Chapter 4

Energy profiles and case studies for Helsinki and Shanghai

This chapter describes the present energy infrastructure in Helsinki and Shanghai. Consumption and production profiles are represented. Since direct hourly data of the consumption profiles was not available, the chapter describes how the hourly load profiles were created based on the available data. Finally, the chapter tells what types of renewable energy scenarios for the cities are simulated with the model. The results are represented in the next two chapters.

4.1 Helsinki

Helsinki is a northern city (60°N) with about 590 000 inhabitants. The population of the whole metropolitan region is over 1.3 million. Helsinki is fairly sparsely populated which has its influences on the energy infrastructure. The population density is only $2800/km^2$ ($450/km^2$ in metropolitan region).

The climate in Helsinki has very large seasonal variations which affect the energy consumption a lot. The temperature may vary from -30 °C at winter to over $+30$ °C at summer. The amount of daylight varies too. At winter, the light time is very short (only about $5\ \frac{1}{2}$ hours of daylight during the winter solstice), and at midsummer, the sun shines over 18 hours a day. This has a direct impact on the lighting needs, and thus on the electricity consumption.

Only electricity and heat are considered in Helsinki cases. The cooling load (1 TWh) throughout the year is so small compared to electricity and heating demands that it is neglected here. Data from year 2006 was used in the simulations. The yearly electricity demand in Helsinki was 4.37 TWh and the heating demand 6.60 TWh. [38]

Traditionally in Helsinki, electricity and heat are produced in large centralized power plants that use mainly natural gas and coal as their fuel. The plants are combined heat and power (CHP) plants that can produce both electricity and heat with an overall efficiency of about 80 %. Because of the combined production, there is more electricity produced than consumed in Helsinki. In 2006, altogether 6.31 TWh of electricity was produced in the city, and the share of CHP production was 4.93 TWh [39]. In practice, all this Helsinki-produced energy originates from fossil fuels. In other words, Helsinki produces much more fossil electricity than it needs itself.

The heat is produced mainly with CHP plants but during the cold days at winter additional production is needed. For this purpose, there are ten pure heating plants in the city. Seven of them use oil as their fuel and three of them natural gas. Similarly to electricity, also heat is thus produced almost in its entirety by fossil fuels. Delivering the produced heat to the customers, there is an extensive district heating network in Helsinki. It is wide and covers practically the whole city. 93 % of the heat load of the city is met by district heating [40]. Thus, there is an existing infrastructure to transport not only electricity but also heat energy everywhere in the city.

4.1.1 Electricity consumption profile

Because no hourly data were available, the consumption profiles had to be made with the help of the available information. The electricity profile is characterized by daily, weekly and annual rhythms. The consumption is much higher at daytime than at nights, and at weekends, it drops significantly. At summer it is smaller than at winter.

The profile (consumption for every hour of the year) is based on two graphs (not numerical data) acquired from energy company Helsingin Energia and the consumption data of the whole Finland in 2006 (available in numerical form in [41]). Helsingin Energia graphs showed the electricity consumption of Helsinki in 2010 throughout the year and one typical load of one week.

The starting point was to fit a cosine curve to the national data. After the wave length was fixed as one year, the cosine curve is defined by its amplitude, average and phase angle. The phase angle (i.e. the moment of the maximum consumption) was taken directly from the national data fit. It is logical to assume that the maximum occurs approximately at the same time in Helsinki and in whole Finland. The maximum of the cosine was found to be on 20th of January.

The average (constant term) of the consumption was calculated by dividing the overall consumption of 4.37 TWh with 8760 (number of hours in a year). It was thus 499 MW. The last free parameter, amplitude, was estimated based on the yearly graph from Helsingin Energia. It was chosen to be 100 MW.

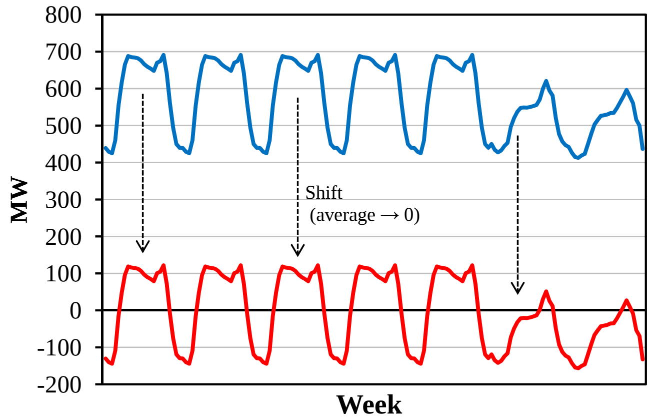


Figure 4.1: Typical week profile and how it is shifted so that the average is zero.

The cosine tells only the yearly variations. Daily and weekly profiles had to be added still. This was done with the help of the weekly profile of Helsingin Energia. The numerical values of one weekday, Saturday and Sunday were extracted from the graph, and then combined as one-week profile (blue curve in Figure 4.1). The values were shifted so that the average of the week became zero (red curve). The weekly and daily variations were added to the profile by just summing the shifted week profile (extended to all weeks of the year) and the annual cosine curve together.

On top of the seasonal variations, momentary perturbations like extreme weather conditions or national holidays were added to the profile. They were taken into account by calculating the moving weekly average of the national data which was then compared to the national cosine fit. It was found out how much the average differs from the cosine relatively. The same relative variations were then added to the Helsinki profile. The variations were scaled by factor 0.7 so that they were not as striking as on national profile.

The final electricity consumption profile for the city is shown in figure 4.2. The red curve is the cosine curve on which the daily, weekly and other temporal variations were added.

