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# Solar and heat pump systems, analysis of several cases in Russia

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**Abstract**

Russia has a few renewable energy facilities in the buildings. In the buildings, the main source of the energy is provided by Russian fossil fuel resources. Based on the EU experience, Russia has started own research activity in the field of renewable energies in order to reduce the energy consumption. The combination of solar thermal with heat pump systems (SHP) is one of the promising systems that can provide the renewable energy in extreme weather conditions. Solar heating with a heat pump system for buildings has been designed to achieve different values of the fraction of a primary energy saving using the Flat Plate Collectors (FPC) for Solar Thermal (ST) and other supply energies like solar photovoltaic (PV) or wind technology, and having the higher efficiency of the system with net zero energy in thermal production.

Keywords: *Solar Thermal, Heat Pump, Photovoltaic, geothermal, combisystems*

## 1. Introduction

The combination of solar-thermal collectors and heat pumps provides interesting possibilities for innovative and energy efficient heating systems, with a high fraction of solar energy. Despite its high cost, these systems are gaining more and more importance due to the rising cost of the limited fossil resources. The Task 44 concluded in 2012 that it is possible: i) make up 87% of renewable energy share combining solar thermal and photovoltaic energy supply; ii) or to reach about 90% of renewable energies with geothermal resources.

This study analyzes one configuration of solar systems with a new water-to-water heat pump, in different cities of the Russian Federation, meant to cover all space heating and domestic hot water demand with renewable energy, solar and wind according to the weather conditions. PV has been a very interesting way to produce electricity and thermal energy if we combine this with heat pumps(vapor compression cycle). The final price for households in Russia varies from night tariff 3 c€/kWh to day tariff 9,6 c€/kWh in 2014 (without taxes), and the PV cost between 5 to 10 c€/kWh according to the Russian average radiation and supposing 20 years of duration. PV has not arrived to grid parity in Russia like in other northern countries of the EU. Counting that a modern compression machine has a 3-5 Coefficient of Performances (COP), and according to the Directive 2010/31/EU it's considered like another kind of renewable energy, the actual cost of thermal production with heat pumps is 1-4 c€/kWh depending on the working temperatures, refrigerant and quality of the machine (ASHRAE).

The resulting thermal energy costs obtained for FPC for DHW, simplified cost are from 3 to 7 c€/kWh depending on the collector type and the working temperature in Russia and solar radiation, in Russia ranges from 700-1500 kWh/m$^2$. The cost of the natural gas in Russia (it's one of the largest producers in the World) it's between 1,2-1,4 c€/kWh, very low compared with the ST and even with the Heat Pump. For the areas where there is gas pipe the solar thermal is only competitive for DHW not for heating, in this case it is not competitive yet, so we have to add the environment cost or the increasing of the gas prices. The fossil fuels are growing more than 0% annually, and the gas for households has grown more than 16% the last years (Gazprom), it's quite sure they won't reduce the price in the future.


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**Tab. 1: Results of one year simulation different Russian cities for domestic hot water**

| Location | Latitude | Solar Radiation | FPC. Working temperature 45ºC-75ºC | | SHP. Working temperature 0ºC-75ºC | |
|---|---|---|---|---|---|---|
| | | | Solar Efficiency | Solar Fraction | Solar Efficiency | Solar Fraction |
| **Vladivostok** | 43º | 1.320 | 72% | 21% | 71% | 83% |
| **Irkutsk** | 52º | 1.126 | 63% | 28% | 65% | 80% |
| **Samara** | 53º | 1.119 | 64% | 30% | 65% | 77% |
| **Moscow** | 55º | 973 | 63% | 32% | 66% | 73% |
| **Ekaterinburg** | 56º | 1.059 | 52% | 23% | 66% | 76% |
| **Krasnoyarsk** | 56º | 1.045 | 55% | 16% | 64% | 75% |
| **Dubna** | 57º | 1140 | 59% | 26% | 66% | 69% |
| **Saint-Petersburg** | 59º | 894 | 47% | 30% | 67% | 69% |
| **Yakutsk** | 62º | 1.086 | 44% | 28% | 58% | 61% |
| **Average** | | **1.085** | **58%** | **26%** | **65%** | **74%** |

Recently, reductions in electric PV costs and mature technology of air-to-water and water-to-water heat pump have provided a new model: solar-electric assisted heat pump. This system comes with fewer drawbacks than solar thermal energy, a smaller price tag for residential applications. Nevertheless, the best system will be a combination of both. The development of modern net zero-energy buildings (NZEB) became possible not only through the progress made in new renewable energy and construction technologies and techniques, but it has also been significantly improved by the combination of all the techniques and advanced combisystems.

