TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING

Department of Materials and Environmental Technologies

EFFECT OF A PHOTOVOLTAIC ENVELOPE ON THE ENERGY PERFORMANCE AND THE INDOOR CLIMATE OF AN OFF-GRID OFFICE BUILDING IN ESTONIA

EHITISINTEGREERITUD PÄIKESEPANEELIDE MÕJU AUTONOOMSE KONTORIHOOHE ENERGIATARBELE JA SISEKLIMALE

MASTER THESIS

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Tallinn, 2018

AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.
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EHITISINTEGREERITUD PÄIKESEPANEELIDE MÕJU AUTONOOMSE KONTORIHOOHE ENERGIATARBELE JA SISEKLIMALE

EFFECT OF PHOTOVOLTAIC FACADE ON THE ENERGY PERFORMANCE OF AN OFF-GRID OFFICE BUILDING IN ESTONIA

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Tallinn, 2018.a.

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Abbreviations and Acronyms

Symbol	Description	SI Unit
EoT	equation of time in minutes	min
Gtitl	irradiance on titled surface	W/m2
HA	hour angle, converts the local time to degrees	
Kt	clearness index	
LT	locakal time	h
NOCT	normal operating cell temperature	
Pmax	nominal power of PV module	W
R	reflection Coefficient of the Cell Share	
T	transmission Coefficient	
Tair	air temperature	°C
Tmod	indoor air temperature	°C
Toutd	outdoor air temperature	°C
TC	time correction factor	mon
U-value	heat transfer coefficient	W/m2K
α	azimuth o the plane normal and sun position in radians	radians
αs	sun position in radians	radians
γ	temperature Coefficient	
δ	sun declination angle	radians

Abbreviations and Acronyms

BIPV	building integrated photovoltaic
GHG	greenhouse gases
HVAC	Heating ventilation and air-conditioning
m-Si	mono-crystalline Silicon
p-Si	poly-crystalline Silicon
PV	photovoltaic

1. Introduction

On 19 May 2010, the directive on the energy performance of buildings (EPBD) came into force and had to be implemented by the EU Member States at the latest on 19 July 2010 [1]. This document replaces previous one (2002/91/EC). According to the new version, all residential and office buildings built after 2018 should be ‘nearly zero energy’, considering minimum energy performance requirements and implementing the energy performance certificates. The policy of the directive is intended for the improvement of energy efficiency and the decrease of greenhouse gases (GHG) emission. Such strict regulations will require another approach to the design of buildings and use of renewable energy for to satisfy these requirements. One of the feasible solutions might be using of solar energy. As the most abundant and almost discontinuous resource of energy will play a significant role among in common energy production in the future [3].

Even though roofs are still the most preferable places for photovoltaic installation, facades and windows became more popular among engineers. Moreover, today is a very popular trend to integrate photovoltaic materials in conventional materials, such as steel and glass. For example, in big cities the big height of the buildings allows additional opportunities to place additional equipment in overcrowded downtowns when roof area is already busy [3]. Therefore, architects are increasingly beginning to pay attention to the facades and windows that have huge free areas.

The main problems of such places are overheating during summertime, especially in hot climate. In this case, PV modules might be used in term of electricity production, but also, like shading elements as part of overhead glazing structures providing semitransparent facade. Such envelope protects interiors from overheating during hot but reduces solar gain which provides passive solar heating during winter time.

Another popular trend, especially in Scandinavian countries, is autonomous off-grid self-sufficient building. Such dwelling is not connected to common infrastructure, especially to the electricity net. Some people prefer such housing due to their ideological reasons because this lifestyle has a low environmental impact. So people, even in Europe, still have no electricity connection. For instance, Estonia has more than 1500 islands, many of them are habitable, but some of them are disconnected to the electricity grid.

The aim of the thesis is to demonstrate a possibility of an off-grid office building in Estonian climate conditions and determine the impact of the building integrated photovoltaic envelope on its energy performance and built environment.

2. Literature review

2.1. Review of BIPV technology

Building-integrated photovoltaics (BIPV) are photovoltaic materials that are incorporated into traditional building materials in parts of the building envelope such as the roof, or facades [5]. By the end of the 1970s, the U.S. Department of Energy started investments to projects of distributed PV systems and began collaborations with companies such as General Electric, Solarex, and Sanyo to develop PV shingle prototypes and integrate them with building materials [6]. The pilot project of pioneer residential house with BIPV was built in 1980 [7], and one of the first office skyscrapers the 4 Times Square Building in New York City was constructed in 2001 [8]. One of the biggest BIPV was constructed in n Graz, Austria. At Science Tower with 60 meter of high is a building covered by different type of solar cells. [9].

BIPVs have some advantages compared with non-integrated systems [10]:

- improving the indoor climate of a building due to reducing internal temperature and consequently, the lower energy consumption demanded by the air conditioning system

- may replace almost all external building materials and thereby decrease the long-term over-all costs of a building via operational cost savings and increased energy efficiency.

- saves building materials and labor Costs

- become more and more popular among architects due to ability be integrated into the building envelope to give a modern look to a building.

- can be installed on building structures and roofs where Solar Panels cannot be installed.

At the same time the BIPV technologies have also some disadvantages:

- are less cost-competitive with conventional PV panels;

- in general, the efficiency of the BIPV lower in cases with using thin-film PV cells as more applicable materials in these parts of building envelope where using crystalline silicon is not suitable;

- smaller market, many technologies are still under development; are not cost-competitive with conventional panels;

- infrastructure, standards, expertise needs to be developed.

Based on the application, the materials used, BIPV products are classified into several categories [11]:

analysis.

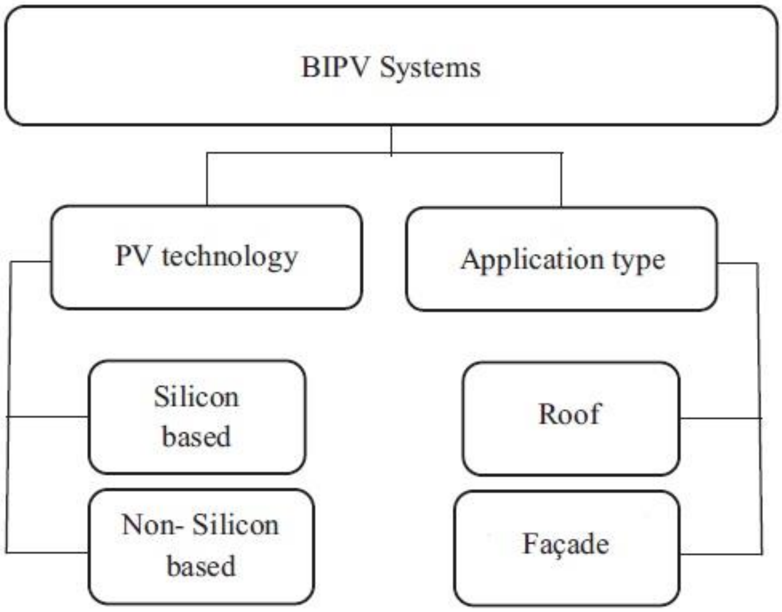

Figure 1. BIPV classification.[11]

Paper in Ref. [12] distinguish 2 types of BIPV applications: Façade and Roofing.

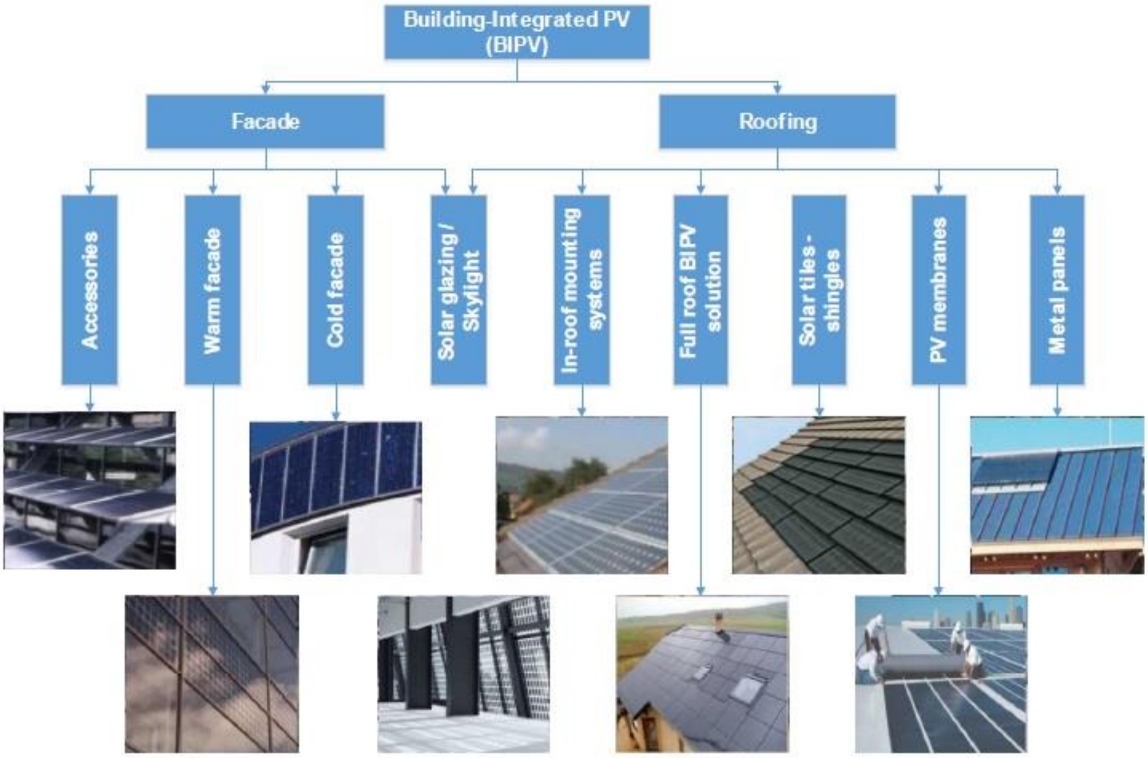

Figure 2. BIPV classification categorization used throughout the application type analysis.

Report in Ref. [13] forecasted global installation capacity in MW till 2020.

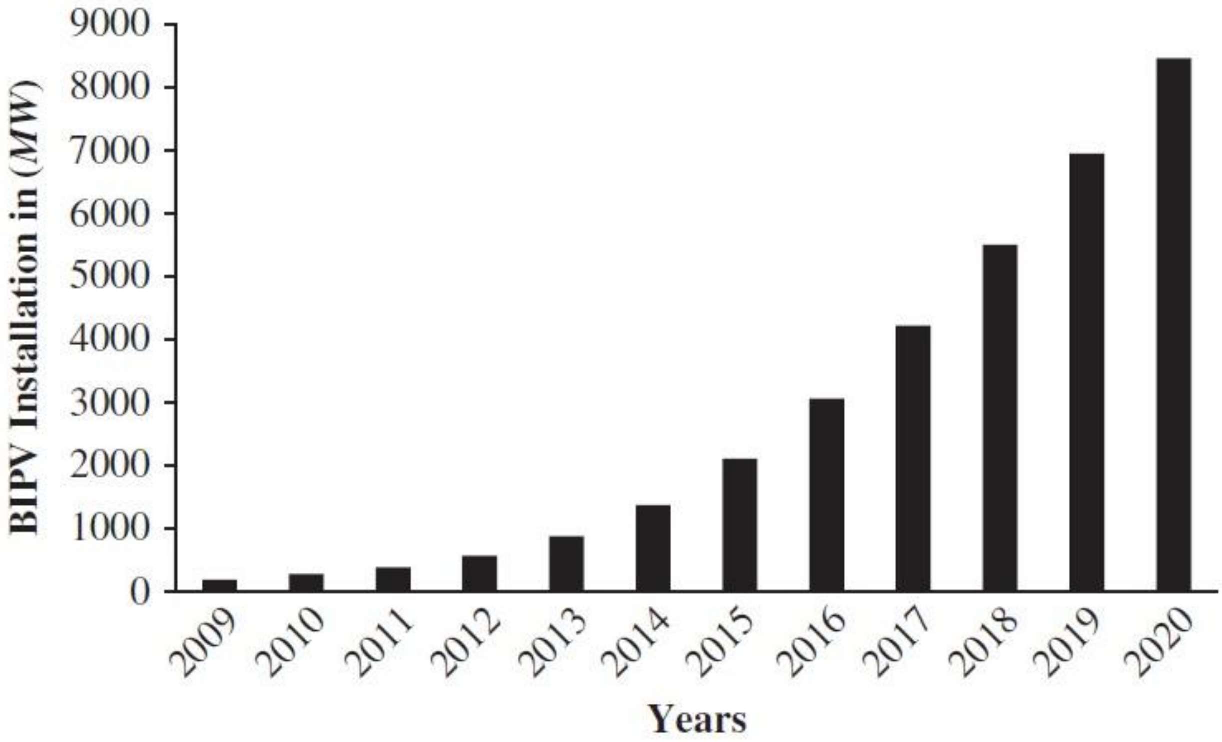

Figure 3.[13]

Polman et al. and Margolis et al. have conducted efficiency and market share analysis of the PV modules based on mono-crystalline Silicon (m-Si), poly-crystalline Silicon (p-Si), amorphous Silicon (a-Si), Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS), Heterojunction (HIT) solar cells in the Ref. [14], [15].

