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Importance of Demand Side Flexibility and Management for Large-Scale Variable PV Integration in Urban Environment

Jyri Salpakari, Jani Mikkola, Peter D. Lund

New Energy Technologies Group, Department of Applied Physics

Aalto University, School of Science

Espoo, Finland

Abstract—**Photovoltaics (PV) is well suited for clean, renewable energy provision in urban areas, which also offer demand side management possibilities to mitigate PV variability. This paper investigates the importance of electricity-to-thermal (E2T) strategies and electric load shifting for large-scale PV integration in an urban environment, with Helsinki, Finland as the case city. The study was conducted as an hourly simulation with detailed input data. An increase of 26–99% in PV self-use limit was obtained with the considered measures, with E2T measures more effective than load shifting. E2T with electric resistance heaters was the single most effective of the studied measures: it could increase the PV self-use limit to 1000 MW_p, or by 81% compared to the reference case with no flexibility, with a corresponding increase in PV share of electricity from 10.1% to 17.4%. Spatial analysis was also conducted to identify possible network bottlenecks during the hours when all electricity in the city is produced by PV. With a scheme combining distributed and central E2T with electric resistance heaters, the full city-level self-use limit of 1000 MW_p could be integrated without network congestion problems.**

Keywords—Photovoltaics; urban energy system; demand side management; electricity-to-thermal; residual load; power system; district heating; spatial analysis

I. Introduction

Urban areas will be increasingly important in climate change mitigation, as they already represent around half of all energy use and carbon emissions [1], and the growing population in the world is concentrating in cities [2]. Fulfilling the energy requirements of cities with renewable energy sources instead of conventional fossil fuel based production would therefore have a major impact for climate change mitigation, and requires urgent solutions.

Photovoltaics (PV) is a very suitable renewable and clean energy source for use in urban areas: it can be easily integrated to buildings, is silent and has no moving parts [3]. However, its variability presents challenges to the flexibility of the urban energy systems [4]. Loads in urban areas offer possibilities to provide this flexibility with demand-side management (DSM) instead of dispatchable power plants that are often fossil fuel based, investing in energy storage or stressing the regional energy system outside of the city through interconnections [4].

Heating, cooling and shiftable appliances, such as dishwashers, offer high flexibility potential in urban environments while interfering only slightly with human or business activities. Thermal loads can be leveraged for power system flexibility with electricity-to-thermal (E2T) strategies [4,5], i.e. replacing other sources of thermal energy, such as combustion, with electric resistance heating or heat pumps. The thermal masses of heating or cooling loads can provide additional flexibility.

This paper investigates the importance of DSM to provide flexibility for large-scale PV integration in an urban environment, focusing on the middle-size high-latitude (60 °N) city Helsinki, Finland. Good-quality and diverse input data is available for this city, enabling a detailed analysis. The population of the city is 0.6 million.

E2T strategies to produce heat to the district heating network are analyzed, along with leveraging the thermal mass in refrigeration loads in households, grocery stores and refrigerated warehouses. District heating covers over 90% of the heat load in the city [6]. Shiftable wet appliances in households, namely dishwashers, washing machines and tumblers, are also included. The analysis is conducted for a full year as an hourly simulation, including an intra-city spatial analysis at district level to take possible network bottlenecks into account.

II. Data and Methods

A. Energy Consumption and PV Production

The annual electricity and heat consumption in Helsinki in 2006 [7] is presented in Figures 1 and 2, respectively. Figure 1 also shows the shiftable loads considered in this paper, which range in total from 27 MW to 215 MW or 5–38% of the total load.

Figure 3 presents the production of a 1-kW_p PV system in Helsinki in the corresponding year [7]. The total production is 836 kWh/kW_p. Due to the northern location, PV production is concentrated to the summer season.