The Geothermal heat pump systems have only just begun to penetrate the Russian market in the opposite of countries with similar weather conditions ( Sweden, Denmark, Germany,..). Until now there the conventional sources where most known. The maximum values of COP are 4.24 in the southern regions of Russia, and the minimum values of, correspondingly, 2.73 in the north.( Vassiliev and Gornov 2010). For this system they need a vertical borehole at least 40 meters deep and horizontal of 400 m. of length, and not always there are the correct conditions, space or environment to do it, with a big initial investment. From previous studies it has been studied that geothermal can have a similar efficiency like the combisystem with solar thermal and heat pumps.

## 2. Description of the system

The auxiliary energy is coming from a heat pump (water-to-water system with inverter control) usually used for geothermal systems that can work with electricity from the grid or the PV system. A high efficiency heat pump in the range of 5 to 20 kW has been used to cover the energy needs of households with low energy demand occupied all the year.

Simulating the whole year system we reach different solar fractions depending on the efficiency of the system, the working temperature of the storage system, and the different COP of the heat pump. This system can operate with outside temperatures from -20ºC to 20ºC, with a high solar fraction and with a high efficiency of the solar collector. The storage operating temperature has to change during the year according to the external temperature and the solar radiation, in order to obtain a higher efficiency from the collector, and to work with the maximum efficiency of the heat pump. Only in summer or spring the solar energy can be used directly for thermal production. The FPC works in serial with the heat pump during the cold days and parallel during hot days, usually it will be in the spring and summer. Finally we will use the cooling of the evaporator to increase the PV efficiency. This system can have a very high performance coefficient and adapt its efficiency for whichever conditions. It is ideal for both cold and mild climates.

The typical configuration of the solar thermal systems is with a fixed working temperature, near to 60ºC. But in the task 44 a lot of cases have been studied with a heat pump working temperature lower than 60ºC, due to the fact that this high efficiency system can supply the rest of the energy with electricity. Most of the geothermal heat pumps are working with a maximum temperature of 20ºC in the evaporator, and they can arrive to 60ºC in the condensator to cover all the thermal energy demand. The southern countries we could use unglazed collectors and air-water systems(Moià-Pol et Alt 2012) but in the northern countries, where there are some months with a lot of hours below 0ºC, we need to work at temperatures below 25ºC (Moià-Pol et Alt 2014) and work with high efficient FPC, specially designed for extreme conditions. There are some manufactures that providea good quality water-to-water heat pump, with high efficiency, working with an inverter compressor. The studied one has a maximum heating power of 13 kW and a nominal COP of 3,56 for heating temperatures of 35ºC-45ºC, and evaporating from -5ºC to 10ºC, with a refrigerant R-410A.

