based on renewable energy sources (RES) like e.g. wind or photovoltaic (PV) generated locally (Beckmann et al., 2013; Gailing & Röhring, 2015). On a spatial scale, this leads to changes in the spatial arrangement of energy systems and regions, which were previously not actively involved in energy generation may benefit economically from renewable energies. The brut electricity generation in the German Land Thuringia for example increased from 2.2 gigawatt-hours (GWh) with a share of renewable energies of 4% in 1991 to 8.4 GWh in 2014 with a share of renewables of 55% (LAK, s. a.). On the other hand there is still a strong, socioeconomic significance of fossil energy systems in some regions, and a skeptical view on renewable energy (RE) developments as illustrated by Keppler (2008) for the Lausitz lignite mining area. To overcome the intense sociocultural significance of economic activities related to fossil fuels in a region, which may lead to lock-in effects and hinder the application of new technologies (Grabher, 1993; Unruh, 2000) in regions, positive aspects

of RE developments like ecologic and economic effects should be demonstrated to increase acceptance of RE (BMVBS, 2013).

This acceptance is needed because decision making processes on the development of renewable energy projects are not always national but rather regional issues, as shown by Jacobsson and Bergek (2004) for Dutch wind power developments. Decision power depends upon the legislative responsibilities of different governmental levels in a country. In Germany, decision making power lays to a large extent on the regional or local level (ARL, n.d.), which is also the case in other countries (e.g. Austria (Stix, 2014) or the US (Kayden, 2000)).

In the analysis, the focus lies on PV-systems, which is a technology where the dynamics in the global renewable energy market are particularly visible. In recent years, a spatial reorganisation of the PV industry, leading to job losses in the German PV manufacturing industry takes place (Wirth, 2017). Furthermore, decreasing feed-in tariffs for generated PV electricity lead to the impression that PV systems were not profitable for operators (Taunus Zeitung, 2012; Bröcker, Burmeister, Preisler-Jebe, & Albery, 2014).

Conclusively, there is a need to show the benefits of PV developments for a region, even after market changes in terms of losses in the manufacturing industry and decreasing feed-in tariffs.

The benefits of PV developments are evaluated in the district of Aachen (Section Characteristics of the region and PV developments in the region), as an exemplary region which is supposed to suffer in the future, due to expectable economic losses in conventional energy

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generation industries, illustrating that investing in renewable energies is a beneficial strategy (Section [Regional economic impacts of PV](#)). Additionally, the environmental and economic benefits of avoided emissions due to PV developments are illustrated (Section [Estimating the impact of PV on avoided greenhouse gas emissions and air pollution](#)).

Characteristics of the region and PV developments in the region

The district of Aachen (German: Städteregion Aachen) is located in the West of Germany in the Land North Rhine-Westphalia ([Fig. 1](#)). It has an area size of approximately 707 km² and a population of 554,000 inhabitants in 2015 ([IT.NRW, n.d.](#)) and is subdivided into 10 municipalities. The region is categorised as a NUTS 3 region in the European statistical classification, which is the lowest category for regions ([Eurostat, n.d.a](#)), and is, therefore, classified as a small region on a European scale.

The Aachen mining region in the north of the region has been one of the oldest European black coal mining regions whose last coal mine was closed in 1997 ([Bergbaumuseum Grube Anna e.V, n.d.](#)). The lignite power plant Weisweiler, producing 15.3 Terrawatthours (TWh) of electricity per year (mean value of electricity generation from 2012 to 2014) is located in the municipality of Eschweiler in the East of the district, as well as the open lignite mine Inden which lays partly in the district of Aachen and the district of Düren. It is aimed to close the lignite mine by 2030 ([RWE Power AG, n.d.](#)). In 2009, the mining and energy company RWE Power AG employed approximately 1600 employees in the open lignite mine and the power plant Weisweiler, which demonstrates the economic significance of fossil fuels in the region ([RWE Power AG, 2009](#)).

The region may be characterised as a forerunner in the development of PV plants, because of the early implementation of cost covering feed-in tariffs for PV operators and a transfer of the costs to electricity consumers (so called 'Aachener Modell') in the region in the 1990s. That model was adapted by other German cities and later on by Feed-in-tariffs regulations (FiT) in the German Renewable Energies Act (EEG) in 2000, which led to large scale PV deployment in Germany ([Edinger, 1999](#); [Mertens, 2015](#); [Willeke & Räuber, 2012](#)).

[Fig. 2](#) shows the PV development since 1994 in the region (left). Until 1996, small-scale developments with 295 kilowatt (kW) of cumulative installed capacity in 1996 dominated. Since 2007, the regional market acts very dynamic with large scale developments especially in 2011 (16.9 megawatt (MW)) and 2012 (18.7 MW). In 2014, the installed capacity of plants that have been installed since 1994 is 70.9 MW. The majority (54.4 MW) of plants are rooftop plants.

In comparison to Germany, there is a relatively high dynamic in the 1990s due to the early implementation of feed-in tariffs in the region ([Fig. 2, right](#)). After 2000 and implementing the EEG in Germany, significantly higher dynamics in the German market take place which may be explicable by more favourable global radiation potentials in other German regions (e.g. South of Germany), which led to large scale deployments ([Agentur für Erneuerbare Energien, n.d.](#)). In the South German Land Bavaria for example, 29% of all PV plants in Germany are installed (data compilation by [Agentur für Erneuerbare Energien, n.d.](#) and [BMW, 2016](#)), whereas it covers only 20% of the total area of Germany ([Destatis, 2017](#)).

Regional economic impacts of PV

Selection of an impact assessment method

Three often applied methods can be identified to assess positive economic and employment effects of renewable energies. These are employment ratios, input-output (IO) models, and analyses of supply chains ([Jenniches, 2018](#)).

As it is intended to look beyond the assessment of regional employment effects only, the advantages and challenges of conducting an impact analysis based on regional IO models and supply chain analyses are solely presented in the following.

The special characteristic of IO models is the representation of interactions in a defined economy (e.g. a country), by illustrating the exchange of goods and services. These exchanges are captured in an overall view which ranges from production to the final use of commodities and thus includes all direct and indirect effects ([Statistisches Bundesamt, 2010](#)). A clear advantage of the approach lays in the comprehensive illustration of economic exchange.

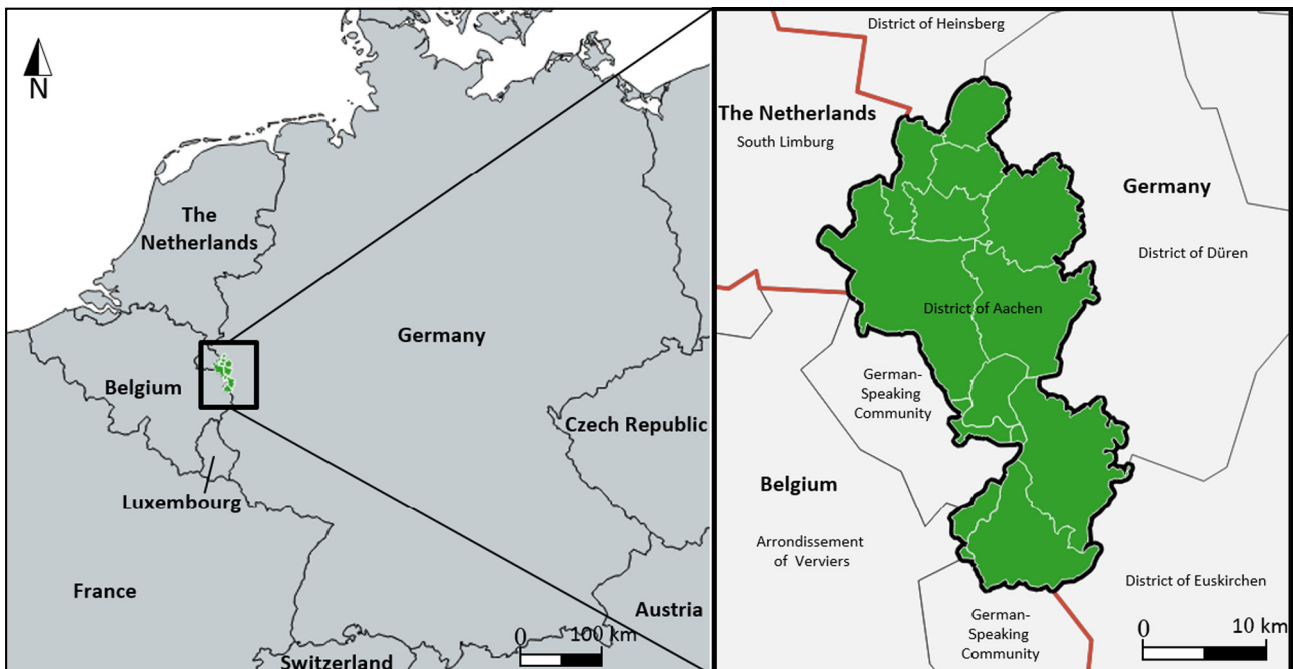


Fig. 1. Location of the district of Aachen in Germany (left side) and neighbouring territorial units on NUTS 3 level (right side). (Source: author's own graph, map data source: [Eurostat, n.d.b](#)).

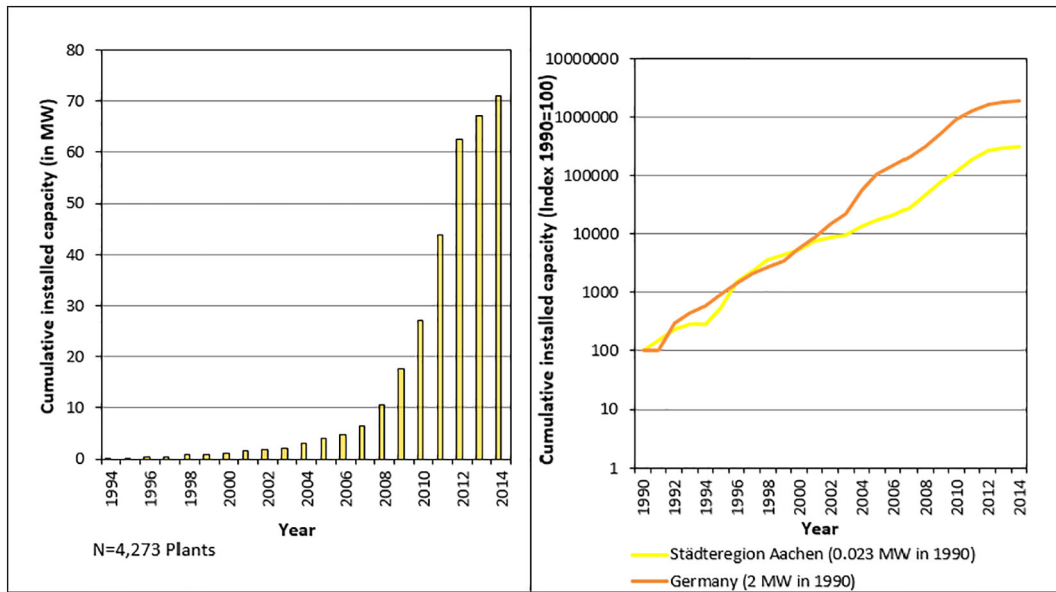


Fig. 2. Cumulative installed capacity of PV (rooftop and open space) in the district of Aachen from 1994 to 2014^a (left) (Source: [render, 2016](#)) and PV developments in comparison to Germany from 1990 to 2014^a (right) (Source: data compilation by [BMWi, 2016](#) for Germany and [render, 2016](#) for the district of Aachen). ^aDue 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.

