Energy modeling of a single-family house with photovoltaics for the Russian Federation

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Abstract. Residential sector in Russia makes up a significant part in the total energy demand of the country. The article demonstrates sensible energy saving potential in case of a single-family house in different climate conditions of the Russian Federation. Modern tools of building energy performance simulation and renewable energy modeling demonstrated a significant effect of the complex energy efficiency technologies, such as using of modern highly insulated constructional materials, installation of efficient heating, ventilation and air conditioning systems, and implementation of sustainable energy. Annual energy use dramatically declines in comparing with buildings built according to outdated technologies. In particular, the use of photovoltaic modules can meet more than half of the building's energy demand and ensure the autonomy of a building during the warm season. These values differ depending on the location due to the large territory and diverse climatic conditions from the Mediterranean in the south to the Arctic ones in the north.

1 Introduction

Taking to account the National energy strategy 2035, the proportion of alternative energy in the Russian Federation will archive about 2 percent by the year 2020[1]. Nowadays, solar energy share is approximately 25MW, mostly used by private consumers [2]. Moreover, following modern trends, the Russian government encourages the implementation of modern green standards, such as BREEAM, LEED, and DGNB [3]. In Russia, with its cold climate, there is always the problem of power supply to a private house. Heating is always the largest consumer in the local energy sector. In this country, this field conventionally covered by natural gas supply [4]. Other building needs are covered by the power supply. The Russian Federation owns the biggest and oldest district heating system with total energy demand, approximately 1700 TWh in 2007[5]. In 2017, individual residential buildings accounted for 41.6% of the total input area of housing in Russia, which amounted to 33.0 million square meters. In 2012, Average annual energy use of a residential building in kilowatt-hours per square meter of the heated area was 363 kW/m2y. For instance, in Finland, this value is 266 kW/m2y where climate conditions are less similar [6]. Therefore,

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the residential sector is a huge area with low levels of energy efficiency and lack of awareness of renewable energy technologies.

2 Materials and Methods

The main goal of our study was to determine the energy efficiency of our building designed with the use of modern energy-saving technologies using alternative energy sources for the diverse climatic conditions of the Russian Federation. For this purpose, it is necessary to calculate separately the energy consumption of the building and the generation of electricity by solar modules. For this purpose, the appropriate modeling tools exist. It allows calculating building energy demand as well as generated electricity by solar modules using hourly weather data. Summarizing these values and dividing by the area of the house, we will obtain a building annual energy use (AEU) per square meter of heated area.
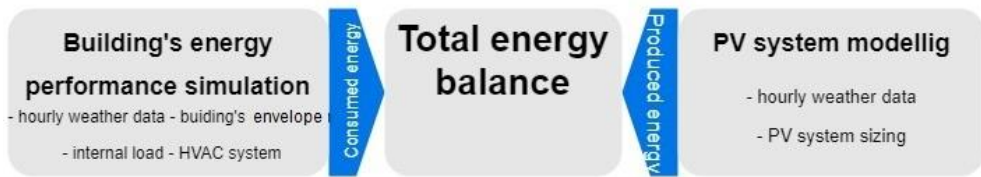

Fig. 1. Overview of the method

2.1 Building description

For our study, a house was taken, built on the wooden frame with insulation technology which is based on the frame structure made of wood. The main advantage of such buildings is the speed of construction. They are suitable for any soil and climate. The low weight of the building is an excuse to save money by making the foundation for small digging. The building is rectangular in plan one-story single-family house with a total area of 66 m2 with a gable roof which slope is 20 ° and total area 35,6 m2. One roof slope is south oriented.
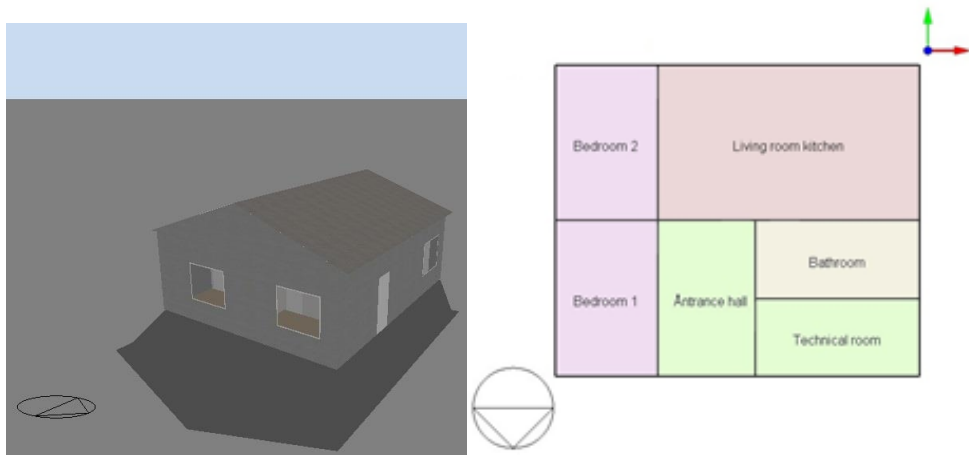

