The impact of regulated charges and solar potential on cost savings from energy sharing: a statistical analysis

Vladimir Z. Gjorgievski*, Daniel Josifovski, Katerina Hadzi-Velkova Saneva,
Bodan Velkovski, Blagoja Markovski, Snezana Cundeva
University Ss. Cyril and Methodius in Skopje,
Faculty of Electrical Engineering and Information Technologies, North Macedonia
e–mail: vladimir.gjorgievski@feit.ukim.edu.mk, daniel.yosifovski@outlook.com,
saneva@feit.ukim.edu.mk, bodan@feit.ukim.edu.mk, bmarkovski@feit.ukim.edu.mk,
scundeva@feit.ukim.edu.mk

Natasa Markovska
International Centre for Sustainable Development of Energy, Water and Environment
Systems - Macedonian Section (SDEWES-Skopje), North Macedonia,
Research Centre for Energy and Sustainable Development,
Macedonian Academy of Sciences and Arts, Skopje, North Macedonia
e-mail: natasa@manu.edu.mk

ABSTRACT

Energy communities can take different measures to improve the economic savings derived from energy sharing, such as optimally aggregating members with diverse generation and load profiles or by shifting electricity demand throughout the day. Nevertheless, the magnitude of the cost savings from energy sharing are always bound by exogenous factors, such as the meteorological conditions that govern the generation from renewable energy sources and the fiscal policies and electricity tariffs, which determine the incentives to share energy with other community members. Given the lack of focus in the scientific literature on the exogenous factor, in this paper we study their impact on the cost savings in renewable energy communities composed of households with photovoltaic generators. To isolate only the impact of the exogenous factors, the cost savings of a single energy community are analysed in 37 different European countries, each with different solar potential and composition of retail electricity price. This study utilizes regression analysis to examine the impact of regulated costs, share of regulated cost in retail price, and specific solar generation as independent variables on cost savings in two distinct arrangements. By discerning their relationships, valuable insights into their influence on savings are gained. The results reveal the relationship between the regulated charges, the share of regulated charges in retail electricity prices and solar potential, on one hand, and the relative cost savings from energy sharing, on the other.

KEYWORDS

Energy community, renewable energy, energy policy, linear regression.

INTRODUCTION

In the quest for sustainable and decentralized energy solutions, the concept of energy communities has emerged as a key model for uniting citizens, small businesses, and municipalities in collective actions to implement localized energy projects [1]. This innovative framework redefines energy ownership and paves the way for energy sharing, thus contributing

*Corresponding author

to enhanced economic benefits, reduced energy costs, and greater resilience against rising energy prices.

By facilitating local energy exchanges among community members, energy communities create an environment suited for energy sharing, a practice that enables community members to virtually self-consume the energy that is generated by nearby generators, as if they were located behind their electricity meter [2]. Energy sharing improves the economic savings of community members, alleviates energy cost burdens and protects consumers against vulnerability to fluctuating energy prices. This interplay of factors underscores the transformative potential of energy sharing within the context of renewable energy communities.

Amidst a backdrop of shifting global energy paradigms, the Member States of the European Union (EU) have responded by enacting legislation that is based on the principles of energy sharing and collective self-consumption. A cornerstone in this trajectory is the Directive EU 2018/2001 on renewable energy [3], which outlines a definition of renewable energy communities and defines the mechanisms for localized energy exchanges. The essence of this regulatory support lies in different incentives that are manifested through regulated charges (network charges, levies, taxes etc.). A comprehensive overview of the different implementations of energy sharing regulation, both in the EU and worldwide, can be found in the works of Minuto et al. [4], Ines et al. [5], Frieden et al. [6,7] and Moura et al. [8]. Notably, the Italian energy community model showcases support for energy sharing through a combination of self-consumption premiums, ensuring guaranteed payments for energy shared within a defined time interval, and reductions in distribution network tariffs. The extensive analysis of this framework within the scientific literature, evident by the works of Stentati et al. [9], Cutore et al. [10], Viti et al. [11] and other, as reviewed in [12], underscores the pivotal role of optimizing energy management in communities and the impact of regulatory frameworks.

