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Research Paper

Interdisciplinary optimization of potential analyses for renewable energies by integrating socio-psychological parameters

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ABSTRACT

In view of climate change and recent political developments, the energy system transformation in Germany continues to gain in importance. Although the expansion of renewable energies is a national goal, implementation takes place at the local level in close interaction with society. Citizen action groups and court cases against renewable energy plants indicate that what is feasible from a technological and economic perspective might not correspond to what is socially accepted or tolerated. Reliable predictions about the feasible potential of renewable energies can thus only be achieved when political, economic, technological, and social requirements on a local scale are considered in a systematic and holistic way. To address this current research gap and support the stakeholders of the energy transition in their decision-making, this article proposes the idea of an interdisciplinary, cross-technological approach to developing a reliable perspective and an expansion concept for the successful implementation of the energy transition by considering parameters of acceptance already in the forecasting of the feasible potential. This approach aims at expanding existing techno-economical potential estimations for renewable energies by the societal dimension to approximate the realistic potential of specific sites and thus predict the feasibility of renewable energy projects more accurately. We exemplify how engineering, urban planning, and social science expertise can be integrated and combined for the forecasting of the feasible potential of renewable energies. Additionally, we identify the challenges that come with this interdisciplinary approach. The proposed approach serves three aims. First, it serves as an example of how interdisciplinary approaches to transformation processes, such as the energy system transformation, can have added value for forecasting and feasible potential analyses. Second, it exemplifies how an interdisciplinary approach to energy transformation can be achieved methodologically. Third, once executed and applied, it can outline the path toward a sustainable and accepted energy transformation.

1. Introduction

In order to limit the global temperature, increase to well below 2°C, as declared in the Paris Agreement, a holistic transformation of the energy system is required [1] as in 2023, the EU27 accounted for 6.1 % of global greenhouse gas (GHG) emissions, with Germany responsible for 1.3 % of global GHG emissions [2]. Taking Germany as a pan-European example, the current and historical expansion rates for wind and PV are far from sufficient to meet the ambitious expansion targets declared in the Renewable Energy Sources Act 2023 (see §4|1,3,4; [3]), so an accelerated expansion of these renewable energies (RE) is necessary. They require significantly more land than conventional power plants [4], which increases the need for suitable construction sites. The land requirements and the techno-economic approach of allocating land based on its energy potential lead to a land rush that focuses on landowners and marginalizes host communities [5]. While RE projects such as wind farms generally enjoy broad public and local acceptance [6], there are cases where local opposition can delay or even derail

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construction projects [7]. At the same time, there are areas that are excluded from development due to legal restrictions, such as the 1000 m distance rule, despite being acceptable to local residents as wind farm sites [8]. As a result, the feasible renewable energy potential for a given site may be either overestimated or underestimated. On a larger scale, this leads to a divergence between the theoretically assumed RE potential in Germany and a feasible potential for meeting societal needs. This is problematic from a planning, political, and social perspective, as it creates uncertainty on many levels. It should therefore be in the interest of politicians, project developers and the public to take social parameters into account in the early stages of potential analysis and planning of RE infrastructure (also from a scientific modelling approach). The importance of socio-political and local acceptance for the successful implementation of RE projects has been increasingly recognized, and research into the nature of public attitudes towards RE has flourished in recent decades, providing a rich body of evidence [9,10]. What is missing, however, is a systematic integration of these findings into the siting of RE infrastructure and potential analyses, both at the planning level and from a methodological perspective [11]. Such an integration can lead to predictions of RE potential that are closer to a realistically feasible potential, allowing for a more controlled, predictable, and plannable expansion of RE. Kirkegaard et al. [12] propose a holistic process that considers all steps of project planning from site selection and design to end-of-life disposal from technological, sociological, and economic perspectives. However, they provide little guidance on how to achieve such a project from a methodological point of view. As they focus more on the idea of interdisciplinary research in the wind energy sector itself, they do not outline practical challenges and strategies on how to concretely integrate the possibilities of the various disciplines.

This article addresses the forementioned challenges by presenting 1) the conceptual idea of an interdisciplinary approach integrating socio-psychological parameters into technological potential analyses in order to develop a realistic expansion concept for the implementation of RE in the context of the energy transition, and 2) discussing the disciplinary and interdisciplinary challenges that may arise. We present a concrete research plan that illustrates how the different disciplines can build on each other and use the results of other disciplines to create a common outcome.