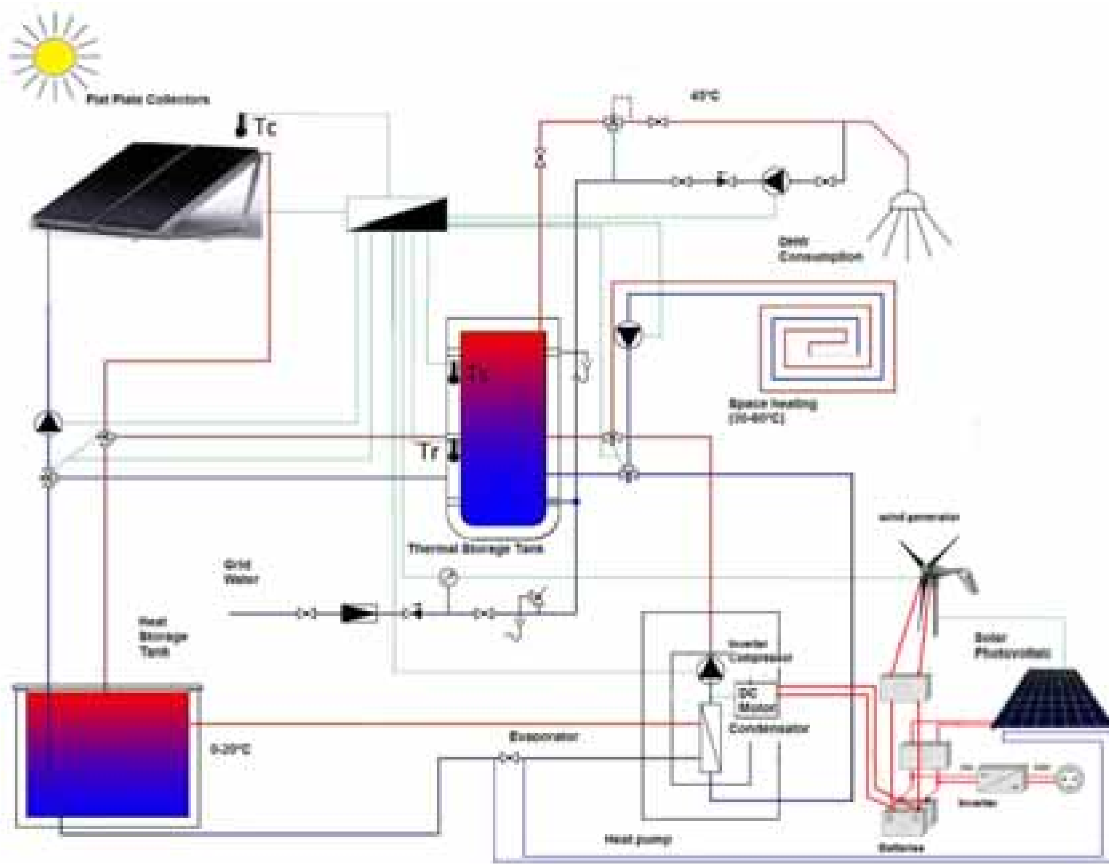


**Fig. 1: Figure of the Solar Thermal and PV Heat Pump system for DHW and Space Heating**

The Photovoltaic system has been a standard one, the panels with polycrystalline silicon 260Wp, and the inverter with an nominal efficiency of 95,5%, with a 95% of  cleanliness and 2% of losses in the cables.

## 3. Simulation and Results

We have studied different houses within the Moscow region, and developed a simulation program from the conclusions and detailed analysis from other studies (c) using the typical meteorological year (TMY). In this second study, we have considered the PV for self-consumption, with small electrical storage with batteries; because the net metering contract with the electrical company doesn't exist yet in Russia nor in most of the EU countries.

ST Collector Efficiency $\eta = 0{,}807 - 3{,}075(T_m-T_a)/G - 0{,}022((T_m-T_a)/G)^2$ (eq. 1)(e)

Unitary Energy Consumption Heat Pump $kWe = 1{,}20122-0{,}0400633Ta+0{,}0010877Ta^2$ (eq. 2)(d)

PV Efficiency $\eta = Ta - 0{,}036G$ (eq. 3)

For the considered model mentioned above, the solar thermal energy has priority in front of other renewable energy sources, and reduces the overheating in the solar panels.

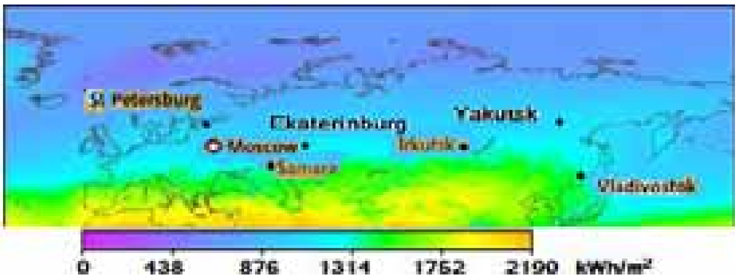


**Fig. 2: Annual Solar Radiation per sqm in Russia. Source; Mattihas Loster 2006**

Eight locations have been studied consisting of a constant hot water demand for 4 people during all the year. The typical residence considered is a cottage of 160 m² heating space for the eastern regions and a house with 80 $m^2$ heating space for the western regions, for the new emerging upper middle class. The studied houses have two floors, according to that the residence has been modeled into two zones: a conditioned zone representing a 50% of the total floor area during the day and another conditioned zone during the night. It has been supposed that it's a good quality house, according to sustainability criteria (insulation, orientation,..), when we are using renewable energies we need a low demand to make the system cheaper, with an efficient ventilation system. It has been considered the Russian law 2003 for the insulation (according to building regulations and rules 23-02-2003).

