Title	Energy and emission analyses of renovation scenarios of a Moscow residential district
Author(s)	Paiho, Satu; Hoang, Ha; Hedman, Åsa; Abdurafikov, Rinat; Sepponen, Mari; Meinander, Malin
Citation	Energy and Buildings vol. 76(2014):June, pp. 402 - 413
Date	2014
URL	http://dx.doi.org/10.1016/j.enbuild.2014.03.014
Rights	Copyright © (2014) Elsevier. This article may be downloaded for personal use only

Energy and emission analyses of renovation scenarios of a Moscow residential district

Satu Paiho[1], Ha Hoang, Åsa Hedman, Rinat Abdurafikov, Mari Sepponen, Malin Meinander

VTT

VTT Technical Research Centre of Finland, P.O. Box 1000, FI–02044 VTT, Finland

[1] Corresponding author, Satu.Paiho@vtt.fi, +358-50-3315160

Abstract

Three building level renovation concepts of a typical Moscow residential district are defined and their energy saving potentials evaluated in a recently published study [1]. This study extends these analyses and concentrates on energy and emission analyses of different energy renovation solutions and energy production alternatives at the district level using the same case district as in the previous study [1].

At the district level, four different energy renovation scenarios, called Current, Basic, Improved and Advanced, were analyzed in terms of energy demand and emissions. Considerable energy savings could be achieved, up to 34% of the electricity demand and up to 72% of the heating demand, using different district modernization scenarios.

As for the emission analyses, switching from natural gas to biogas would result in decreasing greenhouse gas emissions, but increasing generation of SO_2-equivalent and particulate emissions. A better solution would be to still switch to biogas while maximizing renewable energy production from local non-combustion technologies at the same time.

Keywords: Residential districts, energy and emission analyses, renovation scenarios

1. Introduction

In Russia, climate change causes environmental, economic and social stress, why a future reduction in energy consumption could benefit the national economy [2]. In an energy-inefficient country like Russia, there is the potential to weaken the link between GHG (Greenhouse Gas) emissions and economic growth by improving energy efficiency [3]. Ever since the year 2000, Russia's economy has witnessed an upswing, and the government has started to take effective measures to curb energy intensity and reduce CO_2 emissions [4].

Energy efficient renovation increases the value of a building [5]. Improved cost-effectiveness of energy efficiency measures is achieved when they are implemented as part of a building renovation. It is often important to examine the impacts of building level renovation solutions in a wider perspective, since energy renovations reduce the energy demand from the grid or network [6], as well as the primary energy consumption. Greater overall energy efficiency can often be achieved through a district-scale building and district infrastructure renovation. The renovation of buildings should not be separated from the improvement of the surrounding environment. If the surrounding environment is improved, the market value of the land will considerably increase and the area will become much more attractive to investors. Therefore, it is clear that the renovation of a neighbourhood should not be restricted to the renewal of buildings, but should be extended to the whole region [7].

Some general principles for improving energy-efficiency at the district level include: improving the energy-efficiency of buildings, outdoor lighting, energy networks and grids (especially by reducing distribution losses), replacing fossil fuels with renewable energy sources, improving the energy-efficiency of waste and water management systems, reduction of emissions (e.g. change of fuel or flue gas treatment), and energy-efficient transportation [8]. Modernization must follow the urban structure which reflects the principles of sustainable development and corresponds to the quality of life: compactness, multifunctional use of territories, sustainable transport, ensured public interests and visually attractive (unpolluted) environment [9]. Outdoor amenities, i.e. pedestrian and bicycle paths, parking lots, children's playgrounds, sports grounds, benches, litterbins, street lamps, etc., should be renovated and rebuilt because the quality of housing largely depends on them [7].

Paiho et al. [1] present three different renovation concepts for apartment buildings in a Moscow residential district. The energy consumption of a typical Russian apartment building was estimated by taking into account heating of living spaces, heating of domestic hot water, and the electricity consumption. The energy consumption of the selected building stock was thereafter calculated based on the estimated consumptions of the type buildings. First the present state of the district level was studied, including energy chain analyses. The energy saving potentials for the three different building level renovations concepts were thereafter estimated. Results from the calculations showed that the building level energy saving potential could be up to 68% for heating energy and 26% for electricity, respectively.

The energy analyses are continued further in this paper by looking at three district level energy renovation concepts. In combination with this, the paper introduces different energy production scenarios and estimates the annual emissions for each examined case. The purpose was to assess how low emission values could be achieved by comparing and combining technologies for energy generation, and clarify which of the combinations presented would be better in terms of produced emissions.

This study tested the hypothesis that energy renovations are more efficient at a district level than on a building level, thus including the whole energy chain from production to consumption and taking into consideration not only building scale renovations, but also improvements on the energy supply systems. Furthermore, this study aims to explore whether emissions to air correlate with energy efficiency.

2. Background

It is estimated that more than 290 million m^2 or 11 % of the Russian housing stock needs urgent renovation and re-equipment, 250 million m^2 or 9 % should be demolished and reconstructed [10]. Some 58-60 % of the country's total multi-family apartment buildings are in need of extensive capital repair, rising to 93-95 % in those apartment blocks with an average age of less than 25 years [11].

The energy strategy of Russia for the period up to 2030 [12] states that one main problem in heat supply is the unsatisfactory state of heat supply systems characterized by high depreciation of fixed assets, especially of heat supply networks and boiler rooms, insufficient reliability of operation, large energy losses and negative impact onto the environment. The high level of technical abrasion and a low level of investments into modernization of the Russian energy industry cause huge energy wastage and carbon emissions [13]. With the exception of hydropower, Russia's utilization of renewable energy sources remains low relative to its consumption of fossil fuels [14]. In the absence of a clearly formulated long-term strategy for bioenergy and renewable energy, the legal and political processes in this field have been fragmented and weak [15].

2.1. Literature review

There is no relevant literature related to the energy consumption of Russian buildings. Also nothing has been found on the impacts of different options for energy renovations of residential buildings or districts in Russia. Furthermore, no studies have been found, taking into account the different emissions of energy production types when analysing the whole energy chain from production to consumption in residential buildings.

Studies on the energy consumption of Russian buildings have been made in the 1990s by Matrosov et al. in 1994 [16] and Opitz et al. in1997 [17]. More recent studies on energy consumption analyses of buildings elsewhere than Russia have been made by e.g. Balaras et al. in 2005 [18] (heating energy consumption of European residential buildings); Choi et al. in 2012 [19] (comparison of energy consumption according to building shape and utilisation) as well as Kyrö et al. in 2011 [20] and Kim et al. in 2011 [21] (the impacts of residents' behaviour on building's energy consumption). Studies on the reduction of buildings' energy consumption through renovations have been published by e.g. Tommerup & Svendsen in 2006 [22] (energy-saving potential of Danish dwellings through energy-saving renovations), Ouyang et al. in 2009 [23] (life cycle cost analysis for energy-saving renovations of residential buildings) and Siller et al. in 2007 [24] (on reducing energy consumption and greenhouse gas emissions of the building stock through renovations).

The first study on reduction of energy consumption through district renovations was published by Oujang et al. in 2008 [25]. This paper represents the Hot Summer and Cold Winter Region of China and examines buildings which are at least seven years old and are becoming dilapidated. Opposite to the study in China, where even quite new buildings are typically demolished and new constructed [25]; the situation is different in Russia where the designed life time of buildings is significantly longer.

2.2. Moscow residential districts

As of 2012 the need for renovations was estimated at 108 million m^2 (over a half of the total floor area) in 26.3 thousands of Moscow apartment buildings based on their age [26]. From an architectural perspective, residential areas with typical apartment houses look monotonous, lack vitality and are less aesthetically pleasing [9].

