Adoption of Power Balancing Technologies

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Abstract

This article examines the influence of sustainability orientation and knowledge of power balancing mechanisms on the adoption of technologies that support power balancing among photovoltaic (PV) prosumers. Prosumers are individuals who both generate and consume electricity. The findings are derived from a survey of 1054 respondents, conducted among Polish prosumers who own photovoltaic installations generating electricity for household consumption. The survey was designed based on a decision model constructed by the authors incorporating five steps of technology adoption model: knowledge acquisition, knowledge development, technology acquisition, technology implementation, and system development. Statistical analyses confirm that sustainability orientation and knowledge of power balancing mechanisms significantly influence the perceived ease-of-use and the extent of achieved benefits. This research highlights the importance of behavioral factors in shaping adoption of power balancing technologies. These insights offer practical implications for designing policies, business models, and educational strategies that promote engagement with smart energy systems among prosumers.

Keywords: renewable energy, innovation diffusion, technology adoption, power balancing, prosumers

1. Introduction

The key approach to transformation of the energy sector is the development of generation capacity based on renewable energy systems (RES). Various market players install wind farms, photovoltaic panels, and other generation assets across several countries. One of the fastest-growing RES sectors is installation of photovoltaic (PV) systems. In 2023, the installed capacity of German PV exceeded 81.4 Gigawatts (GW), 37.6 GW in Spain, 30.3 GW in Italy, 22.7 GW in the Netherlands, 22.7 GW in France, and 21.8 GW in Poland (IEA PVPS Task. 1, 2024). A significant portion of these capacities have been installed by households. According to the International Energy Association, in 2023, approximately 45% of newly installed PV capacity globally was in rooftop systems, which are typically associated with prosumers.

Distributed RES installations enhance the security of electricity supply, especially when they work closely with electricity consumption locations. However, the rapid development of RES installations poses several challenges, particularly concerning the management of grid stability.

The presence of multiple RES installations opens the market for new business models, like virtual power plants, empowering new market players, like prosumers. Prosumers are customers primarily connected to the distribution network, as they generate electricity primarily for their own needs but can also sell excess electricity. In the case of prosumers, any electricity they generate but do not immediately use, is usually fed back into the grid. In most cases, an additional cost must be borne if the electricity produced is later used by the prosumer. Therefore, prosumers are motivated to use the generated electricity directly to avoid this additional cost.

Power balancing could be offered as a service by electricity suppliers or external service providers, like aggregators. It could also be managed directly by prosumers with the use of power balancing technology. The key technological element for power balancing is software program, capable of forecasting generation and consumption levels, while controlling electric appliances to minimize the generation-consumption gap.

Despite growing availability of residential PV installations, the adoption of power balancing technologies among prosumers remains limited. Some studies identify approaches for optimization of household power balancing, highlighting the potential benefits of such activities (Dutra et al., 2023). However, perceived benefits for households are relatively small, as compared with the costs and

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complexities of the required infrastructure. Furthermore, realizing and interpreting these benefits often demands a technical knowledge that many prosumers lack. As a result, gains from power balancing are unnoticeable or undervalued.

Additionally, empirical studies have shown that many households focus primarily on financial incentives, often overlooking other benefits (Duc et al., 2022). A significant share of prosumers remains unaware of broader challenges tied to grid stability and energy efficiency. Some prosumers are not motivated by sustainability values, further reducing engagement. Meanwhile, energy market stakeholders, such as aggregators, electricity suppliers, and system operators, stand to significantly gain from greater prosumer participation in power balancing. Power balancing activities carried out by prosumers generate positive externalities and yield substantial societal benefits. Realization of balancing services on the prosumer level is transformative for the energy sector, and its realization increases the individual and collective well-being.

The purpose of this paper is to analyze behavioral factors influencing the adoption of power balancing technology by prosumers, framing the analysis within the context of transformative service systems. It proposes a comprehensive analytical framework that integrates Diffusion of Innovation theory (Rogers, 2003), and the Technology Acceptance Model (Davis, 1989). This dual-theory approach allows for exploring how personal factors, particularly sustainability orientation, and knowledge of power balancing mechanisms, shape prosumers' progression through the adoption process and perception of usefulness and ease-of-use. To this end, this study addresses the following questions:

- How does the perceived importance of sustainability influence prosumers' intention to adopt technologies that support transformative energy services, specifically power balancing?
- In what ways does knowledge of power balancing mechanisms and their impact on prosumer well-being and broader societal transformation affect adoption decisions?
- How does the adoption of power balancing technologies enhance prosumers' perceptions of usefulness, and contribute to the realization of benefits for them?