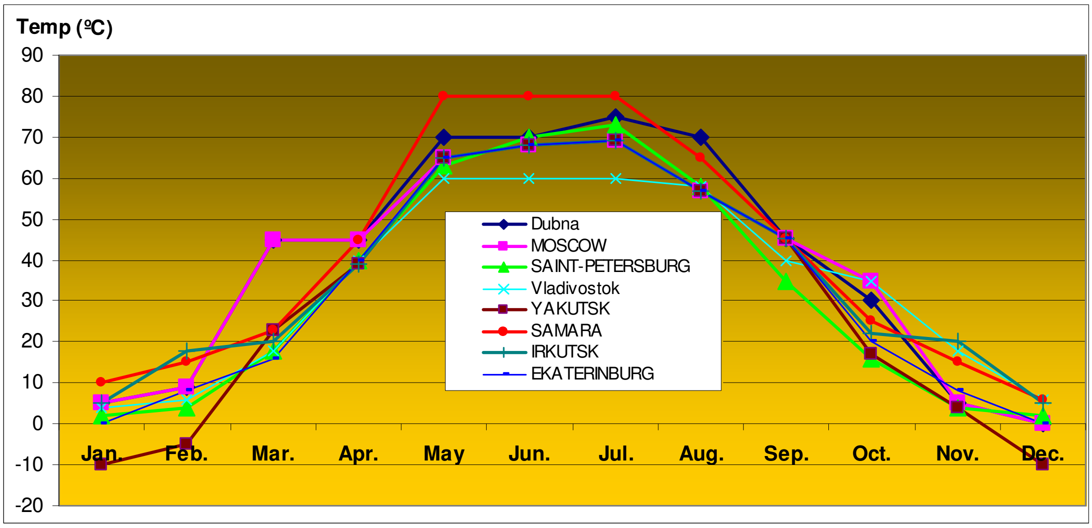


**Fig. 3: Figure of the averaged solar monthly working temperature (ºC) for Russian Cities during a typical year**

In the northern locations the annual maximum solar energy with the medium temperature of the solar collector between 25 and 30ºC (Moià-Pol et Alt 2014). In figure 3 we can see the considered working temperatures, in order to have a minimum efficiency of the 60% for each month, except for Yakutsk where we have -40ºC during December and January, and in this case we have taken the minimum temperature that can work the heat pump, -10ºC with an efficiency of the FPC of a 40%. For temperatures lower than 25ºC the efficiency of the FPC is higher but the energy requirements are lower and, therefore there are many hours with excess energy for a given storage volume. Each location has a different surface, according to the annual thermal necessities as to achieve a similar solar fraction. When the outside temperatures are rising the thermal energy demand is decreasing and during several months there is enough energy to cover the thermal energy demand so it's not necessary to work at the maximum efficiency point. We can work at higher temperatures to avoid overheating and stagnation problems. The system can only be solar thermal between 40 to 70ºC.

