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Assessing the regional economic impacts of renewable energy sources – A literature review

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ABSTRACT

The transition of the global energy system is one of the main trends that offers opportunities as well as challenges for the economy. Most literature evaluates the impact of that transition at a national level. That view is broadened towards a regional scale. Due to the lower energy density of many renewable energy sources, renewable energy generation will be more decentralised, leading to potentially significant changes in the regional economy when transitioning to a renewable energy system. In this paper the current literature and methods of assessing regional economic impacts of a transition to renewable energy generation is reviewed. The findings suggest an overall need to clearly define the topics, such as technologies, that are assessed and the evaluated time period. A guideline for a regional impact assessment is provided, focusing on the suitability of applied impact assessment methods (employment ratios, supply chain analyses, input-output models, and computable general equilibrium models).

1. Introduction

Among researchers in the field of climate, it is widely accepted that the emission of greenhouse gases is changing the world's climate. This negatively impacts the ecosystem [1]. As the highest proportion (25%) of greenhouse gases is emitted by heat and electricity generation [2], increasing the development of renewable energy sources (RES) is an important strategy for reducing greenhouse gas emissions and thus combatting climate change.

Therefore, facilitating and accelerating the development of renewable energy technologies for the generation of heat and electricity is a key point in the global debate about the energy transition as it requires a structural change to the energy system [3]. This structural change creates new economic impulses (e.g. growth of the wind power industry) but also decreases investment in traditional energy industries (e.g. the lignite industry) [4].

On a spatial scale, the conventional energy generation system which is based on large centralised energy generation units is shifting to a smaller scale, decentralised, spatially dispersed system of energy generation [5].

The various renewable energy technologies (e.g. wind power, solar photovoltaic (PV) or geothermal energy) require different location factors and not every location may be equally appropriate. Therefore, a change in the spatial arrangement of energy generation systems is taking place. Traditional locations for energy generation (e.g. lignite or hard coal mining areas) may lose their substantial significance in favour of renewable energy generation locations, if the former do not possess suitable local conditions for the generation of renewable energy (RE),[1] which leads to economic losses. In contrast, locations where energy generation by non-renewable energy carriers does not take place may be integrated in the system and benefit economically due to the possibility of providing energy generation potentials for renewable energy systems, which is especially important for economically less-favoured regions such as rimlands. An example of a region making use of that potential may be the economically less favoured North German state Schleswig-Holstein which has aimed to achieve a share of 300% of its

List of Abbreviations: BEA, Bureau for Economic Analysis; CGE, computable general equilibrium; CHP, combined heat and power; CSP, concentrated solar power; EPRI, Electric Power Research Institute; ESCO, energy service company; FTE, full-time equivalent; GDP, gross domestic product; GVA, gross value added; GW, gigawatt; h, hour; IMPLAN, IMpact analysis for PLANning; IO, input-output; JEDI, Job and Economic Development; kW, kilowatt; LAU, Local Administrative Units; MW, megawatt; NDP, net domestic product; NREL, National Renewable Energy Laboratory; NUTS, Nomenclature des Unités Territoriales Statistiques; English, Classification of Territorial Units for Statistics; O&M, operation and maintenance; PV, photovoltaic; RE, renewable energy; REPP, Renewable Energy Policy Project; RES, renewable energy sources; RIMS, Regional Input-Output Modelling System; RIOT, Regional IO Table; SAM, social accounting matrix; SEED, Sustainable Energy and Economic Development; WEBEE, Modell zur Ermittlung von Wertschöpfungs- und Beschäftigungseffekten durch Erneuerbare Energien (Assessment model for value added and employment effects of renewable energies)

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[1] Regarding the discussion of changing spatial arrangements concerning energy systems from a historical perspective cf. Brücher [6].

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gross electricity consumption from renewable sources by 2025 [7], thus making the region a future electricity exporter. It can be concluded that changes which take place in the spatial arrangements of the energy system are characterised by a transregional crowding out of conventional energy generation plants and a development of renewable energy generation facilities in regions with sufficient potentials for this kind of energy generation.

Although there is a broad body of literature assessing the economic impact of shifting to a renewable energy system on a national scale (e.g. Hillebrand et al. [8]and Lehr et al. [9] for Germany, Wei et al. [10], for the US, or de Arce et al. [11] for Morocco), there is relatively little attention paid to the economic impact of RES on regions, whereas at this geographic level the changes may be more significant. Focusing on a lower geographic level concerning the effects of RES, developments may be beneficial for various reasons. Firstly, decision-making on the deployment of RES sometimes takes place at a local or regional level instead of the national level, because regions may have decision-making power to hinder, or promote the deployment of RES, as Jacobsson or Bergek [12] show this in an example of the Dutch wind power industry. Assessing the economic benefits of RES, will help decision-makers to understand the impacts of the development of RES in their regions. Besides the benefits for RE industry related businesses that are located in the region, information on the economic potentials may support other regional businesses in order to identify market opportunities or encourage businesses from outside to settle in a region. Therefore, the economic potentials of RES may offer a substantial opportunity for many regions.

Moreover, assessing the regional economic impacts of RES may be particularly important in regions where RES developments are observed critically, since illustrating the regional benefits leads to an increasing acceptance of RES by the population [13] which makes it easier for decision-makers and especially for elected ones to communicate positive aspects and decide in favour of RES developments.

Furthermore, because of spatially diverse natural conditions, potential economic impacts should be evaluated rather on a regional than on a national scale (unless the potentials in a country are evenly distributed). For example, the average yearly full-load operating hours of wind turbines are approximately 1/3 higher in Schleswig-Holstein (North Germany), than in Bavaria (South Germany) [14]. Additionally, in some countries RES industries are found spatially concentrated. For example, in Germany, approximately 23% of the employees of the wind power industry were employed in the North German federal state Lower Saxony in 2013 [15].

As conditions vary, it is important for regional decision-makers to evaluate which technologies include the best economic potentials in terms of natural conditions available and where regional economic potentials may efficiently be exploited in order to benefit from the opportunities of the energy transition. Relying on national impact assessments does not adequately take into account the specific local and regional natural conditions and economic potentials in a country and provides no solid decision support for regional decision-makers when defining a regional RES strategy.

In the case of the German wind power industry it has been found that regions take advantage of the potentials because there is a more progressive deployment of wind power in the North of Germany (which has a more favourable wind regime), than in the South (BDB [16] in Leipziger Institut für Energie [17]). Nevertheless, potentials may still not be fully exploited which calls for comprehensive economic impact assessments on a regional scale. These assessments should be attached to regional energy potential studies or regional energy strategies covering economic and ecological effects of renewable energy developments using an integrated approach.

Conclusively, national economic assessments are useful for defining an overall national RES strategy covering e.g. legal frameworks or financial support of economically promising RE technologies. However, when it comes to regional decisions of RES deployments or a definition of a regional strategy for RES developments which may be location and technology specific, regional assessments are more beneficial than national evaluations and complement them. The overall aim of the paper is to provide a review of existing literature in the field of regional economic impacts of RES and to set up a guideline for impact assessments. One cannot claim to refer to economic development as the most important aspect concerning a sustainable regional development which covers issues of “environmental quality, social equity, and economic welfare” [18]. Evaluating environmental quality or social equity concerning RES deployment are also important issues of the discussion [19]. However, the aim of the study is not to narrow down a sustainable regional development only to economic aspects, but to focus on economic development by RES as an important part of the debate.

The paper especially addresses researchers and analysts involved in the field of RES and regional economic impact analyses. Besides presenting existing literature, necessary steps to be taken in assessments are illustrated, as well as a critical review of the advantages and disadvantages of applied methods in the field so as to assist in choosing a suitable method for individual regional impact assessments. Furthermore, practitioners and regional decision-makers are informed about the possibilities and potential benefits of economic impact analyses which may encourage them to integrate such analyses in RES strategies, legitimating RES developments in their regions.

After referring to the procedure of literature selection and analysis (Section 2), evaluated regions, assessed technologies and time periods of publications are illustrated and discussed (Section 3). Four general methodological impact assessment approaches were identified i.e. employment ratios, supply chain analyses, input-output modelling, and computable general equilibrium models. A review of these approaches is provided in Section 4, including a detailed analysis of methodological strengths and weaknesses. The conclusions discuss the findings and provide guidelines for a comprehensive impact assessment for RES transitions (Section 5).

2. Process of literature selection

Although it cannot be claimed that every existing study in this field has been evaluated, a large body of literature has been analysed in order to capture the current debate and developments on evaluating and assessing the regional impacts of RES. Assessment methods which have been applied in the different papers are discussed concerning their strengths and weaknesses and applicability in specific contexts, which may help researchers to identify suitable methods regarding regional impact assessments.

To find relevant publications, a literature search was conducted, using the keywords ‘economic impacts’, ‘economy’, and ‘renewable energy’ in English and German. The most used sources were the internet platforms ‘Google’, ‘Google Scholar’, ‘ScienceDirect’, and ‘Web of Science’.

After scanning the literature references of appropriate publications to further identify literature, all relevant English and German speaking publications were filtered by including only literature concerning economic impact assessments on a regional scale. German publications were integrated as well, since they included various approaches which were not applied in English papers on a regional scale. In addition, German publications were used to evaluate the approaches to a non-German speaking audience.

The term region may be defined differently given the research context [20], and refers to an administrative unit on the sub-national scale in this paper. Because of the fact that the characteristics of administrative units in countries (e.g. size, population) may vary on an international scale, European regions have been categorised into the NUTS (Nomenclature des Unités Territoriales Statistiques; English: Classification of Territorial Units for Statistics) system on EU scale. In the non-European examination areas, which consist of regions in the United States the national classifications have been used (Section 3.1).

