LCA Analysis of STAF Panels and their Application for Heating; Cooling and Hydrogen Production

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Abstract

The combined use of renewable energy technologies and alternative energy technologies is a promising approach to reduce global warming effects in the world. In this paper, the so called "STAF (Solar Thermally Activated Façade)" panels are used in combination with a heat pump or with biomass sources to obtain heat, electricity and hydrogen. On the basis of the Rankine thermodynamic cycle we could obtain hydrogen from water with electrolysis and CuCl thermochemical cycle. Furthermore, this study shows numerical and experimental analysis of façade STAF panels which have a transparent cover in order to improve the efficiency of harvesting solar energy. Furthermore, this study shows a numerical analysis of the thermal behavior and efficiency of STAF panels with and without a transparent cover. A comprehensive life cycle analysis is also a part of this article.

Keywords: solar energy, façade panels, numerical analysis, LCA analysis

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 all the world's total energy needs. We currently generate most of that heat 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% (Chen et al., 2012). Currently, there are several solar thermal generation systems, such as plate collectors, vacuum collectors, hot-air collectors and collectors, with which solar and thermal energy can be simultaneously obtained. In the foreground, there are also solar panels, which can be used to cover the facades of houses. In this way, they could acquire a good portion of the energy required for home and industrial heating. The so called "Solar Thermally Activated Façade (STAF)" panel, which was developed in the course of the Interreg project "ABS-Network SIAT 125", has integrated fluid pipes at the exterior as well as at the interior metal sheet. Fig. 1 shows a schematic of the STAF panel with its formed aluminium sheets (absorbers) by using Roll Bonding technology (Avsec at al., 2018).

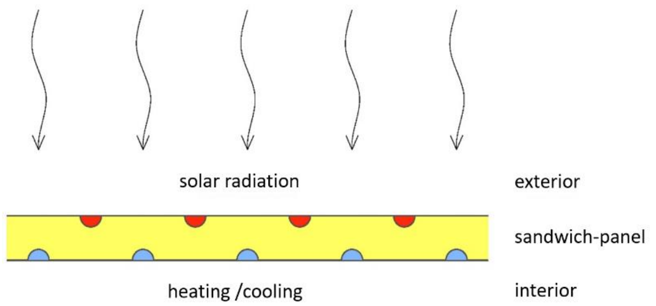

Fig. 1: Schematic of the Solar Thermally Activated Façade Panel

With this special sheet metal forming technique two metal sheets were combined to one steel plate whereby the

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fluid pipes are produced by inflation (one side or double side inflation). In case of the "one side inflation" method only one metal sheet is deformed whereas an equilateral deformation is realized in the "double side inflation" method. The exterior metal plate acts as an absorber of a solar thermal collector for conversion of solar energy into hot water whereas the interior metal plate can be used for heating and cooling of the interior space. Depending on the application and seasonal influences, a through the pipes flowing fluid enables the thermal use of solar energy (energy harvesting) on the exterior surface. In addition, the fluid is able to manage the thermal conditioning (heating and cooling) of the rooms on the interior surface. The insulator located between represents the thermal building envelope and should keep heat losses as low as possible. Due to this sophisticated revision of sandwich panels the field of application can be extended to office buildings, residential buildings, public buildings such as for education, culture, health etc.

2. Numerical analysis

In order to determine the temperature increase of the fluid in the exterior absorber of the STAF panel, the Computational Fluid Dynamics (CFD) method is used. Therefore, this study uses an already proved three dimensional CFD model which is extended by a simple transparent glass cover and an air gap (closed air-cavity) of 40 mm between the glass cover and exterior absorber. More information about the past CFD analysis, the model development and all the simulation model details and the CFD code can be found in the study of (Brandl et al. 2018). Generally, a pressure-based solver was used and the simulations were performed for steady state conditions. The widely used k-e realizable turbulence model with enhanced wall trematment was used, the gravity force was considered as well as the incompressible ideal gas law for the involved fluid in order to take into account the natural convection and buoyancy effects. With the help of the CFD simulations in this study, the fluid outlet temperatures and efficiency of a 3.5 x 1.0 m STAF panel is obtained, that is integrated in a Rankine process combined with the heat pump or fuel cell. Fig. 2 shows some details about the CFD model and the absorber geometry which is used in the analysis.

