Transaction costs as a factor of adherence to institutionalized energy communities – case study of energy clusters in Poland

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Abstract

Adherence to institutions conducive to investment in renewable sources of energy, such as institutionalized energy communities, is an important issue as the RED III directive is being implemented in the EU. In this article, the topic is empirically investigated in the case of Poland, where massive investment in small RES installations can be observed, as well as clear spatial agglomeration of those installations, whilst the owners of those installations clearly refrain from adhering to one prominent institution, i.e. energy clusters. A model is proposed to explain that phenomenon of institutional repulsion, where transaction costs interplay with expected operational surpluses, in the presence of recoverable equity, and an opportunity cost. Empirical material investigated with the model is that on small RES installations in Poland, and their two respective markets: auctions and virtual prosumption. The model serves to explore the hypothesis that rapid deployment of renewable energy sources (RES) creates a temporarily low tolerance for transaction costs on the part of investors, seems to be strongly substantiated by the here-presented research. Still, investors in small RES installations seem to see all the period up to 2037 to as that of rapid investment in an essentially non-Markovitz portfolio, where expectations are shaped within the portfolio of investment in small RES rather than referring it to an exogenous opportunity cost.

Keywords: renewable energy; institutions; transaction costs;

1 Introduction

There is a range of institutions, understood as regulatory solutions to complex social issues, which are supposed to be instrumental in the process of energy transition. Some of these institutions, e.g. capacity markets, become amazingly popular and the economic scale of their application tends to exceed expectations. Other institutions, such as the regulation of energy communities, fall short of expectations: the scale of their practical application is below the anticipated one. The purpose of this study is to develop, explore and tentatively test, on Polish data relative to energy clusters and energy cooperatives, a model which explains the relative popularity of institutions pertinent to energy transition.

The general working hypothesis of this study is that rapid deployment of renewable energy sources (RES) creates a temporarily low tolerance for transaction costs on the part of investors.

The two most general pieces of theory behind the here-presented research are: investment, and transaction costs. Ledoit & Wolf (2025) present a good starting point for discussing the issue, through the concept of Markovitz portfolio: a) investors always have capital allocated in a collection of assets (even if those assets are just bank deposits), and investment consists in reallocating capital, i.e. in passing from portfolio A to portfolio B and b) any investment is subject to the constraint of a desired end-state. By contrast, Framm & Memmel (2010) state that investors learn as they invest and, in real life, the expected end-state is derived from the micro-universum of investments experienced by investors recently enough to be relevant. That dual perspective can serve to make two types of assumptions about the rationale of investment in renewable sources of energy (RES). The logic of Markovitz portfolio suggests that investment could be considered always in the context of other possible inestments, and a general logic of the corresponding policies could state that in order to have abundant deployment of new RES installations, the institutional environment should make those investments systematically more profitable than others. A non-Markovitz approach, on the other hand, could postulate that with enough ethical commitment, investors in RES installations will rather navigate and optimize the realm of those investments, without systematically accounting for the best possible opportunity cost.

Two models, presented consecutively by Müller& Schmitz (2016), and Schmitz (2023), approach the economic value of investments under different contractual regimes. Both bring robust conclusions in two respects. Firstly, the amount of investment optimal *ex ante* for all the contracting parties is below the amount subsequently invested and can be estimated as $argmax_i(R + i - \frac{1}{2}*i^2)$, where R is the expected operational surplus and i is the investment properly spoken. In other words, optimal investment hardly exceeds the operational return expected. Any capital investment above that threshold is to be considered as necessary to put in place and maintain business structures rather than as optimal. Secondly, in the presence of positive transaction costs, ownership of assets (thus effective equity) is a key factor for the aggregate payoffs from investment.

The economic rationale of energy communities should assume that such communities are not particularly apt to optimize energy efficiency per se. Such aptitude emerges only when energy communities have plans of intervention for optimizing energy use (Sifakis et al. 2020). Energy communities need a certain degree of internal coordination, with corresponding contracts and transaction costs, to pass from being local peer-to-peer markets for energy to actually optimizing energy use. Literature seems to confirm that shared PV energy (thus what is called ‘PROSUMPTION’ in this article) is generally more profitable for market participants than schemes based on the intervention of central regulators (thus the AUCTION market in this article) (Perger et al. 2021). Marques et al. categorize business models regarding the factors of transaction costs in shared PV schemes. Three factors are defined: a) mode of compensation for electricity and its practical enforceability b) individual decisions of users and suppliers to join the scheme and c) ownership of the actual installations (Marques et al. 2023)

Land management is a major issue for the deployment of small RES installations, and transaction costs afferent thereto are maybe the most significant transaction costs in that industry. Interestingly, the scope and detail of the corresponding regulations seem to be hard to optimize, especially in densely populated environments (Das & Roy 2023; Ferreras-Alonso et al. 2024). In that context, it could be adviseable to prolong or event supplant the present rapid deployment of solar PV installations in Europe with investment in biomass installations and with growth of biomass in semi-natural grasslands (Winberg et al. 2024).

Projects in energy transition might display institutional specificities and business models experimental enough to escape the logic of transaction costs theory. Contracts relative to energy transition are frequently institutional vehicles for experimentation rather that strictly spoken exploitation of known business models (e.g. Soeiro & Dias 2020; Dubey 2024). In Europe, transaction costs relative to investment in RES are significantly shaped by uncertainty as for the end-game-balance between nuclear power and renewables (Fälth et al. 2021).

There seems to be a correlation between the completeness of contracts and transaction costs generated by those contracts. The more flexible a contract should be, the more discretion it should leave to parties' decisions. The more complete a contract is, and the less it leaves to parties' discretion, the more transaction costs it generates (Saussier 2000; Kosnik 2014).

In energy clusters (or other institutionalized forms of energy communities), agency problems can arise. Entities appointed as cluster coordinators are agents, acting on behalf of the members associated in the cluster. Those members are principals for the agent, and, interestingly, current Polish regulations allow appointing one of the members as coordinator. That entity combines the roles of principal and agent. Contractual provisions in the cluster are likely to prevent excessively opportunistic behaviour on the part of the agent. The more likely such opportunistic behaviour is, the more transaction costs the cluster is likely to generate. Contractual provisions (or institutions) which are supposed to put limits on the agent's freedom of action can be grouped in 3 categories: vicarious liability, secondary liability and mandatory insurance (Mattiacci & Parisi 2003). Vicarious liability is a normative construct where the principal is liable for damages inflicted by the agent and should correspondingly curtail against such risks (Bisso & Choi 2008).

The empirically observable rapid investment in small RES installations can become overshot, which calls for the issue of sunk costs, or more specifically the phenomenon known as sunk-costs fallacy. There is evidence that in the presence of clearly visible risks, such as can be curtailed with contracts that generate transaction costs, investors are not really prone to sunk-costs fallacy and show reverse sunk cost bias (Zeelenberg & Van Dijk 1997; Negrini et al. 2022).

2 The empirical context

The empirical context of the here-presented research is pertinent to the deployment of small installations based on renewable sources of energy in Poland. Those installations will be further designated as 'small RES installations', and 'small' means nominal capacity below 1 MWe. Phenomenologically, energy communities are approached under two angles: as a strictly economic phenomenon of geographical agglomeration in small RES installations, on the one hand, and as institutional emergence of energy communities under various forms allowed by the law in force in Poland: energy clusters and energy cooperatives.

2.1 Institutional forms of energy communities in Poland

Polish regulations, as of January 2025, assume 6 possible legal forms for energy communities: i) Energy clusters ii) Energy cooperatives iii) Closed distribution systems iv) Collective prosumers v) Virtual prosumers vi) Popular energy communities. Forms (i) – (v) are regulated by the Renewable Energy Act[1], whilst the more general Energy Act[2] regulates (vi). All those regulations emerged in 2015 for the first time, entered into force in 2016 and have been subject to subsequent changes. Amendments which are the most pertinent to this article are those in the regulation of energy clusters, although other regulatory changes have their significance too. Without entering into detailed legal analysis, the Renewable Energy Act version 2015 introduced quite a general definition of energy clusters, without giving them much direct6 economic incentives. Energy clusters were subject to certification (by the Ministry of National Assets), yet the certification was not clearly conducive to any substantive legal consequences.

