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Triggering Local Innovation Processes for the Implementation of Sector Coupling Projects: An Integrated Approach

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Abstract: Local implementation projects for sector coupling play an important role in the transformation to a more sustainable energy system. Despite various technical possibilities, there are various barriers to the realisation of local projects. Against this backdrop, we introduce an inter- and transdisciplinary approach to identifying and evaluating different power-to-X paths as well as setting up robust local implementation projects, which account for existing drivers and potential hurdles early on. After developing the approach conceptually, we exemplify our elaborations by applying them to a use case in the German city of Wuppertal. It can be shown that a mix of several interlinked interdisciplinary methods as well as several participatory elements is suitable for triggering a collective, local innovation process. However, the timing and extent of end-user integration remain a balancing act. The paper does not focus on a detailed description of power-to-X (PtX) as a central pillar of the sustainable transformation of the energy system. Rather, it focuses on the innovative methodological approach used to select a suitable use path and design a corresponding business model. The research approach was successfully implemented in the specific case study. However, it also becomes clear that the local-specific consideration entails limitations with regard to the transferability of the research design to other spatial contexts.

Keywords: integrated approach; transdisciplinary collaboration; sector coupling; local innovation process

1. Introduction

Although there have been clear successes in the implementation of the energy system transformation in recent years (especially in the electricity sector), achieving the goals set at all political levels remains a major challenge in Germany [1,2]. Given the decentralised nature of renewable energy production, local implementation projects play a particularly important role in achieving the overarching energy system transformation goals.

From a technical point of view, many projects exist that contribute to achieving the goals, in terms of both efficient energy use and the expansion of renewable energies. Still, particularly with regard to the latter, further efforts are required, concerning the construction of the generation units themselves as well as their integration into the existing energy system. This includes, for example, expanding electricity and heat networks as well as increasing the use of energy storage facilities or sector coupling [3,4]. As the integration of renewable energies is much more easily done in the electricity sector than in the heating, mobility or production domain, sector coupling (hereafter referred to as power-to-X (PtX)) is deemed crucial to the successful realisation of energy transition [1,5].

Despite numerous technical possibilities, which are constantly being further developed, there are various difficulties that both complicate the development of energy scenarios at the (trans)national level and hinder the realisation of local implementation projects. Hindrances result from the complexity of the issue as well as from the high number of involved actors with very different levels of knowledge and interests, operating by various modes of conduct and holding partly diverging interests. Above all, the comparability of different PtX use paths against the background of local-specific framework conditions represents a major challenge.

Section 1.1 shows the state of knowledge from a methodological perspective. Based on that, Section 1.2 states our research aim and chosen methodological approach.

1.1. Integrated Assessment Approaches for PtX Paths

Our research focus is on the methodological advancement rather than on the role of PtX in the future energy system. Therefore, we conducted a literature review of methodologies in existing analyses and included, in particular, studies that deal with the comparison of different use paths and present this in the following state of knowledge. For more in-depth insights into the state of knowledge, reference is made to current reviews with a large number of supplementary sources.

From a methodological perspective, four basic perspectives on PtX paths can be found in the literature:

1. PtX paths are increasingly being integrated into large (trans)national and even global energy system models. These can be used to assess the benefits of sector coupling (e.g., an increase in the overall share of renewably produced energy) and how it affects the primary energy consumption and the total production costs at the overall energy system level. From this, policy recommendations on the design of the regulatory framework or the composition of the future generation fleet can be derived. Current examples for this type of studies are [3,6–8]. In [6], possible development paths and options are examined with which the climate protection goals for Germany for 2050 can be achieved. After a technical analysis of the various options, a more in-depth look at the topic of sector coupling follows, on the one hand, by comparing the sector coupling approaches in existing energy system scenarios in Germany and, on the other hand, by performing model calculations with the energy system model REMod-D. In [7], the PowerFlex energy system model, which previously only focused on the electricity sector, is expanded to include the mapping of the heating and cooling sector. This enabled scenario calculations to be carried out that evaluate the future contribution of sector coupling options such as power-to-gas or power-to-heat to the German energy supply system. In [8], the focus is on assessing the future contribution of power fuels to decarbonising global energy supplies by 2050. For this, the so called LUT Energy System Transition model [9] is applied for several scenario calculations. In [3], the effect of sector coupling respectively the effect of grid reinforcement on the energy supply costs in the European energy system are compared. A variety of other examples of this type of study can be found in [10]. There, this approach is summarised under the term "PtG deployment scenarios at regional and national scale". Further studies with a focus on the contribution of residential power-to-heat applications for the integration of renewable energies can be found in [11].
2. In addition, there are several studies that examine PtX paths in detail without modelling their integration into the energy system. Often, several PtX paths are evaluated comparatively. Many of these studies focus on technical aspects, with interdisciplinary analyses being carried out additionally at times. Yet, there are no scholarly works that systematically deduce which PtX paths are fundamentally possible and relevant to a

specific local implementation context. Instead, all existing pieces on the topic focus on a set of predetermined PtX paths with the aim of investigating and evaluating them more closely. In [12], the multitude of possible paths are shown in a schematic diagram. Five exemplary paths are then subject to a strengths, weaknesses, opportunities and threats (SWOT) analysis, whose focus lies on technical aspects. In the follow-up project, further paths have been included in the analysis, but its focus remains on technical aspects as well as potential assessments for North Rhine-Westphalia [13]. The studies of [14] go somewhat further by carrying out a multi-criteria evaluation of the power-to-liquid and power-to-chemicals paths, taking into account various interdisciplinary aspects. In [15], a review is conducted and, based on it, a morphological analysis specifically for residential energy supply systems. It assesses all possible technologies in the mobility, heating and electricity sectors, including PtX technologies. The results of the morphological analysis are possible configurations of the future residential energy system.

3. Thirdly, there are studies that examine individual aspects of one specific PtX path in detail, e.g., technical or economic feasibility or ecological impact. The analysis is usually based on a specific case study. Examples are [16–18]. In [16], a techno-economic analysis of the integration of a power-to-gas approach (electrolyser and methanation) in the production process of a pulp mill is carried out. The study in [17] develops and applies a two-stage procedure with differently detailed optimisation models as well as a resilience analysis in order to evaluate decarbonisation strategies for entire cities, with special consideration of sector coupling. The study in [18] is an example of the sector coupling approach that combines steel and chemical industries. It develops and applies an optimisation model for methanol production on the basis of steel-making by-product gases. The evaluation compares the effects that result from an economic target function and those from an ecological target function. A variety of other examples of this type of study can be found in [10]. There, this type of study is summarised under the term "distributed-scale PtG deployment scenarios".

Studies from the first three groups analyse and evaluate PtX paths and offer valuable methodological approaches. Although some of them derive policy recommendations, these remain rather abstract and are addressed to high-level political decision making. However, they do not focus on concepts as to how these PtX paths, if they are found to be useful, may be implemented in practice, for example, at the municipal level or in companies.

4. The fourth group consists of projects and studies that aim exclusively at the development of business models, that is, they address the implementation only—yet also without applying transdisciplinary approaches. In addition, an (interdisciplinary) evaluation of the respective path also hardly takes place. In this group, studies on the power-to-eMobility use path are a distinct focus, e.g., [19] and [20]. An exception is [21], which gives a comprehensive overview of various PtX paths before exemplary business models are developed that are particularly suitable for municipal utilities.

The presented approaches provide valuable results and specific assessment approaches. It is evident, however, that integrated approaches are missing that cover the entire chain, from the identification of relevant PtX paths to business model development. Similarly, inter- or even transdisciplinary studies are an exception.

1.2. Resulting Research Approach of PtX Use Paths in Wuppertal

Our research aims at developing a methodology to identify pathways for sector coupling at the local and regional levels and to address the aforementioned obstacles at the local level with a transdisciplinary research design. Following the claim of transdisciplinary science, it is essential to transcend mere problem analyses and yield actual implementation strategies. The aim is to develop a method to identify (I) the fundamentally relevant and, subsequently, (II) the locally (context-specifically) relevant PtX paths among the multitude of possibilities. Accordingly, the focus of this paper is not so much on PtX in general; rather, we focus on the transdisciplinary approach to evaluate and compare different use paths.

These rather specific research objectives were led by the meta goal of making local energy systems more sustainable by integrating a higher share of renewable energies through sector coupling strategies.

The approach can be summarised in four steps, which were closely interwoven. This iterative character of the methodological approach allows the adaption of the concepts to new requirements as they arise. The central elements of the research design were the early involvement of local stakeholders and, more importantly, the iterative adaptation of the methodological concept to the interim results in close consultation with local actors. This significantly increased the practical relevance and implementation probability of the developed product.

In summary, the specific objective is to develop an interlinked mixed-methods approach for the identification and evaluation of different PtX paths. The procedure is intended to enable local actors (municipal planners or local energy suppliers) to identify the PtX paths that best fit the respective local context and to support them in the conception of implementation projects. Furthermore, the inter- and transdisciplinary approach ensures that the implementation projects are designed in a way that accounts for existing drivers as well as potential hurdles so as to meet them adequately. As a result, robust and hands-on business models for the selected PtX path can be identified.

