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CALCULATION OF SOLAR YIELD ON TILTED AND ORIENTED SURFACES, UTILIZATION IN BUILDINGS

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Budapest
2016

1. RELEVANCE OF THE RESEARCH

The relevance of renewable energy sources in the past decade was increasing compared to the fossil energy sources and this trend will continue in the future according to different energy forecasts [1,2]. The projected installed renewable based capacity in the European Union is presented in Table 1.

Table 1. Renewable based built in capacity in the European Union [1]

	2007	**2020**	**2030**	**2050**
	Installed capacity [GW]			
Wind	56	180	288.5	462
Hydro	102	120	148	194
PV	4.9	150	397	962
Biomass	20.5	50	58	100
Geothermal	1.4	4	21.7	77
Concentrated Solar Power	0.011	15	43.4	96
Ocean	–	2.5	8.6	65
Total	**185**	**522**	**965**	**1956**

It is clear that in the next decades the renewable based installed capacity will increase significantly. In the past decade the built in capacity of PV panels was strongly raising with an average increase of 50% every year due to technological development and reduction of investment costs. Because of this trend the produced energy reached 100 TWh by 2012 [3]. By 2014 the installed capacity reached 177 GW from which 40 GW was installed in 2014 [4].

In case of solar collectors a similar trend can be observed like in case of PV modules. By 2014 the installed total capacity around the World has reached 406 GW [4]. Majority (80%) of the installed systems are used for single family buildings' domestic hot water (DHW) production. From the rest 9% is used for DHW in multi-family buildings, 6% is for swimming pool heating and the rest 5% is for the rest of the systems [5]. The characteristic systems for Hungary are presented in Table 2.

The international trend is also noticeable in Hungary. In the National Energy Strategy 2030 [6] the renewable energy source potential was estimated for Hungary and the values are presented in Table 3. It is clearly visible that just the maximal solar potential is higher than the national energy demand of 1085 PJ/y (2010) [6].

Table 2. Installed solar collector systems in Hungary (2013) [5]

	Total collector area [m^2]	Collector area per system [m^2]	Total number of systems [–]	Specific solar yield [$kWh/(m^2y)$]
Swimming pool heating	30252	200	151	344
DHW preparation in single family houses	151260	6	25210	473
DHW preparation in multi-family houses	18908	50	378	522
Solar combi systems	51681	15	3445	422
Total	**252101**	–	**29184**	–

Table 3. Renewable energy source potential in Hungary [6]

Renewable source	Potential [PJ/year]
Solar	1838
Hydro	14.4
Geothermal	63.5
Biomass	203 – 328
Wind	532.8
Total	**2600 – 2700**

The strategy highlights the lack of a detailed nationwide potential roof area study for solar energy utilizing devices. This was a motivation for the main objective of the dissertation to determine the utilizable roof area for solar collectors and PV modules for Hungary's residential buildings. During the work several problems occurred in different areas such as solar energy calculations and the DHW demand calculations for solar collector systems. There are several solar calculation models, however it is hard to find reliable input data and also these models are complicated for every day, on-site use. Thus in the first part of the dissertation a simplified calculation method was developed to calculate the solar yield on different tilted and oriented surfaces within the area of the Larger Carpathian Region, including areas of the following countries: Czech Republic, Croatia, Hungary, Poland, Romania, Serbia, Slovakia and Ukraine.

In case of solar collector systems the DHW system's energy demand should be estimated, which includes consumption and system's characteristics. The main objective of the dissertation was to calculate the national potential of energy produced by PV modules and solar collector systems in the residential sector. Thus the building characteristics, which influence the energy output of the solar energy utilizing systems, had to be determined for the residential building types (e.g. potential roof area and DHW system's total energy demand (consumption & losses)).

During the work a complex approach was followed, which takes into account the domestic demands, the meteorological parameters, and the domestic user behavior and the characteristics of the Hungarian building stock.

2. OUTLINE AND OBJECTIVES

The focus of the dissertation was on the residential building sector and active solar systems. The research can be divided into four major parts. The first part deals with solar energy calculation while the second is about solar energy utilizing system's (PV and solar collector) output calculations taking into account the solar yield and the system characteristics. The third part deals with model building calculations in order to determine the output of the PV and solar collector systems specific for typical residential building types (e.g. single and multi-family buildings). The last part is the extrapolation of the calculated on the national level building type results to estimate the produced heat or electrical energy as well as the corresponding primary energy demand and CO_2 emission reduction potential.

