

## A QUANTITATIVE EVALUATION OF THEORETICAL RENEWABLE ENERGY POTENTIAL OF THE BUILDING SITE

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**Abstract.** Modern building design process is becoming more complex. Local conditions and future constructions are computer-simulated. The aim of this simulation is to evaluate theoretical RE potential for the successful and efficient exploitation of the new building. As usual, in the simulation process of local conditions, the assessment of the renewable energy potential is one of the key elements. This article presents and analyses the idea of the quantitative evaluation of renewable energy (RE) theoretical potential of the building site and the approach on how to prepare initial data file for further process of site energy development concept creation. The study describes a building site that is undergoing the RE evaluation in terms of thermodynamic and descriptive statistics characteristics. The applicability of the offered approach was verified in the case study. The specified evaluation of the combined energy fluctuation throughout the year provides new and potentially crucial information about the issues of the RE hybrid energy transformation systems' modelling and about the efficient use of resources to ensure the same level of energy services.

**Keywords:** building site, energy efficiency, disposable renewable energy, theoretical potential.

### Introduction

The Directive on the promotion of the use of energy from renewable sources (Directive 2009/28/EC 2009) sets the objective of reaching 20% of the EU's energy consumption through renewable energy sources by 2020. On 18<sup>th</sup> June 2010, the recast of Directive 2010/31/EU on the Energy Performance of Buildings (EPBD) was published amending Directive 2002/91/EC (2003). The recast introduces a European-wide definition of "nearly zero energy buildings" and indicates that the new buildings will have to be nearly zero energy buildings by 31<sup>st</sup> December 2020 with public buildings having to fulfil this standard two years earlier. Nearly zero energy buildings are now defined in the EPBD (2010) as constructions that have "a very high energy performance". This definition requires both a decreased energy use in buildings whilst also bringing about a renewable energy requirement: "The nearly zero or very low amount of energy required should to a very significant extent be covered by energy from renewable source, including renewable energy produced on-site or nearby" (Directive 2010/31/EU, EPBD 2010). Directive encourages architects and planners to properly consider the optimal combination of improvements in energy efficiency and use of energy from renewable sources when planning, designing, building and renovating industrial or residential areas.

In the processes of building design, operation and maintenance, the technological, institutional and cultural

cooperation of architects, engineers and constructors (AEC) is very important. From an energy engineering point of view, the development of decentralised energy generation and use should be planned by coordinating quantitative and qualitative indicators of renewable energy (RE) and decentralised generators in the intended construction or an existing building.

The vision of sustainable building was discussed in the last decade (Adeli 2002; Ali, Armstrong 2008; Wang, Adeli 2013; Kaczorek, Koczyk, 2013; Parasonis *et al.* 2012; Džiugaitė-Tumėnienė *et al.* 2012; Brauers *et al.* 2012) pointing that a successful creation of sustainable infrastructure systems and environmentally-conscious designs requires a holistic, integrated, and multidisciplinary approach. Unfortunately, because of the large number and diversity of participants, construction work is characterised by a fragmented decision-making process, fear of venture, and conservatism, which result in innovation avoidance and missed opportunities (Altwies, Nemet 2013). However, these problems are being addressed and building creation tools are being developed. One example is the traditional concept of the construction process based on the Integrated Whole Building Design (IWBD) (Integrated Whole Building Design Guidelines) (Ministry for the Environment Wellington 2008), which is now widely referred to as Integrated Project Delivery (IPD) (AIA 2013), together with lifespan analysis of the building and its engineering systems. Moreover, through a digital building concept (Watson 2011), ICT offers va-

rious tools for the construction process, from CAD engineering, first introduced approximately two decades ago, to the more recent BIM (Umit 2012; Barlish, Sullivan 2012). The integration of IPD and BIM is becoming more popular, and the problems involved in this process are being identified and solved (Cholakakis 2011; Xie *et al.* 2011; Wright, Charalambides 2011; Azari-Najafabadi *et al.* 2011; Sebastian 2010; Popov *et al.* 2010; Migilinskas *et al.* 2013; Lin 2014; Volk *et al.* 2014; Barlish, Sullivan 2012).

In this IPD and BIM development situation, the concepts corresponding to a coordinated integration of RE, particularly in the technological, institutional and cultural development path through AEC collaboration, are required. Therefore, engineering is needed to provide quality assistance in the initial design stage when developing the concept of a building.

To obtain an efficient integration of RE usage, it is necessary to evaluate its potential at the first (“pre-design”) stage, i.e., at the stage of building concept creation. At this stage, the technical conditions of the site should be determined, the synthesis and conflicts of the energy needs and the local conditions generated, and the initial concept development created. The locally available energy should be used to guide the selection of the planned activities. Such guidance facilitates the development of a responsible user, and the distributed energy generation achieved by implementing IWBD process with BIM ensures that the user’s needs are met, which allows, even in the operation and maintenance phase, for the optimal management/improvement of the building.