When using IO tables to illustrate the economic effects of renewable energies, there are several challenges. National statistics do normally not distinguish between economic activities in the field of fossil or renewable energies, like in the case of Germany where IO tables contain only electricity generation in general ([Statistisches Bundesamt, 2010](#)). Therefore, the effects of, for example, electricity generation by renewable energies have to be disaggregated in a resource binding process to illustrate the effects of RES. Original tables illustrating inputs and outputs on a regional scale (regional IO tables (RIOTs)) are not available for small regions in Germany ([DIW, 2014](#)) and have to be derived from national data by calculations (e.g. [Hirschl et al., 2015](#)) or extensive surveys (e.g. [Coon, Leistritz, Hertsgaard, & Leholm, 1985](#)). However, [BMVBS \(2011\)](#) state a lack of precision of non-survey based IO modelling on a small regional scale. Further discussions on IO modelling is found in e.g. [Richardson \(1972\)](#) or [Miller and Blair \(2009\)](#). Studies that use RIOTs with regard to renewable energies are [Coon, Hodur, and Bangsund \(2012\)](#), [Slattery and Lantz \(2011\)](#), or [Stoddard, Abiecunas, and O'Connell \(2006\)](#).

The analysis of supply chains follows the idea of evaluating single economic activities (e.g. installation or operation) of renewable energy deployment. In the evaluation, the costs of the plant operator for the activities (e.g. maintenance) are considered as revenues of the respective companies. In a first step, the revenues are disaggregated into material costs (or intermediate inputs) provided by the suppliers and additional revenues. These additional revenues are needed to calculate the economic effects with regard to the maintenance industry by applying industry specific statistics. The material costs may be interpreted as revenues of the wholesale trade which may be disaggregated into intermediate goods and additional revenues as well. By applying industry specific statistics, the economic effects of the trade are evaluated. The intermediate goods are interpreted as revenues of component manufacturers and so on. A clear advantage of this bottom-up method is that effects of individual activities can be determined very precisely. In a supply chain analysis, a precise distinction between renewable energy technologies and even regarding a particular technology (e.g. between small and large power plants) should be made ([Böhmer, Kircher, Hobohm, Weiß, & Piegsa, 2015](#)).

A challenge is the accuracy and the quantity of information on costs that is needed to perform a supply chain analysis. Moreover, a realistic estimation of activities that can be taken over by regional companies

(Section [Lifecycle analysis and estimation of economic activities carried out in the region](#)) may be quite resource demanding because the renewable energy industry is inadequately captured in official statistics (Section [Assessing the regional economic impact of PV](#)). Examples of supply chain analyses are [Hirschl et al. \(2015\)](#) or [Finus, Lauerburg, Pietz, and Schaubt \(2013\)](#).

For the analysis of the district of Aachen, a supply chain analysis has been identified as the most favourable assessment approach, because original IO tables for small regions are not available and a survey based approach was considered as being too resource intensive. Moreover, according to [Llera-Sastresa, Usón, Bribián, and Scarpellini \(2010\)](#), “analytical models” ([Llera-Sastresa et al., 2010:680](#)) like the supply chain approach are considered as being more transparent in comparison to IO tables, because the weight of specific variables influencing the results can be more easily assessed.

Assessing the regional economic impact of PV

Concerning the components and the assessment of local or regional value added, the paper follows [Hirschl et al. \(2010\)](#) and [Bröcker et al. \(2014\)](#) who define them as profits of enterprises, net income of employees of enterprises, and locally or regionally raised taxes.¹ Employment effects are evaluated in full-time employment person-years. These key figures cover most of the impacts that have been analysed in previous regional economic impact assessment studies of renewable energies ([Jenniches, 2018](#)).²

In this section, the impacts are calculated for the latest available data of plants that is 2014. The conducted supply analysis does not include an overall assessment of the PV industry in a region, but enables a quantification of the impacts directly induced by the deployment of PV in the region. Therefore, the additional impacts of the PV industry are estimated by relying on industry statistics.

¹ All taxes which are not raised by the municipalities in the region are not taken into account as a component of the regional value added. Subsidies are not taken into account.

² By applying the supply chain approach, the gross effects of PV developments are studied. Net effects as a result of crowding out other electricity generation technologies are neglected in the calculation model and, therefore, an estimation of the potential effects on the lignite industry is additionally provided by a separate analysis (Section [Results](#)).

The assessment is structured as follows: After a lifecycle analysis, where activities in the PV lifecycle are evaluated, local shares of the specific activities are defined (Section [Lifecycle analysis and estimation of economic activities carried out in the region](#)). This section also includes the evaluation about the economic benefits of the PV industry in general which are not dependent on regional PV developments only. In a further step, a cost analysis is conducted (Section [Cost analysis of PV systems](#)). The costs of different activities may be interpreted as revenues of regional enterprises (e.g. planning or installation companies), that are needed to analyse the economic effects in the following part of the section (Section 3.2.3). Finally, the assessment of the activity 'electricity generation' (Section 3.2.4) is demonstrated.

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

Illustrating the lifecycle of PV plants, the paper follows [Llera, Scarpellini, Aranda, and Zabalza \(2013\)](#) who define five lifecycle stages of renewable energy plants. In the following, it is referred to these lifecycle stages as research and development (R&D) (1), manufacturing (2), installation (3), operation and maintenance (O&M) (4), and decommissioning (5).

As a first step, the stages of the PV plant lifecycle regarding their specific activities are analysed. These activities have been derived from existing studies in the field such as [BMVBS \(2011\)](#), [Hirschl et al. \(2010\)](#), and PV information platforms like [Heindl Server GmbH \(n.d.\)](#). Evaluating the activities in the PV supply chain that are carried out by regional enterprises is challenging as the renewable energy industry is insufficiently listed in official statistics. Different industry statistics from official and non-official sources such as [IHK Aachen \(n.d.\)](#), [Heindl Server GmbH \(n.d.\)](#), [Cylex International SNC \(n.d.\)](#) have, therefore, been used to identify individual potential enterprises in the renewable energy market in 2015 by hand. In an extensive analysis, which was supported by an online survey, 225 enterprises that were able to be active in the PV market have been identified. This excludes insurance companies, tax advisory enterprises, or financial institutes that are active in the market and located in the region.

For R&D there are methodological obstacles to calculate a realistic and quantifiable economic impact of organisations in the region regarding regional PV developments, because of international cooperation in R&D activities ([de Paolo, Ribeiro, & Porto, 2016](#); [Quitow, 2015](#)), and as it is hard to define an economic value for R&D activities in the price of a plant component, which is essential for the assessed supply chain approach. In the Aachen region, three enterprises and one institute of RWTH Aachen University, involved in PV related R&D activities have been identified. According to [Bundesanzeiger Verlag GmbH \(n.d.\)](#), profits of the three enterprises have been €856,000 in 2014 and the institute employed 16 employees. This value can be serve as a broad estimation since it could not be identified how much of these profits and employment effects are accountable for solely PV related activities.

Although PV related manufacturers are located in the region, it is difficult to define a realistic share of components of PV plants in the region, originating from these manufacturers, because the production capacities as well as the delivering flows of regional manufacturers are unknown and could only be estimated very broadly. That challenge is also stated by [Kirkegaard, Hanemann, Weischer, and Miller \(2010\)](#). Eight component manufacturers, have been identified in the region. Profits of PV related manufacturing enterprises have been calculated by relying on data of [Bundesanzeiger Verlag GmbH \(n.d.\)](#) and are approximately €1,678,000 (in 2014 and for one enterprise in 2013).³ As in the case of R&D, these profits are not only generated by PV related

activities and illustrate the situation in 2014. Like for R&D related activities, these profits are decoupled from the supply chain analysis because they are generated from PV developments inside and outside the region.

As an overall trend in R&D and manufacturing, a rising importance of actors from Asian countries can be observed ([Binz, Tang, & Huenteler, 2017](#) for R&D and [Quitow, 2015](#) for manufacturing). Therefore, it is beneficial from a regional economic development perspective to refer to other parts of the lifecycle stage, which can be done by organisations from the region in the long term. Hence, the focus of the supply chain analysis lies on the stages installation, O&M, and decommissioning ([Fig. 3](#)), where an allocation of activities, done by regional enterprises concerning regionally installed plants is more probable ([Llera et al., 2013](#)).

The local shares for installation, O&M, and decommissioning have been estimated based on the regional industry analysis and assumptions from existing studies. A local share of 100% has been assumed for all activities, excluding grid connection, metering, funding, and insurance. For grid connection and metering, a regional share of 93% has been estimated, based on the distribution of grid operators of the PV plant stock in the region that started operating between 1994 and 2014 ([render, 2016](#)). The regional share of financial institutions (45%) has been estimated following [BMVBS \(2011\)](#). Given the fact that insurance contracts may be taken out by online insurances or a local insurance broker, a share of 50% of insurance contracts between the operator and a regional insurance broker has been assumed.

The effects of PV plants, which have been installed in the region in 2014 are evaluated. R&D of the PV technology has been conducted before the component manufacturing stage that may take place in 2014 or before. After the installation and grid connection in 2014, a plant operation period of 20 years (2014–2034), as assumed by [Bröcker et al. \(2014\)](#), [Hirschl et al. \(2010\)](#), and other authors is assumed, although plants may operate longer ([Wirth, 2014](#)). Decommissioning takes therefore place in 2034. As depicted in [Fig. 3](#), a flow of goods and services takes place starting from manufacturers, to the wholesale trade, to service providers, and finally to the plant operator. In the opposite direction a flow of monetary transactions occurs that is evaluated in the cost analysis. In the following, a cost analysis is carried out, which is needed to calculate the regional economic effects (Sections [Effects during installation, operation and decommissioning](#) and [Calculation of effects during electricity generation](#)) occurring in every activity listed in [Fig. 3](#).

Cost analysis of PV systems

The starting point of assessing the effects that arise in the lifecycle stages of PV plants are the costs for the plant operator (see [Table 1](#)).

For the assessment, data should be highly disaggregated, i.e. every component and activity for different plant sizes with specific costs should be assessed ([Table 1](#)).

Effects during installation, operation, and decommissioning

The total number of plants installed in the region in 2014 is 280 plants with a total cumulative capacity of 3724 kW ([Fig. 4](#)). 227 plants with a capacity below 10 kW and with a cumulative capacity of 1354 kW, 45 plants with a capacity ranging from 10 to 100 kW with a total capacity of 1208 kW, and 8 plants with a capacity above 100 kW with a total capacity of 1162 kW, have been installed.

Regarding the electricity generated by these plants, 900 full load hours that is a mean value for the Land North Rhine-Westphalia ([LANUV, 2016](#)) are used, since specific data for the region is not available. That value may be interpreted as a conservative assumption for the region, because natural conditions in the Aachen region are rather favourable in comparison to most parts of the Land ([LANUV, 2013](#)). By multiplying the installed capacity with the full load hours and the years of operation, the total electricity generated between 2014 and 2034 is 67,032 MWh.

³ In this number, the profits of two manufacturing enterprises are not included, because they were subsidiaries and it is not possible to estimate the share of profits which is generated by them. Moreover, the profits of two manufacturing enterprises (€835,000) have already been included in the R&D enterprises' profits because they are also involved in R&D related activities.