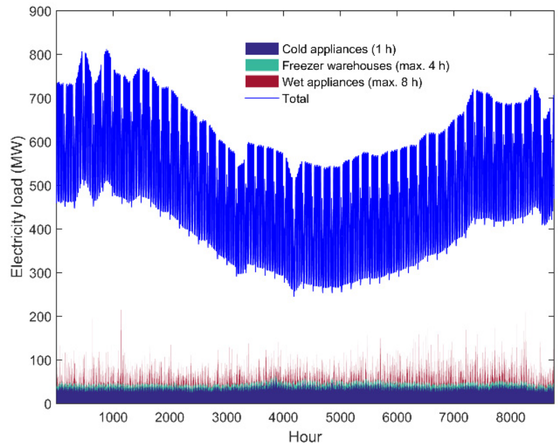

Figure 1. Electricity load in Helsinki [7] with the shiftable components.

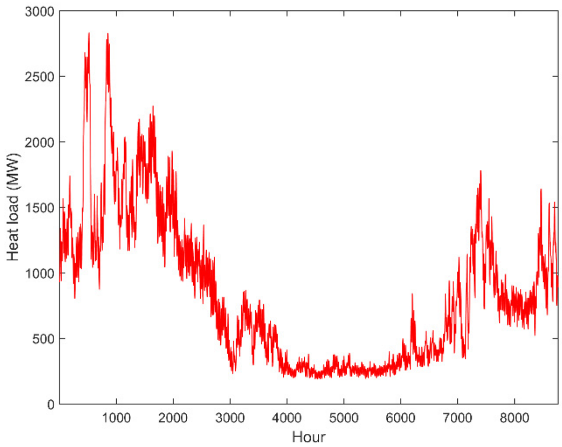

Figure 2. Heat load in Helsinki [7].

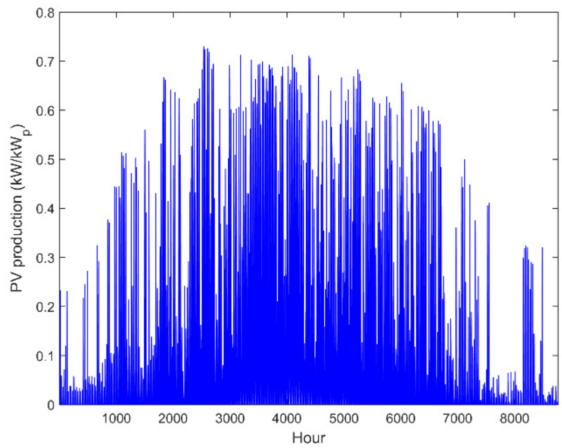

Figure 3. PV power production in Helsinki [7].

B. Electricity-to-thermal (E2T)

A simple E2T scheme is considered in this paper in which electricity is converted to heat and distributed with the district heating network without using thermal storages. The conversion is done with electric boilers (coefficient of performance COP=1) or heat pumps (assuming constant COP=3).

C. Shiftable Load Modelling and Disaggregation

The shiftable loads considered in this study are refrigerators and freezers in households and grocery stores, freezer warehouses, and dishwashers, washing machines and tumblers in households. The loads have been selected for their high potential for DSM and the possibility to control them with minimal effect on human or business activities. The whole populations of the aforementioned loads in Helsinki are aggregated to the modelling for an analysis of the full potential.

The shiftable loads are modelled as aggregate time series shiftable for max. *n* hours. That is, the loads are assumed linear systems, that require the same total amount of energy whether shifted or not. Hence, the effect of the temperature change due to shifting on the energy consumption of cold appliances due to change in thermal losses and refrigerator COP are neglected. As the temperature changes are small as food quality has to be preserved, these effects do not considerably affect the large-scale DSM potential of the loads, which is the focus of this paper. Moreover, the loads are assumed continuously controllable at the aggregate level, owing to large population sizes and the possibility to actually control cold appliances continuously.

The residential cold and wet appliance consumption was obtained based on data from an appliance-level measurement campaign conducted in Sweden in 2005-2008 on 201 detached houses and 188 apartments [8]. As the time use in Sweden and Finland is very similar [9,10], appliance use patterns can be assumed the same. Average consumption time series of the considered appliances for detached houses and apartments were calculated separately from the sample data for the year 2007. Appliance ownership in the sample was scaled to the average ownership in Helsinki [11], and the total consumption in Helsinki was obtained by scaling with the number of detached houses and apartments in the city [12]. Due to lack of data, the distribution of device properties in Helsinki and the sample had to be assumed the same. The cold appliances are assumed shiftable for 1 h due to their thermal mass [13,14] and wet appliances for max. 8 h.

