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MULTI-PURPOSE USE AND LIFECYCLE ANALYSIS OF SOLAR PANELS

VEČNAMENSKA UPORABA IN ANALIZA ŽIVLJENJSKEGA CIKLA SOLARNEGA PANELA

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Keywords: heat pump, life cycle analysis, Rankine cycle, solar panel, thermochemical cycle

Abstract

The combined use of renewable energy technologies and alternative energy technologies is a promising approach to reduce global warming effects throughout the world. In this paper, the solar panel is used in combination with a heat pump or with biomass sources to obtain heat, electricity, and hydrogen. Based on the Rankine thermodynamic cycle, hydrogen could be obtained from water with electrolysis and the CuCl thermochemical cycle. Furthermore, this study contains a life cycle analysis of solar panels.

Povzetek

Kombinirana uporaba tehnologij obnovljivih virov energije in tehnologij alternativnih energij je obetaven pristop za zmanjšanje učinkov globalnega segrevanja v svetu. V tem prispevku se sončna plošča uporablja v kombinaciji s toplotno črpalko ali z viri biomase za pridobivanje toplote, električne energije in vodika. Na podlagi Rankinovega termodinamičnega cikla bi lahko s pomočjo CuCl termokemičnim ciklom iz vode pridobivali tudi vodik. Poleg tega študija prikazuje analizo življenjskega cikla solarnega panela.

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1 INTRODUCTION

The production of electricity and heat from renewable sources is becoming more efficient and economically viable. Given current environmental problems, the utilization of renewable energy sources is becoming desirable. The demand for thermal energy accounts for more than half of the world's total energy needs. Currently, most of that heat is generated from hydrocarbons and their derivatives. Some small amounts are produced through renewable energy sources throughout the world. In the future, it is expected that the production of heat from renewable sources will significantly exceed the current level. For this purpose, all types of renewable energy sources should be taken into account. Particularly interesting is the use of solar energy with solar collectors, which have a yield of over 60%, *[1]*. Currently, there are several solar thermal generation systems, including plate collectors, vacuum collectors, and hot-air collectors, with which solar and thermal energy can be simultaneously obtained. In the foreground, there are also solar panels, which can be used in different ways: mounted on the roof, to cover the facades of houses, and similar. In this way, they could acquire a good portion of the energy required for home and industrial heating. Fig. 1 shows a wall mounting and a roof mounting of a solar panel with aluminium tubes and rock wool insulation material.

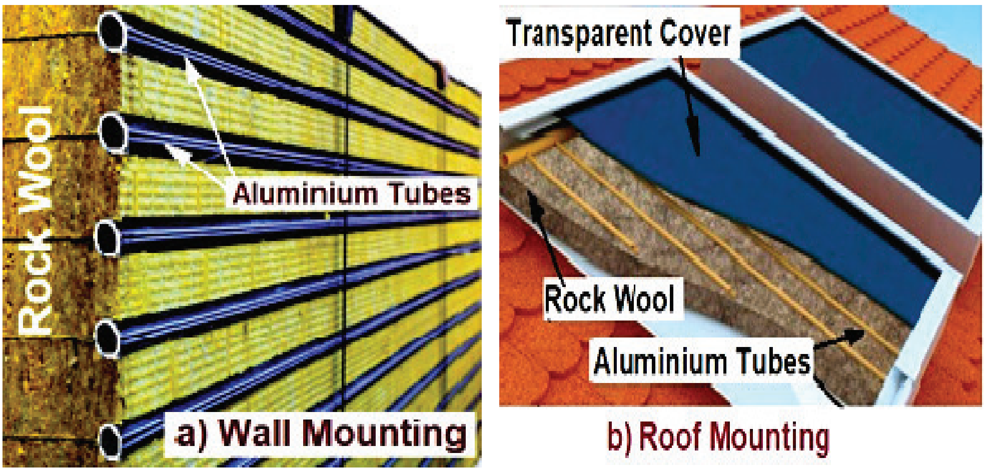

Figure 1: a) *a wall mounting solar panel and b) a roof mounting solar panel*

In this case, the solar panel is comprised of aluminium tubes, rock wool insulation material, transparent cover, circulation pump, etc. The panels are usually roof-mounted; however, they can also be mounted on the building walls or on frames on the ground.

The insulator located between represents the thermal building envelope and should keep heat losses as low as possible. If the solar panel is mounted in the wall, rock wool represents the thermal building envelope. Due to this sophisticated revision of sandwich panels, the field of application can be extended to office buildings, residential buildings, public buildings (e.g., education, culture, health, etc.).

