SZENT ISTVÁN EGYETEM

Energy modelling of photovoltaic and photovoltaic-thermal systems

Thesis of PhD Work

István Ervin Háber

Gödöllő
2016

Doctoral school denomination:	Mechanical Engineering PhD School
Science:	Agricultural Sciences
Leader:	Prof. Dr. István Farkas Dr. of Technical Sciences Faculty of Mechanical Engineering Szent István University, Gödöllő, Hungary
Supervisor:	Prof. Dr. István Farkas Dr. of Technical Sciences Institute for Environmental Engineering Systems Faculty of Mechanical Engineering Szent István University, Gödöllő, Hungary

………………………………………	………………………………………
Affirmation of head of school	Affirmation of supervisor

CONTENTS

NOTATION

A_c: PV cell area (m^2),

A_m: PV module area (m^2),

$\underline{\underline{C}}$: heat capacity matrix (J/K),

c: specific heat (kJ/kgK),

$\underline{\underline{G}}$: heat transfer matrix (mK/W),

h_{wm}: heat transfer coefficient at thermal collector (W/m^{2}K),

I: solar radiation (W),

$I(\tau)$: time dependent solar radiation function (W),

I_b: direct (beam) solar radiation (W),

I_c: ASHRAE „clear sky” coefficient,

I_d: diffuse solar radiation (W),

NOCT: nominal operating cell temperature (°C),

Nu: Nusselt number,

Pr: Prandtl number,

Re: Reynolds number,

Q_v: performance of a solar module (W),

$\underline{T}$: temperature array (°C),

$t_a(\tau_h)$: time dependent ambient temperature function (°C),

t_{be}: ingoing teperature of solar thermal collector (°C),

T_{back}: backflow temperature measured after the heat exchanger (°C),

T_{env}: envronmental temperature (°C),

T_f: surface temperature (°C),

T_{modul}: module temperature (°C),

T_{pvt}: temperature of the PV/T collector (°C),

T_w: medium temperature (°C),

U_{pvt} and I_{pvt} the voltage an current of the PV properties of a PV/T,

v: wind velocity (m/s),

$w(\tau_h)$: time dependent function of the wind velocity (m/s),

α: surface heat transfer coefficient (W/m^{2}K),

$\alpha_{min}(v)$: the minimal value of the heat transfer coefficient on PV surface (W/m^{2}K),

$\alpha_{max}(v)$: the maximal value of the heat transfer coefficient on PV surface (W/m^{2}K),

$\alpha_{avg\text{-}pitched\text{-}N}(v)$: surface heat transfer coefficient for pitched roof mounted module at north wind (W/m^{2}K),

$\alpha_{avg\text{-}pitched\text{-}S}(v)$: surface heat transfer coefficient for pitched roof mounted module at south wind (W/m^{2}K),

$\alpha_{avg\text{-}flat\text{-}N}$ (v): surface heat transfer coefficient for flat roof mounted module at north wind (W/m^{2}K),

$\alpha_{avg\text{-}flat\text{-}S}(v)$: surface heat transfer coefficient for flat roof mounted module at south wind (W/m^{2}K),

$\alpha_{avg\text{-}free\text{-}N}$ (v): surface heat transfer coefficient for free standing module at north wind (W/m^{2}K),

α $_{avg\text{-}free\text{-}S}(v)$: surface heat transfer coefficient for free standing module at south wind (W/m^{2}K),

α $_{avg\text{-}facade\text{-}N}(v)$: surface heat transfer coefficient for facade mounted module at north wind (W/m^{2}K),

α $_{avg\text{-}facade\text{-}N}$ (v): surface heat transfer coefficient for facade mounted module at south wind (W/m^{2}K) ,

$\alpha_{avg\text{-}sidewind}(v)$: surface heat transfer coefficient at side wind, valid for all mounting types (W/m^{2}K),

$\alpha_{déli}(v)$: velocity dependent function of the heat transfer coefficient for south wind (W/m^{2}K),

$\alpha_{északi}(v)$: velocity dependent function of the heat transfer coefficient for south wind (W/m^{2}K),

α_h: heat coefficient of a PV module (%/°C),

$\underline{\phi}$: heat current vector (W),

η: efficiency (-),

η_v: electric efficiency (-),

$\eta_ö$: global efficiency (-),

η_t: thermal efficiency (-),

η_{STC}: efficiency determined under STC standard (-),

1. INTRODUCTION, OBJECTIVES

The efficiency of the photovoltaic (PV) modules is dependent on the temperature, which is influenced by environmental parameters and can be optimized by its proper placement according to full air flow around it. This is passive cooling, but the PV's can be cooled actively too, in these cases the thermal energy can also be used. For cooling, a new micro heat-pipe method can be used as well, and the properties of this new type photovoltaic-thermal collector (PV/T) shouldbe investigated.

The main objective of this research is to minimize PV system losses, through the calculation method made here. By organizing the tests and results my aim is to develop a complex photovoltaic modelling system, which demonstrates the preliminary design of PV and PV/T systems and the accurate cell temperature determination.

The above aims, organized:

- To determine the heat losses of PV's through CFD calculations through which the surface wind dependence of the heat transfer coefficients can be obtained. The results will be compared with wind channel experiments.
- To set up a heat resistance model for PV systems (HR-PV), according to the physical strucure of a PV module, that can be used to calculate the cell temperatures from which the efficiency can be derived. To certify the model, a unique measurement system is needed.
- To investigate, in case of cooled PV's how the cell temperature and the efficiency develops. Similarly, a micro heat pipe (MHP) PV/T module will be investigated and a heat resistace model created. To validate this heat resistance model for PV/T (HR-PVT), a new measurement system has to be built up.
- Applying the HR-PV and HR-PVT models in a complex system that takes the environmental parameters into account, can calculate the system losses and wins, including the wind influenced heat transfer coefficient. The method can be used to determine photovoltaic systems energy production, which will be demonstrated by comparing the production of a PV and a MHP PV/T system.

2. MATERIALS AND METHODS

This chapter introduces the methods and materials, needed to achieve the goals of this work.

2.1. Investigation of the environmental attributes

Heat can be reduced with appropriate installation of the modules, taking the meteorological conditions into account, particularly the prevailing wind direction and thus the air flow over the modules.

In order to be able to count with this, we must consider the regional meteorological conditions. The measurement station of the Meteorological Service of Hungary in Pogány logs the wind velocity, the wind direction, the global irradiation and the ambient temperature. These data are only available for researcherswithin strict limitations. I analyzed the dataset of the Pogany meteo station for the region and from its more years average (2005-2011) functions were made on the wind velocity, the ambient temperature and the irradiation and its parameters were identified (Fig. 1).