Our proposed methodological approach and results are based on our findings in the interdisciplinary research project PtX Use Paths in Wuppertal (as part of the overarching project EnerAct—Energy System Transformation in the Context of Social Megatrends, funded by Stiftung Mercator). As intended by the transdisciplinary approach, the municipal utility company Wuppertaler Stadtwerke (WSW) complemented the scientific consortium as a practice partner for this. Moreover, the project team drew from and sought to align technical knowledge from the engineering sciences, social science, insights into public acceptance as well as the practical experience and local knowledge of the WSW. The involvement of civil society actors was achieved through interviews with designated end users of the selected use paths. In addition to conceptual elaborations stemming from social sciences, this allowed us to effectively account for customer requirements and potential obstacles with regard to the implementation of the selected PtX path.

Instead of following a classic research design, we worked with a living methodological concept, which was continuously adapted to the arising requirements. As described above, this iterative approach should ensure the accuracy of the final product. Intermediate results usually led to the need to significantly adapt the concept of the following work step. Conversely, intermediate results of a work step also contributed to a critical review of the previous work and, if necessary, its adaptation again.

The paper is structured as follows: After a brief introduction to the main building blocks of the methodological concept in Section 2, we present the individual work steps in detail in Sections 3–6, each bringing together methodology and results. In Section 7, a critical reflection of the obtained findings and the methodological design is made. The conclusions in Section 8 give an outlook of the transferability of the chosen approach and makes recommendations for further research.

2. Overview of Methods

When evaluating specific use paths, it is crucial to clearly define the boundaries of the investigated system. Relevant system parameters (driving forces and obstacles) need to be agreed upon for the development of a target vision. The more uncertainties are excluded from the analysis, the less its results will be resilient and suitable for the derivation of appropriate action strategies. If, on the other hand, the scenario is overloaded with external influences, it becomes too complex and sensitive to a multitude of events (of which not all may actually be influential). Thus, a reduction in complexity needs to be balanced carefully with depth of study.

For the selected system parameters, the necessary information must then be prepared in a transparent and coherent manner for all actors involved. This is complicated by the fact that quantitative data are not available for all system variables. Material flows and energy quantities in the considered technology path can be calculated and quantitatively represented. The same applies to economic parameters such as estimates of the development of energy prices and resulting return-on-investment points, with several uncertainties, of course. Less easy-to-estimate aspects encompass, for instance, the acceptance of technical applications by consumers or the interactions of technology implementation with contemporary megatrends such as demographic and social change. This bears all the more relevance since some of the technologies are so novel that they have not been tested in practice yet and, thus, empirical insight into their actual application still marks a gap in research. In addition, social sciences often demand that aspects such as actor strategies, social networks, policy-making and governance processes, learning curves, lifestyles, norms and other social factors be taken into account when developing future paths. Indeed, analyses of the energy system tend to place too much emphasis on the technical matters, while being seemingly oblivious to social aspects such as those mentioned above. However, consumers do not necessarily opt for the most cost-effective solution (in the sense of *homos oeconomicus*) or act according to information campaigns' recommendations. The way people consume energy is strongly influenced by their social norms and cultural environment [22]. Qualitative analyses tend to account for the conditions under which energy-related innovations might unfold in more detail [22,23]. They also allow the development of more uncommon scenarios featuring radical system innovations. Transdisciplinary and participatory approaches offer the opportunity to integrate non-technical aspects and to include the perspectives of a broad range of actors.

Consequently, a broad mix of quantitative and qualitative methods is fit to grasp the selected system parameters and to build a common knowledge base in transdisciplinary projects. Based on existing knowledge, new facts, data and trends, probable and possible developments are systematised and analysed. In doing so, it is important to adhere to central criteria of scientific futurology. This means, above all, disclosing the assumptions made and thereby also ensuring that the normative positions underlying the study are clearly evident [24]. Normativity is an integral part of such projects, although it is often left unaccounted for. Indeed, the future design of the energy system, especially the energy sources to be used, is so complex that value-free analyses taking into account all economic, ecological and social factors and boundary conditions seem unlikely.

The transdisciplinary research design is well in line with scientific standards if it models future developments, both quantitatively and qualitatively, in a comprehensible and transparent manner based on present conditions. If the underlying assumptions and assessments can be made subject to critical scrutiny, they attain scientific validity [25].

Against this background, the following integrated approach was developed (see Figure 1). Step 1 and step 2 have to be conducted only once (however bearing in mind that updating the information is recommendable from time to time). This gives a high degree of transferability, even if the approach is applied to other local contexts. In contrast, step 3 and step 4 are based on the transferable results obtained previously and have to be carried out and adapted individually for each actor's respective location.

In the following sections, these four central steps are briefly explained – as we have carried them out in our study and as we would recommend them in general for triggering future implementation projects. Details on the four steps, in particular the central results, are described in the following Sections 3–6.

2.1. Step 1 in Brief: Identification of Relevant PtX Paths

Step 1 aimed at the identification of relevant PtX paths. The relevance was assessed by a twofold approach. Firstly, theoretical criteria (in particular, technology readiness level, overall efficiency and degree of social acceptance of the PtX path) were applied so as to iteratively reduce the multitude of theoretically possible PtX paths to those of interest (cf. Section 3.1). Secondly, a bottom-up approach was carried out, which collected, clustered and characterised PtX implementation projects in Germany (cf. Section 3.2). The approaches were interlinked iteratively so that in the end, all of the theoretically determined PtX paths could be assigned to several already implemented projects. Further details on step 1 and the corresponding results can be found in Section 3.

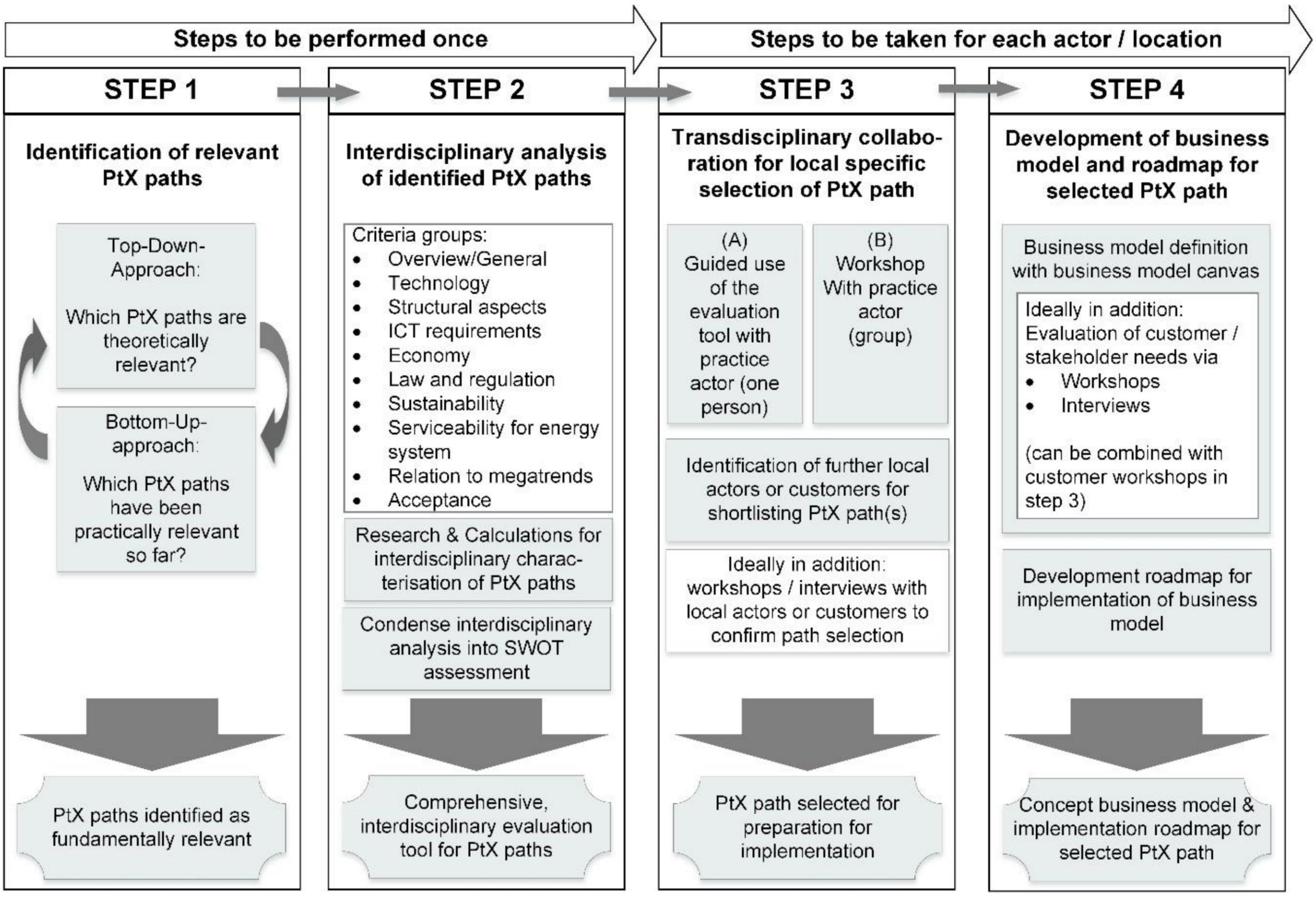

Figure 1. Overview of the developed integrated approach.