Material	Module efficiency (%)	Market share (%)
m-Si	22,40	41,00
p-Si	18,50	54,00
CIGS	17,50	1,00
CdTe	18,60	4,00
a-Si	6,00	0,10
HIT	19,00	>0,1

Table 1

Siinapis et al. [16] and Ref. [17] have performed technologies used in roof and façade BIPV products.

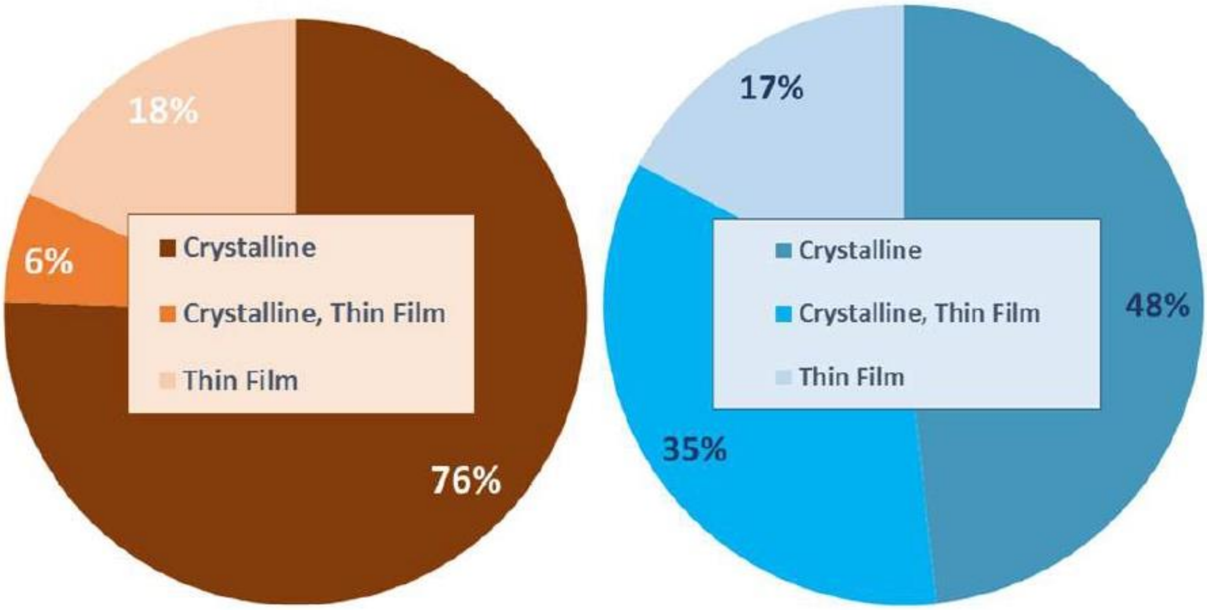

Figure 4. Technologies used in the different product type [16][17]

Zhang et al. [18] have investigated the influence of PV shading on indoor climate in Hong Kong. Simulation of the building was conducted in EnergyPlus software with different tilt angle find optimal design of PV cell in order to obtain maximum PV production and spend less for cooling. Finally, the most beneficial slope to get biggest PV generation is 30°, while the best-titled angle to protect against overheating is 20°.

Yassina et al. [19] have examined BIPV system with energy storage. The aim of the study was to find optimal battery size and to decree dependency on grid-connection. The research was performed for two different regions: Norway and India. As results, the suitable battery size was obtained for both regions and it was made possible to decrease electricity invoice by approximately 17,6%.

Kapsis et al. [20], have investigated the effect of semitransparent photovoltaic windows on daylight conditions for trade buildings. The façade consists of 3 section. Depending on the material, there were 3 types of windows, silicon-based, opaque spaced cells and transparent thin film. Finally, the demonstrates that windows perform sufficient daylight conditions, but also are able to decrees it's potential.

2.2.Review of Estonian regulations in energy performance.

2.1. Methodology for calculating the Energy Performance of Buildings.

According to document, all buildings have six main energy consumers, such as heating, ventilation, air conditioning, domestic hot water (DHW), electricity for appliances and lighting. The regulation also take into consideration solar heat gain, heat losses through envelope and internal heat gains from the people.

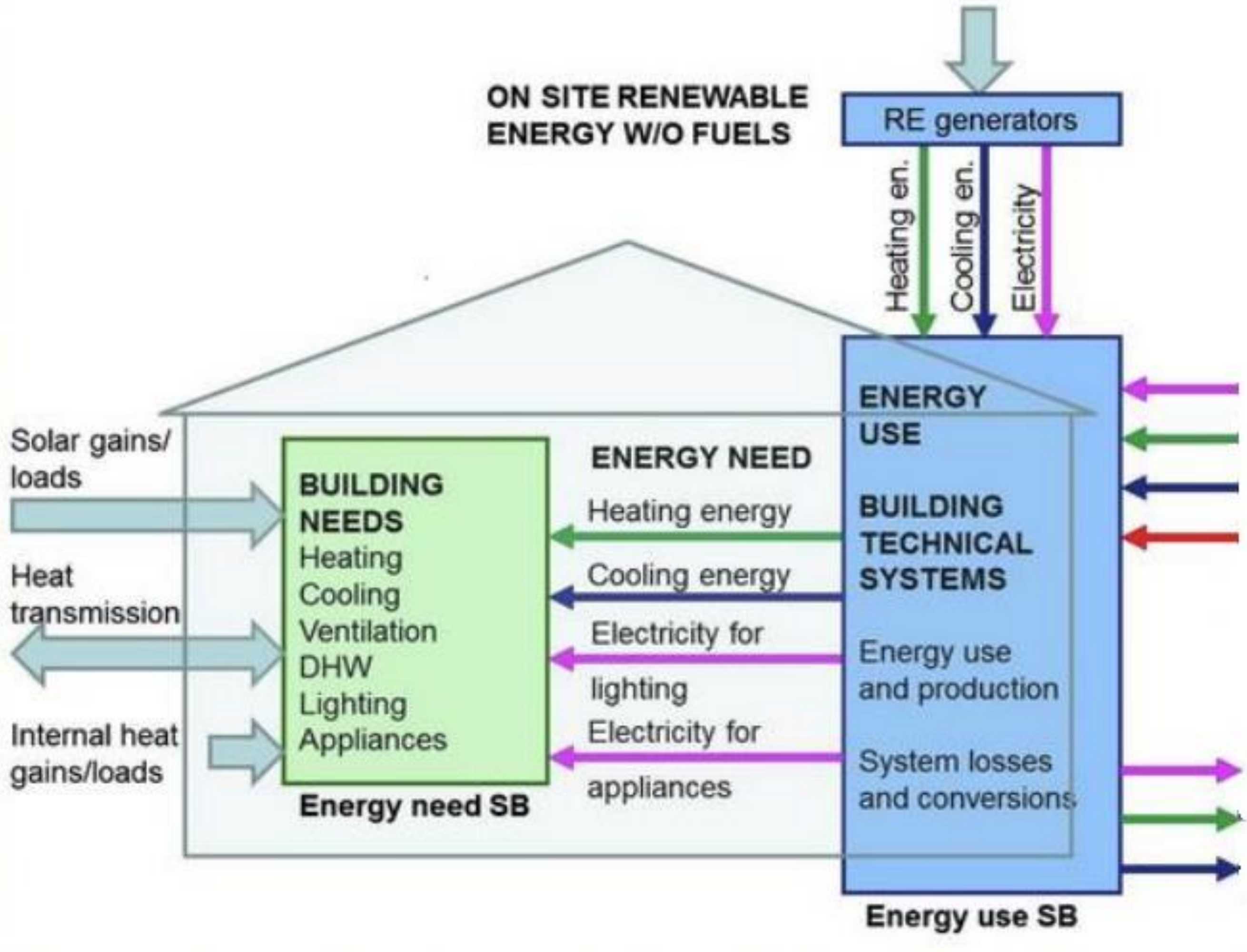

Figure5. System boundary of delivered and exported energy [21].

All buildings have six main energy consumers, such as heating, ventilation, air conditioning, domestic hot water (DHW), electricity for appliances and lighting. Depending on a building purpose, it the regulations define its standard use of the building. This data considers a number of occupied hours per day, the number of days of use per week and the heat gain from lighting and appliances as well as the heat gain from occupants during the building's occupied hours:

Occupied time period	07:00-18:00
h/24h	11
d/7d	5
Usage rate	0,55
Lighting [W/m2]	12
Appliances [W/m2]	12
Occupants [W/m2]	5
Occupants [m2/person]	17

Table 2. Standard use of an office building [21].

2.2 Methodology for calculating the Energy Performance of Buildings.

The document determines a specific range for the energy performance of buildings which means the limits for the energy consumption which can not be exceeded set values. Depending on the amount of consumed energy, buildings are distinguished into standard houses, low energy buildings, nearly zero-energy buildings and net zero-energy buildings.

It is measured by energy performance indicator. It is estimated per square meter of the building's heated area under standard use. The energy performance indicator shows the building's annual energy use for heating, ventilation, air conditioning, domestic hot water, electricity for lighting and appliances. [22].

The energy performance indicator of a building that will be constructed cannot exceed **160** kWh(m2y), while the value of the renovated building cannot be higher than **210** kWh(m2y). To be matched in the classification defined in the document, maximum values of the energy performance indicator of office buildings must not be exceeded following values:

Low energy building	130 kWh(m^2y)
Nearly zero-energy building	100 kWh(m^2y)
Net zero-energy building	0 kWh(m^2y)

Table 3. Limits of energy performance indicator of newly constructed office buildings [22]

The document also defines the air flow rates of the ventilation system and the set-points of indoor temperature used in the energy calculation:

Type of a building	Outdoor air flow rate l/(s m2)	Heating set-point (°C)	Cooling set-point (°C)
Office buildings	2	21	25

Table 4. Requirements for ventilation and indoor temperature for office buildings

High energy performance level also depends on the building envelope. This data considers how much insulation is needed in the walls and roofs. Moreover, the building envelope must be not only sufficiently insulated but also has to be constantly airtight because air exchange is achieved by ventilation. The required U-value of nonresidential buildings to perform a high energy performance level given in Table 5.

Exterior walls	0.15–0.25 W/m^{2}K
Roofs and floors	0.1 – 0.2 W/m^{2}K
Windows and doors	0.6 – 1.1 W/m^{2}K

Table 5. Requirements for the building envelope for nonresidential buildings

2.3 Estonian test reference year for energy calculations.

Heating, ventilation and air conditioning systems design, energy performance and indoor climate simulation and planning of passive and active solar system require hourly weather data. These materials include temperature, global solar radiation, humidity and wind speed. Six meteorological stations in Tallinn, Tartu, Kuressaare, Pärnu, Võru, and Väike-Maarja were selected for the analysis of climate data. Based on this research the territory of Estonia was divided into two climatic areas with more-less similar weather conditions the coastal area, which is directly influenced by the sea, and the inland area [23].

Fig. 6. Climatic areas of the territory of Estonia [23]

3. Description of the building

3.1. Main structure of the building

This is a rectangular in plan one-story office building with a total area of 38,25 м2ю The structure of the building used in this paper was designed to perform low U-values according to European regulation and as result to receive low energy building. In other words, it's energy performance indicator might be no more than 130 kWh/m²*year. Using PV envelope and it's orientation to the south to get the biggest amount of solar irradiance will make the building into energy-plus-building which means that it produces more energy than it uses itself.