4.1.2 Heat consumption profile

The heat consumption profile is based on the hourly temperature data of Helsinki Kaisaniemi meteorological observation station. The data was acquired from the Finnish Meteorological Institute. The outside temperature is by far the most important factor modifying the heating demands. The other factor that is considered here are the daily routines of people. At winters, the heating demand is bigger at nights when the sun does not shine and the temperature is lower. The difference between day and night consumption is however a bit less than what one could think on the grounds of temperatures. This is caused by domestic hot water use

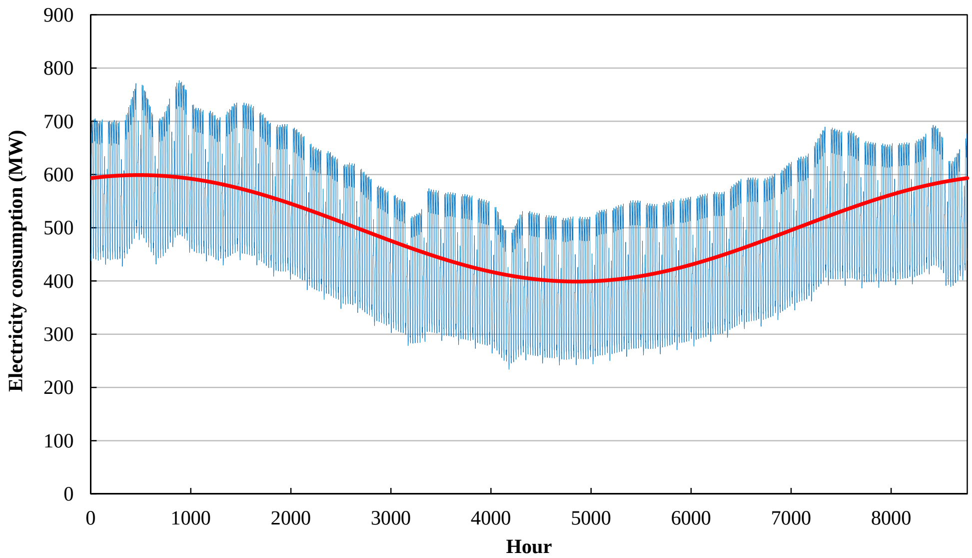


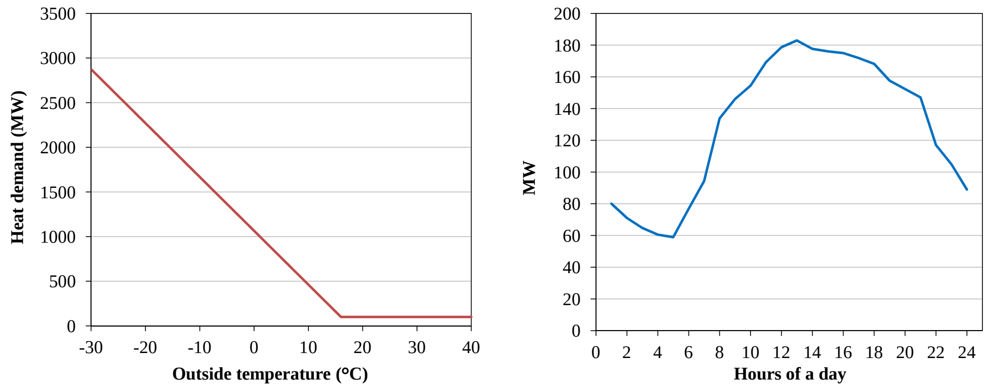
Figure 4.2: Electricity consumption profile in Helsinki and the cosine curve on which it is built.

that is in practice zero at night time. For the same reason, the heat consumption at summers is higher at daytime than at nights.

The first approximation is that the heat flow through the walls (lost heat) is directly proportional to the temperature difference between the outside air and the inside of the house. The temperature-dependent heating demand behaves similarly. The domestic hot water use is assumed to be independent of the outside temperature. These assumptions lead to a curve like the one in Figure 4.3(a). There is a decreasing linear part when the temperatures are cold, and after the temperature rises above a certain limit, no space heating is needed and the function becomes constant that describes the domestic hot water use.

The curve does not take the daily variations into account. This is done with the profile in the adjacent Figure 4.3(b) that presents the daily variation caused mainly by the hot water use. The data for the daily profile was extracted from the example graph of one typical day in Helsinki. The graph was acquired from Helsingin Energia. This daily profile is copied for every day of a year and then summed together with the profile formed on the grounds of the temperature data and Figure 4.3(a).

Helsingin Energia offered same kind of annual graph of the heat consumption than it did with electricity. The temperature–heating demand curve (Fig. 4.3(a)) is defined by its slope, the turning point and the constant. Based on the real annual graph these three parameters were fitted. The fitting was made after the daily variations were added on. Based on the real graph, the minimum of the heat consumption should be about 170 MW and the maximum peaks a bit more than 2500 MW. The strictest boundary condition was



(a) Heat demand as a function of outside temperature.

(b) Daily variation in heat load.

Figure 4.3: Background data for creating the heat load profile.