In the Russian Federation, most of the apartment buildings were constructed between 1960 and 1985 during the Soviet-era, and as a result the urban housing stock today consists mainly of a few standard building types [10]. Each building series represents a specific building design [9], [17], [27]. Correspondingly, residential districts in Moscow have been built with only a few building types. Examples of these building types are clearly defined for example in [1], [10] and [27]. Therefore the energy demand of the whole district can be estimated by using these building types and multiplying their performance with the number of buildings in the area.

In these buildings natural ventilation is dominating. Almost no buildings have mechanical ventilation [28], [29]. Changing the inner layout of panel houses is hardly possible because the spacing between the external and internal bearing walls is small [7], [9].

Energy efficiency of these apartment buildings is typically poor [10]. The thermal insulation of the precast panel walls does not meet modern standards. District heating networks supply heat to about 80% of Russian residential buildings and about 63% of the hot water used by Russia’s population [30].

2.3. The selected housing district

The selected district mostly represents 4-th Microrayon of Zelenograd, Moscow (longitude 37° east and latitude 55° north). Zelenograd is located about 35 km to the North-West from Moscow City centre. The district dimensions are approximately 1x0.5 km. It represents a typical residential district of Moscow and Moscow region with high-rise apartment buildings constructed for the most part in 1960's and 1970's. The district is heated with district heating. Renovation of such buildings and districts is needed in the near future.

The apartment buildings in the area are built between 1966 and 1972. After the initial analysis the most common building type II-18 was selected to represent the average building in further studies since a comparison of the demands of the buildings showed only minor differences [1]. There are also a few other newer buildings but since these analyses concentrated on modernisation of buildings, these newer buildings are excluded from the studies.

In total there are approximately 13 800 residents in the buildings that are included in the calculations which is about 0.12% of the total population of Moscow. The total floor area of the studied buildings is 327 600 m^2 and the total roof area 31,230 m^2. The number of residents is estimated based on the assumption that the average occupancy rate per flat is 2.7 persons [10].

3. Methodology

The principles of the energy chain analyses used are discussed in [1]. At first the present state was studied by selecting both a typical old apartment building and an entire residential district in the Moscow region for the calculations. The renovation concepts were assessed from the perspective of energy demand and associated environmental impacts.

The assessment started with development of a “Current” energy and water demand model of the most common building type (II-18) which represented an average apartment building. From this model, other renovation models were generated. The four models where named according to the concept on which they were based: Current, Basic, Improved and Advanced.

In this study, the building models were used in the energy demand analyses of their corresponding district concepts, also named Current, Basic, Improved and Advanced. Each district concept was further used to examine different scenarios of energy production and the resulting environmental impacts. See Figure 1 for further clarification of the different steps of the energy analysis process.

The renovation concepts and energy production scenarios were selected based on expert experience from field studies of energy efficient renovations in Finland. These were adjusted to Russian conditions also taken into account the existing Moscow building codes for new construction. Relevant detailed building codes, standards etc. do not exist for renovation. The opportunity to utilize renewable energy production was also emphasized.

The scenarios were selected primarily with the view on practical implementation of building renovations as follows: (i) only restoration of buildings to initial condition, (ii) restoration of buildings using nowadays materials available on the market, which properties have improved over the past 40 years, (iii) significant improvement of buildings to meet local requirements to new construction, and (iv) improvement of buildings going beyond the local requirements to new buildings but being “normal” to renovation projects in Finland and Northern Europe.

[Figure1]

After the energy demands were analysed, the life cycle emissions for different energy production scenarios were calculated. CO_2-equivalents, SO_2-equivalents, TOPP-equivalents (tropospheric ozone precursor potential) and particulates were selected to represent the environmental impact of the energy production alternatives. **CO_2-equivalent** emission is a total measure, in which the emissions of different greenhouse gases are summed up according their global warming potential (GWP) factor (Fritsche & Schmidt 2008). **SO_2-equivalent** signifies the total acidification potential, which is the result of aggregating acid air emissions [31]. In the calculation of SO_2-equivalent emissions, the utilized software GEMIS (Global Emission Model for Integrated Systems software) [32] includes SO_2, NO_x, HF, HCl, H_2S and NH_3. **TOPP-equivalent** signifies tropospheric ozone precursor potential (Fritsche & Schmidt 2008). It is the mass-based equivalent of the ozone formation rate from precursors, measured as ozone precursor equivalents. The TOPP represents the potentially formation of near-ground (tropospheric) O_3 which can cause smog. TOPP includes emissions of NO_x, NMVOC (non-methane volatile organic compounds), CO and CH_4 [31]. **Particulates** have a significant effect on the local air quality level [33].

3.1. Emissions calculation

The values for emissions per produced energy (kg/MWh) were retrieved from GEMIS [32] and account for the life cycle of the facility by which the energy is generated. In all, emission values were retrieved for electricity bought from the Russian grid, natural gas combined heat and power plants (CHP), (building integrated) solar photovoltaic (PV), solar collectors, wind farms (WF), Ground source heat pumps (GSHP), biogas CHP plants, natural gas boilers and biogas boilers with flue gas cleaning.

The emission values for the natural gas and biogas CHPs needed to be divided into the proportions for heat and electricity generated. This was done by the *partial substitution method*, where the idea is to split the emissions into equal parts for the heat/electricity quote in relation to the efficiency of the type of energy generated. For this, the following formulas were used:

$$\varepsilon'_{hi} = \frac{E_h}{n_h} \quad (1)$$

$$\varepsilon_{hi} = \frac{\varepsilon'_{hi}}{\varepsilon'_{hi}+\varepsilon'_{ei}} \times \varepsilon_i \quad (2)$$

$$\varepsilon'_{ei} = \frac{E_e}{n_e} \quad (3)$$

$$\varepsilon_{ei} = \frac{\varepsilon'_{ei}}{\varepsilon'_{hi}+\varepsilon'_{ei}} \times \varepsilon_i \quad (4)$$

In equation 1, ε'_{hi} denotes the heat energy to efficiency quotient where E_h is the share of heat generated (in combined heat and power), and n_h the efficiency of the heat generation. The corresponding denotations for electricity generation are shown in equation 3. In equation 2, ε_{hi} represents the partial share of a certain emission type i per produced heat while ε_i is the reference value for the same emission type (Table 1). The corresponding value for the partial fraction of a certain emission type coming from electricity generation is calculated according to equation 4.

[Table 1]

The ε_i emission values for natural gas was retrieved for a 1/0.85 (E_h/E_e) heat to electricity quote and 0.9/0.39 (n_h/n_e) heat- to electricity efficiency CHP plant in GEMIS. The corresponding values were retrieved for a biogas CHP plant with 1.5/1 (E_h/E_e) and 0.,9/0.39 (n_h/n_e), and for a waste incineration CHP plant 1/0.345 (E_h/E_e) and 0.9/0.39

(n_h/n_e). The results for the partial fractions of emission for heat and electricity of both of the CHP plants types can be found in Table 1. Values for the other energy technologies are found in Table 2. The emissions were thereby calculated by multiplying the energy produced by the emission factors of the corresponding energy system (and the partial share of heat and electricity in cases for CHP plants) as in (5).

$$Generated\ emissions =$$
$$Ammount\ of\ energy\ produced\ (\varepsilon)\ \times$$
$$emissions\ per\ unit\ of\ energy\ for\ specific\ energy\ production\ (GEMIS) \quad (5)$$

[Table 2]

4. Energy and emission analyses

4.1. Energy analyses

The energy demands of several renovated district concepts were analysed and compared to that of the Current concept. Each of the proposed Current, Basic, Improved and Advanced districts contained buildings with the corresponding level of renovation and additionally the improvements suggested in Table 3.