Fig. 2. Building description

2.2 Description of the building envelope

Ekström et al highlighted special significance energy efficient building envelope which contributes 65-75% decline of building energy demand in Swedish climate conditions [7]. Wood-frame house structure was chosen to achieve high energy efficiency standards. This technology is tested many times ago in countries with similar climates. Moreover, now it has relevant technical standards in Russia.
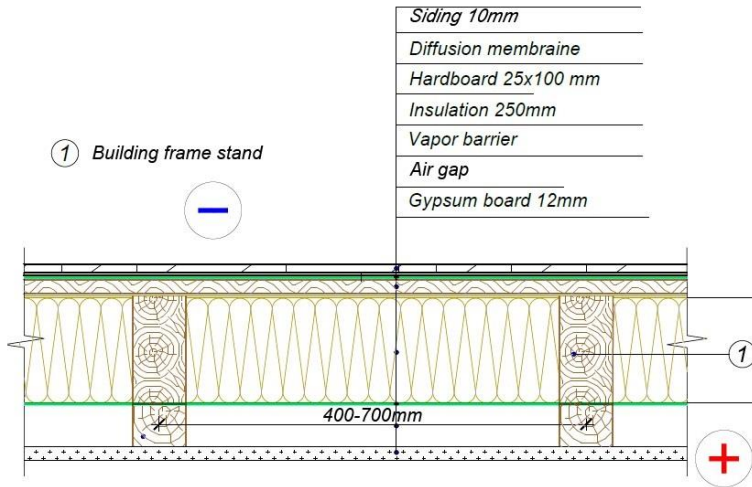

Fig. 3. Structure of external walls.

This technology allows for manufacturing structural elements under factory conditions. and construction of ready houses in a very short time. Using wood and effective insulation allows to minimize thermal loses through the building envelope. The U-value of the external walls is **0.17 W/m2*K**.
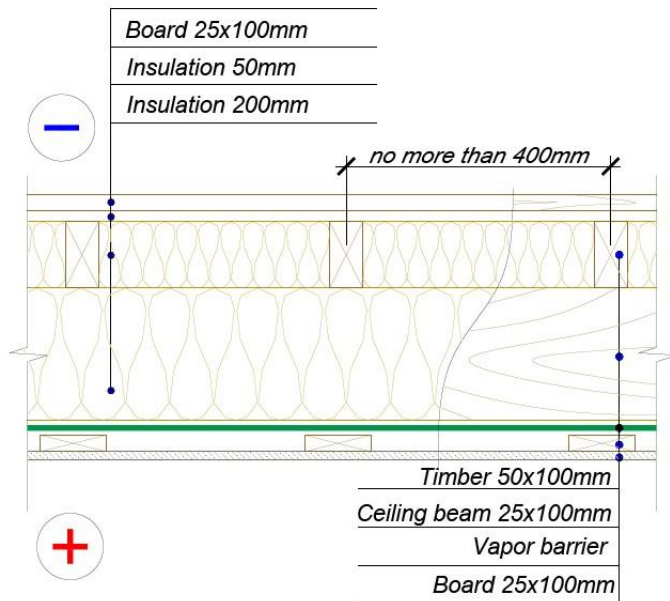

Fig. 4. Structure of ceiling.

The same technology is used for building's ceiling whose U-value is **0.138 W/m2*K**. Windows play an important role in the indoor environment. For current building triple glassing with U-value **0.738, W/m2*K** was chosen.