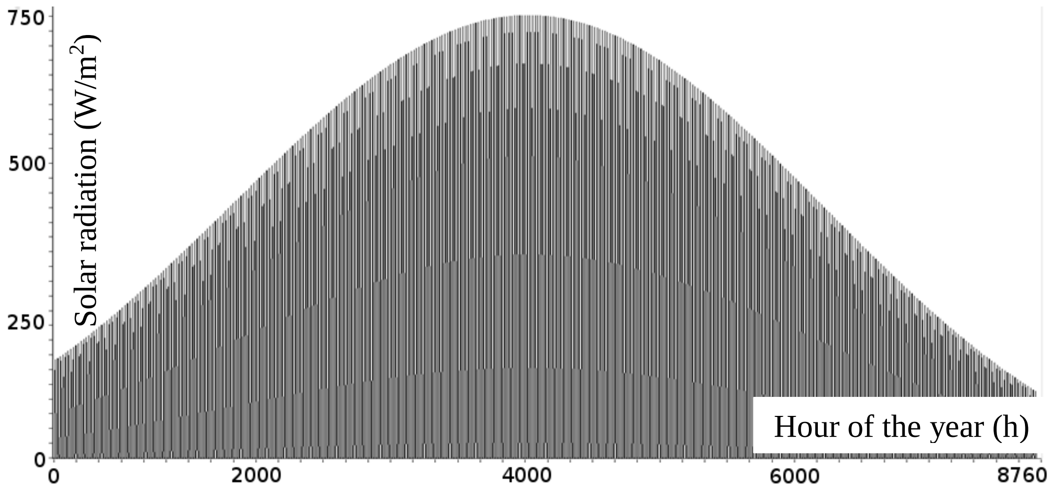


Fig. 1. Calculated chart of yearly solar radiation (W/m^2)

The solar radiation prescribed function may be appropriate for calculating solar systems lying parallel to the ground, but this is rare – and only applied in specific building solutions - since it is not ideal when air can not flow around the module to cool it. If the solar panels are rotated along one or two axes, namely with respect to horizontal plane and south orientation, it is necessary to output data transformation to the pitched/oriented plane, which needs to separate diffuse and direct solar radiation components. Thus, these components must be determined first.

I have dismantled the global radiation with the ASHRAE method. The atmosphere's absorbtion and scattering radiation (diffuse component) varies with time because of the atmosphere and the changing air mass (AM) due to the sun. First, the sunny sky ("Clear Sky") hour value will be determined from the parallel to the ground values, subsequently I will subtract the modeled total / global radiation values from it.

The direct radiation part of the two components (its direction vector is known), can be transformed into a plane which is different from horizontal. Basically, the photovoltaic modules are installed at an angle from the horizontal plane, that is defined as angle β. They often have the angle difference from south too, this angle is γ. While turning from 0° is relatively small (γ = -60° to + 60°), the diffuse component can be handled evenly over the surface of the sky. If so (a higher angle difference only occurs in rare cases, as we always strive to south orientation), then the radiation on the rotated surface (i.e. the surface of the solar cell) can be calculated.

The input of meteorological functions is uniformly the number of the day in a year in all cases, but an interval can be specified as well, and then the ramp up to a full-year can be investigated. As each functions input is the same, the query is uniform and thus can be used in the HR model based Simulink and LabView program as input.

2.2. Determination of the heat transfer coefficients

The temperature of the photovoltaic modules is therefore fundamentally affected by the environmental attributes. One PV module as thermal system has a heat gains and losses. In order to determine the amount of heat leaving, we need to know the value of the surface heat transfer coefficient (α).Between a surface with an L characteristic length and temperature T_f and a parallel flowing medium (by velocity v), and if the mediums temperature is T_w, the heat flow becomes a function of several parameters. To the calculation of this, the equation system containing the Fourier Kirchoff, the Navier-Stokes and the Reynolds equationshas to be solved, or the Nusselt number calculated or measured.

The calculation of the flow field and thus, the ability to determine the number Nu is possible though numerical methods. To do this, the first step is to discretize the flow field. For this purpose, x = 50 m and y = 30 m sized rectangular two-dimensional microenvironment were created where (at x = 15 m), a 3m facade height, 10 m width, 45 ° angle pitched roof house takes place. On the house, parallel to the roof, one 1.25 m long PV module with a 20 mm profile depth is located, with an air gap of 0.1 m. The second environment is a flat-roofed house, on which, in one case the module was placed on the south side, and placed on the north side for all others, whose are regarded as typical placements (Fig. 2).

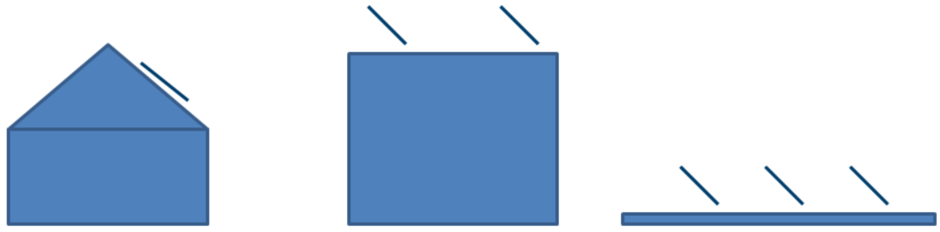


Fig. 2. The applied placements in the CFD simulations

On this one and on two other similar flow field based CFD simulations, the heat transfer coefficients of the PV modules were determined, but these 2D models were supplemented with 3D calculations, where side wind effects and facade mounted placement is examined.

The physical model is based on the equation of continuity and the pulse energy equation (RANS calculation), and Boussinesq's approximation has been used to determine the change in air density.

At the boundary conditions of the equations the physical properties of the air are given, with the exception of density. The environment temperature is 300 K, the wall temperature of the module is constant 350 K. In every case 5 different wind velocities ($v_{szél} = \{0, 1, 3, 5, 7\}$ m/s) were applied to investigate the heat transfer coefficients, since this interval has the highest occurance in Hungary.

2.3. Heat resistance modelling of PV modules

Heat resistance (HR) modeling of solar modules nodes written in the heat transfer process can be determined based on the electric analogy. Each node in the network represents the physical structure (Fig. 3), which is connected with thermal resistance due to material quality characteristics. Grouped on the basis of materials the average temperature of the individual layers of nodes can be determined. Basically, discretization is carried out according to place, which eliminates the need for partial differential equations.