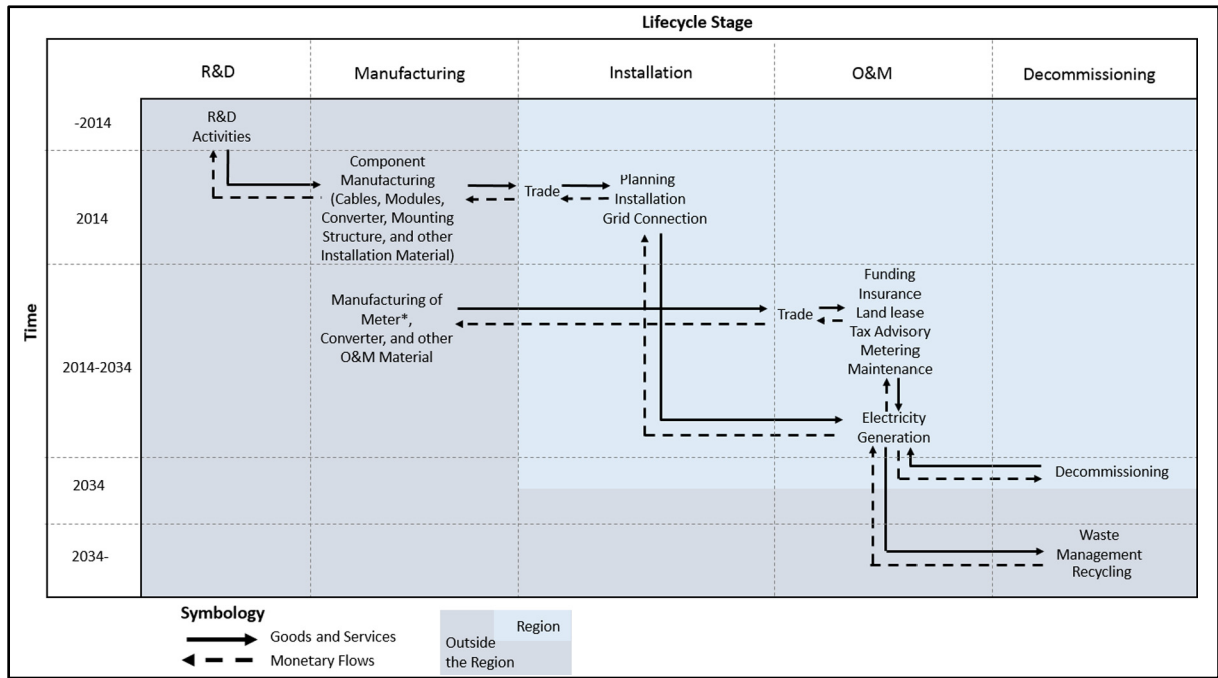


Fig. 3. Activities, flows, spatial scope, and temporal dimension of different lifecycle stages of PV systems, installed in the district of Aachen in 2014. *Meter manufacturing is supposed to happen in 2014 whereas the meter lease happens from 2014 to 2034.

After the cost analysis (Section *Cost analysis of PV systems*), the regional economic impacts of the plants that have been installed in 2014 are calculated. As a precondition, costs for plant operators (Table 1) are interpreted as the revenues of suppliers. Fig. 5 depicts the calculation of economic effects (i.e. enterprise profits, net income, and municipal taxes) for the assembly of all plants with a capacity below 10 kW.

First, the revenues (1) and the regional share of enterprises (Section *Lifecycle analysis and estimation of economic activities carried out in the region*) are used to calculate the regional revenues (2) (Section *Cost analysis of PV systems*). Next, industry specific values have been used to calculate the benefits of enterprises before taxes (3). These values have been derived from Deutsche Bundesbank (n.d.a) for

Table 1
Estimated costs in specific lifecycle stages for rooftop PV plants by power classes installed in 2014 (nominal values)^{a,b}.

Lifecycle stage	Activity	Power class		
		<10 kW	10 < 100 kW	≥ 100 kW
Installation	Planning	€208/kW	€170/kW	€47/kW
	Cabling	€70/kW	€68/kW	€64/kW
	Grid connection (material costs)	€119/kW	€17/kW*	€56/kW
	Grid connection (labour costs)	€51/kW	€7/kW*	€24/kW
	Mounting structure	€160/kW	€155/kW	€145/kW
	Installation	€176/kW	€147/kW	€103/kW
	Inverter	€176/kW	€144/kW	€130/kW
	Modules	€624/kW	€603/kW	€566/kW
	Installation total	€1584/kW	€1310/kW	€1134/kW
Operation	Maintenance	€20/kW/a	€20/kW/a	€20/kW/a
	Meter lease	€40/a	€40/a	€40/a
	Insurance	€100/a	€25/a + €2.5/kW/a**	€25/a + €2.5/kW/a
	Tax advisory	–	–	€3.9/a + €4.1/kW/a
	Liability remuneration	–	–	€1/kW/a
	Management	–	–	€13/kW/a
	Roof lease	–	–	€33/kW/a
	Operation total	(€140 + €20/kW)/a	(€65 + €23/kW)/a	(€69 + €74/kW)/a
Decommissioning	Decommissioning	€176/kW	€147/kW	€103/kW

* Total grid connection costs are €1700 minimum.

** Insurance costs are €100/a (year) minimum.

^a For plants with a capacity above 100 kW, additional costs for management, leasing costs of the roof, etc. have to be considered. The assumed share of borrowed capital for plants with a capacity below 10 kW is 50% (Hirschl et al., 2010), between 10 and 100 kW 63%, and above 100 kW 75% (Kelm et al., 2014). For funding, an effective interest rate of 3% for a credit period of 20 years is assumed (KfW, 2015). The decommissioning stage includes the end-of-life activity uninstallation only. Because future material costs of the plant (e.g. mounting structure) exceed the decommissioning costs (Janzing, 2015) they are cost neutral to the plant operator.

^b (Sources: Installation costs: Kelm et al. (2014) and own calculations based on Reichmuth et al. (2011) for cables, grid connection and substructure; Operation costs: own calculations based on Schormann and Behrla (n.d.) (maintenance), Christian Münch GmbH (n.d.) (meter lease), Eggers (n.d.) (insurance), BMVBS (2011) (tax advisory services), Hirschl et al. (2010) (management and liability remuneration); Decommissioning costs: Kelm et al. (2014) and own calculations based on Reichmuth et al. (2011) (operation excluding funding costs))

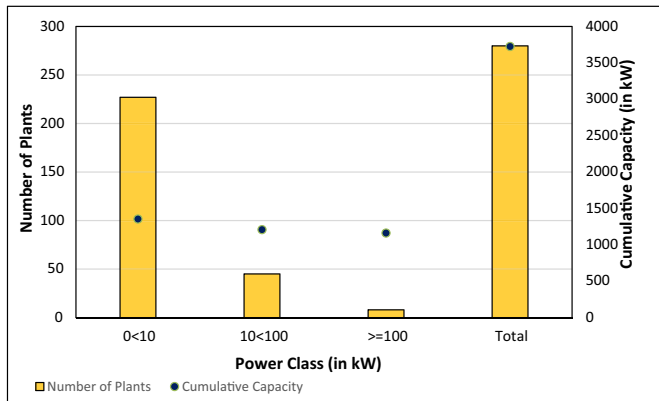


Fig. 4. Number of plants and total installed capacity of plants installed in 2014 in the district of Aachen.

(Source: own calculations based on [render, 2016](#)).

financial institutions and [Deutsche Bundesbank \(n.d.b\)](#) for the other industries, by using a mean value of various years.

For enterprise taxes, national standardised taxes (corporate tax and solidarity tax⁴) (4) depending on the legal form of the enterprise are included. That was derived from the analysis of legal forms of local PV businesses, and locally different shares of trade taxes based on [IT.NRW \(2015\)](#). By subtracting the taxes from the enterprise revenues, the net profits of enterprises (5) are assessed. To assess the compensation of employees, industry specific values have been used (6).

For the employees' taxes and charges (e.g. for health insurance) (7), income specific tax shares based on [Bundesministerium der Finanzen \(2016\)](#) have been used. Municipalities benefit from taxes so that a part of trade taxes (8) and a part of income taxes (9) are allocated by the municipality (10) ([Bundesministerium der Justiz und für Verbraucherschutz, n.d.](#); [Bundesministerium der Finanzen, n.d.a](#)). These calculations have been conducted for every activity and every power class of installed plants.

Calculation of effects during electricity generation

For electricity generation of PV plants in Germany, profits of plant operators have usually been calculated by multiplying the electricity generated with feed-in tariffs that are regularly published by the German Federal Network Agency ([Bundesnetzagentur, 2017](#)), which is also the case in comparable regional impacts studies like [BMVBS \(2011\)](#) or [Bröcker et al. \(2014\)](#).

The feed-in tariffs depend on the capacity of a plant and the larger the capacity, the smaller the fee in c/kWh for electricity fed in the grid is provided. [Formula \(1\)](#) illustrates the calculation of the feed-in tariff for a 40 kW rooftop PV plant (starts operating in July 2010) that is paid for 20 years of operation (source: [Clearingstelle EEG, n.d.](#), modified).

$$\begin{aligned}
 &75\% \text{ (share of capacity below 30kW)} \\
 &\times 34.05 \text{ c/kWh (feed-in-tariff for a plant capacity below 30 kW)} \\
 &+ 25\% \text{ (share of capacity ranging from 30–100 kW)} \\
 &\times 32.39 \text{ c/kWh (feed-in-tariff ranging from 30–100 kW)} = 33.64 \text{ c/kWh}
 \end{aligned}
 \quad (1)$$

Feed-in-tariffs also depend on PV deployment in Germany over time. Tariffs decrease if the PV development path, determined by the

Renewable Energy Act (EEG), is exceeded and increases if the installed capacity falls below.

Since 2012, feed-in-tariffs for plants with a capacity below 30 kW (€0.24/kWh start of operation from January to March 2012, [Clearingstelle EEG, n.d.](#)) are lower than electricity prices for consumers with an annual consumption between 2500 kWh and 5000 kWh (€0.26/kWh in the first half of the year, [Eurostat, 2015](#)) that is a characteristic consumption for private households. Therefore, it is economically more efficient for plant operators to consume generated electricity and minimise overproduction, rather than to feed it into the grid and benefit from the feed-in tariff, especially since feed-in tariffs decreased further. The feed-in tariff for a plant with a capacity below 10 kW starting to operate in January 2014 for example is €0.14/kWh ([Clearingstelle EEG, n.d.](#)). Therefore, PV operators do become so-called 'prosumers' who produce and consume electricity ([IEA-RETD, 2014](#)).

The amount of generated electricity that can be consumed depends on several factors such as load management and consumer behaviour ([von Bost, Hirschl, & Aretz, 2011](#)). Storage systems, which also positively affect internal consumption of generated electricity, are disregarded because they are not sufficiently economically deployable in 2014 in most cases ([Leipziger Institut für Energie, 2014](#)). However, they should be taken into account in forthcoming studies, because of decreasing system prices ([Sterner, Eckert, Thema, & Bauer, 2015](#)).

[Kelm \(2015\)](#) estimates potential internal consumption of PV plants of different power classes ([Table 2](#)). These may be higher or lower due to specific consumption patterns in individual cases, such as stated by [SMA \(2013\)](#) for non-private consumers, but provide an indication.

Following [Kelm \(2015\)](#), the amount of energy that is fed into the grid is estimated 70% for rooftop plants with a capacity below 10 kW and 60% for larger plants. The profitability of plants depends on the development of future electricity prices. To estimate future prices in Germany, the paper follows an energy market prognosis conducted by [Schlesinger et al. \(2014\)](#) (see [Fig. 6](#)).

Following the building types in [Table 2](#) and the derived consumer groups, the household electricity prices have been used as a reference to calculate the avoided electricity costs for plants with a capacity below 10 kW and the trade and industry prices as a reference for larger plants.

Since the introduction of the EEG 2014 in August 2014, the consumption of PV electricity is charged with a fee per kWh from consumers, except for plants with a capacity below 10 kW and an annual internal consumption below 10 MWh. The annual charge is estimated by following [Schlesinger et al. \(2014\)](#). A reduction of the charge may be granted if the operator and the consumer of the plant is the same person ([Bundesnetzagentur, 2016](#)), which is integrated by following [Bundesministerium der Justiz und für Verbraucherschutz \(n.d.\)](#).

The assessment of economic impacts for electricity generation is exemplified by a 80 kW PV plant in the following [Fig. 7](#), which leads to revenues of €59,000 for the plant operator and municipal taxes of €7000.⁵

Results

[Table 3](#) depicts the regional value added and employment effects of plants installed in 2014. The lifecycle stages are illustrated by different frames representing installation, operation, and decommissioning.