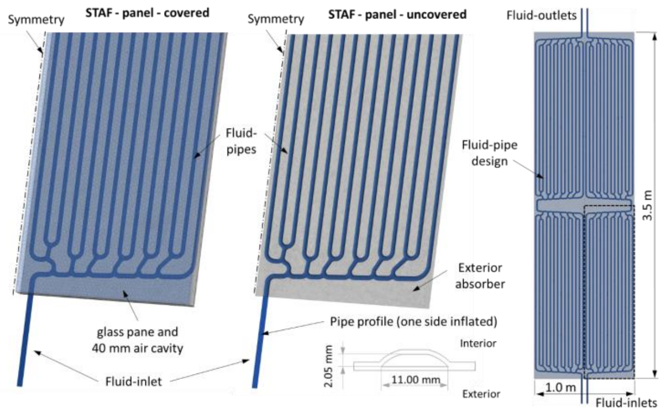

Fig. 2: Illustration of the CFD model of the covered and uncovered STAF panel

Generally, the exterior absorber consists of four connected single aluminum absorber sheets with a fluid pipe design which was suggested by the absorber producer (Talum d.d). Both, the covered as well as the uncovered STAF panel have the same pipe design, absorber sheet dimensions (1750 x 500 x 2.05 mm) and fluid pipe profile. All absorber which are based on Roll Bonding technology have a solar painting with a solar radiation absorptivity of 95 % and a long-wave emissivity of 86 %. For the glass cover a solar transmissivity of 90 % was assumed in the simulations. Since the STAF panel is symmetrical and has two fluid in- and outlets only one half of the panel needs to be modelled and calculated by definition of a model symmetry. The CFD mesh of the uncovered STAF panel contains 9.69 million polyhedral cells, the model of the covered STAF panel consists of 19.94 million polyhedral and hexahedron cells.

In order to determine the efficiency characteristics a parameter analysis is performed by varying exterior at least one of the following boundary conditions: temperature t_{ext}, solar radiation I_{Sol}, solar angle α_{Sol}, fluid flow rate $\dot{V}_{fluid}$ and inlet temperature $t_{fluid,in}$ or the effect of wind in form of an exterior heat transfer coefficient α_{ext}. The result of each scenario in the CFD analysis is a simulated fluid outlet temperature $t_{fluid,out}$, as well as the resulting thermal output $\dot{q}_{fluid}$ and efficiency η which is defined according to the following equations.

$$\dot{q}_{fluid} = \dot{V}_{fluid} \cdot \rho_{fluid} \cdot c_{p,fluid} \cdot \Delta T \quad \text{(eq. 1)}$$

$$\Delta T = t_{fluid,out} - t_{fluid,in} \quad \text{(eq. 2)}$$

$$\eta = \frac{\dot{q}_{fluid}}{I_{Sol} \cdot \cos(\alpha_{Sol})} \quad \text{(eq. 3)}$$

In this analysis water is used as fluid with a density of 998.2 kg/m³ and a specific heat capacity of 4182 J/kgK. The assumed boundary conditions as well as the simulation results are summarized in the following Table 1.

Table 1: boundary conditions and results of the CFD parameter analysis for a covered and non-covered STAF panel

Case	I_{Sol}	α_{Sol}	α_{ext}	t_{ext}	$t_{fluid,in}$	$\dot{V}_{fluid}$	$t_{fluid,out}$	ΔT	$\dot{q}_{fluid}$	η
	W/m²	°	W/m²K	°C	°C	l/h	°C	K	W/m²	-
STAF-uncovered-001	**1000**	**45**	**25**	**30**	**20**	**100**	**38.7**	**18.7**	**621**	**0.88**
STAF-uncovered-002	1000	45	25	30	10	100	34.6	24.6	818	1.16
STAF-uncovered-003	1000	45	25	30	30	100	42.7	12.7	422	0.60
STAF-uncovered-004	1000	45	25	30	40	100	46.7	6.7	223	0.31
STAF-uncovered-005	1000	45	25	30	50	100	50.6	0.6	21	0.03
STAF-uncovered-006	500	45	25	30	30	100	36.4	6.4	211	0.60
STAF-uncovered-007	500	45	25	20	30	100	30.5	0.5	17	0.05
STAF-uncovered-008	1000	45	25	20	30	100	36.9	6.9	229	0.32
STAF-uncovered-009	**500**	**20**	**25**	**-10**	**20**	**100**	**11.4**	**-8.6**	**-284**	**-**
STAF-covered-001	**1000**	**45**	**25**	**30**	**20**	**100**	**38.0**	**18.0**	**597**	**0.84**
STAF-covered-002	1000	45	25	30	20	80	42.0	22.0	583	0.82
STAF-covered-003	1000	45	25	30	20	60	48.2	28.2	560	0.79
STAF-covered-004	1000	45	25	30	20	50	52.7	32.7	542	0.77
STAF-covered-005	1000	45	25	10	20	100	34.8	14.8	492	0.70
STAF-covered-006	1000	45	25	-10	20	100	31.8	11.8	390	0.55
STAF-covered-007	1000	45	25	30	10	100	29.7	19.7	652	0.92
STAF-covered-008	1000	45	25	30	40	100	54.4	14.4	478	0.68
STAF-covered-009	1000	45	25	30	60	100	70.3	10.3	343	0.48
STAF-covered-010	1000	30	25	30	20	100	42.1	22.1	731	0.84
STAF-covered-011	1000	60	25	30	20	100	32.3	12.3	407	0.81
STAF-covered-012	1000	30	25	30	40	100	58.4	18.4	610	0.70
STAF-covered-013	1000	60	25	30	40	100	48.8	8.8	292	0.58
STAF-covered-014	1000	45	100	30	20	100	37.7	17.7	586	0.83
STAF-covered-015	1000	45	5	30	20	100	38.9	18.9	626	0.89
STAF-covered-016	500	45	25	30	20	100	29.9	9.9	328	0.93
STAF-covered-017	250	45	25	30	20	100	25.7	5.7	189	1.07
STAF-covered-018	1000	0	25	30	20	100	45.6	25.6	847	0.85
STAF-covered-019	1000	45	25	30	80	100	85.8	5.8	192	0.27
STAF-covered-020	1000	45	25	30	90	100	93.3	3.3	110	0.16
STAF-covered-021	1000	45	25	30	95	100	97.0	2.0	68	0.10
STAF-covered-022	**500**	**20**	**25**	**-10**	**20**	**100**	**26.6**	**6.6**	**220**	**0.47**

