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User-centered design and evaluation of decentralized energy systems in the Netherlands

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Abstract—Decentralized energy system offer fast and low-risk way to test energy transition pathways at local scale. The technology variety and increased role of user preferences call for a systematic design process in close collaboration with prosumers. We propose a novel methodology to design local energy systems that are technically robust and socially supported – the Participatory Approach to Community Energy Design. The methodology is applied to a neighborhood in the Netherlands. Among four alternative designs, a biogas-fueled and a smart grid systems consistently outperformed the alternatives, regardless of changing the user preferences.

Keywords — community energy, decarbonization, renewable generation, participatory approach, sustainable energy systems

I. INTRODUCTION

A. Background

Climate change, energy security, resource scarcity motivate societies around the globe to install more renewable energy. However, as renewable energy production grows, the energy system experiences several grid challenges [1], [2]. On one hand, renewables can produce more energy than the local demand – the oversupply in the grid may affect stability and overload the grid capacity. On the other hand, the system also requires extra energy backup and spinning reserve for periods of undersupply.

These effects could be addressed by centralized solutions requiring system-wide changes and multi-lateral collaboration among countries [3], [4]. This results in large investment and planning commitments, as well as delays due to negotiations. Furthermore, there is a risk to be locked in a specific technological pathway. In the mid-term, decentralized energy solutions allow for a faster and more affordable way to test technologies based on local preferences and constraints. Furthermore, the end-users are increasingly committed to actively participate in energy landscape and becoming prosumers [5], [6].

Any new energy system must perform at least as well as the present centralized system – be technically robust against extreme weather events such as atypically long cold winter or long periods without solar or wind energy. New systems also involve more stakeholders; in particular, end-users gain influence as their willingness to support novel installations near their residence is definitive for implementation [7], [8]. Public acceptance, user satisfaction, perceived usefulness and ease-of-use features can bring barriers, as it is the users who interact with the system on a regular basis [9], [10]. Top-down projects typically encounter resistance from the users when their values are neglected [11], [12]. Furthermore, even when residents agree in principle, they may resist an installation near them in practice – ‘Not In My Back Yard’, or NIMBY effect [13], [14]. To anticipate such risks, it is essential to understand the energy ambitions and objectives of end-users, and to grant them with a decision-making power over the choices.

A range of new and mature technologies can be combined to create multiple energy systems, yet there is no shared view on how sustainable energy systems should look like in the future [15]. Physical location and user preferences dictate the configuration of a new system. To guide the design process of a novel energy system adapted to physical location and user preferences, a systematic approach is instrumental to align the different dimensions of requirements.

B. *State-of-the-Art*

No integral approach currently exists to co-develop energy system solutions by explicitly including users [16]–[18]. Therefore, a co-creation approach must be developed which would enable multi-criteria assessment of systems to identify those that are both preferred by users and technologically sound. A pertinent methodology exists in Germany in the field of water management, the Participatory Integrated Assessment (PIA) [19]. However, the objective there is to reach a decision that will satisfy most of the affected parties, while in the case of energy systems there are fewer stakeholders and the main objective is also to ensure the quality of long-term system performance. Because of this, the original methodology is redesigned such that the interests of the end-users are prioritized and negative impacts on the grid are avoided. Certain elements of such an approach have been used in the energy-related projects in the Netherlands [20]. In particular, attitude studies and willingness-to-pay assessments are executed in order to extrapolate the effects of consumer preferences on the market potential of a product or service [21]. However, it has rarely been the case that the original concept is re-designed after receiving the attitudes or feedback from the users.

Energy systems re-designing is not practiced due to large expenses needed. An approach that allows for the rapid assessment of virtual designs and their optimization would promote the realization of the energy transition. To address these challenges, our research proposes a holistic approach to design, evaluate and select a technically robust and socially sound decentralized system. The approach is applied to a neighborhood in Groningen, the Netherlands.

The rest of the article is organized the following way: Section II presents the Participatory Approach to Community Energy Design (PACED) methodology in detail, including models used to simulate demand patterns. Section III the results of the PACED method applied to the neighborhood in the Netherlands are detailed. Section IV discusses sensitivity of the outcomes to variations in costs and weights, as well as limitations of this study. Finally, Section V summarizes the conclusions and major contributions of this study.