These are the results of the calculation of the total regional value added of every economic activity with regional enterprises involved ([Fig. 3](#)) as demonstrated in [Fig. 5](#) for the activity installation of plants with capacities below 10 kW⁶ and in [Fig. 7](#) for an individual plant for

⁴ The solidarity tax is a tax that has been introduced in the 1990s to finance the German reunification ([Bundesministerium der Finanzen, s.a.b](#)).

⁵ Due to individual revenues (e.g. the feed-in tariff depends on the date when the individual plant starts operating), calculations cannot be illustrated aggregated for a market segment as in the case of the activity installation ([Figure 5](#)) and have been conducted for every single plant that has been installed in the region in 2014 individually.

⁶ Due to rounding effects, values vary slightly.

Step No.	Key Figure	Calculation
1	Revenues of Installation	$\text{€}176/\text{kW} \times 1,354 \text{ kW}$ $= \text{€}238,304$
2	Revenues of Regional Installation Companies	$\text{€}238,304 \times 100 \%$ $= \text{€}238,304$
3	Pre Tax Profits of Regional Installation Companies	$\text{€}238,304 \times 8 \%$ $= \text{€}19,064$
4	Taxes of Regional Installation Companies	32 % (15.8 % Trade Tax + 15 % Corporate Tax + 0.83 % Solidarity Tax)
5	Net Profits of Regional Installation Companies	$\text{€}19,064 \times (100 \% - 32 \%)$ $= \text{€}12,964$
6	Compensation of Employees	$\text{€}238,304 \times 60 \%$ $= \text{€}142,982$
7	Net Income of Employees	$\text{€}142,982 \times 54 \%$ $= \text{€}77,210$
8	Regional Taxes (Share of Trade Tax)	$\text{€}19,064 \times 15.8 \% \times 84.3 \%$ $= \text{€}2,539$
9	Regional Taxes (Share of Income Tax)	$\text{€}142,982 \times 2 \%$ $= \text{€}2,860$
10	Total Regional Taxes	$\text{€}2,539 + \text{€}2,860$ $= \text{€}5,399$
Symbology — Profits — Taxes		

Fig. 5. Calculation of profits, income, and taxes regarding the installation of rooftop PV plants with a capacity below 10 kW installed in 2014 in the district of Aachen (nominal values).

the activity electricity generation, which is included in the aggregated result of electricity generation of plants with capacities between 10 and 100 kW.

Overall economic effects equate to €3,796,000 consisting of the components profits (€2,334,000), net income (€1,151,000), and taxes (€311,000). Most of the effects occur during operation between 2014 and 2034 with total effects equating to €2,999,000 (€0.03/kWh for electricity generation and €302/kW for operation excluding electricity generation), followed by the effects during installation (€579,000) (€156/kW installed) and decommissioning (€217,000) (€58/kW decommissioned). The rather large proportion of effects during the operation depends strongly upon the effects of electricity generation that contribute to 62% of the effects during operation.

The highest share of effects is attributable to electricity generation with approximately €1,874,000, or 49% of total effects, of PV plants installed in 2014. Concerning the PV installation industry, total effects

of €774,000 are generated, which represent the second highest share of effects regarding the industries. Approximately half of these effects (€339,000) arise during the operation stage. The other effects occur in 2014 during installation and 2034 during decommissioning of PV plants. Effects arising concerning land (i.e. roof) lease represent the

Table 2
Building typologies and internal consumption of typical PV power classes.

Power class	Building type	Internal consumption
<10 kW	Detached and semi-detached homes	≈30% on average
10–40 kW	Apartment buildings, barns, stables, small businesses, small administration buildings, schools	≈40% on average
40–100 kW	Large apartment buildings, barns, stables, schools, administration buildings, trade buildings	≈40% on average
100–1000 kW	Large farming buildings, large supermarkets, factory buildings	≈40% on average

(Source: Kelm, 2015, modified)

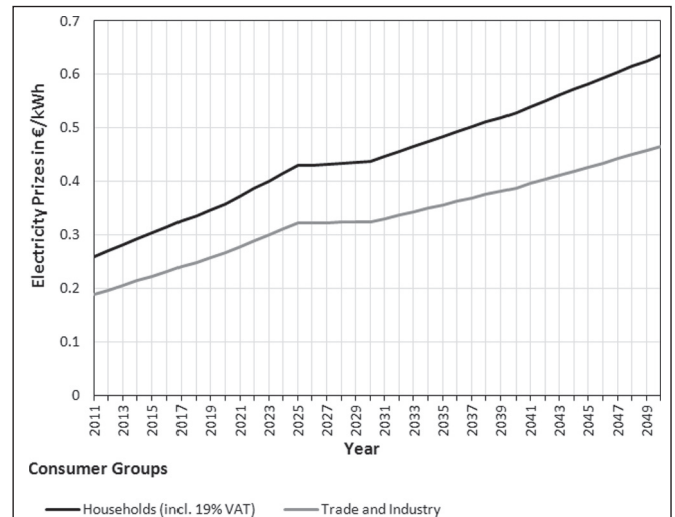


Fig. 6. Development of annual electricity prices in €/kWh (nominal values) for households (including value added tax), trade, and industry (excluding manufacturing and energy intensive industries).

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

Step No.	Key Figure	Calculation
1	Electricity Generation	$80 \text{ kW} \times 900 \text{ h} \times 20 \text{ a}$ $= 1,440,000 \text{ kWh}$
2	+ Revenue Feed-in-Tariff	$1,440,000 \text{ kWh} \times \text{€}0.1164/\text{kWh} \times 60 \%$ $= \text{€}100,570$
3	+ Revenue Avoided Electricity Costs	$1,440,000 \text{ kWh} \times \text{€}0.29/\text{kWh} \times 40 \%$ $= \text{€}167,040$
4	./ Installation Costs	$80 \text{ kW} \times \text{€}1,274/\text{kW}$ $= \text{€}101,920$
5	./ Operation Costs	$(\text{€}65 + \text{€}23/\text{kW} \times 80 \text{ kW}) \times 20 \text{ a}$ $= \text{€}38,100 + \text{€}21,932 \text{ (Funding Costs)}$
6	= Revenues	$\text{€}105,658$
7	./ Income Taxes	$\text{€}105,658 \times 42 \%$ $= \text{€}44,376$
8	./ Solidarity Tax	$\text{€}44,376 \times 5.5 \%$ $= \text{€}2,441$
9	= Revenues after Taxes	$\text{€}58,841$
10	= Municipal Taxes	$\text{€}44,376 \times 15 \%$ $= \text{€}6,656$
Symbology — Profits — Taxes		

Fig. 7. Regional economic impacts of electricity generation of an 80 kW PV plant, installed in July 2014 in the district of Aachen (nominal values).

third highest share with €512,000, where €222,000 of the effects occur regarding private and €290,000 concerning public landlords. Other effects are between €200,000 and €100,000 except those regarding tax advisory and insurance services that are lower.

Employment effects are 16 full-time jobs in 2014 (4 full-time jobs/MW installed), 20 person-years between 2014 and 2034 (0.06 person-years/GWh electricity generation and 4.3 person-years/MW for operation excluding electricity generation) (which is equal to one full-time job per year), and 7 full-time jobs in (1.9 full-time jobs/MW installed) 2034. Total employment effects are, therefore, 42 person-years.

Most of the employment effects arise in the PV installation industry with approximately 26 person-years, or 62% of the total employment effects. Other employment effects are relatively lower. The comparison of income and employment effects shows that relatively high employment effects per total income occur in the PV installation industry. That is due to lower employment compensation compared to other industries. Therefore, there is a need to provide additional information about the calculation of the effects, like providing the average income in the specific industries where the employment effects occur.

Complementary to Table 3 that depicts the total aggregated value added of the plants installed in 2014, Table 4 illustrates further characteristics of the sample. The minimum value added ranges from €-413 for a 1.3 kW plant to €211,986 for a 180.0 kW plant. For smaller plants, fix costs of plants have a greater impact on the profits of plant operators than for larger plants which negatively affects the profits of plant operators and conclusively the value added which explains the negative result of the 1.3 kW plant. According to the used model and data, system capacities' should be minimum 2.5 kW for a profitable operation.

Conclusively, it can be stated that the greater the capacity of plants, the higher are the regional economic effects.

The estimated municipal tax revenues from the deployment of PV in 2014 totaled €56,000, represent 0.01% of the total municipal share of income-, and trade taxes in the district of Aachen (IT.NRW, 2017a). Noted, however, that corporate taxes are included in the taxes in the district and only the plants installed in 2014 are recorded. The total municipal tax effects of the facilities installed in 2014 yield €311,000 over their presumed lifetime from 2014 to 2034, representing 0.07% of the share of income-, and trade tax in 2014.

The results show 16 fulltime jobs in 2014 which is 0.008% of the total employment in June 2014 in the district of Aachen (IT.NRW, 2017b). If all effects related to the plants installed in 2014 were supposed to occur in 2014 it would be 0.02% of total employment in the region. In comparison to the employment effects of the open lignite mine Inden and the power plant Weisweiler in 2009 (approximately 2672 employees⁷) the total effects of PV plants installed in 2014 account for a share of 1.6% of employment effects. The lignite industry accounts for 0.2 jobs per GWh electricity generated, whereas PV developments lead to 4.8 jobs per GWh electricity generated in 2014 in the region.

As the generation of electricity by PV may lead to a crowding out of conventional power generation, this may have an effect on the regional economy which relies on the lignite industry. According to Memmler et al. (2014, based on Klobasa and Sensfuß, 2013), PV substitutes 3% of electricity generated by lignite. Therefore, the generation of electricity leads to a substitution of 101 MWh electricity generated by lignite per year. This implies only marginal negative employment effects of 0.01 less employees.⁸

Comparison of the results to other studies in the field

To compare the results to existing work in the field, studies that carried out a comparable analysis of effects of PV plants in German regions, examining a regional value added, consisting of profits, income, and regional taxes have been chosen. Studies' results on an international level such as Simons and Peterson (2001) or Bezdek (2007) are illustrated more aggregated, which does not allow to evaluate the impacts in the specific lifecycle stages and the assessed regional economic effects vary regarding the indicator regional value added as defined and evaluated in this paper, which hinders a comparability.

Bröcker et al. (2014) assessed the value added for the Land Schleswig-Holstein taking taxes into account which occur on Land level as well, whereas the other studies regard taxes on municipal scale only, which leads to lower taxes and therefore to a lower regional value added. BMVBS (2011) define the costs for activities in the operation stage as income costs and material costs and define all income costs as incomes of employees, without differentiating between employee income and profits and taxes of enterprises, while the latter two components of the value added are not calculated for the operation stage (BMVBS, 2011), which leads to a relatively high value added as well. The studies' results are illustrated for the stages installation, operation (while displaying the activity electricity generation separately), and decommissioning.

Because of different cost structures (Table 1), only small PV plants (0–10 kW) that are usually installed on top of, for instance, single family homes (Table 2) are considered. Bröcker et al. (2014), Hirschl et al. (2010), and BMVBS (2011) distinguish between two types of rooftop PV plants - small and large. A differentiation between three power classes for rooftop PV plants as in this paper has not been made, which is of course dependent upon available cost data.

Hirschl et al. (2010) explore the potentials by assuming a 100% regional share of activities taken over by enterprises in a region (i.e. a community in Hirschl et al. (2010)), BMVBS (2011) and Bröcker et al. (2014) assume individual shares for activities executed by regional enterprises. In the Aachen region, regional shares are assumed as well and the regional economic potentials are explored first by identifying individual enterprises in the region, which has not been done by another study to such an extent.

⁷ 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.

⁸ In this calculation, a linear correlation between the 1600 RWE employees in 2009 and the electricity generated in 2014 (15.3 TWh) has been assumed.

Table 3

Detailed overview about total regional value added and employment effects of PV plants installed in 2014 in the district of Aachen (in € nominal and person-years).

