LIFE CYCLE ASSESSMENT OF ENERGY GREEN TRANSITION GOALS IN SLOVENIA AND SERBIA: HEAT PUMP EXAMPLE

Jelena TOPIĆ BOŽIČ [1,2*], ***Simon MUHIČ*** [1,2,3], ***Mirko S. KOMATINA*** [4], ***Milica M. PERIĆ*** [5], ***Jože DIMNIK*** [6]

[1] Faculty of Industrial Engineering Novo mesto, Šegova ulica 112, 8000 Novo mesto, Slovenia

[2] Rudolfovo - Science and Technology Center Novo mesto, Podbreznik 15, 8000 Novo mesto, Slovenia

[3] Institute for Renewable Energy and Efficient Exergy Use, Cesta 2. grupe odredov 17, 1295 Ivančna Gorica, Slovenia

[4] University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, 11000 Belgrade, Serbia

[5] Innovation Center of the Faculty of Mechanical Engineering in Belgrade, Kraljice Marije 16, 11120 Belgrade 35, Serbia

[6] Ministry of the Environment, Climate and Energy, Langusova cesta 4, 1000 Ljubljana, Slovenia

[*] Corresponding author; e-mail: jelena.topic.bozic@rudolfovo.eu

Heat pumps are a promising technology to reduce greenhouse gas emissions (GHGE). Their use benefits from decarbonization of the national electricity mixes across the EU, as running on cleaner electricity would reduce the emissions associated with the heat generated from heat pumps. The study aimed to perform a life cycle assessment (LCA) to compare the impact of using heat pumps as a heating source in Slovenia and Serbia under different electricity scenarios that align with measures presented in National Energy and Climate plans. The results show significant differences in the environmental profiles of Serbian and Slovenian electricity sectors and improvements from the current to the future mixes (2030) with a higher share of renewables such as photovoltaics. In the impact category of global warming, an 84.7 % higher value of 1 MJ of heat produced by ground source heat pump in Serbia (0.080 kg CO_2 eq) was observed compared to Slovenia (0.033 kg CO_2 eq) and 85.9 % higher value compared to Europe (0.032 kg CO_2 eq). The reduction in the impact category global warming in NECP 2030 scenarios that model reduction in coal and increase solar PV was observed in both countries (-17.1% Serbia; -28.6 % Slovenia). On the other hand, an increase in the impact category of mineral resource scarcity was observed, with values higher in Slovenia than in Serbia due to a higher share of PV. The study demonstrates that LCA provides a powerful tool to consider GHGE reduction and other environmental impacts, such as land use and mineral resource scarcity, and it can be used to support decision-

makers dealing with future national energy plans and decarbonization strategies.

Keywords*: life cycle assessment, decarbonization, heat pumps, Slovenia, Serbia, green transition*

1. Introduction

Renewable energy systems (RES) are under the spotlight to fulfill Sustainable Development Goals (SDGs) [1]. The European Union (EU) adopted the European Climate Law (ECL), which writes into law the goal set in the European Green Deal: to become climate-neutral by 2050 [2,3]. The ECL sets an intermediate target goal of reducing net greenhouse gas emissions (GHGE) by at least 55 %, compared to 1990 levels [4,5].

The heating sector is a significant contributor to climate change, and in Europe, 67 % of final energy use in the building sector is used for space heating and 13 % for water heating [6,7]. The heating sector significantly contributes to climate change, emphasizing the need for sector decarbonization [7,8]. Based on the 2022 Eurostat data final energy use in residential sector, the shares of energy use for space heating and water heating in Slovenia is 61.4 % and 16.5 %, while in Serbia, it is 65.9 % and 11.9 % [9]. Although electrification of heating is an often-cited approach to decarbonizing the heating sector [9], challenges remain, as extensive electrification can burden the system heavily and require capacity expansions [10]. Depending on the electricity mix, rising demand might produce additional CO_2 emissions [11]. With the increased awareness about reducing energy use and lowering environmental impact, the issue of home energy use has attracted a lot of attention [12]. Electricity generation significantly contributes to global GHGE, NOx, and SO_2 emissions and their related impact. However, GHGE alone cannot be used as a single indicator to represent the environmental impact of a system or technology. As electricity use is a major hotspot in many products' environment, electricity production's environmental impact can be measured with life cycle assessment (LCA) [13,14]. The LCA approach has been used to evaluate the environmental sustainability of several electrical country mixes such as Italy [15,16], Ecuador [17], United Kingdom [18], and Spain [19].

