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Macroeconomic impacts of energy communities and individual prosumers: an assessment of transformation pathways

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Abstract

Background Active citizen participation, especially as collective prosumers in energy communities or as individual prosumers, is vital for a sustainable energy transition. As such, it is explicitly supported by European Union policy. It is the aim of policy-makers that a large proportion of the residential energy demand will be met in this way. At present, there is limited analysis on the macroeconomic impacts of such an increase in prosumers. In this study, we develop and apply an approach for assessing the macroeconomic impacts of transformation pathways, which depict potential developments of individual and collective prosumers.

Results The paper methodologically demonstrates how to macroeconomically assess scenarios and transformation pathways originating from cross-impact balance analyses by means of an input–output analysis. In particular, it is shown how qualitative data on future developments can be transformed into financial flows so as to enable an input–output analysis. Based on the assessment of two transformation pathways, our main findings suggest that there might be positive regional and national effects on net value added and employment as well as reductions in CO_2 emissions. We find that the scale of the effects strongly depends on the spatial distribution of heterogeneous households and the underlying economic structure.

Conclusions Our study represents a methodological advancement by showing how scenarios and transformation pathways can be assessed in terms of their macroeconomic consequences. This study shows that energy communities and individual prosumers might generate positive effects on value added and on employment. Given that households fix their energy supply options for decades, political decisions to support the energy transition in the residential sector should be taken as soon as possible.

Keywords Energy communities, Input–output analysis, Economic impact, Renewable energy, Prosumers, Citizen participation, Energy transition

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Background

Active citizen participation is vital for a sustainable energy transition. One avenue for such active participation is the individual adoption of renewable energy systems by households. Another avenue is participation in local energy communities.[1] Individuals thus actively

[1] A local energy community can be defined as "an association of private households in a neighborhood that jointly operate and use a spatially limited renewable energy system" [1], e.g., a community in which its members are connected to decentralized district heating fueled by renewable energy sources.

become both a consumer and a producer of energy (a prosumer). The importance of such individual and collective prosumers in supporting the energy transition is explicitly reflected, for example, in European Union policy.[2]

While the EU is primarily concerned with the general development and increased use of renewable energy, significant additional benefits are seen in the active participation of citizens—especially in energy communities. EU policy-makers see a number of benefits with respect to individual and collective prosuming [2, 3]. These benefits are mainly as follows: increased local acceptance of renewable energy (e.g., [4, 5]), an increase in options available to consumers along with access to affordable energy [6], the attraction of local investment via private capital [7], and the generation of positive (local) employment impacts. Other benefits range from social cohesion and community spirit [8], energy citizenship, and democracy [9] to local governance, ownership, and control [10, 11]. Security of supply and independence from fossil fuels has long been an important consideration for citizens regarding investment in renewables and related technologies [12–14]. Intended impacts on a local policy scale are similar to those on a national scale, but there is a stronger focus on the impact of such activities on regional development. Against the backdrop of a shortage of skilled workers, the goal of job creation has lost some of its appeal. However, in the context of promoting energy communities, job creation on a local scale is still viewed as a key objective. In terms of supporting the deployment of energy communities, an assessment of employment effects on a local scale is therefore important and recommended [2, 3]. To this end, prosumer growth is required and should be promoted according to EU directives [2, 3]. However, the current macroeconomic consequences of such growth have not yet been researched in depth. In particular, there is a lack of studies showing how information on attitudes and the actions of certain actor groups at a local level can be included in macroeconomic models.

In our paper, we are primarily interested in identifying the macroeconomic impacts (in terms of employment and value added) of increasing numbers of individual and collective prosumers supporting the policy-making process on a local scale. The identification of such impacts is also of interest to other stakeholders, such as policy-makers at a national level in their pursuit of energy, environmental, and economic goals.

Our study develops and employs an approach to illustrate how qualitative information on the transformation pathways of the prosuming activities of actor groups can be assessed to identify macroeconomic impacts. We aim to contribute to the literature by assessing macroeconomic impacts triggered by the activities of actor groups at a regional level. By applying our approach to three example municipalities, we demonstrate the flexibility of the selected approach.

For our macroeconomic analysis, two types of information are necessary: To what extent do citizens become active?[3] And which renewable energy technologies will they adopt in the process? To determine these several factors is important. Firstly, information must be available about which groups of actors become active among citizens as well as how they become active (i.e., as individual or collective prosumers) and at what point in time. This primarily depends on the characteristics of the citizens (attitudinal and socio-economic) as well as on the changing political and economic conditions. Secondly, spatial conditions play an important role in technology choice. Citizens thus remain inactive or become prosumers individually or by joining energy communities because of socio-economic factors (especially income) as well as their attitudes and values [1]. Their final decision is also influenced by their housing situation (e.g., owners of single-family houses vs. tenants) [15], spatial conditions and infrastructure required by the technology (e.g., south-facing roofs for solar panels vs. open spaces for wind turbines) [16], and regional conditions (e.g., rural areas with space but limited infrastructure vs. urban areas with high population density and spatial restrictions), which might all significantly restrict citizens in their options for action [17–19]. On a macro-level, this will lead to a diverse range of prosumers using diverse renewable energy sources.

There is a large body of research that focuses on assessing the macroeconomic impacts of individual renewable energy technologies on a national [20–23], subnational [24–42], and multiregional scale [23, 43–46], assuming fixed diffusion rates. However, there is scarce literature concerned with explicitly assessing the impacts of prosumers and especially energy communities. There are some studies that assess the impacts of specific energy communities (e.g., [26, 47]) and other studies that consider the effects of different ownership structures (e.g., [24, 27, 28]). Table 1 summarizes a selection of studies that assess the impacts of renewable energy technologies

[2] See, for example, the Directive (EU) 2018/2001 [2] on the promotion of the use of energy from renewable sources.

[3] Becoming "active" is to be understood here as either investing in an individually owned renewable energy technology or joining an energy community. For a more detailed explanation of how the term "active" is understood here, see the subsection entitled "Transformation Pathways" in the next section.

Table 1 Selected studies assessing the macroeconomic impacts of renewable energy technologies on different regional scales

Studies	Renewable technology		Regional focus			Ownership structure assessed		Type of model
	Single	Multiple	National	Subnational/ single region	Subnational/ multiregional	Energy community	Various incl. community ownership	
[20–22]	X		X					CGE, IO
[25, 26, 47]	X			X		X		IO, CM
[27, 28]	X			X			X	CGE, SAM
[29–38]	X			X				IO, SU, CGE,
[23, 49]		X	X					IO, EC
[24]		X		X			X	AC
[39–42]		X		X				AC, EC, IO
[44]		X			x		X	IO
[23, 43, 45, 46, 50]		X			x			AC, EC

IO input–output model, *CGE* computable general equilibrium model, *CM* change mapping, *SAM* social accounting model, *SU* survey/literature, *EC* econometric/multiplier, *AC* accounting

and categorizes these studies according to their regional focus as well as the renewable technology and ownership structures they assessed.[4] They reveal that there are strong differences in macroeconomic impacts across renewable energy technologies (e.g., [23]). Furthermore, those that focus on ownership structures find differences in local macroeconomic impacts due to different ownership structures. In particular, they report that community ownership yields the highest macroeconomic benefits on a local scale [24, 27, 28].

The research summarized in Table 1 employs a variety of methods and models ranging from econometric models, input–output analysis, social accounting, and computable general equilibrium to survey-based impact assessments.

In principle, current studies assessing the macroeconomic impacts of renewable energy technologies (see Table 1) do not tend to focus on citizens as main actors, lack consideration of diverse actor groups with individual characteristics and a resulting variance in willingness to become renewable energy prosumers, and therefore do not consider key drivers of renewable growth rates. A recent study by [1] addresses the majority of these deficiencies by identifying transformation pathways. These pathways map out potential future citizen participation in energy communities and alternatives such as installing renewable energy systems in their homes. However, a macroeconomic analysis of these pathways was not attempted by [1]. The present study seeks to fill this gap.

By conducting a macroeconomic assessment of transformation pathways that map out how, when, and which actor groups become active, we contribute to the literature in two ways. We shift the perspective to citizens who become prosumers. As a result, technology growth is not evaluated at an individual level but rather as a mix of technologies (e.g., PV/battery systems, heating pumps, condensing boilers, and woodchip furnaces in combination with district heating) with different ownership structures (joint or individual prosumers). Consequently, it is not the importance of a technology for a region that is determined (which has been achieved numerous times, see Table 1), but the effects of citizens becoming active in the energy system. The evaluation of transformation pathways mapping out future developments of active citizen participation in the energy system (i.e., in the energy transition) thus provides additional information that macroeconomic evaluations have so far failed to provide. Furthermore, our article represents a significant methodological contribution to the literature by illustrating how a macroeconomic assessment of transformation pathways focused on actor groups is possible using stylized examples, which are easily exchangeable.

We seek to address the apparent gap in the literature by using the transformation pathways on citizen participation identified by [1] within a regional Input–Output (IO) analysis to identify the potential macroeconomic impacts. The IO analysis is conducted for three example municipalities, chosen to represent three different settlement types—city, town, and village—in three different regions (i.e., administrative regions in NUTS 2[5]). Our

[4] See [48] for a more detailed review of the macroeconomic impacts of renewable energy technologies.