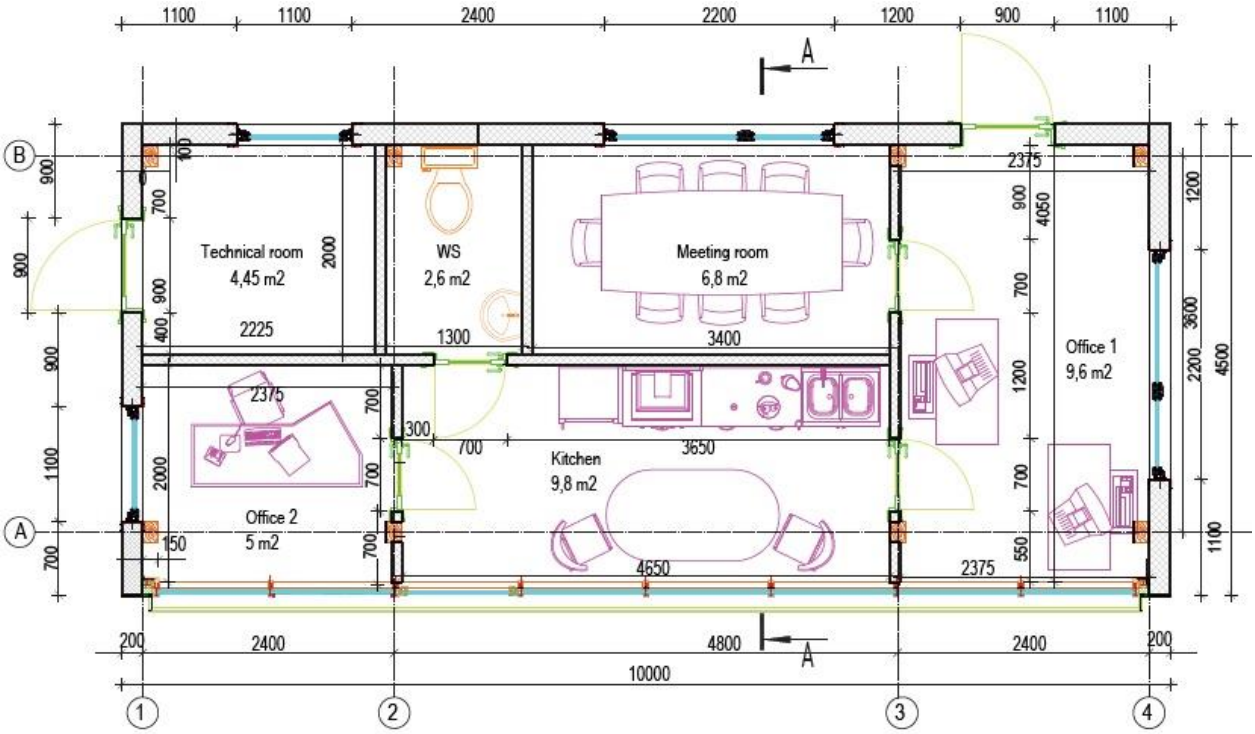

Fig. 7. Plan of the first floor

The external and internal walls, slabs and the roof are made of foam panels which consist of two galvanized (covered with zinc coating, eliminates the possibility of corrosion) corrosion-resistant steel sheets that have polyisocyanurate between them which make sufficient thermal insulation. External sheets are painted with the weatherproof coat, internal sheets with a polymer coating.

Thickness [mm]	Material
0,5	steel
200	polyisocyanurate
0,5	steel

Table 6. Exterior wall structure

For floor, roof and external wall panels 200 mm thick panels with a U-value of 0,11 W/m2K were used. For internal walls we use 100 mm thick panels with a U-value of 0,21 W/m2K were chosen.

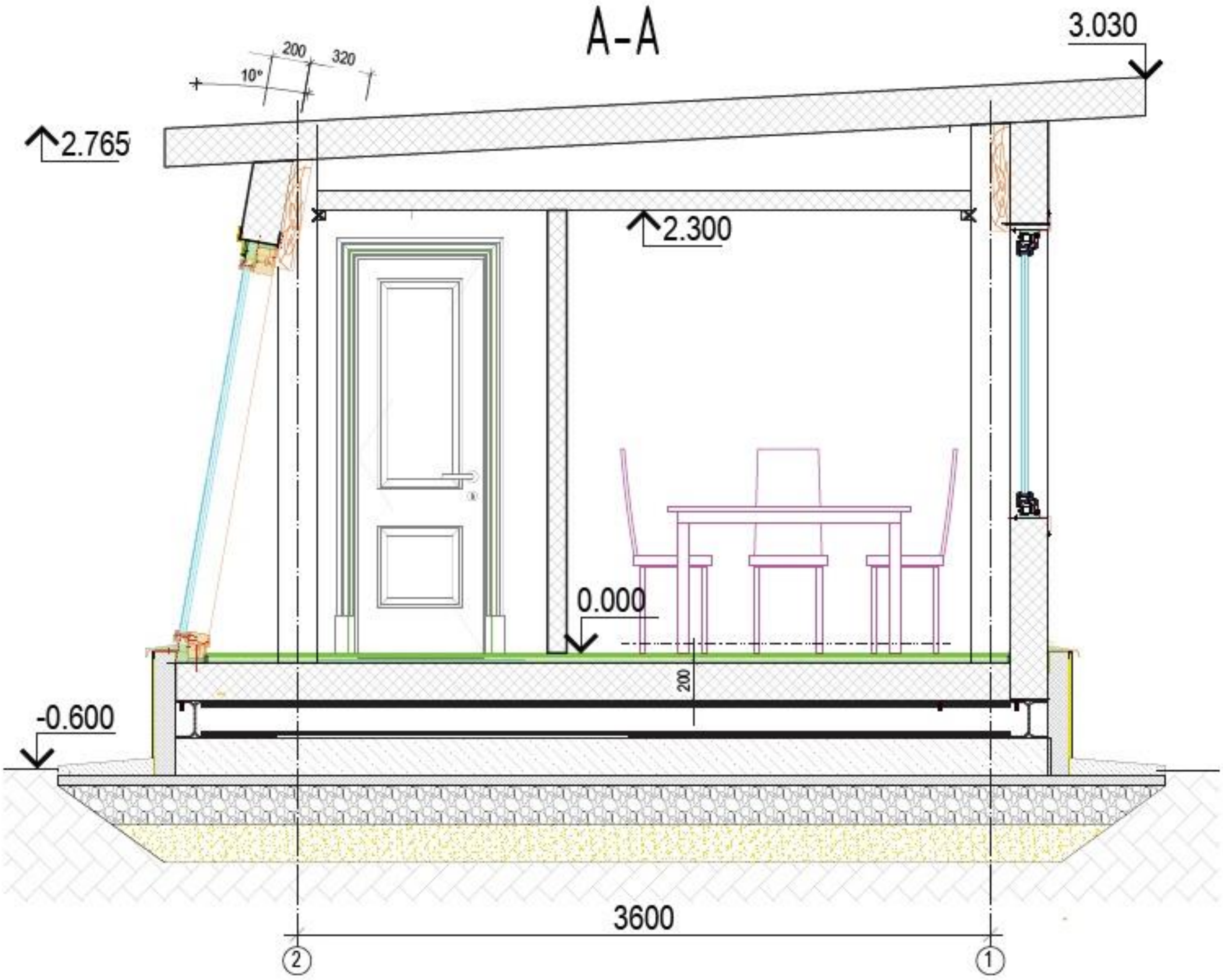

Fig. 8. Cross section A-A

Floor sandwich panel is based on the I-beams. The foundation structure is given in Table 7 and the total U-value of foundation system is 0.497 W/m2K.

Thickness [mm]	Material
200	reinforced concreate
1	waterproofing film
50	extruded polystyrene
200	gravel
200	sand
1	geotextile

Table 7. Foundation structure

The load-bearing frame consists of glued laminated timber columns and beam. This material is not only more strength and lighter than conventional wood, can be used to cover long spans fire-resistant, but also does not create cold bridges which are very important for current work.

Moreover, to the main structure, the windows play a significant role in the energy performance of the building. For this building, windows with the U-value 0.727 W/m2K were used. The structure of these windows can be seen in Table 11.

Thickness [mm]	Material
4	low energy glass LoE270-4
12	gap (Argon)
4	clear glass
12	gap (Argon)
4	low energy glass LoE270-4

Table 8. Windows structure

3.2. PV facade

On the south side of the building, a photovoltaic façade width of 9600 mm and a height of 1900 mm is added. The construction of the façade consists of timber and aluminum frames with triple glazing. Used Pane: 40 mm (8/12/4/12/4). Inner glass consists of two clear glass layers and the photovoltaic cells solar cells embedded between them. The gap betweem solar cells is horizontally 80 and 60 mm. verticallyю In addition, the cells are implemented in ethylene-vinyl acetate (AVE).This structure results in a U-value of 1.05 W/m2K.

Thickness [mm]	Material
4	4 mm Clear Glazing
0,5	ethylene-vinyl acetate
0.5	monocrystalline solar cells 156x156mm (67% share)
0,5	ethylene-vinyl acetate
4	4 mm Clear Glazing
12	gap (Argon)
4	clear glass
12	gap (Argon)
4	comfort TiAC36 glass

Table 9. PV facade structure

Moreover, for daylight level simulation, it is necessary to have such input parameters like the transmission and reflection coefficients of the PV-façade. Basing in the fact, that the usual glazing has a transmission coefficient of 0.95 and a reflection coefficient of 0.03, meanwhile the PV-cells have a transmission coefficient of 0 and a reflection coefficient of 0.1. The sizes of a 5W solar sell is 156 mm x 156 mm, the square of the cell is 0.02323 m2. Concequently, the packing density of the PV-cells is 0.67 for two left and right section, 0,6 for intermediate ones and one section has no cells because it is openable. This means that PV-cells are implemented in 67% and 60 % respectively of the PV-façade and 40%, 33% of the PV-façade is transparent.

The coefficients for the whole PV-façade are calculated as follows:

$$R_{total} = (R_{cell}S_{cell}) + R_{glazing}S_{glazing} \quad (1)$$

$$R_{total} = 0,1 * 0,6 + 0,03 * 0,4 = 0,072$$

$$R_{total} = 0,1 * 0,67 + 0,03 * 0,33 = 0,0769$$

where R_{cells} - Reflection Coefficient of the Cell Share, S_{cells} - Share of the Cell Area of the Façade, $R_{glazing}$ - Reflection Coefficient of the Glazing Share, $S_{glazing}$ - Share of the Glazing

Transmission Coefficient of the total Façade:

$$T_{total} = (T_{cell}S_{cell}) + T_{glazing}S_{glazing}) \quad (2)$$

$$T_{total} = (0 * 0,6) + (0,95 * 0,4) = 0,38$$

$$T_{total} = (0 * 0,67) + (0,95 * 0,33) = 0,3135$$

where T_{cells} - Transmission Coefficient of the Cell Share, S_{cells} - Share of the Cell Area of the Façade, $T_{glazing}$ - Transmission Coefficient of the Glazing Share, $S_{glazing}$ - Share of the Glazing.

The nominal power of the façade is calculated as follows:

$$W_p = n_{cell}P_{cell} \quad (3)$$

$$W_p = 350 * 5W = 1750W$$

where n_{cells} – number of cells, P_{cells} – nominal power of solar cell.

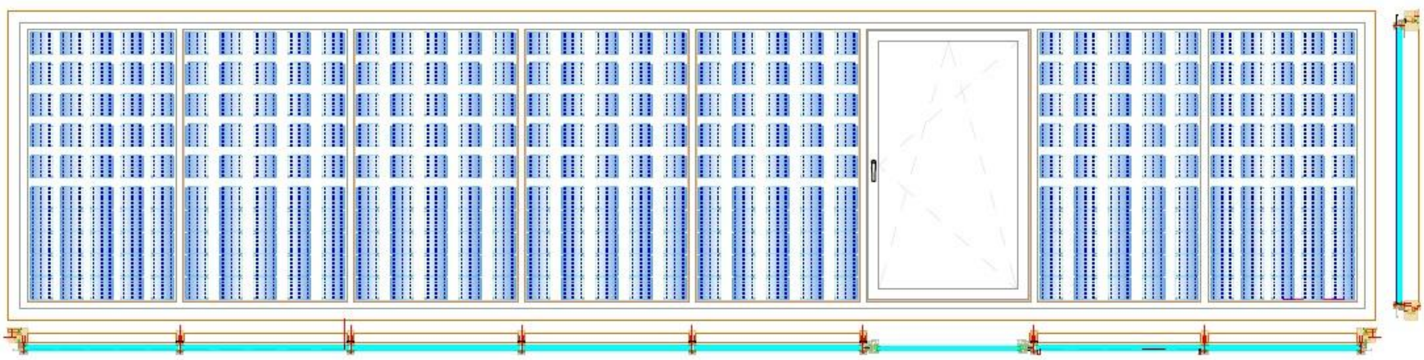

Fig. 9. PV façade

3.3. PV roof

As the external and internal walls, roof are made of foam panels 200 mm with width 1200 mm and height 5100 mm. The single difference is that inner consists of a metal sheet with highly durable PUR coating, tempered low-iron glass with anti-reflective technology and photovoltaic cells solar cells laminated between them. As well as in case of PV facade, two layers of ethylene-vinyl acetate (AVE) were also used. The of the roof is 0,11 W/m2K. Finally, we have 9 panels.

Thickness [mm]	Material
3,2	temperad low-iron glass with anti-reflective technology
0,5	ethylene-vinyl acetate
0.5	monocrystalline solar cells 156x156mm (67% share)
0,5	ethylene-vinyl acetate
0,5	0.5 mm metal sheet with highly durable PUR coating
200	polyisocyanurate
0,5	0.5 mm metal sheet with highly durable PUR coating

Table 10. PV roof structure

The electrical power of the façade is calculated as follows:

$$W_p = n_{cell\ in\ one\ panel} n_{panels} P_{cell} \quad (4)$$

$$W_p = 224 * 9 * 5W = 10080W$$

where $n_{cellsin\ one\ panel}$ – number of cells in one panel, n_{panel} – number of cells , P_{cells} – nominal power of solar cell.