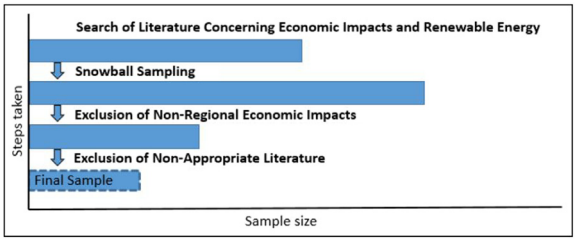

Fig. 1. Schematic illustration of the literature research and scaling down process with steps taken (in bold letters) and approximate sample size.

The 81 publications identified were scaled down to 54 publications (these include 42 publications in English and 12 in German). Excluded publications contained a different version of studies reported in earlier studies. Solely methodological papers were included in Section 4 in this paper. Fig. 1 illustrates the literature research process schematically. Limitations of the approach are that literature which was not found might exist, because it was not registered in the used search engines, nor cited by the reviewed articles. Moreover, literature which has not been published in English or German is not included.

If an English and German version of a publication existed, the English version was evaluated due to a better comprehensibility for non-German speaking readers. Most of the publications (70%, n = 42) were published from 2005 to 2015, whereas only one publication dating from before 2000 (1995) was identified and one publication contained no publication date.

Eleven publications were journal articles in peer reviewed journals and 43 publications were grey literature such as project reports. This demonstrates an apparent lack of attention in the peer reviewed literature, despite a quite broad body of literature in the field.

3. Evaluated regions, technologies, impacts and time periods

At the beginning of this section, countries and regions where regional economic impacts have been evaluated are discussed (Section 3.1). The next step presents RE technologies that have been analysed in the publications (Section 3.2). Additionally, different economic impact measurement indicators that have been investigated in the reviewed literature are defined including an assessment of the quality of individual impacts (Section 3.3). The studied time periods of the impact assessment are discussed in Section 3.4.

3.1. Regions covered by the reviewed publications

Most of the publications refer to regional economic impacts in the United States (US) (n = 33), followed by Germany (n = 12), Spain (n = 5), Austria (n = 2) and the United Kingdom (UK) (n = 2). Concerning the publications about US regions, short fact sheets about the economic benefits of 1000 MW (MW) of wind power in 15 different states were identified. Due to the fact that these short reports were written by the same authors using exactly the same methods [21–35] they have been counted as a single publication (Table 1).

To enable an approximate categorisation of the different regions regarding their spatial scale, the publications which concern European regions are categorised using the NUTS system. The NUTS classification is a European system which enables a broad comparability of administrative units on an international scale. In the classification, a NUTS 0 region refers to countries and NUTS 1–3 regions refer to regions. The difference between the categories is based on population thresholds and covers administrative divisions, whereas the higher the classification number, the smaller and less populated the region. LAU (Local Administrative Units) refer to municipalities or comparable administrative levels in the EU [36]. However, European NUTS classifications are naturally not existent in the United States. Concerning US states the US spatial categorisations ‘states’ and ‘counties’ are used. In the following table, other regions refer to territories which are not defined by the NUTS classification or which are aggregated regions (e.g. the Mid-Atlantic region in the US which is formed by four states but not clearly defined as an administrative unit). Some regions have been analysed multiple times. Therefore, the number of different evaluated regions in a country is depicted in brackets.

Regarding the publications concerning European regions, the most often assessed administrative units are on NUTS 1 level, whereas specific economic impacts have been assessed for all 16 NUTS 1 regions in Germany. Consequently, a comparability of European regions regarding an impact analysis may be more reasonable at the NUTS 2 level, for which publications from three different countries have been identified. However, when comparing the impacts of RES in different regions, specific regional characteristics should be considered, which are discussed in Section 5.

In the US, the most often evaluated territories are at county level, followed by regions on state level. On state level, 25 different states have been assessed including the State of Texas which is the most analysed region in the whole sample (4 publications).

When assessing the impact of RES, it is important to clearly define the country or region where impacts are assessed due to, for example, different characteristics of the regional economy, individual costs for products and services, or labour productivity in various regions [37]), which obviously affect the results. Assessing impacts on an aggregated territorial scale without differentiating between individual administrative units bears further disadvantages. First of all economic statistics, which are necessary for a comprehensive analysis are often not available on an aggregated scale. Moreover, policy actions that are based upon impact assessments are in most cases initiated by individual political institutions in the respective administrative units and if benefits for individual administrative units are not illustrated, actions may not take place. Therefore, regions should be clearly defined administrative units.

The NUTS classification is a useful system that enables a cross-state categorisation of European regions, but unfortunately there is no comparability to non-European administration systems such as the US. Therefore, to enable a comparison between European and non-European regions, data about the specific characteristics of regions such

Table 1
Spatial scale of the analysed territories and language used.

	Country	NUTS 1	NUTS 2	NUTS 3	LAU 2	Other	Language	
							English	German
Europe	Austria (n = 2)		1	1		1	2	
	Germany (n = 12)	25 (16)*	1	2	11	4		12
	Spain (n = 5)		5				5	
	UK (n = 2)	2					2	
USA	USA (n = 33)	**State**		**County**		**Other**	33	
		42 (25)		49		2		

* Total number of assessed regions ‘25’ and different analysed regions in brackets ‘(16)’.

as the area size, population, etc. should be taken into account.

Nevertheless, in terms of comparability of economic impacts of RES in regions, individual characteristics of regions like the regional economy [38] or natural conditions (Section 1) play a role which makes them unique and in a way incomparable. Therefore, the primary goal of an impact assessment should not be the comparability of regions but rather to develop a scheme to optimally measure regional economic impacts (Section 5).

3.2. Technologies covered by the reviewed publications

It is important to define which RE technologies are assessed, because regional economic impacts differ between various technologies. For example, the impact of a small solar PV plant on the local economy may differ from the impact of a large hydro plant. Moreover, in some regions a technical or economical potential for the applicability of a technology might not exist (e.g. installing solar PV systems in a region with insufficient global radiation or wind plants in regions with unfavourable wind conditions).

A first distinction of RE technologies may be made by the applicability of a technology. In this case, heat, electricity, or fuels can be defined as potential energy types. Some authors do not clearly define the type of energies being assessed. In the analysis the focus lies on heat and electricity only. Only a few regional studies focusing on heat and electricity evaluate the economic impacts of biofuels as well (e.g. Moreno and Lopez [39]), which is insignificant in the subsequent literature review. Fig. 2 shows the technologies evaluated and the type of energy such as electricity or heat which is produced by that RE technology.

In the graph only 51 articles are included, because three articles did not focus on the economic impact of a defined RE technology but on an aggregation of several technologies to a RE system.

Most publications deal with RE systems regarding electricity generation. In the sample 15 specific technologies, and 111 evaluations of electricity generation technologies were identified. Heat generation was assessed for 8 technologies and 24 times in the sample. Some RE technologies, like biomass, provide the potential to generate electricity as well as heat (e.g. in a combined heat and power (CHP) system). Therefore, some authors did not distinguish between electricity or heat regarding the assessed technologies. Moreover, some authors did not clearly refer to the kind of energy which is produced by the technology. In these cases, it has been assumed, that both heat and electricity are generated. Regarding the technologies solar and bioenergy, the authors used the terms as an aggregation of several technologies.

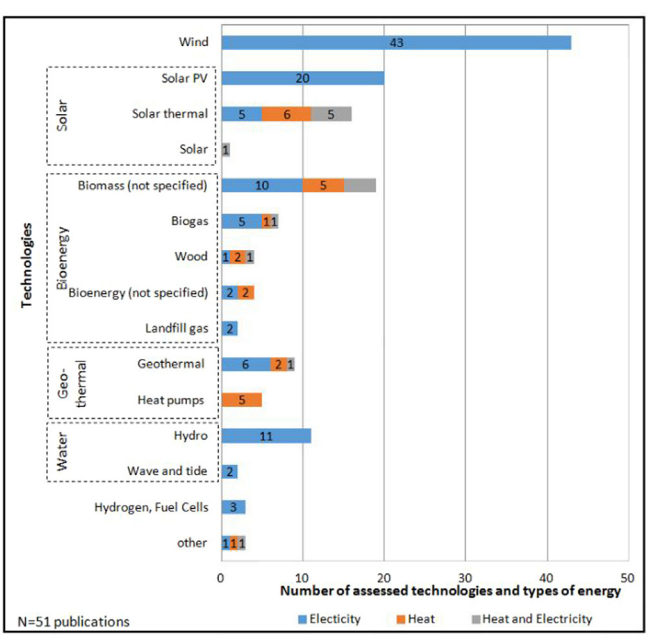

Fig. 2. Number of assessed technologies and types of energy carrier.

84% (n = 43) of the publications deal with electricity generation using wind power. The following most important technologies are solar PV (n = 20) and biomass (n = 19). Therefore, it can be presumed that the outcomes of often analysed RE technologies are more robust than less evaluated technologies. Conclusively, the technology as well as the type of energy (i.e. electricity or heat) should be precisely indicated by the authors in their publications, to permit a clear distinction between technologies assessed and their comparability concerning an impact assessment in different regions. A distinction between technologies is important because of different conditions (solar irradiation, or wind pattern) which may lead to different economic impacts. Moreover, not every technology may be efficiently deployable and usable in every region because of varying geographic conditions (Section 5). Distinguishing between technologies in a study may help to understand this factor better.

3.3. Economic impact indicators assessed by the reviewed publications

Economic impacts can be evaluated by different criteria. One of the most assessed criteria is the number of employees, which is assessed by 93% of the publications (Table 2). There is sometimes no comparability of the indicator employment because some studies take into account part- and full-time jobs [10] or even do not provide any information about whether part- or full-time jobs are assessed (e.g. Moreno and Lopez [39] SEED Coalition and Public Citizen's Texas office [40]). To enable a comparability between different publications and to the number of total jobs in an area, the number of jobs should always be assessed in full-time equivalents (FTE) or person-years. This is the case for 62% of the publications which assess RE related jobs (93% of all publications).