2 SOLAR PANEL MULTI-PURPOSE USE ANALYSIS

2.1 The solar panel as a hydrogen producer

The main idea of the present article is the use of solar energy and biomass (wood chips) to produce cheap hydrogen. We combined two processes for hydrogen production: electrolysis and the thermochemical CuCl cycle. The working Rankine cycle system combined with the CuCl process, *[2]*, and the electrolysis system is presented in Fig. 2 and Fig. 3.

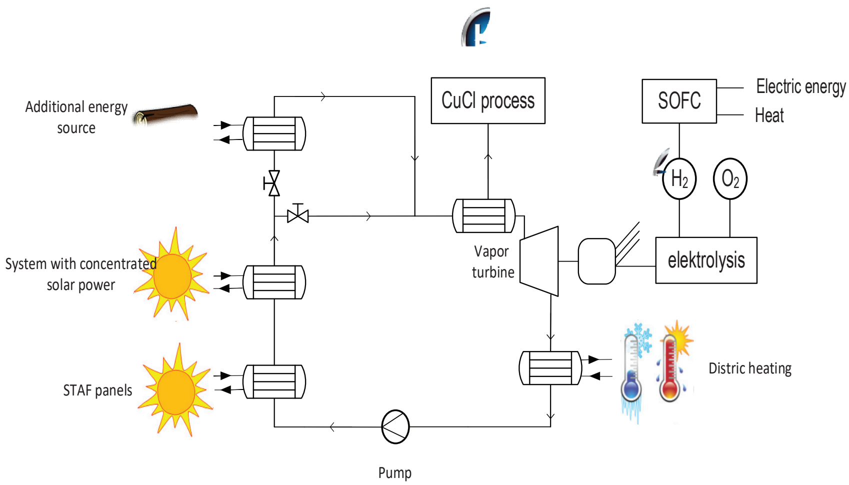

Figure 2: Solar panels in combination with Rankine cycle

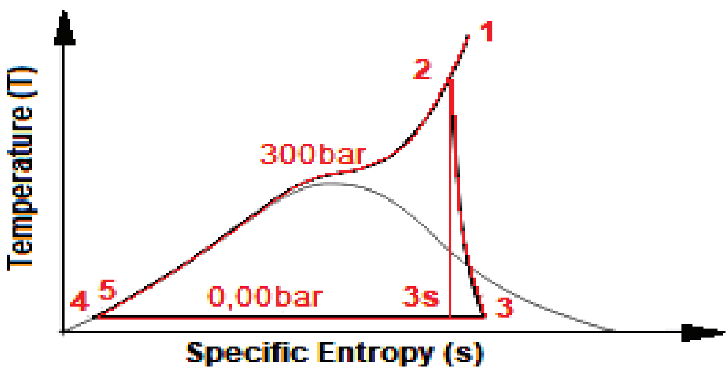

Figure 3: T-s diagram of the Rankine cycle

Apart from hydrogen production in the process, we can also use waste heat from the Rankine cycle for district low-temperature heating of buildings and houses. All necessary data to calculate thermodynamic efficiency are presented in Table 1.

***Table 1:** Results of the Rankine system calculation*

Rankine system and CuCl system		
State	***Pressure [bar]***	***Enthalpy [kJ/kg]***
1	300	3883.43
2	300	3599.4
3s	0.06	1972.8
3	0.06	2135.46
4	0.06	151.5
5	300	186.765
Parameter	***Value***	
$\dot{W}_t$	10 MW	
η_t	0.9	
$\dot{m}$	6.831 kg/s	
$\dot{Q}_c$	–13.552 MW	
$\dot{m}_w$	403.346 kg/s, ΔT = 8 K	
$\dot{W}_p$	240.9 kW	
η_p	0.85	
Q_{add}	25.252 MW	
$\dot{W}_{CuCl}$	1.94 MW	

This relatively small cogeneration unit was built for the Posavje region of Slovenia. The idea of the present work is primarily to exploit solar energy for hydrogen production. Large amounts of solar energy are available, especially in the summer, spring, and autumn. To this end, we have used a model of covered solar panels, with which we could obtain approximately 20 °C of temperature increase. Additional heat for the processes is obtained from wood chips. With the help of solar calculation software found on the web page "The European Commission's science and knowledge service", *[3]*, we have calculated the average amount of solar hours. For solar panels integrated into building for Posavje region, we calculated 1060 effective solar hours for solar angle 450 and 716 effective solar hours for solar angle 900.

Fig. 4 shows the production of hydrogen per day with the Rankine cycle system, electrolysis and CuCl system. On the basis of thermodynamic calculation, we could determine the amount of hydrogen produced by the CuCl process and by electrolysis per day. As seen in Fig. 4, the total production of hydrogen is 3931.5 kg/day; the ratio between the hydrogen obtained by electrolysis and the CuCl process is more than 5.