2. Current planning approaches for RE infrastructure within the political framework

In 2019, the German government became the first government in the world to make its national climate protection target binding. The Climate Protection Act (CPA) declares efforts to limit global warming to well below 2 °C and it was further reinforced after the amendment in August 2021 (see §1; [13]). As a result of the Paris Agreement and Germany's wish for energy independence, partly as a reaction to the Russia's invasion of Ukraine, Germany has dedicated itself to transforming its energy system [14]: As part of the Renewable Energy Act (REA), Germany aims to achieve a minimum of 80 % of its gross electricity demand from renewable sources by 2030 (see §1|2; [3]). In 2022 and 2023, respectively 44.1 and 52 % of its gross electricity production was generated by RES [15]. Part of the significant increase from 2022 is due to the decrease in total electricity production. However, in 2023, both wind and PV electricity production reached their record highs [16]. Consequently, in order to reach the 80 % target, expansion paths for various RE technologies have been defined, including onshore and offshore wind power, rooftop and ground mounted PV, and biomass plants (see §4|1,3; [3]). These three technologies differ significantly regarding the status quo of their expansion, their impact on the landscape, and, consequently, their social constraints.

The performance targets for biogas plants have been met and there will be no further significant expansion of their capacity [3,17]. In contrast, onshore wind power (onWi) plants and ground-mounted PV (gmPV) are still well behind the expansion rate that is needed to meet the ambitious REA targets of 115 GW onWi and 215 GW total installed PV capacity (rooftop and gmPV) by 2030 [3,18,19]. In 2023, 61 GW of onWi was installed in Germany in total, but only 3.2 GW was added in 2024, while rooftop and gmPV reached a total installed capacity of 100 GW in 2024 [20,19]. With numerous impediments to achieving a fully RE sector, a paradigm shift is needed to accelerate the capacity growth both for onWi and gmPV.

For wind energy, the German government published the "Wind Energy Site Requirement Act" in 2023, which specifies the proportion of the total area of each federal state that must be available for the construction of wind energy plants by 2027 [21]. However, bureaucratic obstacles retard expansion, and structural challenges regarding decentralized energy production and distribution need to be overcome [22,23]. To accelerate the expansion of renewable energy sources across Europe and effectively combine the financial, technological, and siting resources of European member states, the European Commission launched an international call for proposals in 2020 that will provide financial support to the most cost-effective project [24]. The focus on cost-effectiveness and the economic orientation of the technology leads to a preference for supporting large-scale utility-scale wind farms [25]. Kirkegaard et al. [25] use the example of Denmark to illustrate how this policy subsidy landscape skews the market in favor of large investors and disadvantages local cooperatives.

The trend towards ever-larger RE farms and plant sizes, particularly in the wind energy sector, is often the focus of local protests, as the size of the facilities has a significant dominant impact on the landscape [25] and, by expanding into new areas, brings them closer to people [26]. There is a substantial body of research on the relationship between sense of place, place attachment, and local acceptance of energy projects, but the results are inconclusive [27]. This makes landscape intervention, also known as technology-landscape fit in the social sciences [27], an important subject of study and decision-making criterion in the siting of RE projects [28]. The importance of landscape has also been recognized at the political level: The Council of Europe's Landscape Convention [29] recognizes that every landscape has cultural, ecological, environmental and social values that must be taken into account in planning and management. Therefore, in addition to techno-economic parameters, site selection for the construction of renewable energy plants must take into account aspects of (local) acceptance and (local) landscape value (e.g., [30]), in accordance with current legislation.

Diverse scientific projects and studies focused on community acceptance [31,32] and highlighted the dynamics of the process and the difficulties of involving citizens in the energy transition (e.g., [9,33]). While the recognition of landscape, place, and social understanding is a positive and important development in the policy domain, well-intentioned policy decisions and legislation aimed at protecting the well-being of residents and local landscapes can sometimes be driven by requirements and concerns that are not aligned with acceptance-relevant factors, as demonstrated by the example of setback requirements. The setback requirement, which initially mandated a minimum distance of 1,000 meters between wind turbines and residential areas, was introduced as a way for project stakeholders to consider the needs and desires of residents when selecting sites for wind turbine construction. It was intended to protect residents from potential negative impacts such as property devaluation, increased noise and visual pollution [34]. However, experience has shown that in some cases the setback requirements have hindered the search for socially acceptable sites and have therefore been partially revoked [8]. To facilitate the identification of suitable areas, the government has recently adjusted the legislative framework to provide more flexibility in decision-making by reducing the minimum distance between wind turbines and residential areas [34]. This legislative amendment of the distance regulation is seen as an important milestone towards the national expansion targets [34]. This change also empowers the local communities affected by these projects, giving them more decision-making power and thus promoting acceptance-oriented expansion [8].

The examples of distance regulations and the European financial support system show that top-down measures to increase local acceptance of renewable energy infrastructure may not fully capture the underlying motives and needs of local residents. This shows the way to an energy transition that is not dictated from above, but rather co-decided and supported by citizens. At the beginning of 2023, a new law for the promotion of community energy has been implemented, providing financial support for community energy enterprises and reducing bureaucratic obstacles [35]. The new law emphasizes the role of citizens as key stakeholders in the energy transition. At the European level, the European Union has called for the empowerment of citizens through the formation of RE communities. However, attention needs to be paid to disparities in financial resources, which may lead to unequal opportunities for participation and inequitable outcomes in business models and roles within these communities [12].