Fig. 3 and 4 show a comparison of the temperature contours between covered and uncovered STAF panel at different climate conditions. While at hot climate conditions the performance is very similar (slightly better for uncovered STAF panel) the uncovered STAF panels cannot keep up with the covered panels for intermediate and especially at cold climate conditions (Fig. 4). While the temperature is heated up from 20 °C to 26.6 °C inside the covered STAF panel, the fluid is cooled down to 11.4 °C in the uncovered STAF panel.

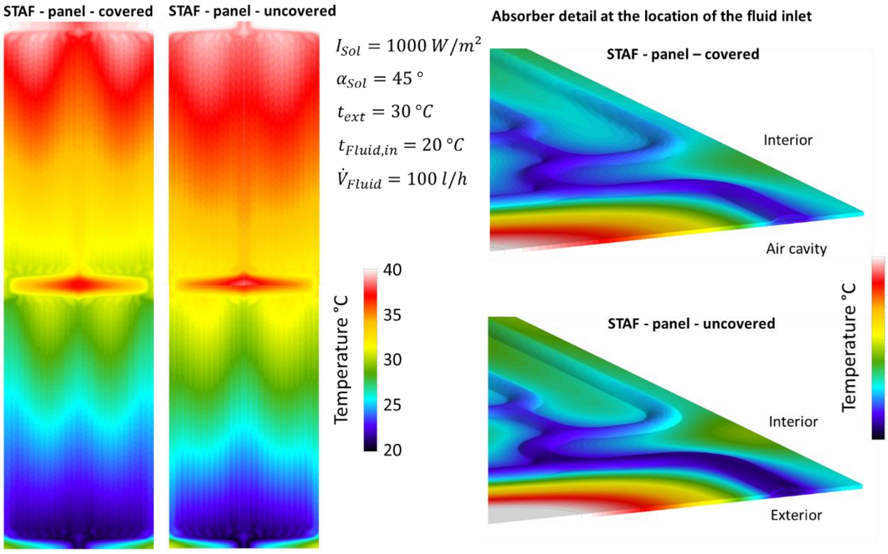

Fig. 3: Comparison of the absorber´s temperature contours between covered and uncovered STAF panel at hot climate conditions.