[Table 3]

In the Current district, the annual energy demands per floor area were 219 kWh/m^2,a and 47.2 kWh kWh/m^2,a for heating and electricity, respectively [1]. The heating demand of the buildings was estimated to be fully covered by district heating with 20% heat distribution losses [30], while transfer losses of the electrical grid were estimated to be 10% [34]. Energy needed for water purification was estimated to be 7 kWh of heating and 49 kWh of electricity per person in a year, and respectively 23 kWh of heating and 62 kWh of electricity for wastewater treatment [35]. Outdoor lighting was estimated to consume 350 kWh per lamp per annum, while a factor of 0.167 lamps per inhabitant was used [15], [36].

The Basic district consisted of buildings where the annual calculated demand of heating was 134 kWh/m^2,a and of electricity was 37 kWh/m^2,a. Distribution losses of the district heating network were reduced to 15% by system improvements, while transfer losses of the electrical grid remain the same as in the Current district. The energy demand for water and wastewater treatment was reduced by 36% and outdoor lighting by 50% from the previous concept.

For the Improved district, each square meter of floor area was calculated to require 104 kWh/m^2,a of heating and 33 kWh/m^2,a of electricity on an annual basis. The losses of the district heating network and the electrical grid were kept to the same as in the Basic district. The energy needed for water and wastewater treatment was 48% less than for the Current district, while the outdoor lighting electricity demand was reduced by 70%.

The advanced district was not only a further improvement on the previous district in terms of energy demand. It was further used in several scenarios for energy generation from various combinations of renewable energy sources. These alternatives will be discussed further in the emission analyses. The annual energy demands per square meter of floor area in the Advanced district were 71 kWh/m^2,a and 35 kWh/m^2,a for heating and electricity, respectively. An exception of the Advanced district from the others is that smart meters are used in the buildings, which lowers their electricity demand by 5% (estimation based on [37]). Distribution losses of the district heating network were estimated at 7% (which is a typical level in Nordic countries), while transfer losses of the electricity grid were reduced to 9%. Energy demand for water purification and wastewater treatment is now reduced by 56% from the Current district, while electricity needed for outdoor lighting was 70% less.

The data for distribution losses of the district heating network and the transfer losses from the electrical grid used in the models were derived from [34] & [38]. [36] and [39] were consulted for estimating electricity consumption of the different district concepts. Corresponding values for water and wastewater consumption have been obtained from [27] and [40].

Calculations show that the energy need is mainly affected in the Basic and Advanced concepts. This has mostly to do with the fact that the buildings are accounting for close to all the energy demand of the case district. The calculation results are shown in Table 4 where the energy demand of the district has been categorized into buildings, outdoor lighting, and water and wastewater treatment. Transfer and other losses have been accounted for in the numbers presented. Looking at electricity and heating demand separately, it is notable that the potential for reduction is 34% and 72%, respectively.

[Table 4]

It has to be noted that transportation or other services resulting in further energy demand were not accounted for in the district energy analyses that have been carried out. These usually form a significant share of the total energy consumption in a district but were left outside the scope of the analyses where the focus was on buildings and infrastructure. Also, some of the improvements presented in the Table 3 are directly related to pollution or the comfort level of the inhabitants, and would not be notable in the results from the energy

4.2. Emission analyses

All the concepts presented were further extended with different scenarios of how the energy needed is either being acquired or produced within the area and the amount of emissions that this would result in. As shown in Figure 1, altogether 11 district energy production scenarios were analysed. All the district concepts had two scenarios, except the Advanced, which had five in total.

Since almost all energy produced in the Moscow area comes from natural gas [41], the scenario of heat and energy production from natural gas (Nat) was created for each district type. To evaluate the opportunity for using renewable energy, a scenario where natural gas is being replaced by biogas (Bio) was additionally examined for each scenario. Table 5 summarizes the scenarios analysed.

[Table 5]

For the Advanced district concept the A3, A4 and A5 scenarios involving renewable energy were created in addition to the natural and biogas scenarios. In the A3 scenario, solar panels (PV) mounted on the roofs of the buildings was calculated to cover 7.5% of the total electricity demand, while the rest would be bought from the Moscow grid. All the heating needed would in this scenario be provided by ground source heat pumps (GSHP), which on the other hand would consume a considerable amount of electricity. The A4 scenario differed from the A3 in the way that all grid electricity was bought from a wind farm (WF). In addition to the A4 scenario, 30% of the energy needed for domestic hot water in the district was produced by solar thermal collectors (STH) in scenario A5. This would eventually lead to fewer boreholes and less electricity needed for ground source heating.

4.2.1. Emissions for the Current district

The reference emissions of the Current district (Moscow Ref.) were calculated using the equivalent values for the whole Moscow multiplied by the number of inhabitants in the selected district. Heating energy in Moscow is up to 70% generated by large scale combined heat and power (CHP) plants, 5% by small scale CHP plants and 25% by heat only boilers (HOB) [42]. This corresponds to 79.290 GWh of heat generated by the large scale CHP plants, 5.664 GWh from the small scale CHP plants and 28.318 GWh from the heat only boilers. The fuels used in large scale CHP plants are 98% natural gas, 1.4% coal and 0.6% heavy fuel oil. The fuel used in both small scales CHP plants and HOBs is 100% natural gas [42]. The fuels were in the calculations presumed to be 100% natural gas since the share of coal and heavy fuel oil was considered to be insignificantly small in comparison to the total. The total electricity production corresponding to the consumption in the city[1] was split into 45.045 GWh produced at large-scale CHP plants and 3.234 GWh produced at small-scale CHP plants. The emission values for the Moscow reference case were calculated based on this data.

Based on the calculated energy demands (Table 4) the emissions for the Current district were calculated both for the existing natural gas CHP plant and for an alternative biogas CHP plant. The emission from all the scenarios are pictured in Figures 2 to 5

4.2.2. Emissions for the Basic and Improved district scenarios

The annual emissions from natural gas CHP energy production and from biogas CHP energy production for both the Basic district scenarios and the Improved district scenarios were calculated based on the energy demands (Table 4) and corresponding distribution losses. See Figures 2 to 5 for results

[1] The City of Moscow is characterized by a surplus electricity balance, i.e. more electricity is produced than it is consumed and the excess is exported to the surrounding Moscow region.

4.2.3. Emissions for the Advanced district scenarios

The advanced district scenario is a further improvement of the Improved district case in terms of energy demand (Table 4). Additionally, it contains several alternatives for energy generation from various combinations of renewable energy sources: natural gas CHP biogas CHP, building integrated solar photovoltaic (BIPV), solar collectors (STH), ground heat pumps, wind farms and electricity bought from the grid. The emissions from these can be found in Figures 2 to 5

For generating energy from solar radiation, the photovoltaic potential estimation utility Photovoltaic Geographical Information System (PVGIS) was used for estimating solar irradiation in Moscow [43]. According to this, the average yearly solar radiation on a horizontally inclined surface is 1.154 kWh/m^2 for an optimal surface in Moscow that has an inclination angle of 39° and south-orientation.

The annual electricity generation of the **solar photovoltaic** (**PV) system** was calculated as follows. Using CIS technology based solar panels (copper-indium-selenium) would give an annual generation of 1.060 kWh/kW_p (temperature and reflectance losses included) which means that for every kW-peak power installed we get a 1.060 kWh of electricity in a year. Further losses (wiring, inverter, array mismatch and distribution) of the PV system were estimated to be a total 20% of the whole production [43] & [44]. The peak power per square metre ratio for the system was presumed to be 0.125 kW_p/m^2 [45]. The same number was multiplied with half of the roof surface of the buildings in the district for estimating the total annual electricity generation. Half of the roof area of the district was accounted for installing solar panels, and further that the roofs were horizontal which meant that solar panels could be oriented and inclined for optimal solar gain. The total annual production from the PV system is 1.655 MWh.