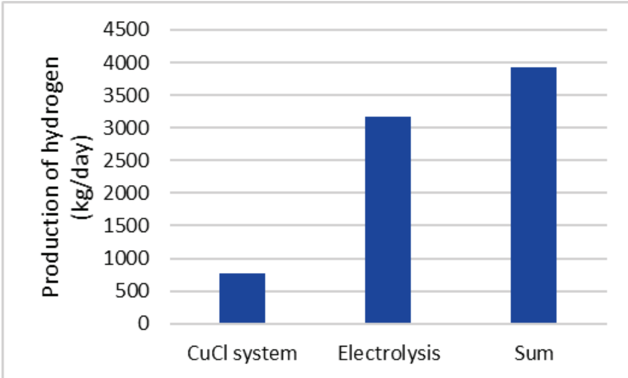

Figure 4: The amount of produced hydrogen

2.2 The solar panel as a cooling system

The use of thermal energy produced by a solar panel for cooling processes is also extremely interesting from a technical point of view. For this purpose, two cooling systems are presented. The first system represents cooling by means of an absorption refrigeration device and solar panels (Fig. 5). The second system represents cooling by means of solar panels, the ORC system and compressor heat pump (Fig. 6).

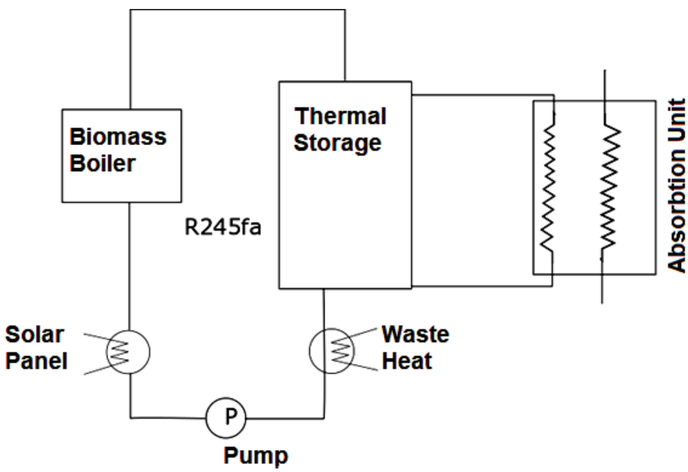

Figure 5: Cooling by means of an absorption cooling device and solar panel

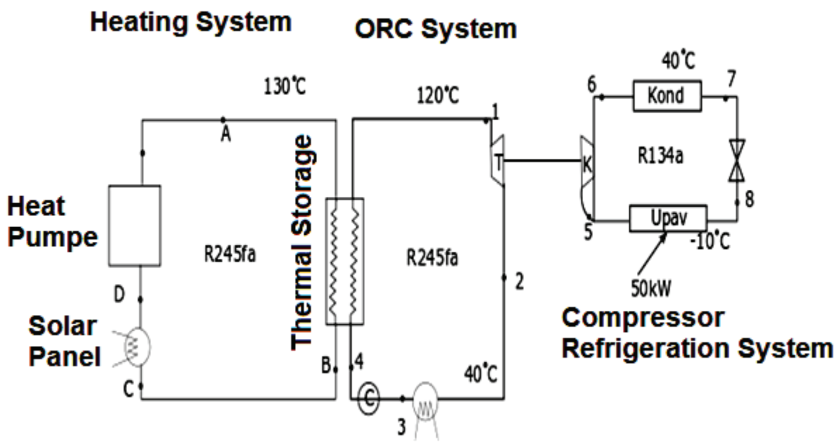

Figure 6: Cooling by means of solar panel, ORC system and compressor heat pump

3 LIFE CYCLE ANALYSIS OF SOLAR PANEL

Life cycle analysis is a tool for assessing the energy and environmental profile of a product or technology from design to recycling. It provides global guidance and criteria, based on which decisions are made on further product development and which accompany the product or technology throughout the life cycle. Life cycle analysis covers the entire energy and environmental aspect from production, transport, installation, lifetime and decommissioning of a product. It is a methodology that includes four life cycle phases in a comprehensive and transparent way, on the basis of facts and expertise and in conformity with the ISO 14040 standard *[4]*. These phases are study goal and scope definition, data acquisition, modelling and interpretation of results. As regards new process and product development, the relationship between processes, product characteristics and environmental impacts have to be taken into consideration for each product. The international ISO 14025 standard, *[5]*, was introduced to ensure comparable environmental efficiency among products. The main stages of life cycle analysis are presented in Fig. 7.

