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Smart Choices: The Influence of Energy Literacy on Energy Technology Adoption#

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ABSTRACT

As societies transition to renewable energy sources and combat climate change, understanding the factors that drive the adoption of new technologies becomes increasingly important. This paper focuses on how energy literacy—an individual's understanding of energy concepts and technologies—affects the adoption of Electric Vehicles (EVs), Photovoltaic (PV) systems, and Home Energy Monitoring (HEM), using household-level survey data. The logistic regression analysis reveals that an increase in energy literacy significantly boosts the probability of adopting these technologies. Specifically, a one-point rise in energy literacy increases the likelihood of adopting any of the three technologies by at least 20.2%. Notably, energy literacy has a heterogeneous impact on individual technologies, significantly enhancing EV adoption by 38.9%, while showing no statistically significant effect on PV adoption. Our findings highlight the importance of targeted energy education in promoting specific technologies, suggesting that tailored informational campaigns could be more effective in driving the adoption of EVs and HEM.

Keywords: Energy literacy, Energy technologies, Electric vehicles, Photovoltaic panels, Home Energy Monitoring

NOMENCLATURE

Abbreviations

EV	Electric Vehicles
HEM	Home Energy Monitoring
RPV	Rooftop Photovoltaic

1. INTRODUCTION

Electric Vehicles (EV), Rooftop Photovoltaic (RPV), and Home Energy Monitoring (HEM) are pivotal technologies that support the ongoing energy transition to combat climate change [1]. Despite the great benefits of these technologies and the active role of policymakers to encourage adoption, the penetration of these technologies is still below the necessary to reach the Paris Agreement targets [2, 3]. To understand the low adoption rates, much of the literature has focused on the role of socio-demographic factors (e.g., education, income, and household size) [4, 5, 6, 7]. However, the role of energy literacy has received limited attention, despite several studies indicating its potential to promote energy-saving behaviors and investments in energy-efficient technologies [8, 9, 10].

This paper studies the effects of energy literacy on the probability of adopting three energy technologies: EVs, RPV, and HEM. Using household-level survey data from Luxembourg, the analysis relies on logistic regression models to first identify the effects of energy literacy on all three energy technologies. Subsequently, the analysis focuses on each individual technology.

In a closely related paper, [11] find that high energy knowledge can decrease the likelihood of co-adopting RPV and EVs in Georgia, U.S. The authors rely on multinomial logistic models to analyze the effects of energy knowledge on the adoption of EVs, RPVs, and efficient heating, ventilation, and air conditioning. Expanding upon this study, this paper's contribution is threefold: first, we compare the effects of energy literacy on the adoption of each different technology; second, our study takes place in Luxembourg, an European country where 95% of households has a smart meter; third, we adopt a more comprehensive and practical measurement of energy literacy.

Our results show that energy literate households are more likely to adopt new energy technologies. In fact, one point increase in the energy literacy score leads to a 20.2% increase in the probability to adopt at least one of the three technologies. Furthermore, the results suggest that the effect of energy literacy varies depending on the technology. Smarty+[1] and EV adoption is significantly affected by energy literacy; however, energy literacy has no significant effect on RPV adoption.

Improving energy literacy can be a valid strategy towards meeting climate goals by encouraging people to purchase EVs and to better understand their energy consumption. As a result, policy-makers can make use of education to increase the diffusion of these new energy

[1]Smarty+ is a dongle that connects to the smart meter providing detailed energy consumption information. More details in Subsection 2.3.

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technologies. Since not all of them are equally affected by energy literacy, the educational programs should focus on the ones related to EV and HEM to maximise their impact.

We elaborate on the literature related to energy technology adoption and energy literacy in Section 2. In Section 3, we describe the data collection process and data analysis methodology. In Section 4, we describe and discuss our results. Finally, we add our conclusions and future research avenues in Section 5.

2. BACKGROUND AND RELATED WORK

2.1 Adoption of new energy technologies

This sub-section provides an overview of the determinants of the adoption of new energy technologies. Specifically, we focus on EVs, RPVs, and HEM.

In the case of EVs, demographic factors such as age, education, and profession significantly influence adoption: well-educated, professional, middle-aged individuals have a higher likelihood of adopting them [12, 13, 14]. It is not clear whether strong environmental values are an important determinant of adoption [12]. [11, 15] found a positive association between the two, while [16, 17] could not confirm it. Contextual factors such as infrastructure and policies such as incentive schemes also play an important role. A robust and widespread charging network is fundamental [12], including both public and domestic charging opportunities [18]. Additionally, financial incentives can alleviate the high upfront cost of purchasing an EV and may positively affect adoption [19].