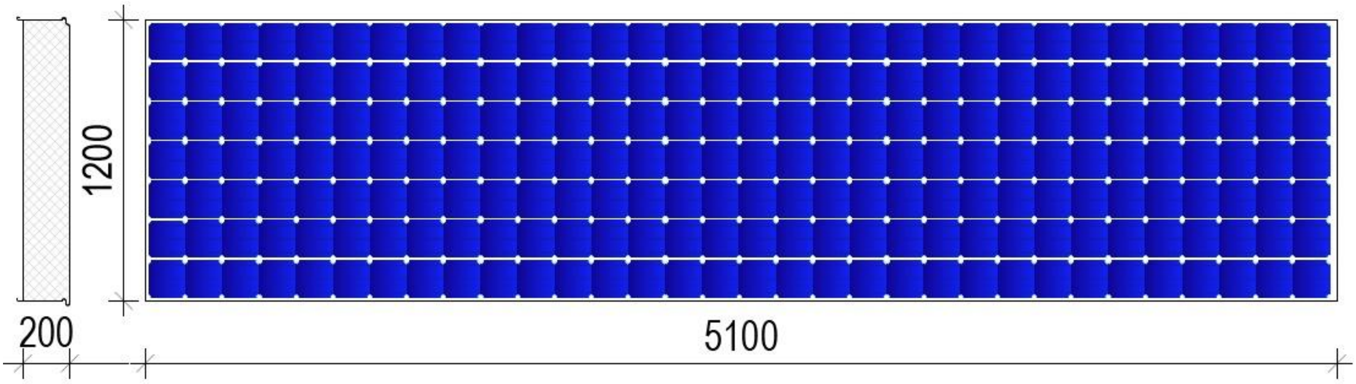

Fig. 10. PV roof

Normal Operating Cell Temperature (NOCT) and temperature coefficient γ are 45 °C and -0,4%/K respectively.

3.4.Heating, ventilation and air conditioning (HVAC) system and hot water supply.

HVAC system of the building is presented by air handling unit (AHU) or air handler which is device used to regulate and circulate air.

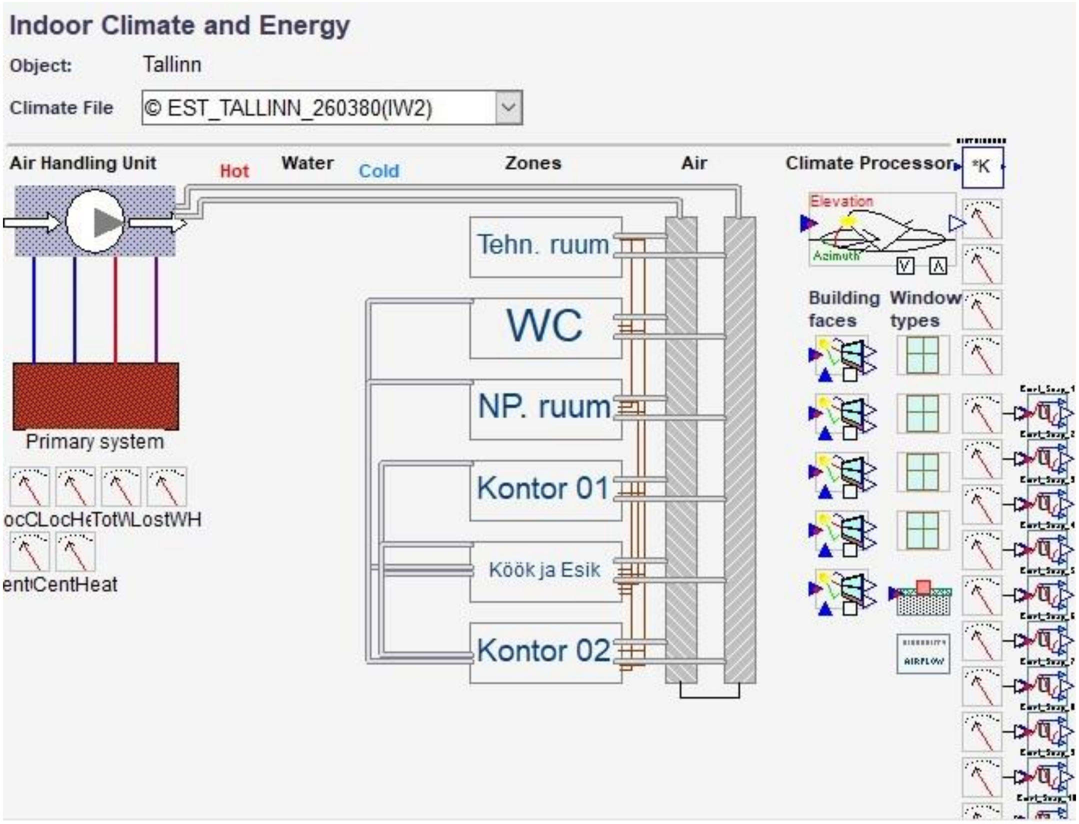

Fig. 11. HVAC system of the building

In general, a box containing fans, heating or cooling elements, heat exchanger with efficiency o,8 and some additional equipment.

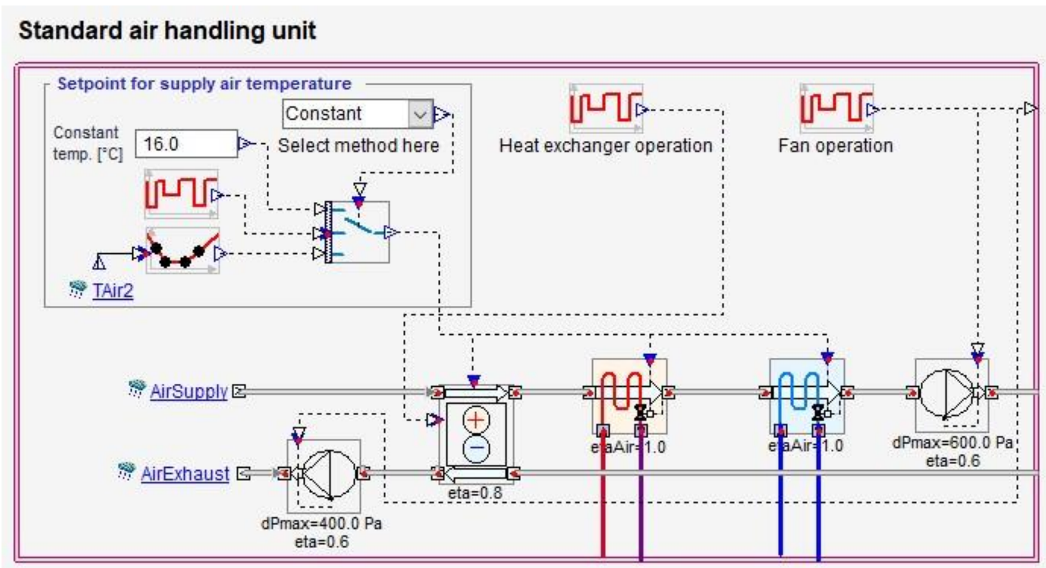

Fig. 12. AHU scheme

HVAC system is key element in building's system because it maintains healthy and comfortable inner climate. Correctly working ventilation protects buildings and property from humidity, eliminates the possibility of the house to become too dry and increases inhabitants' content, comfort and thus propitiates working efficiency.

The basic purpose of the AHU is take away outdoor air, to condition it and supply fresh air to a building. Depending on the required temperature of the conditioned air, the fresh air might be either heated by heating coil, or cooled by a cooling coil. A heat exchanger is usually added to the AHU for energy savings and increasing capacity. Running through the heat exchanger outgoing air passes most of its heat to the incoming air without the two airstreams actually mixing together.

Hot water supply system is presented by maintenance free electrical water heater.

4. Simulation methodology

4.1.IDA ICE

According to the ref. [24], IDA ICE is a dynamic simulation software. It is intended for energy performance calculation and simulation of indor climate. It might be used for all type of building depending on their purpose and climate conditions. It is able to calculate energy demand for heating, ventilation, air cooling, appliance taking to account heat gain from occupants, electrical equipment, solar heat gain and considering thermal losses through the envelope, air leakage. The software may also simulate inner temperature and daylight level depending on building's orientation and shading from surrounding buildings