The dissertation is not dealing with passive solar systems, just with active solar systems, such as PV modules and solar collectors. However the results of the solar yield part can be used for passive system modeling as well.

2.1.1 Solar yield calculation

At a given location the amount of incoming solar energy greatly depends on the location, and meteorological parameters. Meteorological indicator can be the sunshine duration, which is easy to measure and it doesn't require an expensive measurement device. Several solar yield calculation models use sunshine duration and global radiation as input parameter. In this field the main points of the research were:

- to determine an average solar radiation year for the Larger Carpathian Region;
- to select the most appropriate solar calculation model for the region, based on measurement data;
- to develop a simple calculation method with which it is possible to calculate the yearly solar yield on any given surface at any location in the Larger Carpathian Region.

2.1.2 Energy production of active solar systems

The most common active systems for buildings are the PV modules and solar collectors. To estimate energy production of the designed systems is an important task of system's designers. The produced energy greatly depends on the yearly solar yield, however in case of solar collectors the demand side is also an important factor. During the research only DHW preparing solar collector systems were examined. For these solar collector systems the following points were examined:

- DHW demand in Hungary (heat and water);
- modeling of heat losses in the DHW system;
- energy production of solar collector systems.

The calculation of PV system's output is simpler than the solar collector systems' whilst the demand side can be neglected and the local distribution losses are low, thus the energy output can be calculated based on the module and inverter type. It has to be noted that in case of PV modules the shadows have a significant effect on the energy production. The aim was to develop a remote method to identify shadowing objects at operating PV systems.

2.1.3 Solar collectors in residential buildings built with prefabricated sandwich panels

Among other building types a bigger focus was on residential buildings built with prefabricated sandwich panels (also called as "commi-block buildings"). These buildings were built in the post-communist countries in seventies and eighties in large numbers with a uniform design. Therefore a typology can be easily created. Also for this building type the heating and DHW demand is usually measured. Thereby long datasets are available, which provide opportunity for more detailed research.

The monthly DHW demand and system losses were determined for 15 different commi-block building types. The system losses include the distribution, circulation and storage losses. After that specific demand and heat loss values were determined for different building types which are more accurate than the currently used standard values. In case of the commi-block building types the main goals were as following:

- to determine heat produced by solar collectors for each commi-block building type;
- to determine the yearly solar fraction and system efficiency for each commi-block building type.

2.1.4 Urban and national scale solar potential

With the use of the previously elaborated sub-goals a model was developed to determine an urban or a national scale solar potential. The main goal of the dissertation was to estimate the nationwide potential of solar collector and PV module energy production on residential buildings' roofs. In case of solar collectors two types of energy production potentials have been estimated. The first one is the theoretical maximum potential, the second one is the economically and technically optimal potential. For the nationwide estimation a preliminary study was made for Debrecen, the second largest city of Hungary and the results and experience were used for the nationwide estimation. nationwide energy production potential estimate was supplemented with primary energy savings and CO_2 emission reduction estimates.

The flowchart of the model can be seen in Figure 1. From the figure it is visible that the main input data are the global radiation the solar collector and PV module types and the building typology. For every building type the amount of solar collectors and PV modules has to be determined along with the building's DHW demand. Based on the input data the energy production can be calculated for every building type and then an urban or nationwide estimation can be made based on the building statistics.

