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Determination of urban structures' solar potential using energy simulation software

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ABSTRACT: The educational process should reflect the actual needs of a society, confront its current issues and seek appropriate solutions to its specific problems. As a major consumer of energy, the city will have to face many challenges in housing, transportation, etc. This article suggests one possible scheme for the reduction of energy demand of cities by using solar energy as a local renewable energy source. The authors compare various types of existing settlements in the City of Bratislava - Ostredky, Krasňany and Petržalka, which represent typical urban typologies of the socialist era. By determining the energy performance of structures the potential for hypothetical utilisation of photovoltaic and solar thermal collectors installed on roofs and façades is compared. The case studies introduce both the concept of energy cooperativeness within the urban structures, and a new energy town planning indicator (cooperation indicator). All evaluation and simulation methods of urban structures should become integrated as part of architectural and engineering education in order to ensure the sustainable development of cities.

INTRODUCTION

This contribution has as its ambition to outline the possible direction that could be followed to reduce the ecological footprint of cities. In juxtaposition to this new development stands the effort to preserve the existing building structures and cultural values they represent. Recent developments in the field of IT allow for the analysis of the urban solar potential *in silico* by various simulation software tools (DIVA, Autodesk Ecotect Analysis, Autodesk Revit Energy Analysis, etc). Orientation towards the cardinal points, the ratio of transparent surfaces or distances between objects becomes essential for reducing the energy demand of buildings. All these IT tools and approaches in design need to be transferred into the architectural education process with the aim of examining sustainable models of city developments and raising ecological awareness of future generations of architects, urban planners, decision makers and law makers.

Analysing the solar potential, proven by three case studies, enables the creation of energy neutral/energy productive urban layouts with their subsequent energy cooperation (Figure 1). The energy surplus structure can subsidise the deficient settlement. The existing buildings are engaged in energy cooperation concept by integrating active solar systems into façades and roofs, thus, transforming sunlight into energy. This synergy is a form of urban ecological measurement standard. The use of enormous solar energy potential depends on the integration of two solar principles - the *active* (application of solar appliances - photo thermal/photovoltaic conversion) and the *passive* (energy gains through transparent surfaces). Both of these principles require solar exposure. Therefore, in the authors' view, direct sunlight exposure becomes a critical factor in urban planning and architectural design.

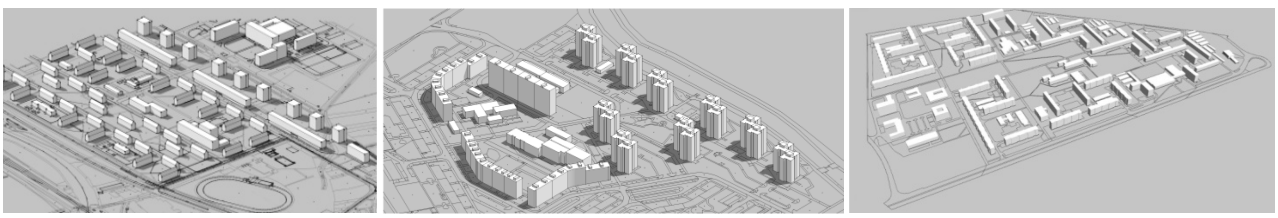

Figure 1: Urban patterns of three examined areas in Bratislava. From left: Krasňany, Petržalka and Ostredky.

THE KRASŇANY HOUSING ESTATE

Krasňany is the first post-war housing estate to have been built in Bratislava. It is based on an orthogonal grid covering 25 hectares. The building process was carried out in two stages. The first, during the 1950s, known as *Old Krasňany*, was realised as a Garden City. Buildings have three storeys, a semi recessed basement and a non-residential loft. The second, entitled the *New Krasňany*, ran during the early 1960s. Five-storey buildings with a multifunctional first floor and tower blocks of the T18 structural system with seven floors were built. The local centre with services and civic amenities is situated in the western part of the territory. To the north of the residential area are Slovenská Grafia Inc. industrial factories and former industrial objects of MEOPTA, the state-owned enterprise. They are also included in the area examined. The southern part of the territory is characterised by low-rise buildings with a built-up area ratio of 0.18, a floor area ratio (FAR) of 0.7 and with the density of 150 inhabitants per hectare. Following these indicators, Krasňany reaches a density level of urban environment and creates the adequate potential for the emergence of services [1][2].