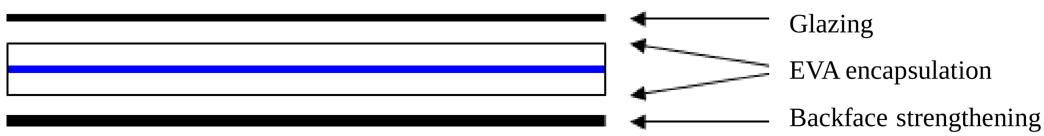


Fig. 3. The structure of a PV module

In the HR model the heat capacity of the parts is assigned to the network nodes and the nodes are connected with heat transfer resistances.

The heat resistance model can be applied to the transient heat transfer equation:

$$\underline{\underline{G}}\,\underline{T}(\tau)+\underline{\underline{C}}\frac{d\underline{T}(\tau)}{d\tau}=\underline{Q_h}(\tau), \tag{1}$$

where $\underline{\underline{G}}$ is the heat transfer matrix, $\underline{\underline{C}}$ is the heat capacity matrix, $\underline{T}$ is a temperature array and $\underline{Q_h}$ is the heat current vertical array.
The LabView-based simulation program runs parallel to the data acqusition system (which is also in LabView), the measured data can be given to the model and renfered visually in a graphics window (ie Waveform Chart), and the results can be compared „on the fly”.

2.4. The data aquisition system for the HR model validation

The research aims to examine the energetics circumstances of photovoltaic modules, in particular the cooling effect of natural flows (wind and natural convection). Air flows around the modules which influences the rate of the heat transfer coefficient. We have created a HR model, which describes the heat flow on the inside of the module structure. Based on this, the mathematical solution can be given for the heat transfer, resulting in the temperature values in the nodes of the structure to develop into a matrix form, which can be easily solved by Matab/Simulink.

It was practical to establish a Labview model, because the results can be compared to the live measurements, so the mathematical model can be validated. However, for this, equipment that can communicate via Labview is needed.

For these reasons, a whole new DAQ (Data AcQuisition) system has been built, which includes wind direction and -speed sensor, a pyranometer and two PT100 sensors. One temperature sensor is installed inside a standard thermometer housing, the other is adhered to the back of the solar cell, where the back side of the module at the sensor has been cut out to reach the cell – through this the exact temperature of the cell is returned. Our goal is to calculate the same temperature in the mathematical model, so that data is comparable.

2.5. Calculating the working temperature of PV/T modules

The thermal resistance model, used for the testing of photovoltaic modules, extended by the nodes which meets the structure of PV/T collectors and parameter identified, suitable for this type of module efficiency calculation as well. The test PV/T module uses HeatRuler stripes as thermally conductive material, which is a micro-tube flat aluminum profile (micro-heat pipe; MHP), whose prominent feature as specified by the manufacturer is the 1000000 W/mK thermal conductivity coefficient.

The manufacturer gives an unreallistically value for the thermal conduction, so this was checked by measurement. The heat conduction of an unknown substance can be measured easily by comparing to a known thermal conductivity material with same geometry. The same thermal power is contacted to them, the temperature is measured in the same point, plus all other other circumstance are the same. The conduction of the MHP material should be examined around 50 °C, since at these collectors it is a typical value based on my measurements.

The test material (one MHP stripe) was taken out from one module, it has a dimension of 50 mm*500 mm*5 mm, it has a rectangle cross-section. The heating was delivered by a Peltier cell, which has a well known characteristics, so the needed temperature can be set. At 12,5 V (given by proffesional laboratory power supply) the cell transfers 65 W to the heat conduction material, through its 40*40 mm surface area.

Based on 3 measurement at 45° degree angle, the temperature of the control point was 46,4 °C in average. In the simulation the temperature of the aluminium test material had only 3,2 Celsius higher temperature than the 20 °C ambient temperature at the control point. Based on this comparision the MHP structure has 8,25 time higher conduction than the aluminium, namely1955,25 W/mK. In vertical position this value is a little bit higher: 2140,4 W/mK, while ΔT=28,9 °C.

The heat resistance model based on the structure of the MHP PV/T will be the base for the energy production simulations, to make the PV/T cell temperature calculations more egzact.

The „HeatRuler® is used for cooling the PV modules back side, which highers the efficiency of the PV cells. Through indirect fluid or air based cooling, the PV temperature can be kept under 50 °C, which can raise the efficiency by 10-20%. Artificial fluid cooling can help to keep the temperature under 42 °C, that could cause 20-30% raise in efficiency, in addition the thermal energy can also be used.

3. RESULTS

In this chapter the results of the measurements and calculations will be introduced, whose are the base of new scientific thesises.

3.1. Surface heat transfer coefficient of photovoltaic modules

In this research I have investigated 4 placement types of solar modules (pitched-, flat roof, facade mounted, free standing), how the air is flowing around the through computational fluid dynamics method (CFD). As result, the the heat transfer coefficients were calculated in relation with the wind velocity an direction. The simulation of the facade mounted system was based on a real building. (Fig. 4).

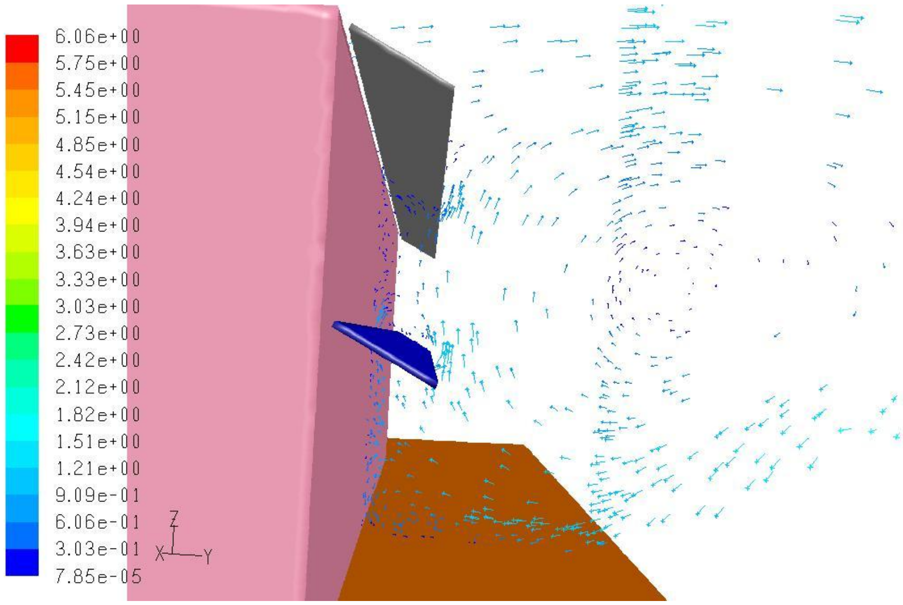


Fig. 4. The air flow vectors colored by the velocity in case of 3 m/s north wind

All the results were specified, and a linear trendline function fitted on them. As it can be seen on Fig. 5 in case of façade mounted modules, these functions can be connected to the heat resistance models (HR-PV & HR-PVT), where v is the wind velocity measured or given by the meteorological model.

