Dissemination of PV-Battery Systems in the German Residential Sector up to 2050: Technological Diffusion from Multidisciplinary Perspectives

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Abstract
A decarbonization of the European energy system implies great changes in the residential sector. Recently, the sector does not show the necessary dynamics. Apparently decarbonizing the sector requires a new momentum. Using PV-Battery systems as key technology for the residential sector for becoming more environmentally sustainable as an example, we take a closer look at the complexity of technology diffusions in the residential sector. By employing a socio-techno-economic (SoTeEc) framework approach we consider that diffusion processes are impacted by a broad range of measurable and non-measurable factors. Our framework combines a techno-economic with a socio-economic analysis. With the techno-economic analysis we assess the drivers of technology diffusion of PV-Battery systems in private households whereas the socio-economic analysis focuses on the role of a) the household sector in the overall social-economic system and b) actor specific factors like attitudes. The link of the two approaches enables us to identify which techno-economic scenarios are feasible from socio-economic point of view and vice versa. Hence, we can identify scenarios which fulfill simultaneously requirements from techno-economic and socio-economic point of views. Such scenarios can serve as a starting point for policy recommendations.

Keywords: residential sector, decarbonization, socio-economic modelling, socio-techno-economic framework

1 Introduction

According to the IEA the residential sector accounts worldwide directly for more than 2,000 million tons of CO_2 and more than 21 % of the total final energy consumption [1, 2]. Hence, without radical changes in this sector, targets like the ones set at the Conference of the Parties (COP) in Paris in 2015 will not be reachable. There are countless studies that focus on transformation pathways for the residential sector showing possible options and their impacts on emissions and energy reduction targets (see e.g., [3], [4], [5]).

PV-Battery systems could create an important momentum for private households to support the transformation of the energy system. They could provide (more) self-sufficiency, while helping to increase the share of renewable energy carriers at the national electricity mix. However, the willingness to invest into PV-Battery systems and thus, the dynamics of their technological diffusion depends on manifold factors (e.g. also non-climate change related). A holistic knowledge of the main drivers and their interrelationship seems to be necessary to understand the technological diffusion of PV-Battery systems.

In respect to possible conditions for the diffusion process in the literature two strands can be identified: one focuses on the techno-economic constraints, while the other one concentrates more on socio-economic conditions. Techno-economic aspects include vintage structure of capital stock and changes in cost figures as key factors for innovation and transition processes in general (see e.g., [6], [7], [8]). In studies focusing on the diffusion of PV-Battery systems the meaning of increasing retail electricity prices, cost reductions in combination with incentives as driving forces for the diffusion process have been highlighted (see e.g., [9], [10], [11]). In such studies, PV-Battery systems are considered as elements of techno-economic systems that consist of a greater set of technologies being linked with each other (see e.g., [12], [13]).

Socio-economic factors like preferences and attitudes of companies and individuals as well as demographic factors frame the future of energy systems and thus the diffusion of technologies (see e.g., [14], [15], [16]). In the last years more and more attention has been paid to these factors. As a result these factors are considered within consistent storylines and narratives (see e.g., [17]; [18], [19]). Socio-economic analysis emphasizes the meaning of factors like attitudes, behavior patterns, institutions and other kinds of societal aspects for complex systems like national energy systems [19]. A challenge for socio-economic modeling is that many of these factors cannot be quantified exactly. The qualitative characteristic of such factors challenges the modeling of energy systems. On the other hand, the consideration of these factors enables us to understand e.g., decisions of policy makers, investors, and consumers. In socio-economic analysis technologies are seen as possibility to satisfy the demand for a selected kind of service [20].

Techno-economic approaches focus on the technological aspects like availability of technologies, possible applications of them as well as related costs. They do not care for the reasons of the demand of service, instead they study how the demand can be met. For techno-economic analysis each factor has to be quantifiable. Usually, trend extrapolations or expert adjustments are used for drawing conclusions on the development of the factors' level. Trend extrapolations as well as expert adjustments are based on a lot of explicit and implicit assumptions (e.g., assumed learning effects resulting from R&D expenditure or increases in labor productivity). The broad range of these assumptions challenge the transparency of energy models. In contrast to socio-economic modeling more attention is paid to physical laws and constraints. Thus, techno-economic modeling ensures that all technological constraints are fulfilled [20], whereas market decisions are simplified [21]. The overarching aim of the contribution is to combine these different approaches of diffusion analysis in a comprehensive approach focusing on the dissemination of PV-Battery systems in private households. To be more precise, the contribution aims at a) completing the picture of preconditions and requirements of technological change as well as to assess the umbrella of impacts of such developments, and b) discussing the gains and challenges to combine both perspectives and the underlying approaches, with their complementary strengths, to profit from additional insights, as implied by a).

By focusing on the possible dissemination of PV-Battery systems in the German residential sector we show the additional value of a multidisciplinary analysis of future developments of this sector. In particular, we stress that, since the diffusion of PV-Battery systems in the German household sector is directly and indirectly determined by a broad range of linked societal, technological and economic factors, transformation processes have to be analyzed within a socio-techno-economic (SoTeEc) framework. Within this framework it is necessary to deal with hardly quantifiable, i.e. qualitative (e.g. attitudes of actors as well as with quantitative (e.g. costs, changes in efficiency) factors.

The necessity of a combined approach is implicitly emphasized by Geels and Schott [22] by stressing the relevance of co-evolution of industry, technology, markets, policy, culture and civil society for economic systems. Hence, the aim of socio-economic studies should not be limited to providing socio-economic context scenarios. Studies focusing on innovation processes (e.g., by applying Multi-level-perspective [23] or National innovations approach [24], [25]), for instance, show the high relevance of considering the interaction of socio-economic (incl. attitudes, behavior patterns, institutional aspects) and technological factors and thus the need for adequate approaches.

As examples for approaches which have been developed to extend the view on socio-techno-economic systems the Multi-level perspective [23], and Cross-Impact Balance approaches (see e.g., [26], [19]) have to be mentioned. In particular, the integration of socio-economic aspects into storylines and linking these storylines with techno-economic models fostered the multidisciplinary view on possible futures. According to IPCC, the consideration of socio-economic factors in form of storylines helps to think more coherently about the complex interplay between qualitative and quantitative driving forces within each and across alternative scenarios [27]. Since the integration of technological, economic and societal aspects in a model is very difficult and costly [28], storylines approaches providing information on the development of socio-economic frameworks are more disseminated than fully integrated approaches. Storyline/techno-economic modeling approaches are easy to implement. However, since links between the techno-economic system and the assumed storyline are ignored, inconsistencies are not unlikely.