The assessment of fiscal effects, which is evaluated by 59% of the publications are a good example of the financial participation of local or national governments in the local RE industry. This impact is hardly comparable on an international scale because of the various tax systems and different tax rates [41]. Regarding the example of Germany, Hirschl et al. [42] for instance, assess every tax occurring in the whole RE industry (e.g. taxes of operating RE by the plant owners as well as taxes of manufacturers of RE equipment and businesses involved in the installation and operation of RE). Another economic impact are the salaries of employees in the RE industry. The significance of that impact is qualitatively higher than the mere number of employees which does not

Table 2
Number of assessed economic impacts in the reviewed publications.

Number of Evaluations (N = 54)	in %	Impact Categories
50	93	Number of employees (incl. FTE)*
31	57	Number of employees in full-time equivalents (FTE) or person-years
32	59	Regional taxes
27	50	Salaries of employees
21	39	Landowner benefits
19	35	Gross output
15	28	Other economic impacts
13	24	Gross value added
11	20	Owner of plants revenues
9	17	Proprietor income of firms
4	7	Investment
4	7	Regional GDP
1	2	Turnover

* If it not has been pointed out, that full-time equivalent jobs or person-years have been assessed, it has been assumed that only the number of employees has been evaluated.

include the quality of generated jobs, which may be highly paid white- or low paid blue-collar jobs. Highly paid jobs have potentially larger economic impacts because earnings are ideally spent in the local economy leading to higher regional economic impacts (i.e. induced effects). Induced effects have been calculated by for example [43].

Landowner benefits arise from land lease payment from the plant operator to a landowner and occur mostly for the development of wind power plants. However, for some other space-intensive technologies such as large roof-top and ground-based solar PV plants, affordable spaces may also be not owned by the operator. In Germany, platforms already exist like for instance Solardachbörse, where property owners let spaces for roof top systems (Internationales Wirtschaftsforum Regenerative Energien [44]), which is a common business model. Therefore, an assessment of land lease payments for other land intensive technologies such as large-scale solar PV plants, or concentrated solar power (CSP) should be assessed in more detail, which has been done by for example BMVBS [45] or Hirschl et al. [42].

Moreover, macroeconomic key figures such as gross output, gross value added and gross domestic product (GDP) are evaluated by some publications. Gross output at market prices refers to all revenues of economic agents in a territorial unit. It is calculated by the addition of sales of these agents in a defined period [46]. Gross output is investigated by approximately one third (35%) of the publications. Because of different cost structures and specific characteristics (e.g. the performance) of different RE technologies (e.g. Bröcker et al. [47]), it is important to precisely define economic impacts of specific technologies and not the impacts of RE by aggregating several technologies like for instance Deyette and Clemmer [48] who illustrate the aggregated employment impacts of solar PV and Wind. Gross output, which is referred to as 'economic activity' in some publications (Costanti [49]or Lantz [50]), is mainly assessed for the wind power industry (Table 3).

The gross value added (GVA) at market prices can be calculated by subtracting all inputs at purchaser prices from the gross output. Gross value added has been assessed by one fourth (24%) of published studies and has been evaluated for nearly all RES technologies. Regarding the assessment of GDP, it has only been analysed by two publications for wind, biomass, and a number of aggregated RES technologies. By adding the taxes on products less the subsidies on them, the gross domestic product which includes the final monetary value of goods and services [51] is assessed. The net domestic product (NDP) is the product of the subtraction of consumption of fixed capital. Because of the spatial scale of analysis, only the gross domestic product on a regional scale, which may also be referred to as the gross regional product [52] is assessed in the publications.

Other economic effects such as value of rights of conserved water, (Heavner et al. [53]) or costs avoided for the generation of coal and gas (e.g. Deyette and Clemmer [54]) are pointed out by approximately one fourth (28%) of the publications as well.

Benefits of plant operators have been assessed and depicted by only 11 (20%) of the publications but for almost every technology, whereas 9 publications refer only to RE in Germany. The generation of renewable energies is linked to locations where the deployment of RE plants is technically and economically feasible because the potential economic benefits for the generation of energy are dependent upon the region's natural resources (e.g. solar irradiation or the wind pattern). Moreover, the development of RES is dependent upon economic profitability of the project and therefore is the main factor for the installation of RES. Henceforth, there is a lack of comprehensive evaluation of owner revenues among the publications about regional economic impacts of RES.

Other effects include the proprietor income of renewable energy industry businesses, investments in RE and turnover of involved businesses (Table 2).

Table 3 shows the indicators assessed for the specific RE technologies, distinguishing electricity and heat. Some technologies enable the generation of electricity and heat, which is referred to as electricity, heat aggregated in the table (Table 3).

Economic impacts may also be classified as primary or secondary effects. Primary effects refer to direct and indirect economic effects [55]. Direct impacts refer to purchases of one industry from other industries to satisfy the demand for new RE plants, for example. In order to enable these transactions, these other industries have to purchase goods or services from suppliers which also purchase goods from their suppliers. These effects are defined as indirect effects [56]. An increase of production by the generated demand leads to additional income of employees and business proprietors of directly and indirectly affected industries. The part of income which is spent by these subjects for example for consumption goods leads to additional secondary effects which are described as cumulative or induced effects.

Direct and indirect effects are assessed and presented by 21 papers. However, the definition and differentiation between direct and indirect effects vary among the publications. Whereas, for example, the Job and Economic Development Impact model (JEDI) that is used by Lantz [50], Slattery et al. [43] and others (Table 7) defines all on-site effects of installation, construction, and manufacturing of plant modules as direct effects [57]. BMVBS [45] defines benefits generated by the generation of electricity by RES as direct effects and all other effects, such as installation and maintenance of RE as indirect effects. Therefore, it is not possible to compare direct and indirect effects among the papers if they do not use the same definitions or methodology. Induced effects have been illustrated by 14 publications. However, total impacts are the same although the categorisation of direct and indirect effect varies. Therefore, in order to enable a comparison of impacts, publications should explicitly describe the impacts concerning their stage in the product lifecycle before categorising them into direct and indirect effects according to their individual definitions.

With respect to the economic impact of different stages in the product lifecycle of different technologies, it is important to stress which stages are assessed in the analysis of economic impacts. Although their specific characteristics may vary between technologies, the lifecycle of RE systems can be divided into five stages which are; research and design, development and manufacture, construction and installation, operation and maintenance (O&M) or service, updating and/or dismantling [88]. Most authors use only an aggregated version of the lifecycle by dividing it into two stages which are 1) manufacturing, construction, installation, and 2) operation, maintenance.

Authors often use the term construction for the stages manufacturing, construction, and installation (e.g. Reategui and Tegen [58]; Stoddard et al. [59]) to describe the different stages. In order to refer to the ambiguous meaning of the term construction, which may concern the construction activities during the installation of a RE plant only, it should be pointed out clearly which stages are included in the analysis and a clear distinction between manufacturing, construction and installation and operation and maintenance should be made. Authors that take into account installation separately without aggregating the installation and the manufacturing lifecycle stage are for example Algoso and Rusch [60] or Hirschl et al. [61]. A separation is important in order to estimate the economic impact and compare it to other regions because while a region may not have potential manufacturing resources, local businesses may nevertheless participate economically in the installation phase.

Most authors do not specify which industries may benefit from economic impacts. This may be an important piece of information for businesses or local economic development organisations. Some authors refer to specific sectors such as finance, insurance and real estate or construction [62,63] that allows a more specific view on affected industries. However, the RE industry is a cross sectoral industry that is difficult to define because it is usually not statistically classified as an industry (Section 4). Therefore, it is challenging to identify which businesses in the sector finance, insurance and real estate may be involved in RE related activities.

Regarding other economic activities affecting local impacts of RE such as research and design, only one publication [42] points out their

Table 3
Total number of assessed economic impacts per renewable energy technology.

Type of energy	Assessed Technologies	Number of employees (including FTE)	FTE	Regional taxes	Salaries of employees	GVA	Proprietor income of businesses	Owner of RE plants revenues	Other economic impacts	Landowner benefits	Gross output	Investment	Regional GDP	Turnover
Electricity and electricity, heat aggregated	Hydro (n = 11)	9	6	8	6	6	5	5	2	1				
	Wind (n = 43)	39	25	26	22	10	8	9	7	20	15	1	1	
	Solar (n = 1)	1												
	Solar PV (n = 20)	18	12	9	9	7	6	6	3	2	2	1	1	
	CSP (n = 10)	9	3	3	2	1	1	1	2		2	1		1
	Wave and tide (n = 2)	2	1		1	1			1		1			
	Bioenergy (n = 2)	2	1	1	1	1	1	1						
	Biomass (n = 14)	14	8	4	5	4	4	4	2		1	2	1	1
	Biogas (n = 6)	5	4	5	5	5	4	4				1		1
	Wood (n = 2)	2	2	1	2	1	1	1			1			
	Landfill gas (n = 2)	2		1	1				1		1			
	Geothermal (n = 7)	7	5	3	2	2	2	2	2			1		
	Hydrogen, Fuel Cells (n = 3)	3	2						2					
	Other (n = 2)	2	2	2	2	2	2	1						
Heat and electricity, heat aggregated	Solar (n = 1)	2												
	Solar thermal (n = 11)	11	6	5	5	5	5	4	2			1		1
	Bioenergy (n = 2)	2	1	1	1	1	1	1						
	Biogas (n = 2)	2		1	1	1	1							
	Wood (n = 3)	2	2	2	2	2	1	1	1		1			
	Biomass (n = 8)	8	5	4	3	4	3	3	2			1		1
	Heat pumps (n = 5)	4	4	5	5	5	5	4						
	Deep Geothermal (n = 3)	3	3	2	2	2	2	2		1				
	RES aggregated (n = 3)	3	1	3	2	1	2	1	3	1		2	1	
	Other (n = 2)			1					1					

local economic impact. Other authors also include this in their studies, but aggregate it with other activities (e.g. Bezdek [64] or Faulin et al., [65]).