3. Shortcomings of current developments and derived research pathways

The recognition of the relevance of local acceptance for energy infrastructure planning and the rich body of research on social responses to energy infrastructure provide a valuable basis for integrating these findings into energy infrastructure planning. However, several shortcomings challenge this integration.

Gap 1: Lack of systematic coverage and structuring of acceptance-relevant parameters

A challenge in the social sciences lies in the systematic clustering of acceptance-relevant location and project factors. Numerous identified factors are related to the specific construction (such as wind turbines), to the individual, community, or the planning process, e.g., benefits for local communities [36], perceived influence on health [37], distance and number of wind turbines [38], general visual impression (including distance, movement) [39], compensation payments [40], landscape disruption and aesthetic evaluation. However, some factors are 'symptomatic' for underlying latent attitudes. E.g., the distance regulation as a proxy for local acceptance mirrors NIMBY principles [41]and simplifies complex patterns of place attachment, place identity, and sense of place [27]. Aesthetic preferences for PV on rooftops to blend in with the landscape [42]hint at underlying place attachment and the wish to 'keep things as they are'. Similarly, while noise disturbance from infrastructure (e.g., wind turbines) has been identified as relevant for acceptance, it has been shown that the perception of noise levels is highly subjective and differs from objectively measurable levels, being significantly correlated with the attitude towards the wind turbines and the perceived project fairness [43,44]. To systematically capture the relationships a) among different influencing factors on acceptance of RE infrastructure and b) the relationship of those factors with the target variable "acceptance" itself, theoretical models have been developed (e.g., [45]): Besides being not extensive, these models do neither cover individual or situational factors nor do they account for possible differences between different RE technologies. The work by Hübner and colleageus [46] meets this gap but does not account for different aesthetic and procedural design concepts.

Research Aim 1: Realization of an extension of existing acceptance models for RE by individual and situational factors and analysis of the generalizability of acceptance-relevant factors across technologies using bottom-up approaches.

Gap 2: Lack of depth in research on acceptance of gmPV and biomass

Not every renewable energy technology has been studied in the same detail with respect to social and local acceptance. Compared to wind turbines and rooftop PV, less is known about the acceptance of biomass installations and gmPV. For PV, studies have mainly examined the acceptance of rooftop PV systems by homeowners in terms of "market acceptance" (e.g., [47,10]). Methods for analyzing landscape impacts have been explored for gmPV [48], but the body of research on landscape impacts is much smaller than for wind turbines [27]. A few single-case studies have focused on local biomass acceptance, examining the acceptance of specific projects (e.g., [49]). Although research has examined the general acceptance of biomass and its influencing factors (e.g., [50]), it is significantly less comprehensive than, for example, wind energy. In addition, some approaches already combined the perspectives of technological considerations of regional potentials with the acceptance of the population comparing different RE technologies but focusing not on spatial and urban design (see Gap 3) [51]. Hence, further research is needed on the acceptance of different RE technologies, in particular gmPV and biomass plants, to determine whether some acceptance-relevant parameters are the same for all technologies or whether all technologies show individual acceptance patterns.

Research Aim 2: Generalizing acceptance-relevant factors would open up the possibility of developing a holistic strategy for integrating social parameters into energy infrastructure planning, independent of specific technologies.

Gap 3: Lack of comprehensive approaches combining energy supply and urban design

The aesthetics of RES installations, especially wind turbines, have already been investigated as influencing factors for local acceptance (e.g., [52,53]), and design aspects of RES are prominent factors for local acceptance [12]. In particular, if wind turbines are perceived as visually disruptive to the landscape, this may affect local acceptance [54]. In addition, landscape has special meaning for people: people feel connected to places, have normative ideas about different types of landscapes, and partly identify with them [27]. The construction of RE facilities can be perceived as an intrusion into the landscape, leading to a sense of loss of home [53,55], especially if the landscape change is rapid, widely perceived, and does not provide individual benefits to residents [56], which can lead to rejection of an RES project [27]. Conversely, there is ample evidence that public participation can have a positive impact on local acceptance of wind turbines if they offer a perceived added value, which may be financial or identity-building [27]. Although people have been shown to become accustomed to wind turbines in the (local) landscape over time, it is at least questionable to rely on these habituation effects for project development [12]. Therefore, site-specific procedural and aesthetic design plays a crucial role in the acceptance assessment of a site and thus presumably influences its real potential [57]. In considering the specific design of RE in site selection, we build on, but differ from, the concept of Kirkegaard et al. [12]. Here, planning and design are considered as two separate process steps. However, we argue that site selection and design should necessarily be linked. While research has explored alternatives in the siting and design of wind farm projects to enhance acceptance (e.g., [57]), the impact of different aesthetic and participatory design options for integrating energy generation facilities into the landscape has remained largely unaddressed as a potential factor influencing acceptance.