Solar collectors are estimated to cover for 30% of the energy for heating of domestic water which is a rough estimation based on the results of a pilot project in Helsinki in Finland [46]. The performance of **solar thermal heat (STH)** systems that were installed on multi-storey buildings was evaluated in the report. However, the saving potential of STH varies with solar radiation availability, system efficiency, outside temperature and utilization of heat collected which all complicates any accurate prediction. By accounting for solar thermal energy, the yearly demand for domestic water heating for an Advanced building will decrease from 32 kWh/m^2 to 23 kWh/m^2 resulting into a total heat demand of 61 kWh/m^2. This means that the total heating energy needed for the buildings in the Advanced district will become 20.011 MWh/a which is over 14% overall decrease when including solar thermal heating. One collector square meter produces annually 200 – 400 kWh for different types of systems and locations in Finland [47], and 450 kWh in Germany [48]. Results from PVGIS shows that the potential in Moscow is closer to that of Berlin than Helsinki. The value 400 kWh was used meaning that the total needed surface area needed for the solar collectors would be 8.011 m^2. The solar collectors might be roof-installed or placed on an open field and thereafter interconnected to form a large scale solar thermal heating system. The solar panels would occupy around 50% of the roof total roof area of the buildings and the collectors around 30% in case they were to be roof-top mounted.

The **ground source heat pumps (GSHP)** were decided to have a coefficient of performance (COP) value of 3, which means that each unit of electricity put in will generate three units of heat. Depending on how much heating is required there will be a certain amount of vertical boreholes needed for the ground source heating pumps. The amount of boreholes was calculated by calculating the total pipe length needed and dividing this with twice the maximum depth of a vertical borehole (200 m). Based on the demanded heating energy D_h, the length L of the pipe is calculated by

$L = \frac{D_h}{G} \times 0{,}67$ [49] (6)

The term G denotes the extractable amount of energy from ground which depends on the type of soil. In this study, the soil was assumed to be clay with the amount of extractable energy of 55 kWh/m^3. The value 0.67 in formula 1 comes from the ration of heat production for a GSHP with a COP value of 3. The pipe length can be twice the depth of a vertical borehole since it makes a loop in the end and return back to the surface again. This means that the total amount of vertical boreholes was calculated by dividing the total pipe-length for the whole district by 400.

Boreholes are to be placed 15 metres from each other [49], which means that one borehole occupies at most 177 m^2 of ground surface. It has been considered that each II-18 building has a total floor area of 4.911 m^2 while the total floor area of the district is 327.581 m^2. The district scenarios in this study were considered to contain solely of II-18 buildings which means that the number of buildings in each scenario is 67. This number was later used for calculating how large area is required around each building for the installation of the boreholes.

In the *alternative 3*, 7.5% of the total electricity demand is generated by building integrated solar panels (BIPV), a total of 15 600 m^2 of panels, while the rest is bought from the grid. These would occupy half of the roof area as earlier mentioned. The heating demand is covered by ground source heat pumps (GSHPs) which in turn demand a considerable amount of electricity (included in the total demand). This alternative would require 556 boreholes and the ratio between the floor area and area needed for GSHP is 1/0.382. The energy demand and generation for this alternative are shown in Table 6 and the generated emissions in Table 7.

[Table 6]

[Table 7]

Alternative 4 is similar from the previous alternative except from the part that the additional electricity from the grid will be bought from wind farms (WF) located elsewhere. The energy demand and generation for this alternative are shown in Table 8 and the emissions in Table 9. The solar photovoltaic efficiency, and amount of boreholes and the area required for these are the same as in Alternative 3.

[Table 8]

[Table 9]

In the *alternative 5*, solar collectors (STH) are producing 30% (8 000 m^2) of the heating energy needed for the domestic hot water. The rest of the heat demand is covered by ground heat pumps (GSHP) which use also electricity for operation. Solar panels (PV) are producing the same amount of electricity as in alternatives 3 and 4 while the rest of the electricity demand is generated by wind farms (WF). The total amount of boreholes in this case is 458 which is less than for the precious cases since a share of the heating demand is covered by solar collectors. The ratio between the floor area and area needed for GSHP is thereby 1/0.314. The energy demand and generation for this alternative are shown in Table 10 and the emissions in Table 11.

[Table 10]

[Table 11]

4.2.4. Comparison of the different district cases

Generated emissions from the different scenarios are compared to each other and the value for the Moscow area (Moscow ref.) in Figure 2 (CO_2-equivalent emissions), in Figure

3 (SO_2-equivalent emissions), in Figure 4 (particulates), and Figure 5 (TOPP-equivalent emissions). The Moscow reference values are average emission values from energy production for the whole of Moscow. In order to be comparable, these have been converted to emissions per inhabitant and thereafter multiplied by the number of inhabitants of the case district.

[Figure 2]

[Figure 3]

[Figure 4]

[Figure 5]

Using biogas instead of natural gas would result in larger reduction of CO_2- and TOPP-equivalents but higher levels of SO_2-equivalents and particulates with all examined solutions. The reduction potential is especially high for CO_2-equvalents which can be reduced to below 10% for each scenario when switching to biogas. Buying electricity from the grid is not favorable and would cancel out the effect of using ground source heating pumps for reducing emissions in alternative 3.

By comparing the emission levels, alternative 4, involving PV, GSHP and WF, would generate lowest emissions. However alternative 5, involving STH, PV, GSHP and WF, was almost as good alternative because energy produced by a ground source heat pump is considered to result in fewer emissions than energy produced by solar collectors due to the fact that the electricity used by the heat pump was produced by wind energy. Storing excess heat from the solar collectors in the ground during hot seasons (summer) with help from GSHPs was not considered. Taking this into account could possibly have made alternative 5 the winning scenario.

5. Discussion and conclusions

5.1. Conclusions

At the district level, different improvement scenarios in terms of energy demand, energy production and emissions were analyzed. The district scenarios, named Current, Basic, Improved and Advanced, comprise the building renovation cases of the most typical apartment building type. The improvements accounted for in the district scenarios were the energy consumption of buildings, outdoor lighting, water purification, wastewater treatment, and transfer losses of district heating and electrical grid, and energy generation from renewable energy sources. Several studies [14], [15], [50], [51], [52], [53], [54] show the technical feasibility of renewable energy solutions in Russia.

Considerable energy savings could be achieved in a district through different modernization scenarios. Even with the basic district concept, the total annual electricity demand would reduce 24%, and the total annual heating demand 42% according to calculations. With the improved district concept, the corresponding reductions would be 33% and 55%. With the advanced district concept, potential reductions would be 34% for electricity demand and 72% for heating demand. It is clearly seen that savings in heat demand are easier to achieve than savings in electricity demand. One reason for this is that electricity demand is more connected to people’s behaviors than the heat demand and is therefore harder to calculate and forecast. Almost all renovation activities also improve the quality of living, one such is the installment of mechanical ventilation which often lower heat demand but increases electricity demand. It needs to be understood that a holistic approach to the analysis of the renovation activities is essential to draw the right conclusions.

The importance of analyzing the whole energy chain becomes evident when looking at cases where heat losses in the heat distribution network are very big and heat exchangers are lacking between networks and the buildings (as is the case in Russia). This leads to a situation where the reduced energy demand in a building does not lead to savings in the beginning of the energy chain but may instead even lead to overheating of the building. The energy saving investments might then be beneficial for the building occupants (if the investments also include control devices), but looking at the total benefits for the society such renovations would not bring such benefits as reducing air pollution, global warming, unnecessary investments into utility-level energy (and water) infrastructure etc.