Most of the publications refer only to economic impacts generated by regional demand, for example effects, which are generated by the installation of RE plants within the region studied. Exports outside the studied region by manufacturers or other enterprises, such as RE service companies are often not included in the analyses (e.g. ZSW [66], Coon et al. [63]). However, a comprehensive analysis of local economic impacts generated by the RE industry include regional demand as well as exports. Whereas some regions may have a significant natural potential in terms of energy generation, other regions may have a considerable potential of manufacturing enterprises which produce RE components. Publications which include impacts that are generated by non-domestic regional demand are for example Heavner and Del Chario [53] and Ulrich et al. [38].

Another difference in impact assessment concerns the evaluation of gross or net impacts. Whereas gross impacts concern only the positive impacts generated by RES deployment in the RE related sectors, net impact studies take into account a comprehensive economic analysis of effects. The aim of net impact studies is to provide a view of overall effects which are generated by investment in RES on the one hand and on the other hand disinvestment in for example fossil energy sources [55]. In the sample, a comprehensive net impact study is assessed only by Weisbrod et al. [62]. All other publications are gross impact studies of RE deployment. However, some publications [59,60]take economic impacts of technologies into account which are based on fossil fuels to enable a comparison of potential effects, although they do not carry out a comprehensive net impact analysis. Moreover, studies which are based on computable equilibrium models (Section 4.4) take regional competition for resources (e.g. labour [67] or land rent [68]) into account, which leads to negative impacts as well. Concerning net impact studies, positive and negative effects should be precisely pointed out to enable a comparison with other (e.g. gross impact) studies.

3.4. Time periods analysed in the reviewed publications

The installation costs for wind power plants in the United States, for instance, decreased by 20–40% between late 2008 and 2015 [69]. Therefore, due to transparency and comparability reasons, the time period of economic impacts should be specified so that publications which include different time periods are comparable. Especially in a dynamic market such as the RE industry, costs and therefore impacts are highly volatile over time for specific technologies [70,71]. However, 12 publications do not indicate what periods are assessed in their study and 7 publications only deal with the economic impacts of a single year. Fig. 3 depicts the assessed time periods of the publications. Whereas 3 of them deal with historical economic impacts which occurred before the time the paper was written, most of the 35 papers describe future economic impacts (n = 32). Although an ex-post analysis may be valuable in terms of a precise evaluation of the RE industry because of available and reliable data, the particular strength of an analysis of future impacts lies in the assessment of potential chances for the regional economy. By estimating future RE deployment and therefore economic opportunities, the local economy may successfully adapt knowledge in the context of RE in terms of becoming a "learning region" [72] to satisfy future demand.

Most of the publications (23%) deal with impacts that occur in a period within 21 different years, which is the assumed average operation period for most technologies (20 years plus 1 year if the operation starts in the middle of a year) [47,73]. 19 publications assess up to 20 years of RE deployment (10 up to ten years), while only 8 publications deal with periods longer than 21 years.

The longest period is regarded in Gilmartin and Allan [67] since they take into account the impacts in a period of 100 years. Most of the publications refer to either one or two technologies or many technologies (six or more).

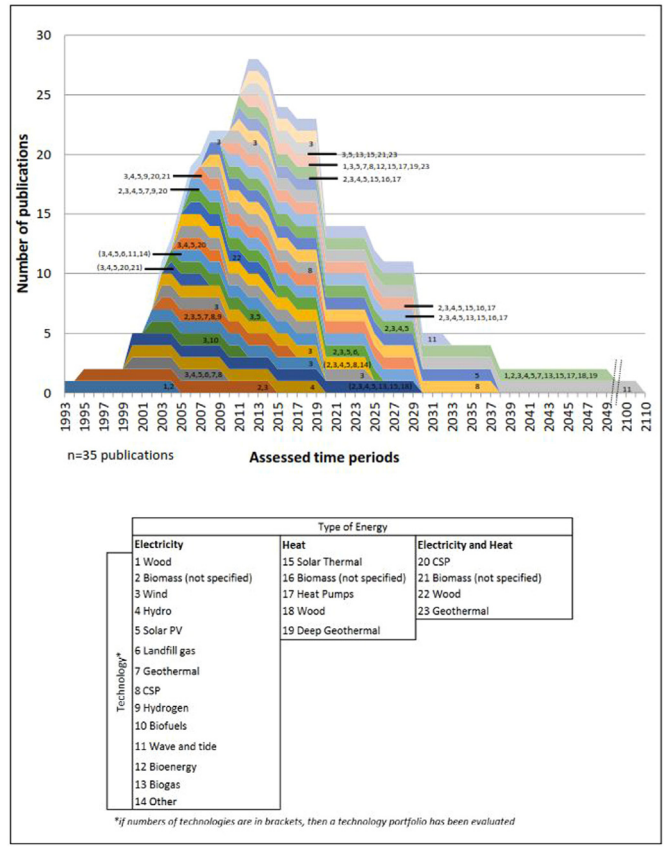

Fig. 3. Analysed time periods and technologies of the publications.

Some publications like, e.g. Loomis and Hinman [74], Finus et al. [75] or Slattery et al. [43] deal with specific RES capacities that are installed at the beginning of the investigated time period and do not consider further RE development in the region during the evaluated period. Other authors like Lantz [50] or Bröcker et al. [47] take into account deployment during the whole period as well. When assessing deployment which occurs during the whole time, cost reductions of specific technologies because of learning effects, economies of scale (because of the market expansion of a technology) [76] should also be taken into account. Even when assessing an allegedly short time period, costs may develop rapidly, as can be shown by the example that the average prices for solar PV systems in Germany decreased by 69% between the second quarter 2006 and the first quarter 2013 [77]. Whereas most of the authors take cost reductions into account (like for example Fanning et al. [78] or Deyette and Clemmer [48]), some authors (like e.g. Heavner et al. [79] or Madsen et al.[80]) point out that they do not consider them in their analysis. Other authors provide no details about cost reductions (Section 4.1).

Some publications (e.g. GAO [81], Algoso and Rusch [60]) take existing scenarios into account such as 20% of electricity needs in the United States is to be generated by wind power by 2030 [82] which is referred to by Lantz [50]. Other authors deal with a stable amount of RE deployment like an installed capacity of 10 MW of RE in the region observed [83,84].

In conclusion, time periods which are analysed should be specified and cost developments over the period should be taken into account when assessing RE development over time. Comparable periods for operation and construction should ideally be assumed, e.g. 20 years for wind or solar PV[2] to enable a comparison of different studies. Moreover, future RE deployment should follow national or regional development scenarios or targets

[2] The lifetime of individual plants may differ from 20 years of operation and last longer [85] for wind power; [86] for solar PV).

to provide a realistic perspective on future impacts.

4. Evaluation of methods

The approaches mainly applied in the reviewed literature sample are analytical methods like employment ratios (Section 4.1) and supply chain analyses (Section 4.2) as well as methods based on economic models such as input-output models (Section 4.3) and computable general equilibrium models (Section 4.4). In the following a description of the strengths and weaknesses of the approaches is evaluated, preparing the ground for the discussion in Section 5 where the most suitable methods depending on the size of the region, the time of assessment, and the economic indicators are proposed.

4.1. Employment ratios

Employment ratios or employment factors are used to assess the employment which is generated regarding the total installed capacity or prospective capacity of a specific technology. The sum of jobs is calculated by multiplying the installed or prospective capacity of a technology (in kilowatt (kW), megawatt (MW), or gigawatt (GW) etc.) with a defined ratio of employment per kW, MW, or GW. In case of Biomass generation, employment ratios may also be illustrated by employment per gigawatt hour (GWh) (Fig. 4).

Table 4 shows the publications that deal with employment impacts of specific RE technologies by using the employment ratio approach. Regarding the energy type, electricity is the most evaluated energy type, whereas heat is only assessed by 3 papers. Most of the evaluations (n = 10) deal with wind power, followed by solar PV (n = 7).

Some authors use employment factors that are derived from the same sources (Table 5). Employment factors which have first been used by Simons and Peterson [89] for example have also been used by Heavner et al. [79], Heavner and Del Chario [53] and Madsen et al. [80]. The approach that is used by Sterzinger et al. [90] in a regional context was originally described by Singh and Fehrs [91]. Moreno and Lopez [39], Llera-Sastresa et al. [88], and ZSW [66] use employment ratios which are derived by the comparison of different publications, which use employment factors. The Sustainable Energy and Economic Development (SEED) Coalition and Public Citizen's Texas office [40] also provides a multiplier for indirect jobs of wind RE deployment which is used by Heavner et al. [79] and Madsen et al. [80] for the calculation of indirect jobs. However, the applied methodology for the calculation of this multiplier remains unclear.

An advantage of the methodology is its simplicity. Necessary information consists only of the installed or to be installed rated capacity and the employment ratio. Regarding disadvantages of the approach, large differences between ratios even for the same technologies and lifecycle stages occur. Moreover, it is not sufficient to use employment ratios from other regions, because of different levels of productivity or other specific characteristics [39]. Llera-Sastresa et al. [88] state that even for the same region employment ratios should be used in combination with additional information such as ratios for specific stages in the product cycle e.g. manufacturing, installation and O&M. This information would strengthen the significance of the approach because reporting the mere number of jobs enables no insight into the quality of jobs, which may be higher paid white- or lower paid blue- collar jobs and hence generate different earnings and economic impacts. Additionally, some regions may not have an available trained workforce for certain lifecycle stages (e.g. engineers for the design of RE technologies), which is assumed in the calculation of the employment ratios.