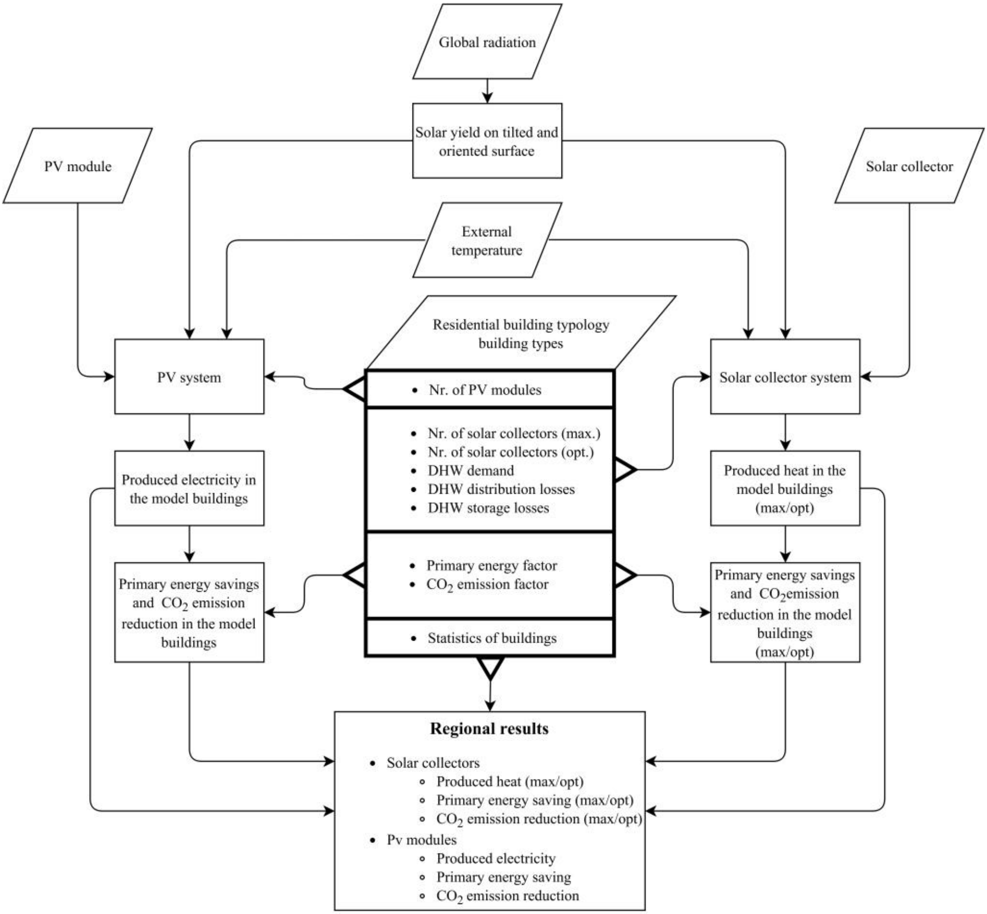

Figure 1.Flowchart of the solar collector and PV module estimation model

3. LITERATURE REVIEW

The main goal of the dissertation was to estimate the solar collector and PV module energy production potential for residential buildings. A similar study was made in 2006 for Hungary [7–10], however it can be concluded that the previous study had several rough estimates thus it is possible to make a much deeper analysis. The energy output calculation of solar collectors and PV modules includes the estimation of solar yield for tilted and oriented surfaces along with the system parameters and the demand side. In case of PV modules the produced electricity can be fed into the grid, thus the demand side was not investigated. In case of solar collectors it is very important to model the supplied system and the demand side, which is a missing step in most studies. The important references are collected below.

There are several models to calculate the solar yield on different tilted and oriented surfaces, which usually are based on three different meteorological parameters: global radiation, sunshine duration and cloudiness. In the dissertation sunshine duration data was used, which is freely available from the CarpatClim database [11]. The sunshine duration data can be converted to global radiation using the Angström–Prescott equation [12]. For the transformation constants determined for Europe (a=0,22; b=0,53) were taken from the publication of Bojanowsky et al. [13]. To separate the direct and diffuse fractions in the global radiation there are several models, which were collected by Khorasanizadeh and Mohammadi [14]. In a widely spread group they use linear equations [15–17], which was also used in the dissertation. With the determined radiation components the global radiation can be transferred to differently tilted and oriented surfaces, in order to do so 6 models [18–23] have been compared and the best performing one was chosen.

To model the Hungarian building stock the bottom-up method was used, which is used in several studies to evaluate different renovation options [24–29]. There were also several studies which used bottom-up modeling for solar potential estimates [30–35]. This method can be used in Hungary as well since there are several elaborated building typologies. The national residential building typology was elaborated in the recent years [36–40]. Another building typology was made for Debrecen, Hungary’s second largest city by Kassai-Szoó [41,42]. Lastly a typology was developed for the Hungarian commi-block buildings by Hrabovszky-Horváth [43]. In the dissertation all previously mentioned typologies were used.