Fig. 13. Scheme of IDA ICE simulation

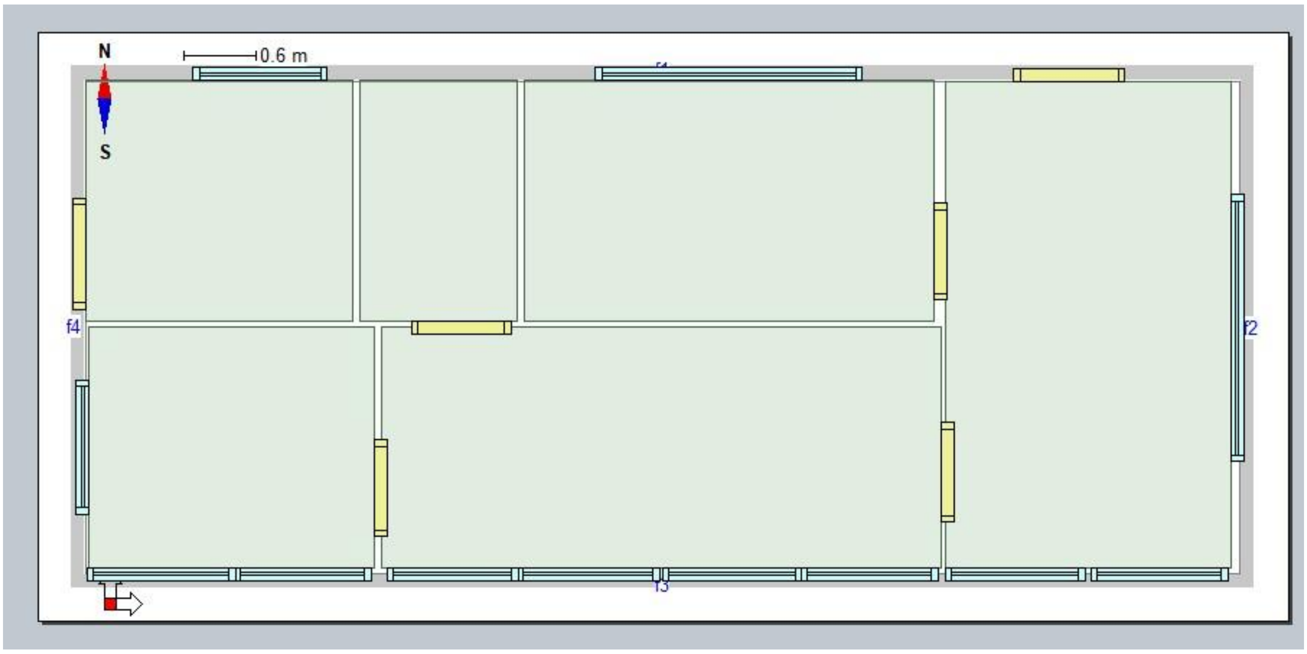

Fig. 14. Building's 1 floor plan in IDA ICE

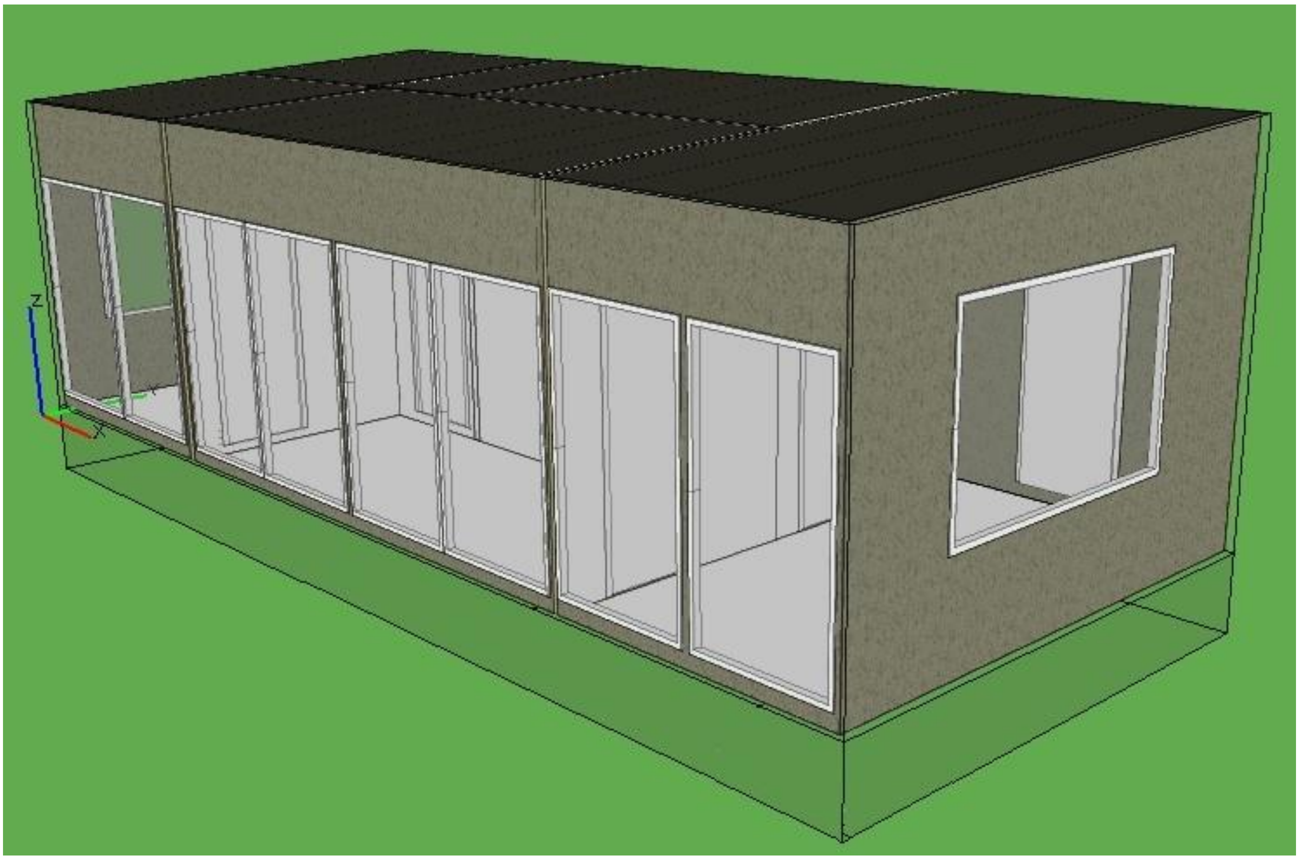

Fig. 15. 3-D view of the building in IDA ICE

4.2.Homer Pro simulation.

The off-grid electrical system of the building designed, simulated and optimized by using the HOMER PRO software.

For the simulation process, the input parameters, such as electric load, location, system components were selected. After simulation, it makes possible to define the annual energy balance of the off-grid electrical system and create possible system configurations that are able to cover the electric load demand. The software sum up the electric demand on the one hand and the electricity produced by the system's constituent element. Summarizing these energy flows, the program defines a feasibility of system configuration and it's ability to support the electricity requirements. For this paper, the electrical load was obtained from previous IDA ICE simulation.

Input parameters for the system components were taken from the PV envelope parameters part of this paper.

The PV module output power is estimated by using equation:

$$P = \frac{P_{max}G_{titl}}{1000}[1 + \gamma(T_{mod} - 25)] \quad (5)$$

where:

P_{max} - nominal power of PV module, W;

G_{titl} – irradiance on titled surface, W/m2

γ - temperature Coefficient;

Tmod – temperature of module;

The Tmod is calculated by equation:

$$T_{mod} = T_{air} + \frac{NOCT - 20}{800} * G_{titl} \quad (6)$$

where:

Tair – air temperature, °C;

NOCT - normal operating cell temperature, °C;

$$G_{titl} = G_{hor}F_c exp\left[-k_t\left(\theta^2 - \left(\frac{\pi}{2} - \beta_s\right)^2\right)\right] \quad (7)$$

where:

θ – angle in radians between sun rays and plane normal (AOI);

βs – sun elevation angle in radians;

Ghor – global horizontal irradiance, W/m2;

Kt – clearness index

Fc – takes to account ground reflection;

$$F_c = 1 + \rho Sin^2\left(\frac{\theta}{2}\right) \tag{8}$$

P – albedo factor.

$$cos\theta = \sin\left(\frac{\pi}{2} - \beta\right)\sin\left(\frac{\pi}{2} - \beta_s\right) + \cos\left(\frac{\pi}{2} - \beta\right)\cos\left(\frac{\pi}{2} - \beta_s\right)\cos(\alpha_s - \alpha) \tag{9}$$

$$\sin\beta_s = \sin\delta\sin LAT + \cos\delta\cos LAT\, LAT\cos HA \tag{10}$$

$$\cos\alpha_s = \frac{\sin\delta\cos LAT - \cos\delta\sin LAT\cos HA}{\cos\beta_s} \tag{11}$$

where:

HA – hour angle, converts the local time to degrees;

β - slope of the plane in radians;

α – azimuth o the plane normal and sun position in radians;

α_s - sun position in radians;

δ - sun declination angle;

$$\delta = 23.45°\sin\left[\frac{360}{365}(n - 81)\right] \tag{12}$$

$$HA = 15°\left(LT + \frac{TC}{60} - 12\right) \tag{13}$$

where:

LT – local time;

TC – time correction factor in minutes;

$$TC = 44(LONG - 15\Delta T_{GMT}) + EoT \tag{14}$$

where:

EoT – equation of time in minutes. Due to eccentricity of Earth orbit.

$$EoT = 9{,}87\sin 2B - 7{,}53\cos(B) - 1{,}5\sin(B) \tag{15}$$

$$B = \frac{360}{365}(n - 81) \tag{16}$$

Where:

n – number of days since the start of the year.

Another important aspect of the electrical system planning is a choosing optimal energy storage device. Batteries are used to store excess of electricity generated by PV system and allow a consumer to use it when solar irradiance is not sufficient. The size of the battery depends on the number of days of needed 'reserve' i.e. the number of days when the system has to meet electricity demand without of any output from PV modules. In some intermediate periods of time, a 3-day reserve is necessary until sun irradiation will be enough for electricity production by PV module. Moreover, according to IDA ICE simulation, the daily average load is no more 1200 Wh per day. As result, required battery capacity is 3 x 1200 = 3,600

Wh. Moreover, energy storage device loses 20-25% because of charging and discharging process, As the result, it's value should be multiplied on 1,25. Final capacity of battery should be 4500 Wh. The two types of batteries most commonly offered for solar PV storage in the home are lithium-ion and lead-acid batteries. Due to such quantities of lithium-ion batteries, such as higher efficiency, lightweight and longer expected lifetime, sonnenBatterie 6kWh eco 6 was chosen from the Homer catalog. Moreover, it is well-known fact that PV modules produce significantly less electricity during winter time, the smallest diesel generator with capacity of 1,5 kWh from the software catalog was added to compensate this disproportion. All of the above equipment is placed in a technical room

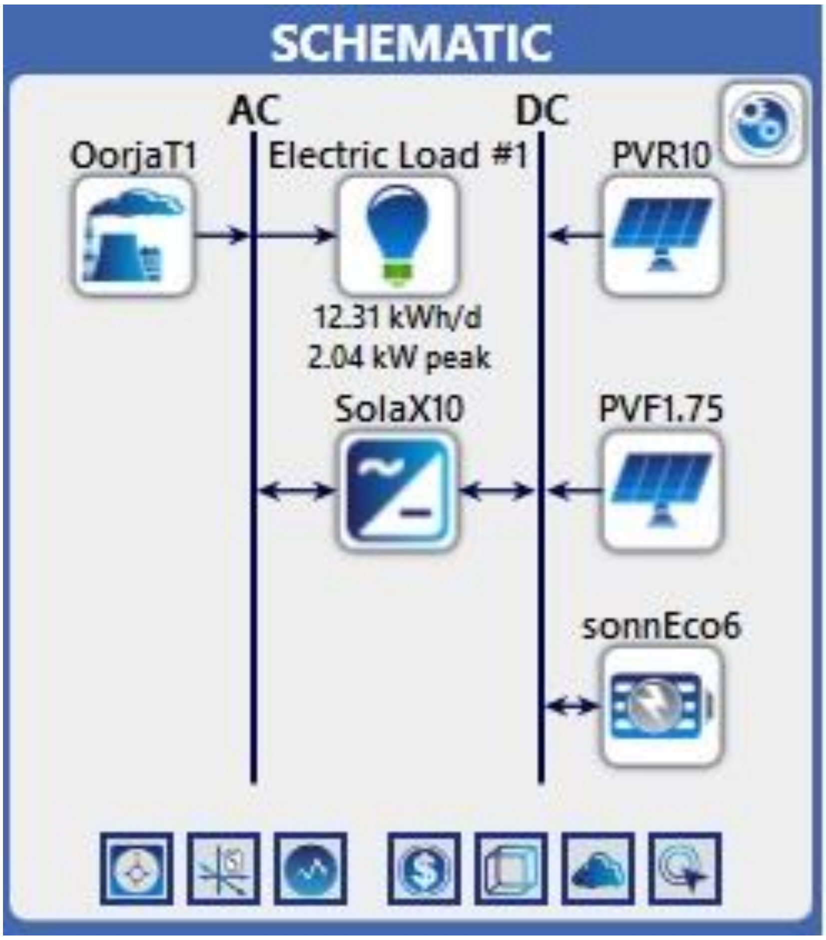

Fig. 16. Scheme of simulation the off-grid system in Homer Pro

5. Results and discussion

5.1.Simulation results for indoor climate

From the simulation, indoor temperature during July, as the hottest period if time, daylight during the December, as the darkest month, the annual energy consumption for version of building with PV façade and for the building without one were received for the Tallinn and Tartu climate regions.

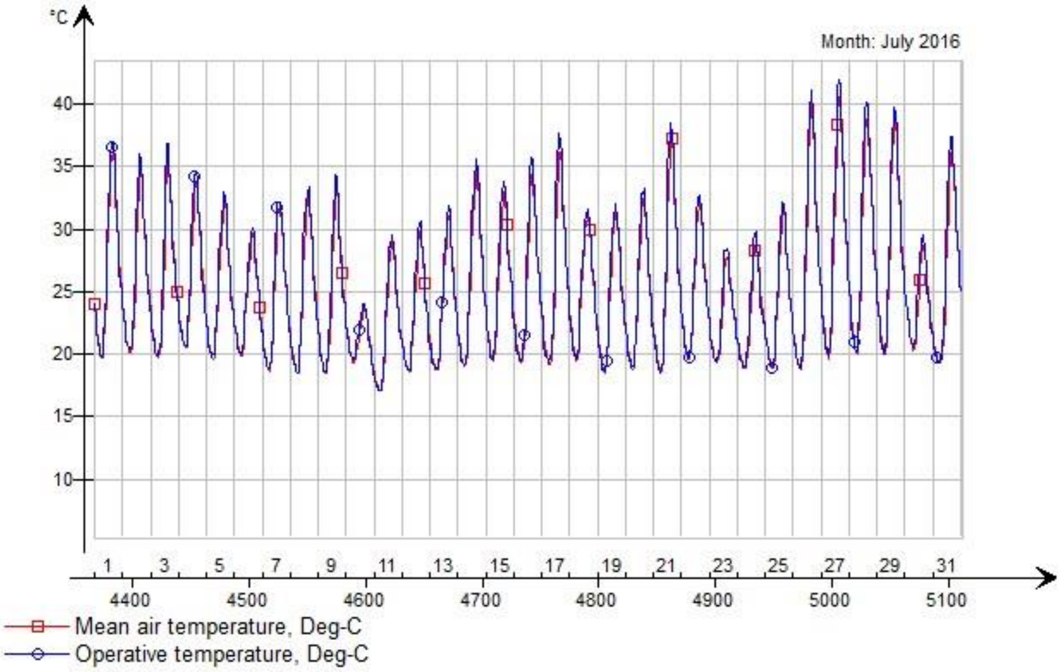

Figure 17. Mean air and opetative temperatures for the building with PV facade in Tallinn