Industries	Activities	Power Classes	Profits	Income	Taxes	Person-Years
Planning Companies	Planning	0<10 kW (n=227)	20,803	66,407	7,739	2.0
		10<100 kW (n=45)	15,167	48,417	5,642	1.5
		>=100 kW (n=8)	4,032	12,872	1,500	0.4
	Total		40,003	127,696	14,882	3.8
Financial Institutions	Financing	0<10 kW (n=227)	14,660	19,267	4,105	0.5
		10<100 kW (n=45)	13,935	18,315	3,902	0.5
		>=100 kW (n=8)	13,987	18,383	3,917	0.5
	Total		42,582	55,966	11,924	1.5
Wholesale Companies	Trade of Plant Components	0<10 kW (n=227)	17,530	43,354	5,433	1.6
		10<100 kW (n=45)	11,258	27,907	3,501	1.0
		>=100 kW (n=8)	7,015	17,733	2,242	0.7
	Trade of Maintenance Material	0<10 kW (n=227)	3,586	8,801	1,069	0.3
		10<100 kW (n=45)	3,199	7,851	954	0.3
		>=100 kW (n=8)	3,076	7,550	917	0.3
	Total		45,664	113,197	14,115	4.2
PV Installation Companies	Installation	0<10 kW (n=227)	13,528	77,753	5,508	3.2
		10<100 kW (n=45)	10,079	57,932	4,104	2.4
		>=100 kW (n=8)	6,791	39,034	2,765	1.6
	Maintenance	0<10 kW (n=227)	17,217	98,958	7,011	4.1
		10<100 kW (n=45)	15,359	88,278	6,254	3.7
		>=100 kW (n=8)	14,769	84,889	6,014	3.5
	Uninstallation	0<10 kW (n=227)	13,528	77,753	5,508	3.2
		10<100 kW (n=45)	10,079	57,932	4,104	2.4
		>=100 kW (n=8)	6,791	39,034	2,765	1.6
	Total		108,143	621,563	44,034	25.9
Grid Service Companies	Grid Connection	0<10 kW (n=227)	10,014	10,206	2,576	0.3
		10<100 kW (n=45)	3,327	3,391	856	0.1
		>=100kWp (n=8)	5,710	5,819	1,469	0.2
	Meter Lease	0<10 kW (n=227)	22,207	22,631	5,712	0.7
		10<100 kW (n=45)	4,402	9,545	4,486	0.3
	Total		46,443	52,389	15,299	1.6
Plant Operators	Electricity Generation	0<10 kW (n=227)	530,425	0	60,502	0.0
		10<100 kW (n=45)	768,325	0	86,918	0.0
		>=100 kW (n=8)	248,685	141,985	36,894	4.0
	Total		1,547,435	141,985	184,314	4.0
Insurance Companies	Insurance	0<10 kW (n=227)	4,541	11,165	1,452	0.3
		10<100 kW (n=45)	1,017	2,499	325	0.1
		>=100 kW (n=8)	621	1,527	199	0.0
	Total		6,179	15,191	1,976	0.4
Landlords	Roof Lease	>=100 kW (private)	200,151	0	21,740	0
		>=100 kW (public)	290,460	0	0	0
	Total		490,611	0	21,740	0
Tax Advisory Companies	Tax Advisory	>100 kW (n=8)	7,081	22,605	2,634	0.7
Total			2,334,140	1,150,593	310,918	42.2

..... Installation — O&M — — Uninstallation

After harmonising data assessments,⁹ results of the installation stage range between €207 and €412 per kW in this stage (Table 5). The differences in the results are mainly explicable because of differences in costs

⁹ Hirsch et al. (2010) and Bröcker et al. (2014) summarised the wholesale of modules and inverters under their defined stages 'investment' or 'plant components' that include manufacturing of modules as well. As for the Aachen region, the results for wholesale of modules and inverters are integrated into the installation stage. Manufacturing of installation material as included by Hirsch et al. (2010) is excluded.

Table 4

Minimum, maximum, and mean regional value added of PV plants in the power classes.

Power class	Mean value added	Minimum value added	Maximum value added
0 < 10 kW	€5125 (6.0 kW)	€-413 (1.3 kW)	€10,189 (9.84 kW)
10 < 100 kW	€28,686 (26.9 kW)	€10,690 (11.4 kW)	€98,709 (99.5 kW)
≥ 100 kW	€162,838 (145.2 kW)	€128,295 (114.4 kW)	€211,986 (180.0 kW)

Table 5

Total regional value added of PV plants (0–10 kW) in different studies in €/kW installed capacity and in €/kWh electricity generated.

Region	NUTS Level	Installation €/kW	Operation		Decommissioning €/kW	Source
			Operation €/kW	Electricity Generation €/kWh		
Friesland	NUTS 3	–	1296	0.055	–	BMVBS (2011)
Nordschwarzwald	Four aggregated NUTS 3 regions	–	1296	0.056	–	BMVBS (2011)
Hannover	NUTS 3	–	1296	0.040	–	BMVBS (2011)
Trier	NUTS 2	–	1296	0.051	–	BMVBS (2011)
Schleswig-Holstein	NUTS 1	412	2366	–0.078	–	Bröcker et al. (2014)
Municipalities in Germany in General	LAU 2	357	330	0.120	–	Hirschl et al. (2010)
Städteregion Aachen	NUTS 3	207	179	0.024	71	This paper

(Source: own calculation and aggregation based on BMVBS (2011), Bröcker et al. (2014) and Hirschl et al. (2010), nominal values)

for plants which have dramatically decreased along past years. Whereas Hirschl et al. (2010), for example, assumed prices of €1566/kW for modules and €331/kW for inverters, prices for the Aachen region were assumed as €624/kW for modules and €176/kW for inverters. Furthermore, the plant assembly costs vary from €304/kW Hirschl et al. (2010) to €176/kW (own results) which may be explicable due to learning effects of installation companies.

For the operation stage, all authors assume a lifetime of 20 years. The results in Table 5 illustrate the total effects per kW for 20 years of operation. BMVBS (2011) did not include the value added of the activity financing, because they classified it as the direct effects occurring during electricity generation, which is included into the operation stage (Fig. 3) for the Aachen region. Moreover, total interests have been interpreted as a component of regional value added without considering a disaggregation of interests into taxes of banks, income of employees, or further costs of banks, which leads to a relatively high value added for operation. Results vary between €179/kW (Aachen region)¹⁰ and €2366/kW (Bröcker et al., 2014) in this stage. Differences are explicable by decreased maintenance material costs (Hirschl et al., 2010 and this paper's results), additional cost positions and methodological differences.¹¹

For electricity generation, value added depends on capacity, as well as on the full load hours of the plant varying with location (800 h (Schleswig-Holstein) to 934 h (Nordschwarzwald)). Value added is illustrated in € per kWh electricity generated, in order to account for the different locations. Regarding the results one sees significant differences. They are partly explicable because of different costs for installation and operation which have an impact on the profits (and therefore taxes) of operators. Other important aspects are the global irradiation potentials of the regions and the decrease of feed-in tariffs. Whereas Hirschl et al. (2010) calculated with a feed-in tariff of €0.4301/kWh according to EEG 2009, Bröcker et al. (2014) calculated with an average feed-in tariff of €0.1529/kWh according to EEG 2012, which is almost three times less than the feed-in tariff of Hirschl et al. (2010). The fact, that operation costs in Hirschl et al. (2010) are lower than in all other studies (except for this study) explains why their value added in electricity generation is much higher than in other studies. Bröcker et al. (2014) is the only study where a negative value added concerning the activity electricity generation is presented. This is due to the relatively high costs for operation, and that benefits of operators were assessed the by taking the profits generated by feed-in tariff only into account, which is lower than the electricity prices in 2012, and not considering internal consumption.

¹⁰ The difference between €179/kW for small plants between 1 and 10 kW and €302/kW for PV plants in general (Section Results) are explicable because the latter include tax advisory services and roof lease for PV plants above 100 kW.

¹¹ Bröcker et al. (2014) and BMVBS (2011) included tax advisory services in their calculations, which have not been considered in Hirschl et al. (2010) and this paper's results for small PV plants. Bröcker et al. (2014) included the costs for e.g. retrofitting requirements which are not included in other studies and assume a relatively high value added for maintenance (~6 times Hirschl et al., 2010). The relatively high values of BMVBS (2011) are due to the interpretation of interests as component of value added.

The stage decommissioning is only taken in this study into account, whereas a regional value added for the activity uninstallation have only been assessed in the Aachen region.

In summary, the comparison of the studies' results shows the dynamics in the German PV market regarding decreasing system costs and changes in business opportunities for operators (feed-in tariff vs. PV electricity consumption). The positive regional value added is decreasing because of lower system costs and learning effects. Furthermore, lower system costs do not compensate the losses in value added for operators because of decreasing feed-in tariffs. Nevertheless, profits for operators are supposed to rise in the future because of further decreases of PV plant component prices (Schröder, Kunz, Meiss, Mendelevitch, & V Hirschhausen, 2013) and increasing electricity prices (Fig. 6) making investments into PV more attractive.

Estimating the impact of PV on avoided greenhouse gas emissions and air pollution

Avoided GHG emissions due to PV deployment

As a climate mitigation strategy, it is aimed achieve a reduction of CO₂ emissions of 40% until 2020 and 80% by 2050 in the Aachen district (StädteRegion Aachen, 2011).

To include total emissions of energy generation systems, a lifecycle assessment (LCA) may be used to calculate the emissions of a product (e.g. PV) during the whole product lifetime from the extraction of material, manufacturing, usage, till waste management (Rebitzer et al., 2004). A compilation of LCA assessment studies that includes PV has been done by for example Sherwani and Usmani (2010), Nugent and Sovacool (2014), Louwen, Sark, Schropp, Turkenburg, and Faaij (2015), and Turconi, Boldrin, and Astrup (2013).

In this paper, data of avoided emissions due to PV deployment in Germany has been evaluated by the Federal Environmental Agency, using a LCA approach (Memmler et al., 2014). GHG emissions of PV plants may be slightly underestimated because emissions during plant operation and emissions regarding the plant components inverters and cables are neglected (Memmler et al., 2014). As data for 2014 was not available, data of 2013 is used. In 2013, GHG emissions of PV deployment are estimated at 55 gCO₂-equivalents (eq)/kWh (Memmler et al., 2014). Comparing these emissions with values from different studies, Nugent and Sovacool (2014) calculated a mean of 49.9 gCO₂-eq/kWh in a comprehensive literature analysis.

Avoided emissions depend on the substitution potentials of a technology. In case of PV, due to fluctuating feed-in because of day and night and seasonal differences, mostly hard coal and natural gas power generation may be substituted (Memmler et al., 2014). Avoided emissions in 2013 are estimated 761 gCO₂-eq/kWh (Memmler et al., 2014). Subtracting the emissions of PV deployment leads to net avoided emissions of 706 gCO₂-eq/kWh. Although, emissions generated by PV systems occur not equally distributed during their lifetime because component manufacturing takes place in or before 2014, an equal distribution is assumed in order to estimate the emissions of PV per year.

Following the assumptions regarding electricity generation by PV plants in the region (see Section [Effects during installation, operation and decommissioning](#)), the net avoided GHG emission potential of PV of the plant sample would be 2365 tCO₂-eq in 2014, if all plants had been installed before the beginning of the year. CO₂ only makes 2194 (93%) of emissions.

In order to estimate the economic benefits of non-emitted GHG gases, the paper follows the European Environmental Agency (EEA, 2014), using the market price of the European Union (EU) European Emission Trading System (ETS) and, secondly, the social cost of carbon (SCC). The mean value of for a ton of CO₂ traded at the European Energy Exchange (EEX) in 2014 is €5.42 (calculations based on [European Energy Exchange AG, 2017](#)).