Many authors use employment ratios without referring to the methodology which has been used to deduce the employment factors. An approach to estimate the ratios may be to evaluate the working hours for every activity in the product cycle of a specific technology and divide it by the typical working hours of a period (usually a year),

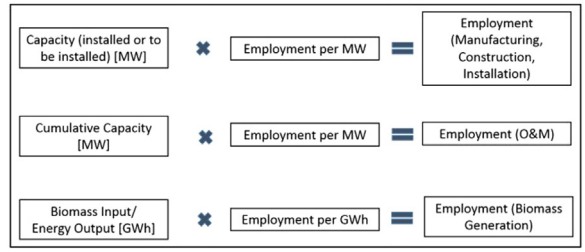

Fig. 4. Calculation of employment using employment ratios (Source: Böhmer et al.[87], modified).

which yields person-years of full-time equivalent jobs per rated capacity of a technology. Such evaluations are accompanied by extensive data assessment and comprehensive surveys. The REPP approach which is used by Sterzinger [90] or Algoso and Rusch [60] for example is based on the inquiry of Singh and Fehrs [91] that assesses the working hours of various RE industries.

When using employment ratios over a period of time (e.g. in a future scenario) some authors use fixed employment ratios over the whole time (e.g. [80,89],). Other authors such as Heavner and Churchill [92] or SEED Coalition and Public Citizen's Texas office [40] assume a simple cost reduction due to learning effects and productivity, but do not point out at which specific stage in the lifecycle cost reductions occur. For instance, it is assumed that costs decrease by 10% for the construction period and 5% for O&M per year [92].

Conclusively, employment ratios are an 'easy-to-use-instrument' to evaluate the employment impacts of RE development in a region. However, ratios should be used with caution and further information is needed to make a more transparent analysis possible. It should be pointed out which technologies and which part of the product lifecycle have been assessed in order to enable a transparent comparability of factors and an adaptability of employment factors if changes occur (e.g. new production technology which enables an enhanced productivity in the manufacturing sector). Moreover, because of dynamic markets, ratios should be assessed up do date to take into account cost changes (Section 3). Finally, cost reductions due to technological learning should be included when using ratios for future scenarios. In any case, the application of employment ratios for employment assessments in future scenarios should be scrutinised with regard to the advantages of other methods.

4.2. Supply chain analysis

Supply chain analysis is a methodology for assessing the economic impact of RE deployment by evaluating the supply chain of individual technologies.[3] The supply chain which consists of subordinated tiers is drawn up and the economic impact of each tier is assessed. By assuming typical project investment and operating costs for specific RE technologies, which may also include different plant sizes, the benefits of RE plant developments can be calculated. Moreover, investment and operating costs may also be interpreted as revenues of enterprises which are part of the tier 0 level, like the turnkey contractor. These revenues may be broken down into material costs, labour costs, and revenues, including taxes. By assessing the net earnings of the employees, the net revenues of business proprietors, and taxes, the economic impact of a RES technology on tier 0 can be estimated. Additionally, material costs of tier 0 suppliers (e.g. turnkey contractors) can be interpreted as revenues of tier 1 suppliers (e.g. suppliers of the wind turbine) (Fig. 5). The costs have to be broken down for each of the suppliers on tier 1 level

[3] The term 'supply chain analysis' is used in Breitschopf et al. [55] for the approach applied by DTI [93] and Böhmer et al. [87] for the approaches used in DTI [93] and Aretz et al. [94] (which contains the IÖW model). We follow that terminology, which could also be named analysis of supply chains [87], because various supply chains are analysed.

Table 4
Studies using the employment ratio approach and evaluated technologies (n = 10).

Electricity	Heat	Electricity and Heat	Technology	Authors
Number of Evaluations				
10			Wind	Algoso and Rusch [60], Heavner and Del Chario [53], Heavner et al. [79],Llera-Sastresa et al. [88], Madsen et al. [80], Moreno und Lopez [39],SEED Coalition and Public Citizen's Texas office [40],Simons and Peterson [89], Sterzinger [90], ZSW [66]
7			Solar PV	Algoso and Rusch [60], Heavner and Del Chario [53], Llera-Sastresa et al. [88], Moreno und Lopez [39], Simons and Peterson [89], Sterzinger [90], ZSW [66]
2	1	2	Solar Thermal	Heavner and Del Chario [53], Llera-Sastresa et al. [88], Moreno und Lopez [39], Simons and Peterson [89], ZSW [66]
3	1	1	Biomass	Heavner and Del Chario [53], Moreno and Lopez [39], Sterzinger [90], ZSW [66]
1	1		Biogas	Moreno and Lopez [39], ZSW [66]
1			Landfill Gas	Simons and Peterson [89]
3		1	Geothermal	Heavner and Del Chario [53], Simons and Peterson [89],Sterzinger [90], ZSW [66]
1			Hydrogen, Fuel Cells	Heavner and Del Chario [53]
1			Hydro	Simons and Peterson [89]

Table 5
Different approaches of impact assessment using employment ratios.

Approach	First Authors	Following Authors
EPRI*	Simons and Peterson [89]	Heavner and Del Chario [53], Heavner et al. [79], Madsen et al. [80]
REPP**	Sterzinger [90]	Algoso and Rusch [60]
SEED	SEED Coalition and Public Citizen's Texas office 40]	Heavner et al. [79] for indirect jobs, Madsen et al. [80] for indirect jobs
Derived from literature	Llera-Sastresa et al. [88], Moreno and Lopez [39], ZSW [66]	–

* Electric Power Research Institute (EPRI).
** The REPP approach has methodologically been described by Singh and Fehrs [91] for the Renewable Energy Policy Project (REPP), Sterzinger [90] is a REPP publication as well.

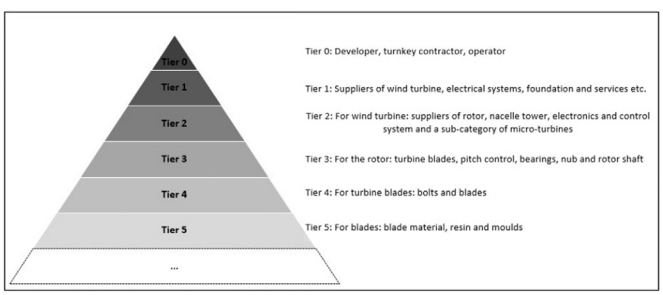

Fig. 5. Example of a supply chain pyramid for wind and exemplary elements *(Source: DTI [93], modified).*

and the material costs of these suppliers may also be interpreted as revenues of tier 2 suppliers. To assess the businesses that are involved in the RE industry in a region that may potentially supply the regional demand, which leads to economic impacts, a detailed analysis of the regional businesses is needed, because they are not classified as RE businesses in official statistics in most countries (cf. Section 4.3). A more comprehensive overview of supply chain analyses is provided by Breitschopf et al. [55].

One of the first studies using a supply chain analysis in the context of RES was conducted by DTI [93] on a national level. For regional supply chain analyses, only studies dealing with the situation in Germany have been identified. The model most often used is the WEBEE (Modell zur Ermittlung von Wertschöpfungs- und Beschäftigungseffekten durch Erneuerbare Energien; English: Assessment model for value added and employment effects in the context of renewable energies) approach, which was originally been developed by Hirschl et al. [95] and was first called the IÖW model (Table 6).

Table 6
Different supply chain approaches.

Approach	Lead Author	Following Authors
IÖW/WEBEE approach	Hirschl et al. [61]*	Bost et al. [96], Hirschl et al. [42]**, Meyer et al. [97], Weiß et al. [98], Bröcker et al. [47]**
Own	BMVBS [45]	–
	Finus et al. [75]	–

* IÖW/WEBEE approach was first described methodologically by Hirschl et al. [95].
** The studies of Hirschl et al. [42] and Bröcker et al. [47] contain an IO model, as well as a supply chain analysis, (author's own graph).

The model contains a detailed analysis of 34 different supply chains of various RES technologies [42] and includes impacts for all stages in the specific product lifecycle, including value added impacts for operators, wholesale trade, manufacturers etc.

The advantage of supply chain analysis is the provision of an exact view of the RE industry in the region. It helps to clearly identify the value added generated by industries involved in RE related business activities, due to the bottom-up approach accounting for the installed capacity in a region and the generated economic impacts. Unlike in a top-down approach, there is no disaggregation of statistical sectors needed because involved industries are defined as RE related due to their activity in the RE industry.

By using the material costs of suppliers and interpreting them as revenues of their suppliers there is no double counting. Moreover, changes in prices which occur rather fast in the dynamic RE industry can be easily integrated by adjusting the costs for specific industries in the supply chain. Decreasing system prices in the context of economies of scale of increasing plant sizes may also be regarded by taking into account different cost structures for specific plant sizes. The approach can be applied in several regions in a country or market, provided that no huge differences exist in technology costs or productivity in industries. The disadvantages of the approach lie in the fact that a lot of detailed information on specific costs of technologies and internal cost structures, such as labour costs and material costs in various industries, is needed in order to conduct a comprehensive analysis. On the other hand, the construction of a comprehensive economic model that calls for even more data gathering (Section 4.3 and Section 4.4) is not necessary.

Additionally, only inputs which are RES related are taken into account. Other inputs like, for example, the value added of the real estate industry that leases property to, for instance, energy service companies (ESCOs) are not included in the approach. However, that could be overcome by combining the supply chain analysis with an input-output model (Section 4.3), which is done by, for example, Bröcker et al. [47]

and Hirschl et al. [42]. The economic impacts of inputs of enterprises which are not directly related to RE related economic activities are then taken into account.