The need to study adoption of power balancing technology by prosumers is evidenced by its transformative role in the energy sector and impact on well-being of several market stakeholders. The adoption of power balancing technologies is conceptualized as a value co-creation process within a service ecosystem with the key role of prosumers. The innovation of this study lies in shifting the analytical focus from purely technological characteristics to behavioral attributes of prosumers. By recognizing the role of user motivation, awareness, and knowledge, it contributes to the design of more inclusive and adaptive service platforms, regulation rules, and business models that support prosumer engagement with power balancing technologies.

The paper is divided into seven sections. In the first section the study is introduced. Section 2 critically examines the existing literature on decision models, transformative service systems, and technology adoption frameworks related to technologies supporting energy transformation. Section 3 discusses key decision steps in the decision model for adoption of power balancing technology. Section 4 presents the research methodology. Section 5 details the survey results and presents regression formulas proving the perception of benefits of the adoption process. Section 6 derives key conclusions from the survey analysis. Finally, section 7 analyzes the potential for using the presented results to support the realization of benefits through further adoption of power balancing technology by prosumers.

2. Review of the literature

This section extends the technology acceptance model based on the approach proposed by Davis (1989). The key motivation for technology acceptance depends on the perceived usefulness and perceived ease-of-use. If technology users understand the value of the benefits and if they perceive the technology as easy to use, then they adopt the technology and proceed with further steps in the adoption process.

To represent different stages of the adoption process, we develop the framework based on the concept of innovation diffusion developed by Rogers (2003). He uses five stages to analyze the adoption process of innovations: knowledge, persuasion, decision, implementation and confirmation.

Some researchers combined both models to analyze adoption of technology. Kotilainen (2020) discusses the application of both technology acceptance model and diffusion of innovation in understanding the adoption of renewable energy technologies. He emphasizes that factors such as ease-of-use, and the availability of turnkey solutions, are significant in adopting complex technologies, highlighting the relevance of integrating these models to assess prosumer behavior. Houda et al. (2018) employ the integrated research model that combines insights from Rogers' model (2003) with other relevant frameworks, to analyze adoption decision-making in the RES sector. Patterson et al. (2021) propose to extend a variation of the technology acceptance model to include perceived trust, agency and complexity in relation to smart grids.

Additionally, various decision models for households have been proposed. For example, Xu et al. (2021) develop a decision model for PV supply chains. Boumaiza et al. (2022) describe a model for the adoption of PV infrastructure. Hansen et al. (2022) analyze the decision criteria for buying PV installations, concluding that technically educated individuals tend to dominate the decision-making process. However, criteria for the decision model related to household energy balancing, have not been consistently identified by other authors. Several studies analyze decision criteria for some specific market characteristics. For example, D'Adamo et al. (2022) analyze economic profitability of PV systems with respect to both household and non-household self-consumers in the Italian market. Fikru et al. (2023) analyze how electricity generated from these systems affects energy consumption decisions, such as the purchase of green electricity from electric utilities, using utility-maximization models. Kacperski et al. (2023) analyze criteria for making decisions regarding peer-to-peer trading of energy produced by prosumers.

Schlindwein et al. (2023) analyze behaviors of different types of citizens including prosumers. They argue that shift towards a more sustainable and low-carbon energy system requires active participation of citizens and consideration of the behavioral dimensions of all types of energy citizens. Öhrlund et al. (2020) investigate the behavioral characteristics of self-selected versus non-self-selected prosumers, revealing that becoming a prosumer does not automatically lead to broader pro-environmental behaviors such as increased self-consumption.

Research on transformative system services indicates the importance of motivation and knowledge of consumers. Wunderlich et al. (2013) indicate that motivation is the key determinant and external rewards and feelings of compulsion have lower impact in adoption of IT-Enabled Services in the case of transformative services in the energy sector. Their findings align with service-dominant logic, which positions users as active co-creators of value rather than passive recipients. Romero et al. (2022) reinforce the importance of knowledge production research in the adoption of transformative services and analyze its impact on realization of sustainable development goals. From a governance and value perspective, Brown et al (2020) explore the normative dimensions of prosumer business models, modes of governance and understanding of value. This research presents how value logics are present within prosumerism, and how they impact energy transition. Campos et al. (2020) extend this view by presenting prosumer initiatives as a part of a transformative social movement. Finally, Polonsky et al. (2024) demonstrate that more complex systems have higher likelihood of foreseen harm. They claim that greater system adoption is required for systems with instances where harm arises.