[5] In Germany, NUTS 2 (NUTS—nomenclature of territorial units for statistics) represents the level of the administrative districts (*Regierungsbezirke*).

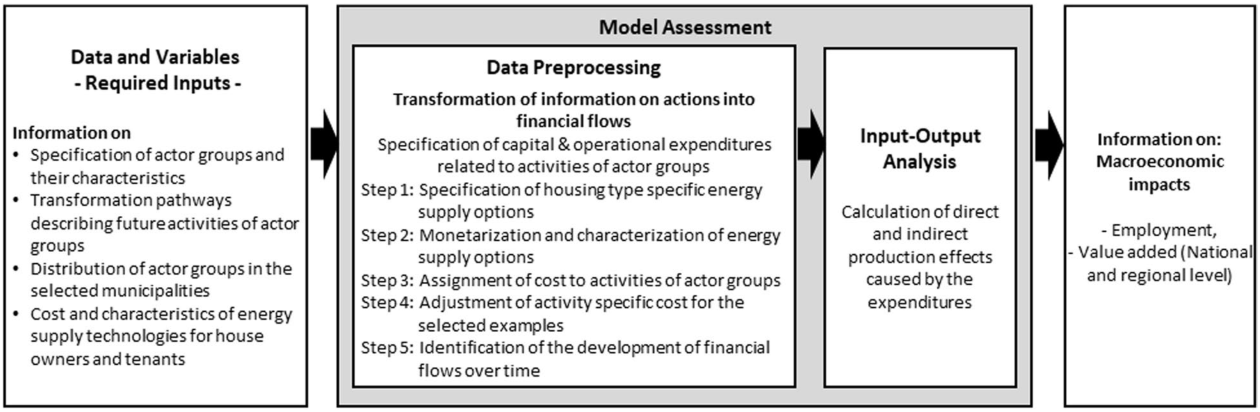

Fig. 1 Methodological approach

study is focused on Germany, given the data from [1], and by necessity looks at a selection of renewable energy technologies. However, the method we employ can be adjusted to different countries and regions, data permitting. Moreover, the method is flexible in that it can be adapted to reflect different (region-specific) technologies.

This paper is structured as follows: the next section outlines our modeling approach, describing the input data and its preparation for the IO analysis—the transformation pathways and information on actor groups and renewable energy technologies—and the method, i.e., IO analysis, in detail. The subsequent section presents the main results, which are then discussed before conclusions are drawn in the final section.

Methods

Overview

Our general modeling approach is summarized in Fig. 1. The approach consists of preprocessing exogenously given information and combining that information with an input–output analysis. The research starts with an assumption that information on the attitudes of actor groups towards joining energy communities or becoming individual prosumers and the timing of their actions is available. To conduct an IO analysis, which aims to identify effects on employment and value added, information on the actions (or inaction) of the actor groups must be translated into financial flows. For this purpose, we combine information on the actor groups with information on the house ownership rates of each actor group, information on the shares of the actor groups in selected municipalities, and information on supply options for owners of single-family houses and tenants as well as the costs of these options. By combing this information and putting it into a dynamic context, we can specify financial flows. These financial flows are used in the IO analysis.

In the following, we elaborate on the preprocessing of the data and the IO approach. Firstly, we describe the data and variables needed for the analysis. In particular, we provide information on a possible classification of actor groups and on transformation pathways. Furthermore, we provide information on the application of our approach to assess impacts on a local scale as well as information on a specific supply option. We then describe how information on actions can be converted into financial flows, which is essential for conducting the IO analysis. The IO approach is outlined at the end of this chapter.

Data and variables

Actor groups and their characteristics

To conduct the analysis, actor groups and their characteristics have to be defined. In our study, we use information provided by Broska et al. [1] as an example for clustering actors and describing their characteristics. In the study of Broska et al. [1], German citizens are clustered into five groups of actors using the social milieu framework of Sociodimensions [51, 52]. For each actor group, information on its housing situation (i.e., type of housing and ownership structure) and milieu affiliation is provided:

Actor group A is described as owners of single-family houses with high income[6] and a medium to high level of education. Actor group B is of the same milieu background, but represents the middle-income tenants

[6] “High income” is defined as a monthly net income above 3000 euros (one-person household). “Medium income” for a single household with a monthly income between 1500 and 3000 euros and "low income for a household with less than 1500 euros per month. The limits used for the classification of "low", "medium" and "high income" increase with the number of household members—by a factor of 0.5 for each person aged 14 and above, and by a factor of 0.3 for persons under the age of 14 [53].

among them. Both A and B are expected to show a high willingness to be active participants in the renewable energy transition. Actor group C consists predominantly of owners of single-family houses with high income. They are willing to invest in renewable energy technologies for personal gain such as prestige and financial benefits. Actor group D represents the middle class and is characterized by medium-level education and income. They are not dominated by one particular housing situation; they can equally be owners of single-family houses or tenants. On average, they are willing to be active in the energy transition and especially energy communities if there are no resulting disadvantages for them. Actor group E summarizes a diverse group that varies greatly in terms of age and education. However, all members of this group are characterized by a low willingness for action in the energy transition and the majority live as tenants and have a low income. Traditional older generations and lower socio-economic groups all fall under this category. In order to specify the data on these actor groups for this paper, further deliberations are necessary.

Milieus, and the actor groups they are based on, are not evenly distributed across Germany [54]. Some are more likely to be found in cities; others in rural areas [55]. In terms of house ownership alone, there are major differences between urban and rural areas, and there are also heterogeneities from region to region as well as among cities [56, 57]. Since the same also applies to the economies of different regions, i.e., each region has its own industrial characteristics, it was necessary for us to take a closer look at the likely spatial distributions of actor groups.

We are aware that compared to other milieu approaches, the Sociodimensions approach is particularly suitable for scientific research, as it transparently discloses the methodological procedure for creating their model [58]. The disadvantage of this approach, however, is that it has only been applied on a comparatively small scale to date. Only limited data are available on spatial distributions or regional heterogeneities (data exist at the state level but with very small sample sizes [54]). There are various concepts, i.e., social situations, milieus, and lifestyle approaches, which cluster society into groups according to their different characteristics [59]. The most widely used milieu approach in Germany is that of the Sinus-Institute [60]. Research is available on these Sinus-Milieus that deals with spatial distributions (e.g., [55]), but comprehensive nationwide data are again hard to come by. Even when using the Sinus-Milieu approach, studies adjust the milieus according to the peculiarities of a region's society [59, 61]. Studies also tend to provide information on some places, while no such data are available for others. Since the different approaches have many similarities [58], we have attempted to make an estimate and have assigned the milieus of regional studies available to the actor groups defined by [1] based on their descriptions.[7]

Transformation pathways describing future activities of actor groups

To assess the impacts resulting from changes in the type of actor group activities, we require information on transformation pathways. Here, we again use information provided by Broska et al. [1]. The study of Broska et al. [1] focuses on the specification of possible transformation pathways for active citizen participation in the renewable energy transition in Germany until 2040. These transformation pathways map out possible growth in the active choice of citizens to supply their households with heating and/or electricity from renewable energy sources by participating in energy communities or by installing individual renewable energy systems in their homes. Broska et al. [1] make a distinction between remaining inactive in the energy transition, i.e., not investing in PV or similar technologies, being "active alone" (i.e., investing in your own PV/battery system), and being "jointly active" (i.e., joining an energy community).

The transformation pathways identified by Broska et al. [1] include all contextual factors that either promote or hinder citizens' changes in actions.[8] We take the framework situation as given and use the results with respect to the increase in the number of citizens becoming active over time in Germany. Table 2 gives an overview of the two selected transformation pathways identified in [1].

Both transformation pathways in Table 2 show that there is an increasing willingness of citizens to supply their households with electricity and heat via renewable energy. However, while the first pathway assumes slower growth, i.e., not all actor groups show such willingness (actor group E in pathway 1), the second pathway is a positive example in which all actor groups are likely to shift towards renewable energy systems.

[7] In the case of the example municipality representing city locations, data were available to both the Sinus-Milieus [61, 62] and the milieus of Sociodimensions [54]. Results for the distribution of the actor groups differed only marginally between the two milieu frameworks.

[8] These factors also include energy-related and non-energy-related extreme events. Thus, occurrences or feared occurrences of energy supply interruptions are included in the conceptualization of the transformation pathways. In particular, the possible effects of these occurrences on the willingness of citizens to become prosumers of renewable energy (thereby making themselves less dependent on centralized energy provision and reducing their possible risk of falling victim to supply interruptions) are explored in that study. Concerns about energy supply security have grown because of two different developments—the energy transition and volatilities resulting from the increased use of renewable energy sources [63, 64] and recent geopolitical developments in conjunction with energy import dependency [65]—and have reached a peak since the start of the Russian invasion of Ukraine in early 2022.