Moreover, if regional industries should be identified to satisfy the demand in a region, a detailed analysis of businesses is necessary, which can be resource- and time-consuming. However, the same obstacles exist, when the RE industry is assessed by an input-output model with a disaggregated RE industry sector (Section 4.3).

4.3. Input-output modelling

Input-output (IO) modelling is an instrument for assessing the interactions in an economy which dates back to the work of Leontief [99,100]. IO tables show the flow of goods and services between the industries in an economy from their production to their final use. By illustrating an IO model in the Leontieff inverse matrix the values in the columns, which are called multipliers, show what all industries (inclusively a given industry) have to produce directly or indirectly (i.e. as inputs) so that the given industry can generate one additional unit for final demand [101]. Concerning final demand, a differentiation between consumption, investment, and export may also be provided [102].

By using IO tables, it is possible to calculate the gross output in an economy, as well as the value added, by subtracting the inputs of an industry from its gross output. Moreover, the value added can be divided into different sub components such as employee and business income including taxes of businesses. Furthermore, it is feasible to transform the tables with additional information and, for instance, evaluate the directly and indirectly employed employees in the industries under investigation [103]. The mostly used form of IO models in the context of the regional economic impact of RE are static IO models which remain unaltered over time. A key assumption of these models is that the input of a sector is proportional to its output, so that economies of scale, changes in prices, technical progress and increasing or decreasing productivity are not considered [103], as well as potential substitutions of goods and services [104].

National IO output tables exist for OECD member states [105] and several other countries. However, by assessing the regional impacts of RES, a national input-output table cannot be used and a Regional IO Table (RIOT) which represents the flows of goods and services in a regional economy should be developed. Those RIOTs can be derived from national IO tables by calculations, (by transforming the tables using for example the LQ or, FLQ approach of Flegg and Thomo [106], which is a non-survey approach that is used for example in the Regional Input-Output Modelling System (RIMS) II model or Hirschl et al. [42]. A more comprehensive approach is the construction of RIOTs with extensive surveys of the regional economy (e.g. Coon et al. [107]). Some RIOTS combine survey and non-survey data from associations such as national statistic agencies or economic development organisations. This is called a hybrid approach [108]. In the sample, the study of Fanning et al. [78] relies on an IO model that has been developed with such a hybrid approach [108]).

After the development of a RIOT, the share of goods, which are sourced locally, has to be estimated by using industry data or expert estimates and the economic impact of a change in final demand for a specific industry (e.g. the wind power industry) can be calculated.

One of the most prominent impact assessment instruments in the context of RES which is based on RIOTs is the Job and Economic Development (JEDI) model, developed by the US American National Renewable Energy Laboratory (NREL) [57]. With the JEDI model it is possible to calculate the regional economic impacts of RE deployment like employee earnings, gross output or jobs at the state level in the US [109]. The model contains a detailed cost analysis of different technologies and can be applied to measure the impact in different industries. The multipliers used in the model are provided by the IMPLAN (IMpact analysis for PLANning) system, which is a computer-based IO model that was originally developed for the USDA Forest Service and is currently hosted by the IMPLAN group [110]. Originally developed for wind power, it has been adapted in order to be suitable for assessing several other energy technologies such as biofuels, geothermal, coal, concentrating solar power, marine and hydrokinetic power, natural gas, and solar PV power plants [111]. It is also possible to use default values for local shares of inputs or to enter one's own information (such as specific construction or O&M costs) into the model. An analysis on county level is also possible, but multipliers, which are available from IMPLAN, have to be inserted by the user independently. Local shares of inputs should be estimated by experts' judgement, surveys or data from associations because JEDI default values are similar among most of the states and only provide a rough estimation of the characteristics of the local economy [111].

IMPLAN IO models are derived from many sources including the U.S. Census Bureau, the Bureau for Economic Analysis (BEA) and from existing IO tables (BEA Benchmark IO tables) [112] and provide multipliers for every county in the US. The availability of such a tool leads to its wide application for impact analyses at a regional level. That becomes evident in the sample, since 19 (82%) of US publications use data originally from IMPLAN or the JEDI model with data from IMPLAN (Table 7).

Due to the fact that IMPLAN has widely been applied it is possible to compare studies, because of the same applied methodology, which is a clear advantage. However, weaknesses and limitations of the model such as lack of disaggregation of the RE industry in the IMPLAN IO model, or the negligence of foreign trade flows in the gravity model, also occur in the reviewed studies.

In contrast, some US publications use other multiplier data from RIMS II, REMI or the IO model of North Dakota of Coon et al. [63]. Fanning et al. [78] use an IO model for Wales which has been developed by Jones et al. [108]. Madlener and Koller [73] use the national IO table of Austria to describe the effects on the national economy by the deployment of RES in Vorarlberg. The German publications use models, which have been developed by their respective organisations (e.g. DIW [122]) and are derived from national IO tables.

The advantages of IO models are that all interactions of the economy are considered especially by integrating all input flows of different industries which are needed to take into account all indirect economic effects. IO models can illustrate a fairly exact view of regional economies by applying model extensions such as gravity models which consider interregional trade by taking into account logistic patterns which are typically for specific goods (e.g. IMPLAN [125]). Moreover, in current discussions different qualities of equal goods are taken into account which can be integrated in the RIOT to avoid interregional cross-hauling in non-survey approaches (Kronenberg [126] or Kronenberg and Többen [127]).

Unfortunately, industries in the IO model may be displayed at a high aggregation level (e.g. manufacturing industry instead of wind power industry) and multipliers of a more general category, such as manufacturing are used instead of taking specific inputs of the industry being investigated (e.g. wind power plant manufacturing) into account. There is no statistical categorisation of the RE industry concerning common national statistics as the RE industry is aggregated with other industries like fossil-based electricity or energy generation. Hence, inputs of the RE industry into the economy are not clearly categorised in IO tables. Some studies exist which deal with this issue by disaggregating original IO table sectors which contain electricity generation into new sectors, for example electricity generation from e.g. wind, solar PV. This is accomplished by extensive data gathering (Lehr et al. [128]).

According to the assumption of static IO models that inputs have to be proportional to the output, several potential economic developments are neglected. Firstly, economies of scale, increasing productivity, and technical improvements that have an impact on the production volume or prices are not represented, which is a disadvantage in dynamic markets such as the RE industry. Secondly, there are no limitations in

Table 7
Authors using different IO models for impact assessment and analysed regions.

IO Modell	Authors	Country	Region
IMLPAN	Carlson et al. [113]	US	8 counties in Illinois and Illinois
	Deyette and Clemmer [48]	US	Texas
	Deyette and Clemmer [54]	US	Washington
	ECONorthwest [114]	US	Kittitas County
	GAO [81]	US	Farms and rural communities in 11 different counties in California, Texas, Minnesota, Colorado, and Iowa
	Kildegaard and Myers-Kuykindall [83]	US	Big Stone County
	Timmons et al. [115]	US	Massachusetts and an aggregated region (5 counties)
JEDI/IMPLAN	A Renewable America [116]	US	Washington
	Coover et al. [117]	US	Utah
	Costanti [49]	US	6 counties in Montana
	Lantz [50]	US	Nebraska
	Lantz and Tegen [21–35]	US	Arizona, Idaho, Maine, Montana, New Mexico, Nevada, Tennessee, North Carolina, Massachusetts, Indiana, Pennsylvania, South Dakota, Utah, West Virginia, Wisconsin
	Loomis [118]	US	Livingston County and Illinois
	Loomis and Hinman [74]	US	Illinois
	Reategui and Hendrickson [119]	US	Texas
	Reategui and Tegen [58]	US	Colorado
	Ratliff et al. [120]	US	Utah
	Slattery et al. [43]	US	Texas
	Torgerson et al. [84]	US	Umatilla County
RIMS II	Stoddard et al. [59]	US	California
	Black and Veatch [121]	US	Pennsylvania
DIW	DIW [122]	Germany	Brandenburg
	DIW [123]	Germany	North-Rhine Westphalia
REMI*	Weisbrod et al. [62]	US	Iowa
Coon et al. [107]	Coon et al. [63]	US	North Dakota
Jones et al. [108]	Fanning et al. [78]	UK	Wales
National IO Table	Madlener and Koller [73]	Austria	Vorarlberg
Own	Bröcker et al. [47]**	Germany	Schleswig-Holstein
	Hirschl et al. [42]**	Germany	Germany and federal states, Berlin, Saxony-Anhalt, Hesse
	Ulrich et al. [38]	Germany	16 German federal states

* REMI is a model which can be categorised as an IO model or a general equilibrium model [124].
** Bröcker et al. [47] and Hirschl et al. [42] use IO modelling as well as a supply chain analysis.

the market volume resulting in the possibility of overestimated production capacities [103]. Furthermore, input of goods and services are unchangeable, so that a substitution of goods as an effect of e.g. innovative production processes is not applicable [73]. Another disadvantage is the availability of IO tables at a sub-national scale [122] which is especially a challenge on a rather small regional scale where non-survey based IO models suffer from a lack of accuracy [45].

Moreover, due to the fact that comprehensive survey-based data assessment and processing is very extensive, the results are published with a delay after the original data has been assessed. This also does not take into account the dynamics of the RE industry. For a more comprehensive overview of strengths and weaknesses of IO models refer, for example, to Miller and Blair [129].

4.4. Computable general equilibrium models

Computable general equilibrium (CGE) models are computerised simulation models, based upon the general equilibrium theory and normally start with a current (or business-as-usual) equilibrium that is challenged by a change (e.g. a policy shift that promotes increasing RES deployments), inducing impacts that lead to an alternative general equilibrium [130].