The energy performance of this urban area has been investigated according to three options. The first, Option 0 shows the current state of energy consumption for heating and domestic hot water (DHW) provision as well as the present electricity consumption. The second, Option 1 illustrates a model of reduction of energy use for heating by 30%, which roughly corresponds to the contemporary energy efficiency measures by thermal insulations of building envelopes. The DHW provision is partly secured by solar thermal collectors, which cover 15% of the roof surfaces. Electricity generation is ensured by PV panels covering 45% of roof surfaces with an efficiency of 15%. The third, Option 2 has the ambition to anticipate the promising energy state of buildings after the year 2020, when the Energy Performance of Buildings Directive (EPBD II) will be fully implemented in Europe. In this case, one can assume that the deep renovation of buildings will be performed into nearly zero energy standards. This requires increasing the efficiency of PV panels to a value of 20% and thermal collectors should cover 50% of energy demand for domestic hot water provision. For the purpose of this research and inter-comparison, the housing estate has been divided into three sectors: sector A (Old Krasňany), sector B (New Krasňany), and sector C (industrial zone).

SECTOR A

Current heat consumption reaches 5,230 MWh per year (MWh/a) and the energy demand for DHW provision is 2,176 MWh/a [3]. In Option 1, by using the 15% of the roof surface for thermal collectors, it is possible to secure 56% of energy demand for DHW heating, which is economically optimal. By covering 45% of pitched roofs with PV panels and in energy symbiosis with the power production on the roofs of school buildings one can ensure up to 100% of needs for electricity per year. Through deep renovation, meeting the nearly zero energy standards in Option 2, it is possible to reduce energy demand by 2,794 MWh/a, representing a 53% reduction compared to the original state. PV panels with increased efficiency to 20% can generate 2,780 MWh/a, approximately the same amount as the savings made by deep renovation (Table 1).

Table 1: Sector A (Old Krasňany - FAR 0.6) and characteristics of energy indicators of three options.

		Energy demand of buildings in sector [MWh/a]	Energy production of solar appliances [MWh/a]	Impact of energy efficiency measures on energy demand (ED)
Option 0	Heating	5,230		
	DHW	2,176		
	Electricity consumption	2,039		
Option 1	Heating	4,118		23% reduction of ED through basic renovation
	DHW	2,176	1,219	56% coverage of ED
	Electricity consumption	2,039	2,087	102% coverage of ED
Option 2	Heating	2,436		53% reduction of ED through deep renovation
	DHW	2,176	1,622	74% coverage of ED
	Electricity consumption	2,039	2,780	136% coverage of ED

Total energy demand for heating in winter is 2,436 MWh/a and 554 MWh/a for DHW provision. The theoretical surpluses of generated electricity are not sufficient to meet energy demand of buildings in this sector and, as well, they are mainly produced during the summer period. The energy accumulation and effective transfer to the winter period has not yet been satisfactorily resolved by scientists. The structure can offer its surpluses to other urban structures. By changing the architectural design to shed roof buildings facing south-west or south-east, it is theoretically possible to cover up to 80% of roofs with PV panels. They would be able to produce up to 3,718 MWh/a, of which 1,679 MWh/a could possibly be offered to the electricity grid.

