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# Solar energy for residential electric vehicle charging in Northern Norway – a feasibility study

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***Abstract*—This paper presents a study of the potential for using photovoltaic (PV) solar energy systems for residential charging of electric vehicles (EVs) in Northern Norway. The objective is to investigate the load match between PV yield and uncontrolled EV charging, in terms of self-consumption and self-sufficiency. The load profile for EV charging is retrieved from a study by the Norwegian Water Resources and Energy Directorate (NVE), based on measurements and a survey sent to EV owners. An adjusted example EV profile that better represents a single household is also proposed. Other household loads are taken into account using measured data from ten single-family buildings in Tromsø, retrieved from local power company Troms Kraft. The PV yield is simulated for roof-mounted and façade-mounted 4.2 kW$_p$ system with different orientations, using PVsyst. The results show that the load match between PV yield and uncontrolled EV charging is poor, as PV power has a peak at noon and the EV charging is highest during afternoon and night-time. A design option for increased load-match (but lower total yield) is mount the PV system facing west, since the PV power peak is shifted towards the afternoon. Solutions for increasing the load match, provide autonomy and reduce negative impacts on the grid are discussed, for example the use of residential battery storage and controlled EV charging. Based on the results, the authors propose that more focus is given to workplace charging combined with solar energy, since this would increase the load match significantly.**

***Keywords-PV; electric vehicle; EV; charging; household electricity; load mach: solar fraction; load fraction; Norway***

## I. INTRODUCTION

The number of electric vehicles (EVs) is increasing in in many countries. EVs are seen as a solution both to reduce the amount of greenhouse gas emissions from the transport sector and to reduce local air pollution. In order to contribute to the reduction of greenhouse gas emissions, EVs should be charged to as high degree as possible using electricity from renewable energy sources (RES) such as solar energy.

Chargeable electric vehicles (EVs) are divided into battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). In this study, the focus is on BEV, i.e. vehicles with only an electric engine. These will be referred to as EVs in the remainder of the paper.

Norway is in the forefront in terms of EV penetration in the personal vehicle fleet, with a current share of around 5% BEV, or 10% of PHEVs are also included [3]. In the National Transportation Plan for 2018-2029 [4], the Norwegian government states that all new personal vehicles sold should be "zero emission vehicles" by 2025.

The major part of the EV charging in Norway takes place at home. According to a survey by Norwegian Institute of Transport Economics (TØI) [5], 94% of EV owners charge their EV at home, 59% do it daily. According to the same survey, only around 13% charge at work and 2% at public charging stations daily [5]. Based on these figures, it is very relevant to study the effects of residential charging on the grid. While it is recommended to use specialized home chargers, two thirds of Norwegian EV owners charge at home by plugging directly into a normal household plug [5]. The disadvantages of not using home chargers is the increased risk of faults and fires, and the fact that the charging cannot be controlled.

This paper presents a study of the potential for using solar energy for residential charging of electric vehicles in Northern Norway. A residential building in Tromsø (70°N), the largest city in Northern Norway, is used as a case. The objective is to investigate the load-match in terms of self-consumption and self-sufficiency of solar energy with uncontrolled EV charging. In addition, we discuss how the load-match between PV power and EV charging could be improved using e.g. controlled charging or battery storage.

## II. METHOD

### A. Average EV charging profile

A charging profile for EVs was retrieved from Norwegian Water Resources and Energy Directorate (NVE) [1]. The charging profile is based on measurements of a number of different EV charging points (residential charging, workplace charging and fast charging), in combination with two surveys sent to Norwegian EV owners. From these sources, NVE has compiled hourly charging profiles for residential, workplace and fast charging.

The hourly residential charging profile is shown in Fig. 1. It is based on measurements from four residential chargers during 9-12 weeks, combined with around 400 survey responses [1]. The profile is given as an average day of the year, with no difference between winter and summer. According to NVE, the measurements show little difference in the charging profiles on weekdays and weekends [1]. The averaging means that days without charging are also included, and the average charging power is lower than it would be during charging: a maximum of 0.4 kW instead of around 2.3 kW which would be expected from charging from a normal household socket with a 10 A fuse, which is a common in residential charging [1]. In addition, the averaging gives a profile with charging during each hour of the day, which would not be the case if the EVs were also used.