The Italian model is characteristic of a broader body of scientific works that cover optimal management, technology sizing, and financial dynamics within energy communities. Among these works, Viti et al. [11] analyze the impacts of regulated charge components on energy sharing savings, casting light on the impact of incentives and exemption of regulated charges. Their analysis finds that the cost savings of the community reduce from 12% to 9% when all network charges are payed for the shared energy, noting that the savings fall to 5% when both network charges and other regulated charges are payed. Stentati et al. [9] introduce an optimization model tailored to the Italian context, focusing on the optimal operation of a community energy system. Furthermore, Cutore et al. [10] study energy community optimization through a comparable approach, additionally probing the dimensions of sizing and design of the community system. Similarly, Moncencchi et al. [13] consider the optimal sizing of an energy community, coupling it with a game-theoretic method for sharing the cost savings in the community. From their analysis, they conclude that the average cost savings are around 31 EUR per community member.

In Germany, the Tenant Electricity Model is deployed to empower building owners to invest in local renewable generators and share energy with their tenants [14]. The confluence of financial incentives, optimal technology sizing, and generation-storage interplay within this model, which are explored in [14], underscores the multifaceted nature of energy community dynamics. Similarly, the Austrian framework is representative of energy sharing incentives manifested as reduced network charges for the local energy sharing and clear guidance on key of repartition (energy sharing keys). Fina et al. [15] assess energy sharing in Austrain communities, contrasting static and dynamic repartition keys in a hypothetical community setting. The findings of [15] indicate that the cost savings from energy sharing for prosumers range around 5%, while the savings of pure consumers range around 5-10%. The pursuit of optimal energy community sizing in Austrian settings is further advanced by Cosic et al. [16] encapsulating their insights within a mixed-integer linear optimization model which is used to explore different electricity tariff designs.

The interplay between network charges, as one type of regulated charge, and energy sharing dynamics are central in the analyses of Schreck et al. [17] and Maldet et al. [18]. These studies highlight the role of network charge design in shaping peak power exchanges, with Schreck et al. [17] advocating for network charges based on connection capacity for optimal outcomes. Maldet et al. [18] delve into the value proposition of peer-to-peer energy trading, navigating the regulatory landscapes of Austria, Norway, and Ireland. The synthesis of these findings underscores the balance between the economic benefits to community members and the fiscal impact for distribution system operators, echoing the importance of enabling distribution system operators (DSOs) to fully recover their infrastructure investment costs.

Most of these works consider solar photovoltaic (PV) generators as a cornerstone technology for the decarbonization of local energy systems and energy communities. A previous work of the authors, exploring the impact of regulated charges on the cost savings from energy sharing in European countries [19], revealed an interesting relationship between the cost savings, on one hand and, i) costs related to regulated charges and ii) specific energy generation from photovoltaic generators, on the other. Both parameters represent exogenous factors, which are outside the control of the community and which are determined by the local and national conditions in which a renewable energy community finds itself. Hence, the meteorological conditions, fiscal policies, and electricity tariffs shape the economic viability of energy sharing.

Acknowledging the lack of focus on these factors within the scientific literature, this paper aims to explore their impact on cost savings in renewable energy communities. An investigation across 37 European countries, characterized by diverse solar potentials and retail electricity price compositions, is undertaken to assess the relationships between regulated costs, their share in retail prices, specific solar generation potential, and realized cost savings. In this paper, the relationships between these exogenous factors and the cost savings of energy sharing are studied through a regression analysis.

METHODS

Two types of energy communities are analyzed – one composed of prosumers with rooftop PV generators (first arrangement), and another for a community composed of consumers that share the generation of a nearby collective PV generator (second arrangement). The same two arrangements were previously studied in [19].

Calculating the cost savings from energy sharing

This subsection presents the approach used for the calculation of the cost savings which community members yield from sharing energy in the community. The energy balances of the community, in each of the two energy sharing arrangements are shown in Figure 1.