This paper contributes to the academic literature on transformative system services by analyzing the factors influencing technology adoption within the energy sector. While existing literature examines factors impacting decisions in adoption across a spectrum of technologies and services, a gap remains concerning impact of behavioral aspects of prosumers on the adoption of technologies enabling transformative services in the energy sector. The decision-making process for adopting power balancing technologies exhibits distinct characteristics, including the level of technology maturity, impact on well-being of various stakeholders, and observability of benefits. Furthermore, the use of power balancing requires specific engagement of prosumers in realization of routines related to their electricity installation. Although prior research has underscored the role of user motivation and knowledge in achieving sustainability goals, it remains unclear how awareness of a technology's impact on individual and societal well-being shapes the adoption process, Additionally, the literature has yet to sufficiently explore how the adoption of such transformative services affects prosumers' well-being and the realization of intended benefits. This study addresses these gaps by examining the interplay between behavioral factors, adoption dynamics, and the realization of benefits from using technology.

3. Decision model for adoption of power balancing technology

Power balancing for households is a complex activity that requires support from technologies to identify the gap between generation and consumption as well as performing the necessary actions for efficiently reducing this gap. Households can adopt different approaches to manage the gap between their RES generation and electricity consumption depending on the level of their involvement and the level at which they use technology (Figure 1). Prosumers are categorized into four groups: those not practicing activities related to power balancing, those manually balancing, those balancing with an external service provider using their technology, and those utilizing own technology solutions for balancing.

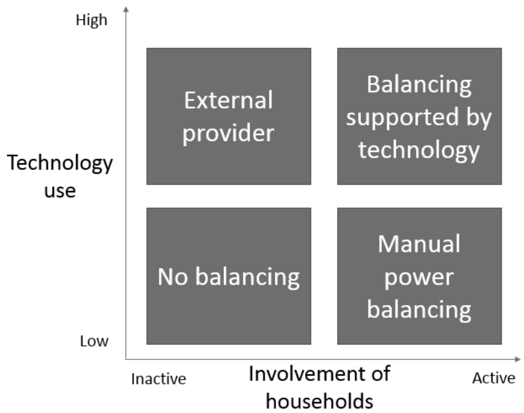

Figure 1. Approaches for power balancing in households (source: own analysis).

In the case of the adoption process for power balancing technology, we distinguish the following steps corresponding to the stages defined by Rogers (2003): knowledge acquisition corresponding to knowledge, development of knowledge corresponding to persuasion, technology acquisition corresponding to decision, technology implementation corresponding to implementation, and system development corresponding to confirmation.

An example of the adoption process and relation to perceived benefits and ease-of-use is presented in Figure 2.

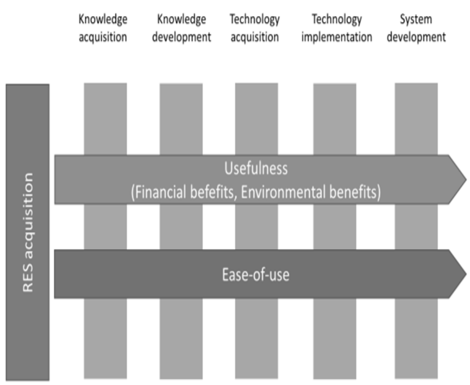

Figure 2. Example of technology adoption model for power balancing (source: own analysis).

In the applied model, knowledge acquisition corresponds to the stage when prosumers acquire knowledge about the power balancing technology and key characteristics. In the stage of knowledge development prosumers develop knowledge about power balancing mechanisms that allow them to achieve benefits for themselves and other market stakeholders. In the stage of technology acquisition, prosumers decide on the access to the power balancing technology. In the stage of technology implementation, prosumers decide how often they use technology, and which use cases they leverage to achieve benefits. In the final stage, prosumers confirm the usefulness of the power balancing technology and decide about development of new functionalities bringing further benefits impacting the ease-of-use. In each step, prosumers hold a unique perception of financial benefits, environmental benefits, and ease-of-use.

The adoption model serves as the basis for the development of a decision model representing logical steps and methods employed by households to use power balancing technology. The decision model outlines the level of prosumer engagement for each step and identifies the specific needs that must be met to advance to subsequent stages of the adoption process. This decision model is identified via the analysis of data collected through a survey conducted by the authors.

4. Research methodology

We employ the Computer Assisted Web Interview (CAWI) methodology to collect data about the way prosumers perform power balancing and their perception of usefulness and ease-of-use of technology. The survey specifically targets prosumers with photovoltaic panels. The data collection period spanned from October 13, 2023 until November 6, 2023. The survey adheres to quality standards of Quality Control of Interviewers' Work Program (PKJPA), coordinated by OFBOR (Polish Association of Public Opinion and Marketing Research Firms).