Similarly to EV, purchasing RPV presents high upfront costs, which can discourage adoption [20]. However, studies on the role of income reveal mixed findings [20, 21]. Higher income generally promotes adoption due to greater financial capacity [22, 23]. On the other hand, [24] suggest that lower-income individuals are more motivated to adopt RPV to reduce energy bills. The impact of age is also unclear: generally, younger individuals are more likely to adopt solar RPV due to greater awareness and potential long-term benefits, despite limited funds [25, 26]. Conversely, other studies find that older household heads might adopt solar RPV later in life due to increased affordability from retirement income [27, 28]. Also in this case, education [23, 29] and environmental values [30, 31] can positively affect adoption. Additionally, since RPV panels are a highly visible product, social influence plays an important role. Living in an area with a high adoption rate and receiving recommendations from friends and neighbours can increase the likelihood of adoption [5, 21].

The literature on HEM adoption is not as extensive as for the other technologies. This can be attributed to the variety of different products on the market, which may complicate generalising findings. Nevertheless, this topic is highly relevant because HEM has shown significant potential for reducing residential electricity consumption [32, 33]. Studies indicate that consumers using such technologies can reduce their electricity usage by an average of 7% [32]. Furthermore, the adoption of HEM technologies is expected to increase due to the widespread use of smartphone applications that integrate machine learning and AI to learn household energy consumption patterns, providing personalized feedback, and aid users in making informed energy decisions [34]. The specific HEM application analysed in this paper is described Subsection 2.3.

While extensive research has been carried out on the determinants of EV and RPV adoption, we cannot say the same for HEM. If we focus on the first two technologies, we notice that findings on demographic variables are inconclusive most of the times with the exception of education. Higher levels of education are linked to higher EV and RPV adoption rates, this is further confirmed by [4] and [5], who assessed the determinants of adoption of multiple technologies at the same time. Based on this evidence, this paper aims to identify whether a specific type of education, namely energy literacy, can affect the adoption of new energy technologies.

2.2 Energy literacy

"Energy literacy is an understanding of the nature and role of energy in the world and daily lives accompanied by the ability to apply this understanding to answer questions and solve problems"[35]. Energy-literate individuals understand how energy is typically utilized and generated. They recognize the implications of energy-related decisions and the importance of conserving energy. Ultimately, they apply this understanding by taking appropriate actions and committing to the efficient use of resources [36].

Energy literacy can foster rational decision-making related to energy consumption. [8] and [10] found that individuals with high levels of energy and investment literacy are more likely to select appliances that minimize their total cost, which includes both the purchase price and the present value of future energy costs. This approach positively impacts the likelihood of identifying the most cost-efficient technology options. Likewise, [9] finds that energy and financial literacy combined influence the adoption of energy-efficient lighting. Furthermore, [37] show that the willingness to invest in energy retrofits is positively correlated with energy literacy. Finally, energy literacy can also influence the acceptance of dynamic tariffs and third-party direct load control. It may help mitigate scepticism and risk aversion towards relatively new products [38, 39].

Contrarily to the above positive effects of energy literacy, [11] find that high energy knowledge can decrease the likelihood of co-adopting RPV and EVs. The authors argue this may be due to understanding uncertainties, which are arguably lower for heat pumps where they find a positive effect of energy literacy. Nevertheless, they claim that the results are counter intuitive and call for more research on the topic.

To our knowledge, [11] is the only article that explicitly investigates the relation between energy literacy and the adoption of EV and RPV. Expanding upon this study, this paper contribution is threefold: first, in addition to assessing the effects of energy literacy on the adoption of a group of technologies (i.e., EVs, RPVs, or HEM), we also analyze the effect on each technology individually. This approach accounts for the heterogeneity of each technology. Second, our study takes place in Luxembourg, an European country where 95% of households have a smart meter. The high smart meter adoption rate suggests that households may be more familiar with energy technologies and can further profit from it. Third, we use a more comprehensive and practical measurement of energy literacy which has been introduced in [40]. This updated measurement encompasses awareness regarding energy consumption of different appliances and activities, energy-related financial knowledge, and familiarity with current energy related issues, providing a more complete overview of the household's energy knowledge.