II. METHODOLOGY

The proposed approach expands upon PIA method applied in water management field [19], [22]–[24]. Our approach – Participatory Approach to Community Energy Design, or PACED – draws on the principles of co-creation where expert knowledge is combined with user preferences to obtain propositions of energy systems that satisfy technical requirements and energy ambitions of users. It is modified to incorporate user input at all three stages, unlike PIA.

PACED proceeds in three stages: (1) situation analysis, (2) system design, and (3) system evaluation and selection (Fig. 1). The first stage includes the analysis user criteria for an energy system, and constraints imposed by the local context. We conducted a literature analysis and a survey among house owners from twelve Dutch provinces, with 72 respondents. Apart from demographic data, the survey assessed the importance that users ascribed to various features of energy systems, e.g. independence from the grid, carbon intensity, ownership of the system. The survey also obtained user preferences about installed technologies (e.g. wind turbine versus rooftop photovoltaic (PV), in-house energy storage), about energy carrier (e.g. biogas versus all-electric system), about whether their house can be further insulated. Finally, the survey gained insight into limitations (i.a. in-house space for battery, or maximum additional financial contribution for a novel system). The survey conclusions are specific to Dutch context only.

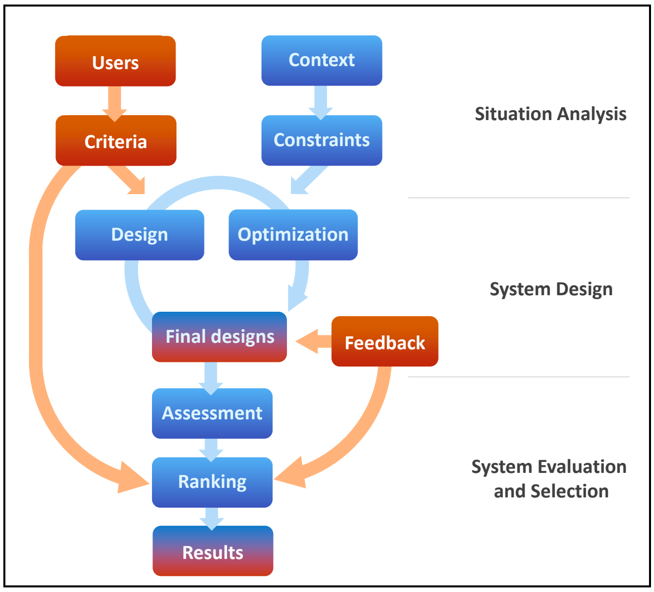

Fig. 1. Participatory Approach to Community Energy Design

Context analysis yielded constraints specific to a neighborhood in Groningen, a region in the Netherlands. The neighborhood was described in terms of its demographic composition, effective rooftop area, housing stock, building energy performance, and energy equipment in place (e.g. PV panels, electric boilers). The considered constraints were space availability for new installations; potential for further insulation; year-long hourly patterns of electricity, heating and gas for cooking per each type of housing type. Additionally, the constraints also include extreme weather events that may occur during the projected lifetime of the system.

The electricity use patterns originate from a simulation software Simulation of energy demand pattern of households (SEPATH), developed by IVAM and Kema Nederland BV [25], [26]. The SEPATH model is a simulator that creates an ensemble of residential electricity usage patterns based on a set of user-defined input parameters and stochastic variations of all behavior-related parameters. The parameters are number of households, season, and thermostat settings, as well as distributions of house types, of age of residents, and of household types (persons per household). The heating patterns originate from Transition Roadmap for Energy Infrastructure in the Netherlands (TREIN), developed by Technische Universiteit Eindhoven, Kema Nederland BV, Alliander, and Centraal Planbureau [27], [28]. The TREIN model simulates the space heating energy demand of an ensemble of houses as a function of the house types, their energy labels, size and construction, the temperature settings inside, and the temperature outside. The program calculates the loss of heat from the houses over a period of several days and thus it creates a pattern of heat demand. The main feature of the TREIN model is that it calculates the dynamic heat flows of 50 similar houses in parallel, with the key occupant related parameters (thermostat settings, ventilation rates, domestic hot water demand etc.) stochastically varied. An additional gas demand pattern is included for cooking. However, it is also possible to have electric cooking in which case the cooking pattern is added to the electricity demand due to appliances. The normalized hourly cooking pattern for four weeks (one week in each of the seasons) are obtained from simulations done by ECN (1992).

