Is dynamic energy sharing really necessary? The case study of collective renewable self-consumers in Croatia

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***Abstract*—With the recent skyrocketing electricity prices and global energy crisis, investments in household photovoltaic (PV) systems can be seen as a pathway towards low-carbon power systems. As investment on the individual household level with a single owner is a well-established scheme, it is also necessary to involve the apartment buildings and multi-apartment blocks. However, some major challenges, such as the early phase of a regulatory framework and lack of demonstration projects which provide the methodology for joint investments and their profitability, hinder the development of joint PV investments. To overcome these obstacles, the paper models the joint investment in a PV system in the multi-apartment building based on realistic load and PV measurement data of 8 apartments located in Zagreb, Croatia focusing on different dynamic keys for PV production sharing and net-metering approaches. The results show that the 15-min net metering approach is less profitable compared to the monthly net metering approach resulting in a longer period of investment return for all types of dynamic keys. Moreover, it is shown that dynamics in key changes for energy sharing on monthly basis are sufficient to adequately distribute PV production among investors in both 15-min and monthly net metering.**

***Index Terms*—collective self-consumption, jointly acting renewable self-consumers, prosumer, self-supply customer, solar power plant**

NOMENCLATURE

γ^{PV}	Calculated monthly price for energy injection in the grid [EUR\kWh]
γ^{HT}	Price for purchasing electricity in high tariff without additional charges [EUR\kWh]
γ^{LT}	Price for purchasing electricity in low tariff without additional charges [EUR\kWh]
E^{HT}	Total amount of consumed energy in high tariff [kWh]
E^{TL}	Total amount of consumed energy in low tariff [kWh]
x_i	Value of energy sharing key
$P_{i,t}^{load}$	15-min load measurement of investor i [kWh]
P_t^{PV}	Total PV production [kW]
$P_{i,t}$	Net load [kW]
$P_{i,month}^{+}$	Total allocated withdrawn power in the settlement on monthly basis in monthly net metering [kW]
$P_{i,month}^{-}$	Total allocated injected power in the settlement on monthly basis in monthly net metering [kW]
$P_{i,month}^{grid}$	Billed injected/withdrawn power on monthly basis in monthly net metering [kW]

I. INTRODUCTION

To involve citizens in renewable energy sources (RES) integration, many ongoing research projects with pilot demonstrations and real-life examples are focused on the implementation of different types of energy communities and peer-to-peer (p2p) trading. Moreover, almost 2000 European cooperatives are currently active with more than one million involved citizens [1]. Energy sharing in energy communities has also gained broad attention in academia.

On the other hand, collective self-consumption and joint investments in low-carbon technology in multi-apartment buildings still have a limited interest in academic and research activities. The main barrier to collective investments is the early stage of the regulatory framework development and the lack of real-life examples which can foster practical implementation. Most of the research is focused on regulation barriers and comparison of the framework development among European countries. Paper [2] gives an overview of the regulatory frameworks in Renewable Energy Communities, Citizen Energy Communities, and Jointly acting Renewable Energy self-consumers in several EU countries. The review paper [3] defines characteristics of peer-to-peer markets, collective self-consumption, and transactive energy markets dividing them into several categories: participation, governance, locality and typology, market services, market design, governance, and market transactions. It defines and categorizes market benefits in total welfare and profit maximization, cost, grid imbalance, and electricity cost minimization.

To ensure citizens' engagement, it is important to inform final customers about the benefits of collective low-carbon technology investments and encourage them to join RES projects. The value propositions of different value-sharing

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methods from the customer's perspective are described in [4]. Sharing methods are divided into three categories: static sharing, dynamic allocation, and participation in local energy markets based on the community and customer type and their willingness to engage in the sharing projects. Ongoing practice in collective self-consumption schemes in apartment buildings in Australia, the USA, and several European countries is described in [5]. PV self-consumption is incentivized with low prices for excess injection in the grid. Collective self-consumption can also be seen as an extra benefit to low-income tenants through their bill reduction. Moreover, changing grid fees from volumetric to maximum load or feed-in power can incentivize local self-consumption and integration of battery storage systems.

A two-stage management strategy for energy sharing defined in [6] is dived into the operational phase and the energy billing phase. The results from a realistic test case in Spain show almost 12% of cost reduction when participants can exchange energy locally. Four different energy management strategies and 10 keys of repartition (keys for allocation of local generation to each consumer) are used to define the most beneficial solution for collective energy actions. The highest savings in collective bills are achieved with the management strategy described as maximization of the self-sufficiency ratio.