2.3 The context in Luxembourg

Luxembourg is relatively more advanced on the adoption of new technologies compared to other European countries. The government is pursuing an intense digitalization and modernisation strategy in several sectors, including energy [41]. Additionally, the main Luxembourgish Distribution System Operator, Creos, has recently launched the Smarty+ campaign. Smarty+ is a dongle that households can plug in their smart meter to receive further insights on their consumption through a smartphone application. So far, around 1500 dongles has been adopted, concentrated in relatively wealthier and more educated households that present higher levels of energy literacy [42]. In this paper, we further investigate that correlation through more in-depth econometric analysis.

3. METHOD

3.1 Survey Development and Data Collection

The data analyzed in this paper is part of the FlexBeAn project, which investigates the energy flexibility potential in Luxembourg. The online survey was distributed through three channels: an email outreach to Creos customers, social media platforms, and the personal networks of Creos employees.

From the 3,959 surveys distributed to Creos customers and the social media and Creos employees campaigns, a total of 544 responses were collected. From the 544 responses, 472 came from the email campaign, 57 from social media, and 14 from the internal Creos campaign. After the data cleaning phase, 461 were considered valid for analysis (395 from the email campaign, 52 from the social media campaign, and 14 from the internal campaign).

As Table 1 shows, most survey participants are homeowners, with a significant number owning electric vehicles (49%) and solar panels (43%), and 18% owning a Smarty+ device. Approximately 88% of the households reported a net monthly income above €5,000.

Table 1 Summary Statistics

Variable	Mean	Obs.
Income >5,000	87.5%	368
Age	48	461
Has Bachelor's Degree or Higher	65.2%	461
Home Owner	92.8%	461
Electric Vehicle	49.2%	461
Solar Panels	43.1%	461
Smarty+ Adoption	41.8%	232
Energy Literacy	7.7	461

Notes: Energy literacy represents the average score from 1 to 13. Income is presented in net household income per month.

To assess energy literacy, we developed an index based on a thorough review of existing literature and included questions from established energy literacy surveys [9, 36, 43]. This index measures respondents' general knowledge of energy consumption, generation, and transmission. Scores range from 1 to 13, with higher scores indicating greater energy literacy.

To reduce response bias, participants were assured that their answers and test scores would remain anonymous [44]. It is important to note that the sample primarily includes customers who requested power connection upgrades from Creos. This implies there is a large share of energy technology early adopters. For instance, the national average of EV users in Luxembourg is 3.13% [45], while in our almost half of the households own an EV. Hence, caution should be exercised when generalizing these findings to the broader population.

3.2 Data Analysis

Based on the survey answers, we construct a binary indicator of technology adoption. The indicator equals one if the household has adopted RPV, EVs, or Smarty+, and zero otherwise. As RPV and EVs are considered complementary products [46], we also investigate the effect of energy literacy focused on these two technologies (i.e., binary indicator equals to one if the household has adopted either of these two technologies). Finally, we analyze the effect of energy literacy on each technology independently.

In addition to energy literacy, other factors can influence the adoption of energy technologies, such as demographic and household characteristics [4, 5, 6, 7]. To account for these factors, we include measures of income, age, gender, and education as demographic controls. Likewise, we include household composition (i.e., number of family members), house type (e.g., detached or apartment), and the use of other appliances (e.g., dishwasher and deep-freezer).

The estimation of the effects of energy literacy on the variables of interest relies on logistic regression analysis. Logistic regression analysis is well suited due to the binary nature of the variables of interest [47]. Therefore, the results can be interpreted as the change in the probability to adopt energy technologies due to a change in the energy literacy score. The logistic function for individual i in household j for technology t is defined by:

$$f_i^t j(z_{ij}^t) = \frac{1}{1 + e^{-z_{ij}^t}}, \quad (1)$$

with $0 \leq f_{ij}^t(z_{ij}^t) \leq 1$, and z_{ij}^t is a linear function of explanatory variables defined as:

$$z_{ij}^t = \alpha + \beta EL_{ij} + X_{ij} + Y_{ij}^t + \epsilon_{ij}^t, \quad (2)$$

where EL_{ij} is the energy literacy score of individual i in household j, X_{ij} and Y_{ij}^t are vectors of demographic and household controls, and ϵ_{ij}^t is the error term.

Based on the logistic function depicted in equation 1 we can derive the logit probability model to be estimated in the next section:

$$ln(\frac{P_{ij}^t}{1 - P_{ij}^t}) = \alpha + \beta EL_{ij} + X_{ij} + Y_{ij}^t + \epsilon_{ij}^t, \quad (3)$$

where P_{ij}^t represents the probability that individual i in household j adopts technology t. We further estimate the odds ratio to be able to interpret the results as the change in the probability to adopt energy technologies due to a change in the energy literacy score.