The emission analyses show that the amount of each emission type produced might depend on different factors. As for CO_2-equivalents, changing fuels from natural to biogas would be an efficient choice of reduction. The same also goes for TOPP-equivalents, where it can be noted that changing fuel type would result in further reduction than implementing the next standard (e.g. Current to Basic) renovation. However, doing so would on the other hand also result in twice the amount of produced SO_2-equivalents and particulates. Concluding, producing energy from other renewable technologies than biogas, such as ground source heat pumps, solar panels, solar collectors or wind turbines, would be a better solution than switching to biogas when it comes to reduced SO_2 particulates emission levels compared to the current situation.

It can be concluded that there is no straight forward answer to which scenario is the best one, not even in terms of reduced emissions. Looking at CO_2 and TOPP emissions gives another conclusion than looking at SO_2 and particulates emissions. It needs to be clear what the objectives of the improvements are in order to make the right decisions in choosing the most efficient improvement scenario.

5.2. Discussion

There is no relevant scientific literature related to energy renovations of Russian residential districts, this study can be seen as a pioneer and forerunner in this sector. Even though the district examinations were made to one pilot area, their results can be generalized to other similar residential areas existing in Moscow as well as in other parts of Russia. The energy renovation of such districts requires often improvements to the whole energy chain while many building level renovations would only improve the energy-efficiency of the building itself. This means that if the same amount of energy is supplied to the building through uncontrollable district heating, the building energy consumption and emissions do not reduce.

The performed analysis highlights also the issue of a wide variety of stakeholders being involved in such renovation activities. City planning aspects need to be considered for example when considering the need for land use for bore holes or local heating plants. The roof top solar installations' inclination angles influence the solar energy production etc. Energy companies naturally have a big role in the infrastructural renovations of the energy infrastructure both considering production plants and the transmission lines and pipes. Ownership and management questions regarding ownership of energy plants, transmission networks and the buildings play a role in making the concepts realized.

Business models for carrying out such large scale renovation activities need to further investigated. The benefits of the different stakeholders, the incentives for realizing energy efficient district renovation concepts need to be elaborated. If energy is being subsidized the economic incentives might be lacking. If investments are paid by other stakeholders than the ones getting the benefits there is a barrier for executing the concepts. Public authorities need to have a clear role and strong will to make the concepts become reality.

Based on the result of this study it can be concluded that the renovation of a neighbourhood should not be restricted to the renewal of houses, but should be extended to the whole territory and whole energy chain in order to achieve the holistically best results. Furthermore, this study has shown (see fig 2-4) that the emissions to air correlate not only with energy efficiency, but are also highly dependent on the source of energy. For certain types of emissions (e.g. particulates) the effect of energy source is especially pronounced.

Acknowledgements

The authors wish to thank the Finnish ministry of foreign affairs for funding this research.

References

[1] S. Paiho, Å. Hedman, R. Abdurafikov, H. Hoang, M. Sepponen, I. Kouhia, M. Meinander, Energy saving potentials of Moscow apartment buildings in residential districts, Energy and Buildings 66 (2013) 706–713

[2] R. Perelet, S. Pegov, M. Yulkin, Climate Change. Russia Country Paper. UNDP - United Nations Development Programme, Human Development, Report 2007/2008, 2007/12, 30 p. (accessed 09.04.13: http://origin-hdr.undp.org/en/reports/global/hdr2007-2008/papers/perelet_renat_pegov_yulkin.pdf)

[3] A. Korppoo, Russia and the post-2012 climate regime: foreign rather than environmental policy, The Finnish Institute of International Affairs. Briefing Paper 23, 2008, 8 p. (accessed 09.04.13: http://www.upi-fiia.fi/assets/events/UPI_Briefing_Paper_23_2008.pdf)

[4] Y.-J. Zhang, Interpreting the dynamic nexus between energy consumption and economic growth: Empirical evidence from Russia. Energy Policy 39 (2011): 2265–2272.

[5] P. Lahti, J. Nieminen, A. Nikkanen, J. Nummelin, K. Lylykangas, M. Vaattovaara, M. Kortteinen, R. Ratvio, S. Yousfi, Riihimäki Peltosaari – Eco-efficient renewable of a neighbourhood (In Finnish). VTT Research Notes 2526, June 2010, 107 p. + app. 13 p. (accessed 17.06.13: http://www.vtt.fi/inf/pdf/tiedotteet/2010/T2526.pdf)

[6] A. Korppoo, N. Korobova, Modernizing residential heating in Russia: End-use practices, legal developments, and future prospects, Energy Policy 42 (2012) 213-220.

[7] E. Zavadskas, S. Raslanas, A. Kaklauskas, The selection of effective retrofit scenarios for panel houses in urban neighborhoods based on expected energy savings and increase in market value: The Vilnius case, Energy and Buildings 40 (2008) 573-587.

[8] Å. Nystedt, M. Sepponen, Development of a concept for ecological city planning for St. Petersburg, Russia. World Renewable Energy Congress 2011 – Sweden, 8-11 May 2011, Linköping, Sweden. Sustainable Cities and Regions (SCR).

[9] S. Raslanas, J. Alchimovienė, N. Banaitienė, Residential areas with apartment houses: analysis of the condition of buildings, planning issues, retrofit strategies and scenarios, International Journal of Strategic Property Management 2011, 15(2): 158-172. ISSN 1648-9179.

[10] United Nations, Country profiles on the housing sector, Russian Federation, New York and Geneva, 2004. 123 p. ISBN 92-1-116917-8. (accessed 10.01.13: http://www.unece.org/fileadmin/DAM/hlm/documents/2005/ECE/hbp/ECE_HBP_131.e.pdf)

[11] International Finance Corporation (IFC) & European Bank for Reconstruction and Development, Financing Capital Repairs and Energy Efficiency Improvements in Russian Multi-family Apartment Buildings, Key Conclusions and Recommendations, 2012, 32 p. (accessed 24.06.13: http://www1.ifc.org/wps/wcm/connect/3f9bbb804cc01dfeadd0edf81ee631cc/PublicationRussiaRREP-AppartmentBuildings-2012.pdf?MOD=AJPERES)

[12] Ministry of Energy of the Russian Federation, Energy strategy of Russia for the period up to 2030, 2010, 172 p. ISBN 978-5-98420-054-7 (accessed 21.06.13: http://www.energystrategy.ru/projects/docs/ES-2030_(Eng).pdf)

[13] M. Garbuzova, R. Madlener, Towards an efficient and low carbon economy post-2012: opportunities and barriers for foreign companies in the Russian energy market, Mitig Adapt Strateg Glob Change (2012) 17, pp. 387–413.

[14] M. Asif, T. Muneer, Energy supply, its demand and security issues for developed and emerging economies, Renewable and Sustainable Energy Reviews 11 (2007) 1388–1413.

[15] A.O. Pristupa, A.P.J. Mol, P. Oosterveer, Stagnating liquid biofuel developments in Russia: Present status and future perspectives. Energy Policy 38 (2010) 3320-3328

[16] Yu.A. Matrosov, I.N. Butovsky & R.K. Watson. 1994. Case studies of energy consumption in residential buildings in Russia's middle belt area. Energy and Buildings (1994), Pages 231–241

[17] M.W. Opitz, L.K. Norford, Yu.A. Matrosov & I.N. Butovsky. 1997. Energy consumption and conservation in the Russian apartment building stock. Energy and Buildings Volume 25 (1997), Pages 75–92

[18] C. A. Balaras, K. Droutsa, E. Dascalaki, S. Kontoyiannidis. 2005. Heating energy consumption and resulting environmental impact of European apartment buildings, Energy and Buildings 37 (2005) 429–442.

[19] I. Y. Choi, S. H. Cho & J. T. Kim. 2012. Energy consumption characteristics of high-rise apartment buildings according to building shape and mixed-use development. Energy and Buildings. Volume 46 (2012), Pages 123–131.