A mixed-integer linear optimization model is developed in [7] to investigate the difference between investments in PV systems and cost savings in multi-apartment buildings in Austria and Australia. Diverse factors are considered in analyses, such as regulation, climate, financial settlement, heating and cooling technologies used in both countries. The results conclude that higher cost savings can be achieved in Australia due to higher isolation, however, some regulatory obstacles are still present. On the other hand, high PV investment costs in Europe and complicated administration hinder the development of energy sharing in multi-apartment buildings in Austria.

To investigate the possibilities of collective renewable self-consumers in Croatia, our paper develops the methodology for energy sharing from joint PV investment in a multi-apartment building based on realistic load and PV measurement data under different dynamic keys for energy sharing and net metering approaches.

The rest of the paper is organized as follows: Section II describes prosumers in Croatian from the regulation perspective, Section III presents the methodology for different energy sharing keys and net metering approaches, results are described in Section IV, while Section V highlights the main conclusions.

II. PROSUMERS IN CROATIAN REGULATION

To incentivize final customers in collective RES investments, it is crucial to ensure simple and easy-to-understand insight into the profitability of investment and reduce the return of the investment period. Final customers with installed PV systems in Croatia are divided into two categories: self-supply customers and customers with their own electricity production [8]. To be classified into these two categories, the customers should fulfill several requirements, such as achieving the status of privileged producer of electricity, permanent connection to the power system, and total connected power of all production units at one measuring point can not exceed 500 kW, the connection power of electricity injection in the grid does not exceed the connection power of electricity withdrawn from the grid. The difference between these two final customers with onsite PV production lies in the total amount of injected energy in the grid compared to the withdrawn energy from the grid. If the amount of injected energy does not exceed the amount of withdrawn energy from the grid in one calendar year, the final customer with its own PV generation in a household category classifies as a self-supply customer with monthly net-metering and predefined prices for electricity injection [9]. Monthly net metering implies that the total amount of injected excess PV production in the grid on the monthly basis is subtracted from the total amount of energy withdrawn from the grid distinguishing high-tariff (HT) and low-tariff (LT) periods. This type of net metering enables final customers in the settlement process to utilize their excess PV production even if it is injected into the network in case a surplus of consumption exists. The example of the cost calculation for one month is shown in Table I for HT and LT. Realistic electricity prices from Croatia are considered (0.145 €/kWh in HT and 0.075 €/kWh in LT for buying together with 0.06 €/kWh in HT and 0.03 €/kWh in LT for selling energy). Buying prices consider electricity costs, network charges, and RES incentives, while selling prices only have only electricity component.

TABLE I
METHODOLOGY DESCRIPTION FOR MONTHLY NET-METERING FOR SELF-SUPPLY CUSTOMER

Description	Energy balance kWh	Cost €
HT consumption kWh	750	-
HT production kWh	1000	-
LT consumption kWh	500	-
LT production kWh	200	-
Total injection HT	-250	-15 €
Total withdrawn LT	300	22.5 €
Total before tax		7.5 €

On the other hand, if the amount of total injected energy in the grid in one calendar year is higher than the amount of energy withdrawn from the grid, the final customer is classified as a customer with its own electricity production which implies that the total amount of injected and withdrawn energy on a monthly level are billing separately which leads to higher costs compared to the self-supply category. Moreover, selling prices are not fixed and they depend on the total amount of energy withdrawn and injected into the grid on a monthly basis as shown in (1):

$$\gamma^{PV} = 0.9 \cdot \frac{\gamma^{HT} \cdot E^{HT} + \gamma^{LT} \cdot E^{LT}}{E^{HT} + E^{LT}} \tag{1}$$

III. MODEL DESCRIPTION

The described types of prosumers in the Croatian regulation are defined only for a single-owned household. The regulation in Croatia does not clearly specify which type of net metering should be used for collective renewable self-consumers in the apartment building nor the methodology for sharing production from the joint PV system. As 60% of the population in Croatia lives in apartment buildings, it is necessary to expand the regulation and ensure investments in low-carbon technology in the apartment buildings. In order to determine how to optimally distribute PV production among investors, different types of energy-sharing keys (energy coefficients) are proposed in the paper: variable 15-min key, variable hourly key, variable daily key, and variable monthly key. Both net-metering approaches are considered to investigate which one is more beneficial for collective renewable self-consumers. The simulations are based on 15-min load measurement data of each final customer (further in the text we refer to the consumption of their metering points (MP)) and rooftop PV production. The PV system has a 7 kW capacity and produces approximately 7800 kWh on the annual level. The investment price is 1300 €/kW and includes all costs related to the PV system installation (PV panels, inverter, mounts, equipment installation, and PV system commission). The cost of investment is divided among tenants based on their annual consumption share in the total consumption amount in the previous year or observed period. The consumption of each MP and their share on the annual level are shown in Fig. 1.