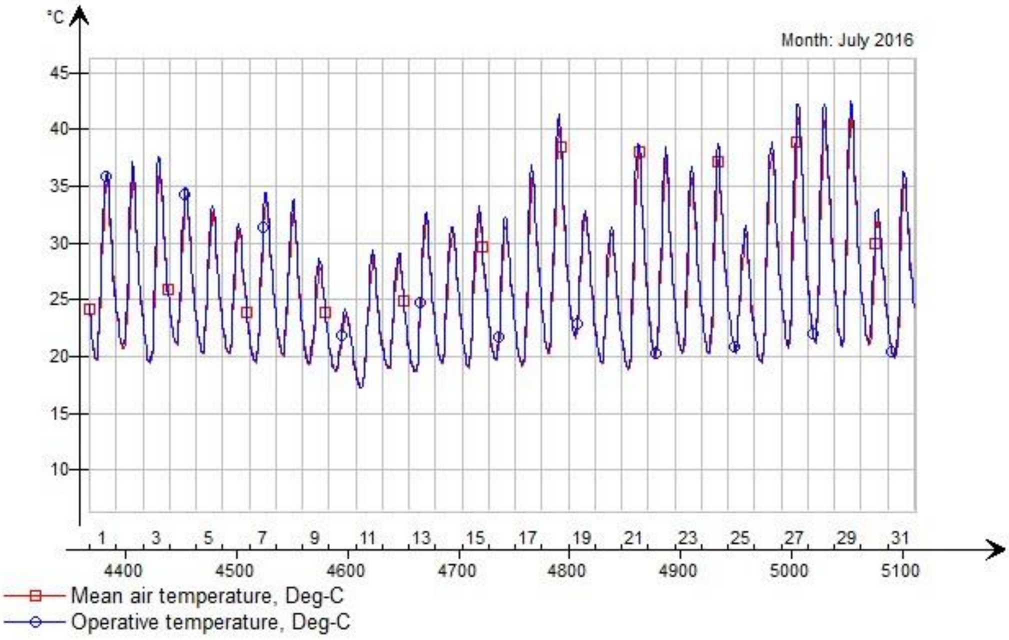

Figure 18. Mean air and opetative temperatures for the building without PV facade in Tallinn

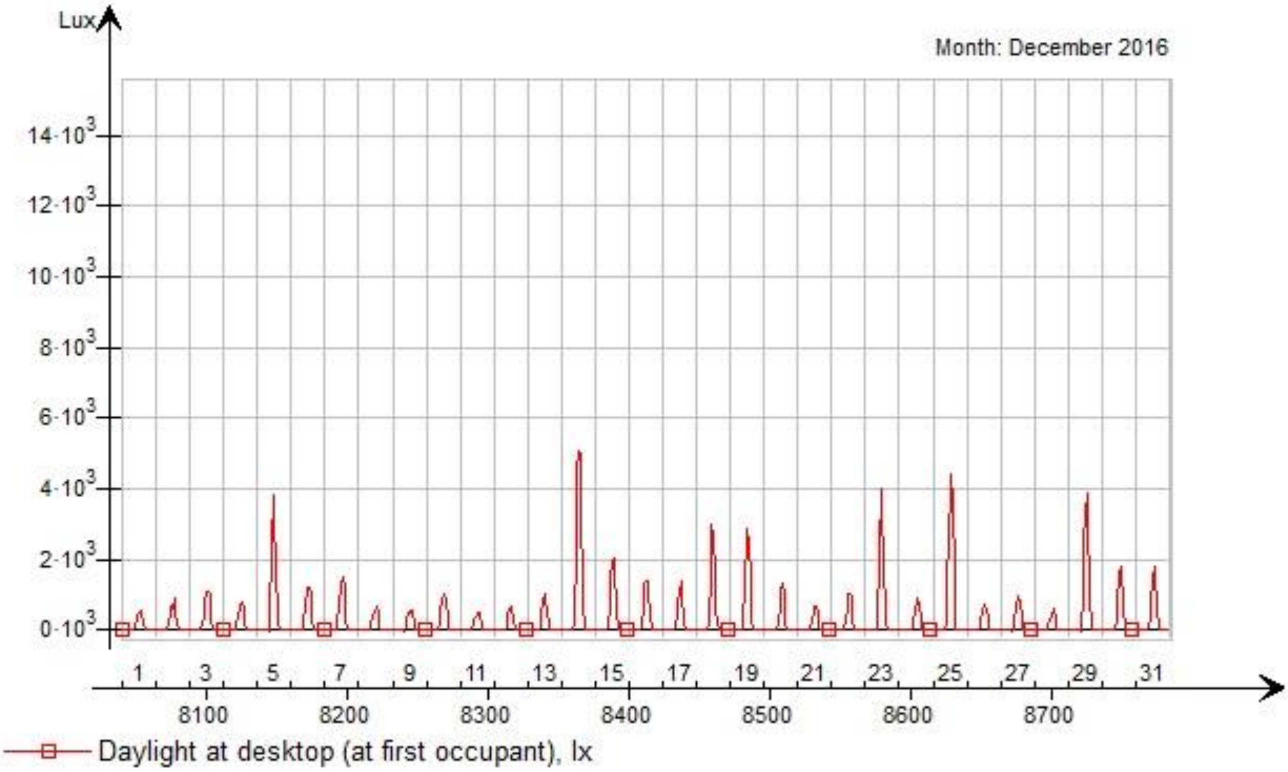

Figure 19. Daylight for the building with PV facade in Tallinn

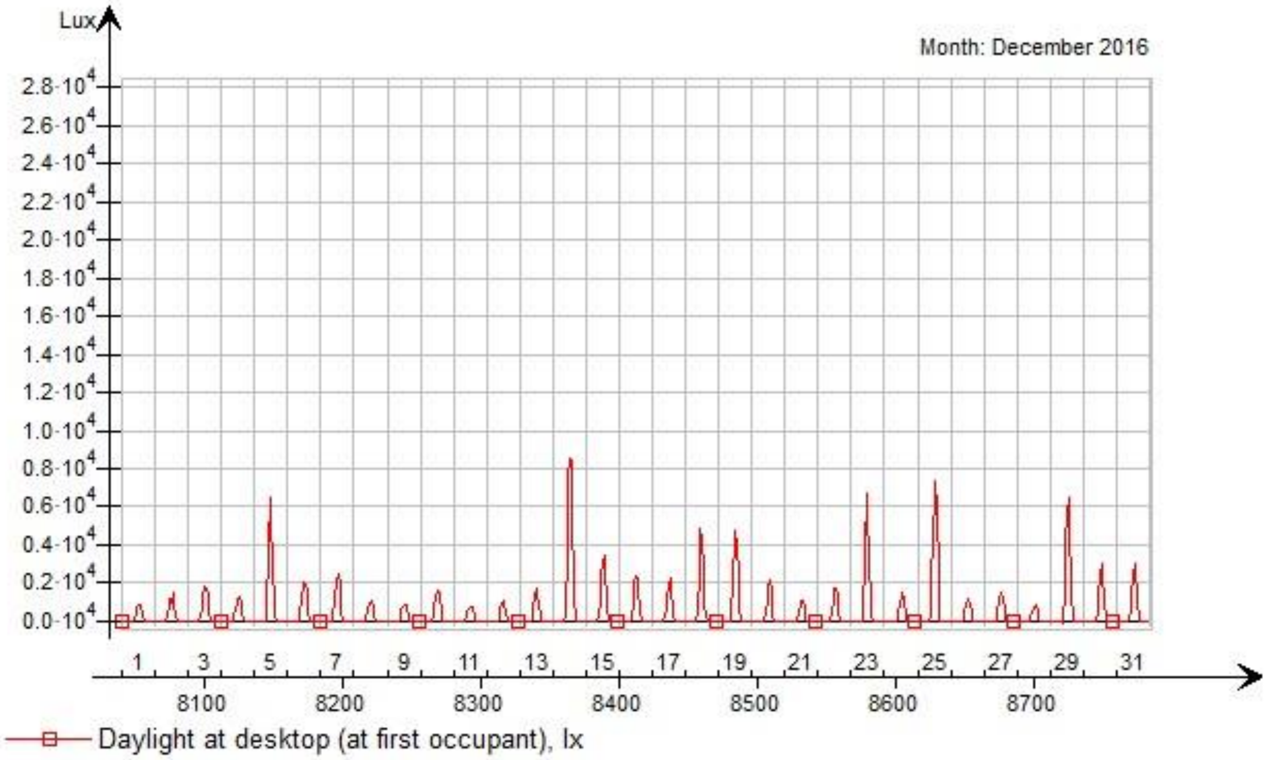

Figure 20. Daylight for the building without PV facade in Tallinn

Month	Facility electric			
	Equipment, facility	Electric cooling	HVAC aux	Electric heating
	(kWh)	(kWh)	(kWh)	(kWh)
1	163.0	0.0	90.3	216.8
2	160.9	0.0	84.3	256.9
3	182.1	0.0	89.9	122.6
4	155.2	2.6	87.4	49.0
5	169.2	21.8	91.3	12.2
6	161.7	34.7	89.2	3.5
7	169.3	103.7	92.9	2.8
8	182.2	76.9	92.6	3.7
9	174.6	6.9	88.6	8.6
10	169.4	0.0	90.7	50.1
11	174.8	0.0	87.3	136.0
12	169.5	0.0	90.4	277.1
Total	2031.9	246.5	1074.8	1139.2

Figure 21. Delivered energy for the building with PV facade in Tallinn

According the results, the PV façade has no sighnificant influence on indoor temperature during the hottest periond of time which results in almost equal values of energy comsumption of electric cooling system in both cases. Even though, the difference in daylight is greater in case with building without PV façade, the fact that comsumpion for lighting and cooling in both situation is similar fact testifies that PV façade block the sunlight not singnificantly and almost doesn't prevent houses from overheating. At the same, bigger excess of expenses heating in 87 kWh in version with PV façade demonstrates that addiional shading leads to a decrease in the solar gains and therefore the increasing of heating during the winter months is increasing.

Month	Facility electric			
	Equipment, facility	Electric cooling	HVAC aux	Electric heating
	(kWh)	(kWh)	(kWh)	(kWh)
1	163.1	0.0	90.2	203.1
2	160.9	0.0	84.1	240.3
3	182.2	0.0	89.8	110.5
4	155.2	2.6	87.3	41.5
5	169.2	21.7	91.3	9.4
6	161.7	34.7	89.2	3.1
7	169.2	103.7	92.9	2.8
8	182.2	76.8	92.6	3.4
9	174.6	6.9	88.6	6.8
10	169.4	0.0	90.7	43.5
11	174.9	0.0	87.2	125.0
12	169.6	0.0	90.3	262.9
Total	2032.2	246.4	1074.0	1052.3

Figure 22. Delivered energy for the building without PV facade in Tallinn

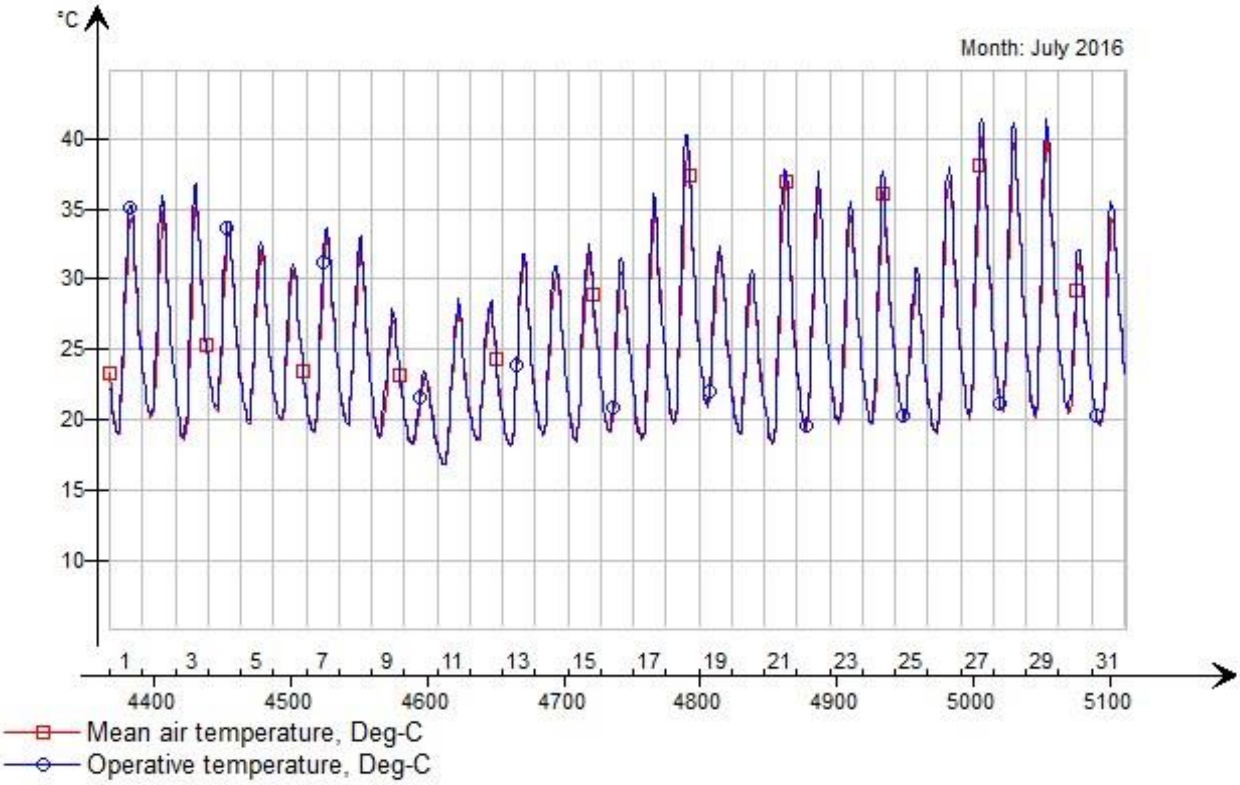

Figure 23. Mean air and operative temperatures for the building with PV facade in Tartu