The second stage – system design – comprises the design of potential systems based on criteria and constraints; optimization of annual hourly operation under typical and extreme weather conditions, and re-sizing peak capacities of the system components based on asset utilization levels plus a safety margin. The optimization of operation was done using Modeler of Three Energy Regimes (MOTER), developed as the engine of a serious game platform that is an energy flow optimizer within the EDGaR research program [29], [30]. An energy system in MOTER can include up to three networks – electricity, heat and gas – where the flow within is enabled by cables and pipelines, and among them by energy converting units, i.e. combined heat and power (CHP), heat pump (HP) and energy storage. The MOTER model minimizes costs by controlling energy flows through the use of converters and storages. The cost calculations were based on capital expenditures (CAPEX) and operating expense (OPEX), as well as priced greenhouse gas emissions associated with each energy equipment. For this study, CPLEX 12.3 version of the solver was used [31]. As part of this research, MOTER was upgraded to a “general purpose energy system evaluator” with an extended set of technologies included, re-fined storage calculations and system time dynamics.

Each system was initially sized at the maximum possible capacity of every device. All systems were required to always meet energy demand, even during extreme conditions. Based on optimized asset utilization rate during an extreme weather year, we sized installed capacities by adding a safety margin of 20% of peak asset use. Then the resulting designs should be presented to the users for feedback. For a real-life project, this would be done in person by explaining the details and practical implications of the designs to the users.

Finally, the third stage encompasses the assessment of aspects of system performance based on user criteria identified at the first stage. Based on these assessments, the ranking of system alternatives is obtained. The best performing systems, given that they satisfy the operational constraints are presented to the users.

III. RESULTS

A. *Situation Analysis*

When analyzing the motivations for the residents to found an energy initiative, a study [32] describes a multiplicity of factors which range from economic gains to green image of the city. A number of scientists examine community motives, grouping them by themes [33]–[40]. The categorization of different motives in the Dutch civil society, the four-themes scheme proposed in [33] is applied. The results of the literature review are presented in TABLE I.

The survey yielded several important conclusions, one of which is the importance ranking of four criteria of a community energy system: environmental impact (carbon intensity), affordable (cost), ownership (user-owned), as well as autonomy from the grid (locally-sourced and -used). Affordability was expressed as additional annual payment on top of the existing energy bill to account for the initial investment. The system ownership is a matter of legal agreement, rather than system design, hence it is omitted from the user criteria. These criteria correspond to the four types of themes presented in TABLE I. The ranking summary is presented in Fig. 2. The survey respondents had an opportunity to add their own criterion. Based on the variety of suggestions, a user satisfaction criterion was introduced to capture several points at once, viz. safety, resistance to errors, comfort, user control, and reaching two objectives specific to a given system design (e.g. affordability and autonomous). Finally, a criterion of resiliency was added as a new system must ensure equivalent energy services as the default one.

B. *System Design*

For the neighborhood of 346 households, four alternative system designs were developed in collaboration with DNV-GL Smart Energy team based on the situation analysis. Together with the reference case of business-as-usual, the four designs were optimized and re-sized. The final new designs are:

- ***Biogas system*** with house insulation, energy generated by PV and biogas digester, installed electric boilers and micro-CHP, gas storage tank and electric battery;
- ***All-Electric system*** with locally interconnected houses, powered by PV and net-neutral grid energy, with installed heat pumps (HP), and electric battery;
- ***Smart Grid system*** with well-insulated, interconnected houses that have some smart appliances, powered by a wind turbine, with installed electric boiler, CHP, and electric battery; and
- ***Power-to-Gas system*** with interconnected houses, powered by PV and wind turbine, with installed power-to-gas, CHP and electric battery.

The feedback step of selecting affordable system designs only was not taken into consideration, as current study has an exploratory nature.

TABLE I. MOTIVES TO INITIATE COMMUNITY ENERGY PROJECTS IN THE NETHERLANDS, GROUPED BY THEME

Motives to initiate community energy projects in the Netherlands grouped by theme			
Environmental	***Economic***	***Social***	***Mistrust to government or companies***
Environmental awareness	Growing energy prices	Energy security	Avoiding oligopoly in energy sector
Concern for next generations	Additional network maintenance prices	Autonomy and independence	Independence from exporting countries
Conservation of biodiversity and habitats	Creating job opportunities	Creating job opportunities	Disagreement with market or governmental priorities and/or values
Preservation of ecosystems (globally)	Keeping added value in the region	Social cohesion	Mistrust of multinational organizations and corporations
Quality of the (local) environment	Investing locally and profiting own community	Taking care of the community	Mistrust of government decisions (corruption, unfair pricing, budget distribution)
Green image of the town / city / country	Increasing personal welfare and comfort	Connectivity (sharing of interests)	Dissatisfaction with inconsistent energy policies
Sustainability of the system		Adding local value and reputation	Sense that society is moving in the 'wrong direction'
Avoiding resource scarcity		Strengthening of community identity	
Avoiding pollution air, soil, water		Ethical and ideological beliefs	