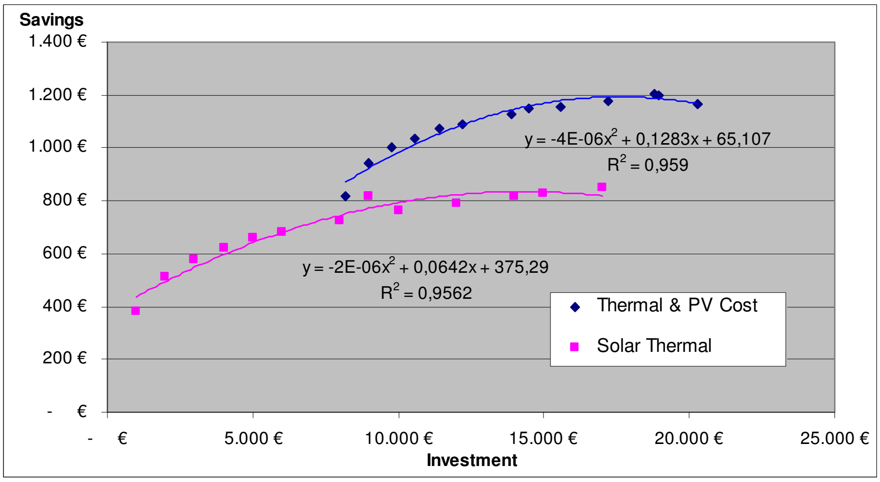


**Fig. 4: Figure of the savings vs. investment with PV and ST for Moscow Region.**

In order to avoid having a low averaged efficiency we should look for the optimal point of solar panels to accomplish the maximum solar energy gains without overheating. The medium temperature will be usually in winter lower than 20 ºC and in spring and autumn lower than 50ºC, in summer the FPC are working with more than 60 ºC in all the locations. When the medium temperature of the collectors would be higher than 45ºC we will make a direct heat transfer to the DHW or heating system, in parallel with the heat pump. The system according to have a high solar thermal fraction will have high temperatures at summer, with some overheating and stagnation problems.

According to the energy cost-efficiency of the PV and the FPC, we have studied different scenarios to find the optimal point of the system, without taking into account the heat pump and the storage of the buffer tank. The lower prices of the PV could imply to use 100% of this technology instead of using solar thermal, but with a detailed analysis of all the system, according to the COP, and thermal demand every month we can see the optimal point is between 12 and 30 $m^2$ in Moscow's region, depending on the electric tariffs, thermal demand and climate conditions.

### *a. Resume of the results.*

Comparing all the locations, we could arrive to a similar efficiency for the solar thermal panels, with high renewable thermal fraction (heat pump + solar thermal), combined with PV, this can be a solution for supplying the 100% of the thermal energy demand.

Increasing the PV system we could cover the rest of the energy demand of the household, but this isn't the aim of this study. Combining with wind power, we can optimize the system in some locations with extreme conditions. The heat pump manufactures have made a big effort the last years in order to arrive to high efficiency systems, and the market of geothermal systems has increased. The heat pump with solar panels working in low temperatures could open a big market in locations with low radiation; even if they have cheap energy prices, like Russia.

**Tab. 2: Results of one year simulation in four locations for DHW and Heating demand for a house of 160 $m^2$.**

| Location | Thermal Demand(kWh) | Solar Energy kWh/$m^2$ | Electric Energy kWhe | ST $m^2$ | Solar Thermal Fraction | Average FPC Efficiency | Power of the PV (Wp) |
|---|---|---|---|---|---|---|---|
| VLADIVOSTOK (L43) | 13900 | 86,9 | 4614 | 13 | 83% | 71% | 3,3 |
| MOSCOW (L55) | 14690 | 91,8 | 5185 | 20 | 65% | 64% | 5,2 |
| DUBNA (L57) | 11875 | 148,4 | 3406 | 18 | 68% | 64% | 3,0 |
| SAINT-PETERSBURG(L59) | 11548 | 72,2 | 4100 | 24 | 69% | 67% | 4,9 |

We can see at the table that the size of the system depends on the solar radiation and the weather conditions. At continental climates with latitudes lower 55º, it gives us systems bigger than the conclusions of the Task

44, with 12 $m^2$ and storage of minimum of 1 $m^3$, in our case it's 13-18 $m^2$ with an storage minimum of 1,25 $m^3$.

**Tab. 3: Results of one year simulation in five locations for DHW and Heating demand for a house of 80 $m^2$.**

| Location | Thermal Demand(kW) | Solar Energy kWh/$m^2$ | Electric Energy kWhe | ST $m^2$ | Solar Thermal Fraction | Average FPC Efficiency | Power of the PV (Wp) |
|---|---|---|---|---|---|---|---|
| IRKUTSK (L52) | 8706 | 108,8 | 2579 | 17 | 78% | 65% | 2,6 |
| SAMARA (L53) | 10017 | 125,2 | 3221 | 18 | 74% | 65% | 2,9 |
| MOSCOW(L55) | 6449 | 40,3 | 1600 | 14 | 73% | 66% | 2,1 |
| EKATERINBURG(L56) | 10170 | 127,1 | 4562 | 18 | 73% | 66% | 4,3 |
| KRASNOYARSK (L56) | 10164 | 127,1 | 3090 | 15 | 75% | 64% | 3,0 |
| YAKUTSK (L62) | 23587 | 294,8 | 5863 | 24 | 60% | 55% | 5,5 |