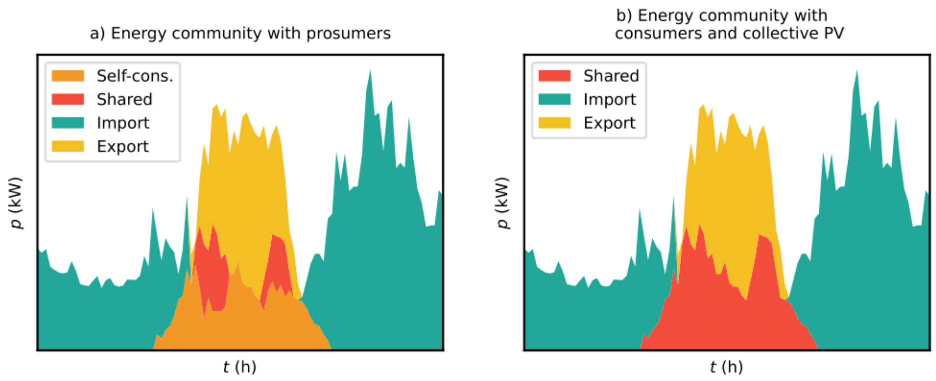

Figure 1. Energy balance of the two energy sharing arrangements

Cost savings in first energy sharing arrangement

In the first arrangement, each member of the energy community has some load $p_{l,i}(t)$ and generation $p_{g,i}(t)$ profile. A portion of the electricity generation is self-consumed on-site $p_{sc,i}(t)$, while the rest is exported in the grid $p_{ex,i}(t)$. The shared energy in the community N is equal to the overlap between the instantaneous exports and imports of community members, where $p_{im,i}(t)$ denotes the electricity import of member i.

$$p_{sh,N}(t) = \min\left(\sum_{i\in N} p_{ex,i}(t), \sum_{i\in N} p_{im,i}(t)\right) \quad (1)$$

When there is no energy sharing, the electricity cost of a prosumer is equal to:

$$C_{P,i} = E_{im,i}(c_{im} + c_n + c_t + c_v) - E_{ex,i}c_{ex} \quad (2)$$

where $E_{im,i}$ and $E_{ex,i}$ are the imported and exported electricity for a given billing period, c_{im} is the energy and supply price payed for the imported electricity, c_n is the network charge, c_t denotes other taxes, c_v is the value added tax and c_{ex} is price of the exported electricity, usually $c_{ex} \le c_{im}$. The previous equation can be rewritten as:

$$C_{P,i} = E_{l,i}(c_{im} + c_n + c_t + c_v) - E_{sc,i}(c_{im} + c_n + c_t + c_v) - E_{ex,i}c_{ex} \quad (3)$$

When community members share energy, member i virtually self-consumes a portion of the total shared energy $E_{sh,i}$ for which he/she pays a price c_{sh} to the other members of the community, such that $c_{ex} \le c_{sh} \le c_{im}$. In order to maximize the savings of community members, assuming $c_{sh} = c_{im}$, the electricity bill of member i in is equal to [20]:

$$C'_{EC,i} = E_{l,i}(c_{im} + c_n + c_t + c_v) - E_{sc,i}(c_{im} + c_n + c_t + c_v) - E_{ex,i}c_{ex} - E_{sh,i}(c_{im} - c_{sh} + \textstyle\sum_{\varepsilon\in \mathrm{E}} c_\varepsilon) \quad (4)$$

Cost savings in second energy sharing arrangement

The same rationale transfers to the second arrangement, comprised of consumers sharing energy from a collective PV. The electricity bill of member *i* is reduced only due to the energy sharing, i.e. virtually self-consumption of the collective PV generation:

$$C''_{EC,i} = E_{l,i}(c_{im} + c_n + c_t + c_v) - E_{sh,i}(c_{im} - c_{sh} + \sum_{\varepsilon \in \mathrm{E}} c_{\varepsilon}) - E_{ex,i}c_{ex} \quad (5)$$

In this arrangement, $E_{sh,i}$ denotes the energy that is shared between the collective PV and the community member *i*. At the community level, the energy shared in this manner is, in absolute terms, equal to the locally self-consumed and shared energy from the previous arrangement, given that the capacity of the PV systems in the two arrangements are equal, thus making the two arrangements comparable. As per (5), the benefit from energy sharing in the second arrangement depends on the shared energy, the price difference $c_{im} - c_{sh}$ and the exemption of regulated charges.

Statistical Analysis

This section introduces the methods and techniques employed in conducting statistical analyses within the two distinct arrangements. The selected variables for the statistical analysis are given in the table below.

Table 1. Analysis variables

Variables	**Abbreviation**
Regulated Costs (EUR/kWh)	RC
Share of Regulated Cost in Retail Price (p.u)	SRC
Specific Solar Generation (kWh/kWp)	SSG
Cost Savings for arrangement 1 (%)	CS1
Cost Savings for arrangement 2 (%)	CS2

The statistical analysis is conducted in the R programming language [21].