In summary, the diffusion of PV-Battery systems in private households depends on a multitude of social, technological and economic factors and their qualitative and quantitative interlinkages. To consider these complex interdependencies, we analyse the transformation process within a socio-techno-economic (SoTeEc) framework. Within this framework we combine hardly quantifiable, i.e. qualitative (e.g. attitudes of actors) with quantitative (e.g. costs, changes in efficiency) factors. Our paper is organized as follows: In section 2, we present the methodical foundation of our approach. section 3 provides the specification of the framework. Results are presented and discussed in section 4. In section 5, we conclude our analysis.

2 Methodical background

In the following we take a closer look at different kinds of analysis by using two typical approaches as examples. In addition, we show how approaches can be linked and what additional values can be expected by combining the approaches.

2.1 Factors framing the future of the residential sector

The energy demand of the private households is determined by a broad range of factors (see e.g., [29], [4]). On technological level these factors include, for instance, size, number, kind of the dwelling, and energy efficiency standards of the employed technologies (such as heating system and of the electric appliances) and the efficiency standard of the buildings. The degree of utilization of the employed technologies is strongly determined by the behavior patterns of the members of the households and the size of the corresponding household. Cost awareness and attitudes towards environment issues, for example, can trigger attitudes to reduce energy consumption [30]. Beside costs and prices, income is an additional factor on the list of economic factors, which determine energy demand. Summing up, technological factors, attitudes (and the corresponding behavior patterns), economic factors, and weather conditions shape energy consumption [31].

Changes in cost awareness resulting from e.g. rising electricity prices, increasing consciousness towards environmental issues in combination with policy measures and decreasing technology costs does not only impact energy demand but also foster the request of a growing share of private households for autarky and self-sufficiency (see e.g., [31], [8]). Of course, existing regimes (i.e. the set of rules and institutions formed by the interactions of science, technology, politics, markets, user preferences and cultural meanings) and aspects on landscape level [23] influences the factors mentioned. Landscapes encompass factors like demographic trends, political ideologies, social values, macroeconomic patterns and other factors [22].

2.2 Socio-economic analysis

In the following we show the construction and application of a) consistent socio-economic context scenarios which can serve as framework for closer analysis of techno-economic analyses and b) socio-economic scenarios focusing on innovation processes of selected technologies.

2.2.1 Identification and specification of consistent context scenarios

Based on the observation that without closer analyses of socio-economic aspects, energy as well as climate scenarios could result in inconsistent views on possible development and hence in inadequate recommendation for policy measures, Bauer et al. [32] stressed the need for modeling frameworks which takes long term development of socio-economic aspects into consideration.

In the last few years different approaches have been developed (see e.g., [33], [19]). One approach which has been applied successfully in many studies is the Cross-Impact-Balance approach (CIB) [26]. This approach is based on the assumption that a) the socio-economic framework with its manifold facets frames energy systems and b) that without taking this framework into consideration, the reliability of calculated scenarios and the conclusions derived therefrom are questionable [34]. Using scenarios for the steel industry as example, Vögele et al. [35] show that input factors can impact each other indirectly and that therefore there is a need to consider a broad range of factors. Another study shows that CIB can be used to assess openness of the future [36]. The CIB approach enables us to deal with qualitative and quantitative factors and their interlinkages [37]. Hence, consistent and reliable scenarios can be identified and tested for their robustness. In particular, with CIB it is possible to specify consistent sets of parameters representing storylines. By providing information on input parameters for other models, the storylines can serve as a consistent frame for e.g. the application of techno-economic models [38].

In principle, CIB analysis consists of four steps: Firstly, identification of factors describing the system under consideration. A typical list of the so-called descriptors used for specification of context-scenarios includes demographic factors (e.g., size of population), economic factors (e.g., GDP, fuel prices), aspects on policy level (e.g., focus on reduction of GHG) and societal factors (e.g., trends towards self-sufficiency). In a second step, for each of the descriptors two to four possible futures are defined. The futures can be characterized either numerically (e.g., 80 million inhabitants) or linguistic (e.g., high oil price). In a next step experts evaluate the links between the futures usually by using a scale from -3 (indicating that the future of one descriptor strongly restricts the future of another one) to +3 (indicating that the future of one descriptor strongly promotes the future of another one). The evaluation of the interlinkages by experts enables to get quantitative and qualitative states of descriptors by considering non-measurable aspects. Finally, a balancing algorithm is employed: All possible sets of combinations of futures are scanned with respect to the sum of impacts which promote and hinder the realization of each future of the set. If all futures of a set dominate other futures the set is considered as being consistent. Based on the consistent sets of futures it is possible to formulate storylines.

Since the futures of the descriptors have to be interpreted as indicative possible states, they have to be used carefully. At the same time, the indicative character of the futures enables further applications of the storylines. For reducing workload, usually, the applicants of CIB approaches reduce the number of descriptors to 20 to 30. However, in principle it is possible to work with more descriptors, using e.g. a multi-level approach [5].

2.2.2 Deployment of PV-Battery systems

The motives to demand and install PV-Battery systems are comprehensive and differ in their relevance according to the state of market penetration [39]. In the early stage of market penetration of a new technology, the main reason of the so-called early adopters or technological aficionados is the interest in a new technology, i.e. the way of functioning of a new technology. Other reasons, like reduction of the electricity cost burdens, contribution to a “better future”, or other non-technological motives could influence the decisions, but they are of lesser importance. With a successful market entry the interest in a new technology evaporates [39].

Jager [40] identified as the strongest non-economic motives to install PV plants “Contribution to a better natural environment” and “Independence from electricity supplier”. Renewable energies, like PV, are seen as a major contributor to reduce the environmental burden, i.e. to slow down anthropogenic driven climate change by a diminishing demand for fossil fuels. Additionally, they could help to smooth the provision of renewable energies, if stored electricity is supplied to the grid during excess demand. PV-Battery systems could also initiate additional investment in PV plants in the neighborhood [41]. The peer effect appears to lead to larger installations and seems to result from the visibility of the panels. The motive to contribute to a better natural environment or to contribute to the energy transition could also be expressed by installing more capacities than is needed for own consumption [42]. The wish for to be independent from utilities is motivated by a set of reasons, attributing a general distrust to future grid stability or to the reliability of utilities as well as to possible developments of the society (see e.g., [40], [43]). According to literature, controlling the future grid system will show a higher complexity compared to today’s system [44]. This is due to not only the fluctuating supply of renewable energies, but also the increasing dependency on changing climate and weather conditions demanding for higher flexibility of the energy system.