Figure 7: Main stages of life cycle analysis

The life cycle analysis of solar panels comprises several phases, and each phase covers input-output data on materials, energies and environmental impact factors. Other authors developed life cycle analysis in a similar way, *[6]*, *[7].* In the solar panel production phase, the life cycle analysis includes extraction, production and transformation of raw materials required for the manufacture of a solar panel first as a semi-finished product, then as a product and finally an end product. The phase of a life cycle analysis involving solar panel production comprises three steps: material production, product manufacturing, packaging, and distribution. The phase of a life cycle analysis involving the solar panel application includes installation, use, and maintenance of a solar panel. The phase of a life cycle analysis involving recycling and waste management includes energy consumption for solar panel recycling and waste management. The environmental factor assessing the environmental burden accompanies all life cycle stages. The life cycle analysis model of a solar panel comprises input-output data and system boundaries. The input data relates to the data on raw materials, energy and hazardous waste used for solar panel manufacture. The output data relates to air emissions, aqueous waste, solid waste, energy, recycled material, and other products. The air emission data includes the data on produced or reduced greenhouse gases of the solar panel life cycle. Aqueous waste affects water management due to its discharge into the environment and the related environmental impacts in the solar panel life cycle. Solid waste is waste generated in the solar panel life cycle without the possibility of recycling. The energy on the output data side constitutes the solar panel energy life cycle and is the ratio between the energy invested, required for the solar panel production, and energy generated by the solar panel in its life cycle. Recycled material is material that can be reprocessed or reused in any other way and has been used in the solar panel life cycle. Other products are undefined products, occurring in the solar panel life cycle. A schematic arrangement of the analysis model of the solar panel life cycle is presented in Fig. 8.

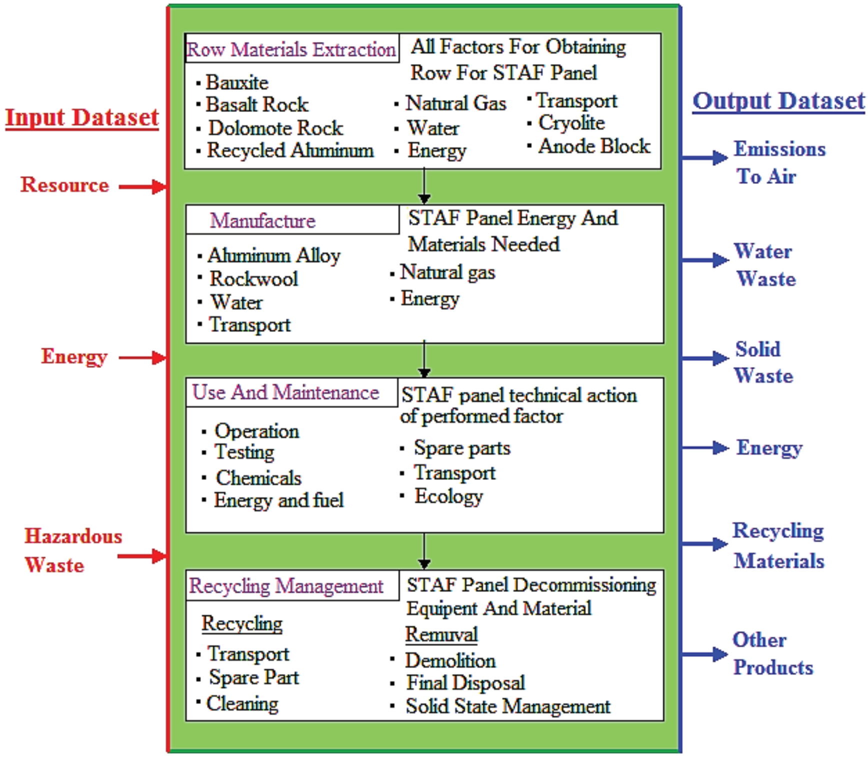

Figure 8: Schematic arrangement of solar panel life cycle analysis model

The quality of a life cycle analysis largely depends on the accuracy and precision of data and databases used. As a result of technological progress and increasingly stringent environmental regulations, the data and databases are constantly subject to changes and updates. The data from various databases differ because they are subject to various regional environmental regulations. The source of primary data in the life cycle analysis of a solar panel was the data provided by the solar panel manufacturer, i.e., Talum, d. d., *[8]*. As a secondary source of data, ee used the databases created by private or academic database developers: Ecoinvent Database, *[9]*, Eurostat, *[10]*, data from scientific literature, *[11]*, *[12]*, data from technical literature, *[13]*, *[14]*, etc. We split the data used in the life cycle analysis model of a solar panel into the following groups: materials, energy, waste, waste heat and air emissions.