Table 2 Transformation pathways depicting the actions taken by citizens in the renewable energy transition up to 2040

Descriptor	Scenarios				
	2020	2025	2030	2035	2040
Transformation pathway 1					
Likely action taken by a citizen of					
Actor group A	Not active	Active alone	Active alone	Active alone	Active alone
Actor group B	Not active	Not active	Active alone	Jointly active	Jointly active
Actor group C	Not active	Not active	Not active	Active alone	Active alone
Actor group D	Not active	Not active	Not active	Jointly active	Jointly active
Actor group E	Not active	Not active	Not active	Not active	Not active
Transformation pathway 2					
Likely action taken by a citizen of					
Actor group A	Not active	Jointly active	Jointly active	Jointly active	Jointly active
Actor group B	Not active	Jointly active	Jointly active	Jointly active	Jointly active
Actor group C	Not active	Not active	Not active	Active alone	Active alone
Actor group D	Not active	Jointly active	Jointly active	Jointly active	Jointly active
Actor group E	Not active	Not active	Not active	Jointly active	Jointly active

Remarks: Referred to as pathway 1.1 and 2.1 in the original; pathway 1.1 ends in 2035 [1]. We extrapolated the descriptor states from 2035 to 2040 assuming that they would not change significantly in those 5 years

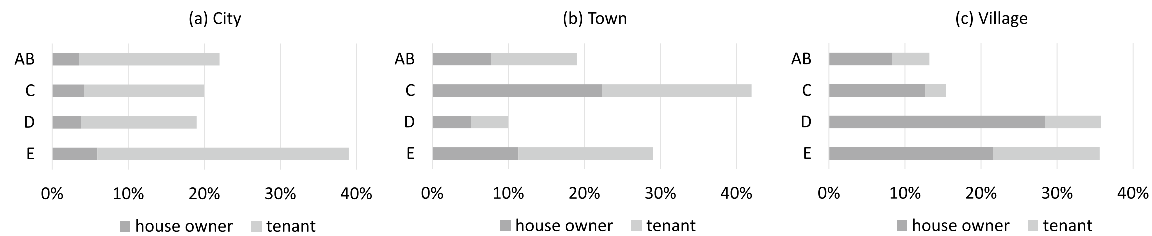

Fig. 2 Actor group distributions in three example municipalities, representing **a** city locations, **b** town locations, and **c** village locations. (Since we look at the exact distributions of tenants and owners of single-family houses in each actor group, A and B represent one actor group (hereinafter referred to as AB). A and B belong to the same milieu (see description of actor groups above); their only difference is described as being either tenants in the case of B or owners of single-family houses in the case of A [1].)

Specification of examples: actor groups in the selected municipalities

In our study, we aim to assess macroeconomic impacts on a regional scale. We thus selected three example municipalities, representing three different settlement types (city, town, and village) in three different regions of Germany (i.e., administrative regions in NUTS2). Our reason for doing so was that no uniform localities exist that could be considered representative for Germany. We referred to these illustrative examples as city, town, and village. They are based on Berlin, Konstanz, and two villages in Bavaria (Großaitingen and Scheuring). We then approximated the distribution of the actor groups in the three municipalities using information on milieu distributions.

We roughly determined the house ownership rates within the actor groups using data on house ownership rates in the municipalities and house ownership rates on a national scale for the Sociodimensions milieus. The results are listed in Fig. 2. More detailed information and the source materials are given in Table 5 in the Appendix.

Figure 2 shows that differences exist between the three example municipalities in the distributions of the actor groups as well as within the actor groups in terms of house ownership rates. City is dominated by actor group E and characterized by a small number of owners of single-family houses (Fig. 2a). Town is dominated by wealthy actor group C and has a fairly even distribution of owners of single-family houses and tenants in its population (Fig. 2b). Village is dominated by owners of single-family houses as well as the lower and middle classes, i.e., actor groups D and E (Fig. 2c).

Costs and characteristics of energy supply technologies for owners of single-family houses and tenants

In addition to information on the actions and the spatial distribution of the actor groups, information on investment costs and costs related to the operation and

Table 3 Characteristics of selected energy supply technologies (costs and emissions for an average single-family house)

		Electricity from grid 1)	Provision of heat by means of conventional gas heating system	PV/battery system 2)	Heat pump 3)	New condensing boiler3)	Woodchip furnace in combination with district heating 4)
Investment needs	**Euros**			**8,820d, 6)**	**15,0002)**	**9,2002)**	**21,0007)**
Subsidies, grants, and similar	Euros			100b, 6)	5,2582)	3002)	8,1007)
Variable cost	Euros/kWh	0.321)	0.0631 1)	0	0.058	0.06311)	
	Euros/year						7957)
Fixed cost	Euros/year		2602)	1296)	1502)	2602)	611 7)
CO_2 emissions	kg/kWh	0.4 a, 3)	0.2	0	0c	0.2	0
Particulate matter emissions	mg/kWh		64)	0	0	64)	764)
Dependence on price fluctuations		High5)	High5)	No c)	Noc)	High5)	Low5)

Remarks: Cost calculations are based on 2021 electricity and gas prices as well as subsidy payments. We also apply these prices for 2020

[a] Average emissions of the electricity mix in 2021

[b] Average revenues from feed-in tariffs

[c] Only indirect emissions, which depend on the amount of electricity taken from the grid

[d] We assume that PV capacity will be expanded if a heat pump is used in combination with PV. In this case, investment requirements for PV will increase by 50%

Sources 1)[68], 2)[69], 3)[70], 4)[71], scaled to one single-family house 5)[69], 6)[72], 7)[73]

management (O&M) of the technologies as well as information on household energy demand is required for the Input–Output analysis. For the latter, we use baseline electricity consumption data for the year 2021. Based on data for the year 2021 we assume that an average household (of 3 persons) residing in a single-family house uses 3500 kWhof electricity per year [66] (excluding electricity usage for warm water). An average of 15,500 kWh is assumed for heating [67]. A similar household residing in an apartment building is assumed to use 2500 kWh [66] (excluding electricity usage for warm water) and 8800 kWh [67] for heating.

Table 3 gives detailed information on the financial characteristics of the energy supply technology options for both electricity and heating. The different energy supply technology options are characterized in terms of investment needs, subsidies, and grants as well as variable and fixed costs. To what extent each technology is affected by price fluctuations is also indicated. Additionally, information is given on CO_2 emissions and particulate matter emissions connected with the use of each technology. These figures are considered indicative, as there are regional differences for example. The data given in the table differentiate between technology options that require supplementation by other technologies and those that do not. For example, a PV/battery system only covers part of the required electricity and so additional sources of electricity are needed.

A supply of self-generated electricity implies that less electricity is drawn from the grid. Costs for maintaining the grid are incurred, even if individual players draw less electricity from the grid. Accordingly, a change in the amount of electricity drawn from the grid can lead to a change in the share of the service charge or to an increase in the grid charges for electricity customers who continue to draw electricity from the grid. Increasing the self-supply can also lead to changes in the payments received to compensate for the provision of, for instance, disconnectable loads and the expansion of the offshore grid. Here, a higher self-supply quota can also lead to an increased burden on the remaining electricity customers.

With an increasing self-supply of electricity, and other conditions remaining the same, the revenues of utilities would drop [74, 75]. In the "electricity and heat supply via energy community" scenario, the utility receives about 0.09 euros/kWh less per single-family house for "energy procurement, sales, and margins" [68]. However, since the utility incurs fewer variable costs in the event of a drop in sales, the drop in sales does not mean that the company's profit would fall to the same extent. As a result, the informative value of the "revenue from the sale of electricity" indicator is limited.

According to the monitoring report of the Federal Network Agency [68], private households pay an average of 6.31 cents per kWh for natural gas. Of this amount, 1.47 cents are for network charges, 0.55 cents for gas tax, and 1.01 cents for sales tax. Gas suppliers receive about 3 cents per kWh for gas procurement and distribution. A reduction in demand for natural gas would thus lead to lower tax revenues and low revenues for gas suppliers.

Table 4 Energy supply options

	Option 1	Option 2	Option 3	Option 4
Owner of single-family house				
Electricity	Electricity from grid	Electricity from grid	PV/Battery system [a)]	Joint use of PV/Battery system [a)]
Heat	Conventional gas heating system [a)]	Heat pump [a)]	Heat pump [a)]	Heat supply via energy community [a)]
Tenant				
Electricity	Electricity from grid	Electricity from grid	Electricity from grid	Electricity supply via energy community [a), b)]
Heat	Conventional gas heating system [a)]	Conventional gas heating system [a)]	Conventional gas heating system [a)]	Heat supply via energy community [a), b)]

Remarks: [a)]Involves investments in new systems; [b]e.g., by using PV and a CHP plant

With regard to the network operators, the level of network charges for the remaining gas consumers can be expected to change, since network costs are very much characterized by fixed costs.

Regarding the direct impact on the state, it should also be noted that technologies such as woodchip plants are currently heavily subsidized (see Table 3). Increased use of these technologies will therefore lead to additional expenditures on the part of the state.

Model for assessments

Data preprocessing: transformation of information on activities into financial flows

In order to specify investments and other spending, we take a closer look at the technologies adopted by the actor groups. The assignment of financial flows to individual technologies follows the approach outline of, for example, Miller/Blair [76], Allan et al. [22], Jenniches et al. [31], and Bröcker et al. [29]. In contrast to existing approaches, however, we focus on the assessment of impacts on groups of actors on a regional scale, while taking changes of technology mixes over time into consideration.

