Electricity Self-Sufficiency and Primary Energy Use in a Swedish Residential Community, after Building Renovation and Implementation of Photovoltaics, Small-Scale CHP, and Electric Vehicles

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ABSTRACT

In order to mitigate the potential harmful effects of global warming reduced energy use, increased share of renewable energy, and decreased use of fossil fuels are essential measures. EU policy obliges the member states to reduce building energy use, increase renewable energy utilization, and encourage combined heat and power production. Technologies for photovoltaic solar cells and electric vehicle batteries are getting cheaper and thus increase their market shares. How will this affect the energy systems in total?

In this article a Swedish residential area with single-family houses is investigated. Three building types in the area are identified, for which energy balance simulation models are constructed. Energy balances are simulated before and after renovation. The heat demand from the energy balance simulations is used to calculate fuel use, heat production, and electricity generation in a biomass fueled combined heat and power unit. Aggregated household electricity demand including energy-efficient appliances and electricity demand for home charging of electric vehicles is simulated. Power production from roof mounted photovoltaic panels is simulated. The electricity self-sufficiency and primary energy use are calculated.

Results show that the degree of community electricity self-sufficiency is 43% and that the primary energy use is significantly reduced with improved energy efficiency in buildings, implementation of local electricity production, and use of electric vehicles. If home charging of electric vehicles is not included the self-sufficiency increases to 69%.

Introduction

To mitigate the consequences of global warming and keep the average global temperature increase below 2 °C, worldwide measures must be taken to reduce primary energy use, increase the share of renewables in the energy supply, and decrease the use of fossil energy resources. The European Union (EU) has through a number of directives signaled its intention to transform the energy system in this direction.

The recast of the Energy Performance of Buildings Directive (2010/31/EU) states that all new buildings should be nearly zero energy buildings by 2021, and it emphasizes the importance to promote measures that transforms existing buildings undergoing major renovations into nearly zero energy buildings. The EU member states have also agreed upon a 2030 framework for climate and energy strategies for the time period between 2020 and 2030. The framework targets 40% less CO2 emissions compared to 1990's level, 27% renewable energy sources, and 27% energy savings compared to the business-as-usual scenario (European Commission, 2016). Furthermore, the member states are obliged to encourage the consideration of combined heat and power (CHP) production according to the directive on energy efficiency (2012/27/EU).

In Sweden, approximately 75% of all residential buildings are in need of extensive renovation within a period of 40 years (IVA 2012). This poses both an opportunity and a challenge in the development of the future Swedish energy system. Well-developed strategies for large-scale building renovation can have a significant impact on the overall energy system.

Distributed electricity generation is an integral part of the future energy system and photovoltaic (PV) solar cells are expected to play an important role. Recently PV prices have dropped and many countries, including Sweden, have implemented subsidy systems to increase the installation rate. In Sweden the subsidy program was introduced in 2009 and since then the PV peak capacity has increased from 4MWp to about 70 MWp (Lingfors, 2015). An increased share of renewable energy sources is in agreement with Swedish and European targets. However, it is important to note that an energy system characterized by a large share of distributed non-dispatchable power generation requires regulative power capacity for balancing.

Electric battery storage can potentially improve the grid balance by providing a short-term buffering effect, and recent advancements in battery technology are promising both for distributed PV systems and for replacement of fossil fueled transportation systems. Electric vehicles (EVs) and plug-in hybrids are expected to increase worldwide (Tran 2012), but successful integration requires a well-planned system for EV charging both at people's homes and elsewhere (Denholm et al. 2013, Tran 2012). Residentially, large amounts of high-power EV charging affect the household electricity use as well as the local electricity grid (Denholm et al. 2013, Grahn 2012). Household electricity use is also affected as modern, high standard commercially available energy efficient appliances replace older household appliances.