In case of solar collectors the demand side is important to be modeled. In order to model the user behavior and system losses there are several publications and different approaches. One option is to estimate the demand and losses based on the heat floor area [44,45], the second option is based on the number of taps in the building [46–48]. In the dissertation a third method was used which is based on rations and heat loss modeling [49–57].

4. RESULTS AND THESES

4.1 Simplified solar yield calculation method

In order to elaborate a simplified solar yield calculation method first the area of usage had to be specified. For this the area of the CarpatClim database, the Larger Carpathian Region was selected, because for this territory there is freely available daily meteorological data. The CarpatClim database contains daily data for the time period 1981 – 2010 for 5895 smaller sections (it is an approximately 10 x 10 km resolution database). From the available daily data the daily average values were calculated for the whole area. The obtained daily radiation data were than used as input data for the Liu–Jordan model to calculate the incoming yearly solar yield for every tilt angle and azimuth angle pair in 1° step. The obtained results create a surface as shown in Figure 2. The simplified equation is basically the description of this surface.

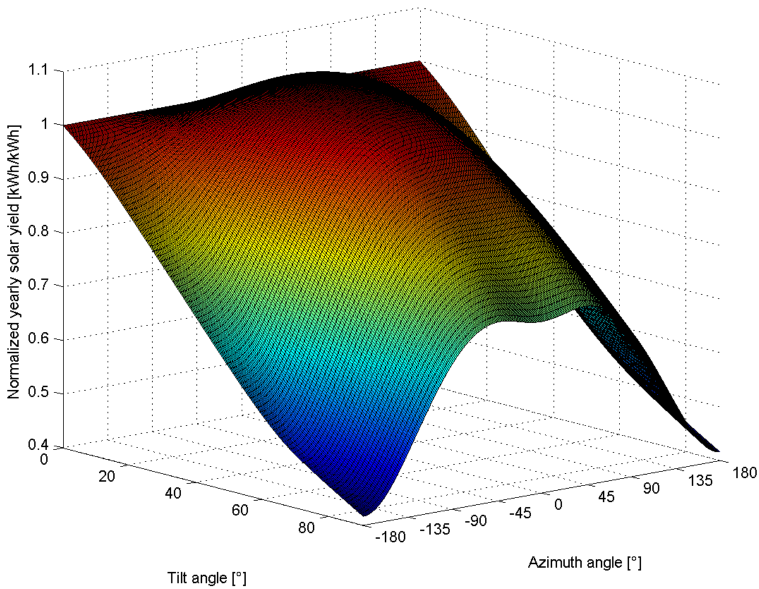

Figure 2. The normalized average yearly radiation for differently tilted and oriented surfaces in the Carpathian basin

1. Thesis

The solar yield on a tilted and oriented surface can be estimated in the Carpathian basin with the following second degree polynomial:

$$G_{yearly,t} = \{[\alpha_a \cdot \cos(\gamma_M) + \beta_a] \cdot \alpha_M^2 + [\alpha_b \cdot \cos(\gamma_M) + \beta_b + \gamma_b \cdot \cos(2 \cdot \gamma_M)] \cdot \alpha_M + 1\} \cdot G_{yearly},$$

where $G_{yearly,t}$ (kWh/m^{2}y) is the yearly solar yield on the tilted and oriented surface, α_M (°) is the tilt angle, γ_M (°) is the azimuth angle from the South, α_a, α_b, β_a, β_b, γ_b empirical constants and G_{yearly} (kWh/m^{2}y) is the global radiation on the horizontal surface, which can be taken from the CarpatClim database. The empirical constants for the Carpathian basin are presented in the following table:

Constant	Value
α_a	$-5.37 \cdot 10^{-05}$
β_a	$-3.98 \cdot 10^{-05}$
α_b	$6.55\ 10^{-03}$
β_b	$-6.97 \cdot 10^{-04}$
γ_b	$-7.15 \cdot 10^{-04}$

Publications: [P1–P4]

4.2 Determining the shadow masks of operating PV modules based on measured electricity production

The energy production of solar collectors and PV modules is significantly diminished by shadowing objects. In order to remotely define shadowing objects for PV modules a new method was elaborated which can determine shadowing objects based on the electricity output of the system. This method can be useful for monitoring PV arrays off-site to determine if there were any production lowering changes in the natural or built environment.