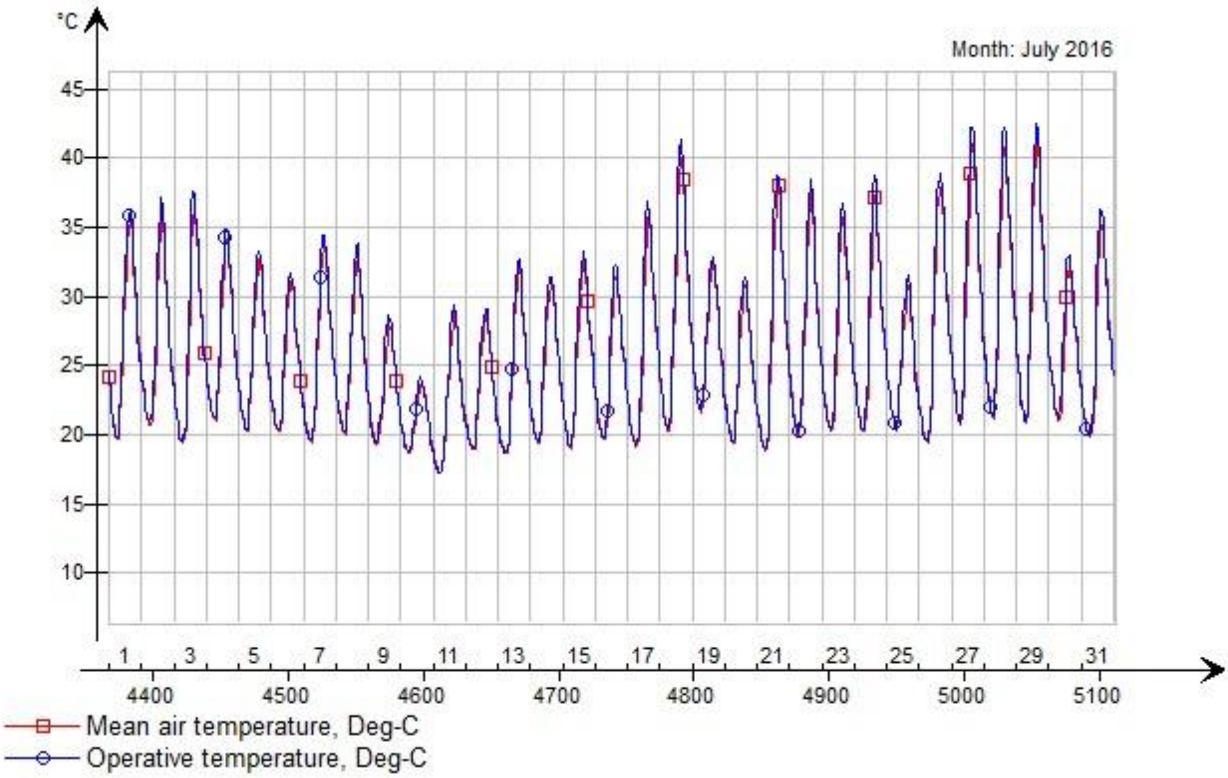

Figure 24. Mean air and operative temperatures for the building without PV facade in Tartu

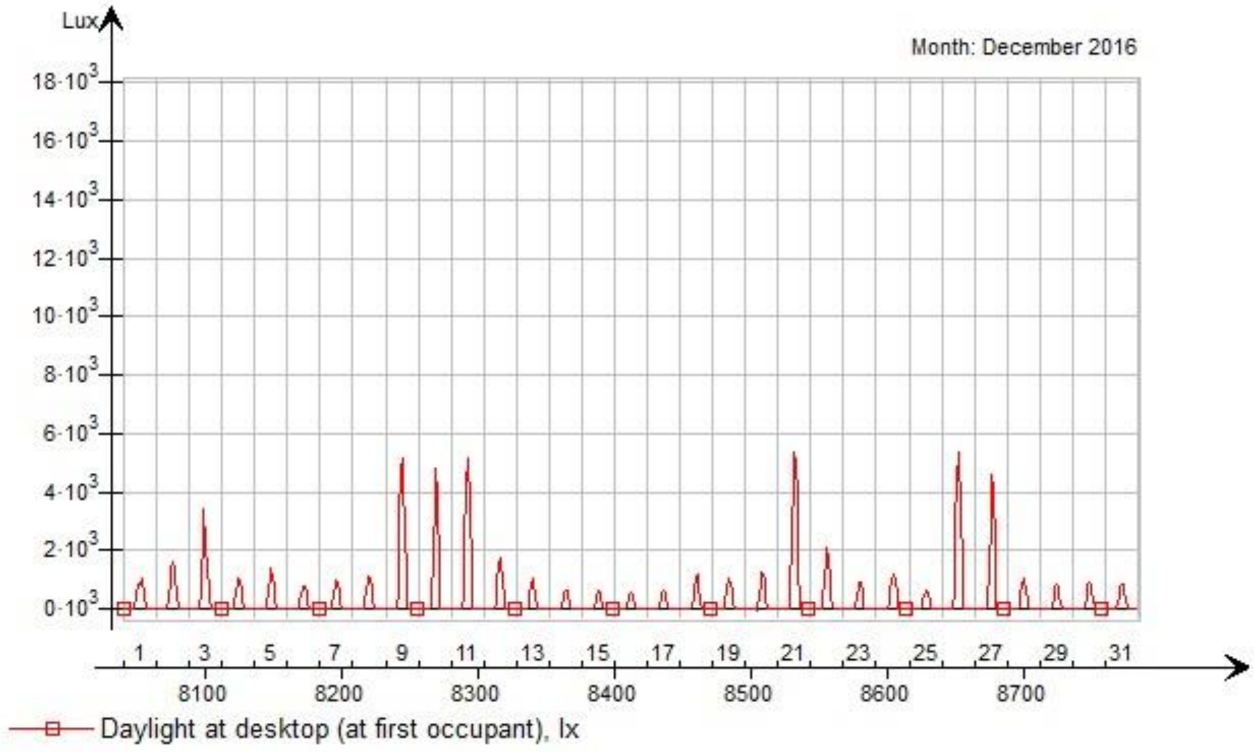

Figure 25.Daylight for the building with PV facade in Tartu

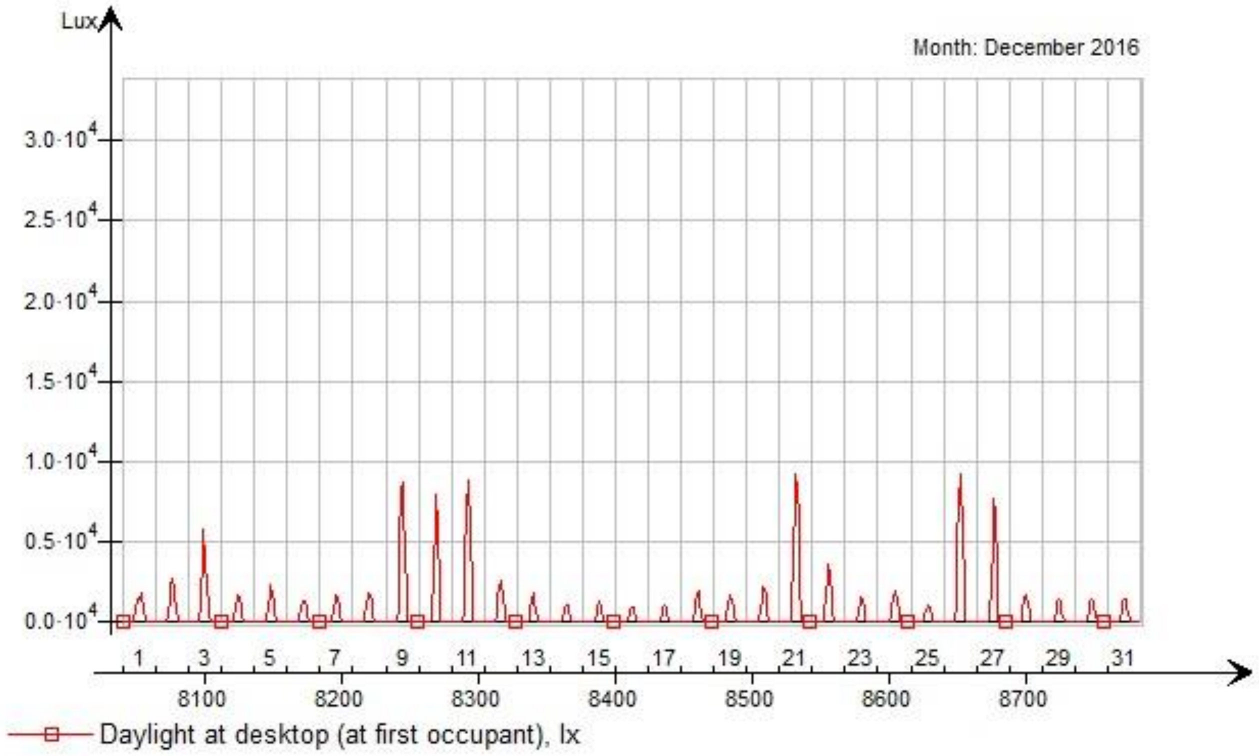

Figure 26.Daylight for the building without PV facade in Tartu

Month	Facility electric			
	Equipment, facility	Electric cooling	HVAC aux	Electric heating
	(kWh)	(kWh)	(kWh)	(kWh)
1	162.9	0.0	90.2	212.2
2	160.8	0.0	84.4	301.0
3	182.2	0.0	89.9	120.4
4	155.3	1.7	87.6	39.0
5	169.2	38.4	91.6	11.9
6	161.8	50.0	89.3	3.1
7	169.1	131.5	93.0	2.8
8	182.2	110.4	92.8	2.9
9	174.6	13.0	88.5	14.7
10	169.3	0.0	90.7	48.3
11	174.8	0.0	87.4	172.5
12	169.4	0.0	90.3	273.1
Total	2031.6	345.0	1075.6	1202.0

Figure 27. Delivered energy for the building with PV facade in Tartu

The analogous situation is possible to recognize for the same calculation in climate condition of Tartu. It is not considerable impact of PV element on indoor temperatures during July and daylight during December which results in close values of lighting and cooling consumption, but in term of heating system, as in previous example, version of building with PV façade requires 89,2 kWh more than the building without such solar façade.

Month	Facility electric			
	Equipment, facility	Electric cooling	HVAC aux	Electric heating
	(kWh)	(kWh)	(kWh)	(kWh)
1	163.1	0.0	90.0	197.8
2	160.7	0.0	84.2	283.7
3	182.3	0.0	89.8	107.8
4	155.2	1.7	87.5	32.8
5	169.2	38.4	91.5	9.9
6	161.8	50.0	89.3	2.9
7	169.2	131.5	93.0	2.8
8	182.1	110.4	92.8	2.8
9	174.6	13.0	88.4	12.1
10	169.2	0.0	90.6	41.6
11	174.8	0.0	87.3	160.4
12	169.5	0.0	90.2	258.2
Total	2031.7	345.0	1074.8	1112.8

Figure 28. Delivered energy for the building without PV facade in Tartu

5.2.Simulation results for off-grid electrical system for Tallinn and Tartu

Figure 29 shows the total energy balance of first version of the building with PV envelope, with a year energy demand of 4492.4 kWh., annual production of PV façade and roof 8358 kWh and 1463 kWh respectively with the excess of electricity during summer time 6066 kWh. Considering the production of electricity 1138 kWh by diesel generator during winter months, the whole hybrid off-grid system demonstrate renewable fraction 89,6 %. Summarizing makes it a plus energy building.

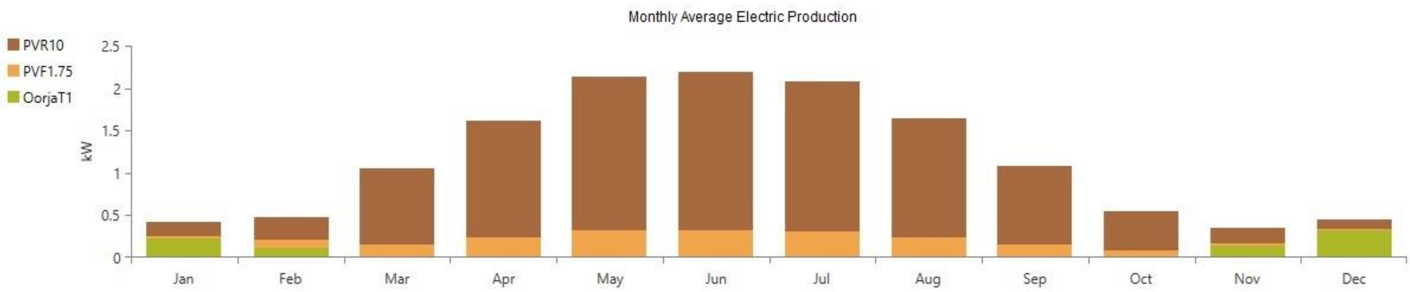

Figure 29. Energy balance for the building with PV façade in Tallinn region

Figure 30 demonstrates the total energy balance of first version of the building with PV envelope, with a total energy demand of 4654.2 kWh., annual production of PV façade and roof 8321 kWh and 1456 kWh with the excess of electricity during summer time 5916 kWh. Considering the production of electricity 1209 kWh by diesel generator during winter months, the whole hybrid off-grid system demonstrate renewable fraction 89%. The fact that produced energy by PV envelope is greater than consumed allows to define the house as a plus energy building.