In **Fig 1,** electricity generation source profiles are shown, and these vary greatly between Slovenia and Serbia [20,21]. The electricity in Serbia is mainly produced from thermal power plants (63.2 %), followed by hydropower plants (31.3 %). The wind has 2.8 % share. In contrast, Slovenia's thermal power plant electricity production accounts for 23.7 % share. Nuclear (41.1 %) and hydropower (25.0 %) are the two sources with the highest share. Regarding solar and wind power electricity generation, wind power in Serbia accounts for 2.8 % share, while in Slovenia the share is

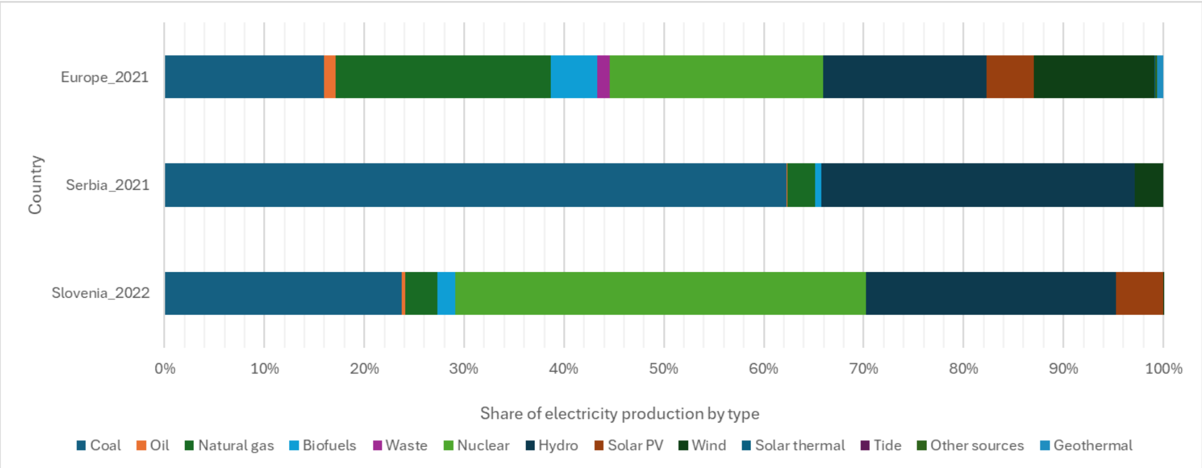

Fig. 1: Comparison of electricity production share by source (source of data [20, 21].

less than 0.1 %. In contrast, solar power in Slovenia has 4.7 % share, while in Serbia solar power share is lower than 0.1 % [20,21].

In terms of electricity imports, the IEA data for 2021 and 2022 show that Slovenia's net electricity imports amounted to 11.4 %, compared to 2.2 % in Serbia, highlighting the higher import dependency of Slovenia [20,21]. Compared to Slovenia and Serbia, Europe has, in general, a lower share of coal and a higher share of wind and natural gas for electricity generation. Additionally, nuclear power has 21.4 % share in Europe, compared to 41.1 % in Slovenia.