2.2. Step 2 in Brief: Interdisciplinary Analysis of Identified PtX Paths

Step 2 was used for the interdisciplinary analysis of the PtX paths determined as relevant in step 1. The analysis was carried out in the following criteria groups: overview/general, technology, structural aspects, requirements for information and communication technology (ICT), economy, law and regulation, sustainability, energy system serviceability, relation to megatrends and acceptance. Each criteria group contained several concrete criteria, resulting in a total of 63 criteria according to which the PtX paths were evaluated. The vast majority of the criteria were characterised qualitatively, based on literature research or based on the exemplary implementation projects assigned in step 1. Other criteria could be quantified based on the literature. Individual criteria were quantified using our own calculations (e.g., greenhouse gas savings by carrying out a life cycle analysis). The results for all criteria groups were partly documented in independent results reports, but in addition, all were compiled in an Excel-based, interactively usable evaluation tool. Due to the large number of detailed results, a summary SWOT assessment was carried out for each path and integrated into the assessment tool, too. Further details on step 2 and the corresponding results can be found in Section 4.

2.3. Step 3 in Brief: Transdisciplinary Collaboration

The third step was to select the PtX path for a specific municipality or a specific supply area (here, from the perspective of the WSW as a local municipal utility in Wuppertal) that is the most relevant for implementation under the local framework conditions. Transdisciplinary cooperation with the local practitioner is essential for this. There are two options for this, depending on whether the selection should be made by (A) a representative of the practice actor or (B) a group of people and also on the level of detail at which the selection should be made. In the present project, option B was chosen by carrying out a workshop with several WSW representatives. Based on the SWOT analysis, the different paths were presented, discussed and compared with the local framework (cf. Section 5.2.2). Afterwards, a sectoral-spatial analysis can be carried out to identify further local actors or, in particular, customers for the shortlisted path(s). It is also recommended to conduct a workshop with the local actors or customers identified in this way (or alternatively to conduct interviews with them) in order to finally make or confirm the selection of the PtX path to be implemented. Further details on step 3 and the corresponding results can be found in Section 5.

2.4. Step 4 in Brief: Development of a Business Model and Roadmap

The fourth step was to develop a business model for the PtX path selected for implementation and then to derive a roadmap of how the business model could be successively implemented. As part of the project at hand, the business model was developed and documented using the so-called Osterwalder Business Model Canvas [26]. Due to the very structured approach, the high customer orientation and the compact documentation, this tool proved to be recommendable. The development of the business model should also take place under transdisciplinary cooperation and ideally explicitly meet the requirements and wishes of future customers. For the latter, synergy effects can be generated with the customer workshops or interviews from step 3. Further details on step 4 and the corresponding results can be found in Section 6.

3. Step 1 in Depth: Identification of Relevant PtX Paths

As mentioned in Section 2.1, the first step was to identify the fundamental, relevant PtX paths for urban contexts. For this, a top-down-approach and a bottom-up approach were interlinked in the methodical form of a stage-gate process. Even if the selected PtX paths are relevant for further analysis, the focus of our proposed framework described here remains particularly on the methodology of the selection process.

The stage-gate process is a comprehensive structured approach to ensure process quality in innovation development. The methodology developed by [27] divides the innovation process into multiple stages and gates. In each of those stages, the planning depth and maturity level of the project is increased and, therefore, the degree of uncertainty regarding the success of the project is reduced. At each gate, an interdisciplinary gatekeeper team examines the progress of the preceding stages and the fulfilment of the set goals. If these goals are not achieved, either the work within the stage can be improved or the whole project can be discarded. Thus, the method offers a clear structure of the work and decision areas, in which all relevant disciplines are involved. However, when choosing the methodology, it should be taken into account that it can be very labour intensive to define the concrete steps in advance, and moreover, the gatekeepers have an essential decision-making function.

The original method comprises a total of five stages and gates for an innovation process from the idea to the full production and market launch. For the intended scientific evaluation method, we focused on the methodology up to gate 3, i.e., the conception phase. The procedure of the stage gate process and the selection of paths is summarised in Figure 2. The further structure of this chapter follows the stages of this process. Section 3.1 depicts the phase of idea generation as well as gate 1, where a first reduction of paths to a long list takes place. Section 3.2 explains stage 1, where the paths within this long list are further investigated, and gate 2, where the long list is reduced to a short list. In the final stage of the conceptual design, stage 2, detailed interdisciplinary analyses of the short list paths are carried out, partly quantitative and partly qualitative. As this stage corresponds to step 2 from our integral method, it is further explained in Section 4. With these analyses, the decision usually requires considerably more financial effort. Based on the analyses, a path is selected that enters the development phase. As this is part of step 3 of our integral method, it is described in Section 5.

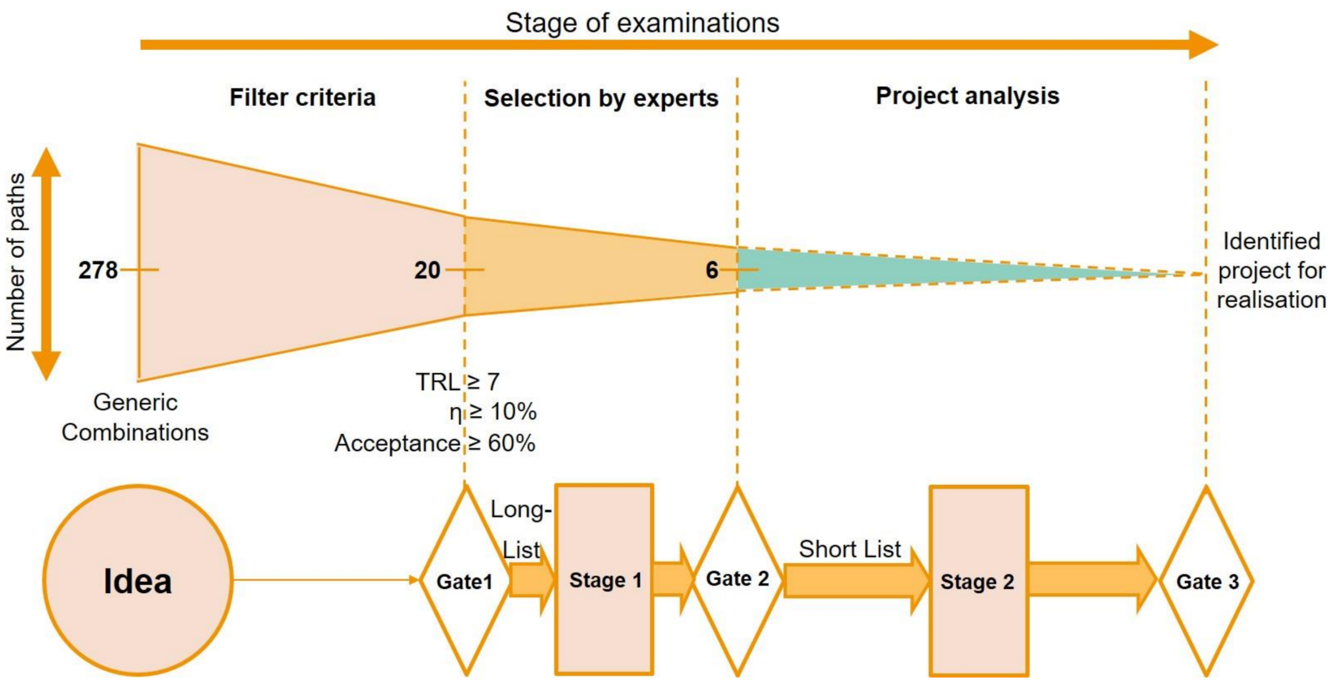

Figure 2. Summary of the stage gate process (based on [18]) and the selection of paths.

3.1. Generation of Ideas and Gate 1

The innovation process is initiated by the generation of ideas within the subject area under consideration. In this case, it is the ideation of potential urban PtX paths, including the technologies used in the different sections of the paths. These sections can be classified as the generation, storage, transport and conversion parts of the path. Combining the different sections and the possible technologies results in a total of 278 potential paths, which can be divided into paths for mobile and stationary use.

The potential paths and their technologies are passed on to the first gate for the first preliminary analysis, where it is analysed which submitted paths should be pursued further. As mandatory criteria, the technologies within the considered paths have to fulfil a certain level of maturity. The systematisation of the development stages of the technology components considered here is based on the concept of the Technology Readiness Level (TRL), which was developed by NASA and is now used internationally [28,29]. This concept divides the various research and development steps on the basis of a nine-level scale, from invention to full marketability. For the observed PtX paths, all technologies used within the path must have a TRL of at least level seven (Prototype test in operating environment); otherwise, the path is discarded.

PtX paths offer flexible use of renewable energies over time. However, too many conversion steps could lead to low efficiency of the entire path. Therefore, the cumulated efficiency of the path has to be at least 10%, or the path will not be followed further.

In addition, a path and the technologies required for it must meet a minimum level of social acceptance in order to be further investigated. For a rough first assessment, the classification of acceptance into the three categories based on [30] is used: market acceptance, local acceptance and socio-political acceptance. Based on a literature search, factors are assigned to the technologies in the respective categories. A path cannot pass through gate 1 if the combined acceptance level is below 60%. With this methodology, a long list with a total of 20 potential paths is identified.

3.2. Stage 1 and Gate 2

Usually, a fast and cost-effective assessment of technical and market feasibility based on technical literature and current studies is conducted in stage 1. In our case, stage 1 was mainly based on an analysis of existing PtX implementing projects in Germany. An extensive literature research was carried out to identify implementation projects for PtX paths in urban contexts.