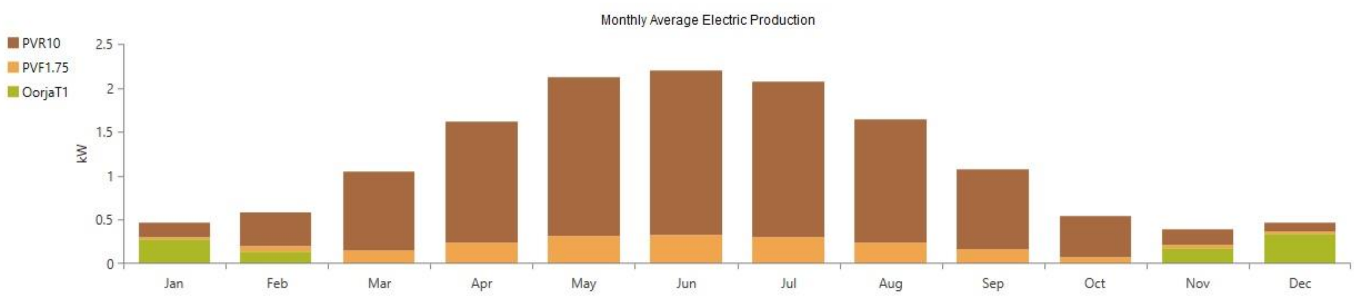

Figure 30. Energy balance for the building with PV façade in Tartu region

6. Conclusions

In this paper, the design and simulation of an off-grid office building with photovoltaic roof and façade were performed for Estonian climate conditions as well as annual photovoltaic envelope production was conducted.

According to the results, the PV façade doesn't affect so much on the indoor temperature in July, so cooling demand for the building with PV façade has same values, like for building without one. The daylight penetration is lower for the building without PV façade, but consumption for cooling and lighting in both cases is almost equal, consequently, PV façade doesn't prevent houses from overheating. However, bigger heating demand shows that using PV façade as decreases solar gains and impede passive solar heating during winter time.

Homer Pro simulation shows the annual energy production of building with PV envelope is 9821 kWh in Tallinn region, whereas energy consumption of the building is 4492.4 kWh. The surplus of electricity during summer time is 6066 kWh. For Tartu, the yearly energy demand of building is 4654.2 kWh., meanwhile annual production of PV envelope 9777 kWh with the excess of electricity during summer time 5916 kWh. Unfortunately, during winter time, PV envelope produces less electricity than the building consumes, but this problem was solved by adding the diesel generator and energy storage battery. Common contribution to the off-grid electrical system from non-renewable source is 1138 kWh for Tallinn and 1209 kWh.

The investigated photovoltaic envelope has several benefits but demonstrates also some features which should be investigated more properly. At first, due to the energy production of the photovoltaic facade and roof to call the building as a plus energy building which means that a building produces more electricity than consumes. Moreover, the structure of the building with renewable energy equipment shows with some limitations possibility of constructing an off-grid building in different climate regions of Estonia with a considerable fraction of renewable energy. Indeed, a negative effect of the façade is the reduction of solar gain increasing of heating consumption due to shading effect of solar cells. However, all these disadvantages are insignificant and may be neglected.

Résumé

The goal of this research is to share experience in designing and modeling of an off-building office building in diverse climate conditions (Tallinn, Tartu) in order to demonstrate the possibility of this technology and investigate the impact of a photovoltaic envelope on its energy performance and indoor climate.

The main structure of the consists of glulam wood beam structure, external and internal walls, floor and roof. Exterior and interior walls, floor, and roof external borders are made of sandwich panels with a thickness of 200 mm and U-value of 0.11 W / m2K The panels with 100 mm of thickness and U- the value of 0.22 W / m2K are used for internal walls. The U-number of the foundation is 0.497 W / m2K. The building is equipped with plastic, triple-glazed PVC windows, and exterior doors. The U-number of windows and the outside door is 0.78 W / m2K and 0,9257 W / m2K respectively. The average U-value of facade-integrated PV is 1.05 W / m2K. The design of the building corresponds to passive house conditions. HVAC system of the building is presented by air handling unit (AHU).

To analyze the feasibility of the system, the hourly simulations in Estonian climatic conditions for a period of one year is necessary. It performed by using IDA ICE, energy performance of buildings and indoor climate the computer software which takes into account Estonian climatic conditions, structure, and geometry of the building. The off-grid solution is possible with energy storage battery and a diesel generator that was modeled in the computer software Homer Pro.

As result, the study demonstrates that photovoltaic envelope has rather a negative effect on indoor climate, but not significant. The energy consumption for lighting and cooling doesn’t change, but the heating demand increases. However, annual production of PV façade and roof 8358 kWh and 1463 kWh respectively for Tallinn and annual production of PV façade and roof 8321 kWh and 1456 kWh allow consider the building as a plus energy house, annual consumption of the building is 4492.4 kWh in Tallinn and 4654.2 kWh in Tartu.

Resümee

Töö eesmärgiks on autonoomse kontorihoone projekteerimine, modelleerimine erinevates kliimaoludes (Tallinn, Tartu) ja ehitisintegreeritud päikesepaneelide mõju teadusuuringud energiatarbele ja sisekliimale.

Põhikonstruktsiooni moodustavad liimpuidust kandekonstruktsioon. Välis- ja siseseinad, põrand ja katuse välispiirded on valmistatud sandwith paneelidest. Kasutame majade ehituseks 200 mm paksusega paneele, mille U-arv on 0,11 W/m2K. Siseseinte jaoks kasutatakse 100 mm paksuseid paneele, mille U-arv on 0,22 W/m2K. Maja kuulub plastmaterjalist kolmekordse klaaspaketiga PVC aknad ja isoleeritud välisuksed Akende ja välisuste kaalutud keskmine U-arv on 0,78 W/m2K. Sihtasutuse U-arv on 0.497 W/m2K. Fassaadintegreeritud päikesepaneelide keskmine U-arv on 1.05 W/m2K. Maja on projekteeritud vastavalt passivse maja nõudele ilma soe sildadeta. Kütuste-, konditsioneerimise- ja ventilatsioonisüsteem on elektriline soojusvahetiga.

Süsteemi teostatavuse analüüsiks viisime läbi simulatsioonid tunniajalise sammuga 1 aasta Eesti klimaatiliste tingimuste baasil. Selleks kasutasime hoonete soojuslikku käitumist modelleerimist ja analüüsib arvuti tarkvara IDA ICE, mis arvestab Eesti kliimatingimusi ja maja struktuuri ja geomeetriat. Võrguühenduseta lahendus on võimalik energia salvestamisega ja diiselgeneraatoriga mida me modelleerisime arvuti tarkvaras Homer Pro.

Ehitisintegreeritud päikesepaneelide mõju autonoomse kontorihoone sisekliimale on negatiivne aga tühine (ehitisintegreeritud päikesepaneelidega maja tarbib rohkem energiat). Pikema perioodi simulatsioonide tulemused erinevate geograafiliste piirkondade kohta näitasid, et ühe aasta jooksul ehitisintegreeritud päikesepaneelid toodavad elektrienergiat Tallinnas 9821 kWh, aga hoone tarbib 4492.4 kWh. Tartus ehitisintegreeritud päikesepaneelid toodavad 9777 kWh, aga maja tarbib 4654.2 kWh. See on plussenergiamaja lahendus (ehk maja toodab aasta jooksul rohkem energiat kui seda tarbib).

References

[1] European Parliament and the Council (2010) Directive 2010/31/EC on the energy performance of buildings.

[2] https://en.wikipedia.org/wiki/Directive_on_the_energy_performance_of_buildings.

[3] E. Kabira, P. Kumarb, S. Kumarc, A. A. Adelodund, K.H. Kime. Solar energy: Potential and future prospects. Renewable and Sustainable Energy Reviews 82 (2018) 894–900.

[4] Polysolar Ltd. 2015. Guide to Building integrated photovoltaic. Available: http://www.polysolar.co.uk/_literature_138380/2015_Guide_to_BIPV [Accessed 18 March, 2012].

[5] Strong, Steven (June 9, 2010). "Building Integrated Photovoltaics (BIPV)". wbdg.org. Whole Building Design Guide. Retrieved 2011-07-26.

[6] SDA and NREL (Solar Design Associates and the National Renewable Energy Laboratory). (1998). Photovoltaics in the Built Environment: A Design Handbook for Architects and Engineers. Prepared on behalf of the U.S. Department of Energy.

[7] Arthur D. Little, Inc. (1995). Building-Integrated Photovoltaics (BIPV): Analysis and U.S. Market Potential. Prepared for the U.S. Department of Energy's Office of Building Technologies.

[8] Available:https://www1.eere.energy.gov/buildings/publications/pdfs/commercial_initiative/29940.pdf

[9] Available: http://h.glass/inauguration-de-la-tour-scientifique-science-tower-a-graz/

[10] Mary Debbarma, K. Sudhakar ∗, Prashant Baredar " Comparison of BIPV and BIPVT: A review" *Energy Centre, Maulana Azad National Institute of Technology, Bhopal, M.P., India 2017.*

[11] Emrah Biyik , Mustafa Araz , Arif Hepbasli , Mehdi Shahrestani , Runming Yao, Li Shao, Emmanuel Essah, Armando C. Oliveira, Teodosio del Caño, Elena Rico, Juan Luis Lechón, Luisa Andrade, Adélio Mendes, Yusuf Baver Atlı, "A key review of building integrated photovoltaic (BIPV) systems," *Engineering Science and Technology, an International Journal 20 (2017) 833–858*.

[12] G. Verberne1, P. Bonomo2, F. Frontini2, M.N. van den Donker1, A. Chatzipanagi2, K. Sinapis1, W. Folkerts1 "BIPV PRODUCTS FOR FAÇADES AND ROOFS: A MARKET ANALYSIS," *Solar Energy Application Centre (SEAC), Eindhoven, the Netherlands, SUPSI, Institute for Applied Sustainability to the Built Environment*

(ISAAC), Lugano, Switzerland.

[13] Frost & Sullivan. European building integrated photovoltaic market. Report [October 2008].

[14] Albert Polman,*, Mark Knight1, Erik C. Garnett1, Bruno Ehrler1, Wim C. Sinke, "Photovoltaic materials: Present efficiencies and future challenges, 2016.

[15] Robert Margolis, NREL David Feldman, DOE Daniel Boff, DOE, “Q4 2016/Q1 2017 Solar Industry Update” April 25, 2017.

[16] K. Sinapis and M. van den Donker, “BIPV REPORT 2013 - State of the art in Building Integrated Photovoltaics,” Eindhoven, 2013.

[17] SUPSI, “BIPV products,” 2014. [Online]. Available: http://www.bipv.ch/index.php/en/products-en-top. [Accessed: 16-Sep-2014.

[18] W. Zhang, L. Lu. Evaluation of potential benefits of solar photovoltaic shadings in Hong Kong. Energy 137 (2017) 1152e1158

[19] M. Yassina, M. Kolhea , A.Sharmaa, S. Garud. Battery Capacity Estimation for Building Integrated Photovoltaic System: Design Study for Different Geographical Location. Procedia 142 (2017) 3433-3439..

[20] K. Kapsis*, V. Dermardiros & A.K. Athienitis. Daylight performance of perimeter office façades utilizing semi-transparent photovoltaic windows: a simulation study. Energy Procedia 78 (2015) 334 – 339.

[21] Minister of Economic Affairs and Communications Estonia (2013) Methodology for calculating the energy performance of buildings.

[22] Estonian Government (2012) Minimum requirements for energy performance.

[23] T. Kalameesa, J. Kurnitskib "Estonian test reference year for energy calculations," *Proc. Estonian Acad. Sci. Eng., 2006, 12, 1, 40–58*.

[24] N.Björsell, A.Bring, L.Eriksson, P.Grozman, M.Lindgren, P.Sahlin, A. Shapovalov, Bris Data AB1and M. Vuolle, HVAC-laboratory, Helsinki University of Technology "IDA INDOOR CLIMATE AND ENERGY".

Appendix 1

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