SECTOR B

At present, in Option 0, the energy consumption for heating is 3,828 MWh/a and energy demand for DHW provision reaches the value of 1,655 MWh/a [3]. In Option 1, thermal collectors are mounted on 15% of the rooftops, so 27% of heat and energy demand for DHW heating can be secured. It represents only one half of roofs' solar potential. Especially in tower blocks, the coverage ratio of roof surfaces by solar appliances is very low. By covering 45% of pitched roofs with PV panels and in symbiosis with the power production on the roofs of school buildings, 48% of demand for electricity per year can be ensured. This structure has no potential to secure its needs by renewable solar energy. In Option 2, by performing deep renovation to meet the nearly zero energy standards, the reduction of energy demand by 2,510 MWh/a can be reached. It represents 65% savings compared to the original state (Table 2).

Table 2: Sector B (New Krasňany - FAR 0.9) and characteristics of energy indicators of three options.

		Energy demand of buildings in sector [MWh/a]	Energy production of solar appliances [MWh/a]	Impact of energy efficiency measures on energy demand (ED)
Option 0	Heating	3,828		
	DHW	1,655		
	Electricity consumption	1,608		
Option 1	Heating	3,195		17% reduction of ED through basic renovation
	DHW	1,655	455	27% coverage of ED
	Electricity consumption	1,608	779	48% coverage of ED
Option 2	Heating	1,318		65% reduction of ED through basic renovation
	DHW	1,655	974	58% coverage of ED
	Electricity consumption	1,608	1,038	64% coverage of ED

Because of the sector's multi-storey buildings of 5-7 floors, the ratio of the roof surface to the floor area of building is small, which is also reflected in a low ability to use solar energy. In particular, within the tower blocks, it is important to optimise the ratio of solar thermal collectors on roofs, so that the coverage of energy demand for domestic hot water provision will exceed the 50%. In this case study, the increase of the area of thermal collectors was 25%. By increasing the efficiency of PV panels to 20%, it would be possible to produce 1,038 MWh/a, but this capacity is not sufficient to achieve an overall energy balance within the given urban area. The remaining energy requirement of 570 MWh/a could be met from the energy surplus of the Old Krasňany urban structure. Both structures are able to complement each other.

SECTOR C

By its nature, sector C with FAR of 0.78 constitutes a separate part of the housing estate Krasňany. Both areas are characterised by low-rise buildings of warehouse facilities. At present, large areas of MEOPTA roofs are equipped with PV panels with a total annual capacity of 1,023 MWh [3]. Annual capacity of the solar photovoltaic array mounted on the rooftops of Slovenská Grafia Inc. buildings represents 2,760 MWh. Together, both PV plants can generate 3,783 MW/a, which is enough to cover power consumption of sectors A and B (3,647 MWh/a), apart from energy consumption of warehouse facilities (these data could not be obtained for this research).

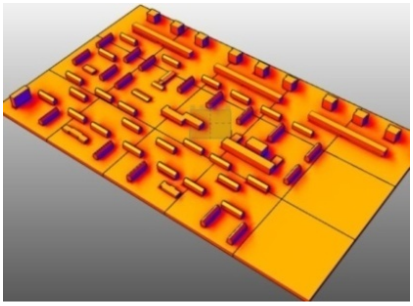

Figure 2: Solar potential of urban structure Krasňany determined using the simulation software Autodesk Ecotect Analysis.

The impact of energy efficiency measures by using PV panels can also be expressed by the indicator of *electricity production per capita*. A similar indicator, *thermal production per capita* can be used for thermal collectors. In relation to the number of inhabitants in an urban area, they simply characterise the ability of solar appliances to cover the power consumption/energy demand for DHW heating of residents. Considering the average power consumption per person (876 kWh/a), the Old Krasňany housing estate is positive and New Krasňany is negative. The average energy demand for DHW heating and its distribution is 1,200 kWh/a. So, both sectors are negative (Table 3).

Table 3: Electricity and thermal production per capita in the housing estate Krasňany calculated for Option 1.