2. Thesis

The shadow mask of polycrystalline silicon PV modules or arrays can be determined by measuring the PV array's output and the global radiation via following steps:

1) **Simultaneous measurement of PV output and global radiation at least in hourly intervals. To achieve more accurate results the direct or diffuse radiation measurement is recommended, in this case the 2nd step can be skipped.**

2) **From the measured global radiation the diffuse fraction can be calculated for Budapest with the following equation, and if there is no more accurate equation than for Hungary as well:**

$$\frac{D}{G} = \begin{cases} 0.85 & if\ \frac{G}{G_0} \leq 0.27 \\ 1.25 - 1.488 \cdot \frac{G}{G_0} & if\ 0.27 < \frac{G}{G_0} < 0.71 \\ 0.195 & if\ 0.71 \leq \frac{G}{G_0} \end{cases},$$

where D (W/m^2) is the diffuse radiation, G (W/m^2) is the global radiation on the horizontal surface and G_0 (W/m^2) is the extraterrestrial radiation.

3) **By knowing the global and diffuse radiation the direct radiation can be calculated as follows:**

$$I_t = (G - D) \cdot \frac{\cos\theta}{\sin\alpha_s},$$

where I_t (W/m^2) is the direct radiation on the tilted and oriented surface, D (W/m^2) is the diffuse radiation, G (W/m^2) is the global radiation on the horizontal surface, θ (°) is the angle between the Sun and the normal vector of the surface and α_s (°) is the solar altitude angle.

4) **The PV module performance should be shown in a diagram as a function of the direct radiation.**
5) **The values which fulfill these requirements should be selected from the diagram:**
    a) **the value is lower than 20% of the nominal value of the PV module,**
    b) **the value of direct radiation is higher than 100 W/m^2.**
6) **For the selected values the Sun's altitude and azimuth angles should be calculated and presented in a Sun path chart.**
7) **The shadow mask is the contour line of the dots on the Sun path chart.**

Publications: [P5,P6]

4.3 *Monthly DHW demand of commi-block buildings based on the yearly DHW demand*

In case of solar collector systems the produced energy greatly depends on the available roof area, incoming solar yield and system demand and losses. In case of solar collector systems at least monthly calculation is recommended in order to avoid overheating periods in the summer, which is not noticeable in case of a yearly calculation. The oversizing of a solar collector system can result in damaging the system and also the economical operation is questionable.

During the research the monthly DHW demand data from 117 buildings, for an 8 year period was evaluated. Based on the data an equation was elaborated with which it is possible to estimate the monthly demands based on the yearly demand. The result is presented in Figure 3. This result is more accurate than the previously used estimation in Hungary.