To prepare information on the required area that reflects the potential RE sources, it is necessary to identify the types of RE sources and evaluate their quantities and qualities. For decision making, this combined information is a crucial one. To determine RE availability, various tools and methods are applied (Angelis-Dimakis *et al.* 2011). The main evaluation principle is that the determined potential can be of three levels: the theoretical potential, the technical potential and the exploitable potential. To obtain theoretical RE potential, as a first stage of assessment a quantitative (energy) (Liao *et al.* 2012; Jorgensen, Svirezhev 2004) and qualitative (exergetic) (Wall, Gong 2001; Hermann 2006; Valero *et al.* 2010; Beyene *et al.* 2012; Shukuya, Komuro 1996) resource evaluation is performed as well as statistical data are processed. Statistical data processing can be performed in the initial meteorological data generating stage, as well as in the stage of recalculating them into the quantitative/qualitative indicators. As shown by some of the most recent examples (Demirhan *et al.* 2013; Muratori *et al.* 2013) the statistics methods are widely applied. The statistical analysis provides additional characteristics that enable to evaluate inconsistency in terms of RE flow variation in time.

Developers having information on possible renewable energy sources of available building sites could select most appropriate from the alternatives that are consistent with the development concept.

In the combined evaluation of the energy potential, the review (Angelis-Dimakis *et al.* 2011) sets methods to evaluate the types of RE that should be integrated with each other and presented at the same level of particularity. In order to not restrict the way of choosing technological solution, it is obligatory to have RE potential data which has to be in uniform detail and affected by local conditions.

With the development of technology and the expansion of data sharing and storage area network, the databases which can be accessed remotely were created with meteorological data as a primary information about RE for many places of the world (Sorrentino *et al.* 2012). Approximate meteorological data could be obtained using widely applied interpolation method of any spot of the world (Meteotest 2013). Evaluating the potential of the RE, its layout in the territory, GIS is widely known and applied (Van Hoesen, Letendre 2010; Ondreka *et al.* 2007; Omitaomu *et al.* 2012). The particularity of information used in the maps is applied to the cities or regions for the use of RE potential planning. It presents average values of the available potential of RE for the particular area or zone. In addition to the technical data provided by this method, optimization methods are used (Omitaomu *et al.* 2012; Malczewski 2006; Monstvilas *et al.* 2012) which allow to plan the new areas and the volumes for RE projects more objectively and efficiently.

The review shows that in the modelling of buildings as individual energy users there is a lack of unified approach to the assessment of the potential RE in the building site and site initial RE potential information that would allow to choose in uniform level of detail the most acceptable source of energy or to adopt primary technology solutions. An engineer should have the initial data file from which he could retrieve initial appropriate conceptual engineering solutions for further modelling. This article presents method based on thermodynamic analysis for determining the theoretical potential of RE of the building site and statistical evaluation of disposable RE flows. In this way, the initial data file of the building site RE potential is formed so that it could be used for further modelling of site development concept.

Conceptual framework of main energy efficient building planning and design stages is presented in Figure 1. In this paper the analysis is performed on the stage 1 (building site data analysis and limitations) of energy efficient building planning and design process. Detailed description of the first stage approach is presented in Figure 2. This paper is focusing on renewable energy (RE) theoretical potential of the building site only. In future the authors plan to assess technical potential of building site by analysing RES technologies and energy use profile. Separate conceptual building sustainability solutions on different stages of research were discussed earlier (Motuzienė *et al.* 2013; Lapinskienė, Martinaitis 2013; Motuzienė, Vilutienė 2013; Mikučionienė *et al.* 2014; Žėkas *et al.* 2013; Motuzienė, Bielskus 2014; Lapinskienė *et al.* 2014).

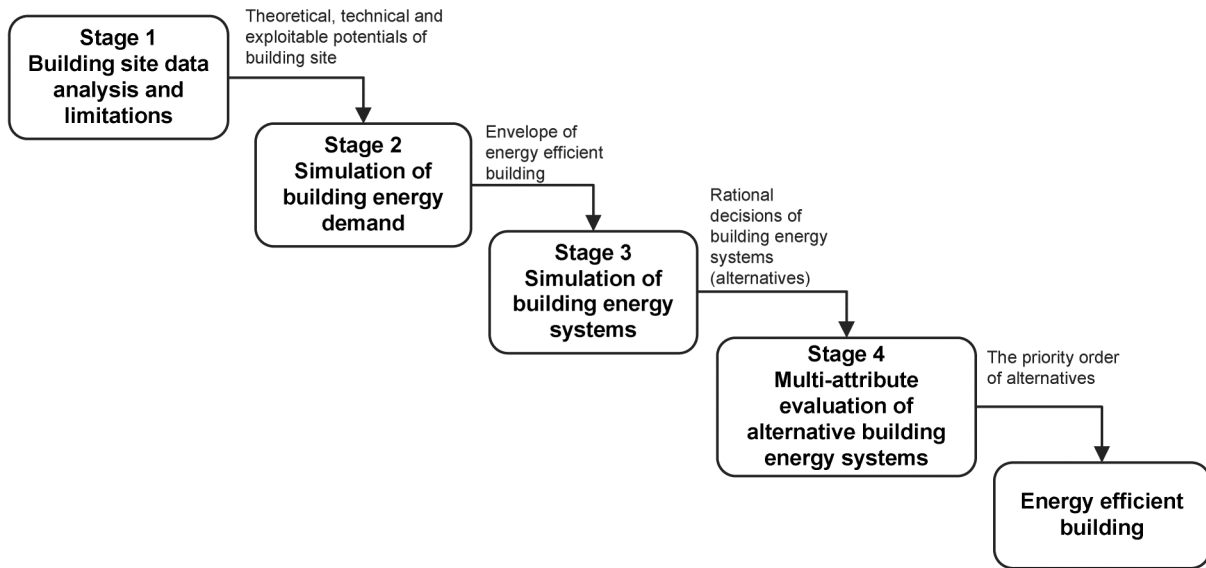


Fig. 1. Conceptual framework of main energy efficient building planning and design stages

