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Analysing electricity demand in neighbourhoods with electricity generation from solar power systems: A case study of a large housing cooperative in Norway

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Abstract. An energy management system can be introduced on a neighbourhood level, to achieve energy goals such as increased self-consumption of locally produced energy. In this case-study, electricity generation from photovoltaic (PV) systems is simulated at Risvollan housing cooperative, a large housing cooperative in Norway. The electricity generation from PV systems of different orientations and capacities are analysed with the electricity load. Key performance indicators (KPIs) such as self-generation, self-consumption and generation multiple are described, based on hourly values. The electricity generation from the south-oriented building façade PV systems are about 5-6% higher than for the east-west oriented rooftop PV systems on an annual basis, since the façade PV systems generate more electricity in the spring and autumn. The self-consumption factor is the most important KPI in Norway, due to the national tariff structure. For the total housing cooperative, a PV capacity of about 1,000 kW_p seem suitable, giving a self-consumption factor of 97% for a rooftop system, based on 2018 electricity and climate data. From the perspective of the housing cooperative, it is financial beneficial to aggregate electricity loads for common areas and apartments, since a higher share of the electricity can be used by the cooperative. For this to be possible, also housing cooperatives with PV must be facilitated for in the prosumer agreement. Comparing a single 1,100 kW_p PV system providing electricity to the total cooperative with 22 PV systems of 50 kW_p behind 22 garage meters, the self-consumption factor decreases from 95% to average 14%, resulting in a 41% lower financial value for the PV electricity.

1. Introduction

In zero emission neighbourhoods, thermal and electric energy should be managed in a flexible way, to achieve reduced power peaks, reduced energy use, reduced CO_2-emissions and increased self-consumption of locally produced energy [1]. Further, smart energy management systems (EMS) with building loads can provide energy flexibility services to distribution system operators (DSOs) and district heating companies, both on a building and a neighbourhood level.

A prosumer agreement exists in Norway, for locally produced electricity [2]. AMS meters (Advanced Metering System) at each customer measure net electricity export and import on an hourly basis. Financially, consumers normally receive less payment for electricity sold to the energy company than what they pay for buying electricity. This makes it beneficial to maximise self-consumption, i.e. minimising export of electricity to the grid.

Risvollan housing cooperative is a large housing cooperative in Trondheim, built in the 1970s. Risvollan cooperates with energy companies and researchers to develop a neighbourhood EMS. In Risvollan, there are 1,058 apartments with in total 93,713 m^2 heated floor area, distributed on 121 similar apartment blocks, as shown in Figure 1. In total 2,321 residents live in the apartments: 53% female and 47% male [3], as shown in Figure 2. Previously, measurements of electricity and heat loads of Risvollan in 2018 have been analysed in respectively [4] and [5]. The electricity loads also include around 55 electric vehicles (EVs) in the parking houses, which is expected to increase within the next years. Space heating and domestic hot water (DHW) is provided by district heating.

To be partly self-sufficient with electricity, the housing cooperative considers installing photovoltaic (PV) systems on some of their buildings. This article analyses the electricity demand at Risvollan together with possible electricity generation from the PV systems. In this article the electricity delivery is also referred to as electricity use, demand or load.

Figure 1. Example of apartment blocks at Risvollan housing cooperative, with 121 similar building blocks.

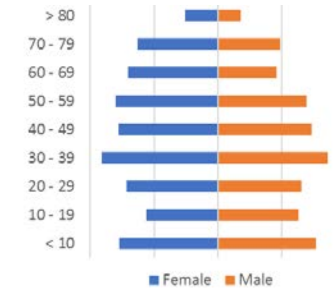

Figure 2. Age and gender distribution of the 2,321 residents.