To identify and specify developments regarding the technologies that are and will be adopted by actor groups, we employ a three-step approach:

Step 1: Specification of energy supply options specific to type of housing In a first step, we distinguish between owners of single-family houses and tenants of flats. This distinction is made, since the availability of options for action depends on the ownership structure and the technology options depend on the type of housing. In terms of energy supply, we distinguish between the supply of electricity and heat. Since there are numerous technological options and combinations that are either possible or in use (see e.g., [77] for renewable energy heating technology options), we focus on four illustrative energy supply constellations (see Table 4). The selected constellations represent the commonly used supply systems at present. Each of the four energy supply constellations is given for both tenants and owners of single-family houses.

At present, the most widespread supply constellation for both tenants and owners of single-family houses is the supply of electricity via the public power grid and the provision of heat by means of gas heating. We refer to this as the “initial situation”. Option 1 differs from the initial situation by assuming the need for investment in a new gas heating system. Taking into consideration the current discussion on regulations regarding the minimum share of renewable energy for residential heating systems [78], for Option 2 we assume the use of heat pumps in combination with electricity from the public grid as the option for single-family houses. Option 2 remains identical to Option 1 for tenants. Regarding Option 3, it is assumed that single-family house owners use heat pumps in combination with a PV/battery system, which covers 60% of the household electricity demand. This option (Option 3) again remains identical to Option 1 for tenants. Covering the heat demand without using gas from the public gas grid is considered for Option 4 (i.e., heat supply via energy community). Here, it is assumed that the heat supply is covered by a combination of a combined heat and power plant and a woodchip furnace. In addition, a supply of electricity based on PV/ battery systems, which belong to the energy community, is part of Option 4. Option 4 is identical for tenants and owners of single-family houses (see Table 4).

The combination of information presented in Table 4 and information on the shares of tenants and owners of single-family houses in each actor group and each municipality in Fig. 2 enables us to draw conclusions as to which technology will be used by which actor group under a specific energy supply constellation.

Step 2: Monetarization and characterization of energy supply options By combining information provided in Table 4 with technology-specific data listed in Table 3, we are able to describe the options with respect to financial and non-financial aspects.

Initial situation: Using data provided in Tables 3 and 4, we calculated an expenditure of 1,120 euros per year for electricity for a single-family house. If an existing gas heating system is used, the expenses for heat would amount to 1,234 euros per year. We calculated annual CO_2 emissions of 4.4 tons of CO_2. For the average tenant household, we calculated annual expenditure of 800 euros for electricity and 704 euros for heat. CO_2 emissions for a tenant's energy supply amount to approximately 2.7 tons of CO_2 per year.

For an appropriate comparison of the different options, we included investment costs for each heating supply in a similar way. An investment in a new heating system is thus made for each option (see Table 4).

Option 1: Option 1 includes the investment in a new gas condensing boiler. Taking into account the annualized cost for the purchase of a gas condensing boiler, heating costs would increase to 1,590 euros per year for a single-family house. For the average tenant household in which a new gas condensing boiler is installed, we assumed that the tenant participates proportionately to the investment costs. Therefore, the expenditure for heat supply increases to 958 euros. Emissions and electricity costs remain the same compared to the initial situation.

Option 2: Assuming that owners of single-family houses install heat pumps instead of gas heating systems, their expenditure would increase by 530 euros compared to the initial situation. CO_2 emissions would amount to around 3.4 tons annually for owners of single-family houses.

Option 3: For a combination of PV/battery systems and heat pumps, we calculated a roughly 8% decrease in expenditure for owners of single-family houses for the year 2021 compared to the initial situation (saving of 199 euros) and a decrease in CO_2 emissions by 42%.

Option 4: For the supply option "electricity and heat supply via energy community", the total annual costs are 3,298 euros per household for of single-family houses s and 2,150 euros per household for tenants. It is assumed that heat is supplied by the energy community (central wood chip plant in combination with a small CHP plant) and electricity is generated via PV in combination with the CHP plant. Compared to the initial situation, this represents an increase in expenditure of 39% (owners of single-family houses) or 42% (tenants) with a reduction in CO_2 emissions of 76% (owners of single-family houses) or 75% (tenants).

Step 3: Assignment of costs to activities of actor groups To translate information on activities into financial flows, we matched the options defined in Step 2 (Table 4) to the three actions that actor groups can take, as given in the transformation pathways (see Table 2). To do so, we first defined the term "active", as used by Broska et al. [1] for our interpretation of the transformation pathways. The term "active" in the transformation pathways is not to be generally understood as "becoming active". Instead, the term "active" refers to the energy transition, i.e., citizens taking an active role as prosumers of renewable energy.

As a result, Option 1 and Option 2 are attributed to being "not active" for the actors that need to renovate their heating systems. They are "not active" because they do not become prosumers of renewable energy. Option 1 is the scenario that is possible in 2021 in the two transformation pathways. Option 2 replaces Option 1 from 2025 onwards due to regulatory changes, which demand that by 2025 all newly installed heating systems are to be powered by 65% renewable energy [78].[9] This assumption is based on current expectations that heat pumps become the standard for single-family houses to fulfill the regulatory requirement [79]. Option 3 is described as "active alone". Here, we assumed that when single-family house owners act without joining an energy community, they install a PV system on the roof of their houses in combination with a heat pump. Lastly, Option 4 is denoted as "jointly active". If owners of single-family houses or tenants[10] join an energy community, this means that heat and electricity are obtained from the community in our example calculations.

Based on these assumptions, we can translate information presented in Table 2 into a selection of energy supply options. In Step 2, we assigned costs to the options. Linking information on the costs of the options with information on the timing of the use of options, conclusions on financial flows can be drawn.

In order to translate the information from the transformation pathways into financial flows for the IO analysis,

[9] We define this as "not active" because the option merely fulfills the minimum requirement of installing heating systems based on 65% renewable energy. Furthermore, the heat pump is fueled by electricity from the grid and not from electricity generated by the household itself (e.g. via PV).

[10] In the case of tenants joining energy communities, the important role of the landlords needs to be highlighted. In the instance of electricity supply, the mechanism is landlord-to-tenant electricity supply under tenant electricity law [80]. Without the landlord's active involvement by operating the renewable electricity system, the tenant is unable to consume locally generated renewable electricity. In the instance of heat supply, neighborhood energy concepts (*Energetische Quartierslösungen*) are key [81]. Here too, the landlord needs to initiate and support the decentralized renewable energy system. Frequently, successful examples of neighborhood energy concepts in tenant-occupied homes seem to be in housing cooperatives in which tenants are also members of the cooperative [19].

we matched the options defined in Step 2 to the three kinds of activities that actor groups can take (see Table 2).

Step 4: Adjustment of activity-specific cost for the selected examples As mentioned in Fig. 2, each selected municipality can be interpreted as a set of different actor groups. The overall financial flows related to the use of, and investment in, the energy supply options of a municipality can thus be calculated as the sum of the option specific financial flows weighted by the share of the options that have been chosen by actors.[11]

The results illustrate that owners of single-family houses who decide, on average, to remain "not active" face average investment needs of 8900 euros in 2021 and 9750 euros from 2025 onwards. The average annual O&M costs amounts to 2375 euros (2021) and 2,516 euros thereafter. According to our assumptions, tenants require less energy, which is why their energy costs are lower. In the case of City, 16% of the actors in group AB are owners of single-family houses and 84% are tenants (see Fig. 2a). Thus, if a member (i.e., household) of actor group AB has to take an investment decision and decides to become active alone, they will invest, on average, 8,997 euros per household. The investment sum consists of investments in PV battery systems linked with heat pumps for owners of single-family houses and investments in gas boiler systems by landlords. The average O&M expenditure of the group amounts to 1,457 euros per household. Since actor group C has a higher share of owners of single-family houses, investment spending for an average household choosing Option 3 amounts to 9,808 euros. Average O&M expenditure amounts to 1,438 euros. For actor groups that decide to become "jointly active" investment spending is higher, since in this case we assign investments to tenants as well as owners of single-family houses.

Step 5: Identification of the development of financial flows over time Following Steps 1 to 4, we identify the share of actor groups' adjusted cost of actions on the municipality scale. The transformation pathways provide information on the possible changes in the actions of the actor groups. However, for the assessment of macroeconomic impacts on a regional scale in a dynamic context, we must specify how many members of an actor group are located in the selected municipality.

In principle, the lifetimes of the energy technologies determine the possibility for changes in the energy supply of households. In particular, heating systems play a crucial role in citizens becoming active with respect to renewables compared to electricity (as many electricity providers offer green electricity from the grid). Heating systems have an average lifespan of 15 to 25 years [82]. It therefore cannot be assumed that a group of actors in their entirety will switch their energy supply to renewables. This will only happen in the context of new construction and renovation. Since the annual renovation rate in the residential sector in Germany is 1% of households [83], we assume that the decision to purchase a self-operated renewable energy supply system or to join an energy community only arises for 1% of households belonging to the respective actor groups annually. By using this assumption in combination with the results of Step 3, we can scale up and total up the costs for each considered period.