According to that first regulation, an **energy cluster** was a private agreement, pertinent to generation, balancing of demand for, distribution of, or trade in energy from renewable sources or from other sources or fuels, within a distribution network of nominal voltage below 110 kV. The agreement could include natural persons, moral persons, research entities, research institutes or entities of local government. An energy cluster was represented by a coordinator, which could be any member of the cluster with such power of proxy granted in the cluster agreement, as well as a cooperative, association or foundation specifically created to that purpose of representing and coordinating. The same Renewable Energy Act of 2015 defined an **energy cooperative.**

In 2023, Amendment from 2023, in force since 2024, introduced a range of financial incentives for energy clusters and energy cooperatives, whilst significantly narrowing down the scope of possible institutional forms for energy clusters, by:

a) forcing the participation of local governments in energy clusters
b) introducing a formal register of energy clusters held by the Energy Regulatory Office
c) treating as officially non-existent all those energy clusters which do not comply with the new regulations
a) imposing a de-minimis structure of cluster agreements by requiring clear contractual dispositions as regards: i) rights and obligations of its parties, further designated as members of the energy cluster[3] ii) the scope of cooperation in the cluster iii) appointment of a specific coordinator for the cluster, as well as rights and obligations of that coordinator, including their power of proxy iv) the territory of the cluster, specified as regards the connection points used by the members of the cluster, both for retrieval and for the input of energy v) duration of the agreement, and the modalities of its possible termination

2.2 Spatial distribution of small RES installations in Poland

Institutions regarding energy communities were being regulated in the presence of rapid changes in the deployment of small RES installations in Poland. Data sourced from the

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[1] original Polish version available at: https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20150000478/U/D20150478Lj.pdf

[2] https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20240000266/U/D20240266Lj.pdf

[3] The cluster agreement, therefore, cannot be purely foundational; it has to specify transactional exchange in the cluster

register of small RES installations held by the Energy Regulatory Office[4], as of December 31st, 2024, provides interesting insights in this respect[5].

Table 1 below shows the spatial distribution of capacity installed in small RES installations at the end of 2018, thus just after the first wave of registration of energy clusters in Poland, and at the end of 2024, after significant amendments to the regulation of energy clusters[6]. Those distributions are presented in the context of demographic geography. Already in 2018, significant disparities between voivodships were to notice, and they deepened in 2024. There is no visible connection between incremental change in the capacity installed and change in population.

Table 1

Voivodship	**Capacity installed in small RES, end 2018 [MW]**	**Population, end 2018**	**Capacity installed in small RES, end 2024 [MW]**	**Population, end 2024**	**Estimate number of retail connection points to the national grid**
Dolnośląskie	34,98	2 901 225	308,75	2 879 271	1 320 766
Kujawsko-Pomorskie	114,67	2 077 775	491,01	1 996 003	915 597
Lubelskie	22,87	2 117 619	280,37	2 011 047	922 498
Lubuskie	16,29	1 014 548	412,08	975 023	447 258
Mazowieckie	31,12	5 403 412	382,67	5 510 527	2 527 764
Małopolskie	19,22	3 400 577	96,84	3 429 632	1 573 225
Opolskie	12,64	986 506	148,61	936 725	429 690
Podkarpackie	0,55	2 129 015	57,48	2 071 676	950 310
Podlaskie	26,57	1 181 533	318,83	1 138 216	522 117
Pomorskie	22,75	2 333 523	205,82	2 359 573	1 082 372
Wamińsko-Mazurskie	44,05	1 428 983	378,63	1 357 910	622 894
Wielkopolskie	75,66	3 493 969	838,76	3 487 973	1 599 987
Zachodniopomorskie	23,31	1 701 030	413,40	1 631 784	748 524
Łódzkie	68,65	2 466 322	357,45	2 362 519	1 083 724
Śląskie	27,70	4 533 565	152,10	4 320 130	1 981 711
Świętokrzyskie	13,37	1 241 546	174,41	1 168 499	536 008

Source: Energy Regulatory Office of Poland

Figure 1 below shows the dynamics of capacity deployed in small RES over time, since 2004, split by voivodships. There is clearly a process of agglomeration going on, although it is not visible at the level of 1st moments (annual growth rates), shown in Figure 2. Singularly high growth rates happen sometimes, but they happen in places endowed with the least capacity

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[4] https://rejestry.ure.gov.pl/o/21

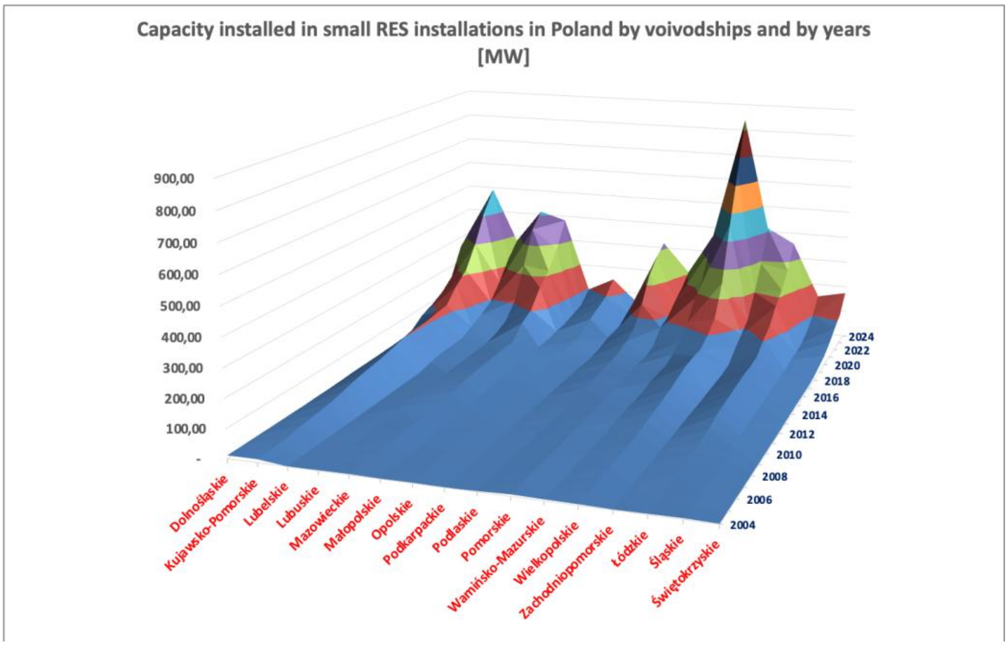
[5] The spatial grid for analysis is essentially the administrative structure of Poland , which is based on three levels of government: I level – Voivodships (similar to provinces), II level – Powiats (similar to counties or districts), III level – Gminas (similar to communes or municipalities). It should be noted that major cities have Powiat status. Currently there are 16 Voivodships, 314 Powiats (including 66 cities of Powiat status), and 2477 Gminas.

[6] This is geographical distribution of physical installations as such, not of their legal owners.

installed. Voivodships which lead the game in terms of sheer capacity show the steadiest growth rates, too.

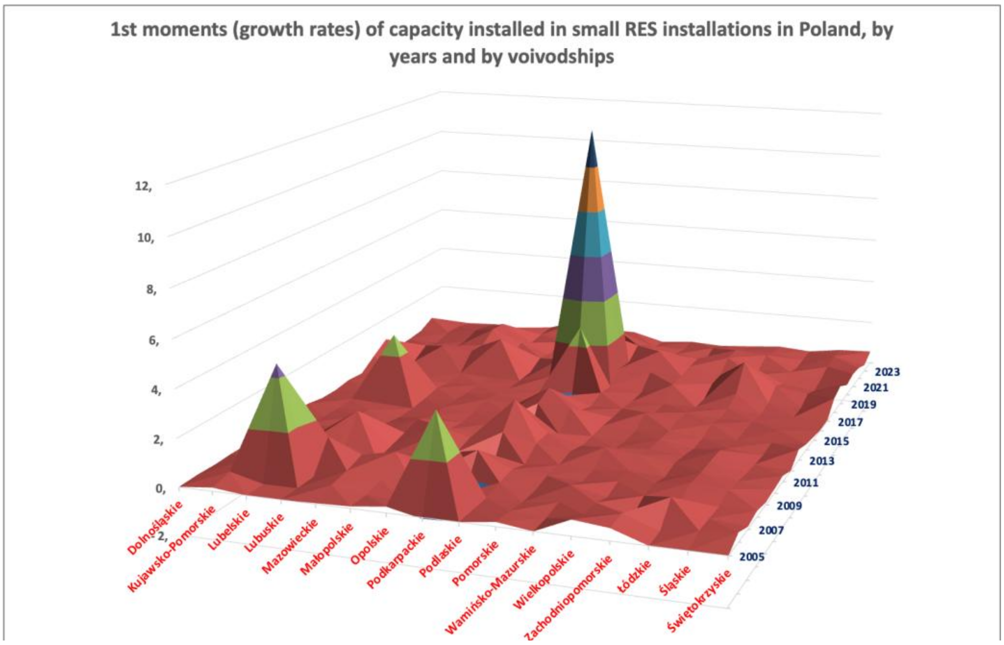
Small RES installations in Poland show a clear proclivity towards spatial clustering. At the first sight, there is no clear technological or economic driver of that clustering. It is worth exploring institutional drivers. The question studied more in depth is: **to what extent that objectively occurring process of clustering reflects at the institutional level of officially registered energy communities?**