Contrary to what is often assumed, this load profile suggests that most of the residential EV charging in Norway does not take place in the afternoon but during night-time, with a peak around midnight [1]. NVE explains this by the fact that many people do not work during standard office hours (8-16 in Norway), and that many people probably wait to plug in their vehicle until other driving activities are done [1].

### B. Adjusted charging curve

As this study is based on the case of one residential building, the average curve is not useful when looking at the PV and EV load match on individual days. In order to provide a more realistic scenario, a charging profile for an example week was also created. This profile uses the same weekly energy demand as would be the result from the average profile, but adapted to an estimated driving pattern where the EV is used to commute to and from work on weekdays, and used for one longer trip (30 km) during the weekend (here assumed to be on Sunday).

Assuming that an EV has and energy demand of around 0.2 kWh/km, which is used in the NVE study [1], the annual commuting distance per day can be up to 13.5 km in each direction with the specified weekly energy demand. Furthermore, we have assumed that the EV is plugged in for charging at 18.00 on weekdays and 17.00 on weekends, based on the average profile. The commuter charging profile is shown in Fig. 1.

### C. Household energy use

The household energy use in Tromsø was estimated based on measured data for ten randomly selected single-family houses in Tromsø, received from local power company Troms Kraft [2]. The data was given as hourly readings for one year (1 August 2017 to 1 August 2018). An average of the ten houses were calculated and is used here as a reference profile, which is shown in Fig. 2. The total annual energy demand of the ten buildings was on average 31 600 kWh, but the range was between 21 500 kWh and 44 500 kWh. The electricity demand in Norwegian households is generally high, since many buildings have direct electric heating.

The hourly profiles for four days in winter, spring, summer and autumn are shown in Fig 3. The commuter EV profile described in Section II.B is added to the right graph, while the average profile described in Section II.A is added to the right graph. The energy demand has a strong seasonal dependence, due to the use of electric heating.

### D. PV simulation

The PV power output was simulated in PVsyst [7] using meteorological data from Meteonorm 7 [8]. Optimal orientation of a PV system in Tromsø is around 50° and south-facing. However, to provide a more realistic residential case, a PV system with 30° tilt angle (roof-mounted) and a façade-mounted PV system were simulated. In addition, south-facing, east-facing and west-facing systems were considered.

The simulated system had an installed power of 4.2 kWp, which was estimated to be around the average for new residential systems in Norway. It was made up of 300 kWp modules (18.42% STC efficiency) and had a total module area of 22.9 m2. A 3.6 kW inverter with 98.03% efficiency is used, giving a power ratio (PV array/inverter) of 1.17.

The PV simulation results are given in hourly values over the year. For a system with optimal orientation (52° south-facing), the simulated annual energy output was 800 kWh/kWp. However, recently compiled measurement values from a PV array at UiT in Tromsø show that an optimally inclined system in Tromsø actually has a yield of around 850 kWh/kWp for a year with average insolation. The annual simulated PV yield is 770 kWh/kWp for a 30° tilted south-facing system, and 620 kWh/kWp for a façade-mounted system (90° tilt).

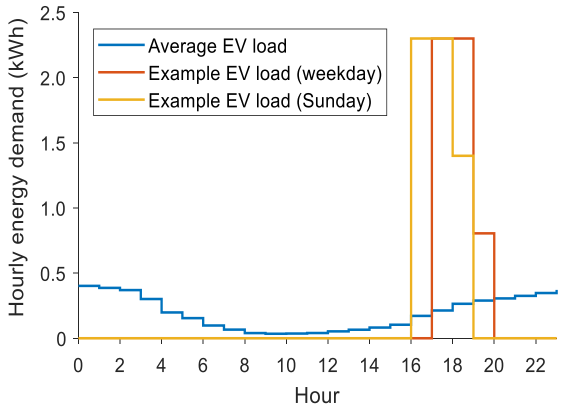


Figure 1. The average hourly EV load retrieved from NVE [1], shown together with the cummuter EV load described in Section 0. Note that the two profiles result in the same weekly energy demand.