At Boreal or Polar Climates or latitudes higher than 55º, the initial dimension of the system is very big, we will need a big investment for houses of 160 $m^2$, at this latitudes for smaller houses we can compare with the results of the Task 44. Other systems could be studied with seasonal storage, with water or chemical storage, and other technologies like wind turbines or hybrid geothermal heat pumps. Other scenarios with cooling demand will have to be studied in order to improve the system, and increase the PV system. Absorption machines with new refrigerants could be developed in order to be able to have solar cooling systems with competitive prices, but at this moment it's cheaper to use compression machines.

Actually in the market there are good geothermal heat pumps, and combisystems with air-to-water systems, but not yet a combination of all of them. This study only wants to make a first approach of these systems in Russia, it will be needed to analyze more in detail for each location, developing new algorithms to study the seasonal storage and make a test laboratory of this new system in a Russian research Institute. The results will change every year according to the prices of the devices and the energy cost.

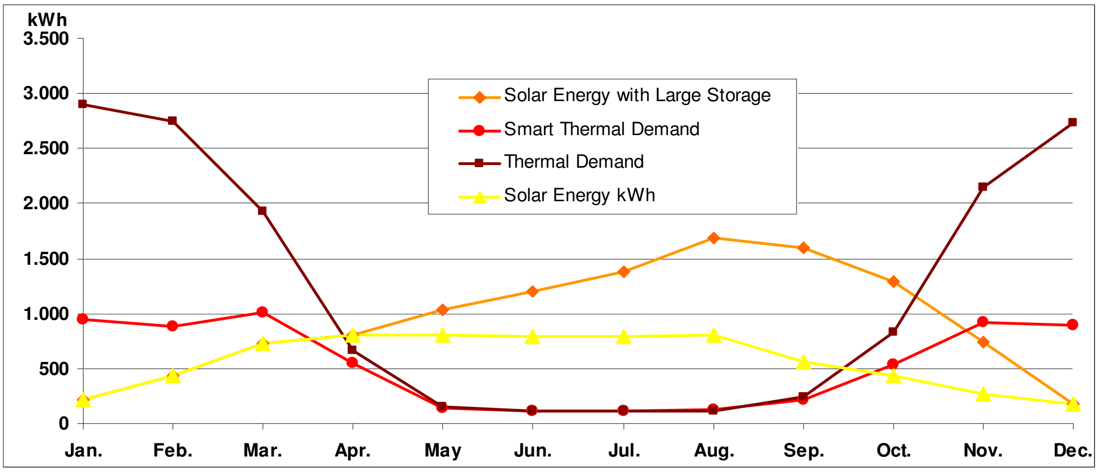


**Fig. 5: Figure annual Thermal Demand and Solar Thermal production in Moscow Region**

From figure 5, we see a normal thermal demand, an intelligent demand, with control temperatures and with timetable. We can see also with a solar thermal fraction of the 73% there are 5 months with overheating, that we can have stagnation problems. There are some parameters to be optimized for arrive to a high ST fraction, like the available volume in order to have a big buffer tank and arrive to have a seasonal storage, or share the solar thermal energy the months that we don't use to district heating systems, very common in the Russian cities.