Before delving into of the regression analyses, an Exploratory Data Analysis (EDA) is conducted. The underlying goal is to explore patterns, potential outliers, and decipher potential relationships nestled within the variables. Our EDA include descriptive statistics that provide an overview of the dataset's central tendency and variability; data visualization; outlier detection and correlation analysis [21].

The core of the study unfolds with linear regression analyses [21, 22] that reveal potential trends and the magnitudes of influence of exogenous factors (specifically, RC, SRC, and SSG) on the cost savings associated for the two proposed arrangements (CS1 and CS2). By utilizing the aforementioned independent variables RC, SRC, SSG as predictors and the dependent variable CS1 (CS2), these analyses quantify linear relationships within the data. To evaluate the distinct impact of each independent variable, the dataset is normalized, i.e. the mean of each variable is set to 0, and the standard deviation to 1. This procedure eliminates inherent scale discrepancies, facilitating an informed evaluation of their respective contributions to the dependent variable. Moreover, the normalization ensures that the intercept of the linear models is set to zero, thereby simplifying both the models and the analysis.

Finally, LASSO regression is explored alongside conventional linear regression. LASSO facilitates variable selection by inducing sparsity in the coefficients. This enhances model interpretability by identifying influential independent variables while diminishing less relevant ones. The outcome is a refined model highlighting variables pivotal in explaining variations in the cost savings across the scenarios. The advantage in using LASSO regression is that it is preventing overfitting the data which results in unreliable predictions of high variance. This way, even though the performance of the model may be worse than the linear regression model, LASSO is more robust to future predictions [22].

CASE STUDY

The impact of regulated charges on the benefits of energy sharing is assessed through the examination of energy sharing in 37 countries, encompassing EU Member States, members of the European Free Trade Association, and EU candidate countries. Energy communities, with no additional incentives or subsidies, apart from the assumed exemption of regulated charges, are assessed in this analysis. Each country possesses its distinct solar potential and electricity prices. A comparison of the benefits of energy sharing between countries is facilitated by the adoption of a single energy community with a fixed electricity consumption and installed photovoltaic (PV) capacity. The savings derived from energy sharing over a one-year span are analyzed for this community, which is composed of 30 households equipped with a PV generation capacity of 100 kWp. This capacity is distributed proportionally to the annual consumption in the first arrangement (community of prosumers) and is aggregated as a single generator in the second arrangement (community of consumers with collective PV).

It is postulated that the community benefits from an exemption from all regulated charges for the locally shared (exchanged) energy among its members. The electricity consumption profiles of community members are sourced from [23]. The original dataset, stemming from a field study in Germany, provides electricity measurements for 200 households with a 15-minute temporal resolution. From this dataset, electricity consumption data for a one-year period from 30 households are selected, each with an annual electricity consumption ranging from 2500-5000 kWh, reflective of the average electricity consumption of European households (3700 MWh) [24].

While the community's electricity consumption and installed PV capacity remain constant, the operating conditions of the community differ depending on the country of location. The initial condition influencing energy sharing within the community pertains to PV electricity generation. To compute the energy generated by the PV in a given country, PVGIS [25] is employed. Hourly generation profiles for the PV are computed for the capital city of each country, utilizing SARAH-2 solar irradiation data for the latest available year, assuming optimized azimuth and slope. The dataset adopts a time step of 1 hour, resulting in the alignment and averaging of electricity consumption data to 1-hour values.

The third set of input data used in the analysis represents electricity price data. The electricity prices utilized in the analysis are sourced from the Eurostat database, which encompasses average electricity price components for household consumers for the year 2021, the latest available data at the time of analysis [26]. Generally, the retail electricity price paid by households comprises components for energy and supply, network charges, value added tax (VAT), and other taxes denoted as "other regulated charges" (the sum of renewable tax, capacity tax, environmental tax, nuclear taxes, and other regulated charges), as defined in [26]. Deductions and tax returns on electricity bills are excluded from the analysis due to their variability and potential transitory nature. For energy sharing, constant values are assumed for "energy" and "supply," both set at half of "other regulated charges," reflecting the trend of lower wholesale prices during daytime and promoting self-consumption.

RESULTS AND DISCUSSION

After calculating the electricity costs of the energy community for the two energy sharing arrangements, as discussed in the previous section, a comprehensive regression analysis was executed to evaluate the factors that impact the cost savings from energy sharing. The analysis followed a systematic methodology encompassing several key steps.