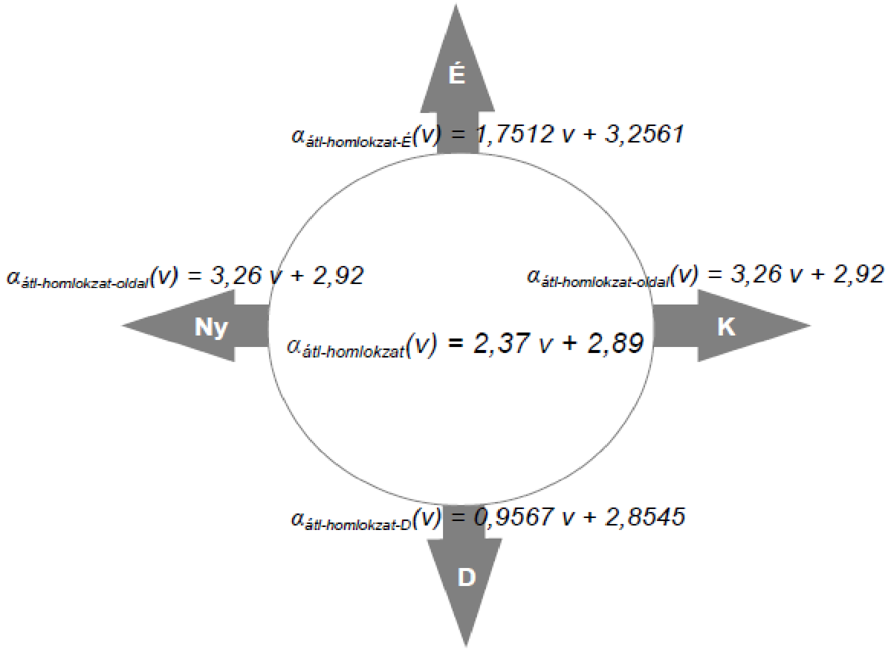


Fig. 5. The averaging of the heat transfer coefficient functions at façade mounted modules

The CFD calculations were validated with wind tunnel measurements with the same geometry as in the facade mounted case.

In connection with the testing of photovoltaic modules I worked out and implemented a method by which a good approximation is possible to determine the heat transfer coefficient. This was supported by wind tunnel measurements. It is important that the calculations can be parametrized, so the environmental and the modules temperature can varied, and the effect of artificial convection can be examined as well, which relate in this case for the cooling effect of the wind. Similarly, the other typical placement methods can be examined, such as distance from the roof, which can improve the quality of the flow around.

3.2. Heat resistance model of photovoltaic modules

The 5 node heat resistance model is suitable for calculating the cell temperatures of photovoltaic modules (Fig. 6). The model was validated with a measurement system, where the measured and modelled temperature values were compared.

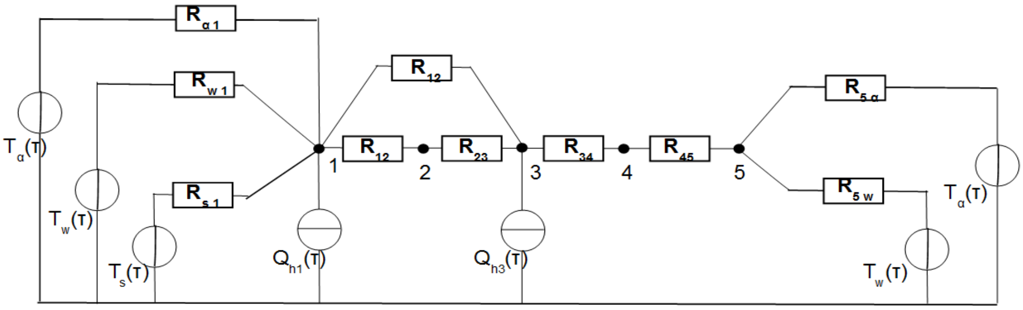


Fig. 6. The heat resistance model of a typical PV module

The R is marking the heat resistances in the model, T is tension generator, Q is current generaator; T_{α} – represents the wind heat transfer, T_{w} – ambient temperature, T_{s} – irradiation, Qh_{1} – the absorbed part of the radiation in the glasing, Qh_{2} – the absorbed part of the radiation on the silicon cells which amount is converted into heat.

The temperature of the modules can be calculated with the help of the heat resistance model, if environmental parameters are known, which can be measured, or it can be provided by the identified functions. The identification of the model parameters is made in accordance with the structural properties based on the material quality (Tables 1-2).

Table 1. The indentified parameters of the heat transfer matrix ($\underline{G}$)

50-(1/αA) Δτ	0,605	1	0	0
0,605	0	72,105	0	0
1	72,105	950	72,105	0
0	0	72,105	0	0,295
0	0	0	0,295	0-(1/αA) Δτ

Table 2. The indentified parameters of the heat capacity matrix ($\underline{C}$), (J/K)

237	0	0	0	0
0	963	0	0	0
0	0	285	0	0
0	0	0	963	0
0	0	0	0	120

These parameters provides the base of the LabView implemented HR model, where the measured and the simulated values can be compared live with the environmental measurement system. On the PV system of the reference building it is possible to make long term analyses on the energy production and the results can be compared with the HR-PV model.

The calculated value (11237,4 kWh/a) can be ordered into monthly, or in daily view and analyzed. For 2013 the measured yearly value is 12 455 kWh/a, which is higher then the calculated value, buti t can be expected, that later this value will be more precise, as it can be seen in the trends. In comparision, the PVGIS has calculated a 13700 kWh/a value.

The production is logged since the 1st of October 2012, 3 whole year is available. (Fig. 7).