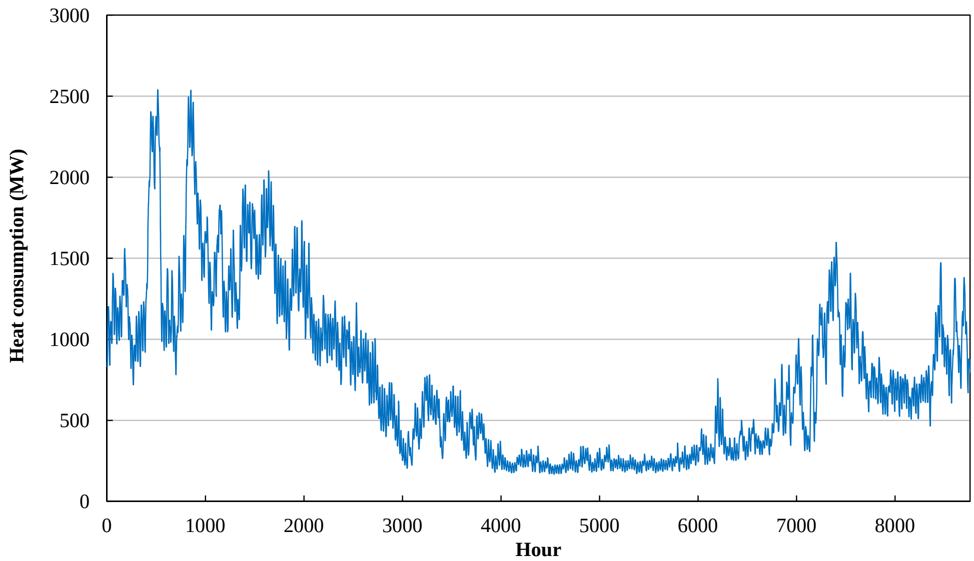


Figure 4.4: Heat consumption profile in Helsinki.

that the total consumption should match with 6.60 TWh. By fitting the parameters, the profile in Figure 4.4 was created.

4.1.3 City model and the node-wise profiles

The land area of Helsinki is 213.75 km^2. If sparsely populated islands and wooded areas are excluded (e.g. the new very sparsely built Östersundom area covers over 30 km^2), the area is close enough to 100 km^2 so that the city can be modelled with 10 km $\times$ 10 km grid. The grid of this size and one hundred 1 km^2 nodes was used for Helsinki.

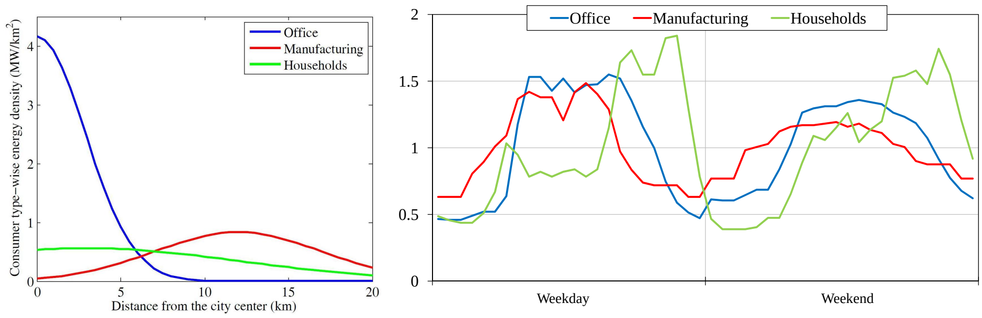
Table 4.1: Parameters to define the consumer type densities.

Parameter	$d_{0,i}$ (MW/km^2)	α_i (1/km^2)	$r_{0,i}$ (km)
Office	4.167	0.06	0
Manufacturing	0.833	0.02	12
Households	0.565	0.006	3

The electricity and district heating networks were made with the method that connects the node to the second closest node from the base node (see Section 3.1.1). The city center was located at the point (3 km, 3 km) so that it is in the south-west corner of the city. The electricity and heat networks are represented in Figure 4.6.

The consumption profiles (Figures 4.2 and 4.4) were divided among the nodes according to Section 3.1.3. The parameters of the Gaussian densities in Equation 3.1 are represented in Table 4.1. The densities are given as megawatts of electricity per square kilometer, which means that the temporal base profiles h_i in Equation 3.2 are dimensionless. They just tell *relatively* how the consumption behaves during a day. The densities were made mainly according to electricity but they were used with the heat profiles as well. The absolute value of the densities are not exactly what it will be in the final node-wise profiles, because Equation 3.4 scales the values finally so that the sum of the node-wise heat consumption values match with the real heating demand of the city. The consumer type-wise energy densities d_i are shown in Figure 4.5(a) and the temporal base profiles h_i for electricity in Figure 4.5(b). The base profiles were scaled so that the average of each of them equals one.

Figure 4.6 shows how the total consumptions (Figure 4.2 and 4.4) are divided among the nodes. The same figure shows also how the consumption is concentrated in the city