To reach EU's declared energy and climate targets by 2030, the EU member and accession countries have drafted and elaborated their 10-year integrated National Energy and Climate Plans (NECP) that will be implemented during 2021 – 2030 [22]. Slovenia published its original integrated NECP in February 2020, setting national targets for Slovenia [23]. Similarly, Serbia has also presented a draft NECP in 2023 for 2030 with projections up to 2050 [24]. Slovenia and other EU member states submitted a draft of the updated NECP per EU regulation with new targets set for 2030 [25]. Set 2030 targets aim to reduce GHGE compared to 2005 under Effort Sharing Regulation by 40 % and increase the share of renewable sources. Slovenia aims to achieve 27 % share of RE according to NECP targets and 30-35 % according to revised NECP targets focusing on the higher share of photovoltaics [26]. In contrast, Serbia aims to achieve a 33.6 % share of RE under NECP targets and a 40.7 % share under revised NECP targets [23–25,27]. Additionally, Serbia has signed the Sofia Declaration on the Green Agenda for the Western Balkans, in which Serbia, along with the countries of the region, committed to several concrete measures that include the introduction of CO_2 taxes and market models to promote RES as well as the phasing out of coal subsidies [28,29].

Heat pumps are a promising technology for achieving decarbonization as they have a high coefficient of performance and energy efficiency ratio, i.e., the ratio of the thermal or cooling energy supplied over the electrical energy used. Heat pumps can reduce energy use and greenhouse gas emissions (GHGE) compared to conventional heating systems such as natural gas boilers [7,8]. Three types of heat pumps are present in the current market: air-source (ASHP), water-source, and ground-source heat pumps (GSHP) [7]. GSHPs utilize the relatively stable temperature of the ground throughout the year. The initial investment cost is higher; however, a better coefficient of performance (COP) is achieved, which results in electricity savings, lower fossil fuel consumption, and lower environmental impact [30,31]. Their use benefits from the increasing decarbonization of the national electricity mixes across the EU as running on cleaner electricity would reduce the emissions associated with the heating sector [32]. Nevertheless, the electrification of heating presents some challenges. The two key risks identified are that heat pumps are most efficient when they supply heat at low temperatures and their efficiency decreases in poorly insulated buildings as they demand higher supply temperatures [33]. In Europe, ASHP are the most commonly adopted type of heat pumps as they are highly efficient, considered environmentally friendly, and capable of maintaining an adequate indoor climate [34]. They present a source of flexibility to the power system, which facilitates the management of electricity supply to meet demand in a power system with high shares of variable RES, reducing curtailment and fossil fuel consumption [33,35]. Although heat pumps represent an attractive option as a heat source and are recognized as key energy technology in the energy transition [36], they need to be driven by use of electric energy. Their environmental impact depends on their performance and the energy mix used for electricity generation [37]. LCA has been used to compare the environmental impacts of heat pumps [38–40]. Studies have shown that envrionmental impact of the use of heat pumps can be lowered by applying RES to provide electricity for the system [37,40].

The widespread rollout of heat pumps faces several technical and socio-economic challenges. Adopting heat pumps to the existing network may increase peak demand for electricity, causing network congestion and requiring additional investment in the electricity grid infrastructure. Heat pumps can efficiently replace conventional heating systems in only well-insulated old dwellings, increasing the overall retrofitting cost. The technology of heat pumps to be installed is location- and application-specific, which can lead to minimal savings and high payback periods in the case of sub-optimal installations. Additionally, the environmental cost of heat produced by heat pumps is low only if the renewable penetration in the considered system is significant [41].

The research aimed to assess the environmental impact of introducing a higher share of RES in the power system using LCA to determine the environmental impact of such an electricity mix.

The second aim of this study was to perform LCA of the heat generated from air-water and ground-water heat pumps to determine the environmental impact under different hypothetical electricity mixes of the two countries, which model the higher uptake of RES in 2030 according to the aims of NECP scenarios.