Batteries can provide short-term balancing, however, the storage capacity is not sufficient to handle seasonal variation. For these biannual variations, other system configurations must be considered. Biomass fired CHP units have traditionally not been available for rural areas and have, therefore, mainly been used in densely populated urban areas that have district heating systems. Technology for biomass fired small-scale CHP units is being developed and is currently about to enter the market.

When different heat and electricity production technologies, building energy efficiency measures, and EV's are combined, a complex energy balance that is not yet fully investigated occurs. This study investigates the balance of such a multi-component renewable and energy efficient hybrid energy solution for a small Swedish single-family house residential community. The energy balance of the residential community is assessed by calculating the degree of electricity self-sufficiency and primary energy use. The specific questions to answer are:

- Do electricity and heat demand profiles match electricity and heat generation profiles, over seasons and diurnally?
- What degree of electricity self-sufficiency is obtained on the community level after introducing PV, small-scale CHP and home-charging of EVs?
- What is the potential change in annual primary energy use for the community compared to the present situation?

The Lövstalöt Residential Community

This case study is based on a residential area called Lövstalöt that is located approximately 80 km north of Stockholm, Sweden. The studied part of the residential area includes 111 single-family houses built in the late 1960's in a relatively homogenous style and in a general need of renovation. Figure 1 shows two examples of typical buildings in Lövstalöt.

There are other houses in the area that are either newly built or built earlier than the 1960's. To simplify this study, these buildings are excluded from this study due to significant variations in building sizes, construction materials and need of refurbishment.

Figure 1. *Left:* The 111 studied houses grouped into three different types, main heat distribution pipes (thick lines), and possible CHP unit location in the area (white box). Possible layout used for heat loss calculations. *Right:* Typical single-family homes in Lövstalöt.

Building Energy Simulations

The heat demand of the detached houses was calculated using the commercial software package VIP-Energy (StruSoft 2016). VIP-Energy is a dynamic simulation program that has been validated according to ASHRAE 140-2007 and EN 15265-2007. The program calculates the energy balance of a building using hourly weather data, material properties, and operational strategies as input. It is possible to simulate different types of heat recovery systems using VIP-Energy, however, district heating with CHP production cannot be evaluated with the program.

For the heat demand calculations, three types of single-story houses were simulated using VIP-Energy. The houses were identified based on geometry and their location in the neighborhood is illustrated to the left in Figure 1. The three housing types are a link-detached house of 107 m² (type 1), a detached house with a 105 m² footprint (type 2), and a detached house with a 125 m² footprint (type 3). Basic building construction information was obtained from the municipality database of building permits and energy performance certificate data were used to validate the models. The houses were constructed between 1968 and 1970, and the basic building components were assumed to be similar for the three different types of houses. For each type of house, two different building models were defined to represent the original version of the houses (referred to as original) and a renovated version (referred to as renovated).

The original building model assumes a construction with wood-siding walls (0.27 W/m²K), joist insulated attic (0.23 W/m²K), double-pane windows (2.60 W/m²K), and insulated slab-on-grade foundation (0.13 W/m²K). The houses were assumed to be heated to 21 °C and have a natural ventilation rate of 0.4 air exchanges per hour (AEH) (Boverket 2010). At the time of construction all heat was supplied using electric radiators, however, a majority of the houses have today been retrofitted with an air-source heat pump that was included in the model. The resulting annual energy use per square meter heated floor area for the original building model was 90 kWh/m² for house type 1, 90 kWh/m² for house type 2, and 78 kWh/m² for house type 3. The specific energy use includes energy for space heating (including electricity for heat pump) and domestic hot water.

The model for the renovated building includes improvements to the thermal envelope. Additional cellulose insulation is added to the attic space (0.10 W/m²K), the windows are replaced with energy efficient alternatives (1.10 W/m²K), and the exterior wood siding is replaced and more insulation is added to the wall (0.14 W/m²K). The renovated building results in a 32-36% reduction in heat demand compared to the original model for the three housing types. However, the reduction in specific energy use is significantly lower (ranging from 1-12 kWh/m²) since the heat pump is removed and the houses are converted from a heating system based on electricity to be supplied from a central CHP-unit.