Descriptive statistics and Data visualization

Firstly, descriptive statistics were computed for each variable, encompassing measures such as mean, standard deviation, median, minimum, maximum, kurtosis, and skewness. These statistics are summarized in Table 2.

Table 2. Descriptive statistics

Statistics	RC	SRC	SSG	CS1	CS2
Mean	0.101	0.569	1247.713	3.606	35.919
Standard deviation	0.056	0.136	215.860	0.443	5.407
Median	0.095	0.591	1211.984	3.648	35.353
Minimum	0.016	0.166	855.851	2.683	27.772
Maximum	0.243	0.765	1751.527	4.824	48.367
Kurtosis	3.257	3.785	2.365	3.155	2.277
Skewness	0.697	-1.049	0.379	0.137	0.342

It can be observed that SSG has very high standard deviation, which is expected considering the different meteorological conditions in the analyzed countries. The kurtosis for each variable has a value around 3 which indicates that there aren't any extreme outliers and they all have distribution similar to a normal distribution. SRC is right-skewed, whereas the other variables are left-skewed.

Utilizing QQ plots, the distribution patterns of variables are visualized in Figure 2. Notable patterns observed are that none of the variables follow a normal distribution because there are data points near the ends of the diagonal that don't lie near it. However, these discrepancies aren’t extreme, so it can be assumed that the data are normally distributed.

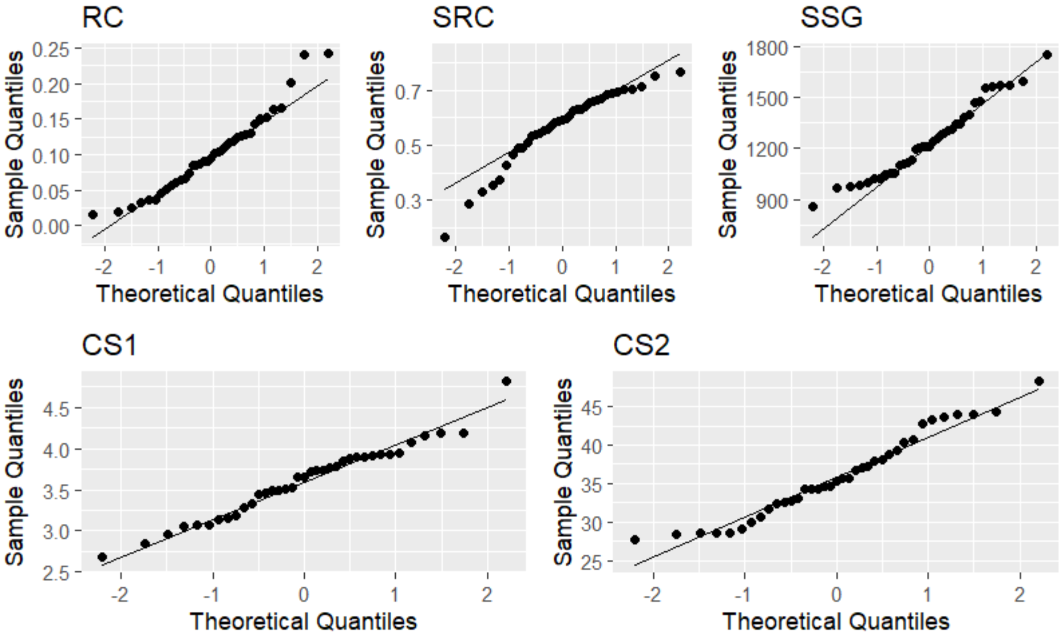

Figure 2. QQ plots of the variables

Correlation analysis

The Pearson correlation coefficients were calculated to quantify the strength and direction of relationships among variables. The results from the correlation analysis are given in Table 3.

Table 3. Pearson correlation coefficients

Variable	RC	SRC	SSG
CS1	0.38	0.44	0.41
CS2	-0.26	-0.51	0.99

The values of the Pearson correlation coefficient indicate there is a weak linear relationship between each of the independent variables and the target variable CS1. This suggests that fitting a linear model is not optimal for representing the relationships in the first arrangement. On the other hand, there is a very weak negative linear relationship between CS2 and RC; a weak negative linear relationship between CS2 and SRC, and a very strong linear relationship between CS2 and SSG. This suggests that SSG could be a better predictor of CS2, meaning that more solar generation could lead to higher cost savings. It should be noted that this statement is valid up to the point that the community is able to absorb the additional solar generation.