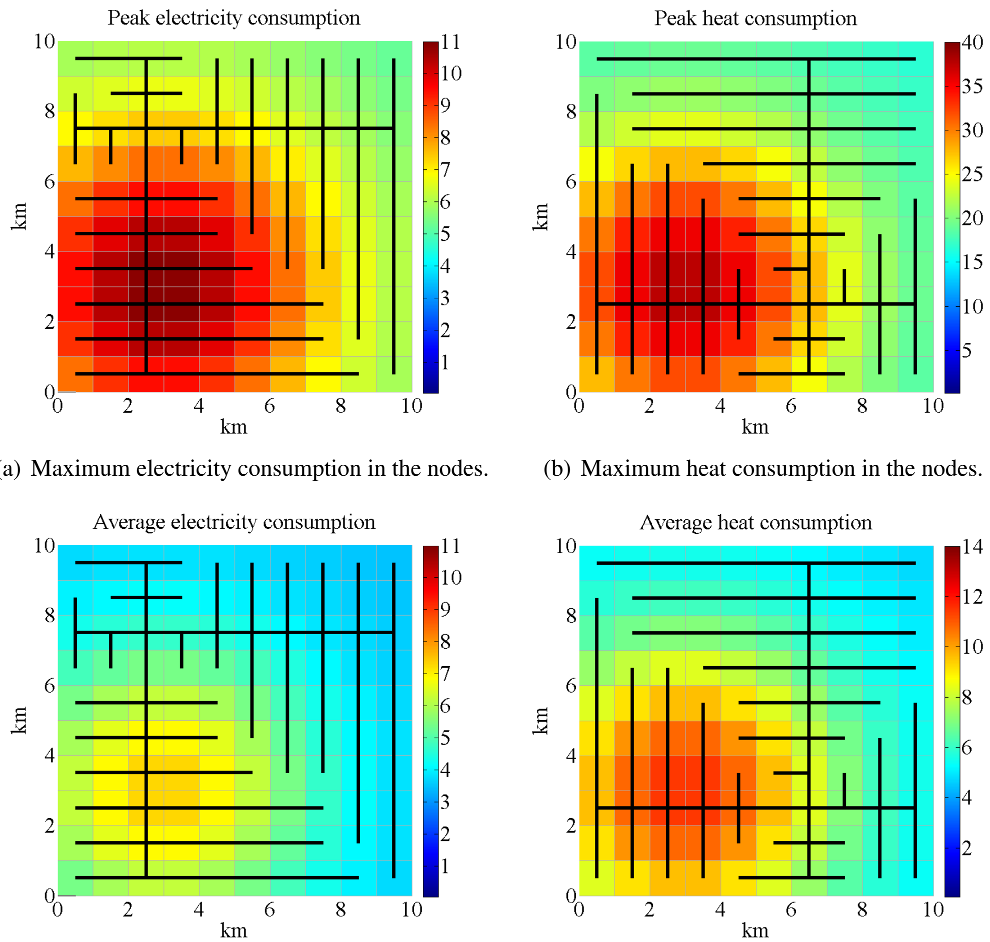


(a) Densities of different consumer types as a function of the distance from the city center.

(b) Temporal relative base consumptions of electricity.

Figure 4.5: Background data for dividing the consumption among the nodes.

center area. The average consumption in the center is about 2–3 times higher than on the outskirts (for electricity, 7–8 MW/km^2 and 3–4 MW/km^2 respectively). The annual variation in heating is much stronger than in electricity. The maximum electrical peak load is approximately 3 times higher than the minimum load. The same ratio for heat is about 13. The difference shows clearly in figures 4.2 and 4.4.



(a) Maximum electricity consumption in the nodes.
(b) Maximum heat consumption in the nodes.
(c) Average electricity consumption in the nodes.
(d) Average heat consumption in the nodes.

Figure 4.6: Maximum and average consumptions of the nodes in Helsinki case. Spatial resolution is 1 km × 1 km and power densities are given as MW/km^2. Energy networks are shown by black lines. One should notice that the color scales in heat graphs (right-hand side) are not same.

4.1.4 Case studies

Reference case. In the Helsinki reference case, no production is located within the grid area. Thus all electricity and heat are imported from the base node. In other words, one node takes care of the whole consumption of one energy type. This imitates the situation where the energy is produced at large centralized power plants.

Large scale wind power. In the first renewable energy case, there was a large scale (hundreds of megawatts) offshore wind farm was located on the sea area south from the city. The annual wind production profile is represented in Figure 4.7. The four-week moving average curve in the figure shows that the turbines produce more electricity at winter than at summer. Because of this, there is a small positive correlation between the energy consumption and wind production, although wind production is very intermittent.

The purpose is to investigate how much wind power could be installed in the system so that no overflows occur (comparison with the reference case). The location of the wind power connection affects a lot to the amount of potential wind capacity, which why different locations in the grid are tested. It is studied how much the capacity could be increased if the production that exceeds the flow channels is converted into heat (by electric resistance or heat pumps) and then fed into the heating network.

Solar cells and electric vehicles. In practice, wind power at least in large scales is centralized production. Solar energy however is not. It can be integrated quite easily into the urban structure. For example roofs offer lots of free and sunny space to be utilized

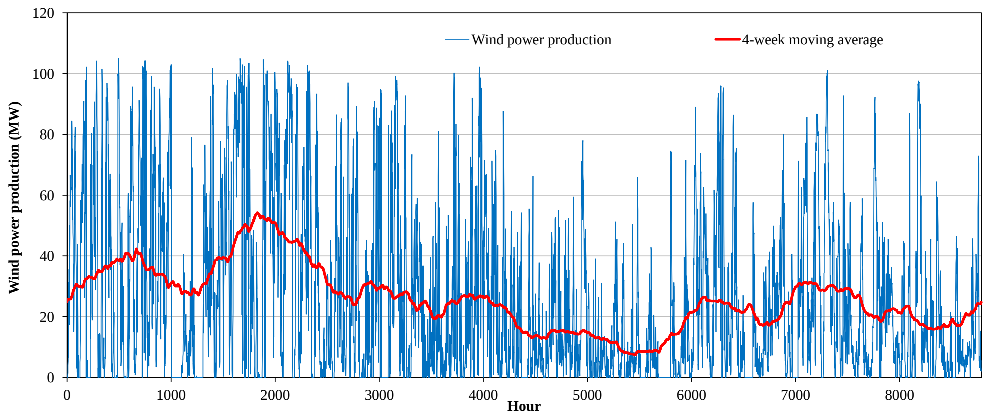


Figure 4.7: Electricity production curve of 100 MWp wind power park and its four-week moving average.

in solar energy production. In opposite to wind power, solar energy production is strongly concentrated in the summer time. This shows clearly in Figure 4.8.

Network-wise, the PV cells should be installed according to the consumption, i.e. more cells in the high-consumption areas. This would minimize the spatial transportation needs. However, the problem may be that the physical area is limited. If the city center has not enough free space for the cells, they have to be located outskirts of the city which can then cause overflows in the grid. The location of the cells and the overflows are studied.

Plug-in electric vehicles may be one solution to the overflow problem. Smart recharging of them could transform the energy balances conveniently. This is option also investigated.