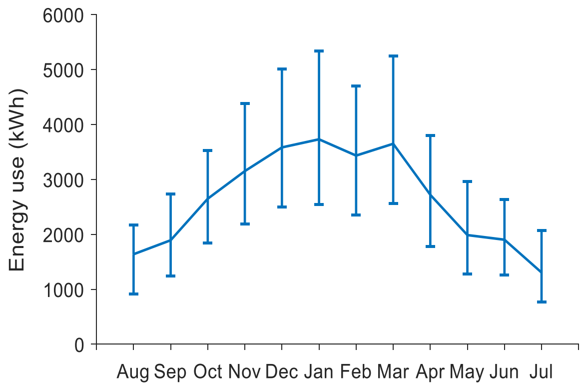


Figure 2. The average monthly energy demand from then single-family buildings in Tromsø, with the highest and lowest value for each month shown with error bars. Data from Troms Kraft [2].

### *E. Self-sufficiency and load-coverage*

The PV simulations were combined with the EV load profile to estimate the load match in terms of self-sufficiency, i.e. to what degree solar energy contributes to the load, and self-consumption, i.e. to what degree the available solar energy is used directly. The rate of self-sufficiency and self-consumption of solar energy are described by the solar fraction, SF, and the load fraction, LF, respectively.

Using the terminology from [6] and [7], the solar fraction is defined by

$$SF = \frac{\int_{t=t_1}^{t_2} M(t)dt}{\int_{t=t_1}^{t_2} L(t)dt}, \tag{1}$$

where *M(t)* is the instantaneously overlapping part of the PV generation profile, *P(t),* and the load profile, *L(t),* defined by

$$M(t) = \min\{L(t), P(t)\}. \tag{2}$$

Correspondingly, the load fraction is defined as [6, 7]

$$LF = \frac{\int_{t=t_1}^{t_2} M(t)dt}{\int_{t=t_1}^{t_2} P(t)dt}. \tag{3}$$

Both SF and LF depend on the period ($t_1$ to $t_2$) over which they are calculated. A high SF value indicates that the load is to a high degree covered by solar energy, which can either be the result of a good temporal coincidence, a high PV yield or a low load. A high LF value, on the other hand, indicates that the PV yield is to a high degree used to cover the load. This can be the result of a good temporal coincidence, but also of a low PV yield.

## III. Results

### *A. Self-sufficiency and self-consumption*

The solar fraction values, calculated for three whole months in spring, summer and autumn (March, June and October), are shown in Table 1. The table also shows both the largest PV daily surplus and the largest EV load daily deficit. during the month, calculated as the sum of the surplus and deficit in each time step. For the EV charging to be completely self-sufficient from solar without energy electricity from the grid, the 24 h EV deficit is the required energy storage capacity. The values are shown for the average EV profile as well as the example EV profile.

The total monthly energy balance between PV generation and EV load is also shown in Table 1, not taking the temporal distribution into account. The energy balance does not depend on which EV load profile is used since the weekly energy demand is the same in the two profiles, except that the load in the adjusted EV profile is different between weekdays and weekends and thus depends on the days in the month. The balance for the average load is shown in Table 1. The balance is positive, i.e. the solar energy exceeds the EV load, for March and July but not for October, regardless of system orientation. The exception is the 30° tilt east-facing system, where the balance is negative also for March.

For the average EV profile, the largest values for SF is achieved for the systems facing west (Table 1). The PV yield curve for a week in June is shown for three different PV system orientations (30° facing south, east and west) in Fig. 4, together with the EV load. The west-facing system has a PV yield profile that is shifted towards the afternoon compared to the other orientations. The west-facing system therefore has a higher temporal coincidence with the EV load, and consequently results in a higher solar fraction.