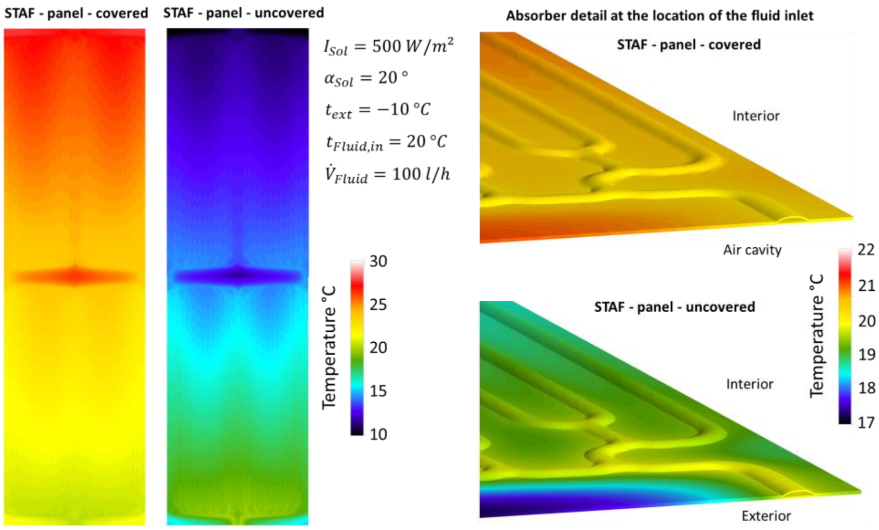

Fig. 4: Comparison of the absorber´s temperature contours between covered and uncovered STAF panel at cold climate conditions.

With the help of the results from Table 1 an efficiency curve is created according to the definition of the collector efficiency curve which can be found in literature (Duffie, J. & Beckman, 1991). The following equation shows the mathematical description of the collector efficiency curve, C_0 is the Solar conversion coefficient, C_1 is the coefficient for the convective thermal losses and C_2 the coefficient for the radiative thermal losses. $I_{Sol,p}$ is the Solar radiation perpendicular to the absorber surface of the solar thermal collector, $t_{surf,avg}$ is the surface averaged temperature of the absorber.

$$\eta = C_0 - C_1 \cdot \frac{t_{surf,avg} - t_{ext}}{I_{Sol,p}} - C_2 \cdot \frac{(t_{surf,avg} - t_{ext})^2}{I_{Sol,p}} \qquad \text{(eq. 4)}$$

Fig. 5 shows the resulting collector efficiency curves for the covered as well as the uncovered STAF Panel in comparison with efficiency curves from (high efficient) solar thermal collectors which are available on the market

(SPF, 2019). Again you can see that the efficiency of the uncovered STAF (red, dotted line) panel is very good at high exterior temperatures but rapidly decreases with exterior temperatures. In this state the STAF panel with (the simple) glass cover (green, dotted line) cannot keep up with the efficiency of such solar thermal collectors (black and green, dashed lines) which have special solar glasses and selective solar coatings but with some material and constructive improvements it might be possible to come close to such efficiencies.

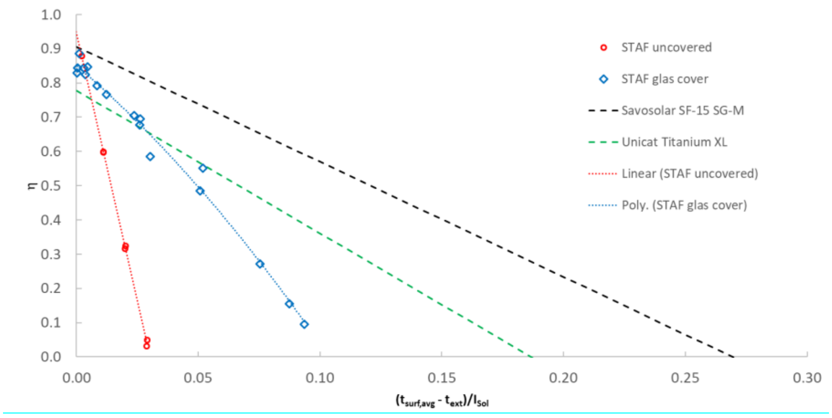

Fig. 5: Comparison of the collector efficiency curve between covered and uncovered STAF panels.

3. The application of STAF panels

The main idea of the presented article is the use solar energy and biomass (wood chips) to produce cheap hydrogen. In the article we combined two processes for hydrogen production, electrolysis and thermochemical CuCl cycle. The working Rankine cycle (RC) system combined with the CuCl process (Avsec and Novosel, 2016) and electrolysis system is presented in Fig. 6. Apart from hydrogen production in the process, we can also use waste heat from the Rankine process for district low-temperature heating of buildings and houses. All necessary data to calculate thermodynamic efficiency are presented in Table 2. This relatively small cogeneration unit was built for the case of Posavje region. The idea of the presented work is primarily to exploit solar energy for hydrogen production. The big amounts of solar energy are available especially in the summer, spring and autumn period. To this end, we have used a model of covered STAF panels (Table 1), where we could obtain approx. 20 °C of temperature increase. Additional heat fort he process we obtain from woof cheaps. With help of solar calculation software found on the web page, http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php, we have calculated the average amount of solar hours. For STAF panels integrated in building for Posavje region we calculated 1060 effective solar hours for solar angle 45^{0}and 716 effective solar hours for for solar angle 90^0.