[20] R. Kyrö, J. Heinonen, A. Säynäjoki & S. Junnila. 2011. Occupants have little influence on the overall energy consumption in district heated apartment buildings. Energy and Buildings 43 (2011) 3484–3490

[21] M. J. Kim, M. Eun & J. T. Kim. 2013. Energy use of households in apartment complexes with different service life. Energy and Buildings Volume 66 (2013), Pages 591–598

[22] H. Tommerup, S. Svendsen.2006. Energy savings in Danish residential building stock, Energy and Buildings 38 (2006) 618–626.

[23] J. Ouyang, J. Ge & K. Hokao. 2009. Economic analysis of energy-saving renovation measures for urban existing residential buildings in China based on thermal simulation and site investigation. Energy Policy Volume 37 (2009), Pages 140–149

[24] T. Siller, M. Kost, D. Imboden. 2007. Long-term energy savings and greenhouse gas emission reductions in the Swiss residential sector, Energy Policy 35 (2007) 529–539.

[25] J. Ouyang, J. Ge, T. Shen, K. Hokao, J. Gao. 2008. The Reduction Potential of Energy Consumption, CO2 Emissions and Cost of Existing Urban Residential Buildings in Hangzhou City, China, Journal of Asian Architecture and Building Engineering, 2008, Vol. 7, No. 1, pp. 139-146, ISSN 1346-7581.

[26] City of Moscow, The Housing programme of the City of Moscow for the period 2012-2016 (in Russian). Government of Moscow, Department for capital repairs, 2011. (accessed 17.06.13: http://www.moskr.ru/dkr/ru/normative_base/n_138/o_50309)

[27] S. Paiho, R. Abdurafikov, Å. Hedman, H. Hoang, I. Kouhia, M. Meinander, M. Sepponen, Energy-efficient renovation of Moscow apartment buildings and residential districts. VTT Technology 82. VTT, Espoo, 2013, 114 p. + app. 5 p. ISBN 978-951-38-7921-1 (accessed 28.03.13: http://www.vtt.fi/inf/pdf/technology/2013/T82.pdf)

[28] I.I. Bobrovitskiy, N.V. Shilkin, Hybrid ventilation in multistory apartment buildings, Published in ABOK journal 3/2010 (in Russian). (accessed 17.06.13: http://www.abok.ru/for_spec/articles.php?nid=4573)

[29] G. Keikkala, A. Kask, J. Dahl, V. Malyshev, V. Kotomkin, Estimation of the potential for reduced greenhouse gas emission in North-East Russia: A comparison of energy use in mining, mineral processing and residential heating in Kiruna and Kirovsk-Apatity, Energy Policy 35 (2007) 1452-1463.

[30] The International CHP/DHC Collaborative, CHP/DH Country Profile: Russia, 2009, 12 p. (accessed 05.02.13: http://dbdh.dk/images/uploads/pdf-abroad/IEA_Russia_16pp_A4_web.pdf)

[31] U.R. Fritsche, Kl. Schmidt, Global Emission Model of Integrated Systems (GEMIS 4.5) Manual, Ökö-Institut, 2008. (Institute for Applied Energy). (accessed 10.01.12: http://www.oeko.de/service/gemis/en)

[32] Global Emission Model for Integrated Systems (GEMIS). [A life-cycle analysis program and database.] (accessed 05.06.12: http://www.gemis.de)

[33] United States Environmental Protection Agency (EPA), Particulate Matter (PM), 2012. (accessed 11.06.12: http://www.epa.gov/airquality/particlepollution/)

[34] IEA, Electricity/Heat in Russian Federation in 2008, International Energy Agency. [accessed 26.09.11: http://www.iea.org/stats)

[35] T. Tukiainen, Greenhouse Gas Emissions of Finnish Water and Wastewater Utilities, Master's thesis, Helsinki University of Technology, Faculty of Engineering and Architecture, 2009, 150 p. (in Finnish) (accessed 14.01.13: http://civil.aalto.fi/fi/tutkimus/vesi/opinnaytteet/tukiainen2009.pdf)

[36] M. Radocha, B. Baumgartner, Energy efficiency in streetlighting and transport infrastructure, Reference material for competence, 2006. (accessed 30.10. 09: http://www.transportlearning.net/docs/Competence_reference%20material_urbandesign_en.pdf)

[37] B. Neenan, R.C. Hemphill, Societal Benefits of Smart Metering Investments, The Electricity Journal, October 2008, Vol. 21, Issue 8, pp. 32-45. 1040-6190.

[38] S. Paiho, M. Sepponen, R. Abdurafikov, Å. Nystedt, I. Kouhia, M. Meinander, H. Hoang, Feasibility on upgrading Moscow apartment buildings for energy efficiency, 7th International Cold Climate HVAC Conference, Calgary, Alberta, Canada, 12–14 November 2012. Pp. 126–134. [Accessed Feb. 20th, 2013: http://www.vtt.fi/inf/julkaisut/muut/2012/Feasibility_on_upgrading_Moscow.pdf]

[39] Echelon, Monitored Outdoor Lighting: Market, Challenges, Solutions and Next steps, 2007, 19 p. (accessed 30.10.09: http://www.echelon.com/support/documentation/papers/EchelonCorporation_StreetlightWhitepaper.pdf)

[40] M. Sepponen, Technologies and solutions for ecocity´s energy supply, Master´s thesis, Espoo, Finland: Aalto University, 2010, 116 p.

[41] City of Moscow, The City programme "energy conservation in construction in the City of Moscow during 2010–2014 and until 2020", Decree of Moscow government from June 9, 2009, N536 (version from 12.10.2010). (In Russian) (accessed 14.08.11: http://base.consultant.ru/cons/cgi/online.cgi?req=doc;base=MLAW;n=120043)

[42] Moscow heat supply scheme, The scheme of heat supply of the City of Moscow for the period until 2020, Annex to the decree of government of Moscow N1508 from December 29, 2009. (In Russian) (Available: http://base.consultant.ru)

[43] European Commission, Joint Research centre, Institute of Energy and Transport. Photovoltaic Geographical Information System (PVGIS), 10.2.2012. (accessed 03.03.12: http://re.jrc.ec.europa.eu)

[44] A. Gregg, T. Parker, R. Swenson, A “Real World” Examination of PV System Design and Performance. United Solar Ovonic LLC, Michingan. Photovoltaic Specialists Conference, Conference Record of the Thirty-first IEEE, 3-7 Jan. 2005, pp. 1587 – 1592. [accessed 15.05.13: http://www.electroroof.com/analysis/PVSC2005.pdf)

[45] European Photovoltaic Industry Association (EPIA), Solar Generation 6, Solar photovoltaic electricity empowering the world, 2011, 98 p. (available at: http://www.epia.org)

[46] Solpros, Ekoviikin EU-aurinkolämpöjärjestelmien jatkoseuranta: Loppuraportti, 2004. (in Finnish) (accessed 11.10.11: http://www.viikinuusiutuvaenergia.net/Ekov_Solpros_loppur_2004.pdf)

[47] Motiva, Auringosta lämpöä ja sähköä, 2012. (in Finnish) (accessed 19.05.12: http://www.motiva.fi/files/6137/Auringosta_lampoa_ja_sahkoa2012.pdf)

[48] L. Bosselaar, Calculating the contribution of solar thermal towards the world energy supply. We should harmonize the methodology. 2011. (accessed 15.05.13: http://www.iea-shc.org/Data/Sites/1/documents/statistics/2-Bosselaar-THerra_Webinar.pdf)

[49] Suomen Lämpöpumppuyhdistys (SULPU), Lämpöpumppujärjestelmän suunnittelu. (accessed 05.06.12: http://www.sulpu.fi/)

[50] E. Martinot, Energy efficiency and renewable energy in Russia, Transaction barriers, market intermediation, and capacity building. Energy Policy. Vol. 26, No. 11, pp. 905-915, 1998.