Research Aim 3: Integrating energy and urban design, traditionally considered separately, to consider the identity of the landscape and the identity the landscape gives to the local community in energy infrastructure planning.

Gap 4: Lack of integrating empirically validated social factors in potential analyses of RE planning to forecast the feasible potential of RE

The analysis of RE potential at a specific site has developed into an active scientific field [58]. Common definitions distinguish between different concepts of potential, starting with theoretical potential as the most general level and narrowing down to geographical, technical and economic potential (Fig. 1, [58]). At each level, the potential is constrained by, for example, geographic or meteorological limitations. At the most specific level, McKenna et al. [58] refer to the "feasible potential," which Jäger et al. [59] also refer to as the "actual achievable economic potential. The feasible potential takes into account factors such as social acceptance and public resistance to renewables. As a result, it is even smaller than the economic potential. For example, if local residents do not accept sites that are considered suitable from an economic perspective and thus have theoretical potential for RE, this reduces the overall potential for RE in a given region. Similarly, it is reduced if the accepted scale of infrastructure (e.g., number of wind turbines, size of gmPV plant) differs from what is economically feasible. An empirically based forecast or estimate of the reduction of the economic potential to the feasible potential, taking into account social constraints, can bring the forecast of the potential of renewable energy sources closer to a realistic scenario and thus improve its planning and deployment. Potential reduction is straightforward when evaluating RE sites based on distance and regulatory constraints, and has been applied several times [58]. However, research has identified a variety of acceptance-relevant parameters (e.g., technology-related aspects such as visual and noise pollution (e.g., [60]), and landscape-related factors (e.g., [61]), for which it is not known how and to what extent they influence the feasible potential of RE. The challenge therefore lies in the methodological integration of further acceptance-relevant parameters into the potential analyses for RE with the aim of deriving a feasible potential that takes into account restrictions due to local acceptance requirements. So far, the first attempts to include social parameters in potential analyses are rough estimates of differences between economic and feasible potentials [62], but a systematic integration of empirically validated social parameters is still lacking. In addition, there is no methodology to derive conclusions on the expansion path of RE based on the estimated feasible potential.

Research Aim 4: Interdisciplinary assessment of energy supply scenarios is required, in which specific technical scenarios are analyzed for their acceptability. An interdisciplinary assessment of RE infrastructure and energy supply scenarios in general has been applied several times (e.g., [63,64]). It has proven to be a promising methodological approach to evaluate energy supply scenarios and infrastructure not only according to technical, but also according to environmental, economic, social and other parameters. Furthermore, there have been attempts to make such acceptance-relevant factors usable as plannable variables and to integrate them into techno-economic models of potential analysis (e.g., [65]). However, these studies lack the scalability of the methodology to apply the approaches on a larger scale. Thus, such findings on perception and acceptance remain locked in the social science context and cannot yet be made interdisciplinary accessible and usable for technology design or even for localization issues [11].

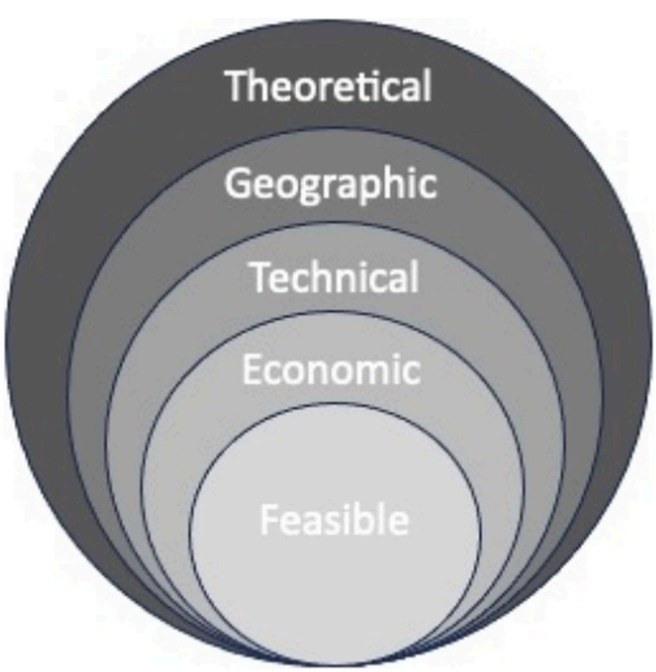

Fig. 1. Hierarchy of different concepts of potential for RE [58].

4. Proposal for interdisciplinary potential analyses of RE

In order to contribute to filling the research gaps, we propose an interdisciplinary research approach that analyzes the potential of diverse renewable energy infrastructures, integrating parameters relevant from social science and spatial planning perspectives.