Table 2: 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	
$\dot{Q}_{add}$	25.252 MW	
$\dot{W}_{CuCl}$	1.94 MW	

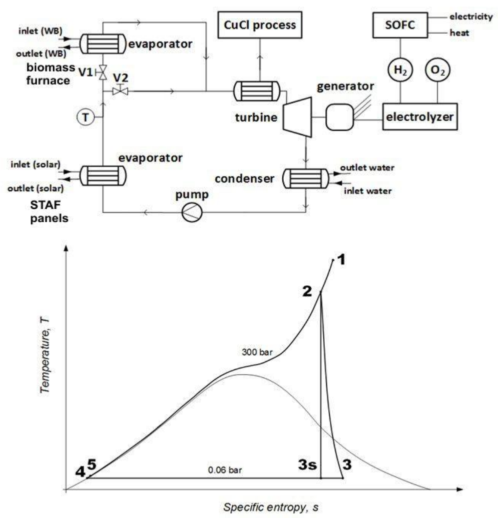

Fig. 6: STAF panels in combination with Rankine cycle

Fig. 7 shows production of hydrogen per day with the RC system, electrolysis and CuCl system. On the basis of thermodynamic calculation we could determine the amount of hydrogen produced by CuCl process and by electrolysis per day. As can be seen from Fig. 7, 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.

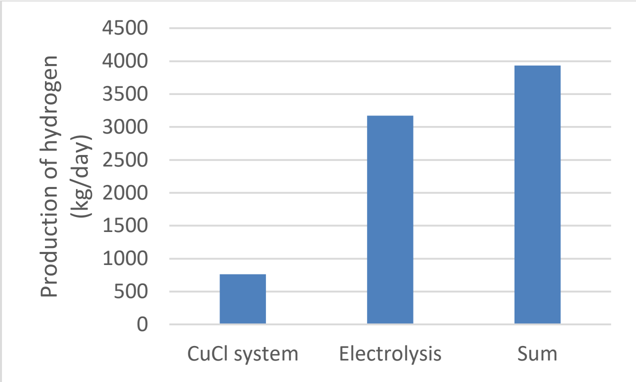

Fig. 7: The amount of produced hydrogen

4. LCA analysis

LCA (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. LCA covers the entire energy and environmental aspect from production, transport, installation, lifetime and decommissioning of a product. LCA is a methodology, which includes four life cycle phases in a comprehensive and transparent way, on the basis of facts and expertise and in conformity with (ISO, 14040) standard. These phases are: study goal and scope definition, data acquisition, modelling and interpretation of results. As regards new process and product development, relationship between processes, product characteristics and environmental impacts have to be taken into consideration for each product. The international (ISO, 14025) standard was introduced to ensure comparable environmental efficiency among products.

The LCA of STAF panels comprises several phases, whereby each phase covers input output data on materials, energies and environmental impact factors. Some other authors developed LCA in a similar way (Springer, 2018), (Millera et al., 2019) and (Kim et al., 2019). In the STAF panel production phase, the LCA includes extraction, production and transformation of raw materials required for the manufacture of a STAF panel first as a semi-finished product, then as a product and finally an end product. The phase of an LCA involving STAF panel production comprises three steps: material production, product manufacturing, packaging and distribution. The phase of an LCA involving the STAF panel application includes installation, use and maintenance of a STAF panel. The phase of an LCA involving recycling and waste management includes energy consumption for STAF panel recycling and waste management. The environmental factor assessing the environmental burden accompanies all life cycle stages. The LCA model of a STAF panel comprises input output data and system boundary. The input data relates to the data on raw materials, energy and hazardous waste used for STAF 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 STAF panel life cycle. Aqueous waste affect water management due to its discharge into the environment and the related environmental impacts in the STAF panel life cycle. Solid waste is waste generated in the STAF panel life cycle without the possibility of recycling. Energy on the output data side constitutes the STAF panel energy life cycle and is the ratio between the energy invested, required for the STAF panel production, and energy generated by the STAF 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 STAF panel life cycle. Other products are undefined products, occurring in the STAF panel life cycle. A schematic arrangement of the STAF panel LCA model is presented in Fig. 8.