Table 1. Structure of windows.

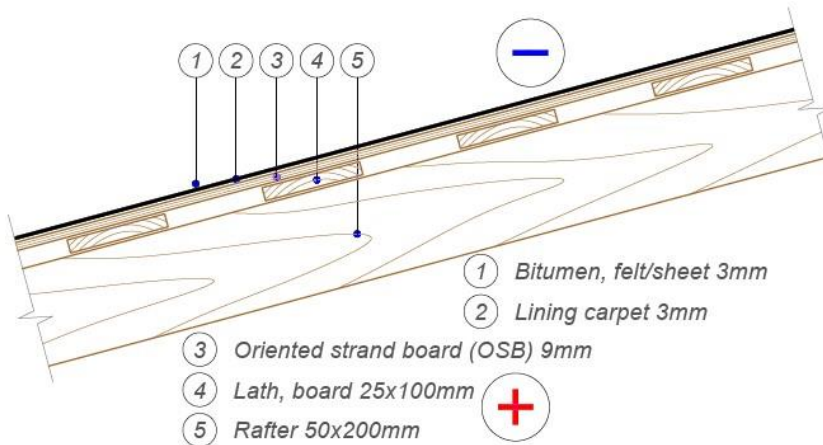| Thickness [mm]	Material
3	Generic Loe CLEAR 3mm
13	gap (Argon)
4	Generic CLEAR 3mm
13	gap (Argon)
4	Generic Loe CLEAR 3mm Rev

Fig. 5. Structure of the roof.

The structure of the roof is without insulation because it isn't unoccupied space where some of the HVAC (heating ventilation and air conditioning) equipment may be situated. It's U-value is **0.424 W/m2*K**. The ceiling provides sufficient insulation for living space. The foundation is a plate made of prestressed concrete insulated by extruded polystyrene. Such structure demonstrated insulating qualities and also allows to avoid significant concrete expenditure. Therefore, such technology contributes to the appreciable price decline, because the foundation is one of the most expensive parts of a building.
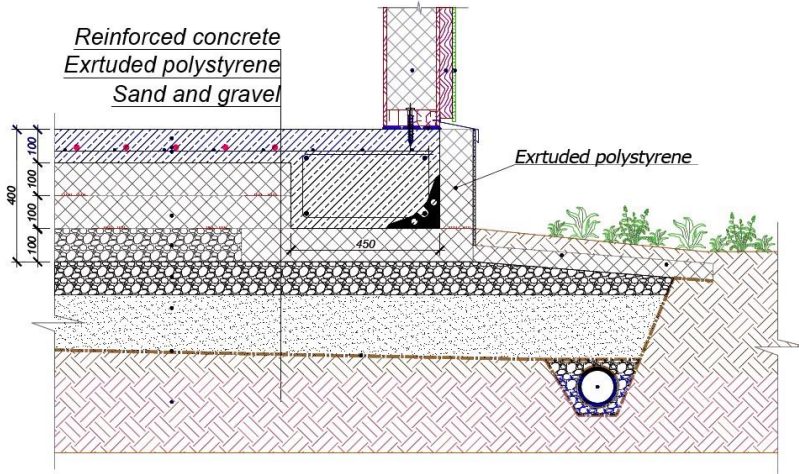
Fig. 6. Structure of the foundation.

2.3 Internal loads and lighting conditions

In the building, it is necessary to provide such physical parameters of the internal environment that create a physiological sense of comfort. It is the provision of temperature and humidity conditions, optimal parameters of the air environment. Mozgalev et al performed a deep investigation of regulations of the Russian Federation in terms of energy efficiency [8]. Russian standards require compliance with the temperature range of 18-25 degrees Celsius. Russian regulation declares the upper temperature limit. For example, for a living room, it is equal to 24 ° C. The optimum temperature for residential premises is considered to be a temperature in the range of 20-22 ° C. The normative for bedrooms is 200 lux, 150 lux for kitchens and living room, 50 lux for bathrooms, halls and service rooms. All rooms are equipped by light-emitting diodes (LED) lams with linear controls. Such lamps are environmentally friendly light sources. The principle of illumination of LED lamps allows us to use safe components in the production and operation of the lamp itself. Tyutikov et al highlighted the significant impact of direct solar radiation on the indoor climate of the buildings in Russian climate conditions [9]. Thus, it enhances cooling load during the summer period, but it contributes to passive heating during cold time. Therefore, appropriate solar shading devices such as shattered blinds were considered in these simulations in relevant time.