Household and EV Electricity Demand Simulations

For this project synthetic EV charging data was used. This data was generated by the EV home-charging extension to the Widén Markov-chain model for generating household electricitiy use. The Widén Markov-chain model was validated and published in (Widén et al. 2009,Widén and Wäckelgård 2010), and the EV extension was validated and publisehd in (Grahn et al. 2013).

The model has settings for apartment or detached house, and generates electricity use profiles based on number of residents in each household. It was calibrated with time-use data on residential activities and validated with household electricity use data (Widén & Wäckelgård 2010). It has activities such as ”sleeping”, ”cooking” and ”watching TV” and appliances such as ”washer”, ”dishwasher” and ”TV”. The Widén-model was published in 2009 with typical appliance electricity use from that time. For this project the model has been updated with modern energy efficient washer (A+++), dishwasher (A+++), fridge (A+++), freezer (A+++) as well as LED-lighting (A+) (SEA 2016). This resulted in a reduced household energy use of about 15 percent for a two-resident household, and 12 percent for a three-resident household.

For this paper, two and three resident households in detached houses were simulated using minute resolution and then averaged to hour resolution. In order to match the average household occupancy of 2.5 residents per household (Sveby 2012), 55 two-resident households and 56 three-resident households were simulated. This matches the total 111 households in Lövstalöt.

EV charging was simulated using minute resolution with the EV extension of the Widén-Markov chain model for household electricity use (Grahn et al. 2013). Since the Widén-model was based on activities, the EV-extension was based on the assumption that for certain amounts of time when the resident is ”away from home”, the resident used the EV for transportation. It was also assumed that the EV was plugged in and charged when the resident returned home. Furthermore, it was assumed that the EV was plugged in until it was fully charged or taken out for another drive. For simplicity only one resident was assumed to operate the vehicle. This ”away fraction” was set to 0.2 to fit estimated EV charging data in (Grahn et al. 2013). The model has free parameters on battery capacity and charging power. The simulations in this paper were made with EV battery capacity of 70 kWh in order to match the Tesla Model S 70D battery capacity. This high battery capacity was chosen to reflect the potential of near future average EV battery capacity. The charging power was set to 2.3kW AC, which is standard one-phase power in Sweden.

Recently it has come to the authors' attention that the EV extension has a tendency for overestimating the electricity use from EV-charging when using large batteries compared with a Nissan Leaf battery capacity, for which it was originally designed. This leads to slightly overestimated charging times for EV home charging in the model.

Power Generation From Roof Mounted PV Panels

The rooftops were investigated through visual inspection on-site and by using aerial photographs. The condition for roof-mounted PV installations in the area is generally good.

All houses are of gable type, which restrict PV installations to the south-most facet of the roof. On some rooftops chimneys had been installed. A previous study on the Swedish house stock suggests that 20-25% of the roof should not be considered due to obstacles such as chimneys and roof ladders and due to shading (Kjellsson 1999). Shading in Lövstalöt is, however, only an issue for a handful of houses in the relatively flat area, and in those cases mainly due to trees. The available roof area was therefore considered to be 85% of the south-most facet. All houses of the same type (1-3) were assigned the same available roof area based on the median.

According to the blueprints the roof tilt was 16 degrees for all three identified house types. A few houses had a modified roof tilt after reconstruction, but this was negligible and assumed in the excluded portion of our assumed roof space. More importantly, the azimuth of the rooftops was determined using aerial photographs. The azimuth is defined as the normal of the longest side of the building and is important for the aggregated PV power production.