Empirical time series at hourly resolution of annual electricity consumption of refrigerators and freezers in a supermarket, and three freezer warehouses were obtained from SEAM Group, a Finnish demand response company [15]. Dimensioning of refrigerators and freezers in grocery stores in three size classes [16] was combined with the numbers of the stores in the size classes in Helsinki [17–23], 219 in total, to obtain the total capacity of these loads in the city. The available data from a single supermarket was assumed representative and scaled to the total capacity. The time that these loads can shift their consumption ranges from 1 h to 25 h, depending on the controlled power and state of the devices [24,25]. As control of the full capacity is allowed here and information on device states is not available, a conservative value of 1 h is used. Because the data shows mainly diurnal and seasonal variations and the dynamics of the load is in the order of the time resolution, no smoothing of the data was done. The data available from the three freezer warehouses was assumed representative of the nine freezer warehouses in Helsinki [26] and scaled accordingly. These loads were assumed shiftable for max. 4 h [27,28].

D. DSM Control Strategy

The rule-based control strategy of E2T and shiftable loads used in this paper aims at hourly matching of the electricity load in the city (Q_{el}) with the PV production (P_{el}). E2T is given priority over load shifting because it can be produced and controlled centrally as part of the district heating system with a considerably simpler control system than the distributed shiftable loads and without any effect on human or business activities, affected to a minor extent by load shifting.

For each hour i in the forward simulation:

1. Add previously postponed consumption that reaches its maximum shifting time at hour i to $Q_{el}(i)$, and subtract consumption previously shifted backwards from the hour i from it.

2. If E2T is used and $P_{el}(i)>Q_{el}(i)$, convert electricity to heat: $Q_{E2T,el}(i) = \max(P_{el}(i)-Q_{el}(i), Q_{th}(i)/\mathrm{COP})$.

3. If load shifting is used and $P_{el}(i)>Q_{el}(i)$, first use previously postponed shiftable consumption that has not reached the maximum number of hours it can be shifted. If that is not enough, shift future consumption backwards to the current hour.

4. If load shifting is used and $P_{el}(i)<Q_{el}(i)$, postpone shiftable consumption from the current hour.

III. Results

A. PV share of energy demand and overproduction

The PV capacity range 0–2000 MW is considered in this paper. 2000 MW of capacity corresponds to a 70% utilization of the rooftop area in the city assuming that the capacity of the PV systems is 150 W_p/m^2. A 50% rooftop utilization which can be assumed not to be limited by shading [1] corresponds to around 1400 MW.

Figures 4–6 show the surplus PV production in the city, and PV shares of total electricity and heat consumption, respectively. Even without any flexibility measure, the surplus PV production is minor slightly above the self-use limit. The studied flexibility measures can increase the self-use limit by 26–99%. E2T measures have a larger effect than load shifting.

The PV share of electricity increases linearly above the self-use limit until 800 MW_p regardless of flexibility measure or lack of one. The increase is lower than linear above that. Load shifting can provide a minor increase compared to no flexibility or only E2T. The PV share of heat increases slowly above the self-use limit when E2T is used. Even though the increase is considerable at higher PV capacities, the total share of heat is minor: less than 8% at all the studied capacities.

E2T with electric resistance heaters is the most effective single measure to increase the amount of PV in the city without surplus production or curtailment. At the self-use limit obtained this way, 1000 MW_p, PV share of electricity is 17.4%, a considerable increase from the 10.1% at the conventional self-use limit. The heat production lost compared to using heat pumps is minor, around 1% of the whole annual heat demand. 315.3 MW of resistor capacity is required. With the approximate cost of electric boilers 0.15 M€/MW_e [29] and PV systems 2 M€/MW_e [30], the E2T capacity investment would be 2% of the PV capacity investment.