3.1 Materials

The materials group contains all materials used in the life cycle analysis model of a solar panel. They were split into two groups, namely aluminium materials for production, installation and packaging of aluminium and materials for production, installation, and packaging of rock wool.

Table 2 shows the database of average quantities of materials used for the solar panel manufacture.

Table 2: *Average quantities of materials for solar panel manufacture*

Aluminium			Rock wool		
Material	**kg/panel**	**kg/kg(AL)**	**Material**	**kg/panel**	**kg/kg(KV)**
Water	1558.336	193.8	Water	-	4.468
Bauxite	39.774	5.100	Bauxite	-	0.086
PE-foil	0.183	0.082	PE-foil	-	0.009
Alumina	14.786	1.910	Briquettes	12.321	1.097
Anode blocks	3.502	0.450	Basalt rock	5.655	0.504
Coke	2.462	0.316	Portland cement	1.158	0.103
Aluminium fluoride	1.362	0.175	Dolomite rock	0.653	0.058
Tar pitch	0.494	0.063	Phenol	0.236	0.021
Green residue	0.045	0.006	Formaldehyde	0.236	0.021
Carbon residue	0.543	0.07	Impregnation	0.022	0.002
Calcium fluoride	0.008	0.001	Iron oxide	0.287	0.025
Cryolite	0.008	0.001	Acrylic dispersion	0.056	0.005
Calcined soda	0.004	0.0005	Total	-	6.399
Total	-	201.974	Total 2	20.624	
Total 1	1621.507				
Total 1+2	1642.131				

As much as 94.9% of water is consumed for the solar panel production, and such water is to a large extent disposed of into the environment as wastewater. The quantity of water required for alumina production is as high as 90%. On average, 39.77 kg of bauxite or 2.4% of the total material consumption is required for the manufacture of one panel. Total consumption of alumina and briquettes amounts to 1.6% of the overall material consumed for the manufacture of a single solar panel. The total quantity of material consumed is 1642.131 kg/panel. The overall amount of the material used for the production of one kilogram of aluminium is 201.974 $kg/kg_{(AL)}$, whereas the overall amount of the material used for the production of one kilogram of rock wool is 6.399 $kg/kg_{(KV)}$.

3.2 Energy

The energy group comprises all energies dealt with in the life cycle analysis model of a solar panel and used in the production or processing stages for the solar panel manufacture. Energy consumed by a solar panel during the one-year or the forty-year operation period and energy generated by the solar panel during the one-year or forty-year operation period is also taken into consideration. In solar panel energy production, the average annual solar radiation for Central Europe [15] is taken into consideration for south-facing orientation and tilt angle of 15°. The energy consumption was split into three groups. We used the consumption of energy per unit of one kilogram of aluminium for the aluminium production and transport, the energy consumption per unit of one kilogram of rock wool for the production and transport of rock wool and energy consumption per unit of solar panel for the manufacture and transport of solar panels. The one-year and forty-year energy consumption and production for solar panel operation are also included. The database of average energy amounts for the manufacture and operation of solar panels with south orientation and a tilt angle of 15° is shown in Table 3.

Table 3: *Average energy amounts for the manufacture and operation of solar panels with south orientation and a tilt angle of 15°*

Production, process, operation	kWh/kg$_{(AL)}$	kWh/kg$_{(KV)}$	kWh/pan
Primary aluminium	23.99	-	-
Secondary aluminium	2.61	-	-
Briquettes	-	0.579	-
Rock wool	-	1.879	-
Ship transport	0.18	-	-
Rail transport	0.03	-	-
Other transport	0.01	0.024	-
Aluminium panel manufacture	-	-	208.6408
Rock wool production	-	-	26.9895
Assembly and packaging	-	-	1.1772
Recycling	-	-	1.426
Consumption for one-year operation (1)	-	-	251.286
Production – one-year operation (2)	-	-	614.324
Consumption – 40-year operation (3)	-	-	698.616
Production – 40-year operation (4)	-	-	24572.96
Net production – one year (2-1)	-	-	363.038
Net production - 40 years (4-3)	-	-	23874.34

The amount of energy required for primary aluminium production and transport is 23.99 kWh/kg$_{(AL)}$ on average and 2.61 kWh/kg$_{(AL)}$ on average for secondary aluminium production and transport. The ratio between primary and secondary aluminium in the aluminium panel production is 80% to 20%. Rock wool is made from prefabricated briquettes.

The briquette production requires 0.579 kWh/kg$_{(KV)}$ of energy on average, and the rock wool production and transport, however, requires 1.879 kWh/kg$_{(KV)}$ of energy on average. Therefore, the overall energy required for the production and transport of one kilogram of rock wool amounts to 2.388 kWh/kg$_{(KV)}$.