Figure 1



Source: Energy Regulatory Office of Poland

Figure 2



Source: Energy Regulatory Office of Poland

2.3 Adherence to institutionalized energy communities in Poland

In 2018, under the regulations from 2016, the Ministry of National Assets certified 66 energy clusters. However, after the regulations of 2023, thus after giving clusters both more limitations and more incentives, the Energy Regulatory Office registered (since 01.01.2024) only 6 energy clusters (**Erreur ! Source du renvoi introuvable.**). At the same time, the National Centre for Support of Agriculture registered 60 energy cooperatives (**Erreur ! Source du renvoi introuvable.**).

Regulation of energy communities in Poland was introduced in parallel to the institution of auctions. Since 2016, the Energy Regulatory holds energy auctions, open for the operators of small RES installations. In those auctions, contracts for the supply of electricity are awarded, denominated in MWh per year. Since 2018 (with regulations in force since 2017), the national grid operator, PSE[7], holds capacity auctions for big suppliers (i.e. all those not categorized as small suppliers).

Spatial distribution of and total capacity installed in small RES installations in Poland, put in the institutional context, suggest a phenomenon of inverse adherence. The more energy communities are regulated, the less those regulations are adhered to by the owners of small RES installations. The latest regulations seem truly dysfunctional in that respect. The research presented further attempts to find an empirically replicable method of assessing the economic well-founded of such institutions.

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[7] https://www.pse.pl/web/pse-eng

3 Material and method

3.1 The model

The here-presented model starts from the basic observation that most of the assets in small RES installations in Poland is deployed outside the very institutional vehicles, such as energy clusters, which are supposed to boost that deployment. Present regulations look largely useless: their hypothetical addressees don't adhere to them.

The model aims at providing a theoretical explanation of that phenomenon, together with analytical tools for calibrating institutions afferent to energy transition. The institutional edge of the model directs attention towards by transaction costs, i.e. non-recoverable expenses resulting from: a) specificity and imperfect fungibility of assets b) commitment of those assets to binding contracts with delayed withdrawal.

In the Polish institutional context, the otherwise intriguing lack of adherence to the newly regulated energy clusters largely boils down to the time of commitment and to the non-recoverable (sunk) costs. The new (AD 2023) regulation of energy clusters imposes on private agents the signature of long-term, officially registered contracts with local governments or their affiliate companies. This is a serious loss of flexibility, thus of fungibility in the capital base, supposedly compensated by a set of economic incentives pertinent to the sales of electricity.

One of the most obvious theoretical generalisations from observable empirics is that economic

agents can choose between adhering to institutions and bypassing them. There is a limited set M of possible commitments relative to energy transition, and each such commitment is connected to the immobilisation for a time T_M of resources in a set of assets S_M, financed with a combination of equity and liabilities. The decision to stay in M for a given time T_M can be interpreted as **a real option**: economic agents immobilize capital to secure a stream of expected future **operational surplus** from the exploitation of energy assets, whilst allowing some of their capital to be consumed in transaction costs $TC(S_M;T_M)$ and economic loss of value $A(S_M;T_M)$, such as depreciation, amortization and impairment.

The perspective of real options invites risk as a factor, and the prospect theory (see e.g. Barberis 2013) as theoretical reference. Therefore, evaluation of the option to stay in the commitment M with assets S_M for a time T_M is relative to a neutral reference point (adaptation level). Outcomes which exceed the reference point are gains, whilst those below are losses. The reference point can be the status quo ('what if I do nothing and stay the way I am?'), or it can be an expected outcome.

In the most basic form of the model, the value C_M of the option to stay in the commitment M with assets S_M for a time T_M is the economic profit derived from M, in the presence of an opportunity cost from placing the value of assets S_M in a risk-free investment (e.g. Treasury bonds).

With a risk-free interest rate r, C_M can be valued as in equation (1):

$$C_M = EQ(S_M) + V(S_M;T_M) - TC(S_M;T_M) - A(S_M;T_M) - S_M(1+r)^{T_M} \quad (1)$$

… where $EQ(S_M)$ is the economic agent's equity in the assets S_M, recoverable from the commitment M in case of withdrawal, $A(S_M;T_M)$ is the total depreciation, amortization and impairment in assets S_M over the time window T_M, and $TC(S_M; T_M)$ are total transaction costs connected to the commitment of assets S_M for the duration T_M. The expression $V(S_M;T_M)$ stands for the operational surplus from exploiting productive energy assets whilst $S_M(1+r)^{T_M}$ is the stream of payments from a risk-free investment of the capital S_M.

Transaction costs $TC(S_M; T_M)$ are the theoretical generalisation of all contract-specific, sunk expenditures which emerge both at the signature of the contract, and at withdrawal therefrom (e.g. penalties for early termination, administrative fees etc.). Total depreciation, amortization and impairment in assets S_M over the time window T_M, namely $A(S_M;T_M)$, encompasses any loss of value due to the specificity of assets, even incidental. When the developer of a solar farm disposes of it, for example, proceeds from disposition might be lower than the book value of the farm due to unfavourable bargaining.

With the above assumptions, the value of economically justified and acceptable transaction costs is defined as (2):

$$TC(S_M;T_M) = EQ(S_M) + V(S_M;T_M) - A(S_M;T_M) - S_M(1+r)^{T_M} \quad (2)$$

A hypothetical state of nature can be further defined, as in (3), where $TC(S_M; T_M) = 0$.

$$EQ(S_M) + V(S_M;T_M) = A(S_M;T_M) + S_M(1+r)^{T_M} \quad (3)$$

Consequently, the given set of commitments M can effectively support non-null transaction costs, i.e. economic agents can accommodate costs of building long-term institutional structures (e.g. committing their assets in energy clusters), when condition (4) is met:

$$EQ(S_M) + V(S_M;T_M) > A(S_M;T_M) - S_M(1+r)^{T_M} \quad (4)$$

Economic agents invest in productive energy assets in and within business structures, i.e. in organized groupings of production factors, which emerge, grow and maintain themselves through contracts which internalize market transactions (Williamson 1973). These contracts give control over a heterogenous set of assets, where productive energy assets functionally coexist with other, complementary productive assets, as well as with the non-productive ones. Capital expenditure I on productive energy assets occurs in business structures, i.e. complex collections of capital aggregates, forming temporary steady states, functionally connected to the business model of the whole industry.

Anecdotal observation of real business structures provides a basic insight: liquidity and fungibility of assets differs greatly with the ambient systemic risk those assets are exposed to. Decreasing financial leverage, thus increasing the role of equity in financing the assets, gives more decisional flexibility, and therefore more fungibility on the active side of the capital account. Companies exposed to significant technological uncertainty, e.f. Plug Power, active in the sector of green hydrogen, tend to rely mostly on equity[8]. On the other hand, significant

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[8] https://www.ir.plugpower.com/overview/default.aspx

risk can induce a propensity to accumulate large balances of cash and liquid financial instruments, which maximizes book value contingent to withdrawal from business. In the energy industry, a good example of that is the later mentioned Polish company ZEPAK, used as one of empirical benchmarks. With a given value of real investment in physical energy assets and a given opportunity cost, relatively big equity and relatively substantial cash balances increase the residual difference $EQ(S_M) + V(S_M; T_M) - A(S_M; T_M)$, and therefore gives more room for economically acceptable transaction costs.