The energy transformation process is happening in a society, which seems to drift apart not only regarding income and wealth, but also regarding the visions about the future. This process is not only observable in Germany, but in many industrialized countries, increasing the uncertainty about the future. PV-Battery systems would help to secure the own electricity supply, reducing the interconnection to the society in an important field of living [45]. The installation of PV and batteries could feed back on user behavior and social networks. Hondo and Baba [46], for example, suggest that the installation of residential PV systems affects people’s concern and norms related to energy and the environment, and consequently influences people’s behavior. To install PV-Battery systems could be also motivated by the wish to reduce the energy cost burden, if, for example, increasing energy prices are expected [47]. Focusing on private households we assume utility optimizing households, with no specific profit orientation. That means, cet. par., households aim at reducing the entire financial burden of energy use. Said that, the decision, whether a household will demand a PV-Battery system, depends on the expected costs to buy electricity from an utility (per kWh) in relation to the expected costs of installing and operating a PV-Battery system reduced by expected support by the public and by the expected yield of selling excess power to the grid (per kWh). The decision depends crucially on the expected conditions on the markets for electricity and energy technologies. The readiness to sell excess electricity hinges on the risk expectations of a household. Trust in the reliance of the (future) grid system or of the technology is one important motive. Selling excess power could have an impact on the support by the public. The existence of “green” virtual power plants (VPPs) could influence the economic advantage of PV-Battery systems, too, as they could guarantee a (more or less) continuous income stream and thus, reduce the risk of a bad investment. VPPs could be also the result of building a community with other likeminded people, supporting the energy transformation. An additional effect of VPPs could be their contribution to stabilize the grid system. Connecting the PV-Battery system to VPPs would mean on the one hand, to reduce the dependency from large-scale utilities, if the VPP is not provided by them. On the other hand, it would increase the dependency from the grid system. Additionally, the providers have remote control over the technology. In this case, the aspect of trust might become relevant: who controls the data and the used electricity (e.g. ensures that renewable electricity is fed in the grid with priority over fossil energy)?

In our study, we assume that the government provides conditions, which allows private households to install PV-Battery systems and to sell excess power. Private households will see further on a support system comparable to the current one, although the financial support will decrease until the year 2050, covering the gains of learning curves of producing such systems. The relevance of the presented drivers varies between the appliers of the technology under review, inducing the typical pattern of the diffusion processes [39]. However, since the focus of the following analysis is on understanding the influence of these factors on the demand for PV-Battery systems after a successful market entry, the interest in a new technology as a motive of early adopters will be excluded from the analysis.

2.3 Techno-economic analysis

The techno-economic analysis pursuits two aims: a) to show the impacts of techno-economic constraints on the demand for PV-Battery systems, assuming a cost minimizing objective by the households, and b) to act as a reference for a plausibility check of the socio-economic analysis, since there technological and economic constraints are not implemented rigorously. The latter implies that the relevant framework conditions of the socio-economic analysis are used in quantified form as input for the techno-economic analysis.

The techno-economic approach evaluates the profitability of PV-Battery systems in the German residential building sector for single-family households under various framework conditions that are specified by the context scenarios for the year 2050 (see section 3.2). Relevant input parameters for a techno-economic evaluation of photovoltaic battery systems include the electricity price for end customers, technology price developments, electricity feed-in tariffs and technology developments. Furthermore, the characteristics of the residential building stock, e.g. roof area potentials for PV and weather conditions have a major impact on the economic operation of a PV-Battery system.

Therefore, in a first step in this study, the German single-family building stock (building size, building age, occupants, building type) is represented at the NUTS3 level using German census data [48]. This information is blended with geometry information from the German residential building typology [49]. The orientation of the residential buildings and the roof pitch angle is drawn using a statistical distribution similar to [50]. In a second step, the locally prescribed buildings are linked with the irradiation conditions and temperature curves in the respective key areas of the NUTS3 regions based on data from the German weather service [51]. Thirdly, 200 buildings that represent the German single-family building stock are selected by using a cluster approach. In the fourth and last step, techno-economically optimized PV-Battery systems are determined with the help of a mixed integer linear programming costs optimization model, taking into account the framework conditions specified above. The object value is the total discounted system costs. Details on the described approach can be found in [52]. Based on the results of the techno-economic analysis, the consistency of the partial aspects of the consistent scenarios from the socio-economic analysis is determined.

2.4 Integrated assessment

The linking of different approaches or models has a long tradition (see e.g. [27]). Usually the models are soft-linked, which means that the models can run on their own. If a hard-link approach is applied this flexibility does not exist any longer. A main advantage of soft-linked approaches is to update models or to add new models without completely to re-configure the entire model system. If several feedback loops between the models are required hard-linking is more appropriate than soft-linking because, in principle, the loops within hard-linked models are automated. Fully integrated models aim at merging different dimensions of economic, technological and environment related factors into one model frame, implying the necessity to define a common quantitative frame with the need to translate hardly quantifiable information into numbers [26]. Hence, they are very complex and difficult to implement.

In our study, we employ a soft-linking approach and show to which extent such an approach provides new insights. Linking of approaches means that information of one approach is used as input in another one. Information includes the level of individual factors but also information on possible factor constellations. These constellations are determined by the assumed system linkages between the factors. In techno-economic modeling special attention is paid for instance to technological constraints

and physical laws whereas in social-economic interactions social factors are stressed. Hence, techno-economic modeling provides information on constellations that are consistent in a techno-economic sense whereas socio-economic modeling information focuses on consistency on socio-economic level. Thus, linking the different approaches enables to ensure overall consistency [19].
The integrated assessment combines the advantages of socio-economic with its explicit consideration of qualitative factors and techno-economic approaches, which ensure that physical laws and constraints are taken appropriately into consideration. By this a more complete picture of the pre-conditions and requirements of technological change is provided, as a qualification for an assessment. Furthermore, we discuss the gains and challenges to combine both perspectives and the underlying approaches, with their complementary strengths, to profit from additional insights (Fig. 1).