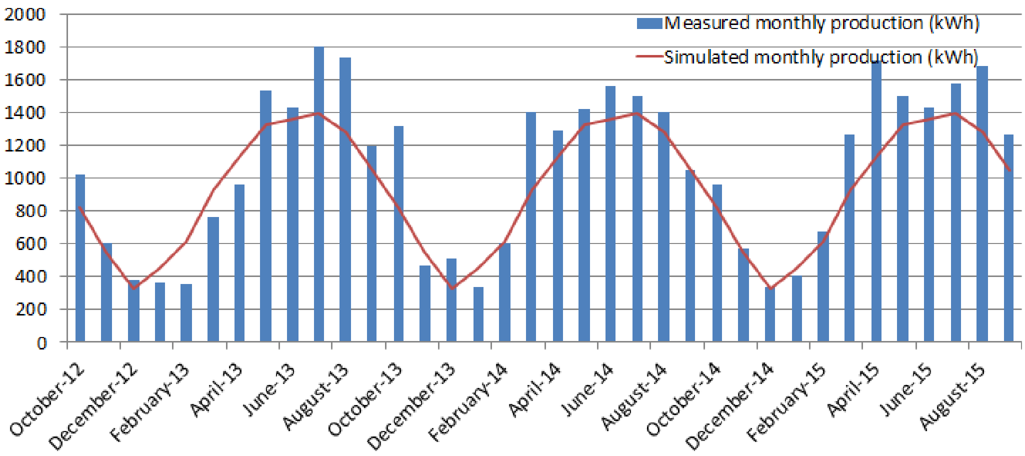


Fig. 7. Comparision of measured and calculated data

If a 3 years monthly average is made, there will be no big protrusions (Fig. 8), it can be expected, that more years will give more consolidated result.

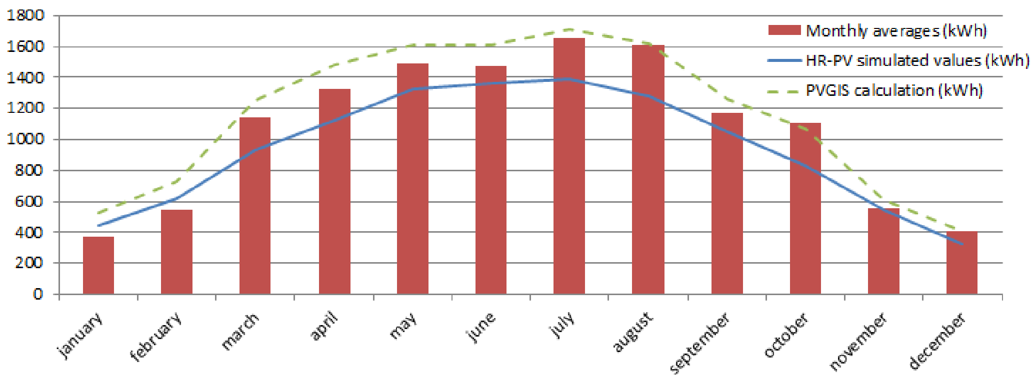


Fig. 8. Comparision of the 3 years monthly averages

The HR-PV model is suitable for energy production analysises, but it would be desired to have more than 10 years dataset to make a more accurate validation. The 3 years dataset already showed, that the difference is getting smaller between the measured and simulated data. In comparision with the PVGIS calculation, the HR-PV based model is more accurate by 1,95% (Table 3).

Table 3. Statistical inspection of the measured data

Date of measurement	Standard error	Biggest deviation (Wh)	Average deviation (Wh)
Oct-2012 – Sept-2015	215,87	491,5	166,5
Average of the first 2 years	111,01	291,45	138,8
3 years average	123,21	330,1	159,5

3.3. Heat resistance network based PV/T model

I have extended the HR-PV model for PV/T systems according to the structure of these collectors (Fig. 9). For the PVT collectors, the operating temperature affects both the thermal efficiency and the solar cell electric efficiency.

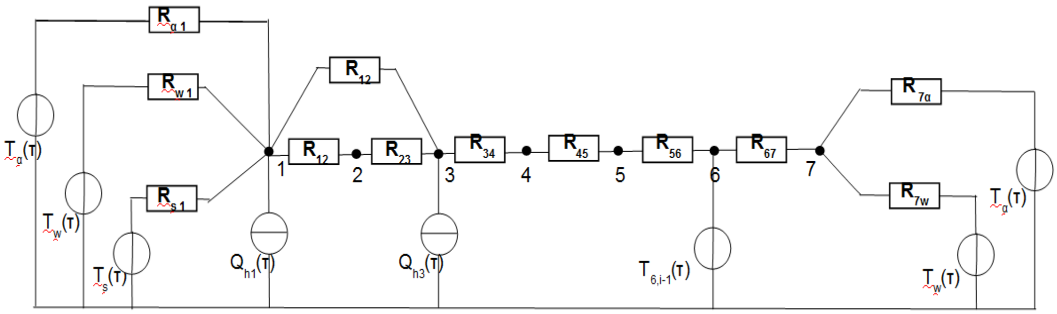


Fig. 9. The heat resistance model of a PV/T module (HR-PVT)

For the HR-PVT model to be completed, the heat transfer parameters had to be identified, whose are given in the heat tansfer matrix in Table 4.

Table 4. PV/T heat transfer matrix (G) [W/K]

50-(1/αA) Δτ	0,605	1	0	0	T_6-5,5	0
0,605	0,0294	72,105	0	0	0	0
1	72,105	950	72,105	0	0	0
0	0	72,105	0	0	0	0
0	0	0	0	4,88	0	0
T_6-5,5	0	0	0	0	2,533	0,295
0	0	0	0	0	0,295	0-(1/αA) Δτ

In the heat transfer matrix, while I have used one unit values for the geometry – the heat transport to the heat collecting tube is calculated by surface ratio. Since the collection tube is 10 cm wide, in proportion to the surfaces this ratio will be 1:0,096.

The heat capacities for the HR-PVT model are stored in the C matrix (Table 5), indexed by the position of the structure nodes.

Table 5. PV/T heat capacity matrix $\underline{\underline{C}}$, [J/K]

237	0	0	0	0	0	0
0	963	0	0	0	0	0
0	0	285	0	0	0	0
0	0	0	963	0	0	0
0	0	0	0	120	0	0
0	0	0	0	0	1350	0
0	0	0	0	0	0	1377

Fig. 10. shows one days simulated and measured temperatures on part a), while on b) and c) the instanteneous power – thermal and electric – can be seen.