Input–output model

As previously mentioned, preprocessing aimed to translate qualitative information on the actions of actor groups into financial flows. This information is essential for an assessment of macroeconomic impacts. In our study, we employ an Input–Output analysis to assess these impacts due to its proven strength as a micro–macro bridge [76]. The strength of the input–output analysis results from the relatively high degree of sectoral disaggregation. This allows us to include information on specific technologies, while also drawing on macroeconomic factors such as value added and employment and taking direct and indirect effects into consideration (see [76] for a more detailed discussion).

For our analyses, we use the 2014 national IO table for Germany along with the socio-economic and environmental accounts as given by [84] in the World Input–Output Tables (WIOT).[12] These data give a comprehensive snapshot of the German economy, as represented in monetary values of all transactions, at 56 sector levels (see Table A7 in the Annex). Following the standard IO approach [76], the output of individual sectors within an economy can be given as:

$$X_1 = a_{11}X_1 + a_{12}X_2 + \cdots + a_{1n}X_n + f_1, \quad (1)$$

$$X_2 = a_{12}X_1 + a_{22}X_2 + \cdots + a_{2n}X_n + f_2, \quad (2)$$

[11] Results for the different municipalities are presented in the Appendix.

[12] The WIOD data released in 2016 for the year 2014 give consistent data on sectoral employment and CO_2 emissions. Such data are not readily available in the more up-to-date IO tables produced by the German Federal Statistical Office. Our analysis is therefore based on information on the economic structure of Germany for the year 2014. The international fragmentation of the production processes have remained relatively stable since then [85], meaning that the production coefficient calculated for the year 2014 still serves as a robust approximation for our analysis.

$$X_n = a_{n1}X_1 + a_{n2}X_2 + \cdots + a_{nn}X_n + f_n, \quad (3)$$

where X_i is the output of sector i, and the a_{ij} coefficients represent the output of sector i needed to produce one unit of output of sector j. The sales of sector i to final demand are shown as f_i. This in turn can be represented in the matrix notation as:

$$\boldsymbol{X} = \boldsymbol{AX} + \boldsymbol{F}, \quad (4)$$

which gives the following solution for X:

$$\boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{F}, \quad (5)$$

$$\boldsymbol{\Delta X} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{\Delta F}. \quad (6)$$

$\boldsymbol{I}$ is an identity matrix, with $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ being the Leontief inverse matrix.[13] Our primary focus is on the direct and indirect impacts, i.e., those arising from Type I multipliers of the transformation pathways (see Table 2) on output, value added, and employment (see [86] for a detailed discussion on the appropriate use of such multipliers). Such impacts can be explored with Eq. (6). This "demand-driven" IO model can be used to estimate the effect of demand changes on any variable that is linearly linked to a sector's output—in our case employment and value added [76].

We identify the macroeconomic impacts of the transformation pathways arising in a city, town, and village on the national economy, and on regional economies. The regional impacts are computed to give an idea of the likely local impacts. To do so, we "regionalize" the IO table to three separate single regions—the NUTS 2 region Berlin (containing the City), Freiburg (containing the Town), and Schwaben (containing the Village). Notably, we do not disaggregate the entire IO table to the regional level, at NUTS level 2, as we are solely interested in identifying regional Type I effects. Regionalizing the national transactions matrix is therefore sufficient. In accordance with [87], transforming the national transactions matrix into a matrix of input coefficients, $\boldsymbol{A} = [a_{ij}]$, the following formula can be applied for the regionalization:

$$r_{ij} = \beta_{ij} \cdot a_{ij}, \quad (7)$$

where r_{ij} is the regional input coefficient, β_{ij} is an adjustment coefficient, and a_{ij} is the national input coefficient. We define the adjustment coefficient according to [88] as:

$$\mathrm{FLQ}_{ij} = \mathrm{CILQ}_{ij} \cdot \lambda^*, \quad (8)$$

$$\text{with } \lambda^* = \left[\log_2\left(1 + E^r/E^N\right)\right]^{\delta}. \quad (9)$$

CILQ (the cross-industry location quotient) is equal to $(E_i^r/E_i^N)/(E_j^r/E_j^N)$, E^r (E^N) is regional (national) employment, j is the purchasing industry, i is the selling industry, and δ is a parameter $(0 \leq \delta \leq 1)$.[14] FLQ is then implemented as:

$$r_{ij} = \begin{cases} a_{ij} & if FLQ_{ij} \geq 1 \\ FLQ_{ij} \cdot a_{ij} & if FLQ_{ij} < 1 \end{cases}. \quad (10)$$

Using this approach, we generate three separate **A**-matrices representing three different NUTS 2 regions. It should be noted that the choice of δ in Eq. 9 is an empirical matter. A value of around 0.3 for δ seemed suitable to give an initial idea of potential local impacts (see e.g., [90–92] for a discussion). We explore a range of values for this parameter in the results section.

Lastly, for the IO analysis, the financial flows by activity (discussed in the previous section) are broken down by individual industrial sector and implemented as a final demand vector (F). Tables 9 and 10 in the Appendix allocate the expenditures to the appropriate WIOD sector(s).

Results

Direct impacts on an individual scale

As mentioned above, expenditure and emissions are calculated by using information on energy supply options reflecting a set of technologies, and information on the use of technology options by actor groups over time.[15] As a result of the likely future actions of actor groups (according to the transformation pathways), changes in expenditure and emissions occur (see Table 6).

Regarding impacts for the Town, we see a slight increase in expenditure between 2021 and 2040 with small differences between pathway 1 and pathway 2. Compared to 2021, the emissions in the residential sector will drop by nearly 6% (pathway 1) and 9% (pathway 2). Without additional measures, payments for grid charges and levies will decrease by 3.7% (pathway 1) or 7% (pathway 2). With respect to revenues, we also calculated greater changes. Due to changes in the heating system, the revenues of the gas suppliers will drop in both pathways by 16%. All transformation pathways are linked to an increase in demand for subsidies. For pathway 1, we calculated a need of 329 euros per household. For pathway 2, 693 euros per household will be needed.

[13] The model adopts a set of conventional assumptions concerning production: fixed technical coefficients and no supply constraints. See [76] for a detailed discussion.

[14] Data from [89] are used for the regionalization.

[15] In the table, we provide information on CO_2, as a reduction in emissions is mentioned as a key factor for supporting the deployment of energy communities.

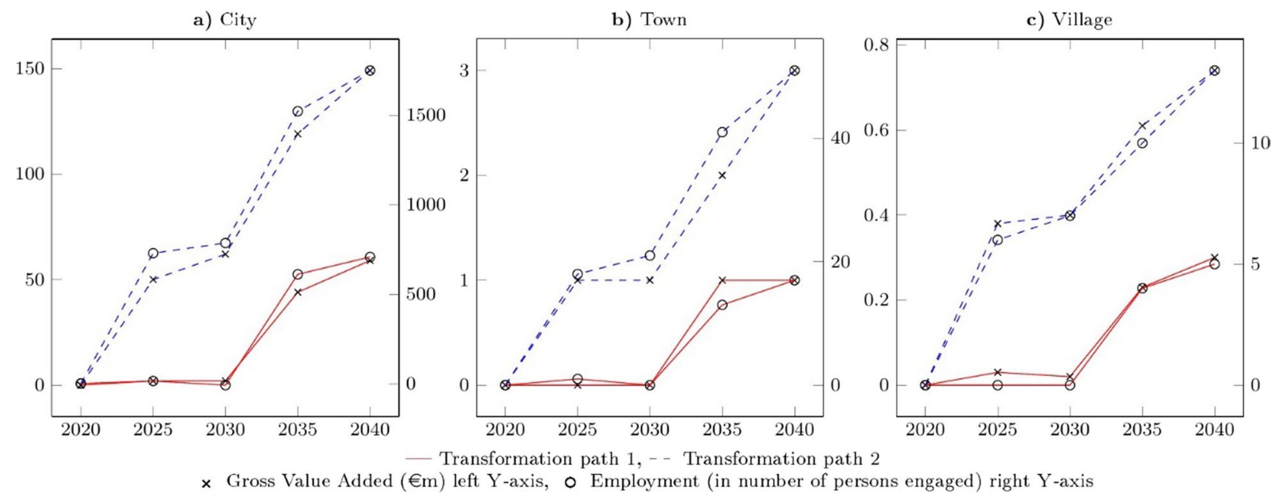

Fig. 3 Direct and indirect effects on value added and employment on a national scale

As a result of differing actor group compositions among the three municipalities, the numbers look partly different for City. The changes in expenditure and CO_2 emissions are only slightly higher than the ones for Town. Lower decreases in gas and tax revenues result from the higher share of tenants in this region. In principle, for the City, the differences between the pathways are greater than for Town. This effect results from the high share of tenants in the City and the assumption that their energy supply system will only change in the case of being "jointly active" (i.e., they are unable to be "active alone" as tenants).

The share of owners of single-family houses is highest in the Village. Since in our study, owners of single-family houses can change their energy supply system more flexibly than tenants, changes in the activities of actor groups impact the results more significantly. In particular, we calculated higher reductions in CO_2 emissions (7% for pathway 1 and 11.4% for pathway 2). High reductions for gas and tax revenues are calculated for pathway 1, resulting from the extensive deployment of PV/battery systems in combination with heat pumps. For pathway 2, we calculated a slightly lower reduction in gas revenues, since we assumed that the technologies used for by the "jointly active" require a small amount of gas for ensuring the energy supply during peak load.