4.1. Essential perspectives on RE and added value of approach

The added value of this interdisciplinary approach lies in the development of a holistic and systematic methodology for the transfer of social aspects of acceptance into a country-wide potential analysis of the RE infrastructure. Based on the identified feasible potential, measures for a controlled, socially acceptable expansion of RE can be derived. The approach requires an interdisciplinary close cooperation between technological, urban (spatial) planning and social science perspectives.

From a **technical standpoint**, it is necessary to transfer factors relevant to the social acceptance of wind energy and gmPV to corresponding technical parameters. For this purpose, empirical studies on factors influencing social acceptance could be used, which allow a quantifiable reduction of the techno-economic potential to the feasible. Taking Germany as an example and in order to be able to calculate for all of the approximately 11,000 German municipalities, similar regions with regard to both technical and socio-structural parameters should be considered using a clustering method. Compared to previous approaches, the main added value lies in a region-specific mapping of the technical potential through a derivation of the realizable potential by linking it with socio-psychological parameters, thus enabling more realistic estimates.

From a **social science perspective**, a holistic empirical identification of acceptance-relevant factors for gmPV as well as a profound reduction of relevant parameters for the acceptance of onWi are necessary in the first step. Furthermore, it could be empirically investigated how the landscape and different design approaches influence the acceptance and perception of the RE infrastructure. Based on this, a concept is to be developed that focuses on the integration of acceptance-relevant parameters into the modeling of technical potential analyses. This perspective adds value by considering acceptance as an integral part of potential predictions. This leads to a better usability and practical relevance of the results as well as a better transfer to policy, planning and practice.

From an **urban and spatial planning perspective**, the physical-material design of RE plants is not sufficiently considered in the context of social acceptance. There are several approaches to integrate energy production facilities in urban and rural areas in a more value-added and creative way. A systematic investigation of these approaches in social acceptance research has not yet been identified. Based on existing urban design approaches and own empirical investigations, different design principles for RE facilities will be derived. These approaches will be visualized and contextualized in order to gain knowledge about the effects of urban design approaches for RE on social acceptance. In doing so, this approach can provide information about the importance of design-related factors as well as key requirements, the importance of landscape identity in the context of RE, and how these can be addressed with design principles. This creates an opportunity to use urban design methods to improve acceptance in the context of RE and to empirically validate this potential improvement.

4.2. Specific research questions and interdisciplinary collaboration

A close interdisciplinary collaboration (see Fig. 2) is necessary to enable a holistic measurement and modeling of the feasible potential of RE infrastructure. To achieve this goal and to fill the gaps described above, we propose the following approach:

Step 1: Disciplinary investigations in close collaboration and exchange

As a first step, detailed parallel disciplinary studies are needed. For this purpose, the technical scenarios for the expansion of RE should be defined and selected from a wide range of existing scenarios for the expansion of the energy transition, including relevant parameters such as the technical definition of the future energy mix, the expected amount of electricity, etc. Furthermore, data on the techno-economic potential of RE are partly outdated due to constantly changing technical and legal constraints or are not available at the required level of aggregation. Furthermore, data on the techno-economic potential of RE are partly outdated or not available at the required level of aggregation due to constantly evolving technical and regulatory constraints. Therefore, the techno-economic potentials have to be collected or determined at the required level of aggregation. In some cases, the approach relies on existing technical models, which have to be extended to the level of detail required for the approach. The potential of gmPV and onWi could be determined based on currently available data or, if not available in sufficient detail, calculated using newly developed models. In order to adjust local acceptance patterns in order to develop a forecast model for a country (e.g., Germany) as a whole, the clustering of regions with similar socio-structural parameters can be a feasible solution, allowing local specifics to be taken into account while at the same time providing a general roadmap. For each of the clusters, the techno-economic potential for RE can then be calculated in a first step.

To enable a systematic coverage and structuring of **acceptance-relevant parameters** (**Gap 1**), it is necessary to collect acceptance-relevant evaluation criteria from various sources, e.g., by conducting a comprehensive literature review, analyzing experiences from failed projects, and conducting empirical qualitative studies (e.g., interviews, focus groups). Based on subsequent quantitative studies that allow detailed analysis and modeling using path models, analysis of variance, and cluster analyses, a strict reduction of acceptance-relevant parameters can be realized. The extension of the research on acceptance parameters related to the perception of PV and biomass allows to close the existing knowledge gap in this research area (**Gap 2**). The overall goal is to identify both generic and technology-specific acceptance parameters. Based on the identification, structuring and reduction of acceptance-relevant parameters, analyses of decision behavior can be realized, which allow conclusions about the most influential acceptance factors and tipping points, where non-acceptance turns into acceptance.