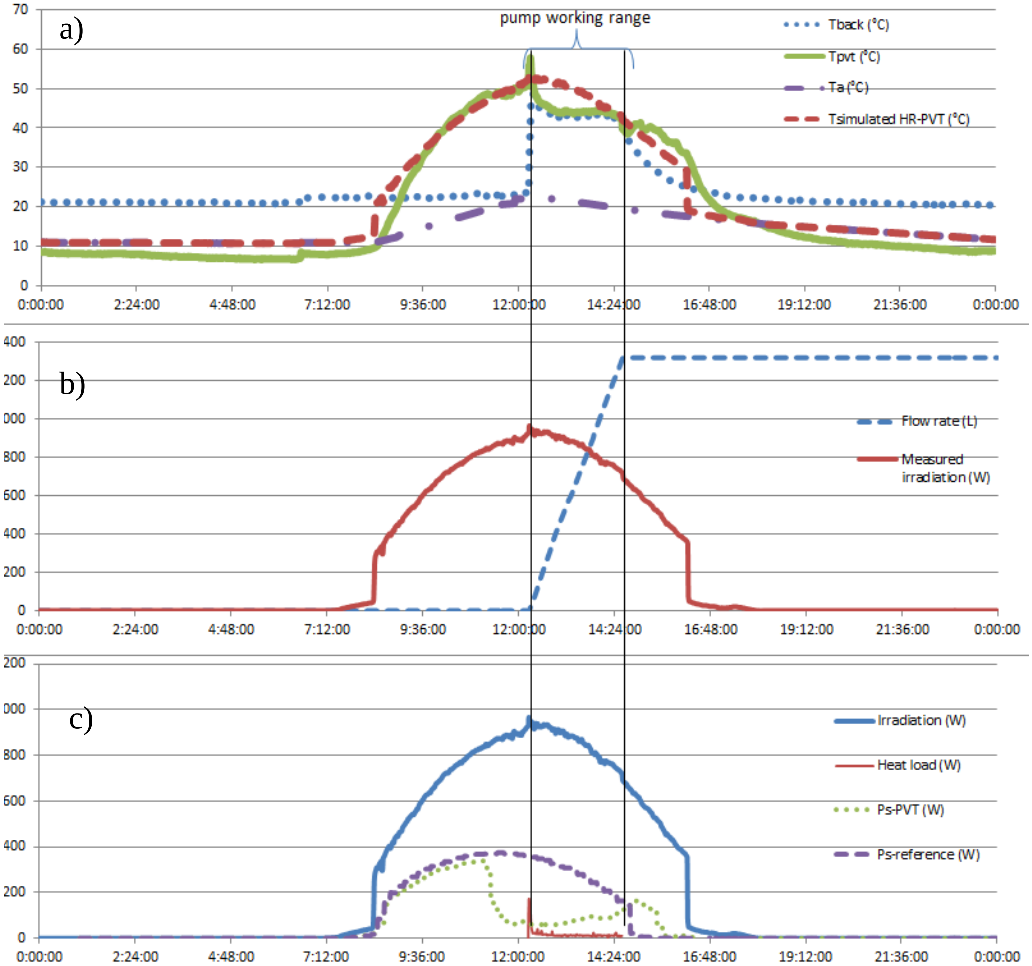


Fig. 10. Measurement results of the PV/T system on 9th of October, 2014

From the measured data showed on Fig. 10. should be highlighted, that on that days working interval (when the pump has worked), the PV/T's average efficiency was 46%, and the highest value of the thermal efficiency was 62%.

If the thermal efficiency is related for the sunny hours, then it’s value is only 22%. However in the whole electricity production interval the PV/T’s average efficiency exceeded 15%, while the average temperature was 32 °C, compared to the average efficiency of the reference PV modules, which was only 14,3%. The reference PV modules peak temperature has reached 64 °C, altough the average was 42 °C, but electrical efficiency drop was major at the PV/T: -11% calculated by the 0,5%/°C temperature coefficient.

The goodness of the HR-PVT model is presented by the Figure 10. a). Utilizing the measurement data as input to the model the PV/T module temperature can be calculated. This is an ideal model that does not take into account the heat transfer by the coolant, so at the statistical verification the operating range of the pump was omitted from the calculations.

In conclusion it may be mentioned that the PV/T modules produce higher energy density, based on the sample data row it is a total of 61% efficiency, or if the total usable period is taken, it is 37%.

3.4. The complex photovoltaic and photovoltaic-thermal sizing system

Through the HR-PV and the HR-PVT models it is possible compare objectively the chilled (MHP type) and the uncooled PV modules efficiency and thei annual development. If we take the test system as basis and its regulation, then with a logical „IF()” function we can cut off the above 50 °C part (since it is assumed that if the pump system is turned on, the part above will be dissipated by the liquid-to-air heat exchangers, which otherwise takes place in the measuring system in real), so the PV/T collectors temperature can’t rise over this limit. As result of the simulation we get, that the PV/T produces 195,4 kWh electric power annually (on 1 m^2 PV surface area), until a „normal” PV module produces 198,2 kWh. This is only 1,4% more for the PV. The yearly efficiency of the PV module is 14,71%, while at the PV/T it is 14,64%, where the overall efficiency is significantly more thank to the thermal portion. If no heat from the PV/T is taken away, then 194,7 kWh electrical power can be produced in a year Table 6).

Table 6. The results of the comparing simulation summarized

	Yearly efficiency η_a (%)	Annual product P_a (kWh/a)
PV	14,71	198,2
PV/T with control	14,64	195,4
PV/T without control	14,61	194,7

Analizing one day highlighted (Fig. 11) from the comparing simulation of the normal PV and the PV/T modules, it can be recognized that the PV/T reaches higher temperature before the PV, but the PV’s peak temperature is higher, altough only for short interval. The uncooled PV module could reach the 70 °C, but the ambient temperature is still low on this day.

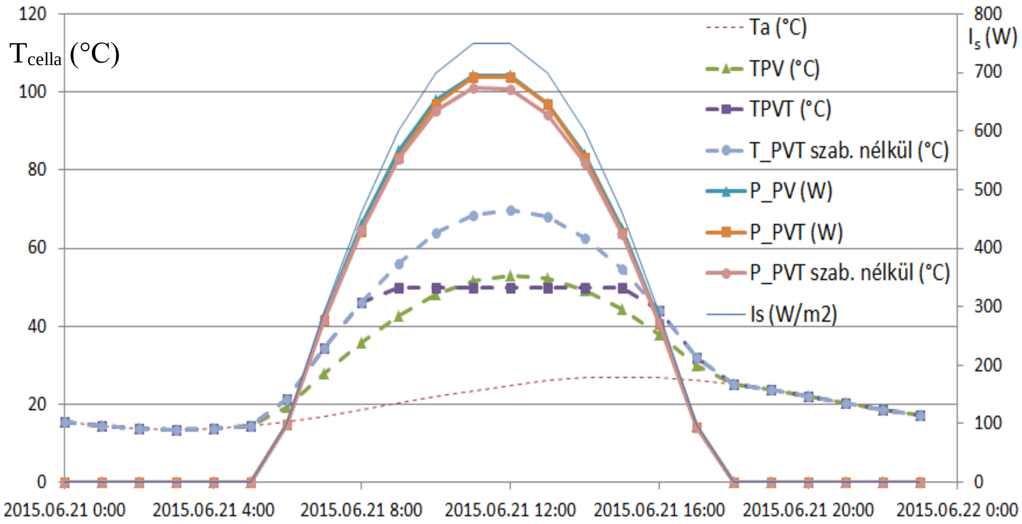


Fig. 11. One day highlighted from the comparing simulation (June 21)