4. RESULTS AND DISCUSSION

This section summarizes the results of the logistic regression analysis. Table 2 shows the effects of energy literacy on the adoption of all three energy technologies and considering EVs and solar panels only. In the first specification, no control variables are included. Subsequently, we report the effects of energy literacy when adding the demographic controls, home characteristics, and household income. The net monthly household income is separately incorporated due to the loss of observations (i.e., not all respondents reported their income).

Focusing on the last specification of Table 2 (which includes all controls), we observe that a one point increase in energy literacy increases the probability to adopt one of the three technologies by at least 20.2%. This means that a household with maximum energy literacy score is 9.1 times more likely to adopt an energy technology compared to a household with minimum energy literacy score. This effect is higher when considering only EVs and solar panels. In this case, a one point increment in the energy literacy score increases the probability to own at least one of these technologies by 23.7% (or 12.8 times more likely comparing households with maximum and minimum score).

Our results are well in line with previous studies [8, 9, 10] that identify energy literacy as a catalyst for adopting new energy technologies. Moreover, building on the analysis of [11], the positive relationship found between energy literacy and technology adoption may be an indication of a more stable and reliable energy technology market in Luxembourg. This stability, enhanced by supporting policies (e.g., subsidies and tax rebates) provides consumers the confidence and financial incentives to adopt new technologies. Further, more energy literate consumers may be more aware of the potential benefits of these technologies, increasing their willingness to adopt them. All in all, these results suggest that energy education should be further investigated as a mechanism to boost technology adoption.

Table 2 : Effects on Adoption of Groups of Technologies

Model	All Tech.	EV + RPV	Obs.
Energy Literacy	23.6***	24.9***	459
+ Demographics	27.4***	29.5***	459
+ Home Characteristics	22.6***	24.7***	447
+ Dem + home	26.0***	28.5***	447
+ Dem + home + income	20.2***	23.7***	358

Notes: Values represent percentages and number of observations. *** represents significance level at 99% confidence.

Table 3 presents the positive effects of energy literacy on the adoption of each energy technology separately. For Smarty+ and EVs, the results are highly significant, while for solar panels the estimates are less precise. The low precision of the solar panels estimates might be explained by the influence of other factors such as peer effects and profitability [5, 20, 21], which are not considered in this study. Nevertheless, the magnitude of the energy literacy effect is relatively robust across specifications and technologies. Focusing on the last specification we observe a 10.4% increase in the probability to own Smarty+, and a 5% and a 38.9% increase in the probabilities to own solar panels and EVs, respectively.

This means that a household with a maximum energy literacy score is 3.3 and 51.6 times more likely to adopt Smarty+ and EVs compared to a household with a minimum score.

The different magnitudes and significance levels reported in Table 3 suggest that the effect of energy literacy on energy technology adoption is not easily generalized to all energy technologies due to their intrinsic differences. In our analysis, energy literacy seems to play an insignificant role in solar panel adoption, while the opposite is true for EV adoption. In addition, even the significant effects found for Smarty+ and EVs are quite different. Based on this difference, targeted energy education may be more effective to incentivise the adoption of highly specific technologies. For instance, to boost adoption of EVs and home energy monitoring technologies, policy-makers may improve energy education highlighting their potential personal and social benefits. Conversely, other mechanisms to encourage adoption may be more effective for technologies like RPVs.[2]

Table 3 : Effects on Adoption by Technology

Model	Smarty+	Solar	EV	Obs.
Energy Literacy	15.3***	4.8	44.4***	459
+ Demographics	15.7**	7.5*	46.5***	459
+ Home Characteristics	11.2*	3.4	41.8***	447
+ Dem + home	11.1*	5.6	43.2***	447
+ Dem + home + income	10.4	5.0	38.9***	358

Notes: Values represent percentages and number of observations. *** represents significance level at 99% confidence, while ** and * 95% and 90% respectively.

5. CONCLUSION AND FUTURE RESEARCH

Understanding what motivates people to adopt new energy technologies plays a vital role in supporting the ongoing energy transition and combating climate change. To advance in this understanding, this paper uses household-level survey data to examine the relationship between energy literacy and the adoption of EVs, RPV, and HEM in Luxembourg.

The results of the logistic models indicate a positive impact of energy literacy on technology adoption. A one point increase in the energy literacy score increases the probability of adoption by 20.2%. Furthermore, the results suggest heterogeneous effects depending on the technology analyzed. For instance, energy literacy significantly increases the probability of EV adoption by 38.9%, while it is statistically not significant for RPV. The different effects on individual technologies suggest that energy education targeted to these technologies (i.e., EVs and HEM) may enhance its effectiveness as a catalyst for technology adoption.