For the adjusted EV profile, there is practically no load match for most of the systems, and both SF and LF are close to zero (Table 1). The exception is the west-facing system with 30° tilt, which actually reaches a SF of 0.58 during June. The

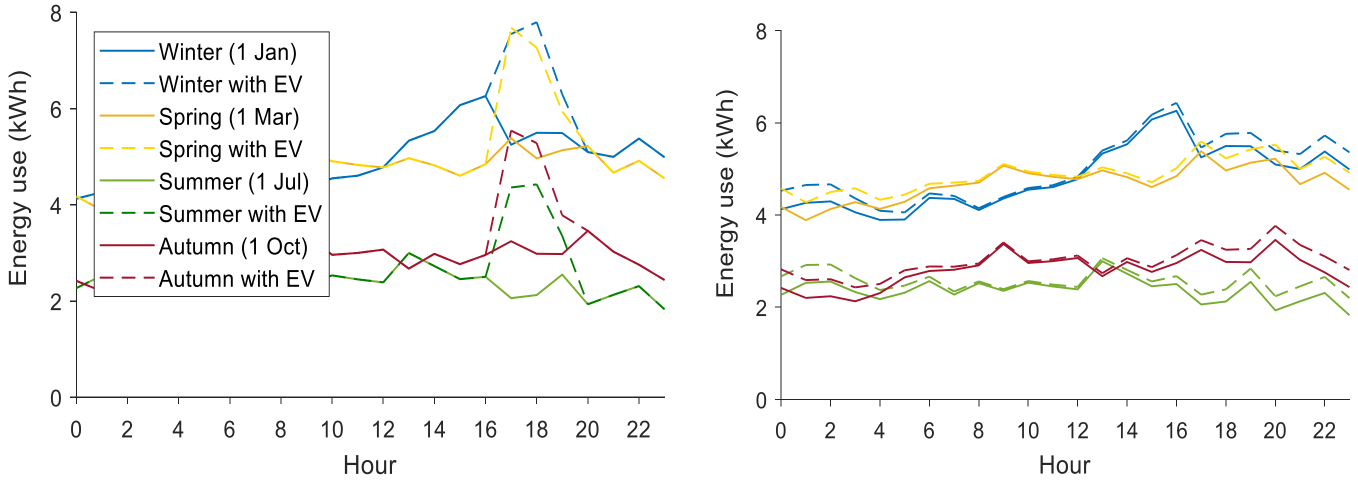


Figure 3. The average hourly energy use in ten single-family buildings in Tromsø during four days in winter, spring, summer and autumn. The example EV load profile described in Section II.B is added to the energy demand in the left graph, and the average EV load profile described in Section II.A is added in the right graph.

TABLE 1. THE SOLAR FRACTION (SF) AND LOAD FRACTION (LF) FOR THREE DIFFERENT ORIENTATIONS OF THE PV SYSTEM DURING ONE MONTH IN SPRING, SUMMER AND AUTUMN. THE MAXIMUM 24 h PV SURPLUS AND EV LOAD DEFICIT DURING EACH MONTH IS ALSO SHOWN.