2. Methods

Future scenarios for PV systems are developed, with varying installed PV capacity. PV generation is simulated with hourly resolution, using the software PVsyst [6]. Input data and system information is shown in Table 1. The PV systems are placed in two directions: 1) rooftop PV systems on flat roofs, with a 15° tilt orientated east and west, and 2) building façade PV systems, south oriented with a 90° tilt. No shadings are defined for the systems. Snow cover is considered by increasing the albedo values during the winter months, as shown in the table. Two system sizes are simulated in each orientation, to develop a scalable 1 kW_p PV system based on the average, since variations can occur between simulated systems in PVsyst. The area suitable for PV on the 121 building blocks varies. Analysing internet maps, it seems that around 600 m^2 roof area may be available on the most suitable buildings, while other building might be evaluated as not suitable at all, due to shadings or roof conditions. In this article, it is roughly estimated that a 50 kW_p system can be placed on one third of the buildings, giving a total of 2,000 kW_p on the roofs. For the systems placed on the façades, less suitable area is available. Assuming that a 12 kW_p system can be placed on one third of the buildings, the total potential is about 500 kW_p on the façades.

Climate data for 2018 collected from eKlima [7] is imported to PVsyst. The outdoor temperatures are mainly from a weather station at Risvollan, where a few missing values are replaced with data from weather station Voll, 2.5 km away. The wind data are also from Voll, while the global radiation is from the weather station Gløshaugen, 3 km away. Based on the 2018-climate data, PVsyst creates hourly meteo-data for the simulations, where the annual horizontal global irradiation is 868.3 kWh/m^2, the horizontal diffuse irradiation 432.96 kWh/m^2 and ambient temperature 5.49°C.

Based on analysis of electricity loads in 2018 [4], this analysis uses load data from 1,009 apartments (95%), 22 electricity meters in garages (88%) and 82 electricity meters in other common areas (92%), excluding metering points with less than 7000 hours of data. Still some missing measurement periods remain, mainly in January, where only 67% of garages, 76% of other common areas and 72% of the apartments are measured. From February, most AMS meters are installed.

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To evaluate the results, the self-generation, self-consumption and generation multiple factors are calculated based on hourly values. The 'self-generation factor', is the percentage of the electrical demand that is covered by on-site electricity generation [8]. The 'self-consumption factor' is defined as the percentage of the on-site generation that is used by the buildings [8]. 'Generation multiple factor' is the ratio between exported and imported peak powers [8].

A range of PV capacities are chosen, up to the maximum of 2,000 kW_p rooftop and 500 kW_p façade PV systems, with capacity steps of 0, 50, 100, 500, 1,000 and 2,000 kW_p. The aim of the chosen steps is to illustrate changes in the key performance indicators (KPIs) with changing PV capacities. In the analysis, the main focus in on the KPI self-consumption, since this is a financial important KPI with the Norwegian tariff structure. When comparing KPIs for several smaller PV systems to a large PV-system, the smallest capacity step of 50 kW_p is chosen for the 22 individual systems, with an aggregated capacity of 1,100 kW_p, which is the capacity used for the single large system. Both the electricity loads and the simulated PV electricity generation are analysed using the statistical computing environment R [9].

Table 1. Input data and system information for the simulated PV systems, with climate data for 2018.

Location	Latitude 63.39° N, Longitude 10.44° E, Altitude 116 m					
Horizon	From GVGIS website API					
Monthly albedo values	Dec, Jan, Feb, Mar, Apr: 0.4, May, Jun, Jul, Aug, Sep, Oct, Nov: 0.2					
PV module	Si-poly, 285 W_p, 72 cells (generic), 14.78% efficiency at STC					
Inverter	12 kWac inverter (generic)					
Orientations, tilts/azimuths	**Rooftop**: 15°/-90° and 15°/90°			**Façade**: 90°/0°		
PV capacity (kW_p)	42.8	68.4	**1**	12.82	42.8	**1**
Nb. modules	150	240	**-**	45	150	**-**
Module area (m^2)	291	466	**6.8**	87.3	291	**6.8**
Nb. inverters	3	5	**-**	1	3	**-**
Inverter power (kW_{ac})	36	60	**-**	12	36	**-**
Produced electricity (MWh/year)	32.25	51.58	**0.75**	10.26	34.18	**0.80**
Specific prod. (kWh/kWp/year)	754	754	**754**	800	800	**800**

3. Results

The total average specific electricity use in 2018 was approx. 56.7 kWh/m^2, used in apartments and common areas [4]. Average specific use of district heating was approximately 139 kWh per heated floor area [5]. In this article, only the electricity use is analysed with simulated PV electricity.