With S_M standing for the total value of assets committed to M, there is a vector i$G = \{E/S_M, R/S_M, L/S_M, A/S_M\}$, where each coefficient is a proportion in and within S_M, material with respect to equations (1) – (3) and condition (4), and more specifically:

I) E/S_M - Equity to Total Assets
II) R/S_M – Plant, Property and Equipment to Total Assets
III) L/S_M – Liquid financial assets (cash & equivalents, short-term financial instruments etc.) to Total Assets
IV) A/S_M – Annual depreciation, amortization and impairment to Total Assets

Note: In terms of accounting practices, $A(S_M;T_M)$ is an operational cash flow, not a capital aggregate *per se*. Yet, in this model, it coexists functionally with strictly spoken capital aggregates, as it impacts their respective values.

Empirical application of equations (1) – (3) and condition (4) is mediated by the following empirical, context-specific variables:

a) *Cap* - Capacity installed in energy assets (small RES installations in the here-presented case)
b) F - Technological capacity factor of the energy assets in question, i.e. real output of MWh per 1 MWe
c) P – price of energy
d) W – payments for capacity, if any capacity agreements are in force regarding commitments M
e) k – capital outlays coefficient, i.e. average amount of financial capital per 1 MWe physically installed
f) *O&M* – the coefficient of Operational & Maintenance costs per 1 MWe of capacity physically installed
g) One or more vectors of coefficients $G = \{E/S_M, R/S_M, L/S_M, A/S_M\}$, empirically observable in the market environment of M.

Empirical variables allow making the basic set of conditions (1) – (4) more specific. Operational surplus $V(S_M;T_M)$ decomposed in equation (5). A given capacity in megawatts can yield an output of energy $Q(Cap)$, shaped by the application of the capacity factor F to a timeline of 24*365 = 8760 hours. Energy sold makes a revenue at market price P, which can be incremented with payments for capacity W, should capacity agreements be applicable to the energy assets under considerations.

$$\begin{aligned} V(S_M; T_M) &= Q(Cap) * P - Cap * O\&M + W = Cap * F * 24 * 365 - Cap * O\&M + W \\ &= Cap * (F * 8760 - O\&M) + W \qquad (5) \end{aligned}$$

Note: In quickly changing markets, assumed duration $T_M > 1$ might not be the best approach. When gradients of change in capacities installed and/or in the prices of energy are substantial, it may be advisable to consider each year as a separate instance. In such case, the model is applied with $T_M = 1$. In such case, the model can be reformulated into a more additive version, where the main question is: *What will be the economically acceptable transaction costs for the operators of small RES installations in year t_i, with the given commitment to energy auctions and a given residual capacity to exploit in the market of prosumption?* **That observation can be generalized in the prospect of replicating the above-proposed model in other markets. The sector of renewable energy changes so quickly that theoretical assumptions formulated as multi-period problems may need to be empirically broken down into a series of non-identical local occurrences.**

In this specific application, the model pertains to small RES installations, and it is realistic to assume at least one scenario with prices of energy either flat or endowed with negligible stochastic walk. Still, should the price of energy follow a Geometric Brownian Motion characterized by a drift $\boldsymbol{\mu_P}$ and a volatility $\boldsymbol{\sigma_P}$, a simplified version of the model presented by Bonaldo et al. (2024) can be applied, as in equations (6) – (9).

$$Q(Cap) * P - Cap * O\&M = Q * \frac{P}{r-\mu_P} + B \quad P^{-\beta_2} \tag{6}$$

where $\boldsymbol{r}$ is the discount rate, and:

$$B \quad = \frac{\mu_P \beta_1 + r}{(\beta_2 - \beta_1)(r - \mu_P)} \tag{7}$$

$$\beta_1 = -\left(\frac{1}{2} - \frac{\mu_P}{\sigma_P^2}\right) + \sqrt{\left(\frac{1}{2} - \frac{\mu_P}{\sigma_P^2}\right)^2 + \frac{2r}{\sigma_P^2}} \quad > 0 \tag{8}$$

$$\beta_2 = -\left(\frac{1}{2} - \frac{\mu_P}{\sigma_P^2}\right) - \sqrt{\left(\frac{1}{2} - \frac{\mu_P}{\sigma_P^2}\right)^2 + \frac{2r}{\sigma_P^2}} \quad < 0 \tag{9}$$

In the presence of $G = \{E/S_M, R/S_M, L/S_M, A/S_M\}$, components of equations (1) – (3) can be proposed as in equations (10) – (12).

$$S_M = Cap * k/(\frac{R}{S_M}) \tag{10}$$

$$EQ(S_M) = Cap * k/(\frac{E}{S_M}) \tag{11}$$

$$A(S_M; T_M) = [Cap * k/(\frac{A}{S_M})] * T_M \tag{12}$$

With the above assumptions, equations (1) – (3) and condition (4) simply not hold. There can be $TC(S_M;\ T_M) < 0$, i.e. the economically acceptable transaction costs are negative and, theoretically, economic agents should not sign any contracts more binding than a spot transaction in the energy market. In such case stable business structures don't exist, and more complex schemes, such as energy clusters, are pure theory.

To cope with such a scenario, condition (13) is proposed. There is a hypothetical amount of capital $OC < S_M(1+r)^{T_M}$, which allows economic agents to cover transaction costs with the money they have or can have quick access to, thus the reserves of cash and liquid financial assets which economic agents hold.

$$TC(S_M;T_M) = EQ(S_M) + V(S_M;T_M) - A(S_M;T_M) - OC \leq Cap * k * \frac{L}{S_M} \qquad (13)$$

If equations (1) – (3) and condition (4) do not hold in a given state of commitments *M*, non-linear optimization - such as **generalized reduced gradient (GRG)** method (e.g. Lasdon et al. 1974; Tavares et al. 2024), - can be used to compute levels of capital commitment S_M which allows them to hold.

With the above assumptions, the model simulates the possible amounts of irrecoverable transaction costs which are, respectively, acceptable, and optimal for economic agents given the amounts of fungible assets held in their balance sheets.

3.2 Empirical material for applying the model

The model is explored and tested in the context of the Polish energy sector and the empirical material used to that purpose is essentially market specific. Nevertheless, to make the calculations which follow as comparable as possible with those performed in other market environments, variables: *F* (capacity factor), *k* (coefficient of capital intensity), and *O&M* (operational and maintenance costs per unit of capacity) are sourced from IEA's World Energy Outlook 2024, and technology – specific.

The vector *{F, k, O&M}* is placed in the context of the already introduced data on the capacities installed (*Cap*) in small RES installations in Poland, this time aggregated into technological categories. Table 2 provides the capacities installed in small RES installations in Poland end 2024, in megawatts of electrical capacity. As of end 2024, over 88% of those capacities were solar farms, 7,86% was installed in onshore wind farms, and 1,96% in hydro installations. The remaining types of technologies are present in shares below 1% each.

The so-far investment in small RES installations is clustered technologically even more than it is spatially. Therefore, in the calculations which follow, only solar farms and onshore wind farms will be considered. Throughout the further-presented calculations, a simplifying assumption is made of constant proportions between solar PV capacity and onshore wind capacity installed in small RES installations in Poland, i.e. 0,92 solar/0,08 onshore wind. Those proportions are used to convert to unique denominators the vector *{F, k, O&M}*, as supplied in IEA World Energy Outlook.

Table 3 further below presents those two types of installations in the context of parameters provided in the IEA's World Energy Outlook 2024 - Capacity factor, Capital costs (USD/kW) and Annual O&M Costs (USD/kW) – which, in turn, allow calculating expected generation from those installations, as well as their total capital cost and total annual O&M cost, expressed in PLN.

For further calculations, a **weighted average vector** *{F, k, O&M}* is assumed, based on solar PV and wind, where ***{F = 14,3%; k = 1041,2 USD/kW, O&M = 16,24 USD/kW}***.