The CAWI is a versatile research approach that enables participants to answer questions across various digital platforms, including laptops, smartphones, and tablets. Profile questions are posed to all participants, while additional questions are directed to those meeting specific criteria based on the stage in the technology adoption process.

The research targets participants who declare ownership of a PV installation. To ensure the inclusion of only participants with PV installations, screening questions are employed. Only participants declaring the presence of a PV installation in their household are considered in the analysis. The survey was conducted in Poland, receiving 1,054 responses from the representative population of prosumers.

The survey instrument is organized into seven thematic sections, each designed to address specific dimensions of prosumer engagement and technology adoption. Questions in section 1 assess the demographic profile of respondents, capturing standard metrics such as age, location, and gender to contextualize subsequent analyses. Questions in section 2 explore the motivational drivers behind prosumer behavior, focusing on the perceived importance of sustainability and electricity costs. These insights support the segmentation of prosumers based on motivational patterns and help validate the study's core research questions. Questions in section 3 gather technical data on the PV installation and household electricity demand, providing a baseline for understanding achievement of the supply security goals for prosumers. Questions in section 4 evaluate the initial stages of the adoption process—specifically, knowledge and persuasion—as outlined in Rogers' (2003) diffusion of innovations theory. This section identifies how prosumers become aware of and understand mechanisms of balancing technologies. Questions in section 5 investigate the transition to the decision and implementation phases of adoption. Questions assess whether prosumers have acquired the technology and examine both existing and desired system functionalities. The list of functionalities is adapted from Przybylik et al. (2024), offering a validated reference for system functionalities. Questions in section 6 examine post implementations usage patterns, including frequency of technology use. It also captures perceived benefits, structured around Ungaro's (2022) triple bottom line framework including economic, environmental, and social dimensions which collectively define the transformative potential of the service. These dimensions reflect how consumers perceive service usefulness with improvements in personal and societal well-being. Questions in section 7 address the final stage of adoption - confirmation. Respondents indicate whether they continue using the balancing system and whether it has been integrated with other household technologies. Table 1 details the survey questions and their types.

Table 1. Questions included in the analysis and survey questionnaire.

	Questions and sections	Type
1	Profile (employment, age, location, gender)	
2	Household	
2.1	What amount do you pay for electricity in your household?	Single answer
2.2	To what extent are sustainability and energy efficiency important?	Single answer
3	Installation acquisition	
3.1	How much electricity do you use in your household in kWh?	Single answer
3.2	What is the peak production capacity of your PV installation in kWp?	Single answer
3.3	What is the yearly production of your PV installation in kWh?	Single answer
4	Knowledge acquisition and development	
4.1	Do you know mechanisms for power balancing in households?	Single answer
4.2	Which power balancing mechanisms do you know?	Multiple answers
5	Technology acquisition	
5.1	Did you acquire technology solutions supporting power balancing?	Single answer
5.2	What was the objective for acquisition of power balancing application?	Multiple answers
5.3	What is needed for you to be interested in acquisition of power balancing technology?	Multiple answers
5.4	What benefits do you need to get to be interested in performing activities related to power balancing?	Single answer
5.5	What functionalities are included in the application supporting power balancing for your household?	Multiple answers
5.6	What functionalities should be included in power balancing application to realize objectives related to power balancing?	Multiple answers
6	Technology implementation	
6.1	How often do you use technology supporting power balancing?	Single answer
6.2	What benefits do you get from using technology supporting power balancing?	Multiple answers
6.3	What is the level of financial benefits from power balancing?	Single answer
6.4	What is the level of environmental benefits from power balancing?	Single answer
7	System development	
7.1	Does your power balancing system include integration with other systems?	Multiple answers

5. Results

Among the surveyed participants, 22% report performing power balancing activities using dedicated technologies, while 17.7% conduct these activities only manually. An additional 7.5% rely on external providers, such as aggregators or electricity suppliers. In contrast, 51.8% do not engage in power balancing activities at all. Notably, fewer than 1% of respondents indicated that none of the listed options matched their approach. Figure 3 illustrates the distribution of prosumers by their indicated approach to power balancing

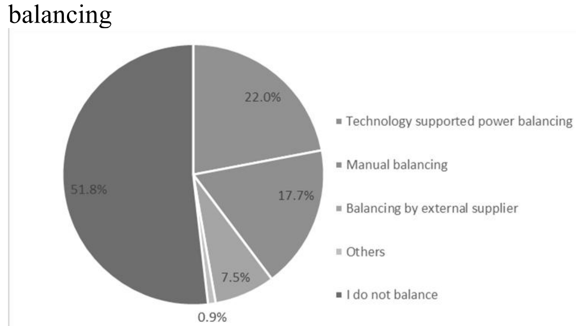

Figure 3. Distribution of prosumers by approach to power balancing (source: own analysis, N = 1054).