3.1. Analysing electricity generation from PV with electricity use in the housing cooperative

Table 2 summarizes KPIs for analysing electricity demand at Risvollan with simulated PV electricity. Both electricity and climate data are from 2018. The results are for the housing cooperative in total, where hourly electricity load from several AMS meters are aggregated.

In the following, the results are analysed for the common areas only, followed by the total Risvollan. For the common areas it is simulated that a 50 kW_p, 100 kW_p or a 2,000 kW_p PV system on the roof could cover about 6.5%, 12.3% or 35.3% respectively, of the electricity use on an hourly basis (self-generation factor). For the façade systems, the self-generation factor for a 50 kW_p PV system is 6% higher than for the rooftop system, and 30% lower for the larger 500 kW_p system. For the 50 kW_p rooftop PV system, nearly all (99.9%) of the generated electricity can be used by the common areas (self-consumption factor). For larger rooftop systems of 500 kW_p or 2,000 kW_p, the self-generation factor is declined to 41.5% or 13.5% respectively. For the façade systems, the range of the self-consumption factor for the common areas is from 100% for the smallest PV system at 50 kW_p, down to 27.6% for the largest PV system at 500 kW_p. For both the roof and wall systems, the ratio between exported and imported peak powers is 0.1 for the 50 kW_p PV system and 0.3 for the 100 kW_p PV system (generation multiple factor). For a 500 kW_p system the generation multiple factor increases to 2.4 for a rooftop system and to 3.1 for a building façade system. For the 2,000 kW_p rooftop system the generation multiple factor is increased to 10.4.

For the total Risvollan, the three KPI factors change. It is simulated that a 500 kW_p PV system would cover about 8% of the loads and a 2,000 kW_p PV system would cover about 23.3%, on an hourly basis. For the façade systems, with maximum capacity of 500 kW_p PV, the self-generation factor is slightly higher than for the rooftop system. The self-consumption factor for a 500 kW_p PV system on both roof and the façades is about 100%. For a 2,000 kW_p PV system, the self-consumption factor is around 77% for a rooftop system, with a ratio between exported and imported peak powers of 0.8.

Table 2. KPIs for analysing electricity use with simulated PV electricity (2018- electricity/climate data).

Type of user (# el meters)	Electricity demand (MWh/y)	Max. load (kWh/h)	PV capacity (kW_p)		Simulated gen. (MWh/y)		Self-gen. (%)		Self-cons. (%)		Gen. multiple	
			Roof	Façade	Roof	Façade	Roof	Façade	Roof	Façade	Roof	Façade
Electricity	576	129	50	50	38	40	6.5	6.9	99.9	100	0.1	0.1
common areas			100	100	75	80	12.3	12.7	94.0	91.3	0.3	0.3
(hourly sum of			500	500	377	400	27.2	19.1	41.5	27.6	2.4	3.1
104 el meters)			1,000		754		31.9		24.4		5.0	
			2,000		1,507		35.3		13.5		10.4	
Total electricity,	4,977	1,126	50	50	38	40	0.8	0.8	100	100	-	-
apartments and			100	100	75	80	1.5	1.6	100	100	-	-
common areas			500	500	377	400	7.6	8.0	100	100	-	-
(hourly sum of			1,000		754		14.7		96.8		0.2	
1,113 el meters)			2,000		1,507		23.3		77.1		0.8	

Figure 3 shows analysis of electricity demand with simulated PV generation, using electricity and climate data from 2018. The electricity demand shown is for the common areas (figures in column 1), and in total, also including apartments (figures in column 2). The sizes of the PV systems shown are 100 or 500 kW_p for the common areas and 500, 1,000 or 2,000 kW_p for the total housing cooperative. The electricity load and PV generation on a monthly basis is shown in Figure 3 a) and b), for PV systems on the roof or façade. The figures show that the façade-placed south oriented systems generate more electricity during the swing seasons, compared to the rooftop east-west oriented systems, but have a lower electricity generation during the summer months. In Figure c) and d), hourly duration curves are shown, for net electricity load (positive values: import from grid, and negative values: export to grid). The figures show how the export increases, if the PV system is large compared to the electricity demand, giving a high generation multiple factor. Figure e) and f) shows example of hourly load and generation during a week in April, showing daily variations in electricity use and PV generation. Average daily electricity profiles is shown in Figure 3 g) and h), for load and PV generation on roofs or façades during spring (Mar, Apr, May) and summer (Jun, Jul, Aug).