Table 2

Type of technology	**Capacity installed in small RES installations in Poland, end 2024 [MWe]**
Biogas - biomethane	1,33
Biogas from waste	39,28
Biogas in cogeneration	45,10
Biomass	6,76
Hydrogen	1,00
Solar PV	4 552,79
Onshore Wind	405,17
Hydro	101,13

Source: Energy Regulatory Office of Poland

Table 3

Type of technology	**Solar PV**	**Onshore Wind**
Cap end 2024 [MW]	4 552,79	405,17
F (%)	0,13	0,29
Expected generation [MWh]	5 184 720,67	1 029 293,87
k (USD/kW) (IEA World Energy Outlook)	$ 990,00	$ 1 630,00
O&M (USD/kW) (IEA World Energy Outlook)	$ 14,00	$ 42,00
Cap * k [PLN mln]	18 254,42	2 674,73
Cap * O&M [PLN mln]	258,14	68,92

Source: author’s

The baseline scenario considered in this research is the one when the mix of 4 957,96 MW, 0,92 solar PV and 0,08 onshore wind generate, at the weighted capacity factor ***F = 14,3%***, an annual total of 6 210 737,33 MWh.

In Poland, operators of small RES installations can sell energy in two basic ways:

a) In the framework of **energy contracts auctioned by the Energy Regulatory Office**, at flat prices set separately for each year. Further below, data pertinent to auctions held in 2023 and 2024 is presented.

b) In compensatory schemes based on **the legal construct of virtual prosumption**. In those schemes, operators of small RES installations grant subsidiary rights to third parties, who, in turn, declare to their regular energy supplier the fact of supplying themselves from those installations and get accordingly lower energy bills. Those third parties share those rebates with the prime owners of small RES installations. Documentation of such deals is private, not disclosed publicly, and therefore prices and quantities encompassed are essentially unknown and must be subject to estimation.

Note: As a rule, operators of small RES installations in Poland are not eligible for participation in capacity auctions and payments for capacity. Since the creation of capacity market in 2018, no capacity agreement has been signed for a capacity lower than 1,2 MWe.

The Energy Regulatory Office of Poland typically holds 7 energy auctions per calendar year, since 2016, and, just as typically, the first 5 usually remain unconclusive, with only the two last ones, held in December, bringing settlement. In the here-presented research the results of 4 conclusive auctions have been used: 6/2023, 7/2023, 6/2024, and 7/2024.

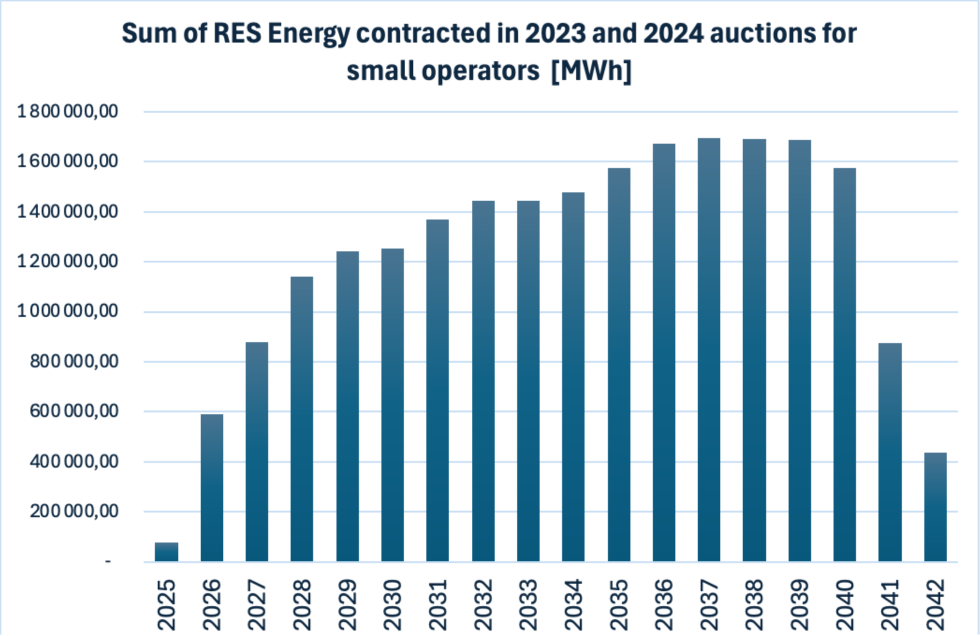
Such as published by the Energy Regulatory Office, the results of a conclusive auction contain the following data: i) Year covered by the auction ii) Energy contracted [MWh] ii) Value of the contracts awarded [PLN] ii) Minimum price contracted [PLN] ii) Maximum price contracted [PLN] ii) Number of bids placed ii) Number of contracts awarded. The literal data pertinent to those 4 auctions has been placed by the author at: https://github.com/krzysztofwasniewski/Small-RES-auctions-Poland/tree/main .

Here below, some general observations are developed, to shed light on market participants' strategies. The span of time covered by those auctions is 2025 – 2041 in the 2023 auctions, and 2025 – 2042 in the 2024 auctions. The aggregate value of commitments for each year is provided, in MWh and in PLN, still it is not specified, how many contracts have been awarded per each of those years. The duration T_M of commitment, according to the model, can be therefore realistically estimated at $1\ year \leq T_M \leq 18\ years$. Dividing the value of contracts awarded by the energy contracted allows calculating the mean price per 1 MWh, for each year separately.

Figure 3 and Figure 4 below present two different aggregations of the 4 auctions considered: the total energy committed per year covered, and the mean price per 1 MWh. Although prices are technically pertinent to future periods, they remain close to flat and look like a little variance around the current equilibrium price. On the other hand, energy committed grows over time, to reach a peak in commitments relevant to 2037.

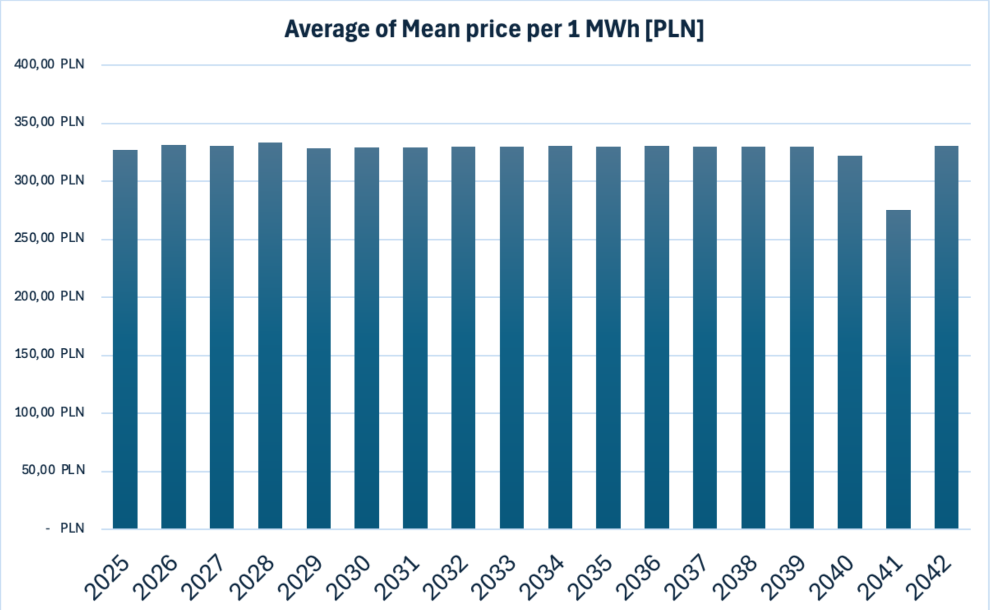
That preliminary insight into empirical material already explains to some extent the low popularity of energy clusters and energy cooperatives as institutionalized forms of energy communities in Poland. Small RES operators seem to bid mostly on future volume of supplies, much less on price. Price-based incentives in exchange of significant immobilisation of energy assets in an energy cluster goes, as a contractual scheme, against the prevalent pattern observable in the market.

Figure 3



Source: Energy Regulatory Office

Figure 4



Source: Energy Regulatory Office

Energy committed in the 4 auctions studied can be cautiously converted into expected future capacity, with a weighted ‘solar/wind’ average capacity factor of 0,143: *Cap = {2025: 61,52 MW; 2026: 472,35 MW; 2027: 701,57 MW; 2028: 911,61 MW; 2029: 990,14 MW; 2030:*

999,35 MW; 2031: 1 092,53 MW; 2032: 1 153,55 MW; 2033: 1 154,32 MW; 2034: 1 180,44 MW; 2035:1 256,05 MW; 2036: 1 336,30; 2037: 1 352,19 MW; 2038: 1 348,99 MW; 2039: 1 346,39; 2040: 1 256,79 MW; 2041: 699,81 MW; 2042: 347,83 MW}.