Building on the identified technical scenarios, the development, design, and visualization of specific new **urban integration approaches** for selected RE facilities can be focused on (**Gap 3**). Each discipline should contribute its own technical, spatial and acceptance analysis perspectives to the design, with the aim of generating realistic results that can be used in the interdisciplinary approach. The developed integration approaches cover a wide range of potential integration strategies and thus address different societal acceptance factors. Therefore, different case studies will be analyzed in order to derive different integration approaches in a first step. Overarching urban integration approaches for technical infrastructures, which generally include a variety of approaches from consciously hidden to unobtrusive to space-defining integration, can then provide the framework for the newly developed approaches. Based on this, first ideas for visualizations can be realized, which could be discussed and harmonized with technical and social perspectives and requirements.

Step 2: Starting cross-disciplinary investigations: outcome pairing

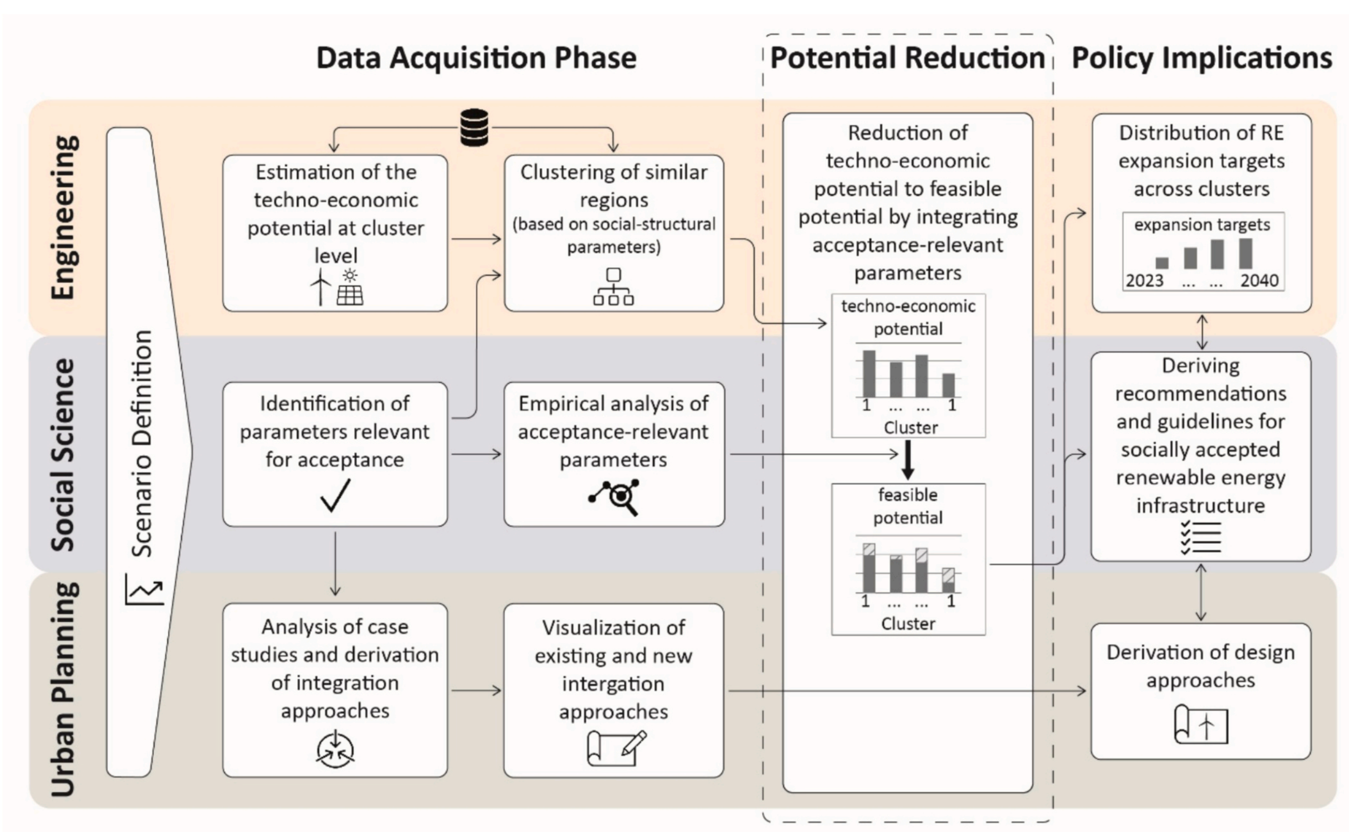

Fig. 2. Schematic illustration of steps and their interactions to assess the feasible potential, including the derivation of policy implications.

and investigations into overarching topics

Based on the first **visualization concepts** and ideas, these integration approaches should be transferred to the various types of RE installations and locations. In particular, the potential for identity formation or the preservation of identity-defining spaces could be considered in concepts for the urban integration of RE. A close interlocking of the three perspectives is necessary: The different perspectives can support the visualization process based on their own technical, legal and acceptance-related expertise and actively participate in the selection of exemplary study areas. On this basis, final designs for the concepts can be developed. These designs can then be integrated into empirical studies focusing on **social acceptance**, e.g., in qualitative studies in terms of discussing and evaluating the visualizations in interviews or focus groups and subsequently also as substantial evaluation parameters in quantitative studies. Beyond the design-related evaluations, the **technical calculation** of techno-economic potential can be harmonized with the acceptance-related perspective by, e.g., integrating socio-structural parameters in the clustering or considering specific technical parameters and scenarios in acceptance evaluations.