	Electricity production per capita [kWh/a]		Thermal production per capita [kWh/a]	
New Krasňany	444	-	255	-
Old Krasňany	1,105	+	565	-

The renewable energy production per capita indicator can have a positive effect on raising awareness in educational processes, as it is easier to understand by regular users. In such a way, the share of renewable energy sources in the energy mix can be achieved. For the purposes of urban planning, a more appropriate *cooperation indicator* has been proposed by the authors, displaying the amount of energy produced and needed in a given urban area.

> *The* cooperation indicator *of an urban structure (or neighbourhood, district or city quarter) is a quantifier of the negative or positive energy balance of a particular urban fragment contributing to overall synergy within an urban structure. It expresses either the structure's capability to offer its energy surplus or its energy demands, towards adjacent structures or city quarters in creation of a smart local energy network utilising available renewable energy sources in actual time* [4].

This indicator can be expressed for thermal energy (*energy thermic cooperation indicator* - eTCI) or for electricity (*energy electricity cooperation indicator* - eECI). Numerical values of the energy thermic and electricity cooperation indicators have been calculated for both Option 1 and Option 2 (Table 4). Application of these indicators in the case study of the Krasňany housing estate is presented for the values of Option 2 (Figure 3).

Table 4: Energy thermic and electricity cooperation indicators set for all sectors of the housing estate Krasňany.

	Option 1		Option 2	
	eTCI [MWh/a]	eECI [MWh/a]	eTCI [MWh/a]	eECI [MWh/a]
Sector A	-5,075	+48	-2,990	+741
Sector B	-4,395	-829	-2,000	-570
Total area value	-9,470	-733	-4,989	+171
Sector C		+3,783		+3,783

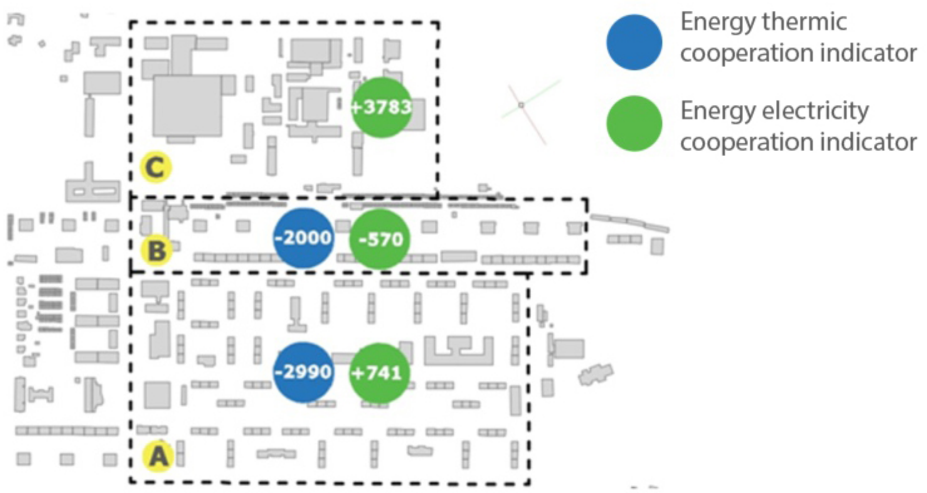

Figure 3: Energy cooperation indicators demonstrated in the case study of the housing estate Krasňany.