Linear regression models

The data is normalized to explore the relative influence of each variable in model building and after that, for each arrangement the following models are built:

- simple linear regressions with each independent variable separately,
- multiple linear regression, and
- multiple linear regression with interaction terms.

Model selection was conducted by the Akaike Information Criterion (AIC). Thus, the multiple linear regression is the model with lowest AIC value of 66.07 for the first arrangement, and the multiple linear regression for the second arrangement with AIC value of -32.92. Thus, the fitted regression model for the first arrangement with regression coefficients rounded to four decimal places is:

$$CS_1 = 0.0682 \cdot RC + 0.8065 \cdot SRC + 0.8339 \cdot SSG \tag{6}$$

while for the second arrangement it is:

$$CS_2 = 0.0966 \cdot RC - 0.0964 \cdot SRC + 0.9681 \cdot SSG \tag{7}$$

By inspection, it is evident that for the first arrangement the SRC and SSG variables have a higher influence on the output CS_1, whereas for the second arrangement only the SSG has a high influence on the output CS_2.

Residual analysis of the models

The residual analysis of the model (6) for the first arrangement is given in Figure 3. It shows that the median of the residuals is centered around zero, so the distribution of the residuals is somewhat symmetrical, i.e., it is slightly right-skewed. There isn't an extreme variability because the residuals are clustered around zero, except for four outliers. This tells that the model is not predicting as well at the higher ranges of the cost savings as it does for the low ranges. The QQ plot shows there are outliers on both ends of the plot, but those on the upper end look more severe than those on the bottom. Overall the residuals look to have a normal distribution.

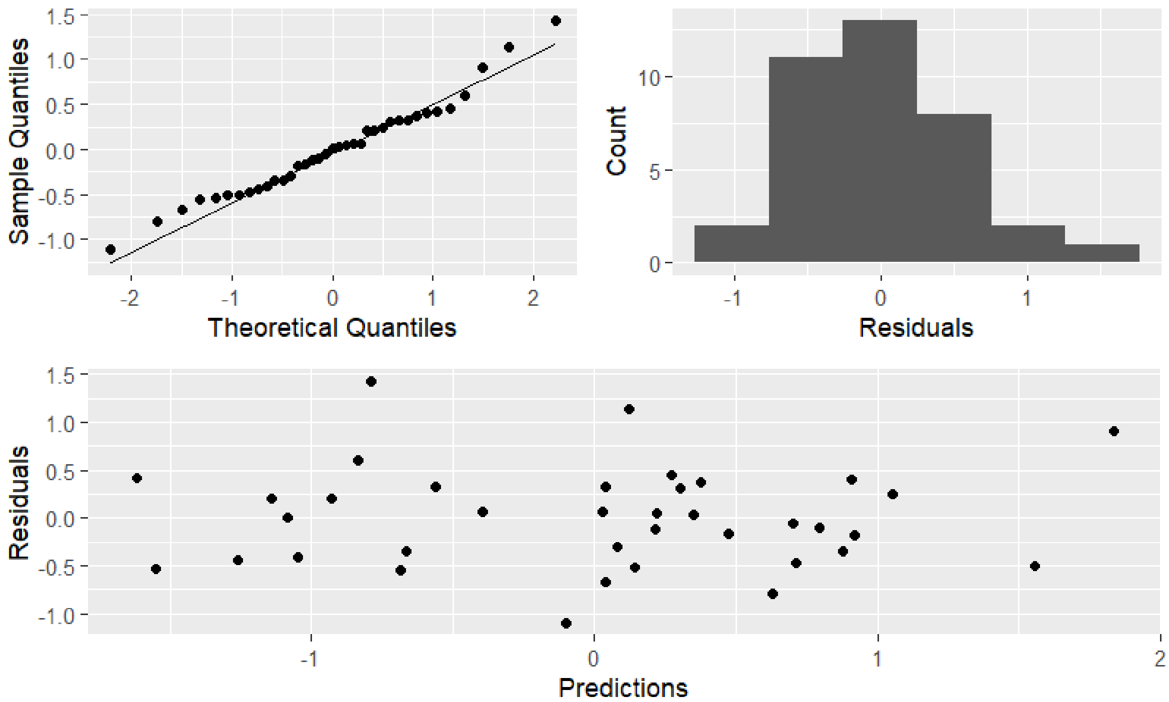

Figure 3. Residual analysis of linear model (6) of first arrangement

As can be concluded from Figure 4, the median of the residuals of the linear model (7) for the second arrangement is also centered around zero and the distribution is slightly right-skewed. It is evident that this model is not predicting well at higher ranges of the cost savings as it does for the low ranges. The QQ plot shows there are outliers on the upper end that are very severe.