Step 3: Combination of insights in holistic evaluation of technical scenarios and derivation of feasible potential

In the final step (**Gap 4**), acceptance parameters should be integrated into techno-economic potential analyses in order to make realistic predictions for the feasible potential of RE, taking into account social acceptance. This requires the previously identified and quantified acceptance parameters, including the most accepted visualizations of integration approaches. The application of specific empirical approaches such as conjoint analyses [66] enables the simulation of "real" decisions of citizens (e.g., weighing of perceived benefits and barriers in terms of relevant landscape-, technology- and organization-related acceptance parameters). As a result, such analyses involve the triangulation of best and worst cases. These identified best/worst cases and scenario-specific preferences of citizens allow the identification of the feasible potential for RE. The techno-economic potential can be reduced to the feasible potential for different pre-clustered regions.

5. Challenges of the interdisciplinary approach

Such a holistic approach requires expertise from the natural sciences, landscape planning and engineering, sociology and political science, and cultural studies [12]. These pose (inter)disciplinary challenges, which in turn can influence disciplinary goals and approaches. While important work has already been done on the challenges of interdisciplinary collaboration (e.g., [67]), the following section focuses specifically on the disciplinary challenges expected for this specific research agenda.

Urban planning and design: In spatial planning, developed designs are usually evaluated and discussed qualitatively. However, the approach presented here also aims at quantifying the identified factors. Specific missing scales and evaluation tools need to be developed. The design process and results need to be adapted so that they can be used for subsequent interdisciplinary collaborations. This requires decontextualizing and abstracting approaches without losing the core ideas. In addition, design concepts usually have a very close relationship to the spatial context. However, the presented concept aims at developing a transferable and scalable, country-wide methodology. The transfer of local design approaches to the national level represents a challenge for spatial planning and design and requires a departure from the principle of the relationship between design and spatial context in favor of the possibility of a flexible integration of design options in different spatial contexts.

Social science: In order to identify and structure acceptance-relevant parameters, it is imperative to establish a unified perspective on acceptance, as the assessment of acceptance can vary significantly depending on its definition [68], e.g., social acceptance of RE in general compared to local acceptance of specific sites. The challenge here is to make local acceptance measurable, but still be able to derive a generalizable concept of acceptance. The extent to which acceptance can be generalized and translated into abatement potential needs to be investigated. Specifically, it is necessary to analyze what form the acceptance data should take, what areas remain "gray areas," some of which cannot be predicted, and how "soft" process factors can be modeled. Finally, and perhaps most importantly, social science is increasingly recognizing the role of citizens as active stakeholders in the RE transformation and as "'experts' in their own right" [28]. Ways of feasible active participation should be developed and applied to bridge gaps between experts and lay people, and to achieve an integrated and accepted allocation and design of the RE infrastructure.

Technical perspective: Accurately accounting for multiple factors relevant to acceptance when calculating feasible potential is a significant challenge. In particular, it is difficult to weight individual factors as objectively as possible [58]. Wendorff [62] adjusts the techno-economic potential based on structural indicators, such as the average age of the population, to arrive at the feasible potential. The acceptance-relevant factors identified in the first steps of the approach should also be translated into measurable technical key parameters that can be determined for a whole country (here: Germany) in order to be able to make similar corrections to the potential. For example, at the municipal level, the self-sufficiency of the municipalities could also be considered in order to assess the realizable potential. Another challenge is the consideration of the characteristics of all individual municipalities. Therefore, an alternative approach is to cluster similar municipalities and consider the correction of potential within those clusters collectively [62].

6. Conclusion

The primary objective of this paper was to propose an interdisciplinary approach for integrating social acceptance factors into technical modeling processes used to estimate renewable energy (RE) potential. The underlying assumption is that such an integrated estimation provides a more realistic and comprehensive view than a purely techno-economic model. By considering social acceptance alongside technological and economic factors, this methodology offers a more nuanced representation of RE potential, contributing to the development of a robust, actionable framework for the nationwide expansion of renewable energy, using Germany as a European case study. This framework can guide the RE transition in a way that is both targeted and aligned with public opinion, ensuring that energy projects are not only technically feasible but also socially acceptable. The key advantage of this integrated approach over traditional techno-economic models lies in its capacity to incorporate social acceptance parameters. By focusing on these factors, it provides a more accurate assessment of the "socially feasible" RE potential, narrowing the gap between what is technically possible and what is politically and socially acceptable. Ultimately, this shift enhances the likelihood of successful RE projects, contributing to the broader goal of a sustainable energy system transformation that aligns with societal values and needs.