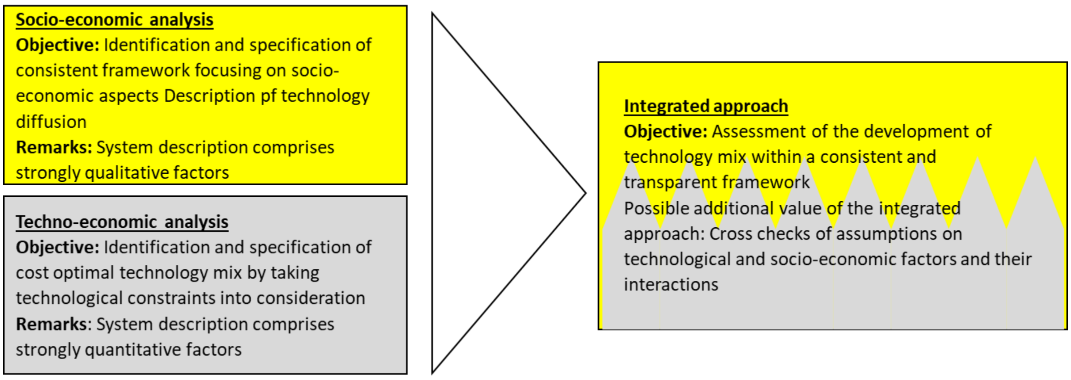

Fig. 1: From disciplinary approaches to integrated approach

In a first step implicit assumptions of the socio-economic and the techno-economic approach are identified. In techno-economic models, for instance, energy demand and supply are determined by a set of assumptions, which are either implicitly given or not disclosed accordingly, beside some socio-economic factors which are explicitly mentioned as inputs. These assumptions refer amongst others to the stability of behavior patterns, on attitudes towards technologies and policies as well as to the future foci of policies. In a second step, factors are identified that play a role in all approaches, either as input or output variables. These so-called coupling factors are key links for the different approaches. Tab. 1 shows the list of factors being identified for our study.

Tab. 1: "Coupling" Factors

	Socio-economic Analysis		Techno-economic Modeling
	Storylines/context scenarios	Assessment of Battery/PV Systems	
Electricity Prices	**Indicator**: Price for fossil fuels **Comment:** Prices for fossil fuels are basis for the calculation of end-user prices for energy carriers.	**Indicator:** Electricity price	**Indicator**: Electricity price
Electricity demand	**Indicators:** Population development, GDP growth, Energy consumption behavior (individual) **Comment:** The combination of these factors determines energy/electricity demand	**Indicator:** Electricity demand	**Indicator**: Electricity demand
Grid	**Indicator:** Infrastructure expansion of power lines, Central/decentralized power generation & -storage **Comment:** The combination of these factors determines grid stability	**Indicator:** Grid stability	
Decentra-lization	**Indicator:** Central/decentralized power generation & -storage	**Indicator**: PV and battery use	**Indicator**: PV and battery use

3 Specification of the Framework Setting(s)

3.1 Setting for the Identification of Storylines

In this analysis, households are understood as socioeconomic systems whose decision-making depends on economic and technological conditions, but also on the goals, perceptions, and beliefs of their members. However, households are not isolated systems. They are embedded in a larger context of political, macroeconomic, societal and cultural conditions that influence not only the decision rules of the households, but also the technological ecosystem within which they can choose. Thus, a consistent analysis of future household decisions requires not only an examination of their socioeconomic determinants of decision-making, but also an idea of the larger context that will shape the playground. In our analysis, the socioeconomic determinants of household attitudes to and decisions about installing PV-Battery systems, as they are outlined in section 2.2, are investigated by a CIB analysis described in section 3.2. A 'big picture' in which future households in Germany and technological conditions are assumed to be embedded in our analysis, is provided by a storyline about political, societal and energy-related developments in Germany until 2050, developed by Pregger et al. [38].
Their proposed storylines are based on an expert elicitation process conducted as part of the ENERGY-TRANS research project [53]. Experts from the fields of energy, sociology, demography, economics, psychology, law, cultural studies, and political science were interviewed about the most influential factors in their field that affect the energy transition, and the interdependencies between these factors were discussed (see [38], Supplementary Materials for more details). Finally, 39 factors were identified, and 2-4 alternative futures were formulated for each factor, some qualitative and some quantitative, depending on the nature of the factor. Factors like "Acceptance of energy technologies", "Energy consumption behavior", "Consumption trend household appliances" and "Residential space trend" are used to assess possible futures of energy demand of private households and their attitudes. Consistent with our approach, the CIB method was applied by Pregger et al. [38] to systematically construct a large set of consistent semi-quantitative scenarios about the broad context of energy transition, some of which favor energy transition success while others increase barriers to energy transition ('landscape of societies'). Correspondence analysis [54] was used to identify a representative sample of scenarios from the 'landscape', and detailed storylines were developed for the selected scenarios. Since in the system under consideration the factors describing energy demand and attitudes of the private households and factors like e.g. expansions of power lines, change in prices and the dominate form of power generation (centralized vs. decentralized) are direct and indirectly linked, the residential sector is seen as an element being embedded in a complex socio-economic system.
From the storylines developed in Pregger et al. [38], we selected the 'Target' storyline because they identified this storyline as a plausible societal background picture of a successful energy transition of the German energy system roughly similar to a target-oriented energy scenario widely noticed in the German energy debate (see e.g. [55]).

3.2 Setting for the description of the decision processes regarding PV-Battery Systems

The list of descriptors as well as the definition of these are listed in the Tab. 2. As mentioned above for each descriptor different possible future states are identified. The scope of this study is Germany including developments from now until 2050.

Tab. 2: List of descriptors, definition, importance and motivation

Descriptor	Definition	Importance and motivation
Electricity price	Price of electricity for private households	Electricity prices influence the economic motivation for own production
Electricity demand	Electricity demand of private households, net Note: Excludes demand for self-produced and stored electricity	The electricity demand reflects the public attitude and electric efficiency. It influences the demand for infrastructures and capacities.
Grid stability	Stability of the grid system	Stability of the grid could incite self-sufficiency
Land availability	Available land for the instalment of renewable energies Note: excludes buildings.	Land can limit electricity supply. It is needed for grid extension as well as for PV, wind power plants and biomass.

PV and battery use	Demand for combined PV - battery systems by private households	Descriptor showing the diffusion of the technology.
Battery use	Available batteries for private households	A wide battery use is coupled with low prices and vice versa. The battery price is, like the electricity price, a main motivation to install the technology.
PV Technology	Electricity provided by PV. Note: includes PV plants operated by private households and companies, situated on tops and at buildings as well as on open spaces.	The use of PV technology in the general electricity supply lowers the prices and thus also supports the application in households.
Fossil fuels	Electricity provided by fossil power plants	The share of fossil energy in the grid influences its design and management. The main function of these power plants is to satisfy the peak load. A high availability implies that a small part of the power plants is used for the base load
Bioenergy	Electricity provided by biomass power plants	Modern biomass power plants are to some extent flexible and could help to smooth the time pattern of the load
Virtual power plants	Virtual power plants connect small power plants, operated by companies as well as by private households	Important future option to design local and regional energy supply. It is assumed that renewables dominate VPPs. Small fossil-based power plants could be supplemented to stabilize the grid
Climate change	Awareness in respect to climate change; not the actual climate change	Three states are differed: high: it is expected that climate change will have a high impact on the personal living standard moderate: it is expected that climate change will have only a moderate impact on the personal living standard no: it is expected that climate change will have no impact on the personal living standard
Pursuit for self-sufficiency	The pursuit for self-sufficiency describes the wish be partly (or completely) independent from the provision of electricity via grid Note: complete self-sufficiency means autarky, i.e. no connection to the grid	Self-sufficiency depends amongst others on electricity prices, grid stability, investment and operating costs of the respective technologies and availability of VPPs. That means, self-sufficiency could be the result of a 'pure' economic calculation, but also 'green' motives could play a role.