2. Materials and methods

The International Organization for Standardization (ISO) has standardized guidelines for the LCA methodology, ISO 14044 and 14040 standards being the most important [42,43]. According to the ISO standards, LCA is a methodology consisting of four phases: (1) goal and scope definition, where the goal and purpose of the study is determined; (2) the inventory analysis in which the data are collected and analyzed and outputs related to the functional unit of the system; (3) the impact assessment, where environmental impacts were evaluated; and (4) the interpretation phase where the results are evaluated, compared with the defined goals to draw conclusions and formulate recommendations [44]. Country-LCA studies of electricity generation are relevant due to the increasing electrification of different sectors, the increase in overall electricity demand, and the significant spatial and temporal changes and variability in electricity generation systems, and they allow the understanding and analysis of electricity matrices and electricity matrices scenarios regarding their environmental impact [45,46].

2.1. LCA modeling and software

This study's modeling was performed using SimaPro 9.5 software [47] and Ecoinvent 3.9.1 database [48]. The characterization method adopted to calculate the impacts was ReCiPe Midpoint (H) method [49,50].

2.2. System definition and boundaries

The study's main goal is to evaluate and compare the potential environmental impact of the different electricity production mix scenarios for Slovenia and Serbia. The second goal of the study was to evaluate and compare the resources consumed and substances emitted during the life cycle of the two heat pump systems – ground-source heat pump and air-water heat pumps with respect to different electricity country mix scenarios (Slovenia vs. Serbia) and the uptake of RES in Serbia and Slovenia concerning NECP plan in 2030 to illustrate the role of electricity mix.

For the electricity generation scenarios, all input and output data were related to the 1 kWh of produced electricity as the functional unit (FU)

All input and output data were related to the MJ of produced heat set as the functional unit (FU) for the heat generation.

2.3. Life cycle inventory

This LCA uses Ecoinvent data about electricity generation in Slovenia and Serbia to report environmental data about the impact of producing 1 kWh of electricity in Slovenia. For the calculation of environmental impacts ReCiPe midpoint method was used. On the whole, Slovenia has three major primary energy sources: nuclear energy plant, hydroelectric power plant and thermal power plant while Serbia has two major primary energy sources: thermal power plant and hydroelectric power plant. In total, eight scenarios were modelled:

1. **SI**: Low voltage electricity mix for Slovenia (year 2020): imports included
2. **SER**: Low voltage electricity mix for Serbia (year 2020): imports included
3. **Europe**: Low voltage electricity mix for Europe (year 2020)
4. **SER_Currentmix**: Electricity production mix for Serbia (year 2020): electricity generation sources with different shares without import
5. **SI_Currentmix**: Electricity production mix for Slovenia (year 2020): electricity generation sources with different shares without import
6. **SI2030**: NECP based electricity production mix for Slovenia that models the decline in TEŠ and additional uptake of solar power without import with shares: Wind 0.04 %, Pump Hydro 1.4 %, Hydro 28.6 %, Lignite 13.3 %, Gas 0.15 %, Nuclear 37.1 %, Biogas CHP 0.01 %, Lignite CHP 2.5 %, Gas CHP 2.3 %, Oil CHP 0.05 %, Biomass CHP 0.05 % and Solar 13.5 %.
7. **SIupdated2030:** NECP based electricity production mix for Slovenia that models durther decline in TEŠ, increase in hiydro and solar power share: Wind 0.04 %, Pump Hydro 1.4 %, Hydro 33.6 %, Lignite 8.3 %, Gas 0.15 %, Nuclear 37.1 %, Biogas CHP 0.01 %, Lignite CHP 2.5 %, Gas CHP 2.3 %, Oil CHP 0.05 %, Biomass CHP 0.05 % and Solar 13.5 %.
8. **SER2030:** NECP based electricity mix production mix for Serbia that models decline in thermal power, higher penetration of wind power and solar: with shares of lignite 42 %, Lignite CHP 8 %, Hydro 27 %, Pump Hydro 7 %, Wind 8 %, Solar 4 %, Industrial CHP 2 %, and Gas and Oil CHP 2 %.