The results indicate that prosumers who use technology to support power balancing are more likely to report additional revenue, compared to those who balance power manually, or do not engage in balancing activities at all. Specifically, 33.2% of prosumers who directly use power balancing technologies report additional revenue. Similarly, approximately 30% of prosumers who rely on external providers, such as aggregators or electricity suppliers, who themselves use technological solutions, also report additional revenue. In contrast, only about 25% of those using manual approach report such gains.

Similarly, prosumers using technology for power balancing are more likely to gain more benefits in subsidies, environment regulations compliance, perception of acting in compliance with global trends, ease-of-use, functionalities, and monitoring of environmental impact. Only in the case of environmental impact benefits do more prosumers using external providers report such benefits, compared with those who use the technology themselves. However, for both groups, more prosumers report environmental benefits as compared with prosumers performing power balancing manually.

Figure 4 illustrates percentages of prosumers reporting benefits by technology approach.

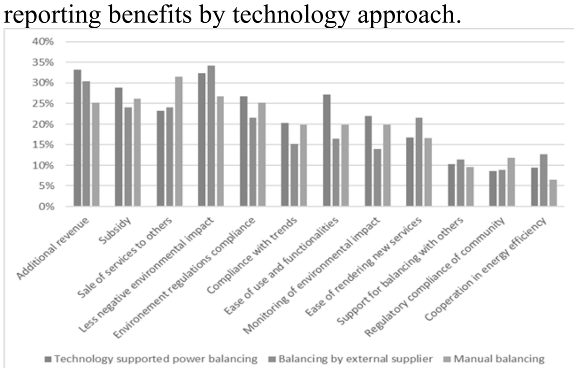

Figure 4. Percentage of prosumers reporting benefits by technology approach (source: own analysis, N = 498)

More prosumers who consistently perform power balancing activities in a structured manner tend to achieve additional revenue compared to those who sporadically perform these activities. Most prosumers who engage in daily power balancing report additional revenue. However, the percentage of prosumers who realize additional revenue decreases to only about 20% for those who engage in power balancing less than once a month. These findings indicate that the frequency and consistency of power balancing activities have a significant impact on the perception of attaining financial benefits. Figure 5 presents the percentages of prosumers with additional revenue in relation to the frequency of their power balancing activities.

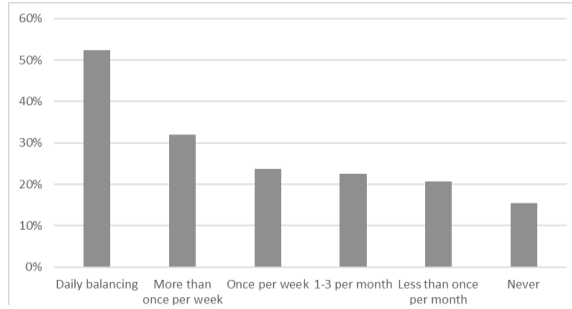

Figure 5. Percentages of prosumers with additional revenue in relation to the frequency of balancing activities (source: own analysis, N=498).

Prosumers with more systematic approach to power balancing perceive more financial and non-financial benefits. A visible exception is the benefit related to compliance with environmental regulations, where more prosumers performing power balancing once per week declare benefits than prosumers performing such activities on the daily basis. Figure 6 presents the percentages of prosumers with benefits in relation to the frequency of their power balancing activities.

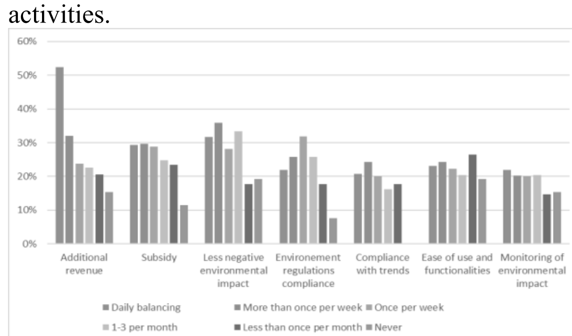

Figure 6. Percentages of prosumers with benefits in relation to the frequency of power balancing activities (source: own analysis, N=498).