The hourly PV power production was calculated for each house using global horizontal irradiance (GHI), direct normal irradiance (DNI), and temperature data. The irradiance data were obtained from the STRÅNG dataset for 2014 (SMHI 2015) and the temperature data were obtained from the MERRA t2m (temperature 2 m above ground) dataset (Lucchesi 2012) using nearest neighbor interpolation. The solar irradiance on a tilted plane was calculated following the method proposed by Hay and Davies (Duffie, Beckman, and Worek 1994) assuming a constant albedo of 0.2 over the year. The PV module efficiency was assumed to be 15% at standard test conditions (STC), but was adjusted according to the ambient temperature following the method described by Evans (1981). The Sandia inverter model was used to compute the AC power output after the inverter (King et al. 2007) . A more detailed description of the method is given in (Lingfors 2015).

Power and Heat Production Using Small-scale CHP

The study modeled hot water for space heating and domestic hot water use produced in a centrally located small-scale CHP-unit, and distributed to the houses through an underground pipe network. The CHP unit produces heat and electricity simultaneously. Figure 1 shows the suggested location of the CHP unit (white box) and a potential layout of the pipework (blue lines).

The CHP unit considered in this project is based on the ORC (organic rankine cycle) technology. The ORC technology is the least costly and most efficienct small-scale (15 – 100 kW_e) biomass fueled CHP production technology according to Dong et al. (2009). An ORC cycle is similar to the most frequently used steam turbine systems for large-scale CHP production, but uses organic chemicals with favorable thermodynamic properties (such as silicone oil or an alkylbenzene) instead of water/steam. ORCs are more efficient than steam turbines at lower temperatures, with both full and partial loads. This makes them suitable for small-scale CHP systems.

The ORC based CHP unit simulated in this study is a theoretical unit based on an ORC plant (case study described in Wood and Rowley 2011). The overall efficiency is 85%, the thermal efficiency is 71%, and the electric efficiency is 14%. The electricity-to-heat output ratio is 0.2. The efficiencies and the electricity-to-heat output ratio are assumed to be independent of thermal output level. The output level is equal to the sum of the aggregated heat demand of all houses at each hour and the heat losses in the distribution grid. The CHP unit is assumed to supply the entire heat demand for space heating and domestic hot water for the houses.

The heat losses from the heat distribution grid are initially calculated for two separately insulated pipes and thereafter reduced by 35%. This is to mirror a twin-pipe distribution network that is currently a common efficient distribution technology where both pipes are within the same casing. The twin-pipe technology reduces heat losses with 30-40% compared to conventional two-pipe solutions (Bøhm and Kristjansson 2005). The calculated distribution pipe network consists of two different pipe sizes. The main pipe dimensions are 70 mm inner diameter and 120 mm outer diameter including insulation and pipe casing. The dimensions of the service pipes are correspondingly 25 mm and 60 mm. The pipes are insulated with polyurethane foam ($\lambda = 0.03$ W/mK). The heat conductivity of the ground is assumed to be 1.5 W/mK. The trench lengths for the pipes are estimated from an area map. The main pipe and service pipe trench lengths are approximately 1700 m and 400 m, respectively. The heat is assumed to be distributed from the CHP unit to the houses at a temperature of 90 °C and returned to the CHP-unit at a temperature of 45 °C.

Self-Sufficiency

As a metric, self-sufficiency is a usable measure to assess the electricity balance of a house or a neighborhood partly powered by renewable electricity.(Schreiber and Hochloff 2013). The degree of self-sufficiency is the share of the electricity demand that is covered by “in-house” electricity production. Self-sufficiency can be applied and calculated for different timeframes. A shorter timeframe generally requires a better match between electricity demand and production in order to maintain a certain level of self-sufficiency. Annual self-sufficiency only requires that electricity production and consumption match on an annual basis. This means that a surplus of electricity during one part of the year can be compensated by an equally sized electricity deficit during another part of the year to maintain the level of self-sufficiency. Hourly self-sufficiency on the other hand requires the use and production of electricity to match every hour of the year.

Off-grid power systems must have an electricity self-sufficiency degree of 100%, since no electricity can be purchased from, or fed to, a power grid outside the system. For small off-grid power systems either a mixture of electricity production technologies can be used, for example PV and diesel generator, or one single power source combined with electricity storage, such as batteries or electrolyzer fuel cell systems (Salas et al. 2015, Guinota et al. 2015).