In addition to the project content, it was important that results be already available so that the general feasibility could be evaluated and risk factors as well as success factors could be derived. It was striking that significantly more implementation examples could be found for some PtX paths than for others. This was especially valid for power-to-heat projects, which showed a boom from 2012 to 2016, and power-to-eMobility projects. As there were almost no calculations for economic feasibility, the great sensitivity of some PtX paths to (fast) changing economic conditions and regulatory framework became evident (this was especially true for the power-to-heat path); we did not exclude paths due to this criterion.

In addition to the analysis of existing implementation projects, expert exchange was carried out to discard paths that could technically meet the filter criteria of gate 1 but still were not useful, e.g., because of too many conversion steps, including repeated changes, between two sectors. Moreover, similar paths (e.g., with photovoltaics instead of wind energy as the power source but otherwise with the same progress) were aggregated into one type of path.

With these preparations, the long list could be reduced to a resulting short list with six PtX paths in gate 2 (cf. Table 1). A distinction could be made between paths that convert electricity in hydrogen (i.e., paths 1–3) and those that use electricity directly within the other sectors (i.e., paths 4–6).

Table 1. Overview of six selected paths and their steps.

<table>
<tr><th>Path No.</th><th>Path Label</th><th colspan="2">Steps within the Paths</th></tr>
<tr><td>1</td><td>Power-to-H_2-to-mobility</td><td rowspan="3">Power generation from renewable energies → electrolysis → (hydrogen storage)</td><td>→ Hydrogen dispenser
→ Fuel cell vehicle</td></tr>
<tr><td>2</td><td>Power-to-gas</td><td>→ Gas network
→ Decentral/central heat supply</td></tr>
<tr><td>3</td><td>Power-to-H_2-to-industry</td><td>→ Industry/chemical production</td></tr>
<tr><td>4</td><td>Power-to-eMobility</td><td rowspan="3">Power generation from renewable energies → (battery storage)</td><td>→ Battery charging station → electric vehicle</td></tr>
<tr><td>5</td><td>Power-to-heat</td><td>→ Electric heat pump/boiler
→ General heat storage tank
→ Decentral/central heat supply decentral/central</td></tr>
<tr><td>6</td><td>Power-to-cold</td><td>→ Compression chiller → (general cold storage)
→ Decentral/central cold supply</td></tr>
</table>

The first step in the chosen sector coupling paths 1–3 is converting the generated electricity in hydrogen by electrolysis. Within the process of electrolysis, water is separated into hydrogen and oxygen by applying an electrical potential to provide the necessary free enthalpy for the electrochemical process. The electrolyser converts the water flowing against the side of the anode into hydrogen and OH- ions. At the cathode, the OH- ions diffuse through the ion-conducting electrolyte and oxidise to water and oxygen. The best efficiencies in sector coupling paths are achieved by alkaline electrolysers, which are therefore chosen for the selected paths. In the chosen paths, hydrogen is marketed regionally and is therefore not transported far. To maintain flexibility in terms of time between production and use, hydrogen can be stored in salt caverns [31].

For the power-to-H_2-to-mobility path (path 1), hydrogen is used directly in a fuel cell electric vehicle (FCEV) via a hydrogen disperser. The hydrogen is further processed by a fuel cell inside the vehicle to drive the engine and thus the vehicle.

In the heating sector, hydrogen can be mixed with gas and used as an energy supplier for heating energy, as described by path 2 (power-to-gas).

Furthermore, hydrogen can be the basis for many other energetically important substances, such as methanol or methane. In path 3, power-to-H_2-to-industry, hydrogen is used in the form of material used in industrial applications.

Hydrogen can be stored much more cost effectively than electricity, but high efficiency losses occur due to conversion. If electricity within the paths is used directly or in combination with battery storage, the efficiency of many applications increases, such as the selected paths 4–6.

The chosen path 4 (power-to-eMobility) couples the transport sector with the energy sector. The steps include a charging station with integrated battery storages. This is used to charge the battery inside the vehicle and power the electric motor while driving. This leads to higher efficiencies due to fewer conversion steps. However, the charging process takes significantly longer than refuelling a comparable FCEV [32].

Heat pumps and chillers are used in many fields of application, such as in private households, in industry or in mobile applications. While refrigeration machines are mainly used for room air-conditioning, food cooling or machine cooling, heat pumps are used for space heating, hot water supply or drying processes. The majority of heat pumps and chillers are based on the cold vapour compression chiller process with electrical compression [33]. Path 5 (power-to-heat) describes the coupling of a heat pump with the heat sector using a heat pump in combination with a heat storage tank. Similar to this, cold is supplied via a compression refrigeration machine in path 6 (power-to-cold). The provided cold can either be stored in a general cold storage first or be delivered directly to the decentral or central cold supply [33].

4. Step 2 in Depth: Interdisciplinary Analysis of Identified PtX Paths

As explained in Section 3, the interdisciplinary analysis of the six identified PtX paths corresponds to stage 2 in the stage-gate process. The applied criteria of our analysis are presented in Section 4.1. Afterwards, the evaluation tool that assembles all information is introduced in Section 4.2.

4.1. Applicable Criteria

The following criteria groups were applied for the interdisciplinary analysis of identified PtX paths:

- Overview/General: This group initially contains a description of the respective path, links information about example projects in Germany and provides information about existing funding opportunities. Moreover, a structured essence of the most important criteria of the other groups is given in the form of a SWOT analysis. In some cases, assessments of the path are additionally taken from the literature.
- Technology: This group includes criteria that provide information on the required technical components as well as their dimensions and properties (e.g., efficiency and TRL).
- Structural aspects: Important criteria in this group are the space required or land use for the technological components of the path and the required infrastructure. Another criterion deals with the necessary security requirements.
- Requirements for information and communication technology (ICT): This group focuses on ICT and infrastructure requirements derived from it. IT includes both systems for monitoring or user interfaces and systems for control/automation.

- Economy: Criteria applied for this group are based on market and technology assessments. These include the addressed stakeholders, potential business models and the associated risks, including entrepreneurial risks. Furthermore, these include the feasibility of the applied technology, potential substitutes on the market and the overall market situation.
- Law and regulation: The criteria for this group focus on the general legal frameworks as well as path-specific frameworks. They include the framework that deals with data collection and notification obligation and building law and safety-related and fee-related framework conditions (including subsidies). Additionally, tax advantages and disadvantages and potential funding opportunities for the potential PtX paths are considered.
- Sustainability: Since social and economic aspects are considered separately, ecological sustainability criteria are in focus here. An important criterion is the contribution to climate protection targets and other emission targets. It aims at assessing greenhouse gas savings in comparison to a (use path dependent) reference technology for the entire life cycle, e.g., on basis of the life cycle assessment method standardised by DIN EN ISO 14040 [34] and 14044 [35]. Pre-chain emissions, e.g., from plant construction or resource extraction, should be taken into account as far as possible. If other emissions, such as NOx or particulate matter, are relevant, they should also be taken into account. Furthermore, energy and resource efficiency play an important role in assessing sustainability. The avoided (or possibly increased) primary energy use compared to the reference technology or practice must be analysed. In addition, the contribution of the technology field to resource efficiency can be analysed and also indicated as a min-max consideration in comparison with the reference technology; the cumulative resource expenditure (allocating the share of energy resources) is the basis for this evaluation. Other environmental impacts, such as noise emissions, air pollution control, effects on flora and fauna and estimates of space requirements and land use, should be added, at least qualitatively.
- Energy system serviceability: As one important goal of sector coupling is to integrate more renewable energies in the energy system, it is of great importance to evaluate which contribution can be made by which PtX path (e.g., in terms of flexibility delivery) and which effects on other sectors (heat, gas, electricity, mobility) can be monitored.
- Relation to megatrends: A new technology's eligibility is decisively determined by its capacity to align with contemporary societal development, which can be analytically grasped by the concept of megatrends. As these are of high complexity, it is often not possible to determine distinct effects of megatrends on the respective technology (such as, broadly speaking, promotion, hindrance or mediation of certain impacts). Essentially, we synthesised respective elaborations of foresight consulting agencies, which yielded 13 megatrends. Thus, while we did not quantify or otherwise approximate their actual occurrence, the megatrends considered proved influential in contemporary public discourse. Irrespective of their actual outcomes, they can be assumed to (at least to a certain degree) exert influence on public and private actors' decisions as they are perceived as far-reaching developments necessitating adequate and timely reactions. The following megatrends were included in our analysis: digitalisation, gender shift, globalisation, health, individualisation, mobility, neo-ecology, new work, security, social inequality, socio-demographic change, ubiquity of knowledge and urbanisation. Popular scientific information on these megatrends (as provided by the foresight consulting agencies identified as most influential in German public discourse) can be found online [36,37]. For recent academic reviews that have yielded a range of similar megatrends, see [38] as well as [39].
- Acceptance: While acceptance is often understood as the populations' active support of a technology and/or a given project (and this is, without question, desirable) [40], here, we understand non-opposition as a minimum requirement for the realisation of a project. Consequently, we focused on factors that are prone to causing rejection,

protest and conflict, such as the involvement of technologies that are perceived as bearing risks to human health or property value.

4.2. Structure and Functionality of the Evaluation Tool

All results of the interdisciplinary analyses were compiled in an Excel-based, interactively usable evaluation tool in a structured manner and made accessible to users from science and practice via an intuitively operable graphic interface. An illustrative overview of the tool is shown in Figure 3. Its contents are described below.