| **Orientation** | **Month** | **Average EV profile** | | | | **Example EV profile** | | | | **Monthly energy balance** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **SF** | **LF** | **24 h PV surplus (max)** | **24 h EV deficit (max)** | **SF** | **LF** | **24 h PV surplus (max)** | **24 h EV deficit (max)** | |
| | | - | - | ***kWh*** | ***kWh*** | - | - | ***kWh*** | ***kWh*** | ***kWh*** |
| **30° south** | March | 0.15 | 0.06 | 17.3 | 4.3 | 0.01 | 0.01 | 18.2 | 6.0 | 126 |
| | June | 0.45 | 0.10 | 29.1 | 3.1 | 0.20 | 0.10 | 29.7 | 4.9 | 325 |
| | October | 0.07 | 0.10 | 11.6 | 4.6 | 0.00 | 0.00 | 12.1 | 6.0 | -51 |
| **52° south** | March | 0.15 | 0.05 | 20.4 | 4.3 | 0.02 | 0.01 | 21.0 | 6.0 | 182 |
| | June | 0.41 | 0.12 | 27.6 | 3.2 | 0.17 | 0.05 | 28.6 | 5.0 | 288 |
| | October | 0.07 | 0.08 | 14.8 | 4.7 | 0.00 | 0.00 | 15.4 | 6.0 | -28 |
| **90° south** | March | 0.14 | 0.05 | 19.5 | 4.3 | 0.01 | 0.00 | 20.3 | 6.0 | 268 |
| | June | 0.29 | 0.13 | 18.5 | 3.7 | 0.06 | 0.03 | 19.5 | 5.4 | 142 |
| | October | 0.06 | 0.07 | 15.5 | 4.7 | 0.00 | 0.00 | 16.0 | 6.0 | -14 |
| **30° east** | March | 0.13 | 0.11 | 9.8 | 4.3 | 0.00 | 0.00 | 10.6 | 6.0 | -14 |
| | June | 0.52 | 0.16 | 26.2 | 3.1 | 0.13 | 0.04 | 28.8 | 5.5 | 312 |
| | October | 0.07 | 0.26 | 3.2 | 4.6 | 0.00 | 0.00 | 3.7 | 6.0 | -112 |
| **30° west** | March | 0.15 | 0.11 | 11.4 | 4.3 | 0.04 | 0.03 | 12.4 | 6.0 | 7 |
| | June | 0.55 | 0.15 | 25.7 | 3.1 | 0.58 | 0.16 | 23.5 | 4.9 | 275 |
| | October | 0.08 | 0.17 | 5.7 | 4.6 | 0.00 | 0.00 | 6.2 | 6.0 | -89 |

adjusted EV profile is shown in Fig. 4 together with the average EV load and the PV yield for three system orientations.

For the average profile, the self-consumption (LF) never reaches higher values than 0.17, but is for most of the calculations in the range 0.05-0.11. This indicates that a small fraction of the solar power is used directly for charging the EV, and that most of the solar energy would need to be either exported to the grid or stored in e.g. a residential battery storage.

## B. *EV and household load*

The combined EV and household load is shown together with the PV yield during a week in June in Fig. 5. The yield for three PV system orientations are shown: 30° facing south, east and west. In Fig. 6, the EV and household load during one week in March is shown, together with the PV yield for four system orientations: 30° facing south, and 90° facing south, east and west. As the figure shows, the façade-mounted systems has a higher yield during this time of year.

The combined household and EV load is higher than the PV yield during most of the time, except for a few hours during midday in June. Similarly to the case with only EV load, the west-facing system has a higher solar fraction than the south-facing systems, since the PV yield is slightly shifted towards the afternoon when both the EV load and the household load is at its highest.

## C. *Annual energy demand*

While the main purpose of the study was to study the self-sufficiency and self-consumption of solar energy during different times of the year, it is also interesting to look at the