While the results are robust across specifications, the analysis presents several limitations. First, we assume that energy literacy affects technology adoption, but the inverse effect may also be true: technology adoption may affect energy literacy. Future research addressing this double causality is warranted. Second, the survey was administered to a sub-sample of the population representative to a specific segment (e.g., more educated and wealthy early adopters of energy technologies). A more extensive and representative sample is required to extrapolate to country-level results. Third, while we employ a robust definition of energy literacy, there are other ways to determine the household energy knowledge. Future research may test the robustness of our results based on different energy literacy definitions.

[2]For instance, [5, 21] argue that peer effects are highly relevant for RPV adoption in European countries and Mexico, respectively.

APPENDIX

Energy literacy questionnaire

1. In general, from a household perspective, which period marks the time where the electricity consumption is the highest? (peak consumption hours)

1. from 23:00 to 03:00, 2. from 14:00 to 17:00, 3. From 17:00 to 20:00, 4. I do not know, 5. I don't understand the question

2. What is the impact if you largely increase your consumption during peak consumption hours (e.g., by charging your electric vehicle)? You can select maximum of 3 choices

1. There is no impact, 2. Increased stress on the electricity grid, 3. Provoking the necessity for electricity expansion works in the electricity grid, 4. A shorter battery lifetime as batteries of smartphones, laptops or electric vehicles heat up more if charged during peak consumption hours, 5. I don't know, 6. I don't understand the question

3. What are the benefits of shifting your consumption from peak hours to a time of day where the consumption is lower? You can select maximum of 3 choices

1. Charging an electric vehicle, smartphone or laptop is faster, 2. To have a lower electricity bill due to lower grid expansion costs, 3. There is no benefit for the household consumer, 4. Generally lower CO2 emissions because fewer gas power plants need to be deployed, 5. I don't know, 6. I don't understand the question

4. Assuming there are a lot of Photovoltaic - PV (solar) installations in your neighbourhood. Are there any benefits of shifting your consumption from peak hours to a sunny time of day?

1. Yes, it is important to consume the electricity when and where it is produced to prevent grid congestions, 2.

Yes, otherwise the electricity is lost as soon as it enters the grid, 3. No, we can easily store all excess energy in summer and use it in winter, 4. No, the electricity can easily be transported over long distances, so it can be consumed elsewhere, 5. No, there is not a lot of electricity production during sunny weather, 6. I don't know, 7. I don't understand the question

5. Do you know how to delay the start of your dishwasher?

1. Yes, 2. Not, 3. It does not have this function, 4. I don't have a dishwasher, 5. I don't understand the question

6. Do you know how to delay the start of your Electric Vehicle charging?

1. Yes, 2. No, 3. It does not have this function, 4. I don't have an Electric Vehicle, 5. I don't understand the question

7. What challenges does the switch to 100% renewable electricity generation entail? You can select maximum of 4 choices

1. Renewable energy generation is highly volatile (changes constantly), 2. Renewable energy generation is decentralized (a lot of small production plants instead of few large ones), 3. Difficult to store renewable energy, 4. Difficult to align generation and consumption, 5. I don't know, 6. I don't understand the question

8. On average, when a device works for one hour, rank them from the highest (up) consumption to the lowest (below) consumption

1. Dishwasher / laundry, 2. Tumble dryer, 3. light bulbs, each at 10 W, 4. Electric Vehicle, 5. TV and music player, 6. Heat pump

9. How much electricity does it take to fully charge an electric vehicle?

1. 0.3 - 1 kWh, 2. 1 - 30 kWh, 3. 30 - 100 kWh, 4. 100 - 300 kWh, 5. 300 - 1000 kWh, 6. I don't know 7. I don't understand the question

10. Do you know the amount of your monthly electricity bill? NB: Please indicate your best guess without checking your bill!

1. No, 2. Yes, I pay approximatively: Enter your bill amount €/month

11. Which heating system would you prefer for your home, considering both have a 15-year lifespan?

1. Model A with a retail price of €3750 and a monthly bill of €100, 2. Model B with a retail price of €5000 and a lower monthly bill of €80, 3. I have no preference, both models are equally adequate, 4. I don't know, 5. I don't understand the question

12. Which of these household appliances uses the most electric energy during one day?

1. fridge/freezer, 2. stove/oven, 3. I don't know, 4. I don't understand the question

13. Which of these household appliances generates the highest peak power demand?

1. fridge/freezer, 2. stove/oven, 3. I don't know, 4. I don't understand the question

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