A new kind of hybrid solar thermal and photovoltaic module (MHP PV/T) is examined in this research. Based on the developed HR model a comparision was performed with the non-cooled PV modules. The results confirm that, although in the case of the application of the MHP PV/T photovoltaic efficiency decreases, but in total production (photovoltaic- and thermal-) a greater energy-efficiency can be achieved. The produced energy by the photovoltaic side is lower, but together with the thermal efficiency, the overall efficiency 14,64% + 8,58%, results 23,22%. Altogether it is 8,51% higher then the general photovoltaic modules and also higher then the double glazed normal themal collectors by 3,72% – calculated the thermal efficiency with the same method.

The model I have developed calculates the PV temperature with a new kind of method, taking the cooling effect of the wind into account and calculates the annual energy production through hourly data. This method can be used to design a photovoltaic, or even a PV / T system's energy production more accurately. The model proved that calculating with 10 years average of the environmental parameters of the MHP PV/T collectors are better in overall efficiency compared to a general PV module and also better then a widely used flat-plate thermal collector.

NEW SCIENTIFIC RESULTS

Through my research I have analyzed the energy circumstances of the general structure photovoltaic modules and the micro heat pipe based photovoltaic-thermal modules and in connection with this my scientific results are the following:

1. *Heat transfer coefficient of photovoltaic modules*

I have worked out new functions for the wind velocity dependent heat transfer coefficients at photovoltaic modules in different placements:

at pitched roof mounted modules:

$$\alpha_{avg\text{-}pitched\text{-}N}(v) = 1{,}85\ v + 2{,}93,$$

$$\alpha_{avg\text{-}pitched\text{-}S}(v) = 3{,}62\ v + 2{,}93,$$

at flat roof mounted modules:

$$\alpha_{avg\text{-}flat\text{-}N}(v) = 2{,}3\ v + 2{,}90,$$

$$\alpha_{avg\text{-}flat\text{-}S}(v) = 2{,}17\ v + 2{,}90,$$

at free standing modules:

$$\alpha_{avg\text{-}free\text{-}N}(v) = 4{,}188\ v + 2{,}90,$$

$$\alpha_{avg\text{-}free\text{-}S}(v) = 3{,}128\ v + 2{,}90,$$

at facade mounted modules:

$$\alpha_{avg\text{-}facade\text{-}N}(v) = 1{,}75\ v + 3{,}26,$$

$$\alpha_{avg\text{-}facade\text{-}S}(v) = 0{,}96\ v + 2{,}85$$

and for side wind in all cases:

$$\alpha_{avg\text{-}sidewind}(v) = 3{,}26\ v + 2{,}92.$$

I have validated the results based on CFD calculations with with tunnel experiment, where the *Cp* pressure coefficients similarity shows the goodness of the simulations. The highest deviation between the measurement and the simulation is 0,64, the mean deviation is 0,23 and the standard error is 0,462.

2. *Heat resistance model of photovoltaic modules*

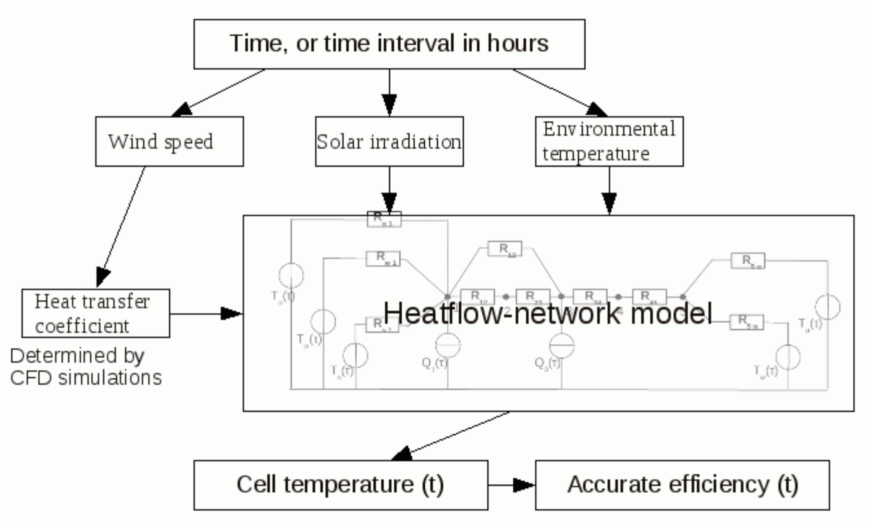
I have developed a 5 node heat resistance model for photovoltaic modules (HR-PV), which can be used as whole new method for determining the cell temperature. I have built up a new measurement system which is suitable for validate the model. Based on the heat resistance network I have worked out a new and complex energy production model and compared to the classic method. This model calculates with the wind velocity dependent surface heat transfer coefficients and with the ASHRAE method separated direct and diffuse solar radiation components, it can stated that it is more precise then the standard methods. Based on two years dataset, the model approximates the yearly sum of energy production by 1,95%.

3. Heat resistance network based PV/T model

I have developed a new method, which is capable to determine the working temperature of the Si cell in micro heat pipe PV/T systems, with a 7 node heat resistance model. As part of the parameter identification the heat conducton value of the MHP structure I have combinated the measurements with thermal simulations. The model has proved and through the calculations I have shown, that the MHP system based PV/T modules have annually higher cell temperature in average than the non-cooled photovoltaic panels.
I have determined the heat removal factor (F_R) of the MHP PV/T modules, which was not given yet and I have proved, that this model can be used for calculate the overall (thermal an electric) efficiency in a yearly interval.

4. *Complex photovoltaic and photovoltaic-thermal sizing system*

With the help of the heat resistance models, the surface heat transfer coefficient and the meteorolgy models, I have developed a complex energy prediction system, and because it uses validated data, it can be used to predict the production of PV and PV/T systems.
The model was validated by measurement, which shows correlation on 3 years average with the yearly measurements.
The results prove that analizing the MHP-PVTs, the photovoltaic efficiency decreases, but it can achieve higher overall efficiency like in this case, where it's value is 23,22%.