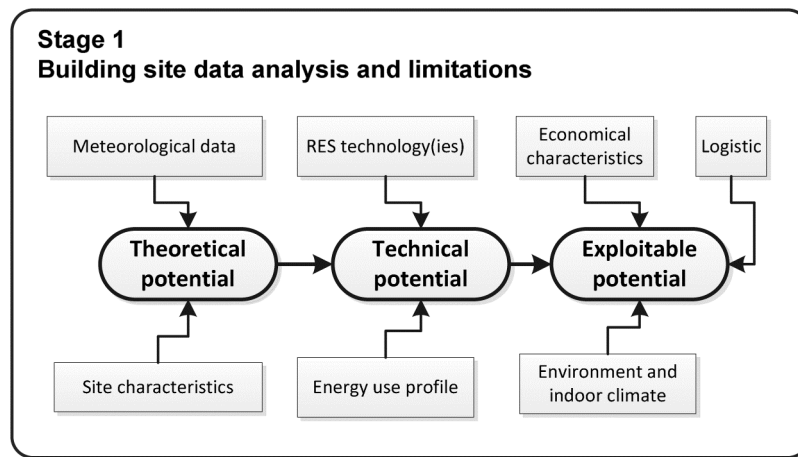


Fig. 2. Detailed description of the first stage approach

### 1. A conceptual combined evaluation method of RE of the building site

In order to ensure a consistent and uniform level of detail of analysed site RE information, it is offered to assess theoretical RE potential by following the approach that is presented in the Figure 3. First, third, fourth and fifth blocks marked in red show the scope of research presented in paper. Second block shows the initial data necessary for simulation. Fourth block of research is based on application of renewable energy flows assessment methods described in Section 2.4. The application for RE flows calculator used on this stage is based on aforementioned energy flows assessment methods and is written in C++ language. The application reads meteorological data and calculates energy flows and visualizes it using interactive plots. To develop graphical user interface applications the Qt cross platform application framework is used. For plotting and data visualization the QcustomPlot (2013) library is used. Application helps analyse data quickly and interactively. Approach gives a unified way to assess site’s RE potential and the possibility to assess objective-

ly the particular site not only when developing opportunities, but also considering different site alternatives.

#### 1.1. Control volume of the building site

For a building as single energy user with existing RE flows, it is possible to adapt the principle of energy analysis and evaluate a defined open space streaming process system, which deposits some of the energy flow formed from the RE sources. In order to unify the site RE potential integrated evaluation method, the site in terms of thermodynamic analysis is considered to be volume, defined by control volume boundaries (Fig. 4). Notations of Figure 4(a) represent three incoming (the solar radiation heat flow  $\dot{Q}_S^+$ ; the ground heat flow  $\dot{Q}_G^+$ ; and the incoming air flow transformation energy  $\dot{W}_A^+$ ) and two outgoing energy flows (the outgoing air transformation energy  $\dot{W}_A^-$  and the radiation heat  $\dot{Q}^-$ ).

The structure and development of available RE in a building site throughout the year is a fundamental factor