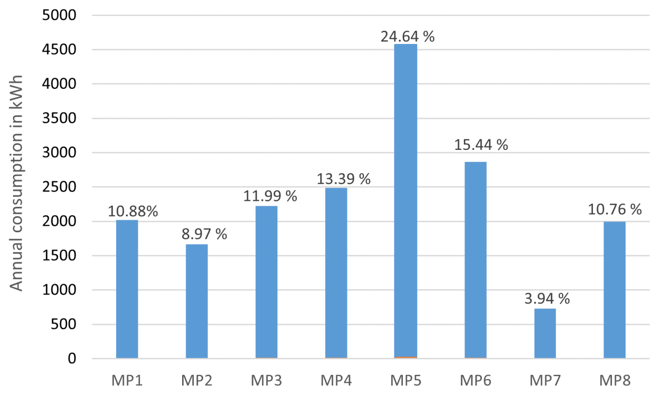

Fig. 1. The annual consumption of each MP in kWh and their share in the total consumption

A. Energy sharing keys

We wanted to investigate which energy-sharing key is the most suitable for dividing PV production in the multi-apartment building, not only from the final customer cost reduction side but also from the Distribution System Operator's (DSO) perspective. As the regulation still does not define how often these keys could be changed and delivered to the DSO for billing purposes, different dynamics in key changes are compared.

In the 15-min key sharing approach, the PV production is shared among MPs based on their consumption share in total consumption for each 15-min interval as shown in (2).

$$PV_{i,t} = \frac{P^{load}_{i,t}}{\sum_{i=1}^{8} P^{load}_{i,t}} \cdot PV_t \tag{2}$$

The key changes every 15 minutes and the DSO receives a monthly list with 2880 keys resulting in more than 35 000 keys for one apartment building. Distribution based on hourly, daily, and monthly keys is similar, however, the consumption of each MP in 15-min is summarized over a predefined time horizon and divided based on hourly, daily, or monthly PV production amount. The methodology is shown in Fig. 2.

IV. RESULTS

To demonstrate the benefits of joint investments for each MP in the multi-apartment building, we wanted to compare the cost savings under different dynamic energy-sharing keys. Fig. 3 shows annual costs for each MP without and with PV installation in 15-min net metering and monthly net metering under different keys for energy sharing. As can be seen from both graphs, energy allocation based on different key-sharing methods does not have a significant impact on cost reduction. The only exemption is the daily key for MP1 and MP5 (yellow bars) for both net-metering approaches.

Croatian regulation does not clearly define what happens if some MP receives more energy than the actual load measured in the specific period. One possibility is that the excess is renumerated as being sold to the supplier. In this case, the price for selling energy is calculated as described in Section II. On the other hand, this excess can be shared among MPs without PV production surplus based on their energy deficit share in the total energy deficit of the building. As the price for buying energy from the supplier is higher compared to the selling price, this difference opens the door for achieving additional cost reductions if the energy is traded between MPs locally. Table II compares cost reductions for different key-sharing methods in the monthly net metering approach when excess PV production is shared among other MPs with the cost when excess is sold to the supplier. It can be seen from Table II that there is no significant cost reduction in almost all cases (except for MP5 with daily key). As described in Section II, in monthly net metering each MP is allocated more energy compared to the 15-min net metering. This results in less energy injected into the grid or shared with other MPs. On the other hand, in the 15-min net metering approach as shown in Table III, sharing excess energy within the building reduces the cost to all involved MPs. The smallest cost reduction is achieved with hourly key (less than 2%), while for daily and monthly key the costs are decreased between 3% and 9%.