[51] OECD/IEA, Renewables in Russia, From Opportunity to Reality, 2003, 116 p. (accessed 25.10.13: http://www.iea.org/publications/freepublications/publication/RenewRus_2003.pdf)

[52] E. Douraeva, Opportunities for Renewable Energy in Russia, IEA, 2003, 23 p. (accessed 25.10.13: http://www.geni.org/globalenergy/library/energytrends/currentusage/renewable/wind/global-wind-resources/russia/renewablerussia.pdf)

[53] K.O. Povarov, V.B. Svalova, Geothermal Development in Russia: Country Update Report 2005-2009, Proceedings World Geothermal Congress 2010, Bali, Indonesia, 25-29 April 2010. (accessed 25.10.13: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0145.pdf)

[54] World Energy Council, 2007 Survey of Energy Resources, 2007, 586 p. ISBN 0 946121 26 5. (accessed 25.10.13: http://www.worldenergy.org/documents/ser2007_final_online_version_1.pdf)

Figures

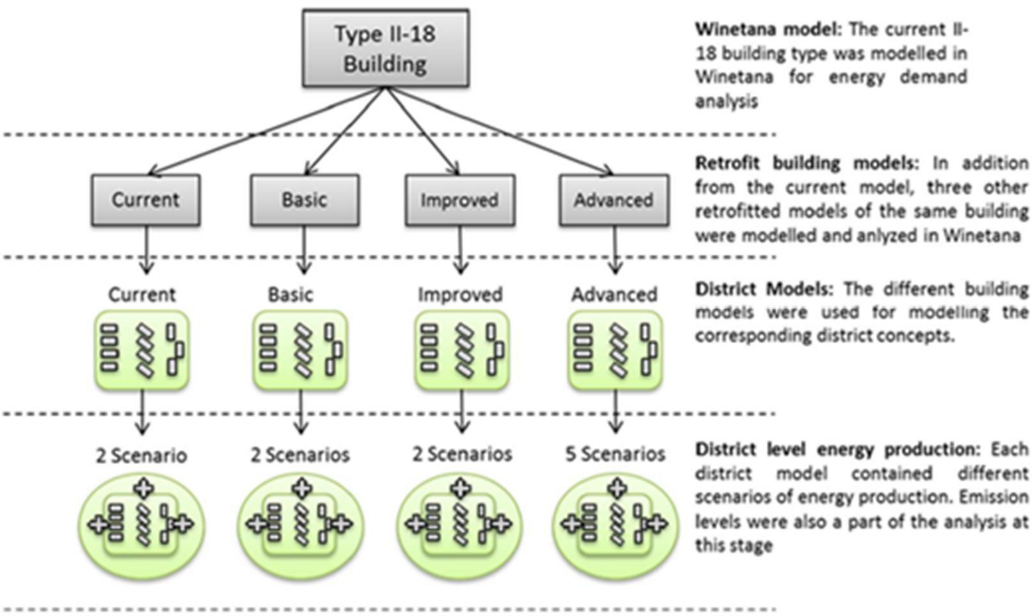
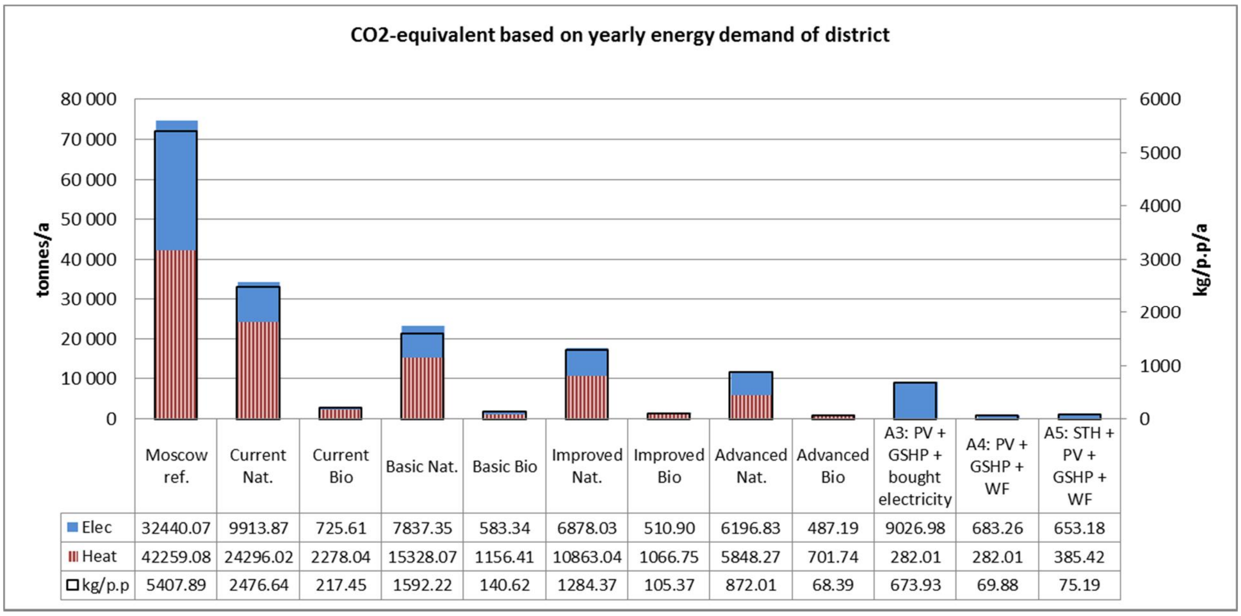
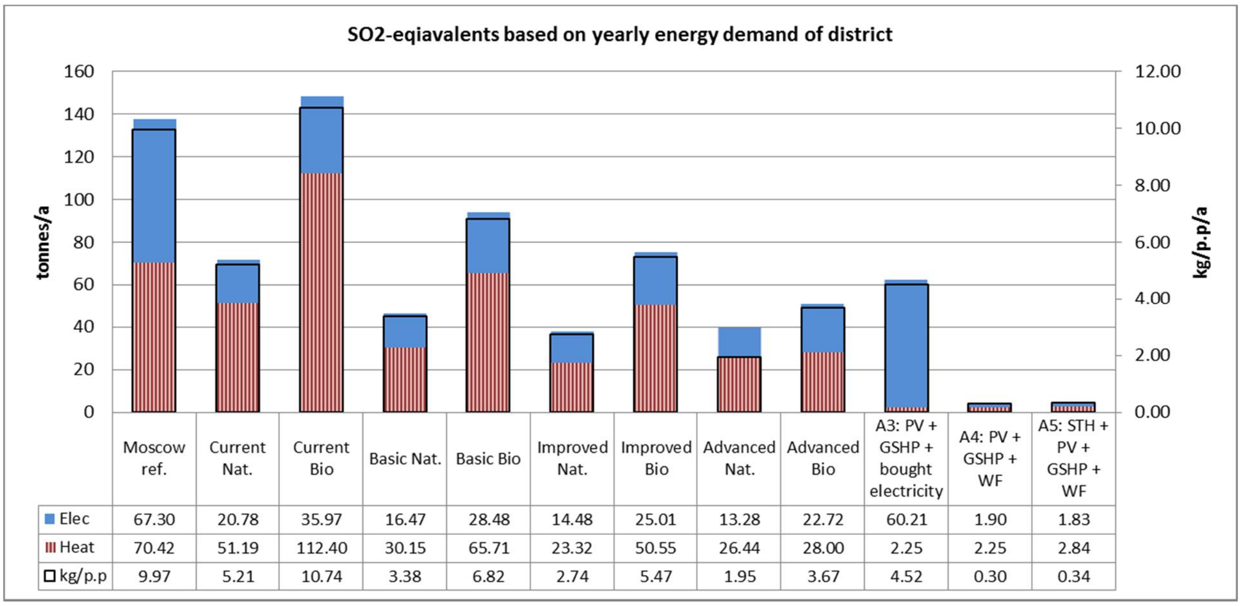


Figure 1.