Table 2. Normative use of a single family residential house

Occupied time period	00:00-00:00
h/24h	24
d/7d	7
Heating set point	21 °C
Cooling set point	25 °C
Normative DHW temperature	65 °C

2.4 HVAC system

The HVAC system is a key element in the building's indoor climate and energy performance. Even though, due to its abundance in Russia, the most popular fuel for space heating is natural gas, air source heat pump is able to perform heating and cooling load even in Russian cold climate. Therefore, the Chinese experience in this field is very interesting. Liu et al investigated the possibilities of air source heat pump uses. It properly works until -25 ˚C by spending on work 1 kW of electricity, the heat pump will produce up to 2 and even 5 kW of heat. During the warm period, it performs air condition function. Analyzing received electrical input, output, and coefficient of performance (COP), the heat pump with COP equal to 2,25 was chosen for heating system seasonal and 3,8 for the cooling system [10].

2.5 PV system and related equipment

The set of equipment as an additional source of electricity allows using electricity in the warm period from May till September. The system consists of 16 crystalline silicon PV modules 0,25 kW with total nominal power 4 kW. Usually, the installed capacity of roof-mounted PV array does not exceed 5 kW. The total area of solar panels is 19,9 m2. Another important device is a power inverter which transforms the direct current (DC) output of a photovoltaic (PV) system into alternating current (AC) for the building's appliances. The solar inverter with 3 kW was chosen for the system. Solar panels work in the daytime, but residential building consumes electricity 24 hours a day. In most cases, solar panels work in parallel with the network and generate environmentally clean electricity for centralized electricity networks. The networked solar station does not use electric power storage (batteries). The electricity generated by solar panels through the inverter goes instantly to consumers. The power generated is proportional to the intensity of solar lighting. With sufficient light, energy from the external power grid is not consumed at all. In case of insufficient illumination and, accordingly, less energy produced by a solar power station, just as much energy is taken from the external network as there are not enough consumers.
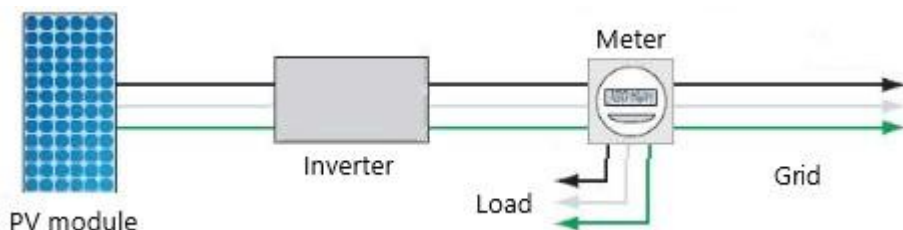

Fig. 7. On-grid PV system

2.6 Weather data

For building performance simulation and PV energy calculation was used climate Energy Plus data files downloaded from PVGIS online free solar radiation and photovoltaic energy estimation tool. The files are available in CSV and EPW formats for the time period 2007–2016 [11]. The climate data is a set meteorological data in a period at least 10 years representing hourly values of climatic parameters such as Direct and Global horizontal irradiances, Dry bulb temperature, wind speed and direction, Relative humidity, Air pressure, Wind speed for the specific location [12].

2.7 Software

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3 Results

Building energy performance PV energy production were conducted for 34 Russian cities. Received data represent monthly energy needs for electrical appliances, lighting, heating, cooling, hot water supply. Received data is compared with monthly electricity production for the relevant location.