3.3 Input data for techno-economic modelling

For the techno-economic evaluation of PV-Battery systems in the German residential building sector, assumptions must be made about the development of electricity prices for end customers, feed-in tariffs for decentralized electricity and prices for technologies. The assumptions on which this work is based for the year 2050 can be found in the following Tab. 3:

Tab. 3: Key techno-economic assumptions for photovoltaic battery systems in 2050

Indicator	2050
Photovoltaic price	1000€ + 650 €/kWp*CAP_PV
Battery price (ref) Battery price (low) Battery price (high)	1000 € + 200 €/kWh * STO_VOL + 100 €/kW * CAP_BAT 1000 € + 133 €/kWh * STO_VOL + 67 €/kW * CAP_BAT 1000 € + 267 €/kWh STO_VOL + 133 €/kW * CAP_BAT
Electricity price for End-consumer	Depending on storyline
Feed-In tariff/market revenues	3.5 cents/kWh
Envisaged profit rate (inflation-adjusted)	4%/a
Remarks: CAP_PV: installed capacity of PV in kWp, CAP_BAT: installed charging capacity of batteries in kW, STO_VOL: installed storage capacity of batteries in kWh	

The electricity demand is based on an occupant simulation carried out using German time use data [56] and a stochastic model to determine synthetic electricity demand profiles [57]. The electricity demand of households is specified top-down proportionally to the number of people living in the household [58].

In addition to previously described impact factors and input variables, the impact of climate change is examined for its influence on the results. A moderate increase in climate change is compared with a strong climate change. The most frequently discussed climate change scenarios are those presented by the IPCC, with the so-called "RCP 8.5 scenario" representing the scenario with the strongest climate change [59]. This scenario assumes an additional radiation drift of 8.5 W/m² in the year 2100 and an increase of the CO_2 concentration to over 1370 ppm. However, climate change will result in large

regional and temporal differences with respect to the extent and consequences [59]. In the RCP 8.5 scenario, it is assumed that the air temperature in Central Europe in 2050 will be 2.4°C higher in summer and 2.8°C higher in winter compared to the average for the period from 1986 to 2005. In addition, extreme events (e.g. heat waves) occur more frequently. With regard to precipitation, major changes occur: In particular, in winter they increase by 12%, while in summer in 2050 there is about 6% less rainfall than in the comparison period.
In general, climate change is expected to increasingly influence electricity supply and demand as well as the energy system in general. For example, one study found that climate change will slightly increase the potential for wind generation in Germany [60]. Another found that for the supply side, the availability of hydropower plants will change as a result of climate change [61]. On the demand side, one study calculated that the number of heating days in Europe will decrease by 27%, while cooling days could increase by 86% on average [62]. In this work, the effects of the change in temperature and radiation due to climate change are investigated. The focus for the techno-economic analysis lies on the impact on the electricity generation.
Further assumptions and input data are described in section 2.2 and Kleinebrahm et al. (2021).
Fig. 2 visualizes the geospatial resolution of the calculated input for the optimization model, taking into account the framing by the socio-economic analysis.

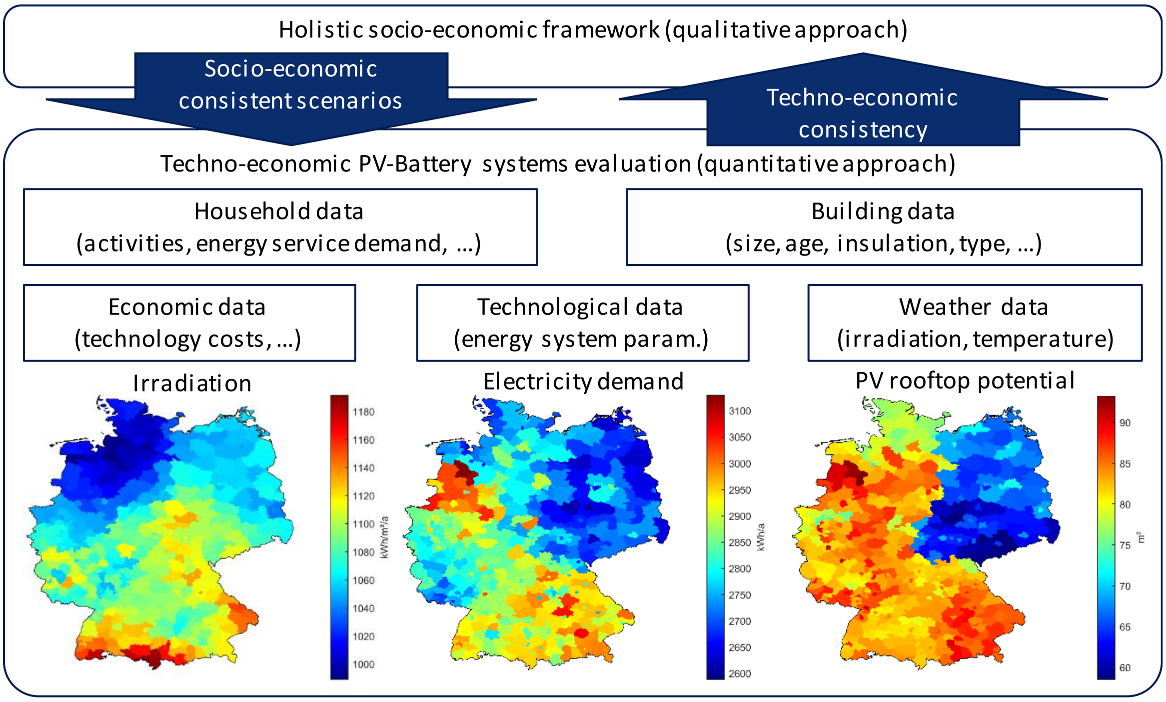

Fig. 2: Interactions between techno- and socio-economic approach

4 Results

4.1 Socio-economic Analysis

4.1.1 Context scenarios framing the future of the household sector

In the Target Storyline the global market paradigm drives the transformation in Germany. Materialism fosters an indifferent attitude toward the energy transition. A downward feedback loop between economic growth, birth rates and migration lead to medium economic success and a declining population. Nonetheless, supported by revitalized EU integration and harmonized energy policies, the ground is prepared for the implementation of ambitious efficiency measures in many (yet not all) fields, stronger European transmission networks, and considerable renewable energy shares in all sectors, although infrastructure development is limited because of governance deficits. The lack of sufficient power lines motivates the development of mixed centralized/decentralized power generation structures. Rather limited efforts in pursuing efficiency of household appliances combined with rebound effects and increased electrification and hydrogen use in transport and heating increase gross electricity consumption [38].