None of these capacities exhausts the presently installed 4 957,96 MW. The best guess is that the remaining part is supposed to be used in virtual prosumption. Therefore, it is further assumed that transaction costs in the sector of small RES installations in Poland occur in two different market segments:

I) The segment 'AUCTION' of energy sold on the basis of auctioned energy contracts, with essentially flat annual prices. As for now, official results of auctions are the best estimation of capacities committed (*Cap*) and expected output of energy *[Q(Cap)]*.

II) The segment 'PROSUMPTION' of compensatory deals based on virtual prosumption. Empirical prices here are essentially unknown and the best guess is to assume they are somehow correlated with stochastically volatile prices in the national day-ahead energy market.

The size of the PROSUMPTION segment can be estimated as a residual difference between the registered total capacity in small RES installations, and capacities committed in the AUCTION segment. That requires a rational prediction of the future total capacity. The best guess for the moment is based on observation: the growth rate in *Cap* reached a peak in 2018, with *dCap = 0,558*, and has been decreasing since then. Somehow crude an assumption can be made: capacities installed cannot grow forever, especially in an environment as densely populated as Poland. It is further assumed, for the purpose of a rational forecast, that *dCap* will be decreasing at a constant rate. Table 4 provides an estimation of future capacities committed in the PROSUMPTION segment, given the known capacities committed in the AUCTION segment.

Table 4

Year	**Known capacity committed in the AUCTION segment**	**Estimated capacity committed in the PROSUMPTION segment**
2025	61,52	5 869,95
2026	472,35	6 215,91
2027	701,57	6 648,67
2028	911,61	6 955,14
2029	990,14	7 269,09
2030	999,35	7 552,44
2031	1 092,53	7 674,32
2032	1 153,55	7 769,84
2033	1 154,32	7 882,19
2034	1 180,44	7 937,39
2035	1 256,05	7 920,05
2036	1 336,30	7 881,43
2037	1 352,19	7 895,23

2038	1 348,99	7 919,58
2039	1 346,39	7 937,23
2040	1 256,79	8 037,53
2041	699,81	8 602,12
2042	347,83	8 959,50

Source: author’s

In the AUCTION segment, quantities and prices *P* will be those for each year in the contracts auctioned in 2023 and 2024, as in Figure 3 and Figure 4. As regards the PROSUMPTION market, equations (6) – (9) will be applied and the empirical data required is that on time series of empirical prices in the day-ahead national market of energy.

Those time series should correspond to the same years, 2023 and 2024. Yet, on June 14th, 2024, the operator of the Polish national grid, PSE[9], officially passed from a 1-hour window of settlement to a 15-minute one, and the corresponding Geometric Brownian Motion took on a pace 4 times faster than before. It is a wise step to check how the parameters of the time series changed from year to year and with the transition to narrower periods of settlement.

Table 5 shows the characteristics of time series in the so-called RCE energy price, which is the mean settlement price for the given window (1 hour, later 15 minutes). Source data is available at: https://github.com/krzysztofwasniewski/Day-ahead-electricity-prices-Poland. All three share the same structural trait of their Geometric Brownian Motion: little drift, large volatility. Still, three are clearly discrepant along the three key metrics: a) Mean price P [PLN/MWh], b) Drift μ_P in the Geometric Brownian Motion of price, and c) the volatility σ observable in that motion.

Table 5

Period	Mean P [PLN/MWh]	Drift μ_P in GBM	Volatility σ_P in GBM
Year 2023	511,79 PLN	0,00988	50,07
Year 2024, Jan 1st – June 13th (1-hour window)	363,50 PLN	0,073098	38,805209
Year 2024, June 15th – Dec 31st (15-minute window)	457,41 PLN	-0,028848	61,525148

Source: author’s

In the here-presented research, the last period of empirical day-ahead prices of electricity, i.e. June 15th – Dec 31st, 2024, with the 15-minute window of settlement, is chosen as baseline. In other words, application of the model to the PROSUMPTION market segment will be a projection of those three metrics into future periods, until 2042.

Eleven real business structures have been used as benchmarks for $G = \{E/S_M, R/S_M, L/S_M, A/S_M\}$, namely:

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[9] https://www.pse.pl/web/pse-eng

I) RWE Renewables (fiscal year 2023)
II) ENGIE Group (fiscal year 2023)
III) Veolia (fiscal year 2023)
IV) Columbus Energy (fiscal quarter Q3 2024)
V) Columbus Energy (fiscal year 2022)
VI) TAURON (fiscal year 2023)
VII) PGE (fiscal year 2023)
VIII) Enea (fiscal year 2023)
IX) Energa (fiscal year 2023)
X) Orlen (fiscal year 2023)
XI) ZEPAK (fiscal year 2023)

The choice of benchmarks is based prevalently on geography and the corresponding relevance for the Polish market. When replicating this method in a different market, business structures serving as benchmarks should be selected accordingly. In the ‘References’ section, readers will find links to investor-relations sites of these entities.

RWE Renewables and ENGIE Group are representative for large international business structures, with branches in Poland, specifically targeting investments in renewable energies. Both RWE and ENGIE own a substantial part of small solar and wind installations registered by the Energy Regulatory Office. Their particular trait is high liquidity in their balance sheets. Veolia is another international group present in Poland, yet with a special edge on co-generative power plants. On the other hand, TAURON, PGE, Enea, and Orlen are representative for large, generalist, state-controlled energy companies, bearing strong marks of internalized capital markets. In other words, commitments in renewable energy projects always compete internally with ventures such as the modernization of transmission grid or energy storage. PGE (Polska Grupa Energetyczna), is the largest supplier of electricity in Poland, supplying and further redistributing some 60% of energy in the Polish national grid. Energa and ZEPAK are in a slightly different category. Whilst belonging to the core of the national energy system, they have a much more pronounced commitment to energy transition.

Compared to those benchmarks, Columbus Energy is a special case. The company is explicitly committed to solar energy, with probably the most aggressive investment strategy in the sector of solar farms. That expansive strategy finds its expression in an unusually branched corporate structure, and a precarious financial stance, which is the reason for taking into account a different fiscal timeframe: 2022 and Q3 2024 (the company has not presented yet audited, consolidated financial statements for 2023, only the mother company’s individual ones).

Table 6 below reports the values of $G = \{E/S_M, R/S_M, L/S_M, A/S_M\}$ for these 11 benchmark structures. Each of them is different, which suggests many possible estimations of (10) – (13).

Table 6

Benchmark company	**Year/ period**	R/S_M	E/S_M	A/S_M	L/S_M
RWE Renewables	2023	0,2705	0,3112	0,0359	0,3859
ENGIE Group	2023	0,2977	0,1835	0,0566	0,1399
Veolia	2023	0,2361	0,2026	0,0419	0,1557
Columbus Energy	2022	0,2031	0,0315	0,0276	0,3876

Columbus Energy	Q3 2024	0,5129	(0,0948)	0,0159	0,0248
TAURON	2023	0,6400	0,3605	0,0447	0,0765
PGE	2023	0,6039	0,4218	0,1186	0,0812
Enea	2023	0,4669	0,3948	0,0422	0,0811
Energa	2023	0,6475	0,3928	0,0377	0,0567
Orlen	2023	0,5098	0,5798	0,0538	0,0603
ZEPAK	2023	0,0920	0,5325	0,0105	0,1519