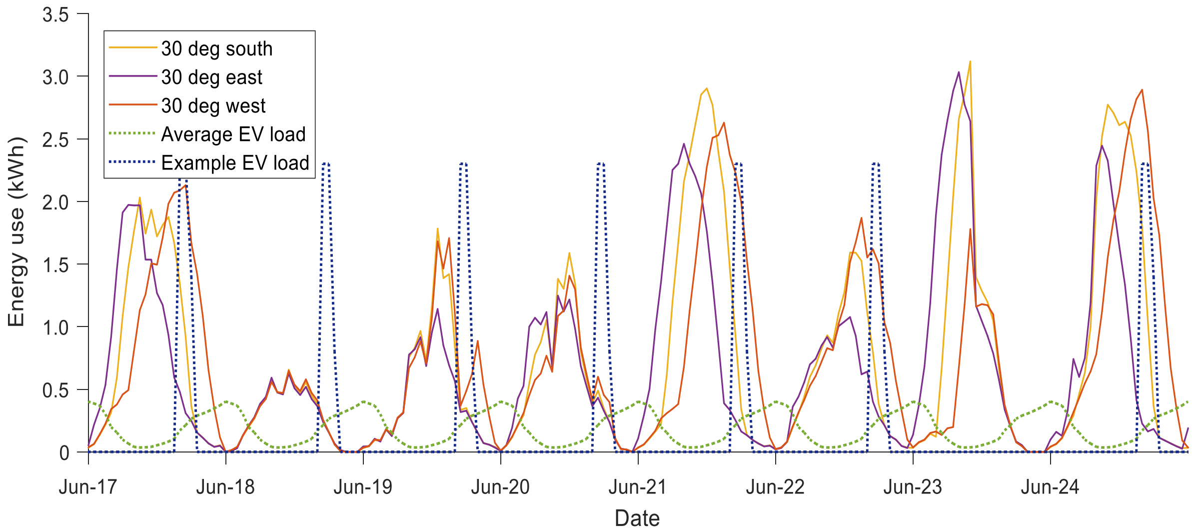


Figure 4. The PV yield for during one week in June for three 4.2 $kW_p$ PV system orientations (30° facing south, east and west), shown with the average EV load profile described in Section II.A and the example EV load profile described in Section 0.

total energy demand and PV yield. The minimum required PV system size was determined based on the energy yield from the PV system simulations. In this calculation, it is assumed that there are no restrictions regarding the exchange with the power grid.

To cover only the EV load, the required size for a PV system ranges from 2.2 $kW_p$ (12 $m^2$) for a south-facing system with 30° or 52° tilt, to 4.1 $kW_p$ (22 $m^2$) for an east-facing façade-mounted system. If the systems should also cover the household electricity load, the range is 41.7-9.3 $kW_p$ (227-432 $m^2$) for the average household or 29.0-55.3 $kW_p$ (158-301 $m^2$) for the household with the lowest electricity demand.

While the PV system sizes required to cover the full load are high, it should be noted that covering of the complete household load with PV might not be a reasonable objective, since the main electricity load from heating occurs during the season with little solar radiation. In this case, it would be better to first reduce the electricity demand through energy-efficiency measures, and to complement a PV system with other renewable energy sources such as a ground source heat pump.

## IV. Discussion

In this study, the load match in terms of self-sufficiency (SF) and self-consumption (LF) was studied. A higher load match means that less solar power needs to be exported to the grid, and that less power needs to be imported from the grid. In a weak distribution grid, it is especially desirable to limit the power levels drawn from the grid, i.e. a high self-sufficiency is sought. Nevertheless, high levels of solar power injected to the grid can also cause problems, especially in areas with a large number of similarly oriented PV systems.

For the energy consumer, or the so-called prosumer (producer and consumer), a high self-sufficiency means that less power has to be bought from the grid. In some cases, power tariffs also make it more expensive to use high power levels. In addition, a high self-consumption is often desirable since less solar power has to be sold to the grid. Even if the prosumer can sell the solar power to the power company, this is often at a lower price than the energy bought.

The easiest way to improve the load match between PV and household energy demand is to install west-facing systems instead of south facing systems, even though the latter has a higher total energy yield.

A residential battery storage can be used in order to further increase the self-sufficiency and self-consumption. To make the studied PV-EV system completely autonomous, i.e. independent of the grid, would require a very large battery storage. Due to the low load-match, the battery would need to store more or less all the excess solar energy generated during the day, that is, up to 30 kWh. With a smaller battery, it would be necessary to cut off PV production, reducing the overall efficiency of the system. A more feasible solution would be to decrease the size of the PV system in order to match the highest peak load.

To keep the EV charging independent of the grid, if this is would be desired, would require a much smaller battery. Due to the seasonal variation in PV yield over the year, it would be necessary for the battery to provide the full daily EV energy demand during winter, which is 4.7 kWh in this case, to ensure energy autonomy. During summer, however, the required battery storage capacity is only around 3 kWh for several of the system orientations.