3.2. Comparing KPIs for a large PV-system to several smaller PV systems

Table 3 summarizes KPIs for several smaller PV system, compared to one large PV system with the same aggregated PV capacity. AMS measurements from the garages are analysed individually, where hourly electricity generation from 22 rooftop PV systems, each with a capacity of 50 kW_p, are located behind the meter of each of the 22 garages. As a comparison, a single large rooftop PV system with a capacity of 1,100 kW_p is delivering electricity to the garages aggregated, to the common areas (including garages), or to the total Risvollan housing cooperative (including common areas and apartments). Figure 4 shows hourly duration curves for net electricity from or to the grid, comparing the 22 rooftop 50 kW_p PV systems with a single rooftop 1,200 kW_p PV system.

Due to the tariff structure in Norway, it is normally financially beneficial to maximise self-consumption, i.e. minimising export of electricity to the grid. Table 4 compares the financial values of four system solutions; 1) 22 PV systems of 50 kW_p, providing electricity to 22 garages only, 2) 1 PV system of 1,100 kW_p providing electricity to 22 garages only, 3) 1 PV system of 1,100 kW_p providing electricity to all common areas (incl. garages) and 4) 1 PV system of 1,100 kW_p providing electricity to all of Risvollan (incl. apartments and common areas). The tariff estimations are based on [10] and [11], and is 1 NOK/kWh for self-consumed PV-electricity, which is the estimated end-user cost for electricity from the grid, and 0.5 NOK/kWh for exported PV-electricity. Only electricity costs are considered, assuming that the choice of PV system solution would not change the investment costs.