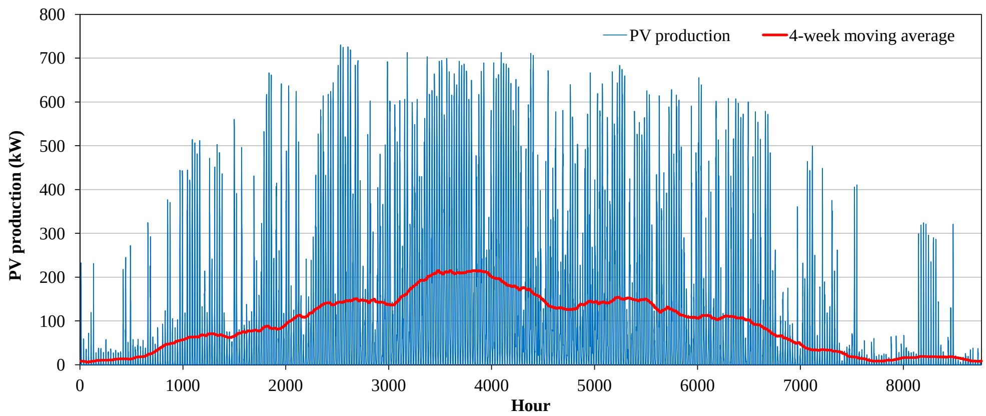


Figure 4.8: Electricity production curve of 1 MWp photovoltaic cell installation and its four-week moving average.

4.2 Shanghai

Shanghai differs greatly from Helsinki in many ways. Shanghai is a southern (31°N) megacity with population over 23 millions. The most densely populated districts have populations over 40,000/km^2. Such huge amounts of people require a lot from the energy system.

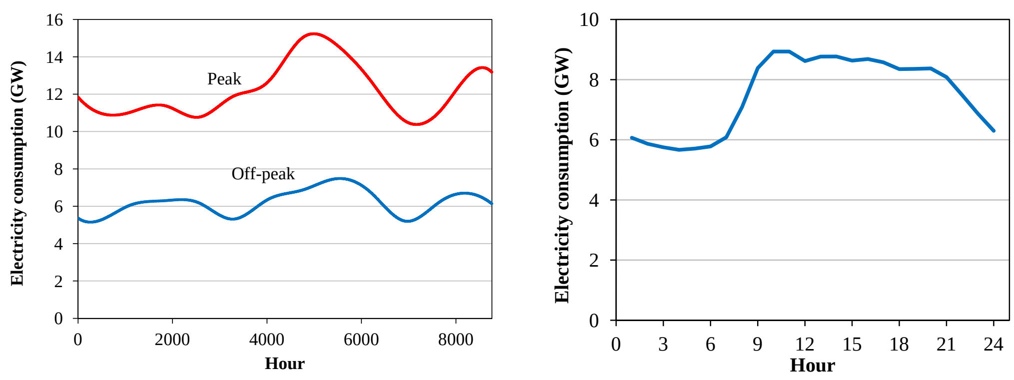
In Helsinki, the total energy consumption consisted of electricity and heat (fossil fuel traffic is not considered in the thesis) and cooling load was assumed to be so small that it could be dismissed. In Shanghai however, the situation is completely different. The summers are so hot that the cooling of the buildings forms an essential part of the energy consumption.

Data from year 2004 was used as input for the model. The electricity consumption was 82.1 TWh. Detailed data on the heat and cooling consumption was not available except some maximum values [42].

4.2.1 Electricity consumption profile

The hourly electricity consumption profile of Shanghai is based on data extracted from two graphs. The first of them tells the monthly peak and off-peak values of electricity consumption [42] and the second one describes the daily variation in electricity consumption [43]. The rough hourly data for the whole year was got from the monthly data of peak and off-peak consumption by spline interpolation. This produced hourly upper and lower limits of the consumption (Figure 4.9(a)). The daily variation curve (Figure 4.9(b)) was then used to get the final profile. For each hour, the final consumption between the peak and off-peak curves was chosen in relation to the daily variation curve. This means that every day the consumption of the 10th hour (the hour with maximum value at daily variation curve) was designated to be the value at peak curve in Fig. 4.9(a). Respectively, the fourth hour of a day got its consumption value from the off-peak curve.

The final consumption profile is shown in Figure 4.10 with light green line. 82.0 % of cooling and 43.7 % of heating load are satisfied with electrical chillers and heaters [42]. Their share is included in the green curve. In the model however, different energy types must have their own consumption profiles. Because of this, there is another graph in the same figure (blue curve) that shows the pure electricity consumption i.e. the one from which the load caused by heating and cooling has been reduced. How the heating and cooling loads were created, is represented in the next section. The annual consumption of electricity



(a) Spline interpolation of monthly peak and off-peak consumption.

(b) Daily variation.

Figure 4.9: Background data for Shanghai electricity consumption.

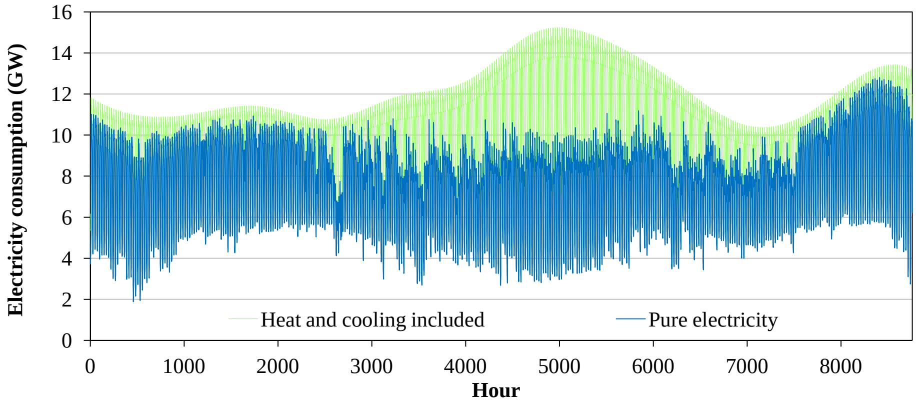


Figure 4.10: Electricity consumption profile of Shanghai. The blue line is the consumption without the electricity used in heating and cooling purposes. The green line takes also heating and cooling electricity into account.

without heating and cooling is about 65 TWh.