We made a comparison between energy flows of average one-year and 40-year solar panel operation at the average annual solar radiation for Central Europe, south-facing orientation and a tilt angle of 15°. We also took into consideration the average consumption of energy for the operation of a circulating pump that sends a fluid to circulate through the solar panel. The average energy consumption for one-year operation, including the average energy consumption for solar panel manufacture and transport, amounts to 251.286 kWh/panel. In one year, a solar panel facing south and having a tilt angle of 15°, produces 614.324 kWh/panel on average. Net production in one year is the difference between the average annual energy produced and the average energy consumption for one-year operation, amounting to 363.038 kWh/panel. Furthermore, a similar calculation was made for the 40-year operation. Fig. 9 shows graphical presentations of average energies of the life cycle analysis of a solar panel.

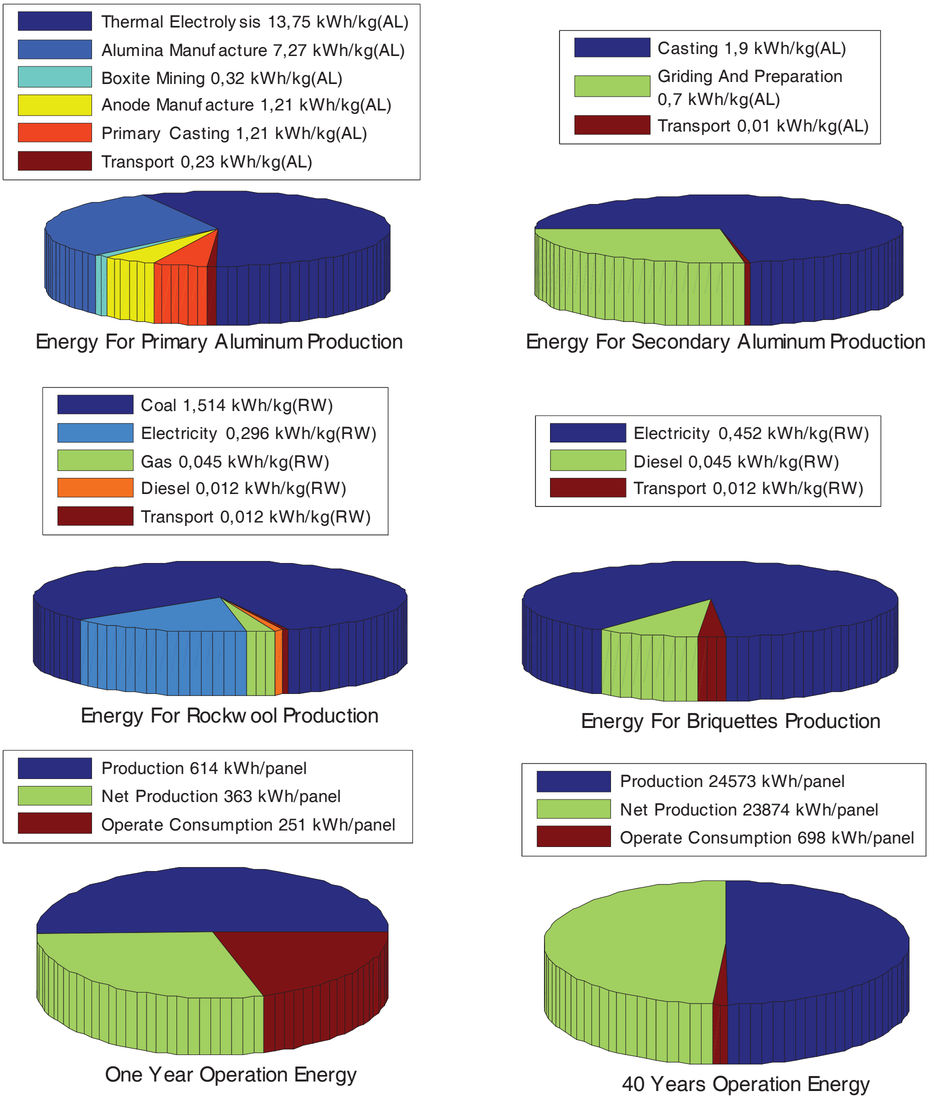

Figure 9: Graphical presentation of average energies of life cycle analysis of a solar panel

Over the one-year period of operation, a solar panel facing south and having at a tilt angle of 15° would produce 2.4 times more energy than the amount required for the manufacture, installation and one-year operation. Over the 40-year period of operation, a solar panel facing south and having a tilt angle of 15° would produce 35 times more thermal energy than the amount required for the manufacture, installation and 40-year operation of a solar panel.