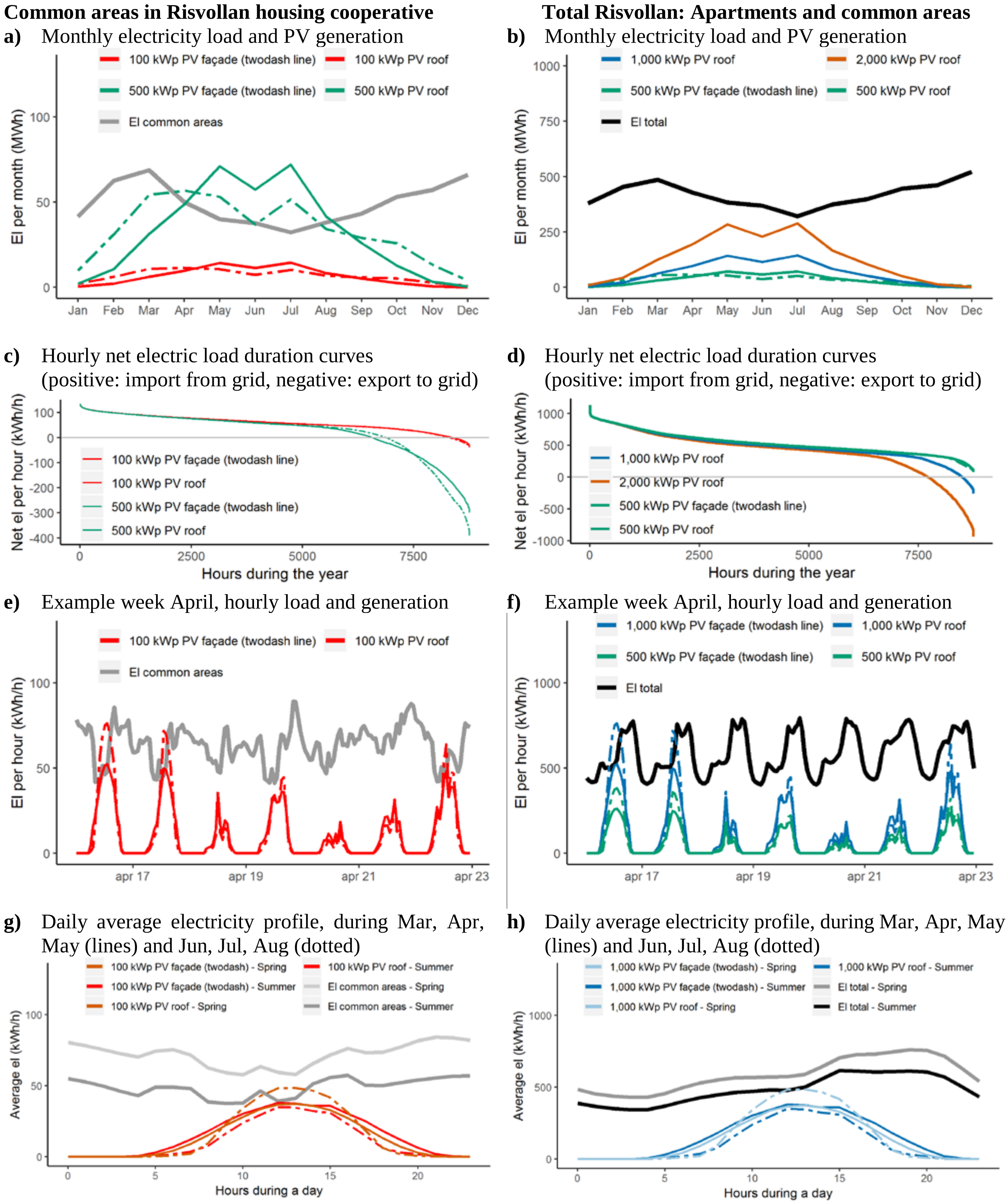

Figure 3. Analysing electricity use in Risvollan housing cooperative with simulated PV generation.

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Table 3. KPIs for analysing electricity use with simulated PV electricity (2018- electricity/climate data). All the PV systems are east-west oriented rooftop systems with a total capacity of 1,100 kW_p.

KPIs for 22 individual PV systems, located behind 22 garage meters:

	Electricity (MWh/y)	Max. load (kWh/h)	PV capacity (kW_p)	Simulated gen. (MWh/y)	Self-gen. (%)	Self-cons. (%)	Gen. multiple
El garages (22 el meters)	Per garage: Max: 56 Mean: 17 Min: 5	Per garage: Max: 34 Mean: 7 Min: 3	22·50 Tot: 1,100	22·38 Tot: 829	Per garage: Max: 46.4 Mean: 34.9 Min: 17.1	Per garage: Max: 31.8 Mean: 14.3 Min: 3.2	Per garage: Max: 11.0 Mean: 6.0 Min: 1.0

KPIs for one large PV system, with aggregated load:

	Electricity (MWh/y)	Max. load (kWh/h)	PV capacity (kW_p)	Simulated gen. (MWh/y)	Self-gen. (%)	Self-cons. (%)	Gen. multiple
El garages	363	91	1,100	829	35.0	15.3	8.1
El common areas	576	129	1,100	829	32.5	22.6	5.6
El total Risvollan	4,977	1,126	1,100	829	15.8	95.0	0.3