There is no established nomenclature for self-sufficiency when it comes to small-scale renewable electricity production, but is somewhat similar to the more well-established measure of self-consumption, i.e. the share of the electricity produced that is also consumed in the house or the community, makes it justified to use (Luthander et al. 2015).

Primary Energy

The concept of primary energy is suitable for comparison of total energy use in scenarios where several different energy carriers are used. The Organization for Economic Co-operation and Development (OECD) defines primary energy as the energy that has not been converted or transformed (OECD 2016). Primary energy factors (PEF) can be employed to calculate the amount of primary energy used to convert the energy into its current form. In this study PEFs from (Gode et al. 2011) are used for pellets (PEF = 1.11), electricity (PEF = 2.29), and gasoline (PEF = 1.1).

The concept of marginal source of electricity is used for assessment of electricity purchased from and fed to the grid. The marginal source of electricity is the most expensive source of power production available in the system for the moment. In Europe and in the Nordic countries, the most expensive power production is currently in coal-fired condensing power plants. It is important to note that electricity production might change in the future and that coal-condensing power plants might be replaced by other technologies, either parts of the year or all year around (Sjödin & Grönkvist, 2004).

The electricity demand for home charging of EVs is used as a proxy for gasoline consumption of current vehicles. An EV use approximately 2 kWh of electricity per 10 km (Grahn et al. 2013). An average gasoline fueled car is assumed to consume 0.8 liters of gasoline per 10 km.

Results

Figure 2 shows the simulated total original hourly demand for space heating and domestic hot water and the demand in the renovated case. The original total annual heat demand (solid black line) is 1310 MWh. After renovation the total heat demand is estimated to reduce to 800 MWh. The solid grey line shows the distribution losses added to the reduced heat demand. The dashed lines in diagrams A and B show the levels of heat distribution losses, which annually amounts to 400 MWh. The energy efficiency measures were exclusively improvements of the thermal envelope and this explains the larger absolute reduction in heat demand during the colder periods of the year. The summer heat demand mainly consists of domestic hot water and is therefore not significantly affected by the energy efficiency improvements. The relative distribution losses are in total about 34% of the heat load after renovation of buildings.

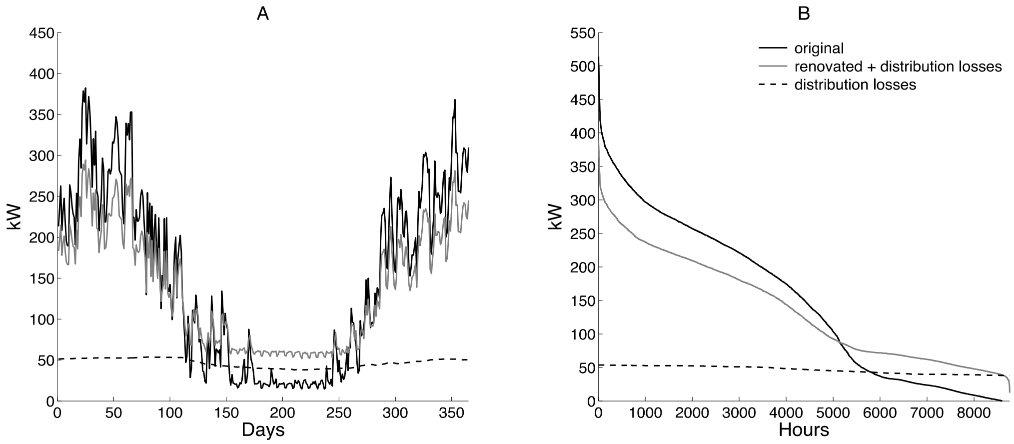

Figure 2. Sequential diurnal average heat output demands (A) and hourly heat load duration diagrams (B) for the annual heat demand in Lövstalöt. The solid black lines show the reference demand and the solid grey lines show heat demand after the medium energy efficiency package renovation. The dashed lines at the bottom are the distribution heat losses.