3.3 Air Emissions

In the air emissions group, we used all emissions of CO_2, the greenhouse gas, covered by the model. The CO_2 emissions were split into three groups: emissions in the production and transport of primary raw materials, emissions in the production and transport of rock wool, and emissions in the manufacture and transport of solar panels. The database of average amounts of CO_2 for the manufacture and operation of a solar panel facing south and having a tilt angle of 15° is shown in Table 4.

Table 4: *Average amounts of CO2 for solar panel manufacture and operation*

Production, process, operation	**$kg_{(CO2)}/kg_{(AL)}$**	**$kg_{(CO2)}/kg_{(KV)}$**	**$kg_{(CO2)}$/panel**
Primary aluminium	10.471	-	-
Secondary aluminium	0.8447	-	-
Briquettes	-	0.3734	-
Rock wool	-	0.6181	-
Ship transport	0.0513	-	-
Rail transport	0.0081	-	-
Other transport	0.0027	0.007	-
Aluminium panel manufacture	-	-	83.127
Rock wool production	-	-	10.399
Assembly and packaging	-	-	0.457
Recycling	-	-	0.546
CO_2 production – one-year operation 1	-	-	98.898
CO_2 reduction – one-year operation 2	-	-	226.865
CO_2 production – 40-year operation 3	-	-	277.818
CO_2 reduction – 40-year operation 4	-	-	9074.604
Net reduction of CO_2 – one year (2-1)	-	-	127.97
Net reduction of CO_2 – 40 years (4-3)	-	-	8796.786

The amount of greenhouse gas emissions in the primary aluminium production and transport is 10.471 $kg_{(CO2)}/kg_{(AL)}$ on average and 0,8447 $kg_{(CO2)}/kg_{(AL)}$ on average in the secondary aluminium production and transport. The ratio between primary and secondary aluminium taken into consideration in the aluminium panel manufacture is 80% to 20%.

Rock wool is made of prefabricated briquettes. The amount of greenhouse gas emissions in the briquette production and transport is 0.3734 $kg_{(CO2)}/kg_{(KV)}$ on average and 0,6181 $kg_{(CO2)}/kg_{(KV)}$ on average in the rock wool production and transport. Therefore, the total amount of greenhouse gas emissions in the production and transport of one kilogram of rock wool is 0.9915 $kg_{(CO2)}/kg_{(KV)}$ on average. Graphical presentation of the average amount of released CO_2 of the life cycle analysis of a solar panel is shown in Fig. 10.

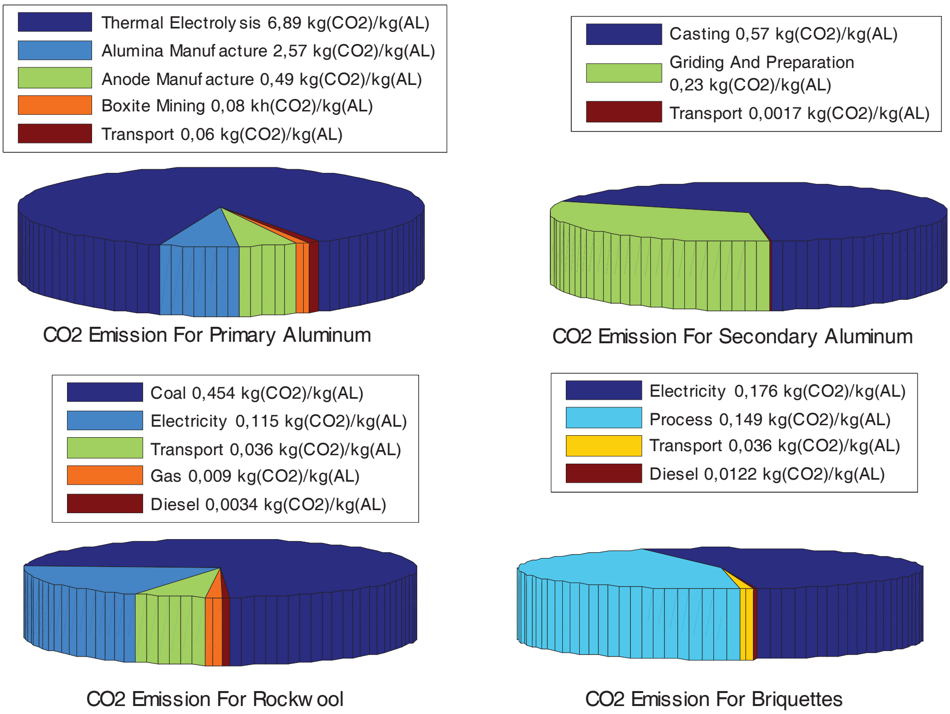

Figure 10: Graphical presentation of the average amount of released CO_2 of the life cycle analysis of a solar panel