Typically, CGEs include anticipation about the actions of economic agents (e.g. households or enterprises) aiming to achieve individual utility maximisation [131,132]. Some CGE models contain further assumptions like non-market clearing because of unemployment [67]. The model assumptions are linked to economic datasets, like a social accounting matrix (SAM[4]). While IO tables illustrate the flow of goods and services from production to final demand (Section 4.3), SAM based CGEs illustrate the interrelations between supply and demand, showing the distribution of income of specific economic agents (e.g. enterprises or the public sector), thus providing a picture of the economy in a fully integrated approach [133].

Characteristics of the model are elastic prices which are dependent upon supply and demand [132], while in static IO models, increasing or decreasing demand does not have an influence on prices and wages [134], which is also the case in the other impact assessment approaches. Since additional variables like migration may be integrated in the model, the approach has the potential to evaluate the impacts of changing conditions in time like an increasing supply of workforce that may have a negative impact on wages [135].

Therefore, the approach is the only approach among the evaluated methodologies where market mechanisms and agent behaviour are taken into account. In summary, the approach

> *"allows one to study the changes in the spheres of production and consumption as well as in income distribution, in response to changes in a given economic policy, as these models explicitly include a representation of the framework of interdependencies among all markets in an economy"* [133].

A further description of specific characteristics of CGEs and their application in regional impact analyses is provided by Partridge and Rickman [136].

SAM based CGE models have not been used for a regional economic assessment of RES on a regional scale as frequently as the other approaches since only a few publications using a SAM based CGE have been identified (Table 8). This goes along with Cansino et al. [137] stating that most economic assessments in the field of RES are based upon an IO modelling approach instead of CGE models, which is also the case in the reviewed literature sample.

[4] There are also CGE models which are based upon IO models (e.g. Gilmartin and Allan [67]). However, as the aim of this Section is to highlight the differences from IO based models, only literature CGEs with integrated SAMs are taken into account.

Table 8
Authors using different economic data models in CGE approaches and analysed regions.

Economic Data Model	Authors	Region
SAMAND	Cansino et al. [133], Cansino et al. [137]	Andalusia
AMOS	Gilmartin and Allan [67]*	Scotland
Own	Trink et al. [68]	East Styria and rest of Styria

* The studies Allan et al. [134], Allan et al. [135] are not included in the sample because differences between Gilmartin and Allan [67] were low as they focused on the economic effects of the marine energy sector in Scotland using a CGE model as well.

Gilmartin and Allan [67] use a CGE model for the assessment of marine energy developments in Scotland and compare the results to a study where an IO model has been used. This comparison shows the differences in CGE models and approaches, where the impact of regional supply and demand on wages and prices are not taken into account.

In comparison to the results of the IO model, Gilmartin and Allan [67] find that IO models may overrate the regional employment impacts especially in the short term (i.e. the investment stage) and underrate the effects in the long term. This is explained by the IO model's characteristic that labour supply is elastic and an increase in demand has no effect on the regional labour market. However, according to the CGE model assumptions, an increasing demand in RES-related economic activities leads to rising wages in the respective industries if there is no sufficient labour supply. That induces a crowding-out of workforce from non-RE related industries to RE-related industries as a result and therefore lower total employment impacts as in the IO model. In the long term, due to adaptations of the supply side by, for instance, migration into the region and a decreasing labour demand after the investment stage, wages fall which leads to positive economic effects in the labour market [67].

Therefore, the advantage of CGE models consists of taking regional supply and demand and the impact of increasing regional demand into account which makes the approach particularly valuable for assessing future developments which are “large relative to the host economy” [134].

However, due to the fact that a global market and a global division of labour for certain RES technologies (e.g. solar PV) [138] exist, material prices are more dependent upon global or national market developments instead of the regional market. An increase in regional demand therefore may not have a very significant effect on regional prices for RES technologies if the demand stays stable for the rest of the world. In the case of biomass, Trink et al. [68] support that statement by illustrating that a higher demand for domestic biomass may only have an effect in a protected market. In an international market however, regional goods may be substituted by imports which does not have an increasing effect on the regional price [68]. Therefore, the effects of regional demand may be negligible at the manufacturing stage.

Nevertheless, in the case of employment especially in the installation and O&M stage which is supposed to be taken over by local employees – depending upon the specialisation of the local workforce though [88]- the advantage of CGE models is the fact that competition between non-RE-related and RE-related industries and a crowding-out of employees are taken into account. However, that may be more important for larger regions than on a local or small regional scale due to a limited supply side and an increased labour demand may be compensated by commuters from neighbouring regions.

Further advantages of SAM based CGEs is that specific economic actors such as households are considered, which allows the evaluation of the effects of higher energy prices because of RES technologies. That is illustrated by Trink et al. [68] for the case of biomass heating which may lead to negative welfare effects for consumers although the net regional GDP is positive due to increasing heating costs. CGEs therefore provide a more comprehensive illustration of a regional economy than the other approaches.

Nevertheless, some assumptions of applied CGE models should be questioned critically like “perfect sectoral mobility” [135], which does not adequately take into account the specialisation of the workforce for economic activities related to RES. Moreover, cost reductions because of learning effects are also not integrated in, for example, Gilmartin and Allan [67] despite the fact that they may be significant in some RES industries [70], which according to the model's assumptions, also have a positive effect on employment. A challenge of applying SAM based CGEs consists in data availability since according to Jahn [139] SAMs are in many cases not even available on a national scale.

4.5. Other methods

Other methods of impact assessment which rely mostly on surveys of the RE industry have been used by Faulin et al. [65], or The American Solar Energy Society [140] and Bezdek [64], that both rely on the same ASES/MISI[5] approach or Tegen [141], who assesses economic benefits in $/kWh (Dollars per kilowatt hours), using cost information from different sources including the JEDI model. These methods will not be discussed in the following.

5. Guideline towards regional RE impact assessment

A potential first step of a regional economic impact assessment consists of choosing and defining a region (Fig. 6). Such a definition should contain a clear distinction of the regions’ boundaries by ideally choosing official administrative units which are classified and internationally comparable in order to enable a comparison of regions and economic impacts.

When assessing regional impacts of RES, certain regional characteristics may be considered that may conceivably limit the comparability of regions. Therefore, that step should include a first analysis of the region of interest. First of all, geographical conditions which have an impact on the operation of RES should be regarded. For instance, the natural conditions like irradiation for solar energy or wind conditions for wind power may define the energetic and economical (which may vary across countries because of different system prizes) performance of a technology. For solar energy, the natural conditions vary between Northern Germany (e.g. full load operation hours of solar PV plants in Lower Saxony were 844 h on average in 2014 [142]) and Southern Germany (full load operation hours of solar PV plants in Baden-Württemberg were 961 h on average in 2014 [143]). In terms of comparability, this leads to higher economic benefits for solar PV operators in Southern Germany provided that system and O&M costs are the same. Henceforth, the economic benefits of a technology, may be illustrated as economic benefits per unit of energy generated (e.g. €/MWh), as an addition to the benefits of the installed capacity (e.g. MW), to take into account the natural conditions of locations.

Furthermore, regional consumption patterns may play a role which may be exemplified by the most energy-consuming processes regarding residential consumption; while in some (northern) regions, technologies for heating may be essentially because of climate conditions, in some (southern) regions, cooling may be more important than heating [144] which has an impact on the RES technologies’ applicability and demand in a region. Moreover, concerning consumption, demographic criteria like the population number and population density (and concentration) in a region should be considered. The possibilities for

[5] American Solar Energy Society (ASES) and Management Information Services, Inc. (MISI).

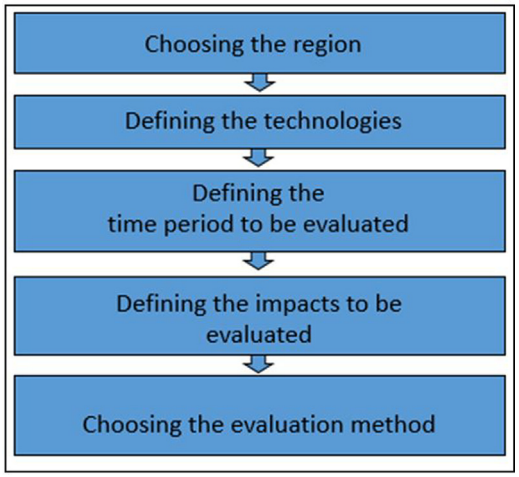

Fig. 6. Steps to be taken when assessing the regional economic impacts of RE.

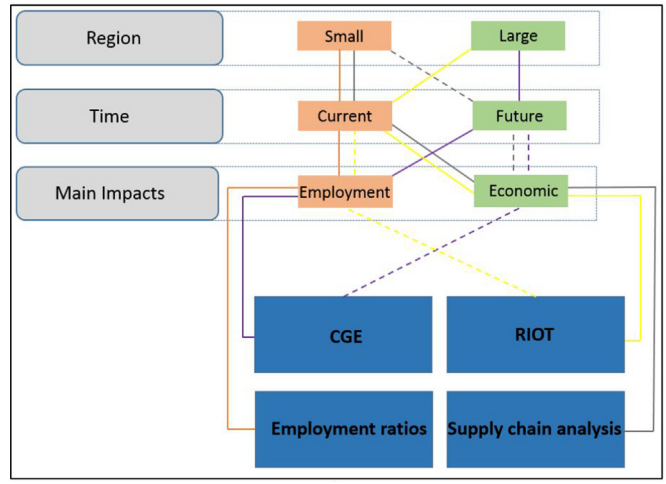

Fig. 7. Most suitable (unbroken line) and promising alternative (dotted line) approaches, depending upon the size of the region, reference time, and types of impacts.

applying certain technologies may depend on the level of consumption and the concentration (e.g. when applying district heating solutions [145]) of the population.