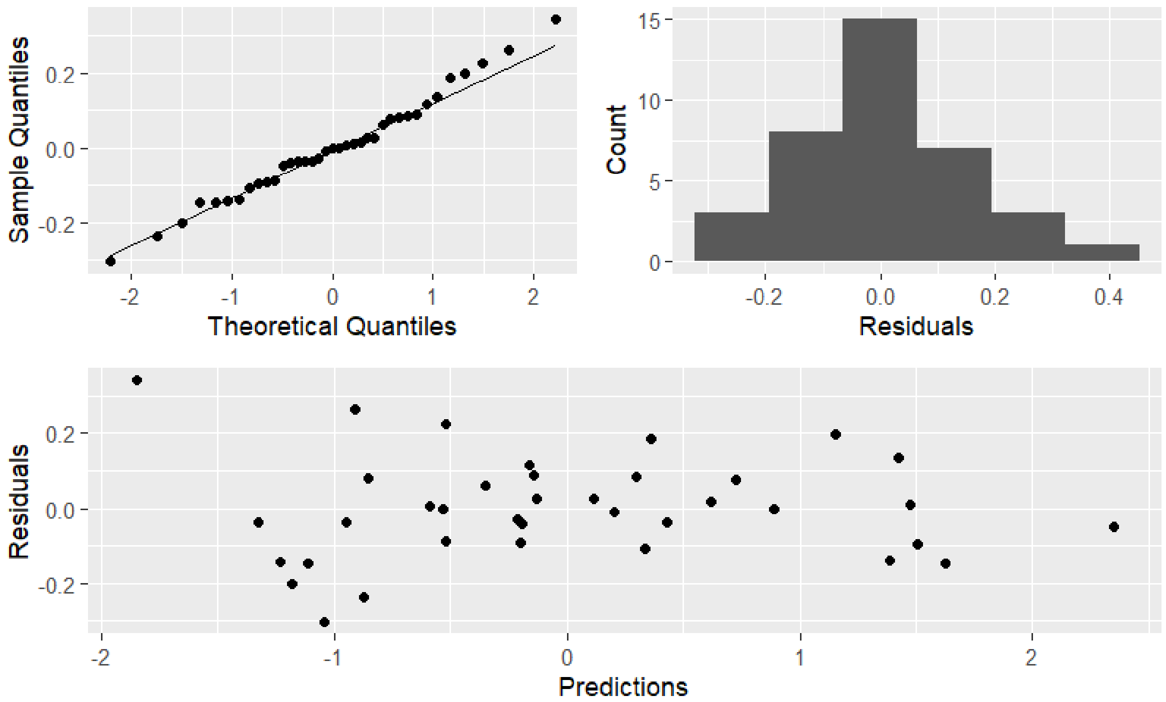

Figure 4. Residual analysis of linear model (7) of second arrangement

Confidence intervals and statistical tests on individual regression coefficients

The 95% confidence intervals on individual regression coefficients in the obtained linear models are given in the Tables 4 and 5, respectively.

Table 4. Results for the coefficients in the regression model (6)

Variable	95% confidence interval	t-statistic	p-value
RC	(-0.189, 0.325)	0.54	0.593
SRC	(0.523, 1.090)	5.789	0.000
SSG	(0.620, 1.047)	7.939	0.000

Table 5. Results for the coefficients in the regression model (7)

Variable	Confidence interval	t-statistic	p-value
RC	(0.029, 0.164)	2.913	0.006
SRC	(-0.171, -0.022)	-2.636	0.013
SSG	(0.912, 1.024)	35.113	0.000