Figure 3. Graphical interface of the evaluation tool.

The criteria introduced above represent the central part of the graphical user interface. The six PtX paths are arranged at the bottom left. By ticking the box, the user can select the paths and criteria in order to have the desired information displayed in the assessment tool. This enables a criteria-based step-by-step comparison of the various PtX paths, if desired. This approach is particularly recommended for the in-depth individual work of a representative of the practitioner instructed by a scientist. Otherwise, the criteria of the SWOT analysis can be chosen. They deliver a quicker (but also more superficial) overview over the different paths and can be used as the basis for a workshop with several representatives of the practitioner.

Moreover, using the sample projects criterion in the graphical interface, detailed profiles of the previously compiled sample implementation projects can also be called up from the evaluation tool. The same criteria are used for this at a more detailed level of each sample project. Particularly noteworthy are the success factors and obstacles identified in the sample projects, because this kind of experience is very valuable for setting up new implementation projects, as success factors and obstacles often cannot be foreseen by theoretical concepts.

In addition, so-called knock-out criteria for path selection are arranged in the upper left of the graphical user interface. These are used to support the user, for example, to hide those paths from the start that, clearly from the start, do not meet the local requirements for an implementation project, for example, because there is no gas network connection available in possible areas to be realised or because a mobility concept is explicitly desired. By ticking the respective knock-out criteria, all PtX paths are blocked for selection, which are thus omitted. As a result, the selection of the knock-out criteria represents both an opportunity (through more rapid identification of the most interesting paths) and a risk (through, if necessary, premature exclusion of paths that could have been very relevant locally on closer inspection).

5. Step 3 in Depth: Transdisciplinary Collaboration

Step 3 marks a critical phase in the process as previously generated data and the developed tool are used and a shift in focus from a quantitative-technological perspective towards a practitioner-led, locally embedded and more qualitatively influenced perspective occurs. The step-by-step approach to transdisciplinary collaboration enables the successive integration of quantitative and qualitative data in the specific local context in which the chosen PtX path will be embedded, while simultaneously allowing for transparency concerning single approaches and decisions. In the following sections, the multiple blocks of transdisciplinary collaboration will be depicted in detail.

5.1. Theoretical Background

In addition to the mix of methods in the evaluation of use paths described above, the transdisciplinary approach in the development of a business model or implementation concept is of great importance. The aim of the process was to design PtX concepts in such a way that direct implementation by the practice partner becomes as likely as possible after project completion.

An innovative project design in the sense of transdisciplinary research was developed for this purpose. The methodological and conceptual structure of such approaches has been continuously developed and tested in practice for about 20 years. There is a broad scientific consensus on the basic procedure.

Accordingly, the research process is characterised by three phases in which representatives from science, business, politics and civil society first develop a common understanding of the problem. This is followed by a phase of joint knowledge generation and development of problem-solving strategies. This theoretical research process is concluded by the integration and application of the knowledge generated, both by science and by practical implementation. This process is to be understood iteratively. This means that the generated knowledge can also be used to re-initiate the process of problem identification and precision or solution development [41–43].

The idea of implementing projects in this form is based on the assumption that the participation of a wide range of different groups of actors will make it easier to grasp highly complex and uncertain issues as early as when the research question is being defined. In other words, the results are more robust because they have been validated in many ways, and their implementation is more likely because those responsible for implementation are involved from the outset [44].

In [43], four basic functions of transdisciplinary research are named:

- Capacity/competence building: Integrating knowledge from different scientific disciplines and representatives from different stakeholder groups and decision makers on concrete social, regional and technological processes of adapting to changing environments
- Consensus building: Reducing uncertainty, gathering state-of-the-art knowledge, informing relevant stakeholders and organising discourses
- Analytic mediation: Scientists operating and assisting as facilitators in problem definition, constraining uncertainty and creating processes to generate solutions
- Legitimisation: Scientists providing knowledge to legitimise political action programs
- In [42], transdisciplinary research approaches are summarised:
- Ensure that the essential knowledge from all relevant disciplines and actor groups related to the problem is incorporated.
- Create knowledge beyond problem analysis, as goals, norms and visions need to provide guidance for transition and intervention strategies.
- Promise to increase legitimacy, ownership and accountability for the problem, as well as for the solution options.

Section 5.2 describes how the transdisciplinary work was implemented in the process following the theoretical considerations. The conception of the method also includes the development of quality criteria for the design of the transdisciplinary processes. Since a great deal of experience has been gained with transdisciplinary work in recent years, it is also increasingly possible to focus on the question of which success criteria emerge for transdisciplinary research and which challenges arise in its implementation [42,44–46]. Reflection on the success of transdisciplinary aspects of the approach follows in Section 7.2.

5.2. Building Blocks of Transdisciplinary Cooperation

5.2.1. Pre-Study

To underline the practical relevance of the integrated assessment, a preceding exploratory study was carried out in which the research questions were worked out together with practitioners. For this purpose, the research consortium held coordination talks with the practice partners in order to identify the fundamental interests of each partner and to ensure that the project could be adapted to existing activities of the practice actor. No pre-selection of the use paths was made in this pre-phase of the project. Rather, it was a matter of comparing the research questions relevant from a scientific point of view with the ideas regarding future business fields on the part of the municipal utility. The customer side, i.e., the end user, was not yet involved at this point, as the thematic possibilities were still too broad. The ideas developed were incorporated into the actual research proposal. After the project was started, the practice partner was involved in the project by a letter of intent. The pre-study was not part of the actual research design (as shown in Figure 1) but simplified the start phase of the main project due to the thematic definition in advance.

5.2.2. Use Path Selection

The research work began with the theoretical analysis, evaluation and pre-selection of suitable use paths, as described in Sections 3 and 4. Subsequently, these results of the multi-criteria analysis were consolidated in a SWOT analysis and discussed in a half-day workshop with representatives of the WSW as the practice partner with regard to a possible implementation at the Wuppertal site (as part of step 3 of the integrated approach; cf. Figure 1). The scientific partners fed six possible paths into this selection process. In the end, two paths (power-to-cold and power-to-eMobility) were selected as most interesting. Furthermore, it was decided that a detailed concept (business model) should be developed for the mobility path that should focus on operational aspects of eMobility solutions for local businesses and highlight the role of the municipal utility as an electricity supplier and infrastructure operator. Both scientific actors and the company carried out the subsequent analysis of potential customer groups as a central component of the envisaged business model.

5.2.3. Scientific Analysis to Identify Potential Customers for the PtX Path Power-to-eMobility

Using a sectoral analysis, the scientific actors identified companies with potentially suitable company mobility needs. Recognising the challenge that investment into new infrastructures and business models only pays out when there is demand for it, while clients will only buy into a new technology if the infrastructure exists, the sectoral analysis aimed at identifying local customers for the chosen PtX path.

In a sectoral assessment, specific industries and branches with potential demand for eMobility solutions were identified. Based on a literature study and the German classification of economic activities [47], a list of sectors requiring passenger cars for their main economic activities was compiled. As different sectors and economic branches have various requirements concerning the usage of passenger cars, the selection was narrowed down. Hereby, three main categories were identified:

(1) Industries whose key products/services suggest a daily and intensive use of passenger cars
(2) Industries whose day-to-day routine suggests daily use of passenger cars only if the enterprises reach a certain size
(3) Industries in which regular usage of passenger cars depends largely on the presence of specific auxiliary activities within the firms (but not the key product or service)

Industries falling in the first category (e.g., catering and delivery services, out-patient treatment, and cleaning and facility services) were considered as highly relevant, while firms in the second category (e.g., service providers, bakeries and mobile traders, and sales representatives) were considered relevant in case the ventures reached a certain number of employees. Firms in the third category were dismissed due to the high heterogeneity of the group, which would require a detailed check on individual enterprises. In a subsequent spatial assessment, companies categorised in the previously identified economic sectors within the city of Wuppertal, the market area of concern, were identified using a commercial database and postcode information. The results of this analysis were then used to (a) contribute to the succeeding analysis of suitable companies by the practice partner, where existing clients' portfolios were assessed, and (b) provide insights into the development of the business model.

5.2.4. Analysis of Suitable Companies from the WSW Customers for the PtX Path Power-to-eMobility

In parallel to this scientific and theoretical approach, the practice partner also tried to identify suitable companies from the existing client portfolio.

Based on experience gained from the WSW's daily customer contact, it was already known at the beginning that the requirements that companies place on their respective production factors are very heterogeneous. Additionally, it became clear that every company places different demands on its respective vehicle fleet. Hence, a common denominator across all known companies seemed too small to be used to develop a product or a service that could give customers real benefits in the sense of pain relief.

As a result, it did not seem sensible to invite a selection of participants from any random companies to a workshop in the hope of developing a suitable number of product ideas.

First, the question was asked whether at least a cluster formation of the companies to be invited to a workshop is possible. To form a cluster, criteria had to be found that covered the requirements of as many customers as possible and according to which a grouping could be carried out. Reasonable criteria could be company size, operational rhythm, fleet structure and resulting requirements for vehicle availability.