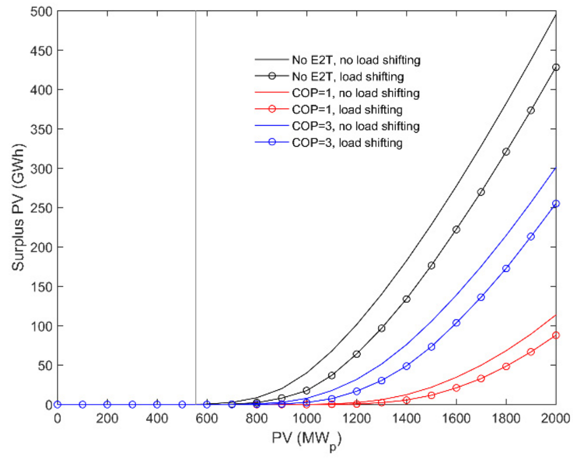

Figure 4. Surplus PV production that would be exported out of the city or curtailed away. The vertical grey line denotes the original self-use limit.

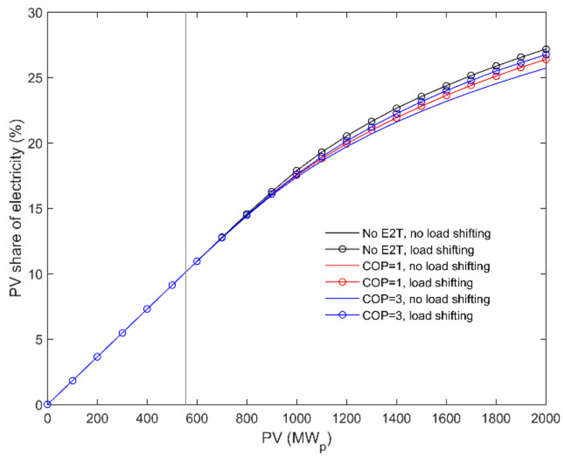

Figure 5. PV share of electricity. The vertical grey line denotes the original self-use limit.

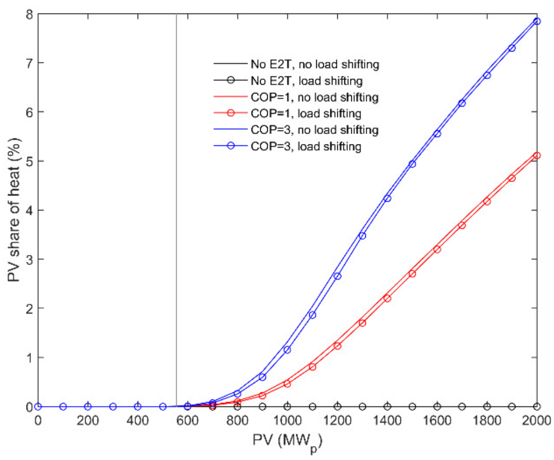

Figure 6. PV share of heat. The vertical grey line denotes the original self-use limit.

B. Effect of PV on the residual load

The effect of PV on the control of conventional power plants is not directly considered in this paper; this effect is analyzed via the residual load. The average magnitude (absolute value) and average 24-h standard deviation of the residual electricity and heat load are used as metrics, presented in Figures 7–10.

Increasing PV capacity decreases linearly the mean electricity residual load magnitude (Fig. 7) up to the self-use limit and above it until the capacity of 700 MW_p, as the PV production covers an increasing share of the load. Above that capacity, the decrease becomes lower than linear. The magnitude shows a minimum which is the lower the more effective flexibility measures are in place. Above the minimum, increasing PV capacity increases the residual load magnitude as the negative residual load increases.

Interestingly, the standard deviation of electricity residual load (Fig. 8) shows a minimum below the self-use limit, an effect enhanced by load shifting. Above the self-use limit, the standard deviation increases approximate linearly when E2T is not used, with load shifting decreasing its value. E2T can further decrease the value and the rate of increase with PV capacity.

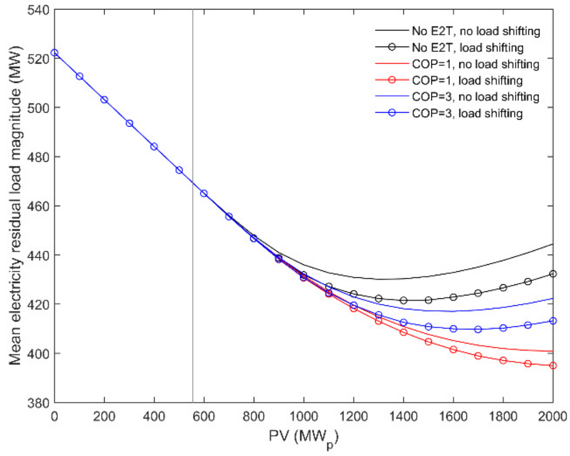

Figure 7. Mean magnitude of the electricity residual load. The vertical grey line denotes the original self-use limit.