The economic value is €11,891 (€0.004/kWh electricity generated) in 2014 which is calculated by multiplying the avoided CO₂ with the ETS allowance price. As the ETS price varies widely and decreased very much in recent years ([Koch, Fuss, Grosjean, & Edenhofer, 2014](#)), the SCC approach is presented as a second method.

Social cost of carbon estimate the “economic cost caused by an additional ton of carbon dioxide emissions” ([Nordhaus, 2014:273](#)). The SCC estimates the avoided damage (or external) costs due to the mitigation of a ton of GHG today by taking future damage costs into account, based upon assumptions on climate change effects ([EEA, 2014](#)). SCC includes a growth rate for “marginal damage costs” ([Tol, 2013:913](#)), meaning that costs increase within time ([Ackerman & Stanton, 2012](#); [Bateman et al., 2014](#)).

Estimating a value for the SCC, it can be referred to a comprehensive review by [Isacs et al. \(2016\)](#) who present a lower and a higher value of the SCC. The lower value (€5.8 per ton CO₂ in 2014¹²) consists of a mean global estimate, based on calculations of [Tol \(2013\)](#). This price, which is comparable to the ETS price is lower than in other studies and can therefore be seen as a value based on assumptions including relatively “low climate sensitivity, less importance of future generations compared to current [...], and less risk concern” ([Isacs et al., 2016:45](#)).

Higher SCC estimations are based on “high climate sensitivity, an equally important weight put on future generations as that of the current [...], and the inclusion of possible catastrophic climate change” ([Isacs et al., 2016:45](#)). Following the higher estimations by [Ackerman and Stanton \(2012\)](#) in [Isacs et al. \(2016\)](#), yields to costs of €698 per ton of CO₂ in 2014.¹³ To take the range of SCC values into account [van den Bergh and Botzen \(2014\)](#) present €94 per ton CO₂ in 2014¹⁴ as a threshold which can be “considered a realistic and conservative value” ([van den Bergh & Botzen, 2014:256](#)). This is, therefore, used in the calculations of the SCC value. Taking the emissions of PV systems into account, leads to a SCC value of €206,220 (€0.06/kWh electricity generated).

The variables influencing the value are hard to quantify and may alter in the future ([Isacs et al., 2016](#)). Nevertheless, the SCC values illustrate a range of occurring damage costs which are dependent upon potential future developments.

Avoided air pollutant effects and their economic impact

Conventional energy generation induces air pollution effects which lead to negative effects for the environment and provokes negative

¹² [Isacs et al. \(2016\)](#) present a value of €6.1 per tCO₂ in 2015 which they calculate based on [Tol \(2013\)](#) and [Bateman et al. \(2014\)](#). To calculate the SCC value for 2014, a damage growth rate of 2.3% p.a. as presented by [Tol \(2013\)](#) and an inflation rate of Germany based on [OECD \(2017\)](#) to calculate 2014 € prices is used.

¹³ [Isacs et al. \(2016\)](#) illustrate costs of €724 per tCO₂ in 2015, based on the estimations [Ackerman & Stanton, 2012](#). To calculate a value for the year 2014, the growth rate of damage costs per year (1.7%) and the inflation rate for Germany based on [OECD \(2017\)](#) are integrated.

¹⁴ The original value of \$125 per tCO₂ of [van den Bergh and Botzen \(2014\)](#) has been transformed into € by using the mean exchange rate of 2014 ([Deutsche Bundesbank, 2017](#)).

Table 6

Avoided air pollution and economic valuation in 2014.

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	0.97	21,316	64,684	20,610	62,542
NO _x	1.48	7666	21,431	11,369	31,786
NMVOCS ^a	0.07	2126	5366	144	364
Total				32,123	94,691

(Source: own calculations based on [Memmler et al. \(2014\)](#) (emissions) and [EEA \(2015\)](#) (economic assessment^b)).

^a [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. \(2014\)](#).

^b The values of [EEA \(2014\)](#) were originally in 2005 €, which have been converted using an inflation rate for Germany based on [OECD \(2017\)](#).

health effects like lung- or cardiovascular damages ([Remais et al., 2014](#)). [Preiss, Roos, and Friedrich \(2013\)](#) for instance estimate annual negative effects of 33,000 years of life lost (YOLL) and 700,000 working days lost (wdl) because of 67 coal power plants operating in Germany in 2010.

Concerning the spatial dispersion of effects, there are different levels of damages in different countries due to the reason that ecosystems or the population density and the emitters of air pollutants are not equally distributed and there are, therefore, regions which are more or less affected. Moreover, effects and damages vary upon the diffusion of the emissions and “differences in atmospheric chemistry (such as chemical transformation rates)” ([EEA, 2014:26](#)) which depends on the position of the emission source. Additionally, specific emissions tend to diffuse in the direction of the sea, which has a more severe impact on countries with access to the sea than for countries without a coastline ([EEA, 2014](#)). Therefore, there is a need to assess the effects of emissions at least country specific.

As for GHG emissions, the paper follows [Memmler et al. \(2014\)](#) to assess the amount of avoided pollutants due to PV deployment in the region of Aachen to rely on a consistent methodology for all avoided emissions. In 2014, the avoided emissions due to PV deployment in the region of Aachen ([Table 6](#)), account for 1.48t Nitrogen oxides (NO_x) per year, 0.97t Sulphur dioxide (SO₂) per year, and 0.07t Non-methane volatile organic compounds (NMVOCS) per year. On the other hand, PV deployments induce emissions of dust (0.02t per year) and (3.64t per year) of Carbon monoxide (CO).

Monetising costs of pollution due to these emissions, data for Germany provided by [EEA \(2014\)](#) that assessed the damages due to air pollution by European industrial facilities from 2008 to 2012 is used.

The economic effects of air pollutants are expressed in the value of a life year (VOLY) and a value of a statistical life (VSL), which is higher than the VOLY. VOLY expresses the damaging costs dependent upon the life expectancy (in YOLLs), whereas deaths of younger human beings are more weighted than deaths of elder human beings. The VSL expresses people's willingness to pay (wtp) for a decrease of the threat of health damages ([EEA, 2014](#)).

By taking the emissions of PV plants into account, a VOLY of €32,000 (€0.01/kWh electricity generated) in 2014 is calculated. The VSL of €95,000 (€0.028/kWh electricity generated) is approximately three times higher.

It should be considered that these benefits do not all occur in the Aachen region, as it is hard to map the spatial distribution of emission reductions due to PV, since the power grid is integrated. Hence, emission reductions may take place outside the region.

Conclusions and policy implications

The results of the supply chain analysis in the region illustrate overall economic effects of €3.8 million, which include the components

Table 7
Economic effects of plants installed in 2014 in €, €/kW, and €/MWh in 2014.

Indicator	Component	Total in €	€/kW	€/MWh
Value added	Profits	234,181	63	70
	Income	439,078	118	131
	Taxes	56,095	15	17
Avoided CO ₂	CO ₂	11,891–206,220	3–55	4–62
	SO ₂	20,610–62,542	6–17	6–19
Avoided air pollution	NO _x	11,369–31,786	3–9	3–10
	NMVOCS	144–346	0.04–0.1	0.04–0.1
Total		773,367–1,030,247	208–277	231–307

profits (€2.3 million) net incomes (€1.2 million), and regional taxes (€0.3 million). The regional economic effects are €1019 per kW for the installed plants with a total cumulative capacity of 3724 kW and €57 per MWh electricity generated with a total electricity generation of 67,032 MWh.

In 2014, the regional value added accounts for €729,000 (€196 per kW, €218 per MWh) the benefits of avoided CO₂ are €12,000–€206,000 (€3–€55 per kW, €4–€62 per MWh) and the benefits of avoided air pollution range from €32,000 to €95,000 (€9–€25 per kW, €10–€28 per MWh). Total effects range from €773,000–€1,030,000 (€208–277 per kW, €231–€307 per MWh). Employment effects are 16 person years (0.004 person years per kW, 0.005 person years per MWh) (Table 7).

The applied supply chain approach is a useful method to evaluate the effects of regional renewable energy deployments, because it is illustrative and easily adaptable when specific cost structures are available. As the benefits for specific economic actors are illustrated very detailed, the approach is beneficial for organisations like industry associations to evaluate the benefits for specific industries. Moreover, these assessments support RES, as demonstrating the benefits of renewable energies to decision makers may lead to increasing developments of RES. In comparison to other studies, data for three different power classes of PV systems has been used, taking the different cost structures of various plant classes into account which makes this paper's analysis more precise, than using two power classes only. The quality of assessments depends on the availability of current data. It is therefore needed, to continuously assess data of the costs developments of the PV industry on a high disaggregation level. Moreover, there is a need to study the regional effects of PV on an international level, as such regional impact assessments have rarely been conducted outside Germany.

Most of the effects are due to operation (approximately half of the total effect). The profits of plant operators depend mainly on the (self-)consumption of generated PV electricity. Higher consumption may be achievable by a more efficient load management or storage systems, which are expected to be economically deployable in the future. The ongoing integration of renewable energy prosumers in the electricity market is a threat to traditional business models of established incumbents like traditional power supply companies. Therefore, there is need for research to define the role of power supply companies in the future energy market.

Taking into account the external benefits of avoided GHGs and air pollution and monetising them is a suitable approach for making benefits illustrative for decision makers. Especially for external costs there is a need for research to realistically estimate the costs of future damage costs and to integrate them in assessments. However, the success of a regional energy transition depends on many other issues as the motives of regional stakeholders, legal situation, acceptance of RES, etc. In that case, interdisciplinary research which combines economic findings with outcomes from other disciplines may be beneficial.

Finally, the development of PV is only a component of a regional energy transition as an analysis of the regional potential shows up that rooftop PV is unable to fully cover the region's electricity demand. Therefore, in an overall analysis of a region's energy demand and supply options there is a need to integrate other energy sources, as well as

flexible demand and storage potentials for volatile energy sources such as PV or wind power (Perez-Arriaga & Batlle, 2012). This also has economic effects, which are not explicitly considered in this study. Further analyses may, however, use data of individual studies like this as a component to study the overall effect of a regional energy transition in an integrated approach.