The WSW analyses showed that the following two main groups of companies should be considered:

- Delivery and services for which the car trips themselves are the object of the business purpose: This group included transportation of people who are handicapped, nursing services and delivery services. Here, the vehicles are at the main location only for a short time and move to many locations throughout the day. Some of the vehicles might be taken home by employees after work. Especially in this situation, one would be confronted with inhomogeneous circumstances concerning the charging requirements.
- Companies in the manufacturing sector and service providers where car trips just serve the purpose of getting to the site of operation or to the respective client: This group included, for example, well-known tool and device manufacturers as well as insurance companies. Here, the vehicles (pool vehicles) typically stay longer at the main location and move to a few, but more distant, locations during the day.

5.2.5. End-User Integration

The analyses of potential customers or customer groups were then combined in order to develop a participation concept for the integration of the user perspective. The original idea was to conduct workshops with interested companies to define the demand-side requirements of the envisaged business model (as preparatory work for Step 4; cf. Figure 1). The necessary framework conditions and potential obstacles were to be taken into account. These assessments are necessary in order to optimise the range of services of the municipal utilities and also to identify where customer requirements cannot be met by the possibilities of the municipal utilities and therefore further service providers must be integrated accordingly. Unfortunately, it proved to be very difficult to approach potential companies, despite a joint approach by scientific and practical actors. Only one company showed a concrete interest in the concept of company eMobility and was willing to participate in a workshop. Instead of being invited to a workshop, this company was asked in an in-depth interview about the requirements for company mobility management with electric vehicles.

The results of this interview were prepared in such a way that the project consortium in an internal workshop could discuss them. This cannot replace a detailed examination of customer requirements, but at least it allowed specifying the service model more precisely. When designing the business model (cf. Section 6), therefore, a clear focus was placed on the information necessary for a targeted customer approach in order to give the practitioner an opportunity to address further customer clusters.

6. Step 4 in Depth: Development of a Business Model and a Roadmap for the Selected PtX Path

As explained in Section 2, the development of a business model and a roadmap forms the fourth step of our integrated approach. The applied Business Model Canvas is presented in Section 6.1. Afterwards, we present the roadmap for the implementation of the business model in Section 6.2.

6.1. Business Model Canvas

According to [26], business models are developed to understand and describe the basic mechanics of an idea and make them transferable to the real world. A business model consists of various elements and their relationships, which embody the logic of how a company can generate sales. It describes the value that a company can offer its customers, taking into account relevant partners in a complex ecosystem. The basic principle is to break down a business model into partial models and design with business model elements. Hence, the presentation of the impact relationships between the individual components of the partial models. There are several models to develop business models, e.g., [26] and [48–51]. In our project, we used Business Model Canvas developed by Osterwalder; cf. [26] and [52,53]. In this model, there exist nine specific elements with which a user has to work.

First, we started by identifying the customer segments in order to specify the relevant target groups and to describe their needs. We used the Value Proposition Canvas to derive the value proposition in a structured way based on the understanding of the relevant target groups. Value Proposition Canvas is a detailed view of Business Model Canvas. It aims to deal in detail with the target groups and their own value propositions.

The customer segments are to be separated into three components: first, the customer jobs that describe what a customer is trying to get done while working; second, the customer pains that describe anything that annoys a customer during work; and third, the customer gains that describe the benefits the customer wants to achieve. We used research results in our project consortium and analysed interviews with customers to identify pains and gains and get an understanding of our customers' jobs.

The second step in using Business Model Canvas is to create the building block value proposition that describes a bundle of products or services that addresses a customer segment. To do this properly, we described relevant service modules to deliver a sufficient product. In addition, we formulated pain relievers that describe how the service modules alleviate specific customer pains. Finally, we derived gain creators that describe how the service modules produce a positive outcome regarding customers' desires.

By finishing Value Proposition Canvas, we transferred the results into Business Model Canvas. There, we analysed how a communication strategy could be designed and which channels could be used to deliver the elements of the value proposition. While we defined the relevant channels to get in touch with the customers, we described several types of customer relationships. After this, we defined how each service module can generate revenue for a company. We distinguished transaction and recurring revenue streams and discussed one-time and ongoing payments. In the end, we defined the key resources, key activities and key partners that led us to deliver the service modules in an effective manner. Finally, we elaborated the cost components and checked which variable and fixed costs will be incurred. The entire process described (starting with the impulses from the preparatory work over the Value Proposition Canvas to the filling of the Business Model Canvas) is shown in Figure 4.

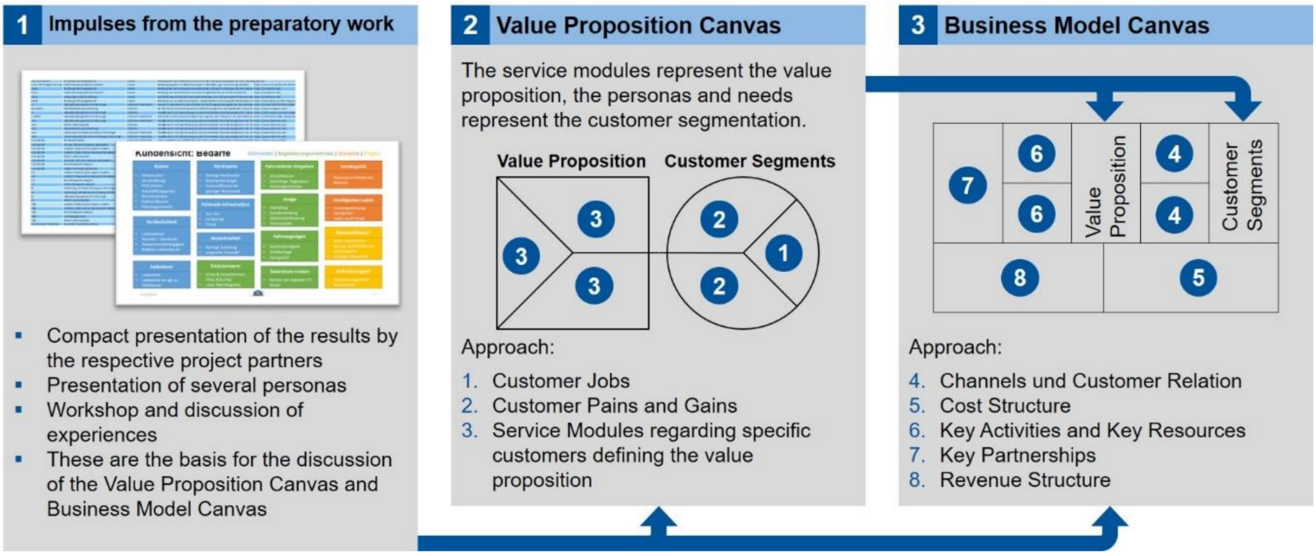

Figure 4. Approach to define and detail a business model.

After designing the method described above, we defined 19 different service modules (see Section 6.2 for details). For our practice partner, who runs some services, it was very important to note that not one partner must run every service. The WSW stated, for example, that services like fleet management are among those services that are not included in its service portfolio because certain core competencies are missing. Therefore, the focus for all the following considerations should primarily be on the provision and, if necessary, the operation of charging stations, including consultation on setting up a customer's charging concept. Considering this, we classified all 19 service modules as mandatory or optional.

We were able to combine the 19 service modules into four central products (see Figure 5). Each central service assigned to the value proposition consists of a certain bundle of service modules. In the following, one example is described: Alpha Consulting supports customers in taking the first steps towards building an electric vehicle fleet. Within this service module is, for example, support for the customer in creating a necessary knowledge base. This service module explains to customers which solutions are available on the market, for example, which vehicles, charging stations and charging management systems are offered. It is also possible to analyse the vehicle fleet in order to design the technical components of an electrified vehicle fleet in a holistic and future-oriented way. It was also found that in the context of power-to-eMobility, it is necessary to work with many different partners. For example, strategic partnerships must be entered into with suppliers of charging stations and charging management systems.

In conclusion, it can be stated that the application of Business Model Canvas significantly supported the collection, structuring and identification of important components for the secure provision of a highly available charging infrastructure.

6.2. Development of a Roadmap for the Implementation of the Business Model

Using the results of Business Model Canvas, we first detailed every aspect of each building block. In the next step, we created fact sheets for every service module and integrated the results of key partners and key activities. This helped us know which service module can be processed with a certain partner and which without one. Further, we separated the roadmap into three parts, which we called the predevelopment phase, the detailing phase and the servitisation phase. This enabled us to classify the service modules and show which preparatory work needs to be carried out before the first service is provided. The process from Business Model Canvas to the roadmap is illustrated in Figure 6.