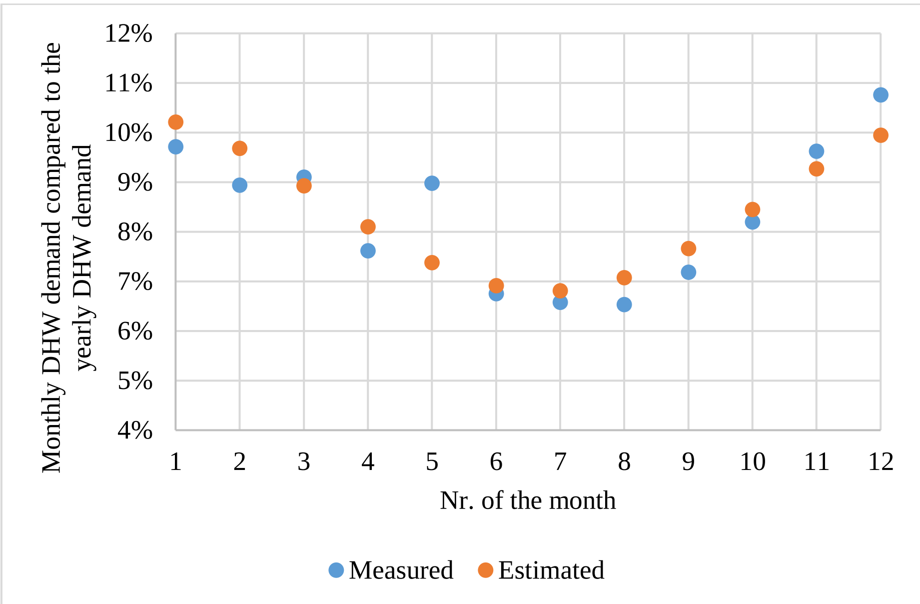

Figure 3. Monthly measured and estimated DHW demand

3. Thesis

For Hungarian commi-block buildings the monthly DHW demand can be calculated as a function of the yearly demand according to the following equation:

$$q_{DHW,i} = (0.18 \cdot \cos(0.463 \cdot i) + 0.086) \cdot q_{DHW,tot},$$

where $q_{DHW,tot}$ (kWh/(m^{2}y)) is the yearly DHW demand of the building, $q_{DHW,i}$ (kWh/(m^{2}month)) is the monthly DHW demand of the building, and "i" is the number of the month

Publications: [P7,P8]

4.4 Energy production in commi-block buildings by solar collectors

In case of commi-block buildings the available roof area for solar collectors is comparatively low to the DHW demand of the building. This also results in a relatively low DHW production compared to the high demand (both consumption and system losses) in the building leading to a low solar fraction which is significantly lower than in single family houses.

The Hungarian commi-block buildings can be easily categorized for solar potential modeling. In the dissertation a previously determined typology was used, created by Hrabovszky-Horváth [43]. As part of the examination a market research was made on solar collectors and an above average solar collector type was chosen for the calculation. The results (solar fraction and system efficiency) of the calculation can be used as input data for bottom-up modeling or as a basis for renovation packages.

4. Thesis

The energy outputs of solar collector systems for the Hungarian commi-block building types were determined, based on building typology and bottom-up modeling. For the 15 commi-block building types there is an upper limit for solar fraction which is between 20.4 – 58.6% with a system efficiency between 24.3% and 41.4% In case of solar energy modeling with bottom-up method this limit should be considered, the results for the different building types are presented in the following table:

Type	q_{coll} [kWh/(m^{2}y)]	f_i [–]	η_{system} [%]
	minimum – maximum (average)		
4M	**10.1 – 12.1 (11.4)**	**28.4 – 36.5 (34.3)**	**38.7 – 39.4 (38.8)**
GYŐR 6/73	**19.9 – 23.1 (22.0)**	**39.2 – 49.6 (46.7)**	**36.5 – 36.5 (36.0)**
H-0	**18.8 – 21.5 (20.5)**	**47.4 – 58.6 (55.4)**	**34.6 – 34.2 (33.9)**
TB 51	**21.0 – 22.2 (21.7)**	**47.7 – 54.5 (52.9)**	**26.1 – 24.3 (24.2)**
1301	**8.4 – 10.1 (9.5)**	**20.4 – 26.8 (25.1)**	**40.2 – 41.4 (40.6)**
3FOG	**20.3 – 23.5 (22.3)**	**41.4 – 52.2 (49.2)**	**36.0 – 35.9 (35.4)**
3FOG - old	**20.3 – 23.5 (22.3)**	**41.4 – 52.2 (49.2)**	**36.0 – 35.9 (35.4)**
6FOG	**11.5 – 13.7 (13.0)**	**24.4 – 31.8 (29.9)**	**32.1 – 32.5 (31.9)**
A10	**15.1 – 17.8 (16.9)**	**31.6 – 40.5 (38.2)**	**34.3 – 34.4 (33.8)**
KB-512	**12.7 – 15.1 (14.3)**	**27.4 – 35.4 (33.3)**	**34.3 – 34.6 (34.0)**
C3	**10.2 – 12.2 (11.6)**	**23.8 – 31.0 (29.2)**	**32.2 – 32.7 (32.1)**
KF10	**12.2 – 14.5 (13.8)**	**25.3 – 32.8 (30.9)**	**32.2 – 32.6 (32.0)**
K-I	**16.3 – 19.1 (18.1)**	**34.2 – 43.7 (41.1)**	**34.6 – 34.8 (34.0)**
KY	**9.9 – 11.8 (11.3)**	**23.2 – 30.1 (28.4)**	**30.0 – 29.3 (29.1)**
P100	**13.1 – 15.7 (14.8)**	**24.1 – 31.6 (29.6)**	**37.1 – 37.9 (37.0)**

Where q_{coll} (kWh/(m^{2}y)) is the yearly produced energy on solar collectors to the heated floor area, f_i (–) is the solar fraction, η_{system} (%) is the yearly system efficiency.