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References

- Ackerman, F., & Stanton, E. (2012). Climate risks and carbon prices. Revising the social cost of carbon. *Economics*, 10, 1–25.
- Agentur für Erneuerbare Energien (n.d.). Förderal Erneuerbar – Bundesländer mit neuer Energie. https://www.foederal-erneuerbar.de/landesinfo/bundesland/BY/kategorie/solar/auswahl/183-installierte_leistung#goto_183, Accessed date: 8 February 2018 n.d.
- ARL (n.d.). Kommunale Planungshoheit. <https://www.arl-net.de/lexica/de/kommunale-planungshoheit>, Accessed date: 13 October 2017 n.d.
- Bateman, I. J., Day, B. H., Argarwala, M., Bacon, P., Bad'ura, T., Binner, A., et al. (2014). UK national ecosystem assessment follow-on work package report, 3 economic value of ecosystem services. <http://uknea.unep-wcmc.org/LinkClick.aspx?fileticket=1n40olhksY%3D&tabid=82>, Accessed date: 2 August 2018.
- Beckmann, K. J., Gailing, L., Hülz, M., Kemming, H., Leibenath, M., Libbe, J., et al. (2013). *Räumliche Implikationen der Energiewende Positionspapier*. Berlin: Difu.
- Bergbaumuseum Grube Anna e.V. (n.d.). Grube Anna Bergbaumuseum. <http://www.bergbaumuseum-grube-anna2.de/>, Accessed date: 8 February 2018 n.d.
- Bezdek, R. H. (2007). *Renewable energy and energy efficiency: Economic drivers for the 21st century*. Boulder, CO: American Solar Energy Society.
- Binz, C., Tang, T., & Huenteler, J. (2017). Spatial lifecycles of cleantech industries – the global development history of solar photovoltaics. *Energy Policy*, 101, 386–402.
- BMVBS (2011). Strategische Einbindung regenerativer Energien in regionale Energiekonzepte – Wertschöpfung auf regionaler Ebene. http://www.bbsr.bund.de/cdn_032/nn_20629248/BBSR/DE/Veroeffentlichungen/BMVBS/Online/2011/ON182011.html, Accessed date: 8 February 2018.
- BMVBS (2013). *Regionalwirtschaftliche Effekte der erneuerbaren Energien II Einfluss der Regionalplanung und Raumordnung auf regionale Wertschöpfung* https://www.bbsr.bund.de/BBSR/DE/Veroeffentlichungen/ministerien/BMVBS/Online/2013/DL_ON223013.pdf?__blob=publicationFile&v=3, Accessed date: 29 October 2018.
- BMWi (2016). *Erneuerbare Energien in Zahlen – Nationale und internationale Entwicklung im Jahr 2015*. Berlin: BMWi.
- Böhmer, M., Kircher, A., Hobohm, J., Weiß, J., & Piegsa, A. (2015). *Wertschöpfungs- und Beschäftigungseffekte der Energiewirtschaft: Studie im Auftrag des Bundesministeriums für Wirtschaft und Energie*. München, Basel, Berlin: Prognos.
- Bröcker, J., Burmeister, J., Preißler-Jebe, J. H., & Alberty, F. (2014). *Wertschöpfungs- und Beschäftigungseffekte als Folge des Ausbaus Erneuerbarer Energien in Schleswig-Holstein*. Kiel: Universität Kiel Institut für Regionalforschung.
- Bundesanzeiger Verlag GmbH (n.d.). Unternehmensregister. <https://www.unternehmensregister.de/ureg/index.html?dest=ureg&language=de>, Accessed date: 8 February 2018 n.d.
- Bundesministerium der Finanzen (2016). Lohn- und Einkommenssteuerrechner. <https://www.bmf-steuerrechner.de/fb2016/?clean=true>, Accessed date: 30 July 2016.
- Bundesministerium der Finanzen (n.d.). BMF Dokumentation – Der Gemeindeanteil an der Einkommenssteuer in der Gemeindefinanzreform. http://www.bundesfinanzministerium.de/Content/DE/Standardartikel/Themen/Oeffentliche_Finanzen/Foederaele_Finanzbeziehungen/Kommunalfinanzen/GemeindeanteilEST-2015.pdf?__blob=publicationFile&v=2, Accessed date: 8 February 2018 n.d.
- Bundesministerium der Finanzen (n.d.). Solidaritätszuschlag. <https://www.bundesfinanzministerium.de/Content/DE/Glossareinträge/S/Solidaritaetszuschlag.html?view=renderHelp>, Accessed date: 8 February 2018 n.d.
- Bundesministerium der Justiz und für Verbraucherschutz (n.d.). Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare-Energien-Gesetz – EEG 2014) § 61 EEG-Umlage für Letztverbraucher und Eigenversorger. https://www.gesetze-im-internet.de/eeg_2014/_61.html n.d., Accessed 08 February 2018.
- Bundesnetzagentur (2016). Leitfaden zur Eigenversorgung. https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/ErneuerbareEnergien/Eigenversorgung/Finaler_Leitfaden.pdf?__blob=publicationFile&v=2, Accessed date: 8 February 2018.
- Bundesnetzagentur (2017). Photovoltaikanlagen – Datenmeldungen und EEG-Vergütungssätze. <https://www.bundesnetzagentur.de/DE/Sachgebiete/Elektrizitaet>

- etundGas/Unternehmen_Institutionen/ErneuerbareEnergien/Photovoltaik/DatenMeldgn_EEG-VergSaetze/DatenMeldgn_EEG-VergSaetze_nodehtml, Accessed date: 23 March 2017.
- Christian Münch GmbH (n.d.). Photovoltaik.org – Unabhängige Beratung. <http://www.photovoltaik.org/photovoltaikanlagen/>, Accessed date: 28 July 2016 n.d.
- Clearingstelle EEG (n.d.). Vergütungssätze und Degressionsbeispiele nach dem neuen Erneuerbare-Energien-Gesetz (EEG) vom 31. Oktober 2008 mit Änderungen vom 11. August 2010. https://www.clearingstelle-eeg-kwkg.de/files/eeeg_2009_verguetungsdegression_Aenderungen_100811_bmu.pdf, Accessed date: 8 February 2018 n.d.
- Coon, R. C., Hodur, N. M., & Bangsund, D. A. (2012). *Renewable energy industries' contribution to the North Dakota economy*. Fargo, ND: North Dakota State University.
- Coon, R. C., Leistritz, F. L., Hertsgaard, T. A., & Leholm, A. G. (1985). The North Dakota input-output model: A tool for analyzing economic linkages Fargo, ND. North Dakota State University.
- Cylex International SNC (n.d.). Cylex-Branchenbuch Deutschland. <http://web2.cylex.de>, Accessed date: 27 August 2015 n.d.
- de Paolo, A. F., Ribeiro, E. M. S., & Porto, G. (2016). Mapping countries cooperation in photovoltaic technology development based on patent analysis. http://iamot2016.org/proceedings/%20papers/IAMOT_2016_paper_259.pdf, Accessed date: 23 March 2017.
- Destatis (2017). Bundesländer mit Hauptstädten nach Fläche, Bevölkerung und Bevölkerungsdichte am 31.12.2015, im Juli 2017 wegen korrigierter Fläche revidiert. <https://www.destatis.de/DE/ZahlenFakten/LaenderRegionen/Regionales/Gemeindeverzeichnis/Administrativ/Aktuell/02Bundeslaender.html>, Accessed date: 8 February 2018.
- Deutsche Bundesbank (2017). Devisenkursstatistik. Stand vom 29.12.2017. https://www.bundesbank.de/Redaktion/DE/Downloads/Statistiken/Aussenwirtschaft/Devisen_Euro_Referenzkurs/stat_euroref.pdf?__blob=publicationFile, Accessed date: 8 February 2018.
- Deutsche Bundesbank (n.d.). GuV Statistik – Statistik der Gewinn und Verlustrechnungen der Banken. https://www.bundesbank.de/Navigation/DE/Statistiken/Banken_und_andere_finanzielle_Institute/Banken/GuV_Statistik/guv_statistik.html, Accessed date: 8 February 2018 n.d.a.
- Deutsche Bundesbank (n.d.). Tabellen – Unternehmensabschlüsse. https://www.bundesbank.de/Navigation/DE/Statistiken/Unternehmen_und_private_Haushalte/Unternehmensabschluesse/Tabellen/tabellen.html, Accessed date: 8 February 2018 n.d.b.
- DIW (2014). *Die ökonomische Bedeutung der Windenergiebranche – Windenergie an Land in Deutschland und Nordrhein-Westfalen*. Berlin: DIW Econ GmbH.
- Edinger, R. (1999). *Distributed electricity generation with renewable resources: Assessing the economics of photovoltaic technologies in vertically integrated and in restructured energy markets* Marburg Tectum Verlag.
- EEA (2014). *Costs of air pollution from European industrial facilities 2008–2012 – an updated assessment* Luxembourg. European Environmental Agency.
- EEA (2015). *Trends and projections in the EU ETS in 2015* (=EEA Technical report NO 14/2015).
- EEFA (2010). *Bedeutung der rheinischen Braunkohle – sektorale und regionale Beschäftigungs- und Produktionseffekte. Untersuchung im Auftrag der RWE Power AG*. EEFA: Münster, Berlin.
- Eggers, M. (n.d.). Photovoltaikversicherung 24. <https://www.photovoltaikversicherung24.de/>, Accessed date: 25 July 2015 n.d.
- European Energy Exchange AG (2017). Ergebnisse EUA Primary Auction Spot – Download. <https://www.eex.com/de/marktdaten/umweltprodukte/auktionsmarkt/european-emission-allowances-auction/european-emission-allowances-auction-download>, Accessed date: 8 February 2018.
- Eurostat (2015). Electricity prices for domestic consumers – bi-annual data (from 2007 onwards). <https://data.europa.eu/euodp/data/dataset/aqDMwMrWaIVNy4eZt2rYOQ>, Accessed date: 7 September 2015.
- Eurostat (n.d.). NUTS – Systematik der Gebietseinheiten für die Statistik. <http://ec.europa.eu/eurostat/de/web/nuts/principles-and-characteristics>, Accessed date: 8 February 2018 n.d.a.
- Eurostat (n.d.). Geodata. <http://ec.europa.eu/eurostat/web/gisco/geodata/reference-data>, Accessed date: 8 February 2018 n.d.b.
- Finus, O., Lauerburg, K., Pietz, C., & Schaubt, M. (2013). *Kommunale Investitionen in Erneuerbare Energien – Wirkungen und Perspektiven*. DUH und IfaS: Birkenfeld/Radolfzell.
- Gailing, L., & Röhring, A. (2015). Was ist dezentral an der Energiewende? Infrastrukturen erneuerbarer Energien als Herausforderungen und Chancen für ländliche Räume. *Raumforschung und Raumordnung*, 73, 31–43.
- Grabher, G. (1993). The weakness of strong ties—The lock-in of regional development in the Ruhr area. In G. Grabher (Ed.), *The embedded firm: On the socioeconomics of industrial networks* (pp. 255–277). London: Routledge.
- Heindl Server GmbH (n.d.). SolarServer – Das Internetportal zur Sonnenenergie. <https://www.solarserver.de/>, Accessed date: 29 July 2015 n.d.
- Hirsch, B., Aretz, A., Prah, A., Böther, T., Heinbach, K., Pick, D., et al. (2010). *Kommunale Wertschöpfung durch Erneuerbare Energien*. Berlin: IÖW.
- Hirsch, B., Heinbach, K., Prah, A., Salecki, S., Schröder, A., Aretz, A., et al. (2015). *Wertschöpfung durch erneuerbare Energien – Ermittlung der Effekte auf Landes- und Bundesbene* Berlin. IÖW.
- IEA-RETD (2014). Residential prosumers – Drivers and policy options. http://iea-reted.org/wp-content/uploads/2014/09/RE-PROSUMERS_IEA-RETD_2014.pdf, Accessed date: 8 February 2018.
- IHK Aachen (n.d.). Netzwerk Energie. <https://energie.aachen.ihk.de/sites/fitaa/welcome.aspx>, Accessed date: 27 August 2015 n.d.
- Isacs, L., Finnveden, G., Dahlöf, L., Håkansson, C., Petersson, L., Steen, B., et al. (2016). Choosing a monetary value of greenhouse gases in assessment tools: a comprehensive review. *Journal of Cleaner Production*, 127, 37–48.
- IT.NRW (2015). Realsteuer-Hebesätze in Nordrhein-Westfalen im Jahr 2014. https://www.it.nrw.de/presse/pressemitteilungen/2015/pdf/180_15.pdf, Accessed date: 8 February 2018.
- IT.NRW (2017n.d.). Realsteuervergleich der Gemeinden in Nordrhein-Westfalen. <https://www.landesdatenbank.nrw.de/ldbnrw/online/online.jsessionid=.worker3?sequenz=statistiken&selectionname=7>, Accessed date: 3 March 2018.
- IT.NRW (2017n.d.). Kommunalprofil: Sozialversicherungspflichtig Beschäftigte am Arbeitsort nach Geschlecht, Nationalität und Wirtschaftszweigen. <https://www.it.nrw.de/kommunalprofil/downloads/index.html>, Accessed date: 8 February 2018.
- IT.NRW (n.d.). Gebiet, Bevölkerung, Haushalte. <https://www.it.nrw.de/statistik/a/sa>, accessed 08 February 2018d.
- Jacobsson, S., & Bergek, A. (2004). Transforming the energy sector: the evolution of technological systems in renewable energy technology. *Industrial and Corporate Change*, 13, 815–849.
- Janzing, B. (2015). Wenn Windräder zu alt werden. <http://www.klimaretter.info/energie/hintergrund/19919-wenn-windraeder-zu-alt-werden>, Accessed date: 8 February 2018.
- Jenniches, S. (2018). Assessing the regional economic impacts of renewable energy sources – A literature review. *Renewable and Sustainable Energy Reviews*, 93, 35–51.
- Kayden, J. S. (2000). National land-use planning in America: something whose time has never come. *Washington University Journal of Law & Policy*, 3, 445–472.
- Kelm, T. (2015). Marktanalyse Photovoltaik – Schwerpunkt Eigenverbrauch. https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/marktanalyse-pv-workshop-01-vortrag-zsw.pdf?__blob=publicationFile&v=3, Accessed date: 8 February 2018.
- Kelm, T., Schmidt, M., Taumann, M., Püttner, A., Jachmann, H., & Capota, M. (2014). Vorbereitung und Begleitung der Erstellung des Erfahrungsberichts 2014 gemäß § 65 EEG im Auftrag des Bundesministeriums für Wirtschaft und Energie – Vorhaben Ilc Solare Strahlungsenergie. <https://www.clearingstelle-eeg-kwkg.de/files/zwischenbericht-vorhaben-2c.pdf>, Accessed date: 8 February 2018.
- Keppeler, D. (2008). „Das persönliche Engagement derer, die hier sind, das ist doch das eigentlich Wertvolle“ – Die Bürgerausstellung als Forum für die Stimmen von BürgerInnen zur Zukunft der Energieregion Lausitz. Berlin: Zentrum Technik und Gesellschaft.
- KfW (2015). KfW – Bank aus Verantwortung. <https://www.kfw.de/kfw.de.html>, Accessed date: 1 December 2015.
- Kirkegaard, J. F., Hanemann, T., Weischer, L., & Miller, M. (2010). *Toward a sunny future? Global integration in the solar PV industry*. Washington, DC: Peterson Institute for International Economics.
- Klobasa, M., & Sensfuß, F. (2013). CO₂ – Minderung im Stromsektor durch den Einsatz erneuerbarer Energien im Jahr 2010 und 2011. Karlsruhe: Fraunhofer ISI.
- Koch, N., Fuss, S., Grosjean, G., & Edenhofer, O. (2014). Causes of the EU ETS price drop: recession, CDM, renewable policies or a bit of everything?—New evidence. *Energy Policy*, 73, 676–685.
- LAK (n.d.). Bruttostromerzeugung nach Energieträgern. <http://www.lak-energiebilanzen.de/bruttostromerzeugung-nach-energietraegern/>, Accessed date: 8 February 2018 n.d.
- LANUV (2013). *Potenzialstudie Erneuerbare Energien in NRW Teil 2- Solarenergie*. Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen: Recklinghausen.
- LANUV (2016). *Energieatlas Nordrhein-Westfalen – Daten- und Berechnungsgrundlagen*. <http://www.energieatlasnrw.de/site/nav2/Allgemeines.aspx?P=1>, Accessed date: 28 July 2016.
- Leipziger Institut für Energie (2014). *Kurzexpertise – Wirtschaftlichkeit Energiespeicher*. Leipzig: Leipziger Institut für Energie.
- Llera, E., Scarpellini, S., Aranda, A., & Zabalza, I. (2013). Forecasting job creation from renewable energy deployment through a value-chain approach. *Renewable and Sustainable Energy Reviews*, 21, 262–271.
- Llera-Sastres, E. L., Usón, A. A., Briñán, I. Z., & Scarpellini, S. (2010). Local impact of renewables on employment: assessment methodology and case study. *Renewable and Sustainable Energy Reviews*, 14, 679–690.
- Louwen, A., Sark, W. G. J. H. M., Schropp, R. E. I., Turkenburg, W. C., & Faaij, A. P. C. (2015). Life-cycle greenhouse gas emissions and energy payback time of current and prospective silicon heterojunction solar cell designs. *Progress in Photovoltaics: Research and Applications*, 23, 1406–1428.
- Memmler, M., Schrempf, L., Hermann, S., Schneider, S., Pabst, J., & Dreher, M. (2014). *Emissionsbilanz erneuerbarer Energieträger – Bestimmung der vermiedenen Verluste im Jahr 2013*. Umweltbundesamt: Dessau-Roßlau.
- Mertens, K. (2015). *Photovoltaik: Lehrbuch zu Grundlagen, Technologie und Praxis*. Carl Hanser Verlag: München.
- Miller, R. E., & Blair, P. D. (2009). *IO analysis: Foundations and extensions* (2nd ed.). Cambridge: Cambridge University Press.
- Nordhaus, W. (2014). Estimates of the social cost of carbon: concepts and results from the DICE-2013R model and alternative approaches. *Journal of the Association of Environmental and Resource Economists*, 1, 273–312.
- Nugent, D., & Sovacool, B. K. (2014). Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey. *Energy Policy*, 65, 229–244.
- OECD (2017). Economic outlook No 101 – June 2017: GDP deflators, forecast growth. <http://stats.oecd.org/Index.aspx?QueryId=61354>, Accessed date: 8 February 2018.
- Perez-Arriaga, I. J., & Battle, C. (2012). Impacts of intermittent renewables on electricity generation system operation. *Economics of Energy & Environmental Policy*, 2, 3–18.
- Preiss, P., Roos, J., & Friedrich, R. (2013). *Estimating health risks caused by emissions of air pollutants from coal fired power plants in Europe*. Stuttgart: Institute for Energy Economics and the Rational Use of Energy.
- Quitrow, R. (2015). Dynamics of a policy-driven market: The co-evolution of technological innovation systems for solar photovoltaics in China and Germany. *Environmental Innovation and Societal Transitions*, 17, 126–148.