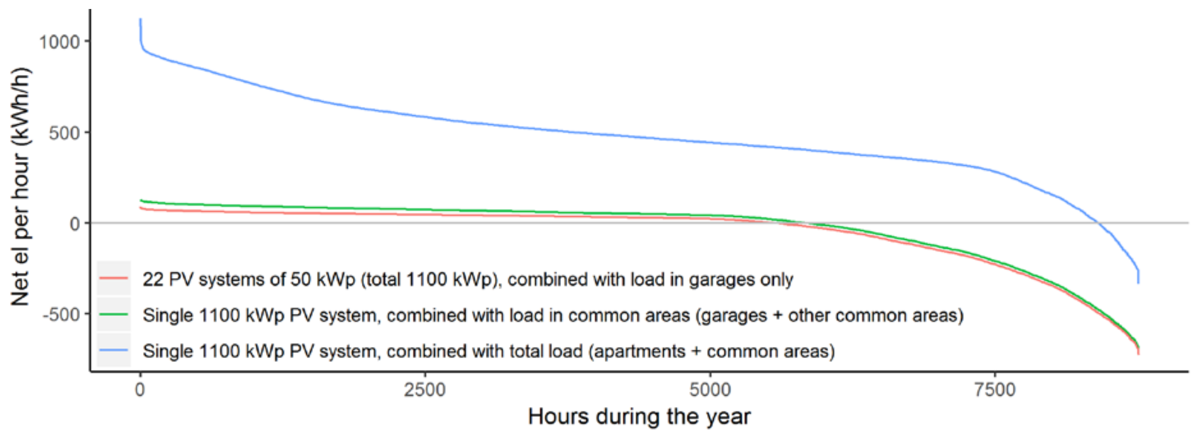

Figure 4. Hourly duration curves for net electricity from/to grid, with 22 rooftop 50 kW_p PV systems or a single rooftop 1,100 kW_p PV system. PV generation from the 22 PV systems cover electricity load in 22 garages. PV generation from the single large PV system cover aggregated electricity loads in all common areas or in the total housing cooperative, including apartments and common areas.

Table 4. Estimation of financial value of PV electricity, comparing four cases with different electricity use, each with a total capacity of 1,100 kW_p rooftop PV system.

Case	Simulated gen.	Self-cons. (%)	Value self-use	Value export	Total annual value
22 PV systems a 50 kW_p, providing electricity to 22 garages only	22·38, Tot: 829 MWh/y	Per garage: Mean: 14.3	121 MWh: 121,000 NOK	708 MWh: 354,000 NOK	475,000 NOK
1 PV system a 1,100 kW_p, providing electricity to 22 garages aggregated	829 MWh/y	15.3	127 MWh: 127,000 NOK	702 MWh: 351,000 NOK	478,000 NOK
1 PV system a 1,100 kW_p, providing electricity to all common areas	829 MWh/y	22.6	187 MWh: 187,000 NOK	642 MWh: 321,000 NOK	508,000 NOK
1 PV system a 1,100 kW_p, providing electricity to all of Risvollan (incl. apartments and common areas)	829 MWh/y	95.0	788 MWh: 788,000 NOK	41 MWh: 20,000 NOK	808,000 NOK

4. Discussion

As a basis for energy management in apartment blocks, this article analyses the electricity demand at Risvollan together with simulated electricity generation from several different PV systems. The total electricity use included in the analysis is 4,977 MWh, where 12% is used in common areas and 88% in 1.009 apartments. It is estimated that the total electricity delivery to Risvollan in 2018 was 5,318 MWh [4], meaning that 6% of the annual electricity use is excluded or missing from this analysis. If all measurements had been available, the KPI factors would have changed slightly. Electricity generation from PV is simulated based on climate data from 2018. The climate data is therefore not general, and

2018 was a year with higher temperatures and less rain than normally [12]. In addition, no shadings were assumed in the simulations, which is rather optimistic. The simulated PV generation may therefore be higher than can be expected in real life.

Comparing the simulated electricity generation on roofs and walls, the façade systems generate about 5-6% more electricity than the rooftop systems on an annual basis. The systems on the façades generate more electricity in the spring, autumn and winter, because of the steeper PV array angle [13]. A south-oriented 100 kW_p system on the façade generates 11% of its electricity during winter, 41% in the spring, 31% in the summer and 17% in the autumn, while the seasonal division for the east-west oriented rooftop system is 4%, 40%, 45% and 11% accordingly. This is positive for the self-generation and self-consumption factors, since PV electricity can cover electricity demand in the swing seasons. However, the wall-placed system is orientated towards south, which gives a higher midday peak than the rooftop east-west oriented systems. More PV power is available during morning or afternoon hours for east west oriented systems [13]. A higher electricity generation early and late in the day is positive for the matching with electricity use. The systems with highest self-generation factor therefore varies: For the smaller PV capacities it is the rooftop systems and for the larger PV capacities it is the façade systems. For the self-consumption factors, the rooftop systems have the highest values. More electricity is exported with the façade systems, giving a higher generation multiple factor. In general, the performance of the façade systems is somehow better than the rooftop systems. However, the area available for façade systems is limited, and it may be advisable with a combination of the two orientations.