Next, the t-statistic of the coefficients indicates whether certain coefficient can be removed from the regression model suggesting that the effect of the corresponding predictor variable is likely to be not significant within the population. The larger the t-statistic is, the more certain it is that the coefficient is not zero. The degrees of freedom of the t-statistic are always associated with the degrees of freedom of the residual standard error. A test of significance of regression is conducted using level of significance 0.05. The null hypothesis that the coefficient is zero is rejected if $|t_0| > t_{0.005} = 2.032$, where t_0 is the observed value of the used t-statistic. The Tables 4 and 5 provide the t-values and p-values of each of the coefficients of models (6) and (7). Based on the results, for the linear model (6) of the first arrangement, the null hypothesis is accepted for the coefficient of RC, while for SRC and SSG the null hypothesis is rejected. For the linear model (7) of the second arrangement, the null hypotheses are rejected for all regression coefficients. The same findings are confirmed from the p-value of each of the coefficients.

According to the previous discussion, after omitting the variable that is not contributing to the target CS_1, new reduced models are fitted. Thus, the final model for the arrangement 1 is:

$$CS_1 = 0.8065 \cdot SRC + 0.8339 \cdot SSG \tag{8}$$

and for arrangement 2 the original models (7) is kept. The performance and the adequacy of the models are judged by the coefficients of multiple determination. For the first model, the coefficient of multiple determination is $R^2 = 0.718$ and adjusted $R^2_{adj} = 0.702$, and for the second model $R^2 = 0.981$ and adjusted $R^2_{adj} = 0.979$. Thus, for the first model 71.8% of the variability of the CS_1 is explained by the predictors, and 70.2% of the variability is explained while accounting for the number of predictors. For the second model 98.1% of the variability of the CS_2 is explained by the predictors, and 97.9% of the variability is explained while accounting for the number of predictors.

Lasso regression models

Additionally, LASSO regression was conducted on both arrangements to discern influential variables and achieve model selections. This procedure entailed subjecting the data to variable selection through l_1 regularization, i.e. constraining the minimization function to l_1-ball with radius $\lambda \in \mathbb{R}^+$ as a hyperparameter, effectively constraining coefficients towards zero. By tuning the regularization parameter, varying levels of variable inclusion is achieved, yielding insights into the most impactful predictors unique to each scenario. The values for $\lambda \in \left[10^{-3}, 10^5\right]$. After 10-fold cross-validation, for the first model the value of λ is 0.008, and the LASSO model is:

$$CS_1^{lasso} = 0.065 \cdot RC + 0.793 \cdot SRC + 0.818 \cdot SSG \tag{9}$$

(with $R^2 = 0.720$ and adjusted $R^2_{adj} = 0.695$). We confirm that the RC has a weak influence on the target CS1 and could be omitted from the model.

For the second model the value of λ is 0.001 after 10-fold cross-validation, and the LASSO model is:

$$CS_1^{lasso} = 0.093 \cdot RC - 0.093 \cdot SRC + 0.986 \cdot SSG \qquad (10)$$

(with $R^2 = 0.981$ and adjusted $R_{adj}^2 = 0.979$). It is evident that the variable with the highest influence is SSG.

CONCLUSION

Our investigation embraced a comprehensive methodology to assess the impact of two exogenous factors (regulated charges and solar irradiation) on the cost savings from energy sharing. Two distinct arrangements of energy sharing were studied, for a single community, in 37 European countries. Using the results from this analysis, an exhaustive exploration of descriptive statistics, core data attributes are explored—mean, median, kurtosis, and standard deviation. QQ plots provided distribution insights, unveiling key patterns such that the distribution of the data approximately normally distributed.

The subsequent correlation analysis uncovered interrelationships among variables, vital for understanding arrangement nuances. The variables in the first arrangement have a weaker linear relationship with the target, and such linear model might not fit the data optimally. On the contrary, for the second arrangement there is a strong linear relationship with the variable SSG. Model selection is conducted by the Akaike Information Criterion (AIC), consistently led to the optimal models for each arrangement. For both arrangements it is the multiple linear regression model.

The analysis demonstrates that within the first arrangement, there is a statistically significant correlation between the cost savings which the community obtains from energy sharing and (i) the Share of Regulated Charges in the retail electricity price and the (ii) Specific Solar Generation. In contrast, for the second arrangement, a statistically significant correlation was found only between the Specific Solar Generation and the cost savings. In addition to the comprehensive analysis, the application of LASSO regression further elucidated the influential variables, significantly enhancing the understanding of the arrangements. LASSO's variable selection methodology extracted predictors that are distinctive to each individual scenario.

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