Based on electricity and gas prices for the year 2022, we performed a sensitivity analysis. The results are shown in the Appendix.

As described in the previous section, the individual supply options differ in terms of the expenses incurred. Therefore, depending on the option, varying financial resources are available for private consumption or investment. In principle, this can result in additional employment and value-added effects. However, since the differences in spending are small, it is unclear whether and to what extent there will be changes in demand for consumer goods. It is also unclear whether there will be increased demand for regional goods or goods from other regions (including abroad); no analysis of income effects is performed. For the same reasons, an analysis of the effects of an additional burden on other households through redistribution of the levies is omitted.

Impacts on a national scale

The direct and indirect effects of the transformation pathways on value added (in millions of euros) and employment (in number of persons engaged) are given in Fig. 3. These results are from the national level from activities occurring at different local levels, i.e., City, Town, and Village. The results are given as the difference to the case where citizens are not active in the generation of renewable energy (i.e., they rely completely on electricity and gas from the main supply). Results suggest that the impacts on value added and employment are positive—on the aggregate national scale. The scale of the impacts varies, however, with City > Town > Village, and negligible national impacts of citizen participation in the Village.

At the national level, citizen participation in the City could generate between 59 and 149 million euros in value added in 2040, depending on the transformation pathway. This would support 707 to 1,749 jobs nationally in 2040. In the Town, citizen participation would result in 1.0 million euros in value added (2.8 million euros for pathway 2) and would support 17 (51 for pathway 2) jobs. Finally, citizen participation in the Village would generate between 0.3 million and 0.7 million euros, and between

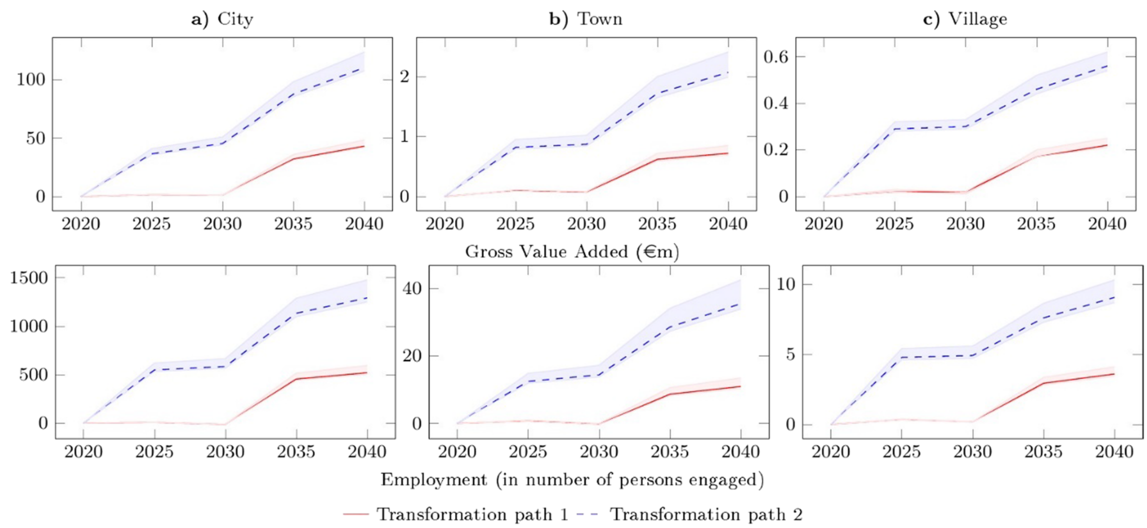

Fig. 4 Direct and indirect effects on value added and employment on a regional scale

5 and 13 jobs nationally in 2040, depending on the transformation pathway.

These impacts are the net effects of the increase in citizen participation and the corresponding decrease in demand for electricity and gas supply sectors, i.e., as individuals active in the energy generation move away from the main electricity and gas supply toward their "own" energy. As such, at the individual sector level, the positive results illustrated above do not necessarily hold true. There are sectors that benefit (directly and indirectly) from the increase in activities, and conversely, there are sectors (particularly the energy supply sectors) that experience a fall in demand and therefore a decrease in value added and employment. While the net effect of the counteracting forces is positive in our model configuration, this is not necessarily the case universally, as outcomes will depend on the technologies adopted, for example.

Impacts on a regional scale

We provide a brief account of the potential regional effects in this section. It is worth recalling that the literature suggests that positive "local effects" on employment are expected [2, 3]. As outlined above, however, the net effects (on employment) depend on several counteracting forces. Given that some sectors will likely experience a fall in demand and vice versa, it can be ascertained that the local effects depend heavily on the presence of these sectors.

Figure 4 summarizes the impacts of the activities of a city, town, or village on value added and employment that might arise on the regional scale.[16] While the impacts are now smaller compared to those seen on the national scale, the regions hold on to a substantial proportion of the overall impacts on value added and employment.

As is the case on the national scale, the probability of such positive impacts occurring depends heavily on the presence of sectors (e.g., manufacturing and services) and the resources required (e.g., skilled labor and materials) for the installation and maintenance of the electricity production technologies.

Discussion

Active participation of citizens is vital for a sustainable energy transition (see e.g., [24, 93]). This could be in the form of households adopting renewable energy systems or participation in local energy communities, for example. A recent study by [1] identified transformation pathways that map out potential future household participation in energy communities—and alternatives such as installing renewable energy systems in their homes. Economic impacts, however, were not identified in that study.

In this paper, we make use of these transformation pathways to identify the macroeconomic impacts (in terms of employment and value added) of such individual and collective prosumers. We illustrate empirically how the macroeconomic impacts of transformation pathways (consisting of information on activities of different

[16] The results are given with a default value of $\delta = 0.3$ (in Eq. 9), but we illustrate the effects of varying δ between 0.11 and 0.36 (appropriate upper and lower values of δ [92]). This parameter essentially alters the degree of convexity in Eq. 9, whereby a higher value of δ increases the allowance for interregional imports [88].

groups of actors with respect to their energy supply) can be assessed. Information on the potential future activities of households is provided in qualitative form by [1]. To identify direct and indirect macroeconomic impacts, this qualitative information needs to be converted into financial flows. Moreover, to identify regional multipliers representing the indirect effects resulting from direct activities, national input–output tables need to be regionalized. These are key challenges we addressed in this paper.

A conversion of qualitative transformation pathways into financial flows enabled us to assess direct economic impacts (i.e., expenditure of individuals, investment needs). By way of necessity, we used an example selection of technologies and assessed a renewable energy technology mix consisting of PV/battery systems, heat pumps, and combined heat and power plants with woodchip furnaces. The assessment can be flexibly adjusted according to the technology mix. An assessment of the resulting impacts requires additional assumptions [76]. In addition to information on the spatial distribution of the actor groups, information on the macroeconomic structure of the corresponding region is needed. In our study, we employed Flegg location quotients to identify regional economic structures [87]. This allowed us to assess the impacts of the activities of actor groups on the demand for investments and intermediate commodities in three example municipalities in three different regions (representing the economic structures of a city, town, and village).

Our key findings are the potential for positive regional and national effects on net value added and employment as well as potential reductions in CO_2 emissions. Depending on the transformation pathway assessed (e.g., pathway 1 with gradually increasing interest of households in joining energy communities and becoming individual prosumers or pathway 2 with accelerated deployment of energy communities) and depending on the settlement form (city, town, or village) and region assessed, between 3.5 and 94 additional jobs per 10,000 households might be created by 2040 (compared to 2021). In addition, between 0.2 million and 5 million euros in value added per 10,000 households could be generated. These results reflect the net macroeconomic effects of the fall in demand for electricity and gas supply sectors (as individual prosumers and energy community members move away from these solutions) and the increase in activities arising from the installation, operation, and maintenance of renewable energy technologies employed by energy communities and other prosumers. The employment and value-added effects as well as changes in CO_2 emissions strongly depend on the spatial distribution of heterogeneous households as well as on the underlying economic structure. The highest impacts per household occur when citizens become individual and collective prosumers in villages.

Conclusions

The results indicate that in addition to climate protection, citizen participation in the energy transition might also have a positive effect on the economy. Our study therefore supports the findings of German Energy Agency (dena) [93] and Hirschl et al. [23]. Individual prosuming and energy communities might create jobs and could provide value added, although the extent of these positive effects depends strongly on the spatial distribution of heterogeneous households and the underlying economic structure as well as the predominant housing types and ownership structures of housing in regions. A comparison of the results of the two transformation pathways yields further insights, especially for the residential heating sector. In contrast to transformation pathway 2, pathway 1 assumes slower growth of collective (but also individual) action by citizens with regard to the deployment of renewables for their household energy supply. Therefore, in the first years of transformation pathway 1, new conventional heating systems are still being adopted. If, as is probably realistic, we assume that only a fraction of households invests in new energy supply options each year (i.e., technology or a mix of technologies), and that through this investment the corresponding households fix their supply system for the next few decades, a slow deployment of renewable heating systems will likely have negative consequences far into the future. Thus, a comparison of the two sets of results for the two pathways highlights how a technological lock-in occurs in the case of residential heating systems that might impede the energy transition if renewable energy technology deployment is not accelerated. Therefore, a political decision to support the energy transition especially in the residential heating sector should be taken as quickly as possible. Furthermore, our results indicate that support of energy communities has particularly major implications for the success of the energy transition in the residential sector.