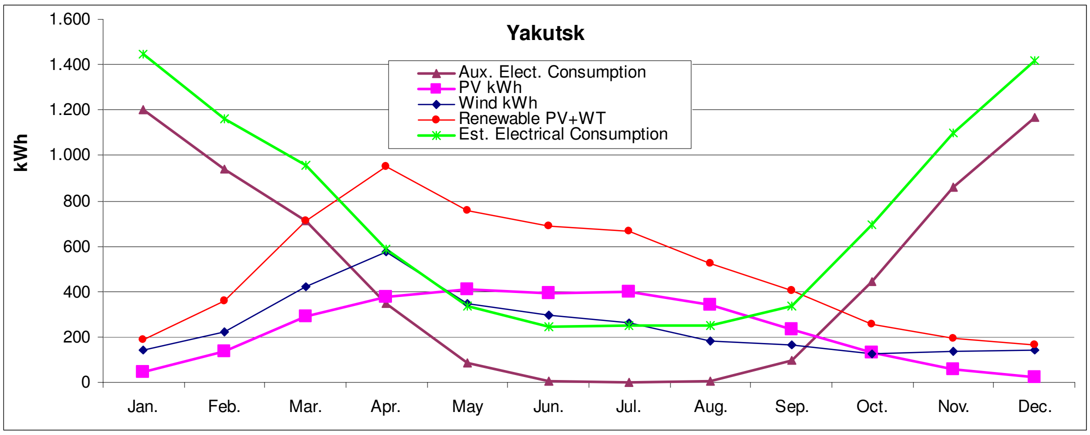


**Fig. 5: Figure annual Electric production vs. demand, using PV and Wind Turbine in Yakutsk**

In some cities with low solar radiation in winter, where they have some months with an average speed of wind up to 3 m/s. We have studied Yakutsk, Ikurtsk and Ekaterinburg where the wind energy has been simulated that could provide a wind turbine, working with 10% of the equivalent time. This could reduce the surface of the PV system and make more constant the renewable fraction every month, but actually the price of the wind power energy it's more expensive than the PV systems, when we have less than 20% of the equivalent hours working, and we have to add other problems, like noise and structure cost. The PV and the wind market for households also have to be analyzed for the government authorities, in order to allow net metering to avoid usage of batteries in this system, as we get closer to grid parity in Russia every year.

When we are working to NZEB we will need a big surface for the solar thermal and photovoltaic panels that some constructions, due to urban models, don't have at hand. In these study no one of the cases the surface of these systems it's more than the house surface. These parameters have to be included in future studies, in order to have the best solution for each case, when we have vertical constructions. Actually some of these systems have already been studied in the Task 53 - New Generation Solar Cooling and Heating Systems (PV or Solar Thermally Driven Systems).

**Tab. 4: Comparing cost of the system vs. Geothermal in Moscow Region**

| | **Estimated cost** | | **Estimated cost** |
|---|---|---|---|
| Heat Pump | 6.000 € | Heat Pump | 6.000 € |
| Solar Thermal + Pipes | 8.500 € | Borehole | 12.000 € |
| Thermal Storage Tanks | 5.000 € | Pipes | 7.400 € |
| PV System | 3.600 € | PV System | 6.000 € |
| **Total** | **23.100€** | | **31.400 €** |

There are some heat pump manufacturers that sell hybrid systems, geothermal and air for heating applications, in order to reduce the initial cost of the borehole and piping system. This could also be analyzed in future studies, adding solar thermal fraction, and finding the optimal point. In table 3 we can see that the estimated cost of the proposed system can be 30% cheaper than a conventional geothermal with close loop, but in the second case we can have excess of electricity production. Both systems, if they are designed during the construction project, could be cheaper and have fewer cost, the piping and thermal storage tank could be at the basement of the building with small over cost.

The savings of these systems are about 100% of the thermal energy demand. That means pay-back between 10-20 years, depending on the energy cost. If we compare this with other systems, like hydrogen fuel-cells, there are two times more expensive (40.000 €-60.000 €) and they need electricity for work, with efficiency lower than 50%.

Another advantage of these systems is that they can provide also cooling for the house during the summer, and saving investments of another system.

This system will be installed in Palma and in Dubna, to have real testing results, improve the simulation program, algorithms and find new technologies, materials and systems to have the optimal system for the cold countries will be able to have the same possibilities to arrive to Net Zero Energy Buildings.

## 4. Conclusions

FPC and PV with heat pump systems are a good solution for family households in Russia, both technologies are necessary in order to arrive to the future scenarios of zero emissions and net-zero energy building, and cover all the thermal demand. The combination FPC and PV in one planar construction is possible. Using in this case a semi-transparent PV not only reduces the overall cost of FPC and PV, but ensure the optimal ratio of generated heat and electrical energy. In the future, as a semi-transparent PV can be used hybrid organic-inorganic solar cells. Net Zero thermal Energy Building are in Europe a technical and economic reality, with the expected future increase of the fossil fuel price and  the reduction of the alternative technology costs. This new combisystems opens new options to cover all the energy demand of the houses with an optimized mix, which benefits from the synergies of the different technologies.

Other combinations, like geothermal with solar thermal or seasonal storage could be analyzed in future studies, according to the results of the real test.

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