Notably, almost 20% of prosumers, who prioritize sustainability, report receiving additional revenue from power balancing. In contrast, the proportion of prosumers with additional revenue in the group indicating that sustainability is not important is only about 6%. Additionally, the small group of prosumers who claimed that sustainability is not important do not report any additional revenue from power balancing. Figure 7 presents the percentages of prosumers with additional revenue from balancing in relation to the importance of sustainability for them.

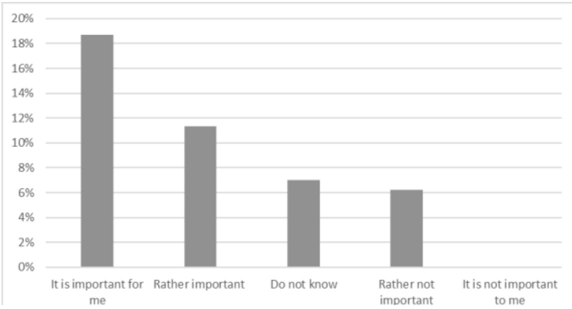

Figure 7. Percentages of prosumers with additional revenue in relation to the importance of sustainability (source: own analysis, N=1054).

A higher focus on sustainability relates to perception of broader benefits from power balancing. More prosumers for whom sustainability is important report additional revenues, subsidies, reduced environmental impact, compliance with trends, and ease-of-use. Only benefits related to environment regulations compliance and monitoring of environmental impact are declared more often by prosumers who do not prioritize sustainability. Figure 8 presents the percentages of prosumers with benefits from balancing in relation to the importance of sustainability for them.

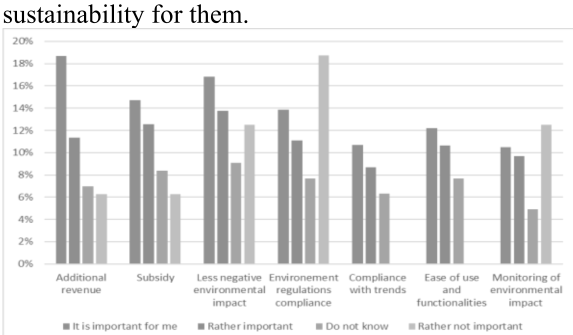

Figure 8. Percentages of prosumers with benefits in relation to the importance of sustainability (source: own analysis, N=1054).

Knowledge of power balancing mechanisms substantially influences the attainment of benefits from such activities. Approximately one-third of prosumers with knowledge of power balancing mechanisms declare additional revenue. In contrast, only about 15% of prosumers, who have heard about balancing but lack knowledge of the mechanism, report achieving additional revenue. Among prosumers who had not known power balancing previously, only 3% declare achieving additional revenue from power balancing. This scenario typically occurs when subsidies, or payments from external providers are offered for using household PV installation for power balancing in combination with other services. Figure 9 presents the percentages of prosumers with additional revenue from balancing in relation to their knowledge about power balancing.

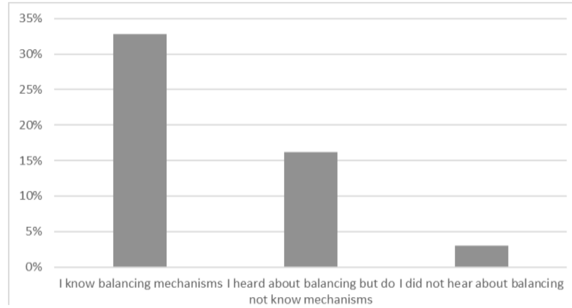

Figure 9. Percentages of prosumers with additional revenue in relation to knowledge (source: own analysis, N=1054).

Knowledge of power balancing mechanisms also significantly influences the perception of the attainment of other benefits from power balancing. As Figure 10 indicates, more prosumers who understand balancing mechanisms declare additional benefits. In the group of prosumers, who have heard about power balancing but do not know how it works, the proportion of those with benefits is higher than among those who have not heard about power balancing.

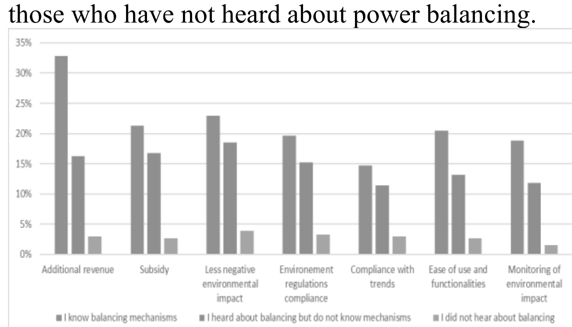

Figure 10. Percentages of prosumers with benefits in relation to power balancing knowledge (source: own analysis, N=1054).