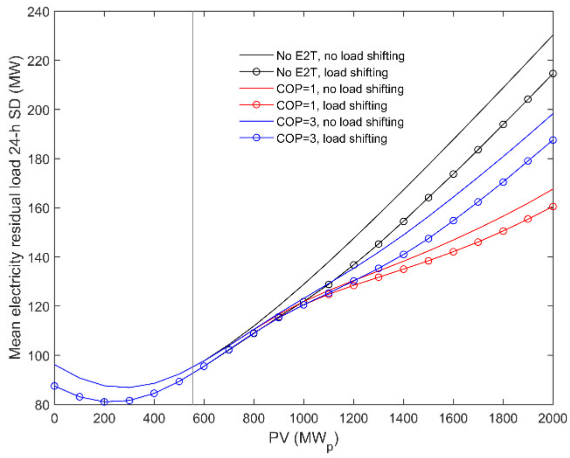

Figure 8. Mean 24-h standard deviation of the electricity residual load. The vertical grey line denotes the original self-use limit.

The heat residual load (Fig. 9) shows a decrease and its standard deviation (Fig. 10) an increase with increasing PV capacity above the self-use limit when E2T is used as more heat is produced by E2T. The changes with reference to the case with no E2T are minor slightly above the self-use limit, as the PV share of heat is small. Load shifting has a minor decreasing effect to the changes.

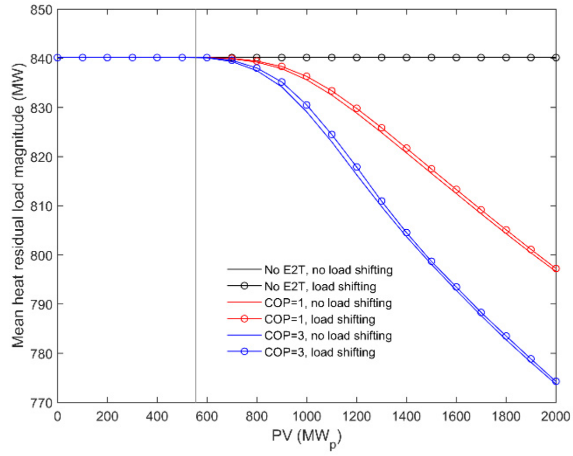

Figure 9. Mean magnitude of the heat residual load. The vertical grey line denotes the original self-use limit.

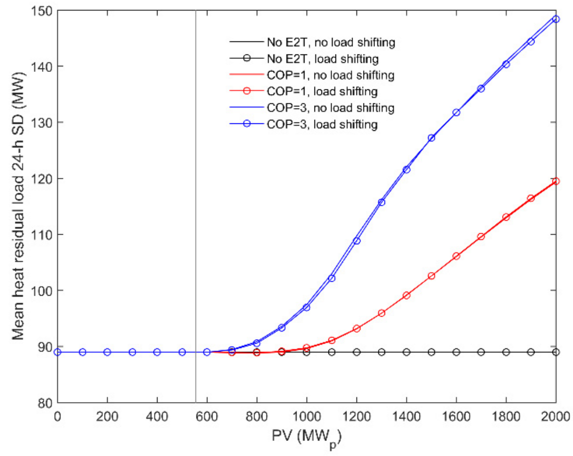

Figure 10. Mean 24-h standard deviation of the heat residual load. The vertical grey line denotes the original self-use limit.

C. *Spatial analysis*

Intra-city spatial analysis is conducted to take into account possible bottlenecks caused by the electricity and heat distribution networks in the city. The spatial analysis in this paper focuses on E2T with resistance heaters, as it is the most effective single measure studied in this paper.