However, the methodology outlined in this paper requires a significant investment of time and resources, particularly for activities such as data collection, model development, and scenario testing. These tasks are resource-intensive, and efficient time management is essential for their successful completion. A potential solution is to adopt a phased or iterative approach, beginning with preliminary models and datasets that can be refined over time as additional resources become available. Furthermore, leveraging existing data, models, and advanced technologies, such as automated data collection tools and cutting-edge modeling software, could streamline these processes and reduce the time and costs associated with their implementation. A key challenge in applying this methodology is defining the responsibility and authority for selecting technical scenarios and the relevant parameters for RE expansion. Ensuring the legitimacy and acceptance of these scenarios is critical, especially since RE infrastructure has direct social and political implications. To address this, a multi-stakeholder approach should be adopted, involving government bodies, industry experts, researchers, and civil society groups in the decision-making process. This inclusive approach would ensure that the perspectives of all affected parties are considered, ultimately increasing the credibility and acceptance of proposed solutions.

Additionally, it is important to clarify who holds ultimate responsibility for implementing the methodology. One promising approach could be to apply the principle of subsidiarity, which advocates for decision-making at the most local level possible. While national or regional authorities may set broad strategic goals and parameters, local entities should have the flexibility to adapt these guidelines to the specific conditions and preferences of their communities. This approach would ensure that the methodology remains responsive to local contexts, fostering greater social acceptance and more effective energy transition outcomes.

The proposed methodology displays considerable promise for application in other countries and cultural contexts beyond Germany. While the social acceptance may differ across regions, the framework's emphasis on integrating public opinion into renewable energy (RE) planning is universally pertinent. The methodology can be adapted by countries with varying levels of public engagement, political structures, or societal norms in order to more effectively address local concerns and conditions. For example, in countries with strong community-based decision-making traditions, such as in Scandinavian nations, a bottom-up approach that actively involves local stakeholders may prove to be an effective strategy. In contrast, in countries with more centralized political systems, such as China or Russia, integrating social acceptance into decision-making processes may necessitate the development of innovative methods for balancing top-down directives with bottom-up feedback mechanisms. Further research could investigate how this approach can be adapted to different political and cultural contexts, evaluating its applicability in countries with diverse governance structures and attitudes towards renewable energy. Potential avenues for future work include the development of cross-national case studies, the creation of flexible social acceptance models, and the expansion of the framework to encompass global trends, such as the growing influence of social media on public opinion regarding climate action.

In addition to its primary focus on integrating social acceptance into the technical and economic modeling of renewable energy (RE) potential, the underlying methodology remains highly relevant for countries with varying levels of environmental concern or where green energy priorities differ. In contexts where environmental sustainability is less central to public discourse, the methodology can be adapted by placing greater emphasis on technical feasibility and economic drivers, such as cost-efficiency, job creation, and energy security. By concentrating on the economic advantages of renewable energy, including reduced energy costs, enhanced grid stability, and local economic growth, this approach can be adapted to align with regions where economic considerations are paramount in decision-making processes. Furthermore, the methodology's flexible framework permits the integration of a range of technical variables, including available infrastructure, resource potential, and scalability, which can be modified to align with the distinctive requirements of different regions. In countries with more centralized governance structures or those where public engagement in energy decisions is less prevalent, a top-down approach may be more appropriate, with the focus placed on developing large-scale, economically viable renewable energy projects. In contrast, in contexts that are more decentralized or community-driven, the methodology could integrate local economic considerations alongside broader technical assessments.

In conclusion, the proposed methodology offers a valuable contribution to renewable energy planning by incorporating social acceptance into technical assessments of RE potential. Its successful implementation depends on effective resource management, collaborative decision-making, and well-defined governance structures—all of which are essential for promoting a socially inclusive and sustainable energy transition. Future work should focus on adapting this approach to diverse cultural and political contexts and refining it through cross-national testing to enhance its global applicability and impact.

CRediT authorship contribution statement

Julia Offermann: Writing – review & editing, Validation, Methodology, Conceptualization, Writing – original draft, Resources, Investigation. **Mona Frank:** Writing – review & editing, Methodology, Writing – original draft, Conceptualization. **Barbara S. Zaunbrecher:** Writing – review & editing, Methodology, Writing – original draft, Conceptualization. **Thorsten Reichartz:** Writing – original draft, Writing – review & editing, Visualization, Conceptualization. **Jannik Wendorff:** Writing – review & editing, Visualization, Writing – original draft, Conceptualization. **Lucas Blickwedel:** Writing – review & editing, Conceptualization, Project administration. **Laura Wendorff:** Writing – review & editing, Conceptualization. **Christa Reicher:** Project administration, Funding acquisition. **Ralf Schelenz:** Project administration, Funding acquisition. **Martina Ziefle:** Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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