The regression analysis has been performed to verify the impact of the stage of the technology adoption process on perceived benefits. In this analysis, two dependent variables have been defined.

a1 - Financial benefits, with a value between 1 and 5, indicating levels defined in the survey (1 - Below 25 USD; 2 - 25 USD - 125 USD; 3 - 126 USD - 250 USD; 4 - 251 USD - 1,250 USD and 5 - Above 1,250 USD).

a2 - Environmental benefits, with a value between 1 and 4, indicating levels defined in the survey (1 - Below 0.11 tons; 2 - 0.11 tons - 1 ton; 2.5 - I do not know; 3 - 1.01 tons - 5 tons; 4 - Above 5 tons)

Additionally, four independent variables have been selected, indicating the following stages of the technology adoption process presented in Figure 2.

b1 - Knowledge acquisition, with a value between 1 and 5, indicating the level of knowledge.

b2 - Technology acquisition, with a value between 1 and 5, indicating the approach for power balancing.

b3 - Technology implementation, with a value between 1 and 6, indicating the frequency of use of the balancing technology.

b4 - System development, with a value between 1 and 14, indicating the number of functionalities for the balancing software.

The regression analysis results of the formula for financial benefits are shown in Table 2 and Table 3.

Table 2. Results for the regression analysis of the formula for financial benefits.

	Esti-mate	St. Error	t Stat	p value
Intercept	0.363	0.074	4.931	9.517E-07
Knowledge acquisition	0.052	0.041	1.289	0.198
Technology acquisition	0.395	0.027	14.418	3.968E-43
Technology implementation	0.254	0.021	11.897	1.043E-30
System development	0.138	0.019	7.455	1.871E-13

Table 3. Parameters for the regression analysis of the formula for financial benefits.

Statistics	
Multiple R	0.875
R squared	0.765
Adjusted R squared	0.764
Residual standard error	0.758
Number of observations	1054

We derive the following regression equation:

Financial benefits households get from using technology supporting power balancing = 0.363 + 0.052 × Knowledge acquisition + 0.395 × Technology acquisition + 0.254 × Technology implementation + 0.138 × System development

The regression analysis confirms that there is a positive impact of each stage of the adoption process on the size of perceived financial benefits. The most impactful on the size of financial benefits is the decision about using the technology and then its implementation. The regression model fits well, with a standard error of 0.758, R-squared value of 0.765 and adjusted R-squared value of 0.764, indicating that the selection of variables and the decision model is reliable. The t values are acceptable for selected independent variables. There is no multicollinearity among selected independent variables. The derived equations are significant, with high F-values and low p-values, as indicated in Table 2 and Table 3.

The regression analysis results of the formula for environmental benefits in CO_2 emissions reduction are shown in Table 4 and Table 5.

Table 4. Results for the regression analysis of the formula for environmental benefits.

	Esti-mate	St. Error	t Stat	p value
Intercept	0.430	0.056	7.733	2.446E-14
Knowledge acquisition	0.069	0.031	2.253	0.024
Technology acquisition	0.355	0.027	17.156	2.425E-58
Technology implementation	0.208	0.016	12.862	2.918E-35
System development	0.098	0.014	7.020	3.977E-12

Table 5. Parameters for the regression analysis of the formula for environmental benefits.

Statistics	
Multiple R	0.896
R squared	0.803
Adjusted R squared	0.803
Residual standard error	0.573
Number of observations	1054

We derive the following regression equation:

Environmental benefits households get from using technology supporting power balancing = 0.430 + 0.069 × Knowledge acquisition + 0.355 × Technology acquisition + 0.208 × Technology implementation + 0.098 × System development

The regression analysis confirms that there is a positive impact of each stage of the adoption process on the size of perceived environmental benefits. The most impactful on the size of environmental benefits is the decision about using the technology and then its implementation. The regression model fits well, with a standard error of 0.573, R-squared value of 0.803 and adjusted R-squared value of 0.803, indicating that the selection of variables and the decision model is reliable. The t values are acceptable for selected independent variables. There is no multicollinearity among selected independent variables. The derived equations are significant, with high F-values and low p-values, as indicated in Table 4 and Table 5.

6. Discussion

The survey responses and their statistical analysis emphasize several key points:

- The characteristics of prosumer segments, particularly their orientation toward sustainability and their knowledge of power balancing mechanisms, influence the technology adoption process. These attributes enhance perceived ease-of-use and the benefits associated with power balancing technologies.