Fig. 5. Monthly energy consumption for Moscow
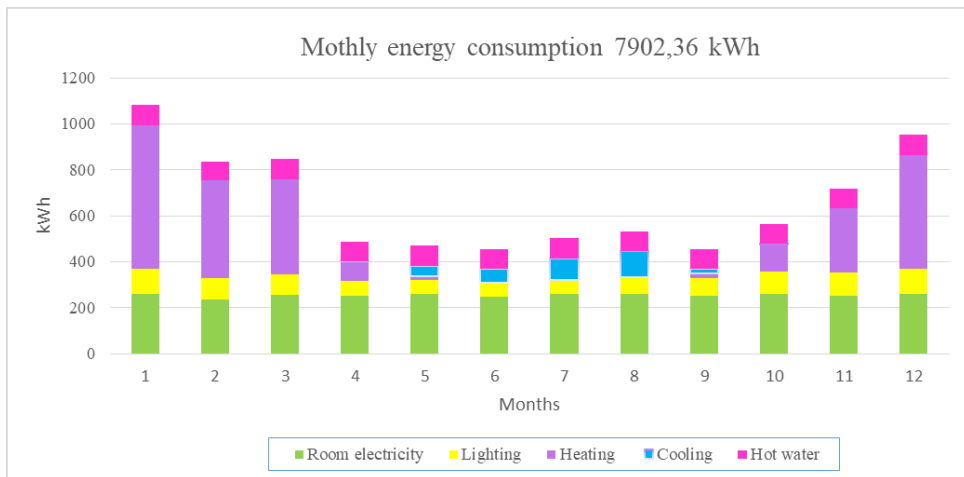
According to calculations, PV electricity output can meet electricity needs from April till September, but during cold time proposed nominal power is not enough to provide building system demands. At the same time, solar panels play a significant role in annual energy balance, significantly decreasing consumed yearly energy per square meter. In Moscow, this value is 46.3 kW/m2y.
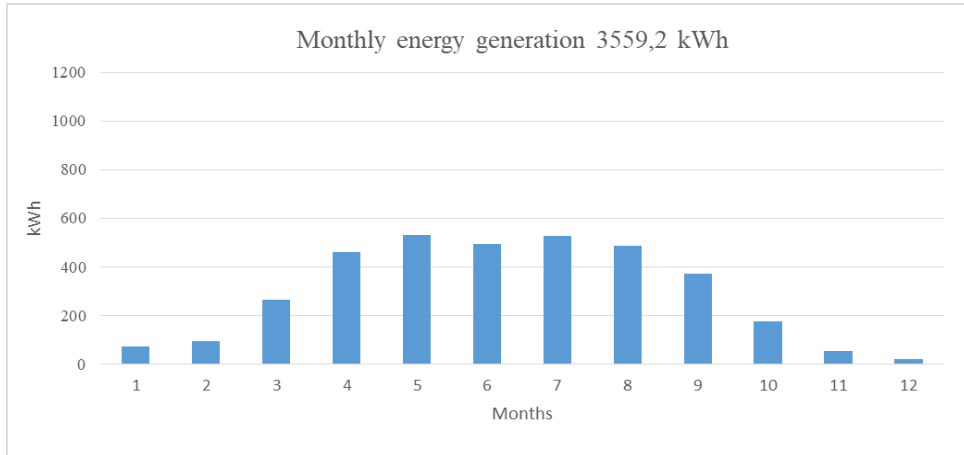
Fig. 6. Monthly energy generation for Moscow

The rated value of the AEU for Moscow is 164 kW/m2y. Our simulation demonstrated 66,4 kW/m2y for the same location. This value changes in a big way when moving from North to South. In Sochi, the AEU is 12.2 kW/m2y, while in Krasnoyarsk it is 102 kW/m2y. More detailed data of the building's energy balance is demonstrated in Table 3.

Table 3. Building's energy balance in different Russian cities

City	Location (latitude, longitude)	Annual energy consumption, kWh	Annual PV output, kWh	Annual energy use, kWh/(m2y)
Sochi	43.61, 39.72	6330.0	4735.6	24.2
Vladikavkaz	43.04, 44.68	6540.3	4716.3	27.6
Astrahan	46.33, 47.98	7788.2	5538.6	34.1
Krasnodar	45.03, 38.98	7302.1	4636.1	40.4
Satvropol	45.03, 41.99	7451.2	4540.7	44.1
Rostov na Donu	47.21, 39.70	7533.2	4209.8	50.4
Ryazan	48.73, 44.49	8089.8	4566.1	53.4
Ryazan	55.73, 37.62	8024.1	3934.2	62.0
Orel	52.95, 36.09	7911.0	3854.8	61.5
Kursk	51.73, 36.20	7996.7	3943.3	61.4
Voronez	51.65, 39.19	8418.3	4132.1	64.9
Penza	53.18, 44.96	8409.7	4105.0	65.2
Ulyanovsk	54.33, 48.33	8588.7	4024.5	69.2
Kaliningrad	54.69, 20.52	7249.2	3726.4	53.4
Bryansk	53.22, 34.37	8059.8	3500.3	69.1
Smolensk	54.77, 32.02	8116.8	3636.4	67.9
Pskov	57.81, 28.35	7779.4	3397.3	66.4
Moscow	55.73, 37.62	7902.4	3559.2	65.8
Vladimir	56.12, 40.40	8496.5	3751.3	71.9