THE BRATISLAVA - PETRŽALKA CITY DISTRICT

This urban area is 13.2 hectares in size, with FAR of 1.27, built-up area index of 0.18 and population of about 2,970, corresponding to a density level of 225 inhabitants per hectare. It is located in the Petržalka - Dvory city district, bordered by Belinského, Ševčenková, Hálová streets, and the Chorvátske Rameno (river arm). It consists of two structurally different sectors. The first one, Sector A includes the eastern part of the territory adjacent to the river arm. It consists of nine pairs of 13 storey tower blocks with a cross floor plan arranged along a diagonal SW - NE axis to prevent mutual shading. Ancillary objects in this sector are two single-storey boiler houses. The sector has an area of 6.15 hectares and FAR of 1.45. This territory offers the space for 864 residential units with about 2,160 inhabitants, which corresponds to the density of 351 inhabitants per hectare. The second one, Sector B, covers the western part of the territory that is more varied in shape and typology of buildings. There are four six-storey linear prefabricated houses and three buildings of civic amenities: a single-storey shopping centre, a building of the Electrical Secondary School, and the Slovak Pedagogic Library located in the former kindergarten building. This sector has an area of 7.07 hectares and FAR of 1.12. This area provides space for 324 residential units with about 810 inhabitants (115 inhabitants/ha).

As with the previous case study, the energy performance of this urban area has been investigated according to three options. Option 0 and Option 1 have remained unchanged. Option 2 for Sector A is based on the Option 1 with the difference of better energy performance of building accomplished through thermal insulation and PV panels mounted on the south-facing façades of tower blocks.

SECTOR A

The current energy consumption for heating is 5,947 MWh/a. After the thermal insulation of building envelopes, in Option 1, this value could be reduced by 30% to 4,163 MWh/a. By covering the 15% of the roof surfaces with thermal collectors, one can secure 16% of the energy demand for DHW provision. Using the 45% of the flat roofs by PV panels, 25% of the annual electricity needs can be ensured. In Option 2, the energy demand for heating is reduced by 70% and the production of electricity is increased. The energy production potential in Option 2 reaches the level of 546 MWh/a, which is about 17% growth compared to Option 1 with 465 MWh/a. Overall, this measure has raised the coverage of electricity consumption from 25% to 29% (Table 5).

Table 5: Sector A (eastern part of the urban area - FAR 1.45) and characteristics of energy indicators of three options.

		Energy demand of buildings in sector [MWh/a]	Energy production of solar appliances [MWh/a]	Impact of energy efficiency measures on energy demand (ED)
Option 0	Heating	5,947		
	DHW	2,160		
	Electricity consumption	1,892		
Option 1	Heating	4,163		30% reduction of ED compared to Option 0
	DHW	2,160	336	16% coverage of ED
	Electricity consumption	1,892	465	25% coverage of ED
Option 2	Heating	1,784		70% reduction of ED compared to Option 0
	DHW	2,160	336	16% coverage of ED
	Electricity consumption	1,892	546	29% coverage of ED

SECTOR B

At present, the energy consumption for heating reaches 8,101 MWh/a. In Option 1, after the thermal insulation of buildings, this energy demand can be reduced by 30% to 5,670 MWh/a. Thermal collectors mounted on 15% of the rooftops can cover 253% of the energy demand for DHW provision. This phenomenon occurred because the flat roofs of civic amenities provide a greater area appropriate for the installation of thermal collectors. The hot water consumption in these buildings is also very low. Therefore, it is possible to envisage the cooperation with other tangential sectors (the *export* of DHW from the territory), similarly, the support of heating. The disadvantage is that the peak production (during summer period) does not correspond to the heating season. Using 45% of the flat roof surfaces for PV panels, and due to the presence of civic amenities objects as well, it is possible to cover 114% of the electricity consumption per year (Table 6).

Table 6: Sector B (western part of the territory - FAR 1.12) and characteristics of energy indicators of three options.

		Energy demand of buildings in sector [MWh/a]	Energy production of solar appliances [MWh/a]	Impact of energy efficiency measures on energy demand (ED)
Option 0	Heating	8,101		
	DHW	840		
	Electricity consumption	954		
Option 1	Heating	5,670		30% reduction of ED compared to Option 0
	DHW	310	785	253% coverage of ED
	Electricity consumption	955	1,086	114% coverage of ED
Option 2	Heating	2,430		70% reduction of ED compared to Option 0
	DHW	310	785	253% coverage of ED
	Electricity consumption	955	1,086	114% coverage of ED

Table 7: Electricity and thermal production per capita in the housing estate Petržalka calculated for Option 1.