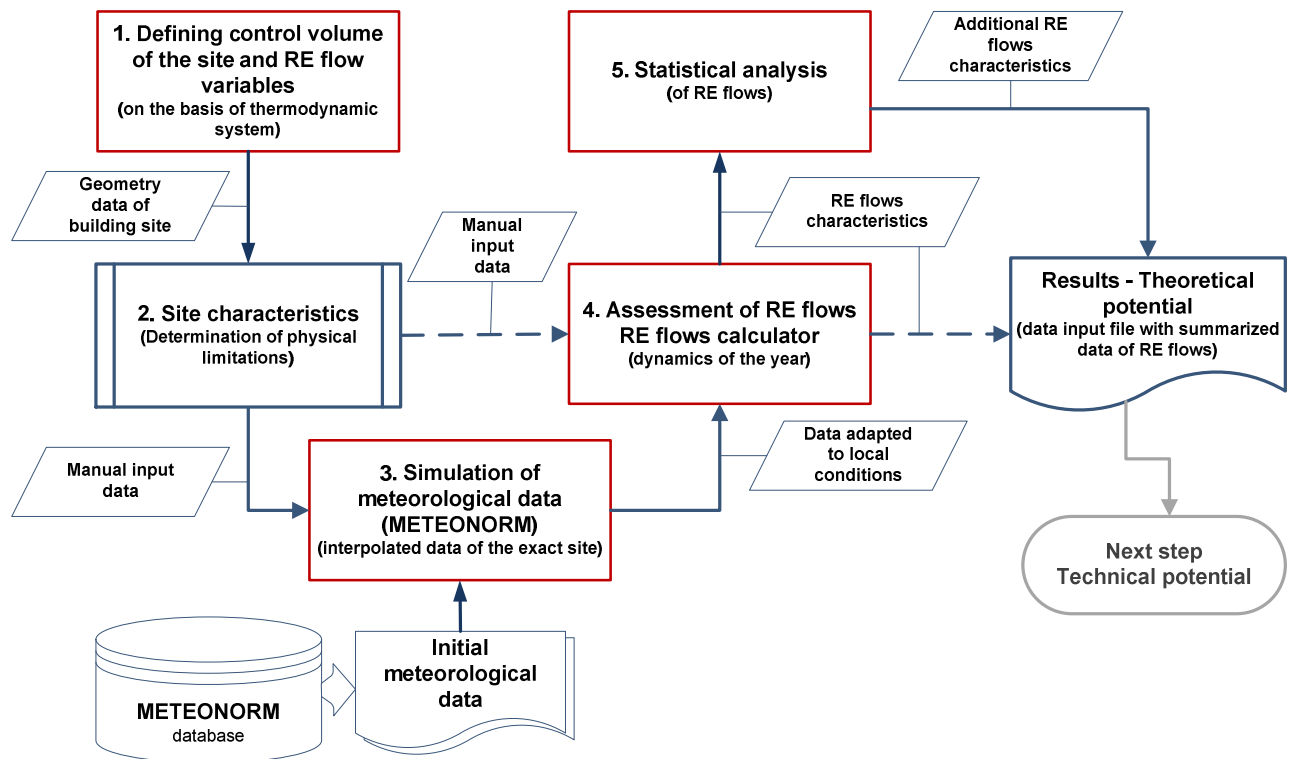


Fig. 3. Algorithm of theoretical RE potential assessment for building site

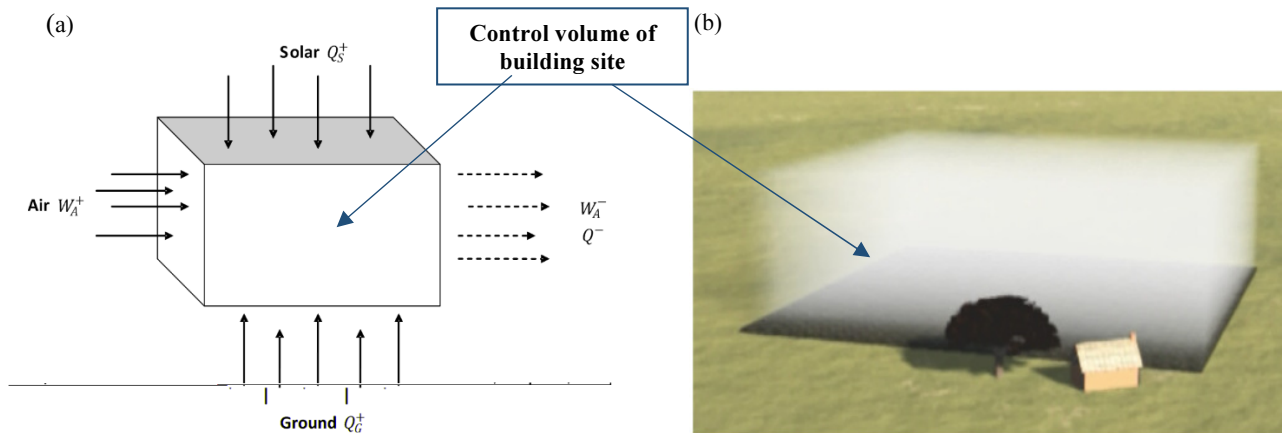


Fig. 4. The energy flows crossing the control volume: (a) RE flow variables, (b) visualization of control volume of the building site

in decision making regarding the usage of RE technologies in buildings. It is assumed that to increase RE integrity and effectiveness, it is necessary to determine the local RE potential that would enable to identify both separate flows as well as technical parameters of complex flow.

## 1.2. Site characteristics

RE potential and its dynamics in the year period, influenced by surrounding factors, is a primary and one of the main theoretical RE potential evaluation tasks. This task involves the description of site's physical characteristics. Summarized site's physical characteristics' data file structure is presented in the Figure 5 scheme.

When physical characteristics of the building site are structured and prepared, a meteorological data file should be prepared, following influences of physical

characteristics. In this way it could be possible to have sufficient detailed input data of a particular site to evaluate RE theoretical potential.

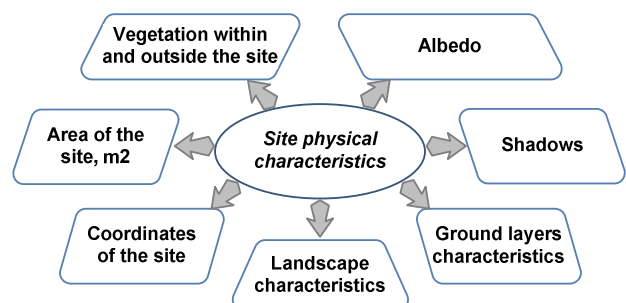


Fig. 5. Structure of building site's physical characteristics

### 1.3. Meteorological data

Taking into account the structure of building site’s physical characteristics the meteorological data should be adapted to the local conditions. METEONORM application has been chosen for meteorological data processing. Initial meteorological data is taken from METEONORM meteorological data base. When forming meteorological data array of a particular site, the following provisions are applied:

1. Central geographical point of the site is picked as a point presenting all site’s meteorological phenomena.
2. RE theoretical potential evaluation is performed using historical data of long-term observations and the program generates the typical meteorological year.
3. Meteorological data is provided by hourly time interval.

### 1.4. Assessment of renewable energy flows

The concept of complex RE assessment is that the control volume limits are crossed by three incoming (the solar radiation heat flow  $\dot{Q}_S^+$ ; the ground heat flow  $\dot{Q}_G^+$ ; and the incoming air flow transformation energy  $\dot{W}_A^+$ ) and two outgoing energy flows (the outgoing air transformation energy  $\dot{W}_A^-$  and the radiation heat  $\dot{Q}^-$ ), which are shown in the Figure 4.