Petersburg	59.93, 30.37	8537.1	3372.0	78.3
N.Novgorod	56.30, 44.01	8644.5	3855.6	72.6
Kirov	58.59, 49.66	9330.5	3329.5	90.9
Arkhangelsk	64.55, 39.79	9312.2	3334.3	90.6
Kazan	55.77, 49.13	8463.8	3945.6	68.5
Ufa	54.71, 55.96	9183.2	4012.5	78.3
Saratov	51.52, 46.02	8868.4	3569.9	80.3
Ekaterinburg	56.83, 60.63	9117.6	3812.0	80.4
Perm	57.99, 56.24	9149.5	3387.4	87.3
Tjumen	57.14, 65.56	9290.7	3994.0	80.3
Omsk	54.96, 73.36	9834.9	4296.7	83.9
Novosibirsk	55.02, 82.94	9859.6	4038.4	88.2
Kemerovo	55.34, 86.10	9933.2	3940.7	90.8
Barnaul	53.34, 83.79	9422.0	4652.2	72.3
Krasnoyarsk	55.99, 92.86	10500.4	3766.7	102.0

4 Discussion

According to research, annual energy use of wood frame residential one family house varies from 24,2 kWh/ (m2y) in South regions till 102 kWh/(m2y) in Siberia. All technologies, listed above, might be adapted in the residential sector for newly constructed and reconstructed buildings. Building materials with good insulation have long been sold in the Russian Federation, and there are no problems with the use of heat pumps, but our research has shown the enormous importance of solar energy in achieving high standards of energy efficiency. Despite the fact that few people in Russia seriously perceive the economic advantages of solar energy, more and more people in Russia take a positive view of solar modules and regard it as a profitable investment. Unfortunately, in this country, there is no preferential procedure for connecting solar panels to the general power supply networks. According to the existing legislation, private consumers can use solar energy for autonomous consumption without connecting to the main grid. Another problem is the lack of knowledge and confidence in green technologies. However, the situation may soon change radically. In the Russian Federation, electricity prices are rising, and the cost of solar panels is falling. Therefore, the Russian government is starting to introduce green technologies by adapting existing practices to local conditions. Owners of private solar panels with a capacity of up to 15 kW can hope for the order of free connection to local power grids and even receive payments for electricity supplied to the grid. This hope is given by the recent Order of the Vice-President to the Government of the Russian Federation on stimulating the development of microgeneration based on renewable energy sources of February 17, 2017. It is possible that soon any owner of a solar module connected to the network through the photovoltaic inverter will be able to receive a small compensation for the surplus of solar electricity sent to the network. By the way, in many countries, the owners of solar cells also cannot sell surplus electricity to the network. However, this does not prevent them from benefiting from their solar power plants on the roof of houses. In such countries, there is another scheme that allows you to deduct the electricity supplied to the network from the consumed one. In our opinion, this option will be more reliable for implementation in the Russian Federation.

5 Conclusion

In this paper, the energy efficiency potential on a household scale was investigated. Implementing modern structural materials, like using advanced HVAC systems and installation on renewable energy equipment have significant opportunities in energy savings potential. Our simulations showed that in climate conditions of the Russian Federation, using solar energy can meet the building's energy demand only in the warm period of time from May till October, but it may significantly improve building energy performance. This study was conducted on a household level. It would be very important to investigate of implementation of these technologies on city and country level. Another important aspect of green building is the life cycle analysis of a building. Moreover, using new technologies will cause a significant increase in the cost of construction. These issues should be investigated in future works.

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