	Electricity production per capita [kWh/a]		Thermal production per capita [kWh/a]	
Sector A	215	-	156	-
Sector B	1,340	+	969	-

Table 8: Energy thermal and electricity cooperation indicators set for sectors of the housing estate Petržalka.

	Option 1		Option 2	
	eTCI [MWh/a]	eECI [MWh/a]	eTCI [MWh/a]	eECI [MWh/a]
Sector A	-5,987	-1,427	-3,608	-1,346
Sector B	-5,195	+131	-1,955	+131
Total area value	-11,182	-1,296	-5,563	-1,215

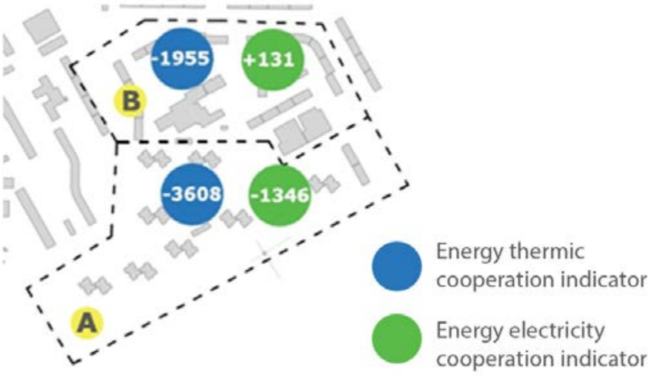

Figure 4: Energy cooperation indicators demonstrated in the case study of the housing estate Petržalka.

THE OSTREDKY HOUSING ESTATE

The Ostredky housing estate (within the city district Bratislava - Ružinov) was built in the 1960s in terms of the needs of socialist state, and it is based on the principles of modernism as a global architectural and urban stream. On an area of 77 ha, a strictly mono-functional residential urban structure for 10,000 inhabitants was created that consists of prefabricated apartment buildings including 4,290 apartments. It corresponds to the density level of 138 inhabitants per hectare. Some basic civic amenities (equipment for pre-school children, primary and secondary schools, retail and services centres) are situated there. This functionalist urban concept was designed during the energy careless era. It can be considered to be a loose-fitting settlement with a high ratio of unarticulated green areas without specified functional use. Because of its size, the territory has been divided into six sectors (A, B, C, D, E and F). Stratification respects the various types of buildings, their functional use or technical organisation of the area. Sector A contains only office buildings. The model of existing urban structure has been exposed to the simulation of annual solar irradiation on horizontal and vertical planes in order to examine its solar potential.

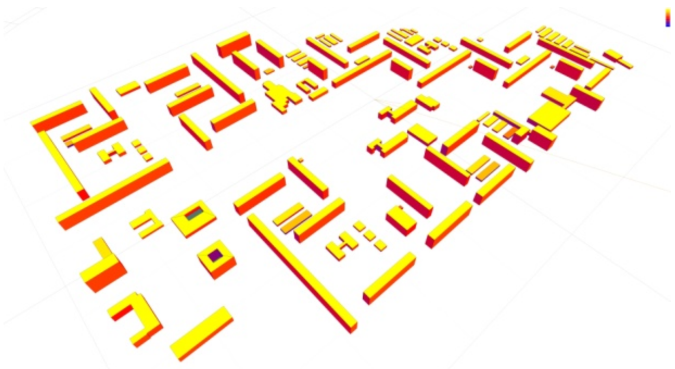

Figure 5: Solar potential of the urban structure Ostredky determined by using the simulation software Autodesk Ecotect Analysis.