In figure 3, the diurnal variations in electricity demand and total electricity production for the first week in July (diagram A) and the first week in January (diagram B) are shown. The total electricity production includes CHP produced electricity and PV produced electricity with 25% utilization of the available (85%) share of the south facing roofs. The broken line shows the household electricity demand and the solid black line shows the total electricity demand including home charging of EV's. The electricity demand peaks in the afternoon. This is, in weekdays, due to residents coming home from work and all household activities (cooking, cleaning, TV, computer, etc.) are concentrated to this part of the day. The home charging of EVs is no exception, and thus, adds to the afternoon peak, as has been previously addressed in Grahn et al. (2013). During the weekends the diurnal demand profiles for household electricity are slightly more leveled during daytime. This is mainly due to a somewhat higher electricity demand during mornings. The summer and winter diurnal electricity demand variations are similar. However, the demand is generally higher in winter, explained partly by shorter winter days and thus a higher demand for indoor lighting.

The total electricity production profile (PV + CHP) on the other hand differs significantly between summer and winter. This is because the roof mounted PV-panels dominate the electricity production during the summer, while the production during the winter mainly comes from the CHP unit. It is clear that the diurnal variations in PV production poorly match those of the electricity demand during the summer and that CHP electricity production does not cover the electricity demand in the winter.

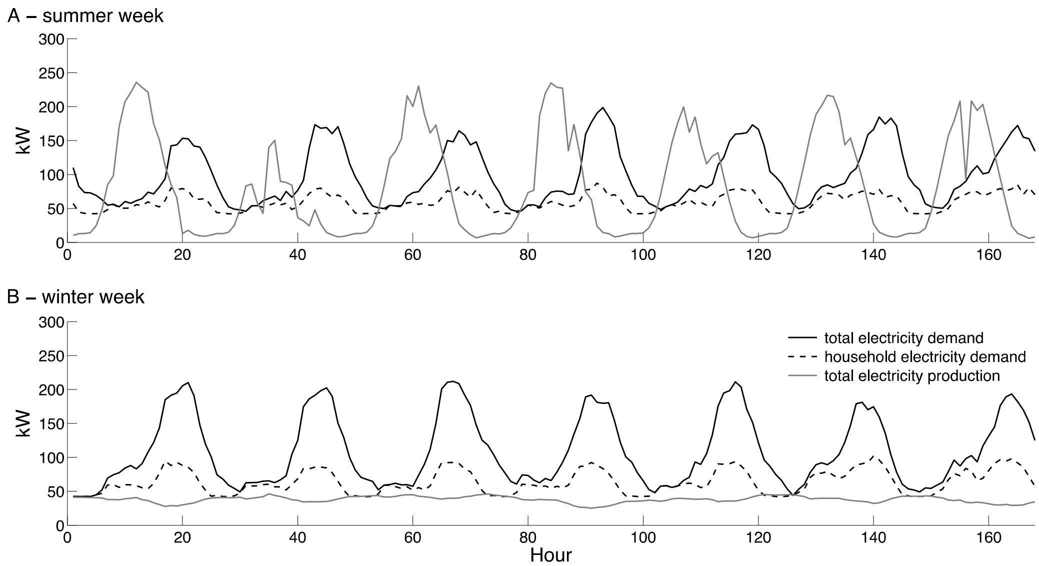

Figure 3. Electricity demand (household demand and total with EV home charging included) and total electricity production (PV + CHP), for one summer week (A) and one winter week (B).

Figure 4 (A) shows diurnal average power outputs from the PV-panels and the CHP unit. There is a clear negative correlation between the electricity productions from the roof mounted PV panels and the CHP unit between seasons. This is of course important for the level of self-sufficiency in the area. In figure 4 (B), the diurnal averages of total electricity production and electricity demands are shown. The electricity demand for home charging of EVs significantly increases the gap between the demand and the electricity production in the area. The electricity production and the household electricity demand are fairly well-balanced.