The energy balance for this system of constant volume with a stationary streaming process can be modelled by the Eqn (1):

$$\sum_i [\dot{Q}_i^{+,-}] + \sum_j [\dot{W}_j^{+,-}] = \frac{\Delta U}{\Delta t}, \quad (1)$$

where  $\dot{Q}_i^{+,-}$  is the heat capacity (flow) delivered by the system (+) or released by system (-) flows (i);  $\dot{W}_j^{+,-}$  is transformation energy;  $U$  is the system’s internal energy; and  $\Delta t$  is the time.

The expanded form of Eqn (1) is Eqn (2):

$$\sum_i [\dot{Q}_i^+] + \sum_j [\dot{W}_j^+] = \sum_i [\dot{Q}_i^-] + \sum_j [\dot{W}_j^-] + \frac{\Delta U_{cz}}{\Delta t}. \quad (2)$$

The sum of the numbers on the left side of the equation is the amount of incoming RE and it could be named as locally disposable renewable energy (LDRE):

$$\sum_i [\dot{Q}_i^+] + \sum_j [\dot{W}_j^+] = LDRE. \quad (3)$$

For assessment of renewable energy flows of building site authors offer to use RE flow characteristics. If they are included, the Eqn (3) could be rewritten as follows:

$$\dot{Q}_S^+ + \dot{Q}_{DG}^+ + \dot{Q}_{SL}^+ + \dot{M}_A^+ \left[ h_A + \frac{1}{2} C_A^2 \right] = LDRE, \quad (4)$$

where  $\dot{Q}_S^+$  – solar radiation heat;  $\dot{Q}_{DG}^+$  – heat coming from the underground;  $\dot{Q}_{SL}^+$  – heat flow of exchanging

heat stream, occurring in the surface of soil (up to 10 m depth),  $W$ ;  $C_A$  – air flow speed, m/s;  $\dot{M}_A$  – mass flow rate of incoming air;  $h_A$  – air enthalpy.

### 1.5. Statistical indicators of RE flows

Descriptive statistical analysis is used to evaluate the reliability of the energy supply. The statistical analysis sample is an hourly time step-year period covering parameters of the RE flow.

## 2. Case study

### 2.1. Initial data

Case study was performed to demonstrate the comprehensive evaluation of RES. The site of typical flat undeveloped area, near Vilnius city, in Lithuania was selected for the case study. The area has a slight roughness of terrain not planted with any greenery.

Independently chosen site is as an open steadily operating thermodynamic system. System volume  $V$  is invariable. The system, limited only by theoretical limits, is surrounded by the atmosphere. Physical characteristics of chosen building site are presented in Table 1.

The calculations are carried out using the meteorological data (from METEONORM application) generated at the central site point. Data taken as average values reflecting the energy status of the whole site. It is understandable that the more detailed determination of the RE potential requires the dimensional computer simulation of flows, including the total volume and the influence of the local barriers (vegetation, area roughness and so on) in this kind of site scale.

Table 1. Building site’s physical characteristics

Physical characteristic	Description
Coordinates of the site	54.792863, 25.279806 (WGS)
Area of the site (control volume)	100×100 m (100×100×52 m)
Vegetation within and outside the site	– Vegetation in the site – grass/field – Vegetation near the site – grass/field
Landscape characteristics	1% over all slope to the NE side
Albedo	Warm period – 0.6; winter – 0.8
Shadows	None
Ground layers characteristics	– Energy flow from deep ground layer – 45.00 mW/m <sup>2</sup> – Heat transfer coefficient – 1.5 W/(m <sup>2</sup> K)

### 2.2. Annual dynamics of the renewable energy flow potential

The available energy dynamics of the selected area during the year is shown in Figure 4. Rounded numerical value of the air flow curve reflects the total available RE potential.

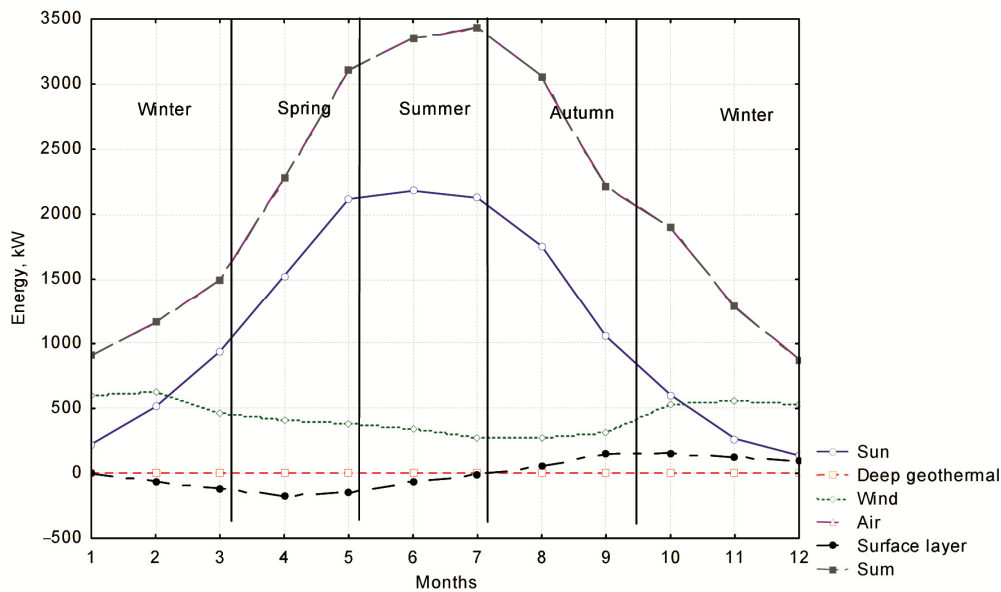


Fig. 6. Year preliminary division into seasons and overall dynamics of RE flows of selected building site