The Ostredky housing estate has also been investigated in three options. The first, Option 0 shows the current state of energy consumption for heating and DHW provision, as well as the present power consumption. The second, Option 1 illustrates a model of reduction of energy use for heating by 30%. The supply of heat is partly secured by solar thermal collectors, which cover 15% of the roof surfaces. Electricity generation is ensured by PV panels covering 45% of the roof surfaces with an efficiency of 15%. In Option 2, the efficiency of PV panels is increased to 20%, covering 45% of the roof surfaces. The efficiency of solar thermal system is set to 40%, covering 15% of roofs and 30% of south facing building façades (walls without window openings, which have high potential for solar energy utilisation).

Current energy consumption for heating and DHW provision of the total housing estate area is 38,630 MWh/a. After basic renovations, within Option 1, this value can be reduced by 30% to 27,041 MWh/a. If only DHW provision were to be considered, thermal collectors mounted on 15% of the roof surfaces would be able to secure 82% of energy requirements. In Option 2, the combined DHW provision and heating demand have been reduced to 13,521 MWh/a. Due to increased efficiency and active solar surfaces extension, it would be possible to produce 97% of the heat consumed in a year (13,049 MWh/a) (Table 9).

Table 9: The Ostredky housing estate (summed up FAR 0.75) and characteristics of energy indicators of three options for heating and DHW provision and production.

	Option 0	Option 1		Option 2	
	Energy demand of buildings in sector [MWh/a]	Energy demand of buildings in sector [MWh/a]	Energy production of solar appliances [MWh/a]	Energy demand of buildings in sector [MWh/a]	Energy production of solar appliances [MWh/a]
Sector A	4,094	2,866	420	1,433	1,173
Sector B	4,447	3,113	459	1,556	1,458
Sector C	10,430	7,301	1,039	3,651	2,939
Sector D	7,755	5,428	1,300	2,714	3,467
Sector E	4,563	3,194	483	1,597	1,695
Sector F	7,341	5,139	780	2,569	2,318
Total area value	38,630	27,041	4,480	13,521	13,049

The total electricity consumption of the present Ostredky housing estate is 14,904 MWh/a. Utilising 45% of the flat roof surfaces for fitting PV panels, in Option 1, 54% of the annual electricity needs can be covered. In Option 2, the production of electricity is increased by higher efficiency of PV cells. Compared to Option 1, the consumption is 11,690 MWh/a, which means a 22% reduction of power supply requirements. This measure has raised the degree of electricity consumption coverage from 54% to 92% (Table 10).

Table 10: The housing estate Ostredky (summed up FAR 0.75) and characteristics of energy indicators of three options for electricity consumption and production.

	Option 0	Option 1		Option 2	
	Energy demand of buildings in sector [MWh/a]	Energy demand of buildings in sector [MWh/a]	Energy production of solar appliances [MWh/a]	Energy demand of buildings in sector [MWh/a]	Energy production of solar appliances [MWh/a]
Sector A	3,146	3,146	756	3,146	1,008
Sector B	1,636	1,636	825	1,095	1,101
Sector C	3,324	3,324	1,870	2,814	2,494
Sector D	2,439	2,439	2,339	1,643	3,119
Sector E	1,774	1,774	869	1,201	1,159
Sector F	2,586	2,586	1,404	1,790	1,872
Total area value	14,904	14,904	8,064	11,690	10,752

If the renewable energy production per capita is considered, most sectors are represented by negative values. Sector C is the exception, in which electricity production per capita reaches 1,072 kWh/a. This value is higher than the average annual power consumption per capita of 876 kWh/a. It results primarily from large roof surfaces of the civic amenities suitable for installation of PV panels combined with the lowest density of 104 inhabitants/ha. Sector D is characterised by low-rise buildings with the density of 137 inhabitants per hectare and in a year many garages can generate nearly the same amount of energy, which the sector consumes (Table 11).

Table 11: Electricity and thermal production per capita in the housing estate Ostredky calculated for Option 1.