Source: author's

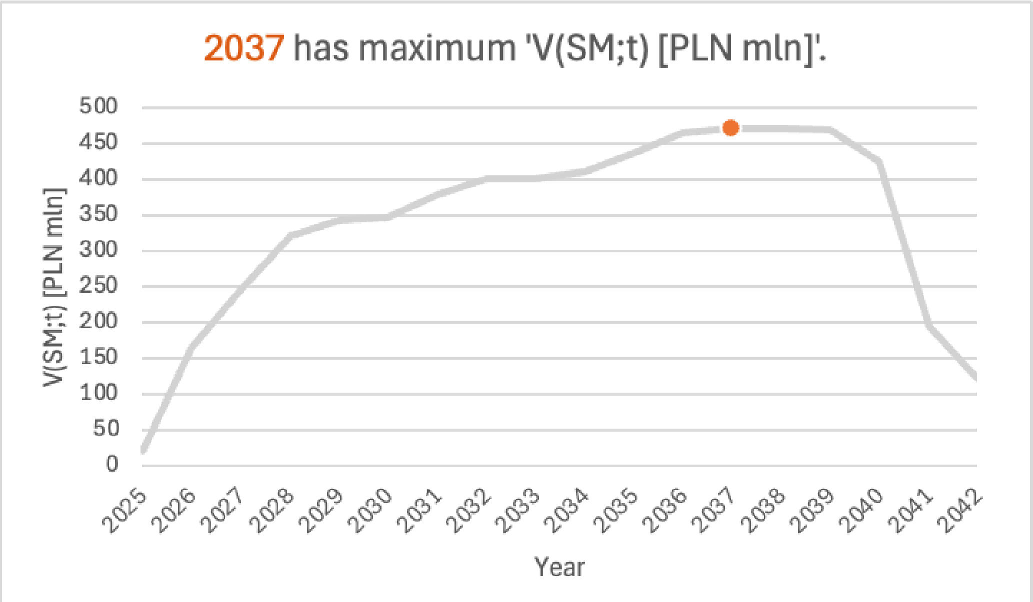
4 Calculations and results

Calculations have been performed in two market segments: AUCTION and PROSUMPTION, separately for each year in the range 2025 ÷ 2042, covered in the auctions held by the Energy Regulatory Office. Detailed numerical results are available at: https://github.com/krzysztofwasniewski/Transaction-Costs-research . In what follows, the most salient traits of the results obtained are presented.

Note: the interest rate applied in the calculations was 5,74% per annum, which is the current mean yieald on Polish Treasury Bonds.

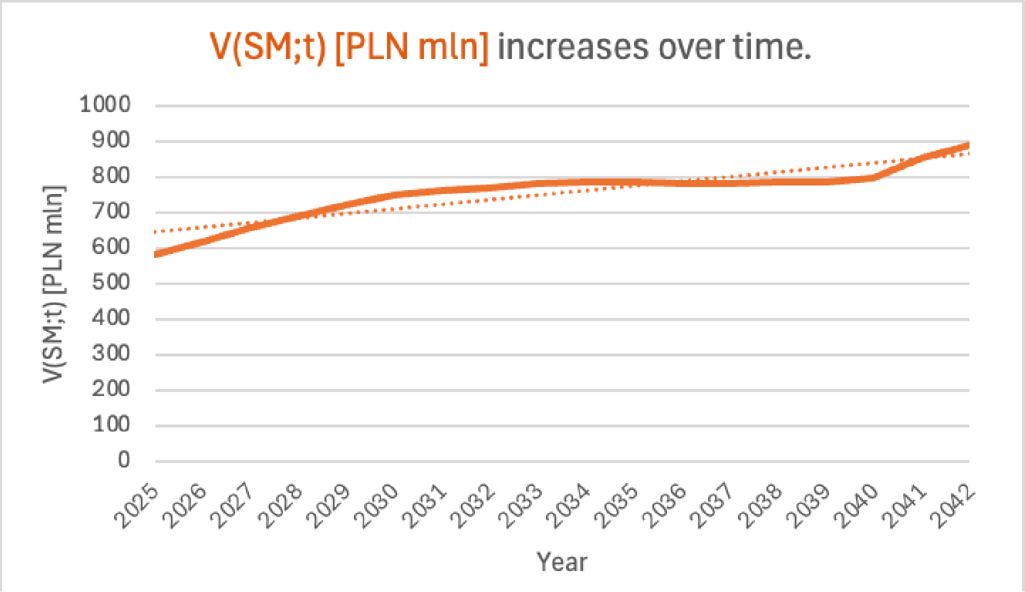
Due to assumptions formulated in the method, results pertinent to the two markets in question present an interesting duality as regards the markets themselves, whilst the structural properties of benchmark financial structures are consistent across the two markets (**Erreur ! Source du renvoi introuvable.** and Figure 6). The AUCTION market has the dynamics of a bubble: swelling up until 2037, and then decompressing violently. By comparison, the PROSUMPTION market shows a gentle trend upwards.

Figure 5 Operational surplus $V(S_M;t)$ *in the AUCTION market*



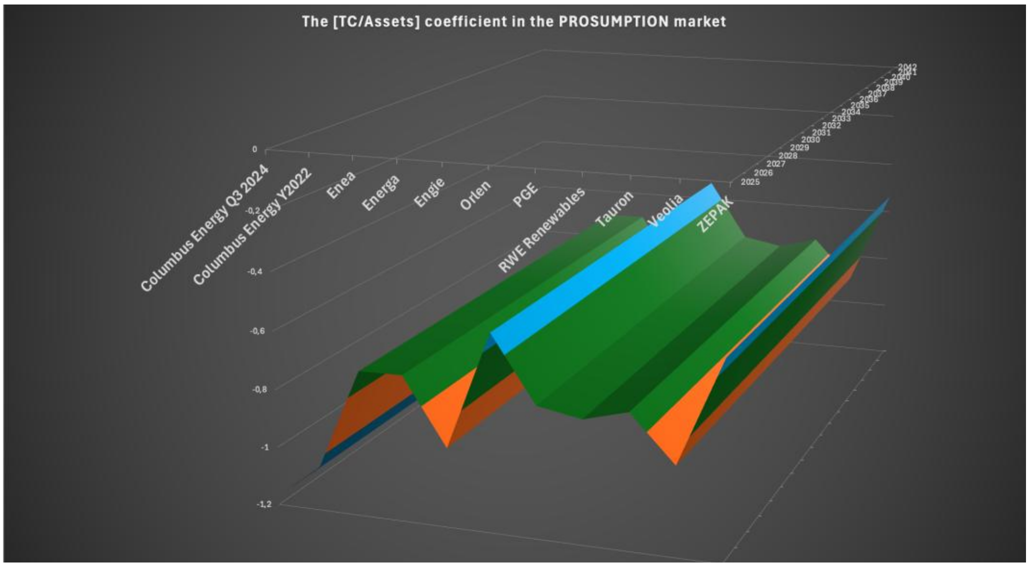
Source: author's

Figure 6 Operational surplus V(S_M;t) in the PROSUMPTION market



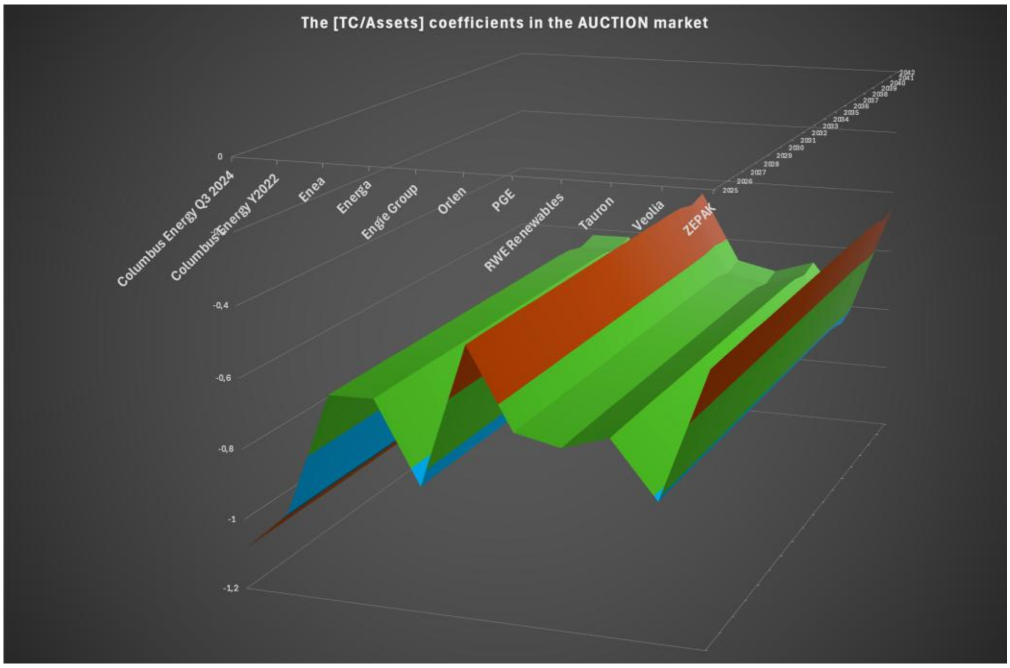
When applied in the strict form of equations (1) – (3) and condition (4), the model holds in neither of the two markets: with opportunity cost from a risk free investment included in the calculation, the economically acceptable transaction costs are consistently negative. When data corresponding to the two markets is run with the **generalized reduced gradient (GRG)** algorithm with respect to $TC(S_M;t)$, it yields the same **paradoxical result for both markets**, namely that $TC > 0$ only if $S_M = 0$, i.e. when there is no real capital commitment, and the real option is valued only on the basis of operational surplus from the market. Figure 7 and Figure 8 below show the distribution of the coefficient [*TC/Assets*] over time and across financial benchmarks in the two markets. One can notice, besides the obviously negative values, that [*TC/Assets*] varies the most strongly across different financial benchmarks, whilst varying much less across the two markets and over time.