4.2.2 Heating and cooling load profiles

The heat and cooling profiles that were created for the simulations are based on the temperature data from Shanghai in 2004 [44]. The data consisted of the highest and lowest temperatures of each day. It was assumed that the highest temperature during a day is achieved at 2 pm and the lowest one at 3 am. This produced two data points for each day, and the spline interpolation was used to get hourly values.

The hourly temperature data was turned into heating and cooling loads. For this purpose a graph from [45] was used. The data is represented in Figure 4.11. The graph shows the energy performance of earth-to-air heat exchangers as a function of ambient temperature. It is a good approximation for relative heating and cooling loads with regard to the temperature data. The original heating graph (red curve) in [45] decreased to zero at higher temperatures, but in order to take the domestic hot water use also at summers into account, the graph was raised so that it levels out as a positive constant at higher temperatures.

Figure 4.11 was applied to create the preliminary heating and cooling load profiles which were scaled so that the overall heating and cooling consumptions matched with the reference values. 82 % of cooling in Shanghai is done by electrical devices [42]. In 2004, the peak electric load of air-conditioning in Shanghai was 6,860 MW [46]. It was assumed that this cooling load was satisfied by heat pumps with COP = 3. These numbers state that the maximum peak of all cooling energy demand is $3 \times \frac{1}{0.82} \times 6{,}860$ MW = 25,860 MW.

In [47], it is represented that the cooling load is approximately two times bigger than the heating load in Shanghai (66.27 kWh/m^2 and 36.95 kWh/m^2 respectively). Based on

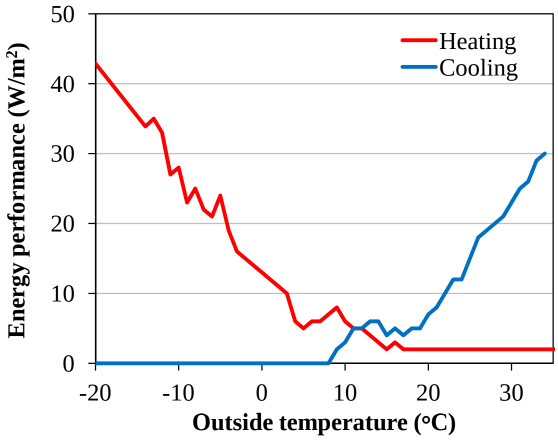


Figure 4.11: Specific energy performance of earth-to-air heat exchangers as a function of ambient temperature [45].

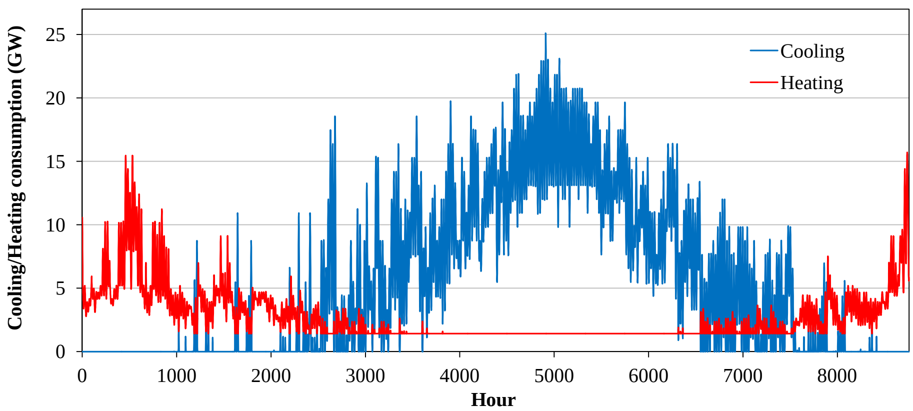


Figure 4.12: Cooling and heating consumption profiles in Shanghai.

this, the heating profile was scaled so that the annual heating energy consumption is about half of the cooling consumption. The final profiles can be seen in Figure 4.12. The overall cooling consumption of the year is 47 TWh and heating consumption 24 TWh.

4.2.3 City model and node-wise profiles

The area of the municipal Shanghai is over 6 000 km^2. The majority of the population is concentrated strongly on a much smaller area. The outskirts of the city have population density of only a few hundred people per square kilometer. In downtown, the number can rise up to 50,000.

Shanghai was modelled with a 50 km $\times$ 50 km grid with one hundred nodes. The grid covers most of the city area. The city center lies in the north-east part of the municipality, and in the model, it was put to coordinate point 42.5 km, 42.5 km.

Population and energy consumption are strongly peaked at the city center. For this reason, a 25 km^2 node was too large to describe accurately the situation in the central parts of the city. Therefore, the city center node was divided into one hundred sub-nodes.

The energy networks were created with the same method as in Helsinki. Every node was connected to the second closest node from the city center. In Shanghai four different energy types were examined (electricity, heat, cooling and gas) but only two of them (electricity and gas) were assumed to have a network. In spite of this, a network was created for all of them as the model requires but heating and cooling networks were never used. The gas network is shown in Figure 4.13. The electrical network is shown with energy consumption distributions in Figures 4.15–4.16.

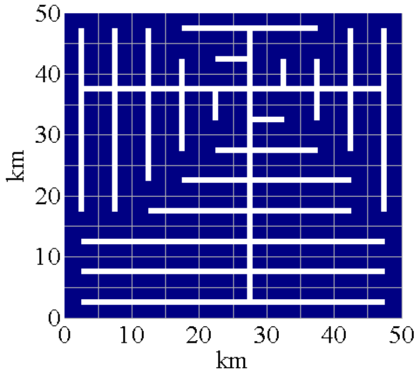


Figure 4.13: Shanghai gas network.