We show how qualitative data from transformation pathways can be transformed into financial flows to assess their macroeconomic impacts. By analyzing different and varied example municipalities, we emphasize the flexibility of the presented approach. In contrast to technology-oriented approaches of macroeconomic assessments, our study focuses on aspects specific to actor groups and emphasizes the impacts resulting from the heterogeneity of actor groups and their spatial distribution. We therefore do not evaluate individual technologies but rather the development of technology mixes with different ownership structures. Furthermore, our assessment of macroeconomic impacts on a regional scale is not only based on information on the societal structure at the locations under consideration but also on information on regional multipliers that help to identify indirect economic impacts. With respect to this input data, our approach differs from other more typical macroeconomic impact assessments. By applying our approach for three example municipalities, we show that differences in societal and economic structures impact the results. Our study thus supports the call for assessments that take local/regionally specific aspects into consideration.

Moving forward, it may be of interest to consider additional impacts that are induced. Our approach is limited with respect to the consideration of induced effects such as those resulting from changes in available income. For example, we do not consider the implications of changes in income and tax revenues. An assessment of such effects is associated with considerable uncertainties. This would require a range of additional information, in particular information on small changes in costs on income distribution, on the locations of parent energy companies that are affected by changes in revenues due to reduced demand in centralized energy services, on institutions that receive the taxes and fees, and on the use of grid charges and levies. An assessment of such effects requires additional information on future expenditure elasticities and saving rates, for example. Furthermore, a key limitation of the Input–Output approach is the assumption of fixed production coefficients. To take price effects into consideration, a more complex model is required along with data on the price developments of fossil fuels, labor costs, and the prices of investment goods. A consideration of such factors is beyond the scope of our study. Furthermore, the current study does not focus on resource restrictions, for example, what will happen under significantly increased demand for wood because of considerable growth in the use of woodchip furnaces. In general, price effects might be an interesting avenue for future research. Furthermore, case studies can be helpful for the verification of calculations. However, it can be expected that for generalization, a greater number of case studies are necessary.

Our approach is focused on Germany given the transformation pathway data from [1] and necessarily considers a selection of renewable energy technologies. The study can thus be seen as an example case study in the sense that it can be easily employed for the assessment of developments in different countries and regions as well as the assessment of alternative technologies and transformation pathways.

Appendix

Tables 5, 6, 7, 8, 9, 10, 11, 12, and 13.

Table 5 Actor group distributions in three stylized regions—detailed information and source materials

Stylized region	(a) City				(b) Town				(c) Village			
Roughly based on	Berlin				Konstanz				Großaitingen and Scheuring			
				Source material				Source material				Source material
Households (total)	2,026,300			[94]	48,800			[95]	1,379**			[96, 97]
Homeownership rate	17.4%			[56, 98]	46.5%			[99]	71%**			[100]
Actor group distribution*		SFH	T	Approximated from [54]		SFH	T	Approximated from [54, 101]		SFH	T	Approximated from [54, 59]
	AB	70,791	374,995		AB	3,769	5,503		AB	115	67	
	C	84,130	321,130		C	10,892	9,604		C	175	37	
	D	76,991	308,006		D	2,498	2,382		D	392	102	
	E	120,665	669,592		E	5,532	8,620		E	298	193	

SFH Owner of single-family house; *T* tenant

*Number of tenant and houseowner households within actor groups (shares calculated using the national-level homeownership rates of the actor groups [54])

**Weighted averages of the two locations

Table 6 Assignment of financial flows to actor groups (example: City)

		AB	C	D	E
Shares in City					
(1)	Owner of single-family houses	16%	21%	20%	15%
(2)	Tenant	84%	79%	80%	85%
Not active*					
Option used		Option 1 (2021) / Option 2 (2025 onwards)			
(4)	Investment needs (euros) (SFH)	8900/9750			
(5)	O&M (euros) (SFH)	2375/2516			
(6)	Investment needs** (euros) (T)	6357			
(7)	O&M (euros) (T)	1519			
	Average investment needs (euros) ((1)*(4) + (2)*(6)	6761/6896	6885/7061	6866/7036	6745/6875
	Average O&M cost (euros) ((1)*(5) + (2)*(7))	1655/1678	1697/1726	1691/1719	1650/1672
Active alone					
Option used		Option 3			
(8)	Investment needs (euros) (SFH)	22,980			
(9)	O&M (euros) (SFH)	1125			
(10)	Investment needs ** (euros) (T)	6357			
(11)	O&M (euros) (T)	1519			
	Average investment needs (euros) ((1)*(8) + (2)*(10))	8997	9808	9681	8895
	Average O&M cost (euros) ((1)*(9) + (2)*(11))	1457	1438	1441	1459
Jointly active					
Option used		Option 4			
(12)	Investment needs (euros) (SFH)	26,471			
(13)	O&M (euros) (SFH)	2322			
(14)	Investment needs ** (euros) (T)	16,680			
(15)	O&M (euros) (T)	1483			
	Average investment needs (euros)(= (1)*(12) + (2)*(14)	18,235	18,712	18,638	18,175
	Average O&M cost (euros) (= (1)*(13) + (2)*(15))	1619	1661	1655	1614

Remarks: T: tenant, SFH: owner of single-family house

*Not active: By 2025, all newly installed heating systems are to be powered by 65% renewable energy [78]. As a result, Option 1 is no longer available from 2025 onwards

**Investment will not be transferred to tenants as lump sums but likely annualized

Table 7 Assignment of financial flows to actor groups (example: Town)

		AB	C	D	E
Shares					
(1)	Owners of single-family houses	40.7%	53.1%	51.2%	39.1%
(2)	Tenant	59.3%	46.9%	48.8%	60.9%
Not active					
Option used		Option 1/Option 2			
(4)	Investment needs (euros) (SFH)	8900/9750			
(5)	O&M (euros) (SFH)	2376/2516			
(6)	Investment needs (T)	6357			
(7)	O&M (euros) (T)	1519			
	Average investment needs (euros) (=(1)*(4)+(2)*(6))	7391/7736	7709/8160	7659/8094	7351/6875
	Average O&M cost (euros) (=(1)*(5)+(2)*(7))	1868/1925	1975/2049	1958/2030	1854/1909
Active alone					
Option used		Option 3 (SFH: PV/battery system+WP)			
(8)	Investment needs (euros) (SFH)	22,980			
(9)	O&M (euros) (SFH)	1125			
(10)	Investment needs (T)	6357			
(11)	O&M (euros) (T)	1519			
	Average investment needs (euros) (=(1)*(8)+(2)*(10))	13,115	15,191	14,867	12,855
	Average O&M cost (euros) (=(1)*(9)+(2)*(11))	1359	1310	1318	1365
Jointly active					
Option used		Option 4			
(12)	Investment needs (euros) (SFH)	26,471			
(13)	O&M (SFH)	2342			
(14)	Investment needs (euros) (T)	16,680			
(15)	O&M (euros) (T)	1,483			
	Average investment needs (euros) (=(1)*(12)+(2)*(14))	20,660	21,883	21,692	20,507
	Average O&M cost (euros) (=(1)*(13)+(2)*(15))	1832	1939	1923	1819

Remarks: T: tenant, SFH: owner of single-family house

*Not active: By 2025, all newly installed heating systems are to be powered by 65% renewable energy [78]. As a result, Option 1 is no longer available from 2025 onwards

**Investment will not be transferred to tenants as lump sums but likely annualized

Table 8 Assignment of financial flows to actor groups (example: Village)

		AB	C	D	E
Shares					
(1)	Owner of single-family house	63.0%	82.4%	79.4%	60.6%
(2)	Tenant	37.0%	17.6%	20.6%	39.4%
Not active					
Option used		Option 1/Option 2			
(4)	Investment needs (euros) (SFH)	8900/9750			
(5)	O&M (euros/year) (SFH)	2376/2516			
(6)	Investment needs (euros) (T)	6357			
(7)	O&M (euros/year) (T)	1519			
	Average investment needs (euros) (=(1)*(4) + (2)*(6))	7960/8496	8452/9153	8375/9050	7898/6875
	Average O&M cost (euros/year) (=(1)*(5) + (2)*(7))	2059/2148	2225/2341	2200/2310	2039/2123
Active alone					
Option used		Option 3			
(8)	Investment needs (euros) (SFH)	22,980			
(9)	O&M (euros/year) (SFH)	1125			
(10)	Investment (euros) needs (T)	6357			
(11)	O&M (euros/year) (T)	1519			
	Average investment needs (euros) (=(1)*(8) + (2)*(10))	16,834	20,054	19,551	16,431
	Average O&M cost (euros/year) (=(1)*(9) + (2)*(11))	1271	1195	1207	1,281
Jointly active					
Option used		Option 4			
(12)	Investment needs (SFH)	26,471			
(13)	O&M (euros/year) (SFH)	2342			
(14)	Investment needs (euros) (T)	16,680			
(15)	O&M (euros/year) (T)	1483			
	Average investment needs (euros) (=(1)*(12) + (2)*(14))	22,851	24,747	24,451	22,614
	Average O&M cost (euros/year) (=(1)*(13) + (2)*[15))	2024	2191	2165	2003