3.4 Carbon Footprint

We made a comparison between the carbon footprint of one-year and 40-year operation of a solar panel facing south and having a tilt angle of 15°. All CO_2 gas emissions generated in all stages of solar panel manufacture and transport were taken into consideration in the operation, as well as the greenhouse gas emissions generated in the solar panel operation and circulating pump drive. Those greenhouse gas emissions were reduced by the amount of reduced greenhouse gases to obtain the carbon footprint result in the one-year and 40-year period. Reduced greenhouse gases are gases emitted into the air if the energy generated by a solar panel is produced by burning fossil fuels. The carbon footprint of one-year and 40-year operation of a solar panel facing south and having a tilt angle of 15° is shown in Fig. 11.

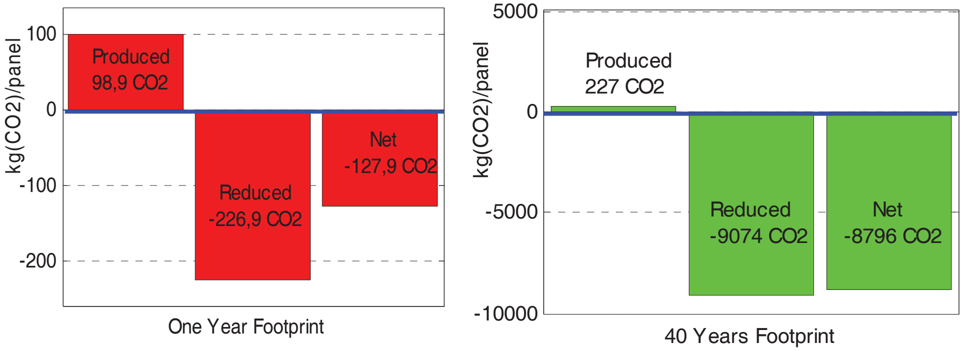

Figure 11: Carbon footprint of one-year and 40-year solar panel operation

Over the one-year period of operation of a solar panel facing south and having a tilt angle of 15°, 98.898 $kg_{(CO2)}$/panel of greenhouse gas are emitted into the air and 226.9 $kg_{(CO2)}$/panel of greenhouse gas are reduced. The one-year carbon footprint is negative, since over the one-year period of a solar panel operation, 127,9 $kg_{(CO2)}$/panel less CO_2 is emitted into the air than if the energy generated by a solar panel in one year is obtained by burning fossil fuels. Over the 40-year period of operation of a solar panel facing south and having a tilt angle of 15°, the amount of CO_2 emitted into the air is 227.818 $kg_{(CO2)}$/panel and the amount of CO_2 reduced is 9074.604 $kg_{(CO2)}$/panel. The 40-year carbon footprint is negative also in this case, since over the 40-year period of a solar panel operation, the amount of CO_2 emitted into the air is by 8796.786 $kg_{(CO2)}$/panel lower than if the energy generated by a solar panel in the period of 40 years is obtained by burning fossil fuels.

4 DISCUSSION AND CONCLUSION

The positive environmental impact of solar panels is reflected mainly in the green production of thermal energy and in its negative carbon footprint. The green production of thermal energy means that solar panels generate 35 times more thermal energy in their life cycle than the energy needed for raw materials production, manufacture, installation and transport of solar panels. The negative carbon footprint, in contrast, means that solar panels contribute in their life cycle to the CO_2 air emissions reduction in comparison with the thermal energy generated by solar panels by burning fossil fuels. Another advantage of solar panels is that at the end of their lifetime, the materials used in solar panels may be almost fully recycled and reused. A negative impact on the environment, however, is associated primarily with the production of aluminium used in solar panels. The aluminium production process requires huge amounts of water which, to a large extent, is disposed of as wastewater or red mud in alumina production. Moreover, the aluminium production process requires high consumption of electricity that is still largely generated in Slovenia by burning fossil fuels. The heat that is released in the aluminium production processes is almost entirely discharged into the environment.

Other heating systems operating in accordance with the solar radiation exploitation principle have characteristics and properties similar to solar panels. Energy payback time ranges from less than a year to three years. Carbon footprints of solar heating systems are negative, which means that they generate far fewer greenhouse gases than by using fossil fuel heating appliances. For example, a photovoltaic panel reduces greenhouse gas emissions, namely by 0.6 kg CO_2 for each kWh of energy produced. Furthermore, energy for the manufacture of photovoltaic panels is 30 times lower than the energy generated by a photovoltaic panel in its lifetime. The advantage of solar panels in comparison with other solar panels lies mainly in the fact that the materials used for the manufacture of solar panels can be easily almost fully recycled and reused.

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