Publications: [P7,P8]

4.5 National scale extrapolation of solar utilization potential

Urban or national scale solar utilization potential can be estimated based on bottom-up modeling. Based on the results calculated for model buildings the results can be adapted for a larger scale based on statistical data. With this method the solar utilization potential for the Hungarian residential building stock was calculated using the following steps:

1. Typology selection
    a. As an initial step the typology should be selected, which describes the building stock in the scope of investigation [39,40].
2. Determining the potential roof area and other geometric and technical data for every building type. Several different methods are available for this purpose:

a. For each building type a model building is selected and examined;
b. Geoinformatic method (drone, or LiDAR);
c. For each building type several (ideally a statistically significant) buildings are examined and model buildings are created.

3. After defining the main parameters of the buildings the solar utilization potential calculation can be made. Before the nationwide results, the preliminary results were calculated for the city of Debrecen, which typology was made previously [41,42]. The experience gained was used to improve the nationwide calculations after.
4. The available data from the National building typology [36–40] was processed for all 23 building types using method "c" from the above options. Apart from determining the maximal and optimal module numbers for each building type the DHW demand was determined for solar collector system calculations. The potential heat and electricity production were calculated based on the previously determined input parameters.
5. Based on the produced heat and electricity the primary energy savings and CO_2 emission reduction were calculated taking into account system parameters.
6. With statistical data the building level results were adapted nationwide.

5. Thesis

The national scale energy production potential of maximal and optimal sized solar collector systems and the maximal energy production potential of PV module arrays located on residential building's roofs were determined for different meteorological conditions, based on bottom-up modeling. Based on the produced energy the primary energy savings and CO_2 emission reduction were also calculated. The results are presented in the following table:

	PV	**Solar collector (MAX)**	**Solar collector (OPT)**
Energy output [PJ/y] min – max (average)	**36.73 – 49.81 (46.90)**	**42.29 – 42.88 (42.14)**	**22.75 – 26.21 (25.04)**
Primary energy savings [PJ/y] min – max	**80.8 – 109.6**	**62.3 – 81.4**	**32.2 – 47.9**
CO_2 emission reduction [kt/y] min – max	**3724 – 5050**	**3551 – 3593**	**1858 – 2146**
Total area [km^2]	**95.60**	**81.62**	**15.92**

Publications: [P7–P11]

5. UTILIZATION OF THE RESULTS

A simplified calculation method was elaborated and can be used by engineers in practice to calculate the incoming yearly solar yield for differently tilted and oriented surfaces within the Larger Carpathian Region simply using the CarpatClim database for input data. This method can be applied in a conceptual stage of design of solar utilizing systems.

The method described in the 2nd thesis can be used for monitoring PV arrays from a distance to determine if there were any production lowering changes in the natural or built environment.

A new formula was determined to calculate monthly DHW system demand of commi-block buildings based on the yearly demand. This can be used for system sizing and demand calculations by practicing engineers.

It was also proved, that the standard values of the practice [45] should be corrected in some cases. Parts of the results can be used to improve or supplement the Hungarian energy rulebook, a few examples below:

- DHW system demand of residential buildings;
- simplified solar collector calculation method for residential buildings;
- simplified PV module calculation method for residential buildings.

The nationwide energy production potential of maximal and optimal sized solar collector systems and the maximal energy production potential of PV module arrays located on residential building's roofs were determined along with the primary energy savings and CO_2 emission reduction. These results are important for professionals and researchers from related areas, such as environmental engineers and policy makers who are dealing with impact analysis, development strategies and action plans. Based on these results the Hungarian standard values can be also updated.

Further research areas could be the combined solar collector and PV module potential analysis and the deeper DHW demand research with a wider scope. Another possibility is the solar utilization potential analysis of the public buildings.

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