The KPIs are calculated based on hourly values. If calculating the factors based on 15 minutes, daily or monthly intervals, the results would differ. For example, for the 500 kW_p PV system providing electricity to all common areas, the self-consumption factor of 27.2% based on hourly measurements, increases to 45% or 48% if calculated based on daily or monthly values. The self-generation factor is 41.5% based on hourly values and increases to 69% or 74% based on daily or monthly values. The generation multiple factor of 2.4 based on hourly values, decreases to 1.0 or 0.6 based on daily or monthly values. It is expected that the self-consumption and self-generation factors would be somewhat lower, using 15 minutes instead of hourly measurements. For load and generation power flows, shorter time steps give more realistic values for how a real system works. However, when estimating financial values, it is usually more relevant to use time steps from the tariff structure.

The self-consumption factor is the most important KPI in Norway, due to the Norwegian tariff structure. When the self-consumption factor is close to 100%, the self-generation factor is around 10% and the generation multiple factor is close to zero, since very little electricity is exported. From the perspective of the housing cooperative, it is therefore beneficial to locate the PV system and the load behind the same AMS meter, or to aggregate electricity loads in the common areas and the apartments. To aggregate electricity load from several AMS meters is currently not possible in Norway, but the authorities plan to facilitate also for housing cooperatives with PV in the prosumer agreement [14]. In principle, all electricity loads in common areas can be behind one AMS meter, but at Risvollan there are 104 such meters, 22 in garages and 82 in other common areas. The annual financial value of the 22 single PV systems of 50 kW_p, providing electricity to 22 garages only was at 475,000 NOK, whereas a single 1,100 kW_p PV system, providing electricity to all common areas (incl. garages), the total value increases with 6%. For the housing cooperative, the best financial option would be to provide PV electricity both to apartments and common areas, increasing the financial value with 70%, to approximately 808,000 NOK per year.

Energy flexibility of Risvollan housing cooperative will be a topic in the further work. According to Annex 67 [15], Energy Flexible Building Clusters should *demonstrate the capacity to react to forcing factors in order to minimize CO_2 emissions and maximize the use of Renewable Energy Sources (RES)*. Electricity loads can be adapted to PV generation, by increasing use of electricity during sunny periods or by storing electricity in heat storages or EVs [13]. EV charging is a main source of flexible electricity use in Norwegian apartment buildings. Besides often being flexible in starting time, duration and charging power [16], EV charging infrastructure is the responsibility of the Risvollan cooperative. A neighbourhood battery could also increase the self-consumption of PV generated electricity.

5. Conclusion

This article analyses the electricity use at Risvollan housing cooperative together with possible electricity generation from PV systems. Risvollan is a large housing cooperative in Norway, built in the 1970s, with in total 1,058 apartments. The study shows that the electricity generation from south-oriented systems on the building façades are about 5-6% higher than for east-west oriented rooftop systems on an annual basis, since the façade systems generate more electricity in the spring and autumn. However, more PV power is available during morning and afternoon hours for the rooftop east-west oriented systems. A combination of PV systems on the roofs and façades seem advisable. The self-consumption factor is the most important KPI in Norway, due to the national tariff structure. For the total housing cooperative, a PV capacity of about 1,000 kW_p seem suitable, giving a self-consumption factor of 97% for a rooftop system, based on 2018 electricity and climate data. From the perspective of the housing cooperative, it is financial beneficial to aggregate electricity loads for common areas and apartments, since a higher share of the electricity can be used by the cooperative. For this to be possible, also housing cooperatives with PV must be facilitated for in the prosumer agreement. Comparing a single 1,100 kW_p PV system providing electricity to the total cooperative with 22 PV systems of 50 kW_p behind 22 garage meters, the self-consumption factor decreases from 95% to average 14%, resulting in a 41% lower financial value for the PV electricity. The analysis will be used in further work, together with analysis of electricity and heat load patterns at Risvollan, aiming to play a role answering how effective management of power and energy at neighbourhood level can be realized.

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