- Rebittz, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., et al. (2004). Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International*, 30, 701–720.
- Reichmuth, M., Erfurt, I., Lorenz, C., Schiffler, C., Kelm, T., Schmidt, M., et al. (2011). Vorbereitung und Begleitung der Erstellung des Erfahrungsberichts 2011 gemäß § 65 EEG im Auftrag des Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit - Vorhaben Ilc Solare Strahlungsenergie. http://www.ie-leipzig.com/010-dateien/referenzen/pdf/vorbereitung_und_begleitung_bei_der_erstellung_eines_erfahrungsberichtes.pdf, Accessed date: 8 February 2018.
- Remais, J. V., Hess, J. J., Ebi, K. L., Markandya, A., Balbus, J. M., Wilkinson, P., et al. (2014). Estimating the health effects of greenhouse gas mitigation strategies: addressing parametric, model, and valuation challenges. *Environmental Health Perspectives*, 122, 447–455.
- render (2016). *Projekinterner Datenbestand der Erneuerbaren Energien Anlagen in der Städteregion Aachen* (unpublished).
- Richardson, H. W. (1972). *Input-output and regional economics*. London: Weidenfeld and Nicolson.
- RWE Power AG (2009). Strom aus dem Westen – Der Tagebau Inden und das Kraftwerk Weisweiler. <http://www.indeland.de/assets/userfiles/img/locations/kraftwerk-weisweiler/kraftwerk-weisweiler-infobroschuere.pdf> accessed 08 February 2018.
- RWE Power AG (n.d.). Die Rolle der Braunkohle. <http://www.rwe.com/web/cms/de/76904/rwe-power-ag/energetraeger/braunkohle/>, Accessed date: 17 January 2017 n.d.
- Schlesinger, M., Hofer, P., Kemmler, A., Kirchner, A., Koziel, S., Ley, A., et al. (2014). *Entwicklung der Energiemärkte-Energiereferenzprognose. Projekt Nr. 57/12 Studie im Auftrag des Bundesministeriums für Wirtschaft und Technologie*. Prog-nos, EWI, GWS: Basel, Köln, Osnabrück.
- Schormann, P., & Behrla, B. (n.d.). Solaranlagen Portal. <http://www.solaranlagen-portal.com>, Accessed date: 8 February 2018 n.d.
- Schröder, A., Kunz, F., Meiss, J., Mendelevitch, R., & v Hirschhausen, C. (2013). *Current and prospective costs of electricity generation until 2050*. Berlin: DIW.
- Sherwani, A. F., & Usmani, J. A. (2010). Life cycle assessment of solar PV based electricity generation systems: A review. *Renewable and Sustainable Energy Reviews*, 14, 540–544.
- Simons, G., & Peterson, T. (2001). *California renewable technology market and benefits assessment*. Palo Alto, CA and Sacramento, CA: Electric Power Research Institute (EPRI) and California Energy Commission (CEC).
- Slattery, M. C., Lantz, E., & Johnson, B. L. (2011). State and local economic impacts from wind energy projects: Texas case study. *Energy Policy*, 39, 7930–7940.
- SMA (2013). Gewerblicher Eigenverbrauch von Solarstrom. <https://www.sma.de/partner/expertwissen/gewerblicher-eigenverbrauch-von-solarstrom.html>, Accessed date: 8 February 2018.
- StädteRegion Aachen (2011). Integriertes Klimaschutzkonzept für die Städteregion Aachen. http://www.gruene-region-aachen.de/wb_kv/media/PDF_Sonstige/IntegriertesKlimaschutzkonzept.pdf, Accessed date: 8 February 2018.
- Statistisches Bundesamt (2010). *Input-Output Rechnung im Überblick*. Wiesbaden: Statistisches Bundesamt.
- Sterner, M., Eckert, F., Thema, M., & Bauer, F. (2015). Der positive Beitrag dezentraler Batteriespeicher für eine stabile Stromversorgung - Kurzstudie im Auftrag von BEE e.V. und Hannover Messe. Regensburg, Berlin, Hannover: Forschungsstelle Energienetze und Energiespeicher (FENES), OTH Regensburg.
- Stix, E. (2014). Leitbilder der Raumordnung in Österreich - Ein beispielhafter Prozess? <https://www.arl-net.de/system/files/stix.pdf>, Accessed date: 8 February 2018.
- Stoddard, L. E., Abiecunas, J., & O'Connell, R. (2006). *Economic, energy, and environmental benefits of concentrating solar power in California*. Golden. NREL: CO.
- Tol, R. S. (2013). Targets for global climate policy. An overview. *Journal of Economic Dynamics and Control*, 37, 911–928.
- Turconi, R., Boldrin, A., & Astrup, T. (2013). Life cycle assessment (LCA) of electricity generation technologies: overview, comparability and limitations. *Renewable and Sustainable Energy Reviews*, 28, 555–565.
- Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy*, 28, 817–830.
- van den Bergh, J. C., & Botzen, W. J. (2014). A lower bound to the social cost of CO2 emissions. *Nature Climate Change*, 4, 253–258.
- von Bost, M., Hirschl, B., & Aretz, A. (2011). *Effekte von Eigenverbrauch und Netzparität bei der Photovoltaik*. IÖW and Greenpeace Energy eG: Berlin, Hamburg.
- Willeke, G. P., & Räuber, A. (2012). On the history of terrestrial PV development: With a focus on Germany. In G. P. Willecke, & E. R. Weber (Eds.), *Advances in Photovoltaics* (pp. 7–48). San Diego, CA, Waltham, MA, Oxford, London: Amsterdam. Academic Press.
- Wirth, H. (2014). Aktuelle Fakten zur Photovoltaik in Deutschland. <http://www.heliosgmbh.de/app/download/5793641699/Fraunhofer+ISE+Aktuelle+Fakten+zur+PV.pdf>, Accessed date: 8 February 2018.
- Wirth, H. (2017). Recent facts about photovoltaics in Germany. <https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/recent-facts-about-photovoltaics-in-germany.pdf>, Accessed date: 31 March 2017.
- Zeitung, Taunus (2012). Weniger Förderung: Lohnt sich die Solaranlage noch? In Taunus Zeitung 05/03/2012. <http://www.taunus-zeitung.de/ratgeber/hausundgarten/Weniger-Foerderung-Lohnt-sich-die-Solaranlage-noch;art780,391100>, Accessed date: 31 March 2017.