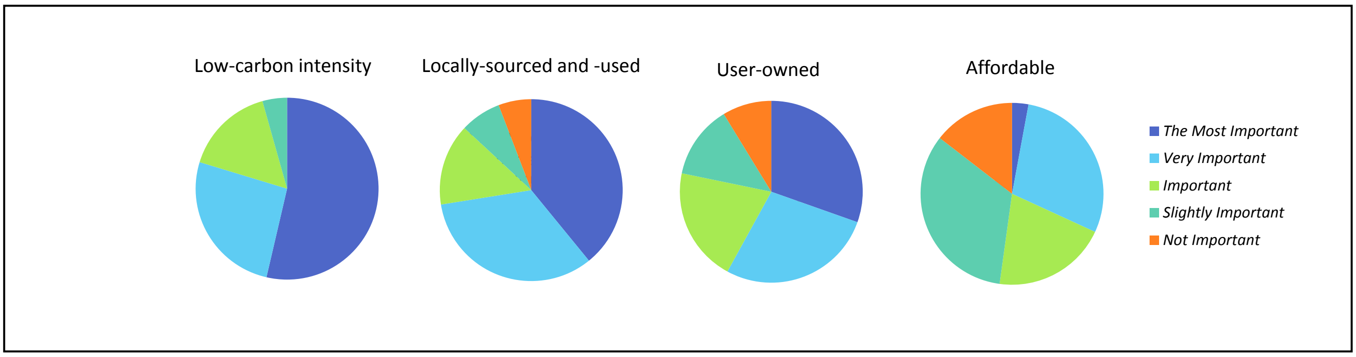

Fig. 2. Importance ranking of user preferences.

C. *System Evaluation and Selection*

The five different performance dimensions were used to evaluate the final designs. We then ranked the systems based on their relative scores. The results are illustrated in Fig. 3.

1) *Single criterion*

Resiliency is the measure of the performance during an extreme weather year, that quantifies the additional energy imported from the grids compared to a typical weather year. The Biogas and Smart Grid systems are more resilient due to improved building insulation – these systems produce and store enough energy to compensate for the long cold winter year.

Energy autonomy measures how much energy is supplied by the central grid during a typical weather year. Energy autonomy is not to be confused with energy neutrality, the net annual grid imports are approximately zero or negative. The autonomy is normalized to the Reference case. The All-Electric and Power-to-Gas systems rely on the grid to bridge the time-gap between supply and demand, so they have a poor energy autonomy performance. By contrast, the Biogas and Smart Grid systems can meet demand with their own supply.

Costs of the systems include CAPEX and OPEX of each system component (i.a. central grid bills, electric network reinforcement, rental of land for wind turbine installation). The costs are based on Dutch market prices in 2015 and are expressed in €$_{2015}$. As expected, any of the new systems costs more than the Reference case – up to 4.5 times more. The Smart Grid and Power-to-Gas systems costs are dominated by electric battery costs. To test the competitiveness of the systems over time, we performed the same calculations with updated prices for 2020 (see Section IV.A).

Environmental impact includes embodied, operational and end-of-life greenhouse gas emissions based on lifecycle analysis studies. It is measured in CO_2-equivalent emissions averaged over the system's lifetime. For example, methane burning contributes the most in the Biogas system, while the national energy mix dominates the emissions in the Power-to-Gas system.

User satisfaction is measured by the user dissatisfaction index. It is a composite of how well a system meets six different measures. The first two measure were defined for each system separately at the design step, the remaining four are the combination of unguided suggestions from the survey respondents. Here the most satisfactory for the users would be the Reference case where there is neither behavioral change, nor installation disturbance and risks.