Based on the simulations results, we wanted to investigate the period of investment return for some specific case studies:

- Case 1: Monthly net metering with monthly key sharing,
- Case 2: 15-min net metering with monthly key sharing,
- Case 3: Monthly net metering with 15-min key sharing,

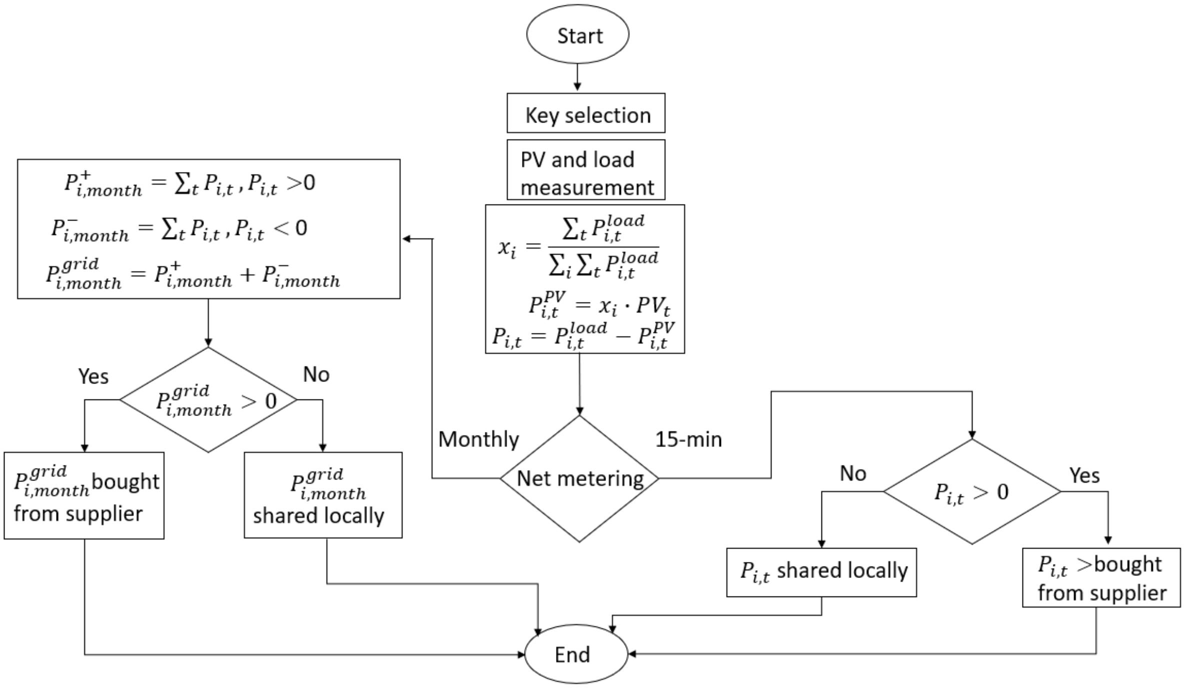

Fig. 2. Methodology for PV production sharing in 15-min and monthly net metering

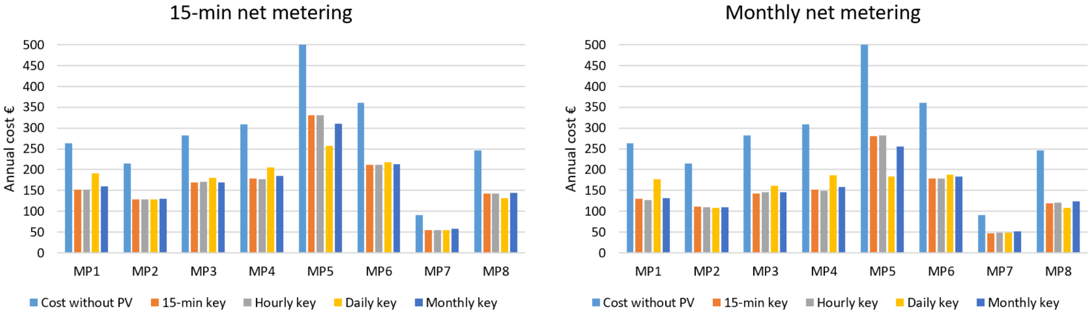

Fig. 3. Costs under different key-sharing in 15-min and monthly net metering

- Case 4: 15-min net metering with 15-min key sharing.