Figure 7



Source: author’s

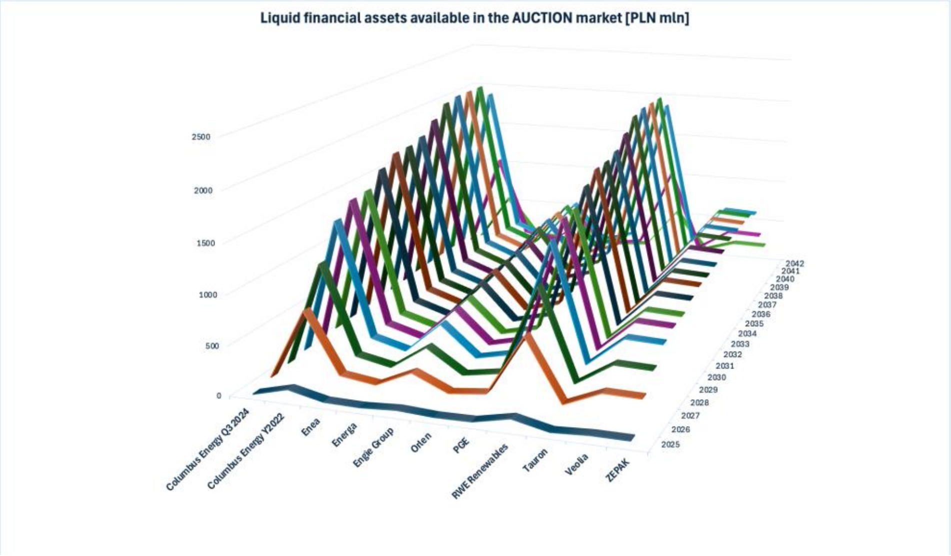
Figure 8



Source: author’s

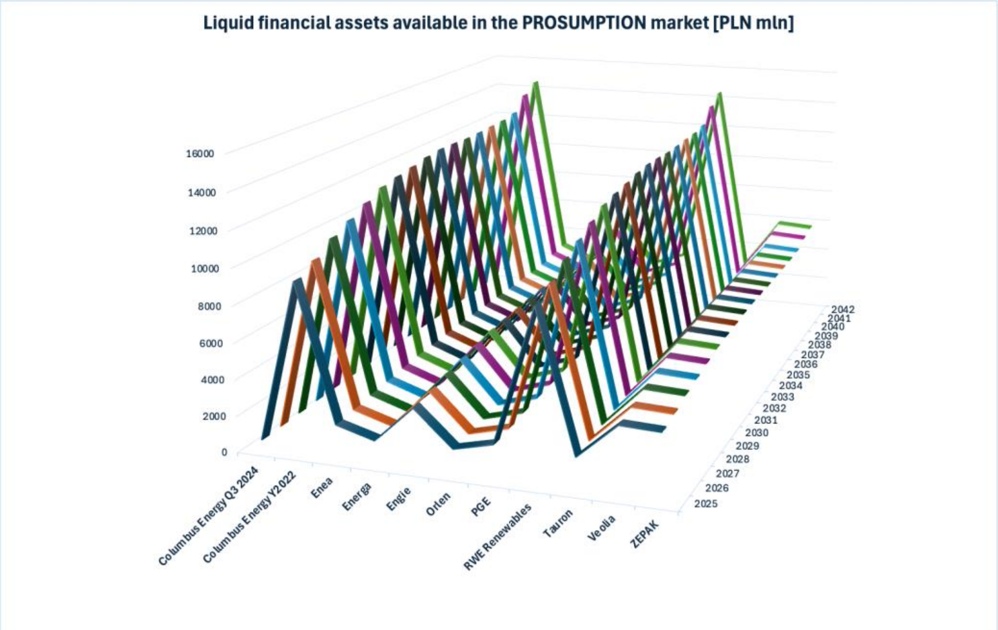
The weaker version of the model, i.e. condition (13), holds only for a few financial benchmarks. In the AUCTION market they are: RWE, Columbus 2022, and Columbus Q3 2024, whilst in the PROSUMPTION market a fourth one passes the test, namely Engie Group. Figure 9 and Figure 10, further below, show the distribution of liquid financial assets – contingent to condition (13) - over time and across financial benchmarks.

Figure 9



Source: author’s

Figure 10



Source: author's

5 Discussion and conclusion

Adhesion to institutionalized energy communities is studied in this article with the case of Poland, where regulations introduced since 2015 are supposed to boost the development of energy communities, and massive investment in small RES installations can be observed, as well as clear spatial agglomeration of those installations. A flagship institution, that of energy clusters, shows adherence inversely proportional to the complexity of regulatory incentives: the more complex those incentives, the lesser is the willingness to adhere from the part of persons and entities owning small RES installations.

Adherence to long-term commitments such as energy clusters entails transaction costs, which, in the here-proposed model , are component part of a real option, values as the residual difference between the sum of recoverable equity and expected operational surpluses, on the one hand, and the sum of irrecoverable depreciation in assets, transaction costs and an opportunity cost, the latter being defined as proceeds from a risk-free investment. A version with weaker assumptions excludes fully appreciation of opportunity cost, and transaction costs are acceptable up to the balance of liquid financial assets held in the capital account at the given moment.

Empirical material investigated with the model is that on the capacities registered in small RES installations in Poland, in the context of the energy market for those installations. With empirically verifiable results of energy auctions held in 2023 and 2024, calculations on that material cover the period from 2025 through 2042. Incompletness of data on energy from small RES installations is a factor of caution, still it is partly compensated by the use of really existing (and active in Poland) energy firms as financial benchmarks, as well as coefficients of capital intensity and operational costs as supplied by the International Energy Agency in its World Energy Outlook 2024. The financial benchmarks in question cover both firms specialized in renewable energies (e.g. Columbus Energy, RWE Renewables, Engie, Veolia), and big generalists in the energy sector in Poland (PGE, Enea, Energa, Tauron, Orlen, ZEPAK).

The part played by empirical estimates in the here-presented research should induce healthy scepticism as regards the results of calculations, although the model seems to be robust even at the most elementary, linear level.

The full version of the model, with full opportunity costs, yields consistently negative transaction costs, which follow remarkably consistent a proportion to the overall assets committed in small RES installations. When tested with the generalized reduced gradient (GRG) algorithm, that strong version of the model yields null commitment in assets ($S_M = 0$) as the only way to have positive capacity for incurring transaction costs. Such results are a paradox: there is no such thing as negative transaction costs in real life, just as there is no null investment in productive assets once those assets are physically in place, and operators of small RES installations in Poland do enter into long-term commitments which entail transaction costs. While they seem to be consistently avoiding as far-reaching commitments as energy clusters (in their present regulation), they still form business structures, sign energy contracts in auctions held by the energy regulatory office, do business based on the institution of virtual prosumption etc.

The weak version of the model, with transaction costs covered with free liquid financial assets, seems to be the only applicable. Still, whilst the strong version proved being inapplicable across all the benchmark business structures, the weak version is applicable selectively: only those business structures endowed with truly significant amounts of liquid financial assets can effectively tolerate substantial transaction costs.

The general working hypothesis of this study, namely that rapid deployment of renewable energy sources (RES) creates a temporarily low tolerance for transaction costs on the part of investors, seems to be strongly sunbstantiated by the here-presented research. Yet, at the same time, the behaviour of investors in small RES installations shows little signs of backing down or slowing down on that path of rapid investment. If the here-presented and used auction results are to be considered as a reliable estimate of the industry's collective sentiment, all the period up to 2037 is expected to be a similar kind of investment race as the one that has taken place so far. Investors seem to behave according to the logic of a non-Markovitz portfolio and shape their expectations within the portfolio of investment in small RES rather than referring it to an exogenous opportunity cost.

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