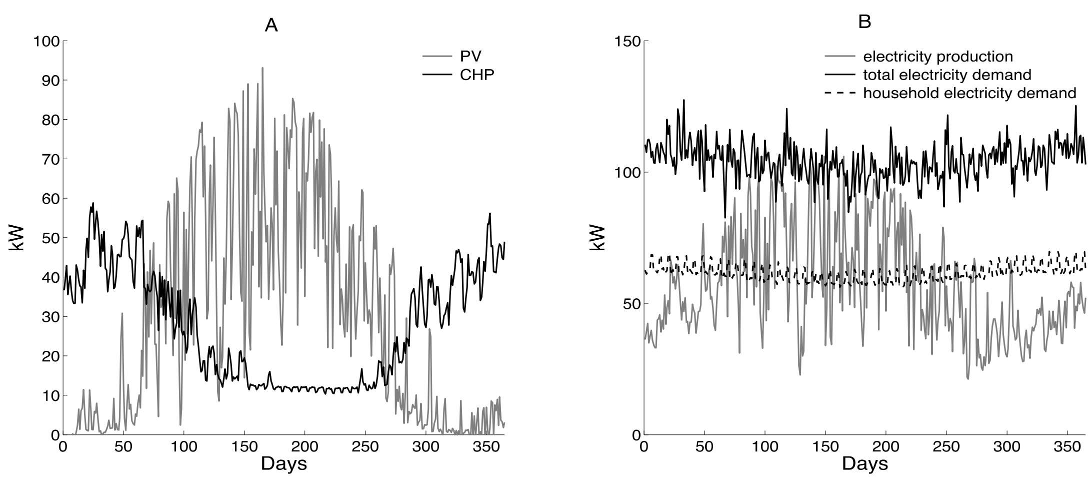

Figure 4. Diurnal averages for PV and CHP electricity production (A), and for the match between total electricity production and electricity demands (B).

Figure 5(A) shows the level of self-sufficiency for different shares of available roof area used for PV electricity production. It is clear that home charging of EVs significantly reduces the potential degree of self-sufficiency. This is because of the diurnal mismatch between EV home-charging and electricity production. Under the given circumstances with building renovations, CHP-production, home charged EVs, and with 25% of available roof area utilized for PV electricity production, a self-sufficiency degree for the area of 43% is possible. If home charging of EVs is excluded from the calculations the possible self-sufficiency degree increases to 69%. Figure 5(B) shows the primary energy use for the current situation (I) and for the multi-component energy system with and without home-charged EVs, cases (III) and (II), respectively. The replacement of fossil fueled cars with EVs decrease the potential electricity self-sufficiency, and decreases the use of primary energy by 23%. This is due to the high efficiency of electric motors and that some of the electricity used for charging is produced in the community. If EVs are not included in the model, the primary energy reduction is 12%.