The investment of each MP and the period of investment return for specific case studies are shown in Table IV. If we compare Case 1 and Case 2 under monthly key sharing, the return period of investment is approximately 2 years shorter in monthly net metering compared to 15-min net metering. The same conclusion can be derived when comparing Case 3 and Case 4 for 15-min key sharing. Moreover, if we compare the same net metering approach under different key sharing methods,i.e. Case 1 with Case 3 and Case 2 with Case 4, there are no significant differences between the return of investment period (from 1% up to 9% for only one MP in both net metering approaches).

V. CONCLUSION

To foster the implementation of joint PV investments in multi-apartment buildings and demonstrate the electricity cost savings in collective renewable energy projects, this paper provides the methodology behind the energy sharing scheme which results in an easy-to-understand approach to investors and DSO enhancing the collective energy sharing which will be implemented in the practice in Croatia in the upcoming year(s). The benefits of different dynamic key-sharing approaches in 15-min and monthly net metering in Croatia based on the realistic load and PV measurement data from the multi-apartment building located in Zagreb are compared. The results show that monthly net metering is more beneficial with a 2-year lower return of investment period compared to 15-min net metering. Moreover, when it comes to the dynamic of key for energy sharing, the authors can conclude that monthly key energy sharing is the most appropriate one. It requires that the key for energy sharing is changed only once per month which reduces the complexity of the algorithm, lowers the frequency of data exchange, and decreases the computation burden for

TABLE II

COST REDUCTION IF EXCESS PV IS SHARED AMONG TENANTS - MONTHLY NET METERING

	15-min key		Hourly key		Daily key		Monthly key	
Consumer	Supplier €	Sharing	Supplier €	Sharing	Supplier €	Sharing	Supplier €	Sharing
MP1	129.42	-0.61 %	127.40	-0.60 %	183.14	-3.33 %	132.54	-0.48 %
MP2	111.87	-1.16 %	111.45	-1.16 %	113.83	-5.30 %	109.24	-0.15 %
MP3	142.56	-0.36	145.65	-0.37 %	162.53	-1.04 %	145.30	-0.11 %
MP4	151.62	-1.07 %	150.60	-1.40 %	190.13	-2.20 %	159.48	-0.43 %
MP5	280.31	-0.54 %	283.41	-0.51 %	205.97	-10.94 %	258.26	-0.78 %
MP6	178.41	-0.53 %	180.06	-0.40 %	191.33	-1.31 %	183.59	-0.23 %
MP7	46.99	-1.32 %	48.26	-1.08 %	51.10	-6.40 %	52.09	-0.71 %
MP8	119.10	-1.61 %	122.54	-1.38 %	114.93	-5.54 %	125.48	-1.00 %

TABLE III

COST REDUCTION IF EXCESS PV IS SHARED AMONG TENANTS - 15-MIN NET METERING

	Hourly key		Daily key		Monthly key	
Consumer	Supplier €	Sharing	Supplier €	Sharing	Supplier €	Sharing
MP1	154.45	-2.05 %	198.71	-3.94 %	168.35	-6.29 %
MP2	130.63	-2.04 %	138.31	-8.84 %	138.99	-6.93 %
MP3	172.30	-1.10 %	187.15	-3.96 %	176.27	-4.69 %
MP4	180.39	-2.00 %	214.42	-4.52 %	193.82	-5.38 %
MP5	333.19	-0.89 %	279.83	-8.71 %	323.17	-4.54 %
MP6	213.99	-1.33 %	226.40	-4.32 %	221.89	-4.34 %
MP7	56.15	-1.96 %	57.52	-6.03 %	59.73	-4.56 %
MP8	144.87	-1.55 %	140.41	-6.56 %	149.88	-4.71 %

TABLE IV

INVESTMENT SHARE OF EACH MP IN € AND RETURN OF INVESTMENT IN YEARS

Customer	Investment in €	Case 1	Case 2	Case 3	Case 4
MP1	989.85	7.49	10.05	7.32	9.24
MP2	816.67	7.70	10.23	7.84	9.84
MP3	1090.86	7.97	10.05	7.82	10.14
MP4	1218.28	8.13	10.21	7.79	9.63
MP5	2242.17	7.69	9.77	8.37	10.65
MP6	1404.83	7.94	9.92	7.75	9.78
MP7	358.27	9.03	10.81	8.11	10.05
MP8	979.06	8.05	9.84	7.77	9.73

the DSO, while at the same time cost reductions compared to the 15-min key do not differ significantly (from 1% up to 9% for only one MP in both net metering approaches). The future work will go one step forward and investigate the benefits of demand response in multi-apartment buildings and joint investment in battery storage.

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