4.1.2 Conditions for pursuing self-sufficiency

The combination of the above discussed descriptors allows for 15 consistent scenarios (Tab. 4). The frame for all scenarios is the Target Storyline, presented in section 4.2.1. As a main constraint only those scenarios with low electricity prices, i.e., below 0.3088 €/kWh are considered. The increasing electricity consumption, as indicated by the Target Storyline is only partly driven by households. That means, in the following analysis different levels of electricity demand by the households are allowed. The same is true for the grid stability. The lack of sufficient power lines could or could not enforce fears by households of unstable grids.

Tab. 4: CIB -Scenarios

<table>
<tr><th colspan="16">Scenario</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th colspan="2">5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th></tr>
<tr><td colspan="16">EP Electricity price: low</td></tr>
<tr><td colspan="4">ED Electricity demand: low</td><td colspan="7">ED Electricity demand: medium</td><td>ED: high</td><td>ED: low</td><td colspan="3">ED Electricity demand: high</td></tr>
<tr><td colspan="4">GR Grid stabil: low</td><td colspan="7">GR Grid stabil: high</td><td colspan="5">GR Grid stabil: low</td></tr>
<tr><td colspan="4">LA Land availability: high</td><td colspan="2">LA Land availability: low</td><td>LA Land availability: high</td><td colspan="2">LA Land availability: low</td><td>LA Land availability: high</td><td colspan="2">LA Land availability: low</td><td colspan="4">LA Land availability: high</td></tr>
<tr><td colspan="3">PB PV & batt: high</td><td>PB PV & batt: medium</td><td colspan="12">PB PV & batt: low</td></tr>
<tr><td colspan="4">Bat Battery demand: high</td><td colspan="12">Bat Battery demand: low</td></tr>
<tr><td colspan="3">PV Technology: high</td><td>PV: low</td><td colspan="6">PV Technology: high</td><td colspan="6">PV Technology: low</td></tr>
<tr><td colspan="4">Fos Fossil fuels: low</td><td colspan="6">Fos Fossil fuels: high</td><td colspan="6">Fos Fossil fuels: low</td></tr>
<tr><td colspan="16">Bio Biomass: low</td></tr>
<tr><td colspan="6">VPP Virtual power plant: low</td><td colspan="6">VPP Virtual power plant: high</td><td>VPP: low</td><td colspan="3">VPP Virtual power plant: high</td></tr>
<tr><td>CC Climate change: high</td><td>CC Climate change: moderate</td><td colspan="2">CC Climate change: no</td><td>CC Climate change: high</td><td>CC Climate change: moderate</td><td colspan="2">CC Climate change: high</td><td colspan="2">CC Climate change: moderate</td><td>CC Climate change: no</td><td colspan="2">CC Climate change: high</td><td colspan="2">CC Climate change: moderate</td><td>CC Climate change: no</td></tr>
<tr><td colspan="4">PS Pursuit for self-sufficiency: high</td><td colspan="2">PS Pursuit for self-sufficiency: medium</td><td colspan="10">PS Pursuit for self-sufficiency: low</td></tr>
</table>

The 15 scenarios give a wide range of possible consistent combinations of motives and frame conditions before the background of the Target Storyline, ensuring the installment of PV-Battery systems. As shown above (section 2.2.2) the level for pursuing self-sufficiency depends on a set of different factors, i.e. descriptors in the CIB analysis, which are influencing the descriptor “Pursuit for self-sufficiency”. Thus, the different states of that descriptor reveal alternative levels of striving for self-sufficiency. Recognizing this, three clusters can be identified:

- Cluster 1: Pursuit for low self-sufficiency: scenarios 6-15
- Cluster 2: Pursuit for medium self-sufficiency: scenarios 4-5
- Cluster 3: Pursuit for high self-sufficiency: scenarios 1-3

The first Cluster shows a rather complex picture of factors companioning and influencing the pursuit for low self-sufficiency. However, common to all scenarios in that cluster is the low availability of PV-Battery systems as well as a low demand for batteries. This pattern indicates that the availability of PV-Battery systems or of batteries are the main limiting factors. The former is a sine qua non for self-sufficiency in the system under review. The latter one is a pre-condition for PV-Battery systems, if (roof-top or façade) PV systems are available. This is the case in scenarios 6-11. In the scenarios 12-15 the low demand for batteries is companioned by a low number of PV systems.

Besides this common pattern, different combinations of descriptors-states are possible. A bundle of motives supports the pursuit for self-sufficiency. The electricity demand could be high (scenarios 12, 14-15) or medium (scenarios 6-11, 13). A high demand for electricity supports the pursuit for self-sufficiency as a measure to secure the additional demand. Gird stability could be high (scenarios 6-11) or low (scenarios 12-15). Instable grids are often seen as one reason for self-sufficiency, to avoid the consequences of a blackout of the electricity system or at least to reduce the fear to be subjected to blackouts. Contrarily, the probability of being involved of a blackout is lower in case of a stable grid. The relevance of the fossil energy carriers for the decisions depends to some extent on the individual preferences and risk aversion. Fossil energy carriers could be of high relevance for the entire system (scenarios 6-11) or not (scenarios 12-15). A high share of fossil fueled based power plants increases on the one hand the grid stability, but on the other hand also the environmental footprint. In case the latter is of high relevance, a high share of fossil-fueled power plants will support the pursuit for self-sufficiency, i.e. to install "green" energy technologies. A low share of fossil-fueled power-plants would reduce the environmental footprint but could be also seen as an indication of a potentially instable grid. Also, a wide-spread offering of virtual power plants (VPPs) (scenarios 6-12, 14-15) or only a low availability (scenario 13) are consistent with a low pursuit for self-sufficiency. VPPs is an opportunity to secure the provision of green electricity, i.e. could be seen as an insurance against electricity with a high environmental impact; but the quality of the "insurance" depends on the stability of the grid system, promoting the pursuit for self-sufficiency. It should be noted that a low pursuit for self-sufficiency can be companioned by a high (scenarios 6-7, 12-13), moderate (scenarios 8-9, 14) or even no (scenarios 10-11, 15) awareness of climate change.