2) *Final ranking*

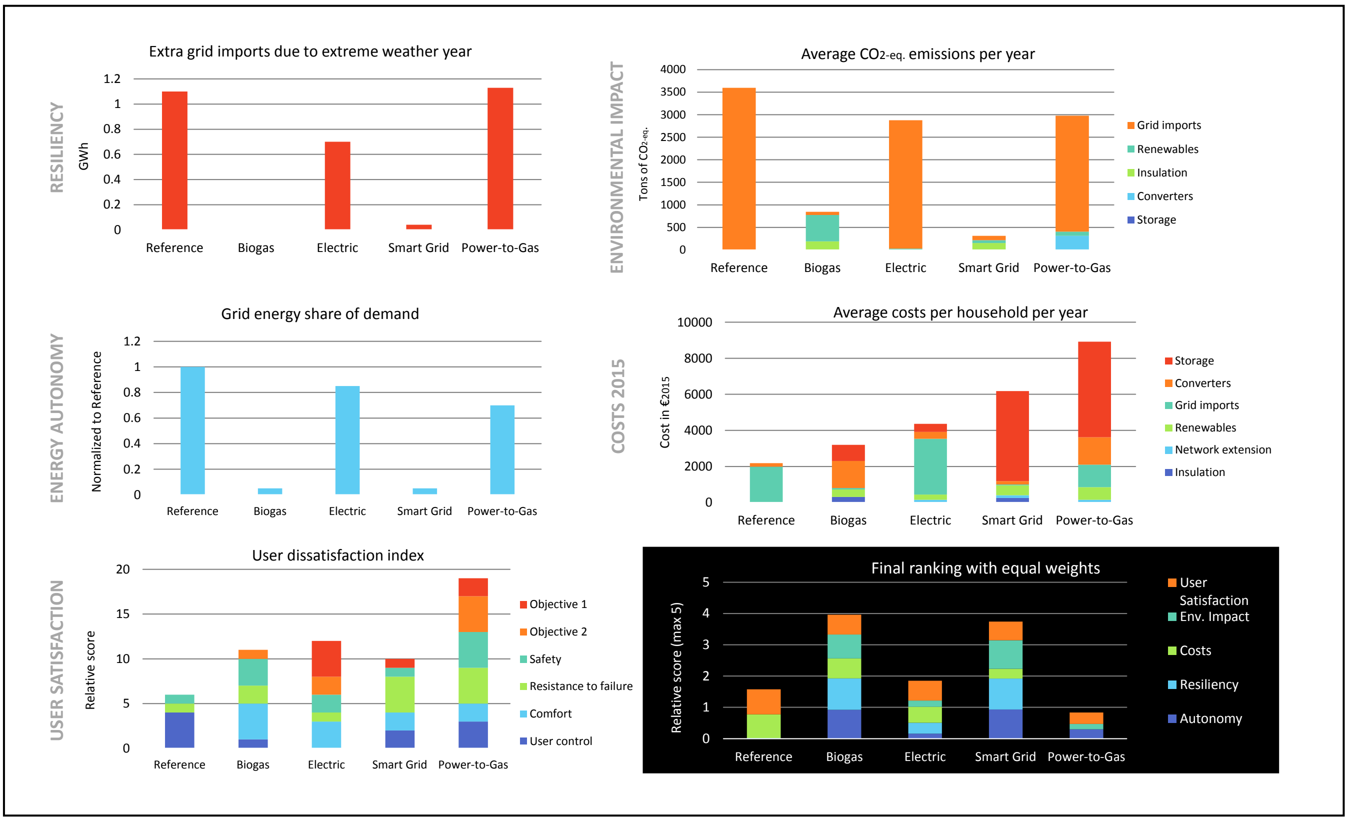

Fig. 3. Evaluation and Ranking of final energy system designs according to user criteria.

With equal weights and 2015 prices, we observe that the Biogas and Smart Grid systems are the best choice for this neighborhood (see bottom right section of Fig. 3). As mentioned, the user feedback at the second stage was omitted for research purposes. Yet, if we would have applied the maximum price the most respondents consider acceptable, the Smart Grid system would be beyond affordable.

IV. DISCUSSION

A. *Sensitivity to Costs*

We quantified system costs for prices in January, 2020 to examine the sensitivity of cost criterion over time. In Fig. 4 we observe the reduction of costs due to reduction of electric storage prices, and an increase in costs due to more expensive electricity tariffs in the Netherlands.

B. *Sensitivity to Weights*

Specific user preferences and values shape final ranking of the possible energy systems. For another location and group of users, the criteria might be different as the trends, norms, and aesthetics vary. Hence, the initial and final system designs, and the weights for final ranking would result in alternative choice of final systems.