The employed spatio-temporal simulation tool [5,31] calculates electricity and heat consumption and production at district level and the resulting flows in the electricity and heat networks. Figure 11 presents the power system topology in Helsinki, with the three combined heat and power (CHP) plants marked with yellow disks. Two E2T strategies are considered: one with all E2T produced centrally at the CHP plants and fed to the district heating network, and the other with also distributed E2T for local use in some nodes. Spatial allocation of the PV capacity is done according to the E2T scheme to maximally leverage the possibilities of E2T for PV integration.

As all the E2T-produced heat that is fed to the district heating network is produced at the CHP plant sites in our scenarios, heat network congestion will not occur as the

CHP plants produce conventionally considerably larger amounts of heat than in our E2T scenarios. Hence, only the electricity network is considered here.

To identify possible bottlenecks in the power system, reference capacities of the network lines are obtained by running a simulation of the conventional operation of the energy system in Helsinki with electricity produced by the three CHP plants [5]. The maximum flows occurring in each line in the simulation are used as the reference capacities. Based on this simulation, the lines are classified to strong main lines (black in Fig. 11), which transfer power from the CHP plants to large areas, and weaker lines (grey in Fig. 11) which only transfer power for consumption in the small downstream branch of the network.

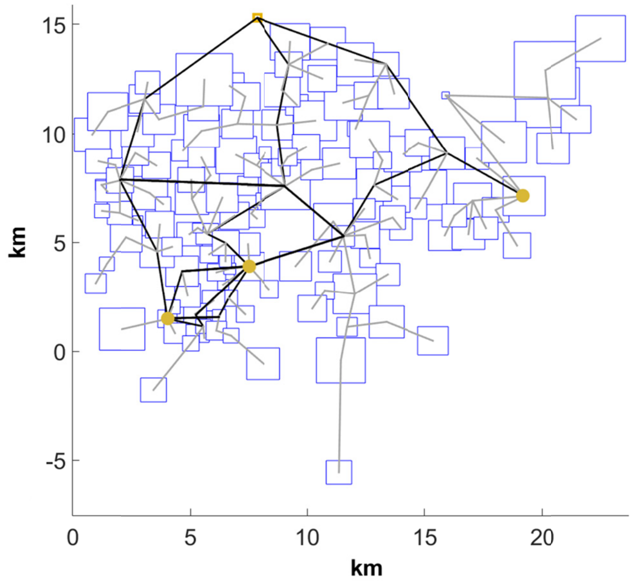

Figure 11. The electricity network topology in Helsinki [5]. Yellow dots denote CHP plants. Main network lines are in black, other lines in grey. The yellow node is the link outside the city.

1) *Central E2T at CHP plants*

To avoid overloading the weaker network lines in this strategy with no distributed E2T, nodes with only weaker lines are allocated PV capacities so that the PV production never exceeds twice the electricity consumption in the node. This limits the maximum outflow of PV electricity from the node to the maximum load which the line can handle. In addition to that constraint, the maximum rooftop area use is 50%, which can be assumed available for PV without shading problems [1]. PV allocation to nodes with main lines is only constrained by the 50% limit for rooftop area use. In this way, 930 MW_p of total capacity is obtained, which is 93% of the self-use limit obtained in the city-level simulations. PV produces annually 0.3% of the heat consumption and 16% of the electricity consumption of the city in this case. Figure 12 shows the spatial distribution of PV capacity. 88.5 MW of E2T capacity is needed at each CHP plant to allow for consuming all PV electricity within the city with E2T as the only DSM measure.

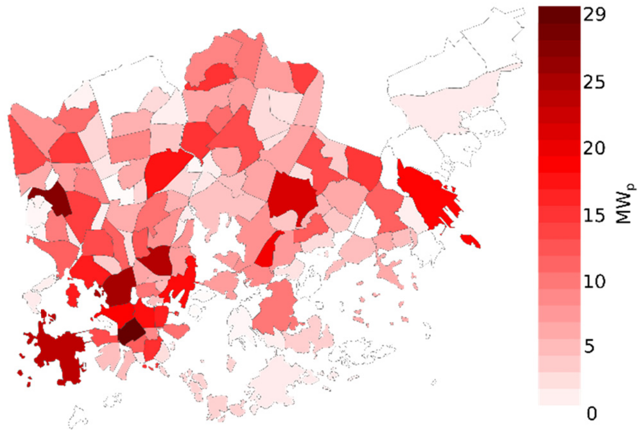

Figure 12. Distribution of installed PV capacity in the case with only central E2T. The total capacity is 930 MW_p.