Summing up, the setting of the different scenarios indicates that different combinations of descriptor-states promote the pursuit of self-sufficiency, i.e., there is any clear-cut pattern of motives that characterizes the pursuit for self-sufficiency. Nevertheless, the low availability of PV-Battery systems or batteries when PV systems are offered sufficiently, constraints this pursuit.

With an improving availability of PV-Battery systems (from low to at least medium (scenarios 4-5)) and batteries (from low to high (scenarios 4-5)), the pursuit for self-sufficiency is enhancing from low to medium. Besides these more techno-economic pre-conditions to pursue self-sufficiency, the entire pattern of influencing it is clearer compared to the first cluster. A medium pursuit is mainly motivated to reduce the impacts of a potentially instable electricity provision, but also by the wish to secure an electricity system with a low environmental footprint. Those factors, which could influence the probability of a blackout, like grid stability, low share of fossil energy carriers at the electricity mix as well as low market penetration of VPPs, are showing in the direction of instable supply of electricity in a renewable energies-based system. A moderate (scenario 5) or even a high (scenario 4) awareness of climate change for the pursuit for self-sufficiency can be noted.

Cluster three summarizes the scenarios 1-3 with a high pursuit for self-sufficiency. The main difference between this cluster and the second one is the availability of PV-Battery systems, which are high in case of a high pursuit. Another difference is the relevance of climate change. If PV-Battery systems are highly available, the awareness of climate change seems to be of less importance for the decision for such systems. The high pursuit for self-sufficiency can be companioned by a high (scenario 1), moderate (scenario 2) or even no (scenario 3) awareness of climate change. All other descriptor-states are identical in both Clusters 2 and 3.

4.2 Techno-economic analysis

The techno-economic approach analysis focusses very much on the interrelationship between the economic (or cost) frame and the decision for installing PV-Battery systems. To identify the efforts to invest in such systems the indicator "Degree of electrical Self-Sufficiency (*DSS*)" is used. This indicator is defined as follows:

$$DSS = 1 - \frac{E_{grid}}{E_{consumption}}$$

E_{grid} describes the amount of electricity that is provided from the grid and $E_{consumption}$ describes the amount of electricity that is consumed by the household during the year under consideration. Fig. 3 shows the total discounted system cost (TDSC) for a techno-economically optimized system design with power grid connection (left) and without power grid connection (right - 100% self-sufficiency) under the economic framework conditions presented in section 3.3 for 2050. The figure on the left shows that from a techno-economic point of view, it is optimal for almost each of the 200 representative German single-family houses to install a PV-Battery system in order to cover part of the electricity consumption in a decentralized way. However, it can also be seen that grid purchase costs represent a significant cost component of the overall system costs, so that from a techno-economic point of view it is not optimal for any household to be 100% grid-independent. Fig. 3 (right) describes the composition of the TDSC of the 200 representative buildings in the event that they are forced to be supplied independently of the power grid. In contrast to the case with grid access, revenue from grid feed-in and grid purchase costs are no cost components of the TDSC. Due to the elimination of the possibility of flexibly drawing electricity from the grid at times of low PV power availability, the PV-Battery storage must now be dimensioned larger, which leads to a significant increase in the TDSC compared to the case with grid access (2.0 to 3.1 times higher).
Hence, from a techno-economic perspective, it is obvious (under the assumed conditions for 2050) that it is cheaper to supply only some of your electricity on your own. Completely self-sufficient single-family houses, on the other hand, require the PV battery system to be greatly oversized, so that a greatly increased willingness to pay is necessary for the implementation of a self-sufficient power supply

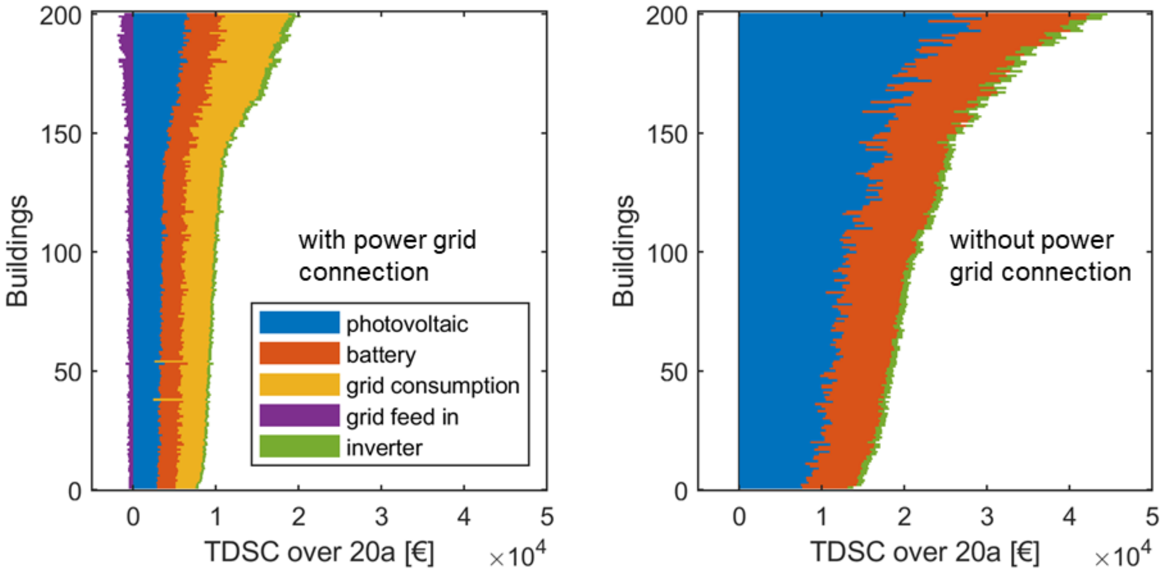

Fig. 3: Visualization of the composition of total discounted system cost (TDSC) over a timeframe of 20 years for 200 representative German single family buildings. The (left) illustration describes the TDSC for a techno-economically optimized system design in 2050 with power grid connection and (right) without power grid connection (100% self-sufficiency).