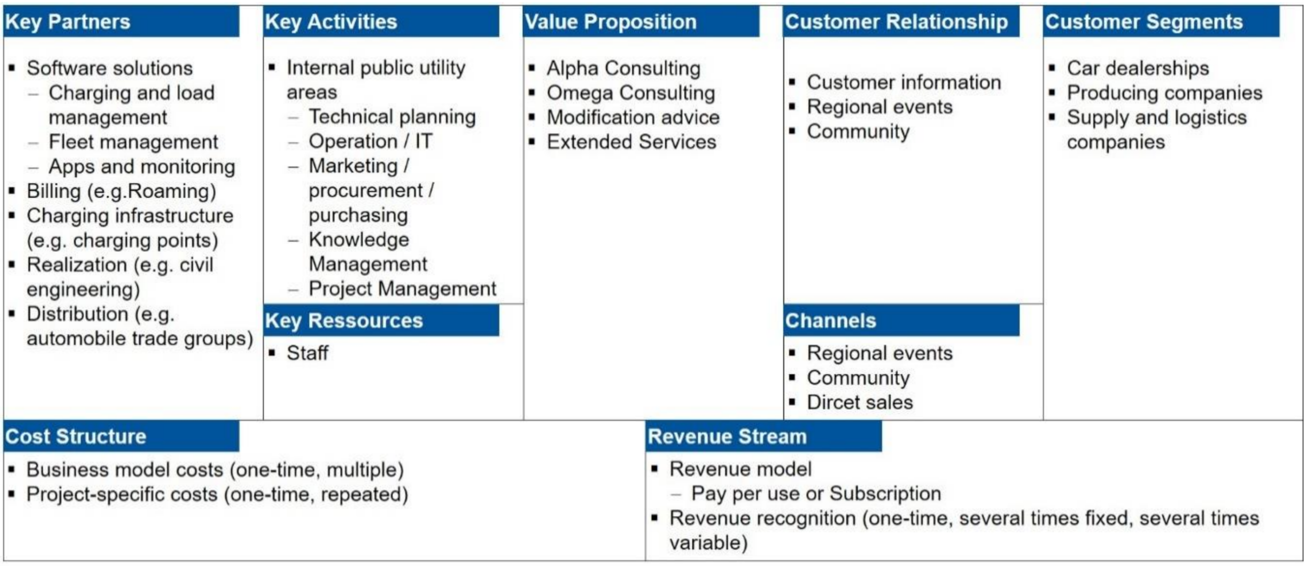

Figure 5. Results of Business Model Canvas.

Figure 6. From Business Model Canvas to the roadmap.

In the pre-development phase, we detailed consulting elements that are necessary to offer the power-to-eMobility path, for example, the determination of the potential of a fleet of electric cars and the creation of a knowledge base. To enable the implementation of a charging infrastructure and the experience of eMobility, further service modules are required in the detailing phase. The planning of the technical realisation as well as the procurement of the necessary technical components are essential parts of the service provision. In addition, the supervision and management of the realisation of a charging infrastructure are of importance. These three building blocks are central to ensuring implementation. In the servitisation phase, building blocks are offered that need to be developed in the future. In the sense of a sustainable business model, it is important to focus on the core areas first. Therefore, the service modules in the context of service are optional. They only add meaningful building blocks to the service portfolio and value proposition in the future.

Based on the results presented above, we were able to develop a roadmap. It enables a local public utility to develop a business-model-oriented service portfolio. The roadmap contains information on the chronological development of the service modules and priorities. Mandatory service modules are preferable to optional ones in order to quickly build a viable business model. In addition, further implications for effective customer communication and winning strategic partners can be derived from Business Model Canvas. The roadmap with the prioritised and chronologically ordered service modules is shown in Figure 7.

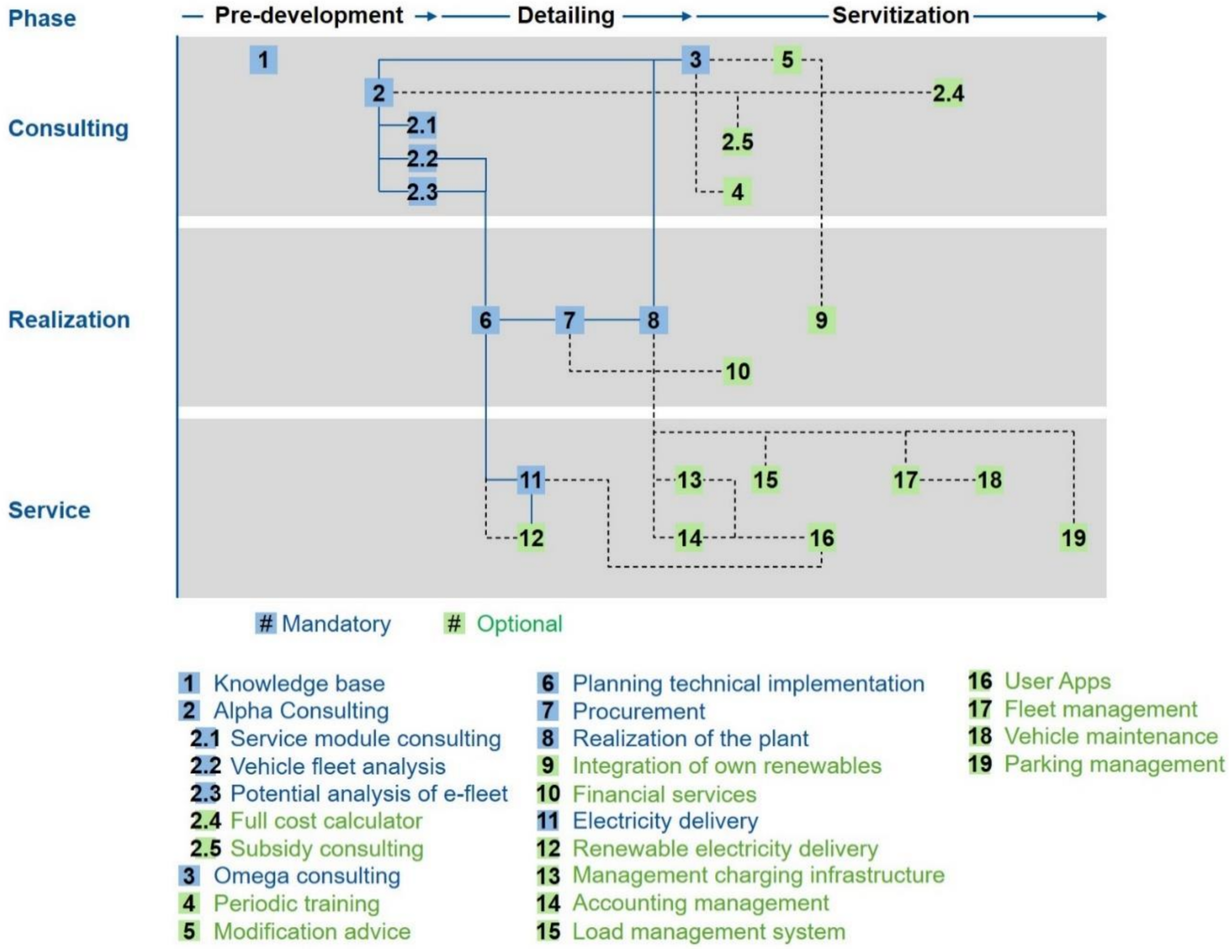

Figure 7. Implementation roadmap for the path power-to-eMobility.

7. Critical Discussion

Due to the multitude of methods that have been combined to form the integrative approach presented here, there are accordingly several possible starting points for improvements in further projects. However, the focus here was on merging a large number of existing individual methods into an integrative transdisciplinary and interdisciplinary overall approach and demonstrating its practical application on a case study. Since it is beyond the scope of this publication to go into the depth of each of the individual methods, the critical discussion will concentrate on the integrated approach as a whole and will only roughly give suggestions for further improvements within the individual methods (cf. Section 7.1). Section 7.2 focuses on the discussion of the transdisciplinary approach.

7.1. Critical Discussion on the Integrated Approach

The strength of the integrated process presented here is that it covers the entire chain, from path identification and characterisation through path selection for the local application to business model development and implementation. In terms of the overall approach, we see some major potential for improvement in further projects. Suggestions for improvements within the individual methods are only roughly given for each of the four steps of the integrated approach.

Step 1: Identification of PtX paths

- Due to the breadth of the developed approach, the steps for path identification and path characterisation have a comparatively high level of abstraction. The project presented aimed, e.g., at all possible sector coupling paths across the board. In projects that are more specific from the start, the same methodology for systematic PtX path identification could be carried out within a path group. For example, a large number of other paths can be subsumed in our rough path power-to-H_2-to-industry if all specific energy conversion technologies are differentiated as possible path components. Due to technological progress and changing framework conditions, we think it is important not to start from ready-made paths but to check from time to time in a systematic and creative way whether new relevant paths should be taken into account.

- From time to time, basic technology components as path modules have to be updated (not only new developed technologies added but also the properties of respective technology components updated, e.g., progress TRL or efficiencies). In addition, the precise design of the criteria or their limit values of gate 1 can be discussed. Both could lead to further potentially interesting PtX paths.
- Likewise, the supplementary bottom-up analysis of existing implementation projects should be updated from time to time. In our analysis, while a multitude of existing implementation projects could be found for some paths, for other paths, there were only two or three suitable projects. Partly, this is because some paths are still so innovative that there are actually few projects. Sometimes, however, little is published, especially when it comes to company-driven projects. Mechanisms have to be found here by science addressing how this practical knowledge can also be harnessed. The importance of this was confirmed again during the implementation of another research project on the power-to-cold sector coupling path [54]. A review that is helpful in this regard but was only published after the end of our project is in [55].

Step 2: Interdisciplinary analysis of identified PtX paths

- The number of criteria and broad coverage of various disciplines are very good, but more quantitative than qualitative criteria could be selected. Especially quantified results for economic criteria seem to be an important improvement as decisions of companies are mostly based on economic benchmarks.
- For a broader applicability of the evaluation tool in a transdisciplinary process, it should be made more interactive and thus more (end-)user-friendly. The revision should go hand in hand with the improvements in the transdisciplinary design.
- With regard to megatrends, operationalising pervasive societal developments (in order to measure them) is generally demanding, as their dynamics might not be fully apprehensible (yet) and are prone to change. In addition, hypotheses concerning the future cannot be tested, as data can only be evaluated retrospectively. As a means used in consulting offered to corporations, the included megatrends, both in their selection and in their content-wise focus, are likely biased by an overemphasis of economic aspects (and, thus, simplified). However, as the objective of our joint analytical efforts was to identify PtX paths most promising for commercial implementation, this does not pose a methodical shortcoming here. By including such (undoubtedly rather fuzzy) concepts in our analysis, we seek to encourage integrated, anticipatory thinking. With a range of megatrends based on normative assumptions and claims rather than empirical evidence, it can be stated that while some megatrends clearly contribute to this aim, others have emerged as too diffuse and arbitrary to deliver valuable additional insights.