Flow analysis is limited to the hours when all the electricity demand in the city is fulfilled by PV (309 hours), as the effect of PV on conventional power plants is not considered here. During these hours, the flow magnitudes in the electricity network are well below the reference values, the maximum relative value being 78%: 930 MW_p of PV can be integrated without network congestion during these hours.

Figure 13 shows the spatial energy balance on the extreme hour 3181 when PV produces all the electricity in the city and E2T is at maximum (265 MW in total). PV overproduction is distributed around the city and the central E2T stations are clearly shown as nodes with highly negative energy balance.

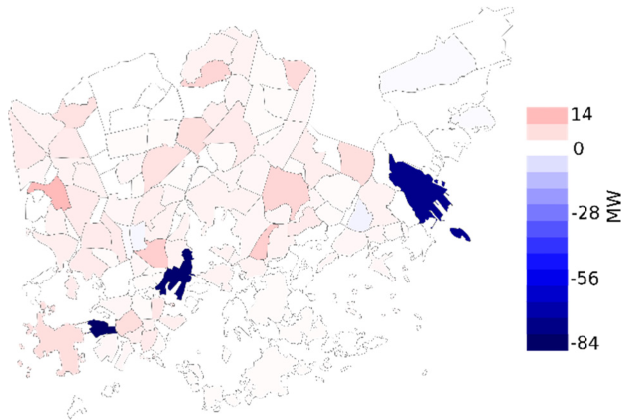

Figure 13. Spatial energy balance with only central E2T on the extreme hour 3181 with maximum E2T (265 MW).

2) *Distributed and central E2T*

Taking advantage of distributed E2T, the total PV capacity is increased from the 930 MW_p in the central E2T case to the city-level self-use limit 1000 MW_p. The PV capacity in nodes that do not already have the maximum 50% roof area utilized with the total allocation of 930 MW_p is increased so that the PV production never exceeds the sum of heat consumption and twice the electricity consumption. This way, the maximum PV outflow from the nodes with weak network lines when local E2T is used is limited to the load. 1115 MW_p could be allocated in this fashion, but here the total is limited to the city-level self-use limit. The spatial distribution of PV capacity obtained with the arbitrary node prioritization used here is shown in Figure 14.

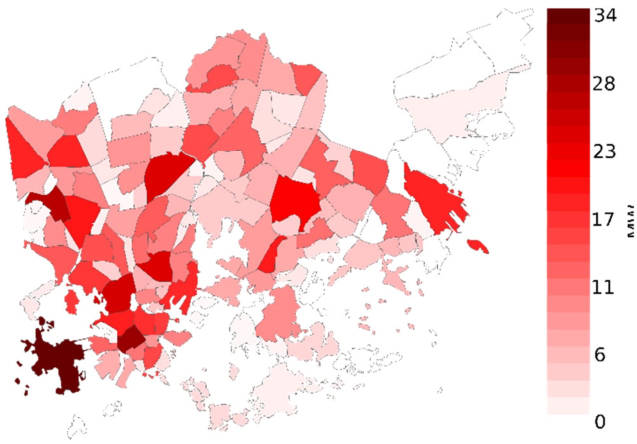

Figure 14. Distribution of installed PV capacity in the case with distributed and central E2T. The total capacity is 1000 MW_p.

Distributed E2T is done each time step in the nodes where PV is dimensioned for it to limit the PV overproduction magnitude to that of the local electricity consumption. If there is city-level PV overproduction after distributed E2T, the extra electricity is consumed with central E2T at the CHP plants. Figure 15 shows the spatial distribution of E2T capacity required for this E2T scheme. The distributed E2T capacity is in 35 nodes and ranges from 58 kW to 7 MW. The central E2T capacities are 94 MW each.