The diagram (Fig. 6) shows that the maximum energy potential (3332 kW) is in the summer. Meanwhile, the energy flow (during the cold season) is relatively small – up to 30% of the maximum quantity of energy or about 881 kW. The minimum positive value of solar energy is reached in winter time while air energy acquires the negative value, indicating the outgoing rather than ingoing energy. In autumn, the soil in 2 m depth starts to radiate the constantly accumulated heat. During the cold season, wind energy flow is a dominant RE flow in a site compared to the sun and soil energy.

It should be noted that both the soil and the wind energy flows are relatively stable over the year, without the exceptional deflection of energy amount, so seasonal accumulation phenomena must be judged only by assimilating solar and air energy flow.

Traditional determination of RE potential treats the air flow only as an energy carrier and excludes it from calculations. In order to assess overall RE potential of building's site in the same detail, the air flow should be considered as another RE source.

Depending on a climate zone there could be various profiles of the annual dynamics. Winter and summer periods are quite distinct in that case study. In addition to these target periods, there are the transition periods such as are spring and autumn (Fig. 6, vertical lines). Naturally, RE flow dynamics does not have clear transition points which could help to distinguish such periods. But various technologies have different efficiency in each period. Awareness of such periods provides additional information in planning hybrid RE systems. In this case study four periods could be excluded: cold period, the transition into the warm period, warm period and the transition into the cold period.

RE potential annual average value of the case study is 2051 kW, i.e. average energy flow reaching the site or LDRE characteristic.

Assessment of the total dynamics of RE flows potential shows that it distinguishes oneself by chaotic

change within the hour, day or month. Usually, average monthly or annual values of individual flows are used in solving the RE absorption tasks. Correct determination of the average flow value is crucial.

### 2.3. Statistical assessment of the RE flows characteristics

Statistical evaluation of the calculated data was performed by a computer program STATISTICA. The evaluation results show different characteristics dynamic of the individual RE flow. Figure 7 provides a monthly minimum, maximum and median flow power values. Lower and upper quartiles are shown separately.

As shown in the curve of statistical characteristics (Fig. 7), different RE flows have distinctive value changing dynamics. The solar energy reaches maximum in late spring, wind energy maximum is in winter, air and soil heat energy reaches its peak in the end of summer. Having this flow dynamics permits a more rational choice of the most acceptable source that would cover RE energy needs.

Average values of 25–75% range (quartile range 1495 kW) are the most scattered ones in solar energy case, about 60% lower average values scatter in air and wind flows and minimum scatter (200 kW) is in soil heat flow case (Table 2). The scatters of those values characterize the permanency of the energy flow. Case study calculation shows that solar energy transformation system should operate in the widest range. When modelling a power transformer, it is reasonable to choose such transformation system so that the highest efficiency would be in the restricted range of quartile values. As it can be seen, in the case of the wind flow, there is a clear influence of single gusts. This is shown by clear passing mean and median values (433 kW mean and 230 kW median). When modelling the use of the wind flow this characteristic must be taken into account. Ground layer energy is the most stable energy flow because of high thermal inertia and temporary storage phenomena remains.

Table 2. Summary of RE flows statistics

Energy form/characteristics	Mean	Median	Minimum	Maximum	Lower Quartile	Upper Quartile	Quartile Range	Std.Dev.
Solar energy, kW	1124	737	38	3523	332	1827	1495	941
Wind, kW	433	230	0	4939	75	554	479	590
Air heat, kW	494	403	-683	2056	169	722	553	452
Ground surface layer heat, kW	6	5	-331	316	-94	106	200	126
<b>Sum, kW</b>	<b>2057</b>	<b>1801</b>	<b>132</b>	<b>6879</b>	<b>971</b>	<b>2924</b>	<b>1953</b>	<b>1331</b>