The concentration of the population in a region may – in addition to the size - also define the potential to install certain technologies like wind power or open space solar PV plants, which are space intensive. Other criteria like nature conservation or water protection may also limit available spaces for the installation of various RES technologies.

Moreover, there is a need for an analysis of the local economy. If specialized enterprises, which are able to provide services for the installation and the operation of RES are located in a region, there is a chance to create more regional economic benefits, when these enterprises are integrated in value added activities of RES in a region.

In conclusion, when defining and assessing a region or evaluating a comparison across regions, these regional characteristics should be considered.

Furthermore, a precise definition of technologies being assessed, including the energy type (i.e. heat or electricity) that is generated by the technology, should also be provided. Additionally, a clear definition of the evaluated time period should be given. When assessing RE development which is installed within the time period, cost developments for specific technologies should be regarded as well. Moreover, different life-cycle stages (i.e. e.g. manufacturing, installation etc.) should be precisely defined. The impacts that are assessed rely on the research question. While in some cases only employment effects are evaluated, further economic effects may also be taken into account.

Fig. 6 illustrates the steps which ideally need to be taken to perform such an analysis; however, the order is a proposal that may vary in some cases.

Before choosing the evaluation method, it is necessary to compare the impact assessment approaches and to select the most suitable approach for the individual study, as each method has its strengths and weaknesses.

Based upon the framework of Figs. 6, 7 shows in which specific situations (e.g. indicators: size of the region, time, and type of impacts), the advantages of the evaluated methodologies are especially useful, and in which circumstances the application of a specific approach is the most efficient solution.

For the indicator 'region', 'small' refers to the local and small regional scale, whereas 'large' covers all larger regions on the sub-national scale. A threshold for large regions can be spatial units above the European NUTS 3 level or US county level depending on the specific regional situation.

The indicator 'time' refers to the period where RES deployments take place. 'Current' analyses cover already installed plants whereas 'future' analyses deal with RES deployments in future periods.

As employment is the most often assessed indicator in impact assessments and some research may consider an evaluation of employment impacts as sufficient, the main assessment impacts are 'employment' or further 'economic' impacts (Table 2).

The situation where the strengths of the specific methods are most valuable is illustrated by an unbroken line and the promising alternative applicability of an approach is illustrated by a dotted line.

Analytical models like supply chain analyses and employment ratios may be especially beneficial on a local scale and in relatively small regions, where no economic models like a RIOT and a SAM exist, since constructing a survey-based RIOT or CGE model solely for the case of renewable energy impact assessment is very resource intensive and applying non-survey-based models in rather small regions may lead to imprecise results (Section 4.3).

If only the current situation is assessed, there is no need to take future regional labour supply and price changes into account and existing data can be used. Therefore, an employment factor approach is the most efficient approach for assessing employment impacts of the current situation in small regions (orange unbroken line). However, in terms of reliability, employment factors should be up-to-date and assessed in the same region where an analysis takes place so that they are open to scrutiny. A best practice example using employment ratios is provided for instance by Llera-Sastresa et al. [88].

The advantage of supply chain analyses becomes especially evident in the analysis of current economic effects in small regions (grey unbroken line). As for employment ratios, there is no need to have an economic model available, a disaggregation of sectors is not necessary, and the approach allows economic benefits beyond employment to be taken into account. Allied to the benefits of analytical methods on a small regional scale for current assessments, the approach may also be used as a potential alternative to CGEs to evaluate future economic effects on that scale (grey dotted line) since scarce resources (e.g. workforce or goods) on a small regional scale may be compensated by international trade or commuters from outside the region. Furthermore, supply chain analyses are the most transparent tool if economic effects of specific RE technologies (e.g. wind power, cf. Fig. 5) are evaluated if – as in most cases - economic models are not finely disaggregated. Supply chain analyses can be more easily adapted than employment factors, RIOTs, or CGE models and changes which occur in the supply chain (e.g. changes in prices, substitution of goods) can be integrated with limited effort. A best practice example of an impact assessment by conducting a supply chain analysis is provided for instance by Hirschl et al. [95].

Typically, RIOTs provide a comprehensive analysis of the flow of

goods and services in an economy because all inputs of industries are taken into account in the model and not just RE related inputs like in the supply chain analysis approach. Moreover, it is possible to assess employment effects with an IO model, so that it provides the same solution as the employment factor approach. IO models may also be used to measure disinvestment if these decline, due to RE development (e.g. coal mining), provided the energy generation sector is sufficiently disaggregated. A disadvantage of most IO models compared to the employment factor approach and the supply chain analysis, is that data is mostly not up-to-date because of the intensive process of data gathering. Moreover, regional IO tables are not available for most regions (except for the US, where a series of models are available) and non-survey methods of constructing IO models may suffer from a lack of precision in small regions (Section 4.3). Because of these constraints and due to fixed coefficients, which inadequately take future market dynamics into account especially concerning employment, other methods are more suitable for evaluating impacts on a small regional scale and future impacts in large regions.

Additionally, if RE industries are not disaggregated (which depends on the aggregation level of the IO table used), impacts of specific technology segments (e.g. small roof top solar PV) are hard to define. A suitable approach may be coupling a supply chain analysis with a regional IO model, because a disaggregation of RE related economic activities in the IO model is not obliged since effects of RE- related activities are covered by the supply chain analysis, which is done for example by Bröcker et al. [47]and Hirschl et al. [42]. Nevertheless, because of their comprehensive illustration of the economy, IO models are a suitable tool in large regions since there may be survey-based IO tables available or, in case of a derivation from national IO tables, inaccuracies in RIOTs may not be as significant as on a small regional scale.

In conclusion, for an impact assessment of current renewable energy developments beyond employment in larger regions, IO tables are the most suitable approach (yellow unbroken line). As it is possible to assess employment with the approach as well, another potential alternative is the assessment of current employment in large regions (yellow dotted line). A best practice example of an impact assessment by using RIOTs is provided, for instance, by Coon et al. [63]. SAM based CGE models extend the benefits of an IO model regarding a comprehensive impact analysis by taking future market dynamics and distribution effects into account, enabling a potential view of future impacts. Due to the static nature of the other approaches that do not take into account the regional supply side, the model is especially beneficial for future assessments, since in historic or current data assessments these benefits of CGEs become obsolete.

CGE models are especially suitable for assessing employment effects because the impacts of increasing demand on wages and employment are taken into account. For some stages in the supply chain, especially manufacturing, a limited regional market may not exist (Section 4.4) but for other stages (e.g. construction and installation or O&M, with a lower level of specialisation) the method has its benefits in comparison to the other approaches. However, future learning effects which have a negative impact on the workforce demand should be taken into account. These benefits occur especially in larger regions, where an increased demand may not be compensated by commuters from outside the region (purple unbroken line).

Another benefit beyond the evaluation of employment effects lies in the fact that SAM based CGEs illustrate distribution effects which allows the negative effects of rising energy prices for consumers to be taken into account. They are therefore a beneficial alternative to IO models when taking further economic evaluations (purple dotted line) into account. In conclusion, SAM based CGEs are the most comprehensive tool for assessing the overall effects of a transition to renewable energies.

Nevertheless, it should be noted that the framework provides a generalised picture assisting in choosing a suitable impact assessment. Further variables, such as resource constraints (e.g. time, money), regional data availability (e.g. existing RIOTs), the technology with its specific market dynamics, the specific stage in the value chain which should be assessed, and the extent of developments, affect the assessment method selection. The extent of developments is an indicator for the usefulness of CGEs, since shortcomings of approaches which do not integrate supply and demand are more apparent in large developments which have a significant impact on the regional economy. Moreover, the extent of impacts is important as SAM based CGEs allow income distribution effects for households to be taken into account, which is not included in the other approaches.

After choosing a method, data sources and the methodology including its strengths and weaknesses should clearly be explained since especially the complexity of a CGE may be considered as a “black-box” [146] for inexperienced practitioners in the field of economic modelling. When conducting a comprehensive analysis of economic impacts, the effects generated by installed RE capacities in the region, as well as regional enterprises which are part of the RE industry, should ideally be taken into account to cover impacts generated by domestic as well as external demand.

To study the regional chances as well as challenges due to energy transformation, potential economic losses in conventional energy generation industries due to increasing renewable energy developments should also be taken into account in comprehensive regional studies. This especially affects regions where conventional energy generation takes place and supports regional decision-makers by evaluating how losses may be compensated by renewable energy developments.

All the studies reviewed focus on relatively clearly assessable RE-related economic benefits (e.g. through job generation), and most often lack a comprehensive analysis of additional benefits, such as changes in regional economic perspectives (e.g. leading to improved export chances), innovation dynamics and spill-overs, as well as further macroeconomic effects through e.g. improved public health (due to reduced air pollution) and other factors. Therefore, from a comprehensive regional economic evaluation perspective, further assessments could be integrated in an analysis. Presenting just the results or impacts may not sufficiently show how regional businesses may profit from RE developments in general and, specifically, the developments of the RE industry in a region. Therefore, regional collaboration between research organisations, RES businesses and industries, as well as aspects of the functional economic specialisation [147] of a region, potentially enhance knowledge spillover effects and employment growth [148] and may lead to innovations [149], should be assessed. Furthermore, subsequent impacts, like avoided greenhouse gas and air pollutant emissions that may have a positive benefit on public health and therefore reduce healthcare costs [150], can also be considered. However, there are methodological challenges in estimating these costs and benefits [150]. Further analysis is recommended for the evaluation of these ancillary benefits in more comprehensive studies of the impacts of RES on regional economies.

In conclusion, if the aspects which are stressed in this guideline are taken into account in future publications, it will strengthen the significance of impact assessment analyses and may lead to a more considerable appreciation of the opportunities of RE deployment in regions by politics, economy, and society.

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