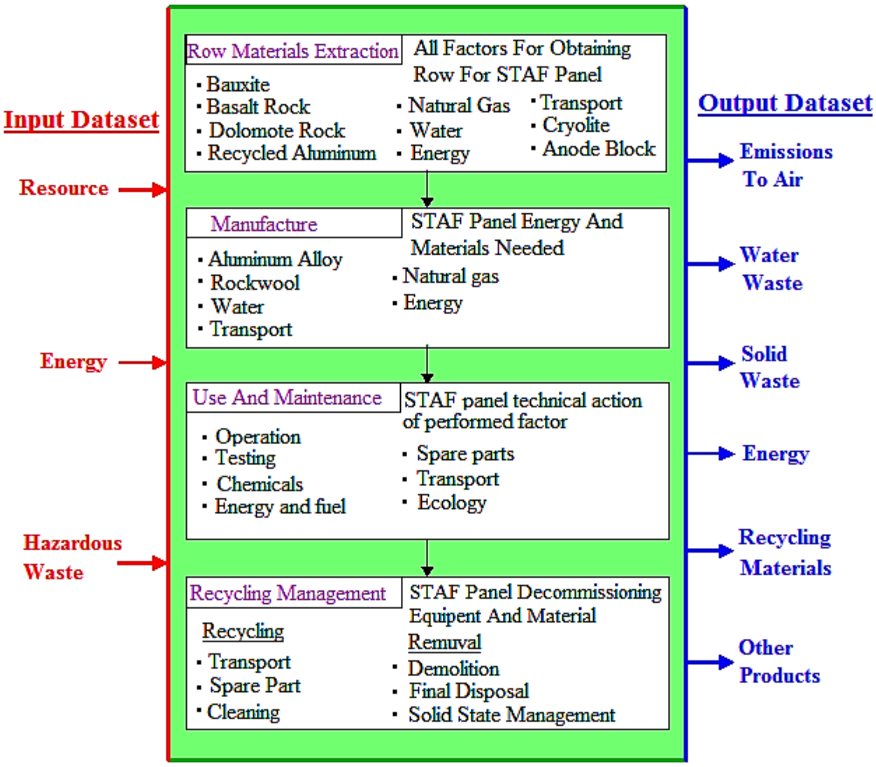

Fig. 8: Schematic arrangement of STAF panel LCA model

The quality of an LCA largely depends on 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 differs, because it is subject to various regional environmental regulations. The source of primary data in the LCA of a STAF panel was the data provided by the STAF panel manufacturer, i.e. (Talum d. d.). We used as a secondary source of data the databases created by private or academic database developers, such as: (Ecoinvent Database), (Eurostat), data from scientific literature (Gielen and Dril), (Farjana et al., 2019), (Palazzo and Geyer, 2019) and (Liu et al., 2017). Data from technical literature (U.S. Energy, 2007), (Calculation of fuel, 2014), (Flury and Frischknecht, 2012), (Farjana et al., 2019) etc. We split the data used in the LCA model of a STAF panel into the following groups: materials, energy, waste, waste heat and air emissions.

4.1 Materials

The materials group contains all materials used in the LCA model of a STAF panel. The materials 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 3 shows the database of average quantities of materials used for the STAF panel manufacture.

Table 3: Average quantities of materials for STAF panel manufacture

Aluminium			Rock wool		
Material	kg/panel	$kg/kg_{(AL)}$	Material	kg/panel	$kg/kg_{(RW)}$
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 STAF panel production and such water is to a large extent disposed of into the environment as waste water. 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 STAF 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 $kg/kg_{(RW)}$.

4.2 Energy

The energy group comprises all energies dealt with in the LCA model of a STAF panel and used in the production or processing stages for the STAF panel manufacture. Energy consumed by a STAF panel during the one-year or the forty-year operation period and energy generated by the STAF panel during the one-year or forty-year operation period is also taken into consideration. In the STAF panel energy production, the average annual solar radiation for Central Europe (ARSO, 2019) 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 one STAF panel for the manufacture and transport of STAF panels. The one-year and forty-year energy consumption and production for STAF panel operation are also included. The database of average energy amounts for the manufacture and operation of STAF panels with south orientation and a tilt angle of 15° is shown in Table 4.

Table 4: Average energy amounts for manufacture and operation of STAF panels with south orientation and a tilt angle of 15°

Production, process, operation	$kWh/kg_{(AL)}$	$kWh/kg_{(RW)}$	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 $kWh/kg_{(RW)}$ of energy on average, and the rock wool production and transport, however, 1.879 $kWh/kg_{(RW)}$ of energy on average. Therefore, the overall energy required for the production and transport of one kilogram of rock wool amounts to 2.388 $kWh/kg_{(RW)}$.

We made a comparison between energy flows of average one-year and 40-year STAF 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 STAF panel. The average energy consumption for one-year operation, including the average energy consumption for STAF panel manufacture and transport, amounts to 251.286 kWh/panel. In one year, a STAF 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 LCA of a STAF panel.