The study focused on the use phase – generation of heat and the environmental impact of using heat pumps under different electricity mix and electricity mix scenarios. The datasets for 1 MJ of heat generated from ASHP and GSHP, available in the Ecoinvent database, 3.9.1, with a geographical denomination Europe without Switzerland, were used for the heat produced. Both processes assume the heat pump's lifetime to be 20 years for use in an average one-family house with a heating requirement of 10 kW and a heat supply of approximately 20.000 kWh with 2000 operating hours. The assumed seasonal performances factors were taken from the Ecoinvent processes, which was 2.8 for ASHP and 3.9 for GSHP, respectively.

3. Results and discussion

3.1. Life cycle assessment of electricity mixes studied

Table 1 shows the environmental impacts of the nine midpoint impact categories generated by producing 1 kWh of electricity in the six scenarios. These represent different geographical locations and involve different shares of some fuels. The scenarios are the current electricity mix for the year

2021 for Slovenia, Serbia, and Europe, available in the Ecoinvent 3.9.1 database, and NECP scenarios for Slovenia and Serbia, which assume a reduction of electricity from coal and its replacement by wind (Serbia) and solar (Slovenia, Serbia).

Table 1: Environmental impact assessment in selected impact categories of 1 kWh of electricity mix scenarios studied.

Impact category	Unit	SI	SER	Europe	SI2030	SIupdated2030	SER2030
Global warming	kg CO_2 eq	0.37443	1.04566	0.36197	0.23539	0.18386	0.78124
Ionizing radiation	kBq Co-60 eq	0.20110	0.03499	0.21036	0.26257	0.26235	0.00716
Ozone formation, Human health	kg NOx eq	0.00084	0.00187	0.00067	0.00057	0.00044	0.00137
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.00155	0.00580	0.00056	0.00119	0.00089	0.00421
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.00085	0.00188	0.00069	0.00057	0.00045	0.00137
Land use	m^2a crop eq	0.00716	0.00371	0.01193	0.00290	0.00284	0.00182
Mineral resource scarcity	kg Cu eq	0.00129	0.00115	0.00143	0.00052	0.00052	0.00031
Fossil resource scarcity	kg oil eq	0.08607	0.26004	0.09803	0.05233	0.04151	0.19776
Water consumption	m^3	0.00450	0.00635	0.00652	0.00241	0.00232	0.00323

Table 1 indicates that 1 kWh of Slovenian electricity production releases 0.37 kg CO_2 eq compared, accounting for a 94.5 % difference in the value of kg CO_2 eq released in Serbia (1.05 kg CO_2 eq). The higher values can be attributed to the higher share of thermal power plants in Serbia (62.3 %) compared to Slovenia (23.7 %). The values of emitted CO_2 eq are higher when electricity is generated primarily from coal and lignite sources [14]. Other sources of high values of emitted CO_2 eq and thus higher impact in the global warming category are electricity systems with higher shares of natural gas and oil, which emit 0.38-1.00 and 0.53-0.90 kg CO_2 eq/kWh_{out}, respectively.

In contrast, hard coal and lignite emit 0.66–1.05 and 0.8–1.3 kg CO_2 eq/kWh_{out}, respectively [51]. Few other studies have also reported on the environmental impact of generated electricity. 1 kWh of electricity produced in the Italian net electricity production mix (44.3 % share of natural gas and 4.4 % share of coal) emitted 0.62 kg CO_2 eq/kWh_{out}, higher than that produced in Slovenia and Europe. The modeled European scenario has a lower share of coal and a higher share of natural gas, resulting in values similar to those for global warming compared to Slovenia. Burchart-Korol et al. (2018) modeled the environmental impact of electricity generation in the Czech Republic and Poland, which showed that the primary determinant of negative impact on the environment was the use of lignite-fired thermal power plants [52]. The higher share of lignite thermal power plants in the production mix has resulted in higher values for impact categories ozone formation, Human health, Fine particulate matter formation, Ozone formation, Terrestrial ecosystems, and Fossil resource scarcity in Serbia compared to Slovenia and Europe, which is consistent with the available literature data [53–56]. The higher share of solar power resulted in a higher impact in the category of mineral resource scarcity for 1 kWh of produced electricity, as the values are 11.4 % lower in Serbia compared to Slovenia and 10.3 % lower compared to the Europe electricity mix, which is consistent with literature data as mineral resources consumption is increased with the uptake in photovoltaic technologies [57]. The 1 kWh of Slovenian electricity production releases 0.20 kBq Co-60 eq, compared to 0.034 kBq Co-60 eq with a 140.7 % difference, resulting in a higher impact in the category ionizing radiation, which can be attributed to the higher share of nuclear power, which is consistent with the available literature [16,17,45].