Distributing the overall consumptions to the nodes was carried out in the same way as in Helsinki. The parameters of the consumer type densities d_i (Equation 3.1) are in Table 4.2. To get the household density to extend to the whole city, a constant term was added to the original equation. Figure 4.14 shows the relative densities of the consumer types as a function of the distance from the city center.

The same temporal base profiles h_i (in Equation 3.2) were used as in the Helsinki case. They can be seen in Figure 4.5(b). A fraction of randomness was added to the nodal con-

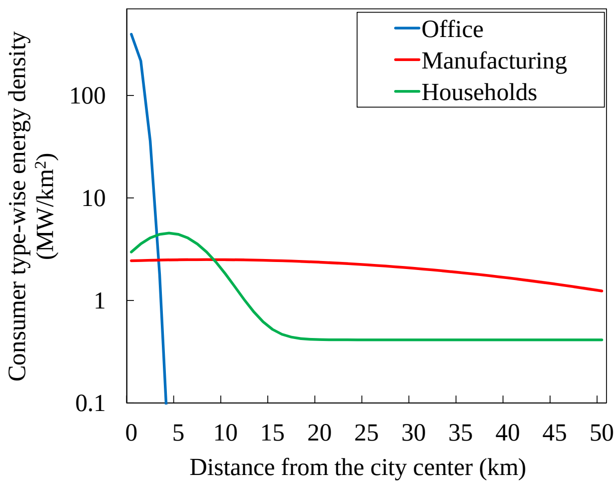
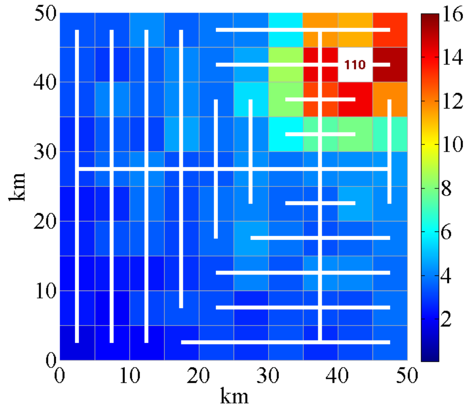


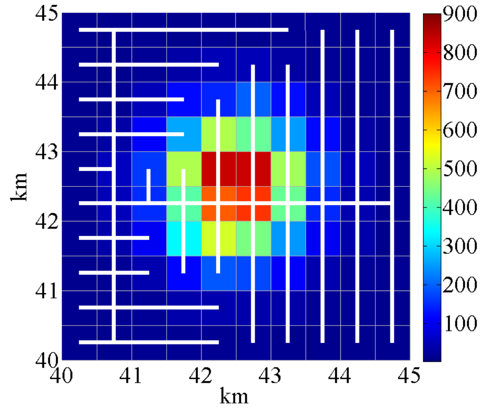
Figure 4.14: Consumer type densities as a function of the distance from the city center.

Table 4.2: Parameters to define the consumer type densities.

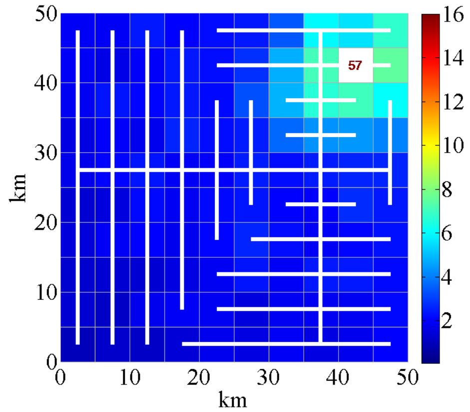
Parameter	$d_{0,i}$ (MW/km^2)	α_i (1/km^2)	$r_{0,i}$ (km)	constant (MW/km^2)
Office	395.8	0.6	0	–
Manufacturing	2.5	0.0004	8	–
Households	4.1	0.03	4	0.6



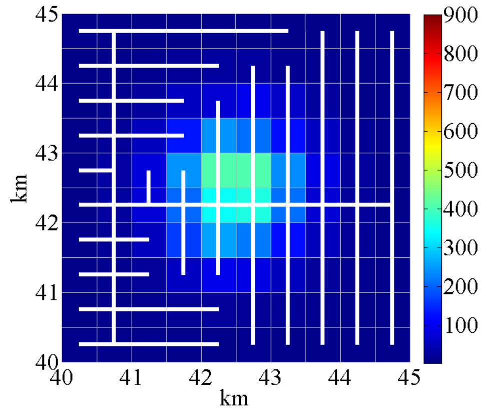
(a) Peak electricity consumption (whole area).



(b) Peak electricity consumption (city center).

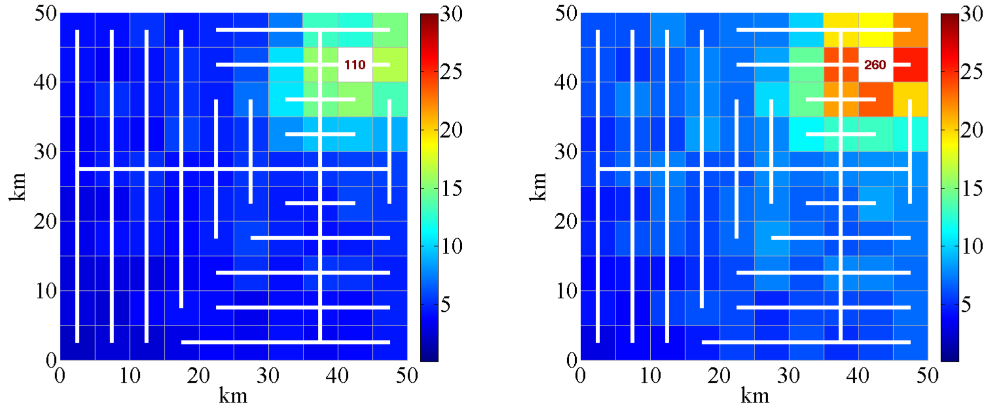


(c) Average electricity consumption (whole area).