A further method to improve the load match is to apply some form of charging control strategy. However, in the example EV load case where the EV was used for daily commuting to work, it is difficult to present an appropriate charge control strategy since the EV is away from home during most of the time with high enough solar radiation levels. Disregarding the load match with PV, a viable charging strategy could be to limit the total peak power demand of the combined household and EV load. The EV could charge at a lower power and shifted towards night time, when the household energy use is lower.

To increase the use of solar energy in EV charging overall, the most effective way is probably to increase the use of workplace charging. When the EV is charged during normal work hours, the load match with solar energy is significantly improved during most of the year, and the authors recommend an increased use of workplace EV charging in combination with PV systems. In combination with workplace charging, it is also of interest to investigate the opportunities related to vehicle-to-grid (V2G) technology, where EVs can be used as mobile energy stores. For example, EVs that are charged using solar energy at the workplace during the day could be used to provide stored solar energy to residential buildings during night, which would reduce the dependence of the grid and potentially increase the renewable energy share of the energy consumption. The storage capacity of current EV batteries (around 20-100 kWh) is quite close to the daily energy demand in households—the average daily demand for the measured buildings in Tromsø was 59-122 kWh. This means that an EV could provide a significant share of the household energy, even if it also requires some energy for driving.

## V. Conclusion

An analysis of a residential EV charging in Tromsø has been presented. The analysis includes a study of the load match between the charging and a residential PV system with different orientations. Two charging profiles, one average and one showing the case of a daily commuting, were used, in addition to measured data on household energy demand of a single-family building in Tromsø.

In general, the load match between an uncontrolled residential EV charging and a PV system is poor. Based on the findings in the presented study, possible solutions to increase the load match were proposed. The easiest way to increase the self-consumption for residential PV systems, both in the case of only EV load and with EV and household load, was to orient the PV system facing west instead of south, since this shifted the PV yield towards the afternoon.

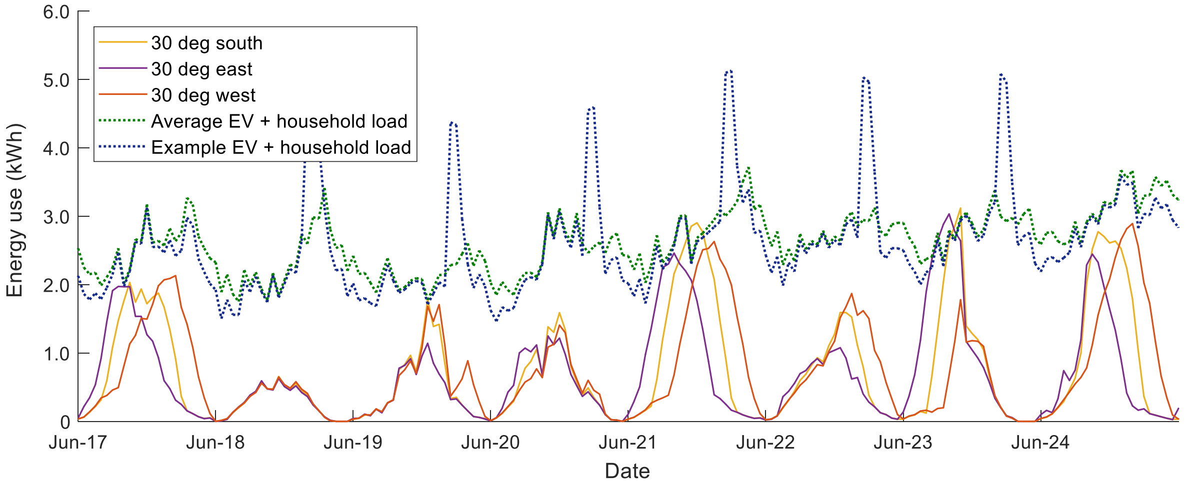


Figure 5. The PV yield for during one week in June for three 4.2 $kW_p$ PV system orientations (30° facing south, east and west), shown with the average EV load profile described in Section II.A and the example EV load profile described in Section 0, in addition to the average household energy load described in Section II.C.