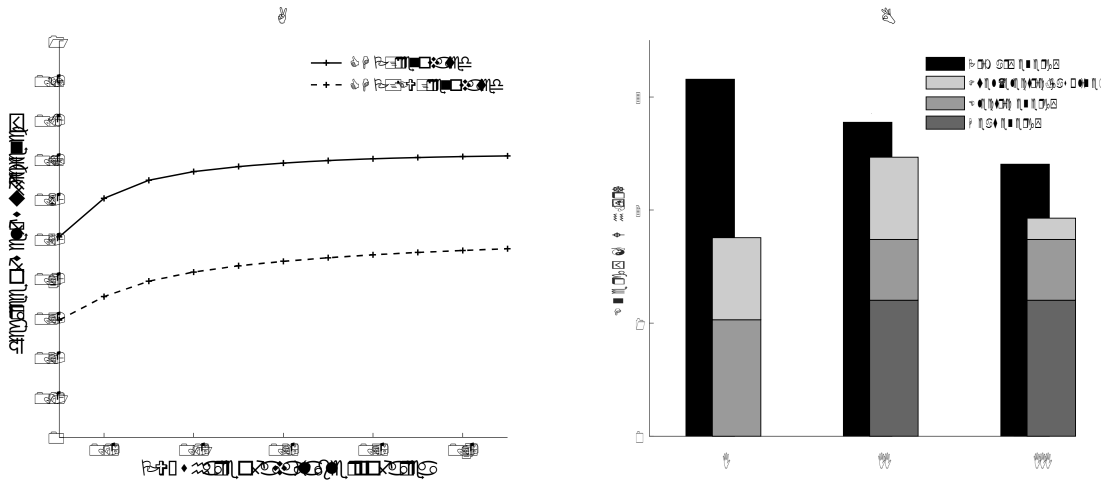

Figure 5. (A) Degree of electricity self-sufficiency for different levels of PV-installations and with or without EV's. (B) Primary energy use for I) current situation, II) renovated houses, CHP and PV, and III) renovated houses, CHP, PV, and home charged EV's.

Concluding discussion

The results from this study show that the combination of small-scale combined heat and power and photovoltaics yields a more leveled annual production profile than the two technologies do separately. The degree of community electricity self-sufficiency is reduced with home charging of electric vehicles. Primary energy use is significantly reduced with improved energy efficiency in buildings, implementation of local electricity production, and use of electric vehicles.

Improving the thermal envelopes of the buildings substantially reduces the total heat demand for the houses in Lövstalöt. The electricity demand is substantially increased due to home-charged EVs that replace fossil fueled cars.

A central CHP unit with an underground twin-pipe network for heat distribution results in relatively large heat losses, especially during the summer. This means that relative to the low summer heat demand, large amounts of biomass must be purchased to off-set the distribution losses in the network. Furthermore, during the summer months the electricity production from the CHP unit contributes less to self-sufficiency due to excessive power production from the PV. Therefore an alternative heat source, such as a PV-supplied electric hot water boiler might be a suitable replacement for the CHP unit in the summer. This will further reduce the use of biomass and increase the utilization of PV produced electricity. An electric boiler is also valuable as back up heat production for both unexpected production stops and periodic maintenance of the CHP-unit. Another option that might be considered is a solar thermal collectors to replace the CHP unit in summer.

The negative correlation between PV and CHP production (seen in Figure 4(A)) shows that the two technologies makes good complements to each other between seasons. The CHP unit produces most electricity during the winter when the demand for heating is high, while the PV systems primarily produces electricity during the summer. The combination of small-scale CHP and PV therefore yields a more leveled annual production profile than any of the two technologies do separately.

In the summer, the peak levels of electricity production are only slightly above the peak levels of electricity demand for household appliances and home charging of EVs. However, these peaks generally occur at different times and are therefore poorly matched. The electricity production during the winter is evenly distributed diurnally, but cannot match daytime electricity demand. Thus, there is a time-of-day mismatch between electricity production and demand in the summer, and an insufficient production of electricity to cover the demand in the winter.

The results show that the community can achieve a self-sufficiency degree of 43% given the implementation of building renovations, CHP-production, home charged EVs, and a PV electricity system that covers 25% of the available roof area. If home charging of EVs is excluded from the calculations the achieved self-sufficiency degree is 69%. Thus, the suggested system configuration is not sufficient for the residential area to go “off-grid”. In order to increase the self-sufficiency degree, different system improvements could be considered. Load management for household electricity use might improve the diurnal match of PV electricity production and summer demand. Encouraging carpools and / or charging of EVs away from home can potentially improve the self-sufficiency. Electricity and heat storages are another possible options to further increase the self-sufficiency degree. The primary energy use of the community is potentially reduced by 12% when heat demand is reduced and electricity and heat are produced within the community. If gasoline fueled vehicles are replaced by EVs, the total reduction of primary energy use is potentially 23%.

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