(d) Average electricity consumption (city center).

Figure 4.15: Peak and average electricity consumptions of the nodes in the Shanghai case. Power densities are given as MW/km^2. The left graphs show the consumption in the whole metropolitan Shanghai and the right graphs in the most central node (the white node on the left that does not fit to the color scale). The electrical networks are shown by white lines.



(a) Peak heating consumption (whole area).
(b) Peak cooling consumption (whole area).

Figure 4.16: Peak heating (left) and cooling (right) consumptions of the nodes in Shanghai case. Power densities are given as MW/km^2. The values of city center does not fit into the color scale and is thus given as number. The electrical network is shown by white lines.

sumption profiles. This was not made in Helsinki case, but since now there are many same type of nodes (with relatively small energy demand in the outskirts), some variation between them was wanted. A random number between 0.8 and 1.2 was chosen for every node and the nodal profile was multiplied with this factor.

The final node-wise distribution of energy consumption is visualized in Figure 4.15 for electricity and in Figure 4.16 for heating and cooling. The figures show also the electrical network.

4.2.4 Case studies

Reference case. 43.7 % of heating and 82.0 % of cooling demand are met by electrical heaters, heat pumps or radiators (see Section 4.2.1). Natural gas is another energy source for heating and cooling. It covers 7.8 % of heating and 4.0 % of cooling energy [42]. In the reference case, the electricity is produced in large power plants outside the city, and in the model all electricity is imported from the base node. It is assumed that all electricity-made cooling is done with heat pumps with COP = 3. For heating purposes also electric resistance (COP = 1) can be used which why the COP for heating is assumed to be about 2 in the model. When converting gas into heat, the COP is set to 1 and for cooling to 0.7. For example, simple absorption chillers work approximately with COP = 0.7 [48]. The rest heating and cooling are done with oil and coal. In the model, this energy is taken from the (virtual) heating/cooling network and its base node.

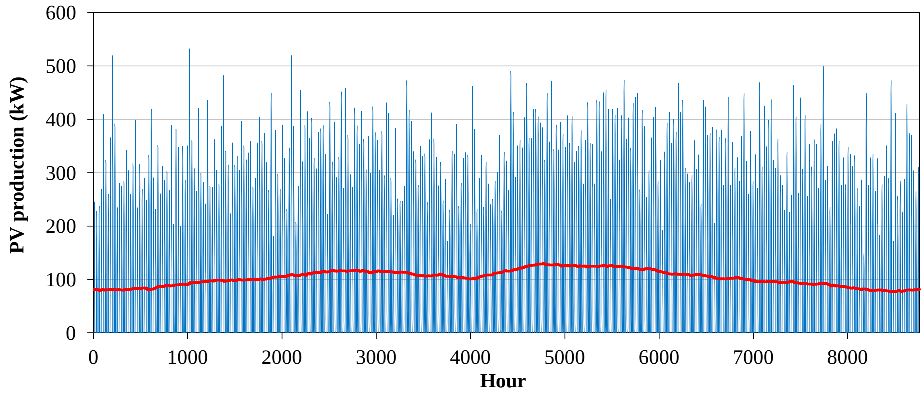


Figure 4.17: Electricity production curve of 1 MWp photovoltaic cell installation and its four-week moving average (red curve) in Shanghai.

Large-scale photovoltaics. First renewable energy case in Shanghai discusses large-scale PV panel installations. Significant shares of PV power are investigated. In the first case, despite the huge electrical load, the city achieves the situation where momentarily all consumed electricity is produced by PVs. In addition, a case is studied where a little overproduction is allowed (at some moments the production may exceed the consumption).

A PV production curve for Shanghai is represented in Figure 4.17. When comparing it with the same graph for Helsinki (Figure 4.8), one can see that it is much more evenly distributed throughout the year, and that also the peak power is not as high. Main reason for the lower peak production is that the temperatures of the panels remain cooler in Helsinki and thus higher efficiencies can be achieved.

The intention is to find out how large shares of the overall consumption can be met by PVs and the magnitude of the overflows that the PV panels cause. Presumably, overflows will occur at some point when adding more and more PV panels. Another way to study this is to find out where does the energy that is consumed in the central city, come from (i.e. how much the outskirts feed the city center).

Trigeneration in the city center. One way to reduce the overflows caused by the heavy PV installations in the outskirts of the city is to replace some of the outskirt PV capacity with small-scale trigeneration plants in the city center. The consumption peaks in the center area are so high that in any case it could be impossible there to install enough PV panels to cover the whole demand.

It was investigated that if the overflows are born, how much PVs have to be removed from the overflow nodes. The removed production capacity was replaced with fuel cell based trigeneration in the center. The fuel cells use natural gas to produce electricity with efficiency 0.4 and heat with efficiency 0.4. Cooling is achieved from heat by absorption chillers working with COP = 0.7.

On top of this avoid-overflows type of approach, another approach was studied. In this case, the self-use limit of electricity should not be broken. This means that at maximum, the distributed production can match with the consumption, but no energy is exported outside the city. The question to be answered is that how much PV panels it is possible to install if certain percentage of the heating and cooling demand is covered with trigeneration. In other words, the fuel cell in the city center produces a fixed share of the thermal energy consumption at each hour. At the same time the cell produces electricity (the amount is determined directly by heating and cooling demands). This electricity production affects the available PV capacity.

Finally, it is studied (on top of the overflow reductions) how the trigeneration affects the shares of DEGS produced energy. Because rather same studies were made for both the pure PV case and the PV case with trigeneration, the results could be compared mutually.