- Prosumers with greater knowledge of power balancing mechanisms exhibit more advanced stages as defined in the five-stage adoption model. They tend to use a broader range of technological functionalities and indicate higher levels of perceived benefits.
- Knowledge of power balancing mechanisms positively affects perceived technology attributes, which in turn enhances benefit perception at various stages of the adoption process, and facilitates technology adoption.
- Prosumers with a strong sustainability orientation are more likely to progress further in the adoption of power balancing technologies. They make fuller use of system functionalities and report more benefits.
- Sustainability orientation influences perceptions of key technology attributes, including usefulness and ease-of-use. This influence is mediated through lower prosumers' expectations regarding technological ease-of-use, and the level of benefits, thereby promoting adoption.
- Prosumers at more advanced stages of power balancing technology adoption perceive more financial and environmental benefits from such activities.
- The prosumer's approach to technology implementation, particularly usage intensity and engagement with multiple system functionalities, plays a critical role in shaping the perception of benefits from power balancing and emerges as a key determinant of progression in the adoption process.

These findings highlight the multidimensional nature of the technology adoption process among prosumers. The acceptance of the power balancing technology, and its adoption, depend on personal values and knowledge, not only on objective features of the technology. The indicated characteristics of prosumers impact the perception of expected usefulness and ease-of-use at all stages.

The study implies a shift in energy systems from passive consumers to active and informed prosumers. Those who understand power balancing mechanisms are more likely to adopt, optimize, and advocate for advanced technology. Like digital literacy in technology adoption, energy literacy, especially understanding how technologies support energy systems, accelerates both adoption and the realization of benefits. Knowledge will support also observability of benefits, especially in relation to the impact of power balancing on the reduction of negative environmental impact. Educational campaigns and communication of benefits could increase adoption.

Environmental concern is a powerful driver, prosumers who act out of sustainability motives are more committed and derive greater value. This aligns with broader behavioral economics literature showing that intrinsic motivation leads to more engagement. A prosumer's mindset, how they approach and integrate technology. largely determines their success and satisfaction with it. Even if power balancing technology is beneficial for market stakeholders, if it is perceived as not useful by prosumers, adoption lags.

7. Conclusions

Behavioral aspects like sustainability orientation and knowledge are important factors in the technology adoption in the energy domain. Understanding how prosumers think, what they value, and how they perceive technologies can significantly enhance the design of energy systems, policies, and outreach strategies. Acknowledging and nurturing this behavioral dimension is essential for a successful energy transition.

Power balancing creates value for several market stakeholders and enhances the advantages for prosumers using power balancing technology. These benefits can be measured by additional revenues from selling electricity, reduced electricity costs, and other advantages such as, lower negative environmental impacts, compliance with regulations, and ease of installation use. Additionally, the balanced flow of electricity in the distribution grid increases its flexibility supporting transformative role in the energy sector. Therefore, it is crucial to support the decision of prosumers to advance in technology adoption process by using technology for power balancing.

Nonetheless, there are multiple barriers to the acceptance of power balancing technology, and its further adoption. Prosumers need more education about power balancing mechanisms, and potential benefits for themselves and other market stakeholders at all stages of the adoption process. Schlindwein et al. (2023) argue that policymakers who aim at fostering energy transition should consider the behavioral dimensions of all types of energy users.

The achieved research results can directly support the definition of decision models for adoption of power balancing technology. Such decision models could be further extended to use in the adoption process of other technologies. Decision models could guide technology companies in determining where they should invest in research, and direct regulators in shaping legislation supporting power balancing.

Supporting research and development programs of technology companies is essential in ensuring the development of proper functionalities tailored to prosumers' needs. Companies developing technologies should invest in proper functionalities that create value for them (Kossecki, 2022).

In further research, this study could be extended in several key directions. Comparative studies of prosumers in several countries could reveal how regional, cultural, and regulatory differences shape power balancing technology adoption. Additionally, future research may explore how environmental incentives interact with economic and technological drivers, helping to clarify the influence of each factor. Another important area of research involves investigating the relationship between perceived and actual benefits, depending on characteristics of prosumers. Some benefits, including financial and environmental ones, are difficult to observe. Thus, the perceived benefits depend on the quality of defined assumptions like the level of pollutions reduction for avoided consumption of electricity. It is also valuable to examine how perceptions of usefulness and ease-of-use evolve as prosumers deepen their knowledge and change sustainability orientation. Such studies would contribute to a deeper understanding of prosumer engagement and help in the adoption of technology.

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