	Electricity production per capita [kWh/a]		Thermal production per capita [kWh/a]	
Sector B	446	-	248	-
Sector C	1,072	+	595	-
Sector D	858	-	477	-
Sector E	444	-	246	-
Sector F	574	-	319	-
Total area value	679	-	377	-

Numerical values of energy thermic and electricity cooperation indicators have been calculated for both Option 1 and Option 2 (Table 12).

Table 12: Energy thermic and electricity cooperation indicators set for all sectors of the housing estate Ostredky.

	Option 1		Option 2	
	eTCI [MWh/a]	eECI [MWh/a]	eTCI [MWh/a]	eECI [MWh/a]
Sector A	-2,446	-2,390	-260	-2,138
Sector B	-2,654	-810	-99	+5
Sector C	-6,262	-1,454	-711	-3,121
Sector D	-4,129	-100	+753	+1,476
Sector E	-2,711	-904	+98	-42
Sector F	-4,359	-1,182	-252	+82
Total area value	-22,561	-6,840	-471	-938

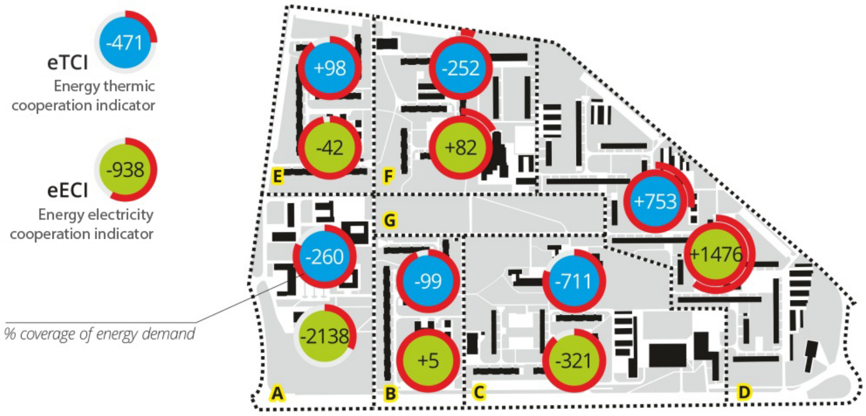

Figure 6: Energy cooperation indicators demonstrated in the case study of the housing estate Ostredky.

CONCLUSIONS

The case studies investigated have demonstrated that the securing of energy demand depends mainly on the types of building. Therefore, it requires site-specific solutions. In some cases, it is possible to cover the electricity consumption of whole urban areas with current technologies, especially, using the roof surfaces of buildings for PV panels. Low-rise apartment houses could, theoretically, achieve self-sufficiency in electricity production. Otherwise, densely built-up structures, especially, with high-rise buildings, do not have such a potential. By increasing the efficiency of PV panels and by reducing the energy demand of home appliances, the impact of energy efficiency measures will be greater. The disadvantage of this solution is the non-uniformity of the solar intensity distribution over time (summer/winter, day/night). Therefore, it is preferable to use the solar potential of roofs for heating and DHW provision by solar collectors due to their greater efficiency. The issue of the energy storage devices should be still examined.

According to the results, the energy demand for DHW provision can be increased to at least 50%. The size of the collector array varies with energy demands and the height of buildings. Because of the higher efficiency, solar thermal collectors now appear as a better alternative to PV panels. In order to achieve overall coverage of energy demand for heating and DHW provision, the solar potential is insufficient, because of the low intensity during the period of the highest energy consumption. For this reason, it is necessary to maximally exploit the potential of energy performance of buildings by means of thermal protection and, then, secure energy demand by renewable sources. The energy demand for heating can be significantly reduced to 30 kWh/m^2/a through deep renovation. In urban areas characterised by a significant proportion of buildings with a functional use other than housing, it is reasonable to consider energy cooperation with surrounding residential areas and to subsidise them by supplying electricity or hot water.

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