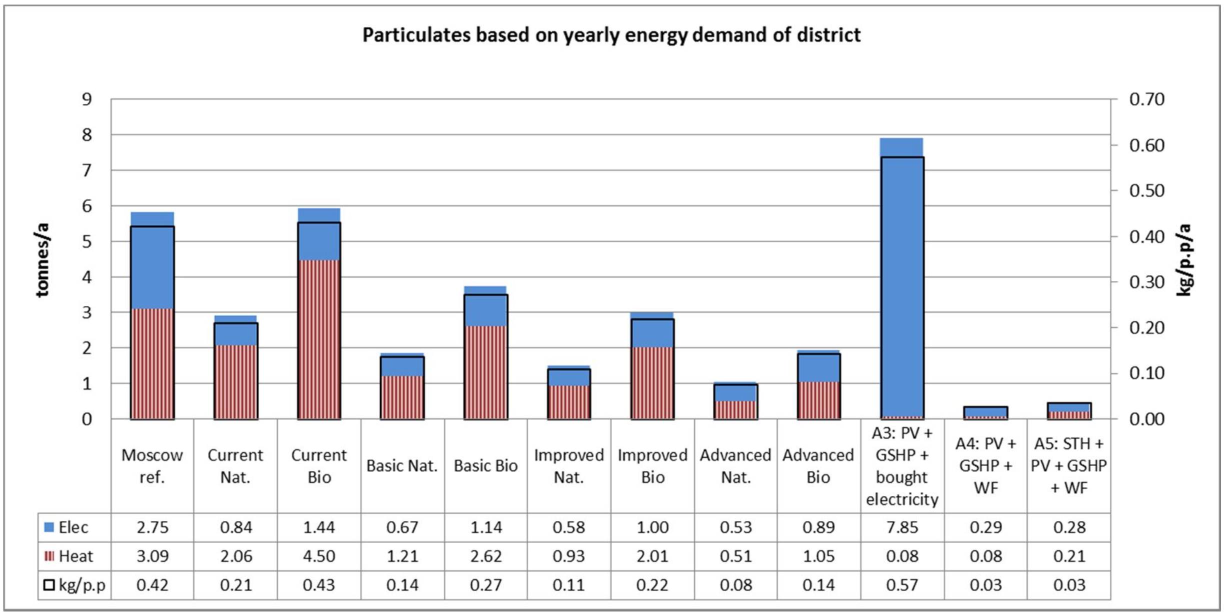
	Moscow ref.	Current Nat.	Current Bio	Basic Nat.	Basic Bio	Improved Nat.	Improved Bio	Advanced Nat.	Advanced Bio	A3: PV + GSHP + bought electricity	A4: PV + GSHP + WF	A5: STH + PV + GSHP + WF
Elec	32440.07	9913.87	725.61	7837.35	583.34	6878.03	510.90	6196.83	487.19	9026.98	683.26	653.18
Heat	42259.08	24296.02	2278.04	15328.07	1156.41	10863.04	1066.75	5848.27	701.74	282.01	282.01	385.42
kg/p.p	5407.89	2476.64	217.45	1592.22	140.62	1284.37	105.37	872.01	68.39	673.93	69.88	75.19

Figure 2.



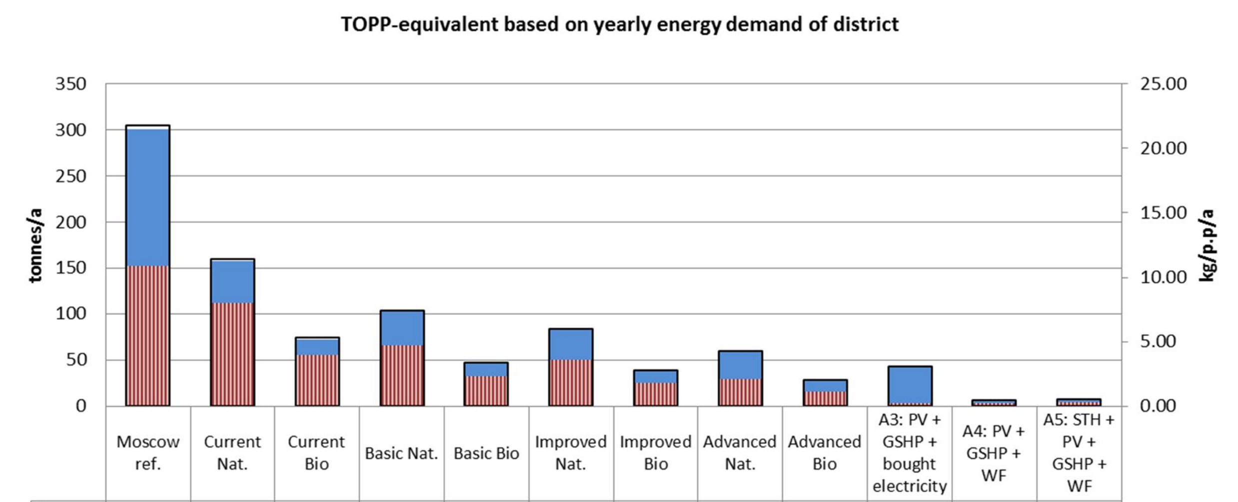
	Moscow ref.	Current Nat.	Current Bio	Basic Nat.	Basic Bio	Improved Nat.	Improved Bio	Advanced Nat.	Advanced Bio	A3: PV + GSHP + bought electricity	A4: PV + GSHP + WF	A5: STH + PV + GSHP + WF
Elec	67.30	20.78	35.97	16.47	28.48	14.48	25.01	13.28	22.72	60.21	1.90	1.83
Heat	70.42	51.19	112.40	30.15	65.71	23.32	50.55	26.44	28.00	2.25	2.25	2.84
kg/p.p	9.97	5.21	10.74	3.38	6.82	2.74	5.47	1.95	3.67	4.52	0.30	0.34

Figure 3.



	Moscow ref.	Current Nat.	Current Bio	Basic Nat.	Basic Bio	Improved Nat.	Improved Bio	Advanced Nat.	Advanced Bio	A3: PV + GSHP + bought electricity	A4: PV + GSHP + WF	A5: STH + PV + GSHP + WF
Elec	2.75	0.84	1.44	0.67	1.14	0.58	1.00	0.53	0.89	7.85	0.29	0.28
Heat	3.09	2.06	4.50	1.21	2.62	0.93	2.01	0.51	1.05	0.08	0.08	0.21
kg/p.p	0.42	0.21	0.43	0.14	0.27	0.11	0.22	0.08	0.14	0.57	0.03	0.03

Figure 4.



	Moscow ref.	Current Nat.	Current Bio	Basic Nat.	Basic Bio	Improved Nat.	Improved Bio	Advanced Nat.	Advanced Bio	A3: PV + GSHP + bought electricity	A4: PV + GSHP + WF	A5: STH + PV + GSHP + WF
Elec	148.23	45.68	17.64	36.19	14.04	31.80	12.38	29.07	11.65	38.52	2.70	2.60
Heat	152.77	112.39	55.31	66.05	32.89	51.01	25.61	29.47	16.12	3.98	3.98	4.50
kg/p.p	21.79	11.44	5.28	7.40	3.40	6.00	2.75	4.24	2.01	3.08	0.48	0.51

Figure 5.