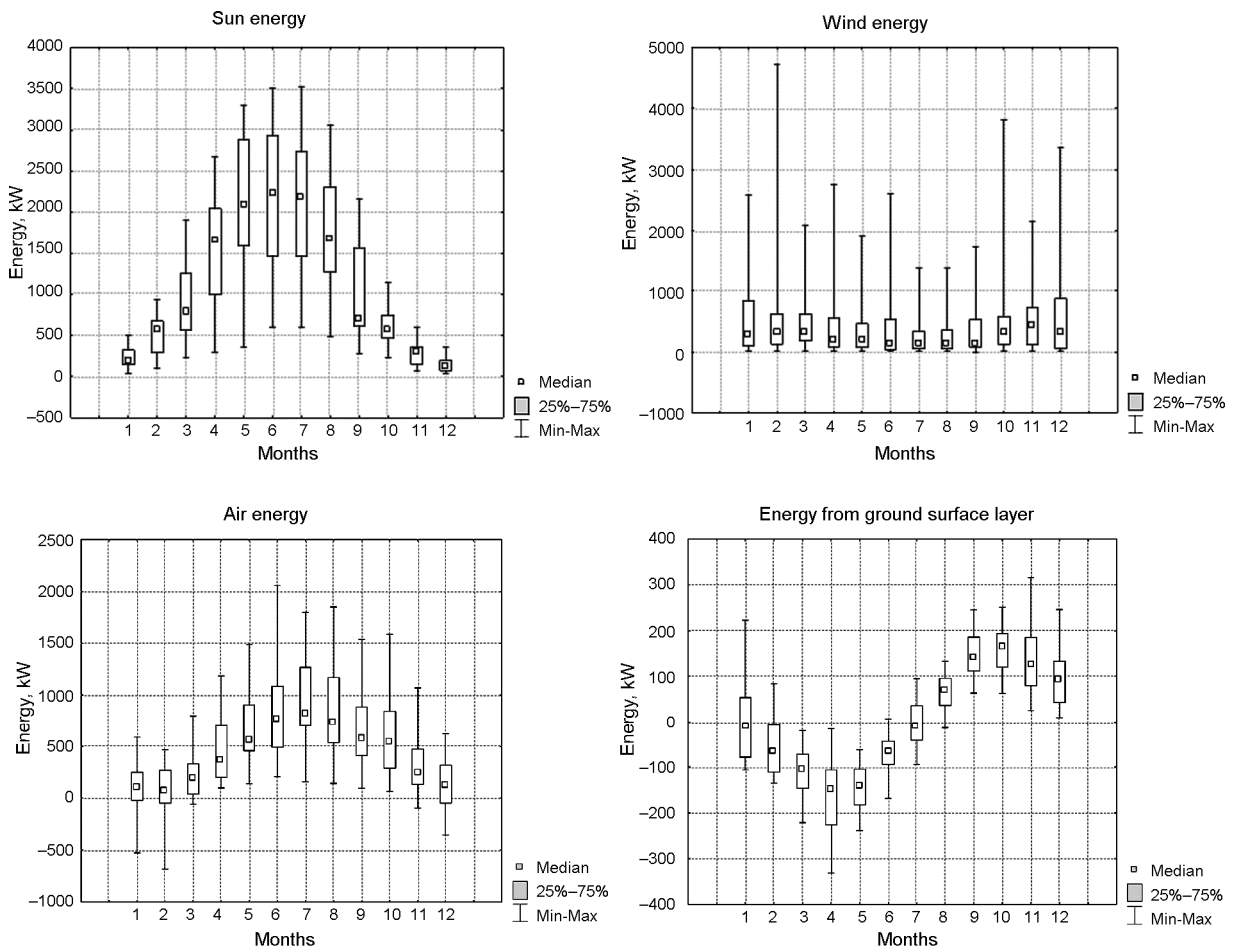


Fig. 7. Dynamic of RE energy flows (wind, solar, air heat and ground) statistics

The lower and upper quartiles in the solution phase allow dividing the energy flow into two parts: 0–50% values and 50–100% values. In this way, there are two medians: the median of the smaller power area (0–50%) and the median of the major power area (50–100%). Having those medians it is possible to make a more rational choice on the energy transformer which operates in a given season or throughout the year more efficiently.

The corresponding RE flow site reaching energy power weighted distribution in different seasons is presented in the Figure 8. Individual powers of the energy flow are divided into three ranges: minor powers – to the lower quartile values, middle-level powers – to quartile range values and major powers – to the flow values above the upper quartile. The main advantage of the graphs is

that the information is presented in the form that allows understanding what is the power limit at which operating RE transformer would generate the biggest amount of energy and in which time of the year it could happen.

As it can be seen from the case study results, in the case of solar energy flow, up to 30% site reaching solar energy flow consists of the flow of energy in the summer, with the capacity reaching 1562 kW of the power level.

Wind energy reaches the site in major power range throughout the year, but considering the available statistical information presented earlier, wind energy is chaotic in a major value range and the main energy quantity is generated by individual extreme wind gusts. Solving a consistent supply of wind energy task it is appropriate choice for a small power range, which is only up to 10% of the total wind energy flow.