Remarks: T: tenant, SFH: owner of single-family house

*Not active: By 2025, all newly installed heating systems are to be powered by 65% renewable energy [78]. As a result, Option 1 is no longer available from 2025 onwards

**Investment will not be transferred to tenants as lump sums but likely annualized

Table 9 Sensitivity analysis (prices: 2022)

		Pathway 1				Pathway 2			
		2025	2030	2035	2040	2025	2030	2035	2040
Town									
Expenditure	%	0.4	0.7	1.1	1.4	0.6	1.2	1.7	2.3
City									
Expenditure	%	−0.2	−0.6	−0.4	−0.2	0.8	1.5	2.9	4.2
Village									
Expenditure	%	0.7	1.5	2.6	3.6	0.7	1.5	2.3	3.0

Remarks: Prices for January 2022: electricity: 0.36 euros/kWh, natural gas: 0.12 euros/kWh, woodchips: 0.12 euros/kWh

Sources: [102–104]

Table 10 Results—assessment of direct impacts (in percentage points compared to 2021)

		Pathway 1				Pathway 2			
		2025	2030	2035	2040	2025	2030	2035	2040
Town									
Expenditure	%	0.7	1.4	2.4	3.4	1.1	2.2	3.5	4.8
CO_2 emissions	%	−0.7	−1.6	−3.6	−5.7	−1.5	−3.0	−5.8	−8.7
Grid charges, levies	%	−1.0	−2.4	−5.2	−8.0	−1.7	−3.3	−6.7	−10.2
Revenues electricity	%	−0.1	−0.3	−2.0	−3.7	−0.9	−1.8	−4.4	−7.0
Revenues gas	%	−3.0	−6.5	−11.4	−16.2	−3.2	−6.4	−11.4	−16.3
Tax revenues	%	−1.6	−3.6	−7.0	−10.4	−2.1	−4.3	−8.1	−12.0
Subsidies	Euros per household	4.8	25.1	177.2	329.4	97.6	195.2	444.0	692.8
City									
Expenditure		0.5	1.0	2.1	3.2	1.1	2.2	4.0	5.7
CO_2 emissions	%	−0.3	−0.7	−2.5	−4.3	−1.7	−3.4	−6.6	−9.8
Grid charges, levies	%	−0.5	−1.1	−3.1	−5.0	−1.7	−3.5	−6.6	−9.7
Revenues electricity	%	0.0	−0.1	−1.7	−3.3	−1.4	−2.9	−5.8	−8.8
Revenues gas	%	−1.3	−2.9	−5.6	−8.2	−2.4	−4.7	−8.4	−12.0
Tax revenues	%	−0.7	−1.6	−3.7	−5.8	−1.9	−3.8	−7.1	−10.4
Subsidies	Euros per household	0.8	9.6	145.4	281.3	127.8	255.6	511.3	766.9
Village									
Expenditure	%	0.8	1.7	3.0	4.2	1.4	2.9	4.5	6.1
CO_2 emissions	%	−1.0	−2.2	−4.8	−7.4	−2.4	−4.8	−8.1	−11.4
Grid charges, levies	%	−1.5	−3.2	−6.3	−9.4	−2.5	−5.0	−8.5	−12.0
Revenues electricity	%	−0.3	−0.6	−2.8	−4.9	−1.8	−3.7	−6.7	−9.8
Revenues gas	%	−4.1	−8.7	−13.7	−18.8	−3.7	−7.5	−11.8	−16.2
Tax revenues	%	−2.4	−5.0	−8.8	−12.5	−2.9	−5.8	−9.5	−13.3
Subsidies	Euros per household	23.6	47.3	284.7	522.1	225.8	3.2	5.6	1,162.4

Table 11 Bridge matrix: focus on investments

	Electricity supply		Owner					Tenant		
			Grid	Grid	Grid	Grid + PV	Energy community	Grid	Grid	Energy community
	Heat supply		Use of exist. gas boiler	New boilers	Heat pumps	Heat pumps	Energy community	Use of exist. gas boiler	New boilers	Energy community
		Reg. factor*	Euros							
C25	Manufacture of fabricated metal products, except machinery and equipment	0.1	0	0	0	0	416	0	0	237
C26	Manufacture of computer, electronic, and optical products	0.1	0	0	0	635	622	0	0	840
C27	Manufacture of electrical equipment	0.1	0	0	0	561	467	0	0	0
C28	Manufacture of machinery and equipment n.e.c	0.1	0	720	1200	1200	1104	0	514	629
C33	Repair and installation of machinery and equipment	1	0	2000	3000	4270	4998	0	1429	2246
F	Construction	1	0	0	0	0	2475	0	0	1411
M74_M75	Other professional, scientific, and technical activities; veterinary activities	0.5	0	0	0	0	1225	0	0	698
Sum			0	2720	4200	6666	11,307	0	1943	6062

Remarks: *Reg. factors reflect the share of the regional economy on the overall financial flows

Table 12 Bridge matrix: focus on O&M

	Electricity supply:		Owner					Tenant		
			Grid	Grid	Grid	Grid + PV	Energy community	Grid	Grid	Energy community
	Heat supply:		Use of exist. gas boiler	New boilers	Heat pumps	Heat pumps	Energy community	Use of exist. gas boiler	New boilers	Energy community
		Reg. factor*	Euros							
A02	Forestry and logging	1	0	0	0	0	362	0	0	206
C33	Repair and installation of machinery and equipment	1	180	180	150	229	611	103	103	348
D35	Electricity, gas, steam, and air conditioning supply	0.1	212	212	237	95	124	56	56	12
K65	Insurance, reinsurance, and pension funding, except compulsory social security	1	0	0	0	50	121	0	0	69
N	Administrative and support service activities	1	80	80	0	0	10	46	46	6
Sum			472	472	387	374	1228	204	204	641

Remarks: *Reg. factors reflect the share of the regional economy on the overall financial flows

Table 13 Sector classification WIOD

Code	Description
A01	Crop and animal production, hunting and related service activities
A02	Forestry and logging
A03	Fishing and aquaculture
B	Mining and quarrying
C10–C12	Manufacture of food products, beverages, and tobacco products
C13–C15	Manufacture of textiles, clothing, and leather products
C16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
C17	Manufacture of paper and paper products
C18	Printing and reproduction of recorded media
C19	Manufacture of coke and refined petroleum products
C20	Manufacture of chemicals and chemical products
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
C22	Manufacture of rubber and plastic products
C23	Manufacture of other non-metallic mineral products
C24	Manufacture of basic metals
C25	Manufacture of fabricated metal products, except machinery and equipment
C26	Manufacture of computer, electronic, and optical products
C27	Manufacture of electrical equipment
C28	Manufacture of machinery and equipment n.e.c
C29	Manufacture of motor vehicles, trailers, and semi-trailers
C30	Manufacture of other transport equipment
C31_C32	Manufacture of furniture; other manufacturing
C33	Repair and installation of machinery and equipment
D35	Electricity, gas, steam, and air conditioning supply
E36	Water collection, treatment, and supply
E37–E39	Sewerage; waste collection, treatment, and disposal activities; materials recovery; remediation activities and other waste management services
F	Construction
G45	Wholesale and retail trade and repair of motor vehicles and motorcycles
G46	Wholesale trade, except of motor vehicles and motorcycles
G47	Retail trade, except of motor vehicles and motorcycles
H49	Land transport and transport via pipelines
H50	Water transport
H51	Air transport
H52	Warehousing and support activities for transportation
H53	Postal and courier activities
I	Accommodation and food service activities
J58	Publishing activities
J59_J60	Motion picture, video, and television program production, sound recording and music publishing activities; programming and broadcasting activities
J61	Telecommunications
J62_J63	Computer programming, consultancy, and related activities; information service activities
K64	Financial service activities, except insurance and pension funding
K65	Insurance, reinsurance, and pension funding, except compulsory social security
K66	Activities associated with financial services and insurance activities
L68	Real estate activities
M69_M70	Legal and accounting activities; activities of head offices; management consultancy activities
M71	Architectural and engineering activities; technical testing and analysis
M72	Scientific research and development
M73	Advertising and market research

Table 13 (continued)

Code	Description
M74_M75	Other professional, scientific, and technical activities; veterinary activities
N	Administrative and support service activities
O84	Public administration and defence; compulsory social security
P85	Education
Q	Human health and social work activities
R_S	Other service activities
T	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use
U	Activities of extraterritorial organizations and bodies

Source: [105]

Abbreviations

CHP	Combined heat and power plant
IO	Input–output analysis
NUTS	Nomenclature of territorial units for statistics
O&M	Operation and management
PV	Photovoltaics
SFH	Owner of a single-family house
T	Tenant

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SV and LB conceptualized the research. LB and SV analyzed and interpreted the data, wrote the manuscript, and worked on the visualization of the results. SV supervised the research. SV developed the methodology and the model. AR commented the research. DR undertook reviewing, commenting, and editing. All authors read and approved the final manuscript.

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