Step 3: Transdisciplinary cooperation for the selection of the PtX path

- Early involvement of relevant stakeholder groups on the user side offers potential for improvement in the locally specific selection of use paths. The transdisciplinary cooperation with our central practice partner (in our case study, the WSW) turned out to be very good: there was valuable input from practice for the scientific development of the overall approach. Conversely, science was able to provide valuable information and expertise for the implementation of a local implementation project for the selected sector coupling path. However, the identification and involvement/activation of possible end users (i.e., the future customers or partners of the central practitioner) turned out to be difficult in our case study. Improvement could lie in approaching an extended group of local actors directly after the path selection, also beyond the announced customer groups of the practice partner. In this way, a broader perspective on the business model to be aimed at can be obtained, even if the negotiation process with the interests of the practice partner becomes lengthier as a result. A more in-depth critical examination of the transdisciplinary approach can be found in Section 7.2.

- The sectoral analysis was performed using data from the Markus Database Company register. Here, information is aggregated for economic entities on the company level. Therefore, further delineation of the results by more detailed criteria (such as employees per local branch or location) was not possible for larger companies comprising multiple locations. Here, data that are more detailed would allow for a more precise analysis and better results.
- Especially for other grid-bound PtX paths (e.g., local heat systems and hydrogen use paths), the spatial approach allows integration of the existing infrastructure (grids, pipelines) into the analysis early on to further delineate users within possible reach of this infrastructure.

Step 4: Development of a business model for the selected PtX path

- Business Model Canvas is a powerful method to create new business models. Primarily, it is a design method and subordinately an analysis method. We used it to analyse the value proposition in the context of the PtX path power-to-eMobility in order to identify white spots on the supply side and develop new products. The analysis and development were oriented just on the customer's demand perspective. Quantitative economic experience values were not taken into account, which could comprehend the results.
- The provided and described method must be adjusted each time it is used for other questions and problems. The result quality depends more on the analytical skills of a team and less on the data input or the accuracy of the method application.

7.2. Impact Analysis of the Transdisciplinary Building Blocks

In addition to the sophisticated integration of content and methods, the project was designed for the extensive participation of relevant stakeholders, in the sense of transdisciplinary research. Transdisciplinary research has been carried out for several years now; it is therefore now possible, through the evaluation of these projects, to identify success criteria and to estimate the impact of the projects [44,46].

In [46], for example, transdisciplinary projects from the field of land-use science are analysed. One of their central findings is that only few projects strived to achieve a process of collaboratively framing the research problem and defining the objectives involving actors from practice at the initial project phase. Furthermore, the study in [46] found that a dominance of natural-scientific-technological disciplines was apparent in many cases.

In the project presented here, this is at least true with regard to the integration of the end-consumer perspective. The project was developed primarily from an energy system perspective. Of course, the interactions with social megatrends were taken into account from the very beginning. Deeper non-technical questions, for example, on the acceptance of the selected PtX paths on the part of the end consumer could only be considered at a very late stage. This may be one reason why the corresponding workshops for the integration of potential customers were not successful.

In Section 7.1, it is already outlined that a more independent involvement of relevant groups of actors following the selection of the PtX path would have been useful. The selection of actors on the consumer side was based on the customer base of the practice partner. Understandably, the business model to be developed could only be tailored on the basis of what the practice partner wanted to offer as a service. The transdisciplinary project work here finds itself in a dilemma between the legitimate interests of the practice partner involved and the greater openness that would actually have been necessary and would have been brought into the project by external actors.

To assess the effect of transdisciplinary work, the study in [44] proposes to differentiate effects of different order. The study distinguishes between first-order effects that arise during the project work in the direct spatial context. Second-order effects are accordingly produced in the immediate spatial and temporal environment of the project. Third-order effects are temporally and spatially detached from the project. In addition, the study proposes impact categories derived from other research projects for a detailed assessment, i.e., learning processes, capacity building, network effects and improvement of the situation. The latter refers to structural changes, the adaptation of institutional framework conditions or the adaptation of organisational processes in companies [44].

After completion of the project, an in-depth interview was conducted with the practice partner in order to evaluate the transdisciplinary cooperation and to be able to understand the chances for continuity. Even if long-term consequences (in the sense of the third order) and immediate effects in the project environment (in the sense of the second order) are difficult to evaluate shortly after project completion, some positive effects can be determined from the concrete project context (first order). The practice partner clearly emphasised the positive aspects of cooperation. Cooperation took place on an equal footing, thus fulfilling a very important criterion in the content of transdisciplinary projects. The high degree of flexibility in the content of the project (path selection) was emphasised in the evaluation. In particular, the added value of neutral knowledge processing by the scientific actors and the visualisation of advantages and disadvantages of individual use paths were stressed. With regard to the impact categories listed above, it can be stated that success has been achieved above all in the areas of learning processes and capacity building. Network effects can only be achieved in the medium term at the earliest if successful implementation concepts are promoted by the WSW in appropriate expert circles. With regard to the political level, no effects are to be expected in terms of changes at the institutional level. There may be positive medium- to long-term effects in the organisational structures of the company if, for example, further renewable energy business models are implemented based on the current concept.

Looking at the functions of transdisciplinary research according to [43] introduced above, it can be summarised that almost all of these functions were implemented in the project. Extensive capacity building took place in the context of path evaluation and selection. For the selected paths, knowledge was gathered in SWOT analyses, which enabled the practice partner to select suitable paths (consensus building). In addition, analytic mediation played an important role. The entire process, from path evaluation to the formulation of the business model, was designed with different participatory methodological approaches.

In the retrospective evaluation of the project, the transferability to other spatial or entrepreneurial contexts must also be critically questioned. This question has to be asked in terms of both content and methodology. From the perspective in [44], the transparent preparation and provision of knowledge ensures that actors from other contexts can take it up and use it in their specific contexts [44]. With regard to the methodological approach, the transferability of the project can be classified as positive. The methods for the evaluation and selection of suitable PtX paths were disclosed and transferred into an Excel-based tool, which theoretically can be used independently of the location and the actors involved. This also applies to the conceptual development of the business model of a company's eMobility but not to the concrete implementation in Wuppertal. Here, it must be assumed that the location-specific characteristics (supply structure of the local energy supplier, potential business customers) strongly influence the design of the business model.

8. Conclusions

Against the background of the energy transition goals in Germany, the project and its underlying process design, presented here, aimed to develop business models and project concepts for the implementation of energy system transformation at local and regional levels, applying a transdisciplinary research design to trigger local innovation processes. Since sector coupling is a key element in integrating the renewable energies necessary for decarbonisation into the energy system, the process design is focused on local implementation projects in the field of sector coupling.

For the conception of robust local implementation projects, an integrated method was developed, which consists of four steps. The first two steps have to be carried out only once and were methodically structured as a stage-gate process according to [18] from idea creation up to and including gate 2. This original method was appropriately transferred and adapted in terms of content so that the most relevant PtX paths could be determined and subsequently be characterised in detail in an interdisciplinary manner. The third and fourth steps, on the other hand, have to be worked out separately for each location/application respectively for each interested implementation actor. They include path selection in the local context as well as the development of the business model and roadmap for its implementation, with special consideration of transdisciplinary aspects. This differentiation is very important for the transferability of the approach to other spatial contexts. While the conceptual work of the first two steps has a high applicability, it has to be concluded for steps 3 and 4 that these must always be adapted to the respective local conditions and specific questions. This is a fundamental limitation of transdisciplinary research approaches. The strong consideration of local-specific concerns increases the probability of implementation but at the same time lowers the general validity of the results achieved.

In the use case we presented, the transdisciplinary collaboration was only partially successful (for a detailed discussion, see Section 7.2).

In particular, the integration of customer requirements was not successful to the desired extent. It should be considered here whether potential end users should be included in the process even earlier in the future. This was not possible in the present project, as the long process of path identification and characterisation was upstream. If the technological and other framework conditions do not change significantly, the results now available can be used (even if an update of steps 1 and 2 seems to make sense at times; cf. Section 7.1). This enables step 3 of the method presented here to be more end-user-centred by integrating not only the central practical actor but also the end user into the path selection. At the same time, such early involvement means a difficult balancing act, since the internal orientation process at the central practitioner would partly take place publicly. Specifically, the future must show to what extent only partial end-user integration in the development of the business model represents an obstacle to its roll-out or whether the well-founded assessment of end-user interests has represented a good substitute. The initial feedback from the WSW indicates that the late involvement of potential end customers was felt to be good and suitable in order to be able to make internal preparations and coordination beforehand.

Understandably, a real impact analysis could be carried out at the present time. In principle, the evaluation of transdisciplinary projects opens up an important field of research. Future analyses must show what impact the extensive involvement of practitioners and civil society actually has and to what extent this impact differs substantially from classical, strongly theory-focused research projects.

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