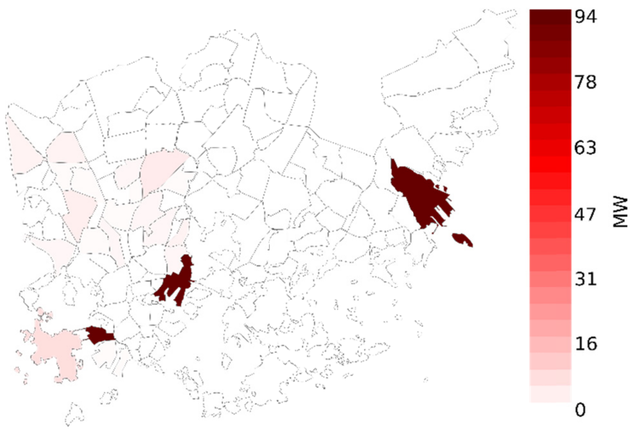

Figure 15. E2T capacity distribution with distributed and central E2T.

In this case, PV produces annually 0.5% of the heat consumption and 17% of electricity consumption in the city. Figure 16 shows the spatial energy balance on the extreme hour 3181 when E2T production is at the maximum value of 315 MW and PV produces all the electricity in the city. The central E2T nodes are clearly visible as negative energy balance areas.

During the 418 hours when PV produces all the electricity in the city, power system congestion does not occur, with the maximum relative power flow magnitude the same as in the central E2T case, 78%. That is, with distributed E2T, the city-level self-use limit 1000 MW_p can be integrated without intra-city network congestion during the hours when PV produces all the electricity in the city.

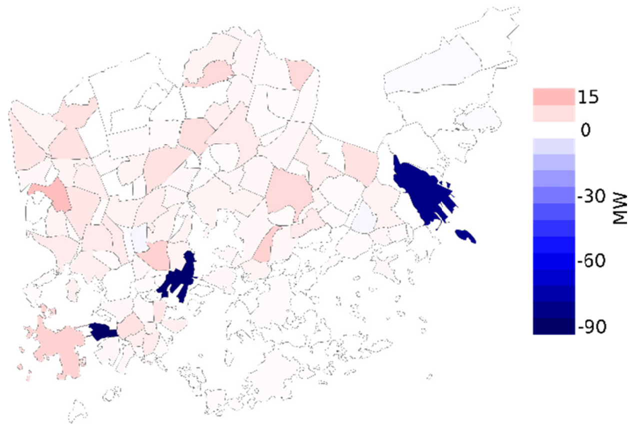

Figure 16. Spatial energy balance with distributed and central E2T on the extreme hour 3181 with maximum E2T (315 MW)

IV. Conclusions

DSM measures from E2T and shiftable loads have been studied in PV integration to an urban energy system with Helsinki, Finland as the case city.

The studied E2T measures were district heat production with electric resistance heaters and heat pumps. The shiftable loads comprised refrigerators and freezers in households and grocery stores, freezer warehouses, and dishwashers, washing machines and tumblers in households.

An increase of 26–99% in PV self-use limit was obtained with the considered measures. The E2T measures were more effective than load shifting.

E2T with electric resistance heaters was the most effective single measure, which could increase the self-use limit of PV to 1000 MW_p, or by 81% compared to the reference case with no flexibility. The PV share of electricity increased from 10.1% to 17.4% with the measure. At the new self-use limit, the heat production lost compared to using heat pumps was minor, around 1% of the whole annual heat demand, and the resistance heater capacity investment cost would add only 2% to the PV investment.

Spatial analysis was conducted for E2T with electric resistance heaters to identify possible network bottlenecks during the hours when PV is able to produce all the electricity in the city. Both a scheme with only central E2T at CHP plants in the city and one with distributed E2T in addition to that were considered, with PV capacities dimensioned accordingly. The central scheme could integrate 930 MW_p of PV without network congestion, and the distributed scheme could increase the capacity to the full city-level self-use limit, 1000 MW_p, likewise without network congestion problems.

In future work, the interplay of these DSM sources with conventional power plants and storage will be studied. The control algorithm will be improved by optimal control, which in addition to allowing price-based optimization, may obtain more benefit from load shifting than the myopic rule-based load shifting algorithm used in this work.

Acknowledgments

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