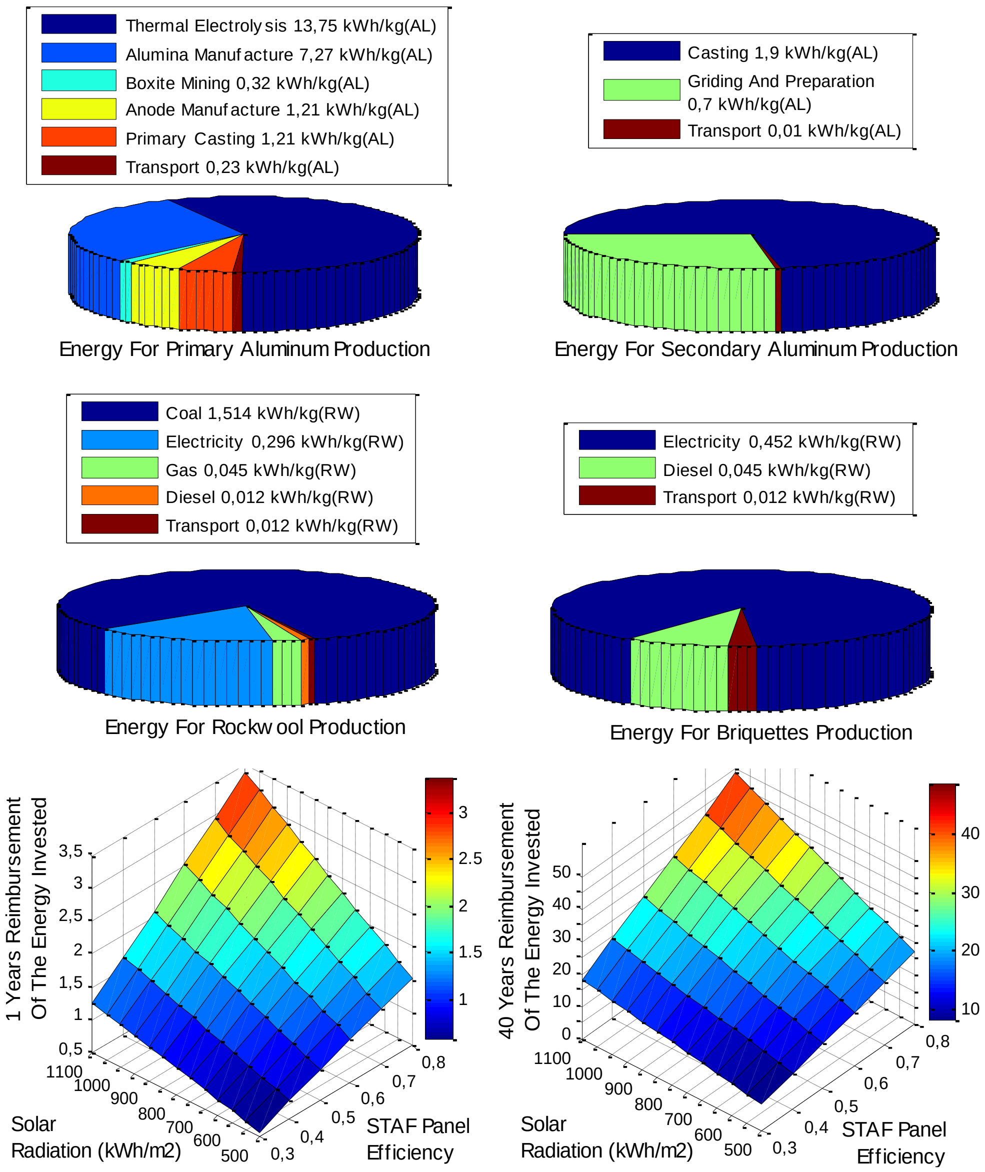

Fig. 9: Graphical presentation of average energies of LCA of a STAF panels

Over the one-year period of operation, a STAF 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 STAF 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 STAF panel.

4.3 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 STAF panels. The database of average amounts of CO_2 for the manufacture and operation of a STAF panel facing south and having a tilt angle of 15° is shown in Table 5.