In the NECP scenario 2030, a decrease in global warming potential is observed due to the modeled reduction in the electricity generation from lignite. The Slovenia uptake of the scenarios results in a 37.1 % decrease in the global warming category for the 2030 NECP scenario and a 50.9 % decrease in the updated NECP scenario. The reduction in the case of Serbia is 25.2 %, and the values remain high due to the 42 % of the lignite-fired thermal plants in the 2030 scenario. In both countries, the reduction of lignite-fired thermal power plants' share in the production mix has resulted in a decrease in impact categories ozone formation, human health, fine particulate matter formation, ozone formation, terrestrial ecosystems, and fossil resource scarcity, which is consistent with life cycle assessment of electricity mixes in other countries such as Italy [15,56], Spain [19], UK [18], and Chile [58].

On the other hand, the higher share of nuclear power plant in Slovenia resulted in a 30.5 % increase in the impact category ionizing radiation. In Slovenia, the impact can be attributed to the production of infrastructure and materials, as Serbia does not have nuclear power plants.

3.2. Life cycle assessment of heat generated from heat pumps: comparison of ASHP and GSHP

Table 2 shows the environmental impact in selected impact categories for generation of heat using heat pumps for Slovenia and Serbia using Ecoinvent low voltage electricity mix for Slovenia and Serbia.

Table 2: Environmental impact assessment in selected impact categories of 1 MJ of heat generated from air-source (ASHP) and ground-source (GSHP) heat pump with electricity mix scenarios for Slovenia, Serbia, and Europe (Ecoinvent 2020 low voltage data).

Impact category	Unit	SI_ ASHP	SI_ GSHP	SER_ ASHP	SER _ GSHP	Europe _ ASHP	Europe_ ASHP
Global warming	kg CO_2 eq	0.0453076	0.0325183	0.1118944	0.0803104	0.0440719	0.0320486
Ionizing radiation	kBq Co-60 eq	0.0199897	0.0143553	0.0035116	0.0025283	0.0209080	0.0150774
Ozone formation, Human health	kg NOx eq	0.0000860	0.0000676	0.0001885	0.0001412	0.0000694	0.0000565
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.0001583	0.0001148	0.0005797	0.0004172	0.0000593	0.0000443
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.0000873	0.0000687	0.0001895	0.0001421	0.0000718	0.0000584
Land use	m^2a crop eq	0.0007459	0.0005375	0.0004040	0.0002921	0.0012194	0.0008874
Mineral resource scarcity	kg Cu eq	0.0001782	0.0001253	0.0001641	0.0001152	0.0001915	0.0001352
Fossil resource scarcity	kg oil eq	0.0087296	0.0065231	0.0259879	0.0189101	0.0099162	0.0074903
Water consumption	m^3	0.0004553	0.0003281	0.0006383	0.0004594	0.0006549	0.0004656