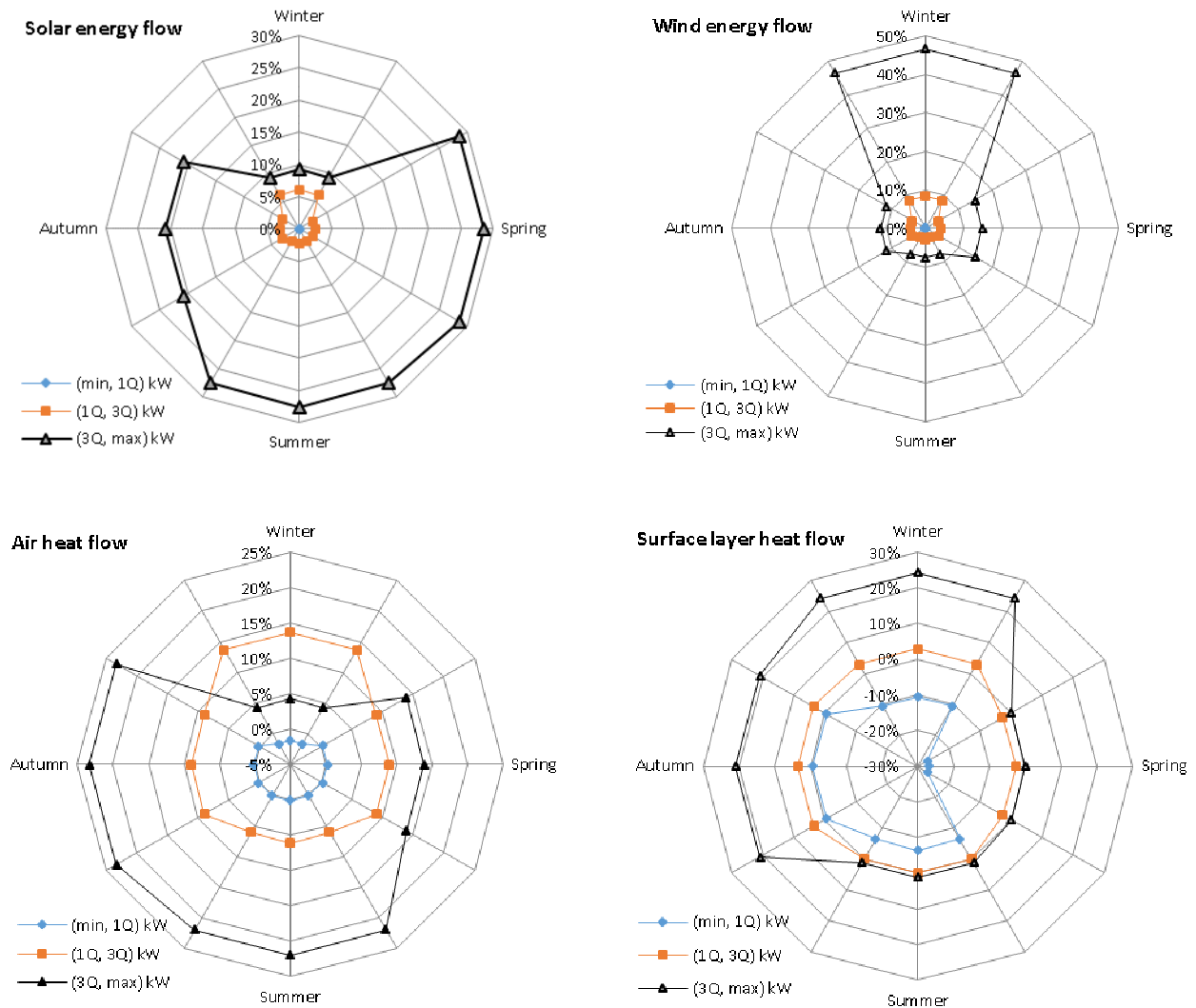


Fig. 8. Frequency of energy flow values throughout seasons.

Air flow energy reaching the site through the entire year is close to the medium, but like in the wind energy case, its part in the total energy flow is relatively small, which is up to 15% of the total air energy flow. Autumn in the air energy flow has its specifics, because in comparison with the spring, in autumn the flow of the energy reaching the site is greater (up to 23%).

Soil heat energy flow calculation shows that the maximum benefit (25% from the total ground heat energy flow) comes in winter, when accumulated soil layer energy during the warm season begins to radiate into the cooling environment.

Having such a complex uniform level of RE flow information the base for the initial development of the site's energy concept is formed. Depending on the intended site's energy demand a RE source or its combination can be chosen. For further modelling energy conversion technologies could be an option as well as the primary powers of system components or proportions of different solutions. Revising this preliminary concept and evaluating the usage of technological solutions, sites' technical RE potential should be determined in the next stage.

## Conclusions

In authors opinion the evaluation of the RE reaching the building's site should be one of the main reference points for providing technical solutions when creating a building as new energy user. Taking into account the local conditions, the theoretical RE potential must be determined without being limited by different technological solutions and must have unlimited freedom for the engineering modelling of potential energy conversion options. The many the possible initial data with the same particularity have been taken into account, the more precisely RE potential was determined.

The proposed combined evaluation method of the RE amount is based on the energy balance of the site control volume. Evaluation model options and operation principle are presented in a case study of the locally available energy. The case study shows that the results of LDRE characteristics (annual average 2057 kW) reveal the general energy state of the site. This helps to compare the alternatives of the site directly. Also the calculations show that when determining the available RE potential, both the annual and the seasonal quantity change of



flows has to be taken into account. Annual average of solar energy flow is 1124 kW, while in summer time it reaches 30% of all solar energy, which average capacity is 1562 kW. The case study confirms the assumption that the mathematical average of potential values is not sufficient for further modelling process. The individual values of extreme flows occurring in nature have to be eliminated. The case study shows that the greatest impact of extreme values is of wind energy flow. The annual average of flow is 433 kW, while excluding the impact of extreme values, the average capacity is only 230 kW. The transformer capacity selection should be based on the recurrence of the energy prevailing values. United statistical assessment of these values for different RE sources proposes additional useful information.

Assessment data doesn't reflect the final availability of energy yet; therefore the shift from a quantitative evaluation to the technology based evaluation is needed. The most sensitive in this approach is an air flow as energy transferring agent that contains a large amount of energy, which indicates the challenge for technologies. On the next step of research authors plan to assess technical potential of building site by analysing RES technologies and energy use profile.

## Nomenclature

### Subscripts

<i>S</i>	solar;
<i>DG</i>	deep geothermal;
<i>SL</i>	surface soil layer;
<i>A</i>	air.

### Abbreviations

AEC	Architects, Engineers and Constructors;
RE	Renewable energy;
IWDP	Integrated Whole Building Design;
IPD	Integrated Project Delivery;
ICT	Information and Communication Technologies;
BIM	Building Information Modelling;
GIS	Geographic Information system;
LDRE	Locally Disposable Renewable energy.

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