4. CONCLUSIONS AND SUGGESTIONS

My new scientific results are revealing the photovoltaic modules energy circumstances in highest details, especially the heat transport processes. The cooling effect of the wind has been used only empirical in the calculations before or by a constant value to determine the heat transfer coefficient. I have developed a new dynamic HR-PV and HR-PVT model with that it is possible to monitor the cell temperature real time, and thus minimize the other losses of the electricity network. The model is also suitable for making energy production forecasts, with the meteorological models, which parameter identification I have carried out for the region. Finally the entire model was successfully applied to the reference building solar system sizing, as verified in later measurements. Based on the above it has to considered, to use the common and widely used models or the seemingly pessimistic HR-PV, but through the PV system life possibly getting more accurate or can give better aproximation, especially in the case of a large systems where these numbers are multiplying.

The ASHRAE method is applied on solar meteorological model whereby the direct and diffuse solar components can then be separated and the direct component transformed to a given collector plane.

Into a potential software resulted – wind velocity and position dependent - heat transfer coefficients can be installed, and thus even more accurate predictions can be made.

I recommend more careful positioning of photovoltaic modules based on my achievements, since the result of the heat transfer coefficients investigation showed that the free-standing or on wall mounted modules have the best flow-around and therefore cooling. In case of roof-mounted modules at least 10 cm air gap must be left between the roof and the modules, while in the case of flat roof installation farther away of the edges (ie around the geometric center) of the building should be installed.

I have analyzed a special new type of combined photovoltaic and thermal modules (MHP PV/ T) and I can carry out an objektive comparision test with the uncooled PV modules. also developed an objective comparative test. The results show, in case of the MHP PV/T the photovoltaic efficiency decreases, but because of the overall (including photoelectric- and to thermal) efficiency a greater energy production can be achieved, this fact clearly shows that the annual photovoltaic efficiency difference is only 0,07%.

It would be worthwhile to test MHP PV/T modules with double glazing, as the photovoltaic efficiency does not deteriorate (only because of the double glazing traszmittancia-value ratio increase) due to the cooling, but the thermal efficiency would increase significantly.

5. SUMMARY

In this work a complex model is presented, which explores the photovoltaic modules energy properties topic from different sides. A number of parameters, including the quality of the flow around of PV modules is important in order to maximize the efficiency of photovoltaic modules, and there are no related previous and such complex and comprehensive work designed that would determine the specific heat transfer values, but several studies in the literature has been found that investigated the optimal placement of PV modules.

In my method for determining the numerical heat transfer coefficient for photovoltaic modules is a new approach that gives accurate results based on wind tunnel tests. The accuracy of the results obtained by the simulation corresponds to other applications, as shown by a comparison with the wind tunnel measurements.

Heat resistant models and the validation of Simulink – LabView implementation of it, with the optimized metering system can together effectively calculate the temperature in the cell and thus can be used for the entire solar system. The complex system is adapted to validate the model, during operation, so it can be applied to any existing or planned system is therefore generally applicable.

The identification of the meteorological models took place for the region, which are suitable for a wide range of engineering (building physics, environmental monitoring, renewable energy, passive solar utilization, etc) application use. ASHRAE method of direct-diffuse solar radiation separation of components were not previously been used for this type of data series, however in this way the global function of solar radiation-based model can be transformed into a given plane.

The heat resistance model, together with the meteorological functions and the functions of the heat transfer coefficient are suitable to develop a software for engineers that accurately predicts the energy output of photovoltaic power plants.

The developed model gives accurate results for the photovoltaic module cell temperature, in this way the recovery of the planned photovoltaic power plants can be calculated more precisely, which gives advantages for the applier during the financing.

The model can easily be extended for photothermal applications to calculate the efficiency, as it works for MHP PV/T systems too.

6. MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Referred articles in foreign languages

1. **Haber, I.**, Farkas, I.: Combining CFD simulations with blockoriented heatflow-network model for prediction of photovoltaic energy-production, Journal of Physics, Vol. 268, 2011, IOP Publishing, pp. 1-7.
2. **Haber, I.**, Farkas, I.: Analysis of the air flow at photovoltaic modules for cooling porposes, Pollack Periodica, Vol 7. 2012, Akademiai Kiadó, Budapest, pp. 113-121
3. **Haber, I.**, Farkas, I.: Monitoring the energy properties of photovoltaic modules, Electrotehnica, Electronica, Automatica, Vol 60. 2012, Editura Electra, Bucarest, pp. 13-19.
4. Kistelegdi, I., **Haber, I.**: Gebäudeaerodynamische Untersuchungen einer Plusenergie-Produktionsstätte mit passiven Lüftungstürmen in Südungarn, Bauphysik Vol. 34., Ernst & Sohn, Berlin, 2012, pp. 107-120, (IF 0,228)
5. **Haber, I.**, Bötkös, T., Farkas, I.: Modelling meteorological parameters in Pécs for photovoltaic energy simulations, Mechanical Engineering Letters, Vol. 8. 2012., pp. 68-76.
6. **Haber, I.**, Kistelegdi, I., Bötkös, T., Farkas, I.: Modelling solar irradiation data for phtovoltaic energy-yield prediction, Pollack Periodica, Vol. 8. 2013., Akadémiai Kiadó, Budapest, pp. 27.-34.
7. **Haber, I.**, Kistelegdi, I., Farkas, I.: Investigation of the solar- and wind energy usage of a positive energy factory building, Technical Gazette Vol. 21., Osijek, 2014, pp. 1243–1248, (IF 0,579)

Referred articles in Hungarian

8. **Háber I.**, Farkas I.: Fotovillamos modulok körüli levegő-áramlás vizsgálata a hőátadási tényező meghatározásához, Magyar energetika, 2011, 02. sz., 28-31. o.
9. **Háber I.**, Farkas I.: Napelemes rendszerek energiaviszonyainak modellezése, Mezőgazdasági technika, 2012.07., LIII évf., 42-44. o.
10. **Háber I.**, Farkas I.: Micro heat pipe rendszerű PV/T kollektorok vizsgálata, Energiagazdálkodás, 2015, 56. évf., 5-6. sz., 30-35. o.

International conference proceedings

11. **Haber, I.**, Farkas, I.: Numerical determination of the heat transfer at free standing solar modules, ECT 2010 Valencia, Civil-Comp Press, Proceedings of Seventh International Conference on Engineering Computational Technology, 14-17 September 2010, Valencia, Spain, No. 132, pp. 1-13.
12. **Haber, I.**, Novak, N.: Composite alternative vehicle with solar equipment, Proceedings of the 1st Regional Conference - Mechatronics in Practice and Education, 08-10. 12. 2011, Subotica, Serbia, pp. 192-200