Fig. 4 visualizes the distribution of the levelized cost of electricity (LCOE) for the 200 representative buildings depending on the specified degree of self-sufficiency (DSS) and for three scenarios of different battery price developments. The LCOE are determined on the basis of the total system costs and the electricity consumption of the respective households over a period of 20 years.

$$LCOE = \frac{TDSC}{\sum_t E_{consumption,t}/(1+i)^t}$$

In the case of no decentralized generation (DSS 0%), the entire electricity is drawn from the grid and the LCOE is 0.3088 €/kWh. If the optimizer is specified to cover 30% of the electricity consumption through self-consumption, photovoltaic systems are installed and the LCOE drops to 0.2831 €/kWh on average. To achieve a DSS of 60% and 90%, battery storage systems must be installed in addition to the photovoltaic system. The LCOE are on average lower with a DSS of 60% than with a DSS of 30% (0.2696 €/kWh), consequently in 2050 a battery storage will be part of a techno-economically optimized system. If no DSS is specified for the optimizer (DSS opt), an average optimal degree of self-sufficiency of 67% results, which on average leads to LCOE of 0.2666 €/kWh. If a DSS of 90% is to be achieved, the photovoltaic system and battery storage must be dimensioned larger than in the optimal system, which leads to higher LCOE of an average of 0.3486 €/kWh. With a DSS of 100%, it is assumed here (analogous to the results presented in Fig. 3) that there are no longer any interactions between the building's energy system and the power grid and thus no more grid feed in is possible. In this case, the LCOE increases on average to 0.6588 €/kWh. As a result, households that want to be completely independent of the power grid must be prepared to pay on average around 2.5 times as much for their power supply in comparison to an optimal system choice and 2.1 times more in comparison to a 100% grid dependent supply. Compared to the effects of the degree of self-sufficiency on the LCOE, the price developments assumed for the various battery price scenarios tend to have less influence on the LCOE.

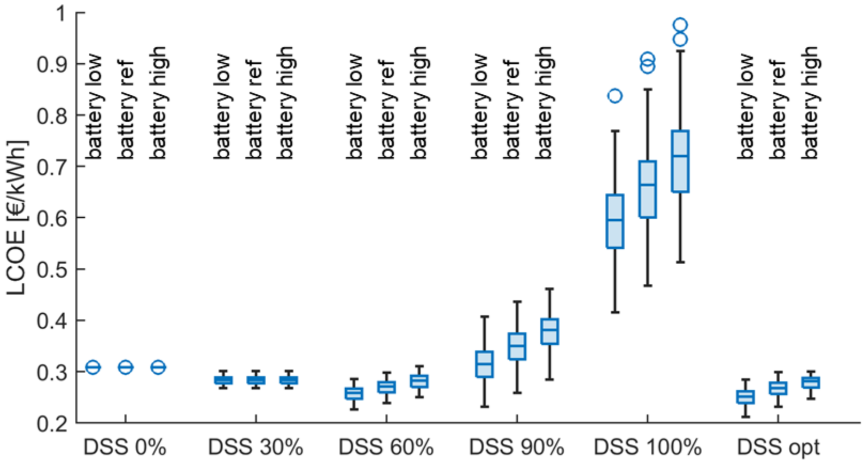

Fig. 4: Dependence of the LCOE on the degree of self-sufficiency (DSS) for three battery price development scenarios described in section 3.3. The fluctuations within the DSS categories are based on the 200 representative German single-family buildings.

4.3 Integrated Assessment

Looking from a multidisciplinary perspective the findings of the socio-economic and the techno-economic analyses reveal a broad range of reasons for pursuing self-sufficiency, although in the first two Clusters cost considerations seem to be an important, maybe dominant, decision factor. Installing PV-Battery systems could lead to lower LCOEs, compared to a situation with no PV-Battery systems, i.e. DSS equals 0% (s. Fig. 4). The CIB analysis reveals the limiting factor of the availability of PV-Battery systems for the level of self-sufficiency. The higher the availability of PV-Battery systems, which can be translated into lower investment costs, the higher is the pursuit for self-sufficiency. Nevertheless, the CIB analysis exposes that the pattern of motives for the decision to install PV-Battery systems, beyond cost driving factors, is not clear. The pursuit for self-sufficiency can be companioned by a low expectation regarding the grid stability, but also by a high expectation. The same can be observed in case of environmental considerations or the awareness of climate change: they can be highly relevant or not at all. Summing up, a low or medium pursuit for self-sufficiency is largely driven by cost considerations; but other motives can support the wish for it.

The scenarios of Clusters 1 and 2 are in line with results of the techno-economic analysis (Fig. 5). Regarding Cluster 3 the findings of the CIB analysis and the techno-economic analysis contradicts. The techno-economic analysis reveals the high costs of achieving a high self-sufficiency, i.e. a DSS larger than 60%. The CIB analysis states that even with low electricity prices a high pursuit for self-sufficiency is possible.

Storyline/context scenario																	
			From socio-economic point of view possible PV-Battery system – scenarios														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
			Cluster 3			Cluster 2		Cluster 1									
Techno-economic scenario	"Low pursuit for self-sufficiency"							X	X	X	X	X	X	X	X	X	X
	"Medium pursuit for self-sufficiency"					X	X										
	"High pursuit for self-sufficiency"	1)	X	X	X												

Note: 1) Assumption in respect electricity prices contradicts results of techno-economic modelling

Fig. 5: Consistent combination of scenarios

However, from a multidisciplinary perspective the findings are largely supporting the findings of the techno-economic analysis. If there is a high pursuit for self-sufficiency, cost has to play a minor role. The distrust in the stability of the grid system appears to be a dominant factor to accept increasing burdens. Environmental or climate change considerations could support self-sufficiency, but they are not required for a high pursuit.

5 Conclusions

An increasing use of PV-Battery systems in the household sector can be an important pillar for the transition of the existing energy system towards one which is in line with requirements of the Paris targets. The diffusion process of this system depends on manifold factors. An analysis of the process by focusing on quantitative factors such as cost and technical characteristics of technological options could provide insights on technological and economic potentials. Since actor specific aspects (e.g. willingness to pay for higher degree of self-sufficiency) as well as factors on societal, political level and the overall frameworks (e.g., prices for energy carriers on the world market) impact or at least shape the diffusion process a broader view on the system is necessary. In our study we show that socio-economic modeling can support the closeness to possible developments by including additional aspects such as attitudes towards autarky. Information gains from techno-economic analyses can help to check if the reliability of identified settings with respect to technological and economic constraints which are not addressed adequately in socio-economic models due to reasons of simplicity.
Regarding the possible diffusion of PV-Battery systems in Germany, our calculations show that the diffusion process will be fostered by a combination of attitudes (socio-economic factors) and costs (techno-economic factors). On the other hand, competing technological options and an enhanced focus on cost will hamper technological diffusion of PV-Battery systems. In contrast to a pure techno-economic analysis our approach provides e.g. framework settings which support changes in attitudes with respect to the use of PV-Battery systems even if they are more expensive than other supply options. In particular, we stress that, since the diffusion of technologies in the households is directly and indirectly determined by a broad range of linked societal, technological and economic factors, transformation processes have to be analyzed within a socio-techno-economic (SoTeEc) framework.

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