To examine the sensitivity of system choice to weights, we adjusted the weights such that the relative weight of one dimension is equal to the sum of the other four. When we adjust the weights, we observe a change in ranking. Fig. 5 illustrates two instances of variations in ranking due to change of the dominant weight. In this case study, the Biogas and Smart Grid systems consistently outperform the other two designs. Yet, by changing weights, the best system changes, which illustrates the importance of user feedback.

C. *Limitations*

For this exploratory study, the feedback input was not applied to prune the final designs, so that all final designs were considered at the third stage. Furthermore, the selected designs were not implemented, so the expected social support and economic viability of the project were not verified.

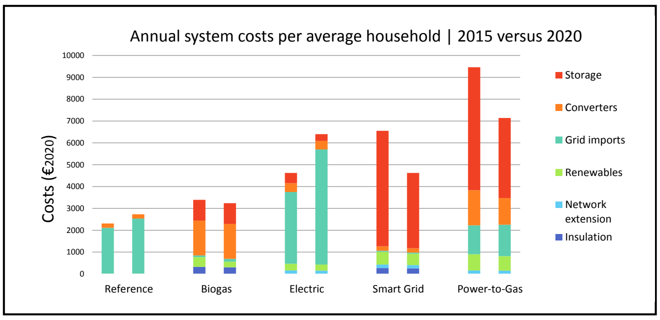

Fig. 4. Sensitivity to system costs in 2015 versus 2020.

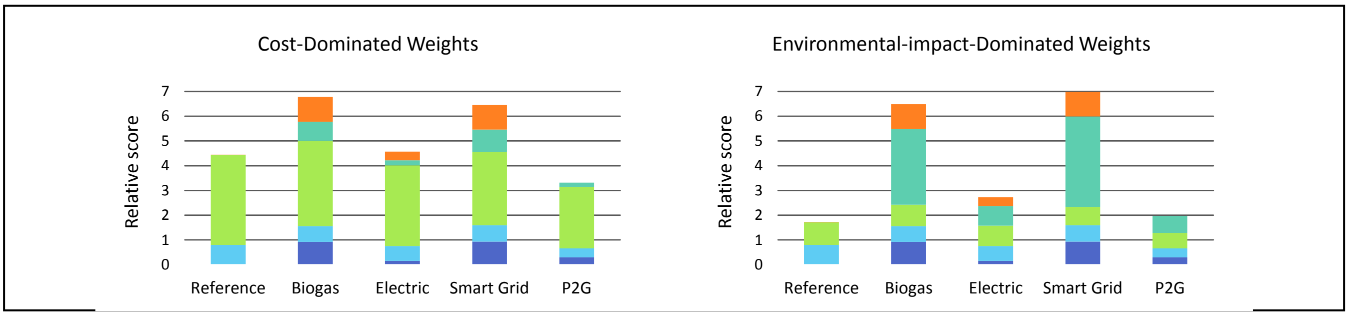

Fig. 5. Examples of weighted ranking: cost-dominated ranking (*on the left*) and environmental-impact-dominated ranking (*on the right*).

The PACED method does not stipulate the size of energy community or neighborhood considered. It would rather depend on the energy use per capita and population density for the users to benefit from the economies of scale for new installations.

V. CONCLUSIONS

Decentralized energy systems are relatively fast and low-risk solutions for local energy transitions on a mid-term time scale. Such solutions allow to explore a variety of technological pathways in parallel. With the Participatory Approach to Community Energy Design – PACED – we can navigate the solutions that would be socially acceptable and fulfill the technical requirements.

The energy transition is not a fixed predestined pathway, as local conditions and values are diverse. The Dutch case study shows the practical feasibility of the PACED method to reach an acceptable and effective energy transition at the local level. For the Dutch case, the Biogas and the Smart Grid systems are consistently more technically robust and socially supported than the alternatives. This can be understood by considering the particularities of Dutch energy landscape such as a relatively weak power distribution system, an intensive agricultural system which produces access of fuel for biogas system, a history of gas exploitation and an environmental movement that leads users to have stronger commitment.

User feedback on criteria shapes weights such that the competitive advantage of the Biogas and the Smart Grid systems can be significantly reduced. This would lead to different criteria and constraints, and therefore, different system designs and results.

In the changing energy landscape, the roles of end-users as well as big energy companies are evolving. While numerous prosumers join energy communities to make a difference in, some energy companies are already looking for ways to engage with prosumers. The PACED methodology can enable the collaborative process and ultimately fuel the local energy transition.

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