Table 5: Average amounts of CO_2 for STAF panel manufacture and operation

Production, process, operation	$kg_{(CO2)}/kg_{(AL)}$	$kg_{(CO2)}/kg_{(RW)}$	$kg_{(CO2)}$/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

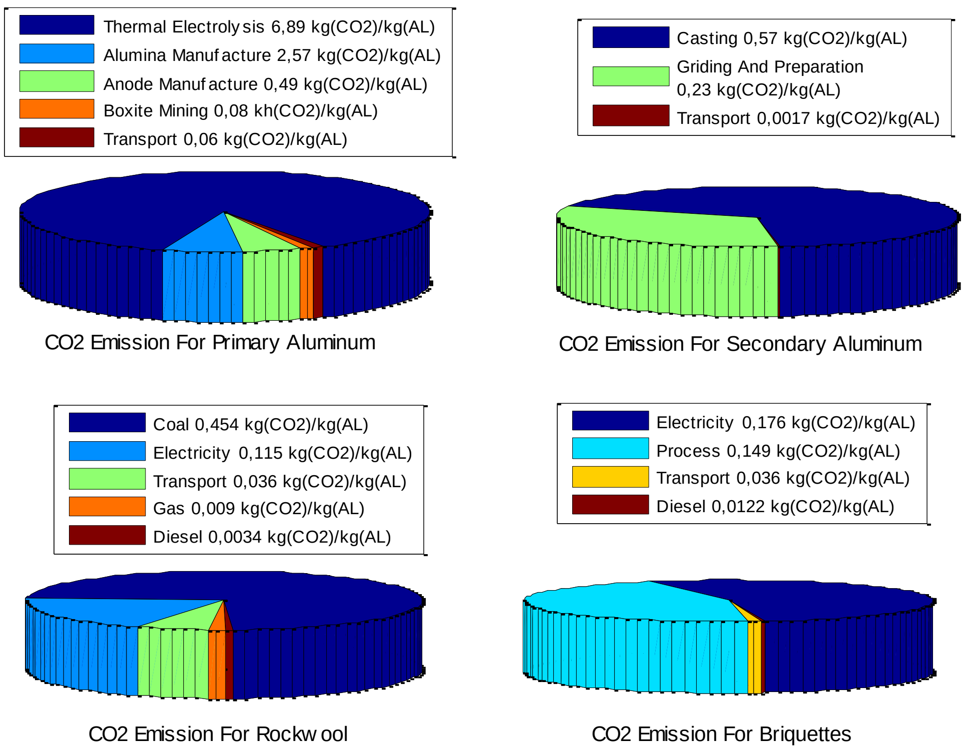

Fig. 10: Graphical presentation of average amount of released CO_2 of the LCA of a STAF panel

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 $kg_{(CO2)}/kg_{(RW)}$ on average and 0,6181 $kg_{(CO2)}/kg_{(RW)}$ 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 $kg_{(CO2)}/kg_{(RW)}$ on average. Graphical presentation of the average amount of released CO_2 of the LCA of a STAF panel is shown in Fig. 10.

4.4 Carbon footprint

We made a comparison between the carbon footprint of one-year and 40-year operation of a STAF panel facing south and having a tilt angle of 15°. All CO_2 gas emissions generated in all stages of STAF panel manufacture and transport were taken into consideration in the operation, as well as the greenhouse gas emissions generated in the STAF 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 energy generated by a STAF panel is produced by burning fossil fuels. Carbon footprint of one-year and 40-year operation of a STAF panel facing south and having a tilt angle of 15° is shown in Fig. 11.

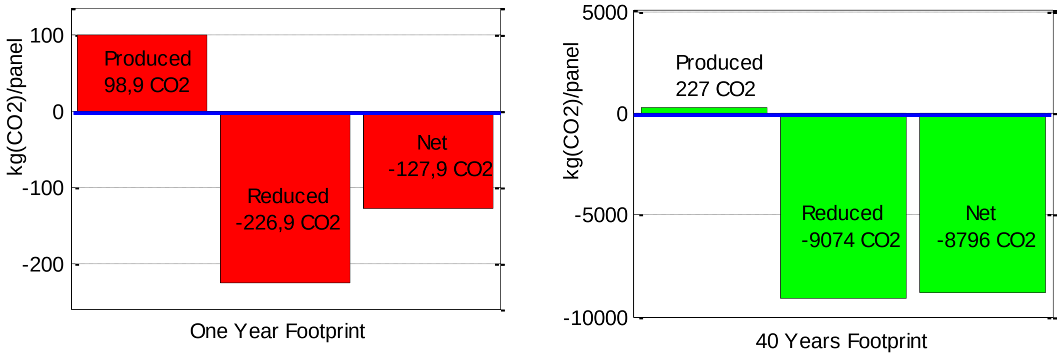

Fig. 11: Carbon footprint of one-year and 40-year STAF panel operation

Over the one-year period of operation of a STAF 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 STAF panel operation, 127,9 $kg_{(CO2)}$/panel less CO_2 is emitted into the air than if the energy generated by a STAF panel in one year is obtained by burning fossil fuels.

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