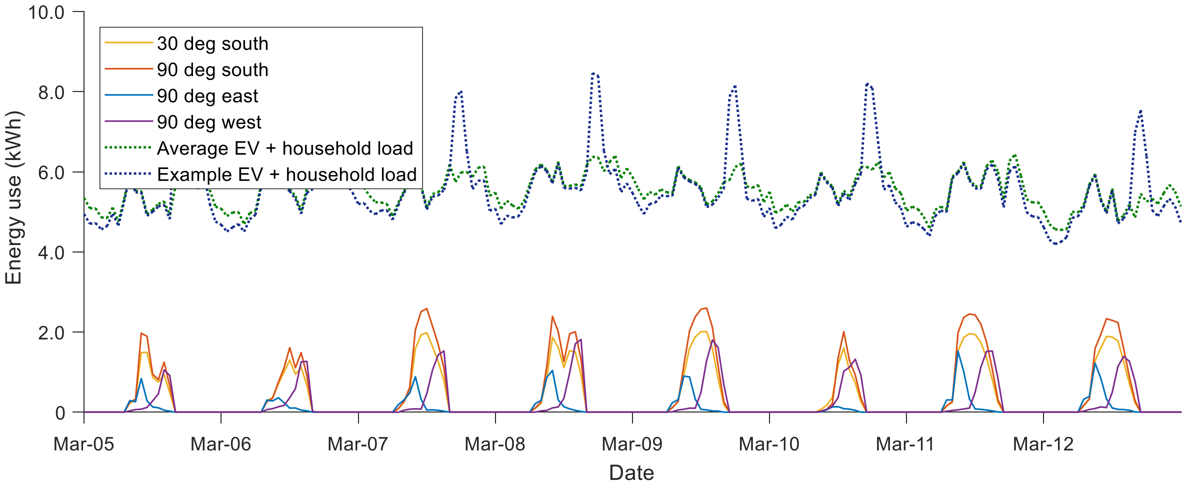


Figure 6. The PV yield for during one week in March for four 4.2 $kW_p$ PV system orientations (30° facing south and 90° facing south, east and west), shown with the average EV load profile from Section II.A and the example EV load profile from Section 0, in addition to the average household energy load described in Section II.C.

Battery storage can be used, but to a very large storage capacity would be required make an EV-PV system completely grid-independent. Controlled charging is another solution, although since the solar availability coincides with the hours when an EV is normally not at home, it is difficult to present an appropriate charging strategy to increase the solar fraction of residential EV charging.

Based on the poor load match between PV yield and EV load in residential applications, the authors suggest that further investigations focus on workplace EV charging using solar energy. This also includes opportunities for vehicle-to-grid (V2G) technology, where EVs can be used as mobile stores for renewable energy.

## Acknowledgment

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## References

[1] Skotland, C.H., E. Eggum, and D. Spilde, *[What does the electric vehicle mean for the power grid?] Hva betyr elbilen for strømnettet?*, C.H. Skotland, Editor. 2016, Norges energi og vassdragsdirektorat, NVE: NVEs hustrykkeri, Oslo.

[2] Troms Kraft, *Measured data from ten randomly selected single-family residential buildings in Tromsø*. 2017-2018.

[3] Statistics Norway (SSB), *Over 140 000 electric cars in Norway*. 2018: Online.

[4] *[The Norwegian National Transport Plan 2018-2029] Nasjonal Transportplan 2018-2029*, in *Melding til Stortinget* 2017.

[5] Figenbaum, E. and M. Kolbenstvedt, *Learning from Norwegian Battery Electric and Plug-in Hybrid Vehicle users - Results from a survey of vehicle owners*. 2016: Oslo, Norway.

[6] Munkhammar, J., P. Grahn, and J. Widén, *Quantifying self-consumption of on-site photovoltaic power generation in households with electric vehicle home charging.* Solar Energy, 2013. **97**(Supplement C): p. 208-216.

[7] Luthander, R., J. Widén, D. Nilsson, and J. Palm, *Photovoltaic self-consumption in buildings: A review.* Applied Energy, 2015. **142**: p. 80-94.