The results show that the use of air-water heat pumps resulted in higher impacts for all impact categories considered in all of the modeled scenarios, which can be attributed to a better COP of ground-source heat pumps which results in the lower use of electricity and subsequently in lower environmental impact [30,31]. Serbia still has a large share of coal-based sector which is not being planned to be completely phased out, resulting in the 84.7 % higher value of impact category global warming for 1 MJ of heat produced by ground source heat-pump in Serbia (0.080 kg CO_2 eq) compared to Slovenia (0.033 kg CO_2 eq) and 85.9 % higher value compared to Europe (0.032 kg CO_2 eq) and in higher values for impact categories Ozone formation, Human health, Fine particulate matter formation, Fossil resource scarcity and Water consumption. The impact in categories land use was 59.2 % lower in Serbia (0.0003 m^2a crop eq) compared to Slovenia (0.0005 m^2a crop eq) and 100.9 % lower compared to Europe (0.0009 m^2a crop eq) due to lower share of solar PV. The values in the impact category mineral resource scarcity were also lower in Serbia compared to Slovenia (0.0001 kg Cu eq) and Europe (0.0002) kg Cu eq, although the difference was smaller (8.4 % and 49.8 %, respectively). The 140.1 % lower value in impact category ionizing radiation in Serbia (0.0025 kBq Co-60 eq) compared to Slovenia (0.0143 kBq Co-60 eq) and 142.6 % compared to Europe (0.0151 kBq Co-60 eq) can be attributed to the lack of nuclear power electricity generation sources.

Recently, the environmental impact of heat generated from combustions of firewood and wood pellets was published [59]. The values in impact category for global warming of 1 MJ of heat was 68.1 % lower in the case of combustion of firewood (0.016 kg CO_2 eq) and 23.1 % lower (0.041 kg CO_2 eq) in wood pellets combustion. The lower values for firewood combustion can be attributed to private ownership, very short transportation routes, and the use of wood log boilers with high combustion efficiency. In the case of wood pellets, the higher values can be attributed due to the pellet production process and modeled long transportation routes as the wood pellets in Slovenia are primarily imported [59]. Miralles et al. (2020) compared the air-water heat pump and wood pellets biomass boiler in Spain, where the impact in category global warming was lower in the biomass boiler [60], which is in accordance with our results and the results published for wood pellets combustion by Topić Božič et al. 2024 [59].

3.3. Life cycle impact assessment of the GHSP: comparison of current electricity production mix and NECP mix for Slovenia and Serbia

Figure 2 shows the environmental impact in selected impact categories for generation of heat using heat pumps for Serbia and Slovenia using current electricity production and NECP 2030 scenario electricity production mixes for Serbia and Slovenia.

The NECP 2030 scenarios for both countries model reduced coal and increased solar PV, which reduces the impact categories of global warming (-17.1% Serbia; -28.6 % Slovenia). Additionally, a reduction in the impact in the categories fine particulate matter formation (-18.1 % Serbia, -38.2 % Slovenia) and fossil resource scarcity (-18.4 % Serbia, -31.3 % Slovenia) is also achieved, which is directly impacted by the share of coal power. The higher reduction in Slovenia can be attributed to the lower share of coal power in the modeled electricity mix. The results are consistent with the published data from other countries, as decarbonization scenarios show a reduction in GHG emissions (global warming impact category) due to the elimination of coal and oil from the mix and the strong contribution of renewables [15,19].

In contrast, the increase in the impact category mineral resource scarcity (17.0 % Serbia, 12.7 % Slovenia) and land use (121.3 % Serbia, 114.7 % Slovenia) is observed compared to the baseline scenarios due to the penetration and higher share of photovoltaics. The higher impact in mineral resource category can be due to the metals in the inverter and to the modules' aluminum frames and support structures [15]. The results show that the electricity mix plays a significant role in the decarbonization of the heating sector and should be considered when deciding which heating options has the potential to mitigate climate change and support decarbonization measures. The increase in the share of renewables has a beneficial effect on reducing the impact of using heat pumps for heating. The trade-off seems to occur between the impact categories related to resource depletion; however, particular attention has to be paid to the possibility of the recycling processes as a reduction in resource depletion impact may depend on recycling [15].

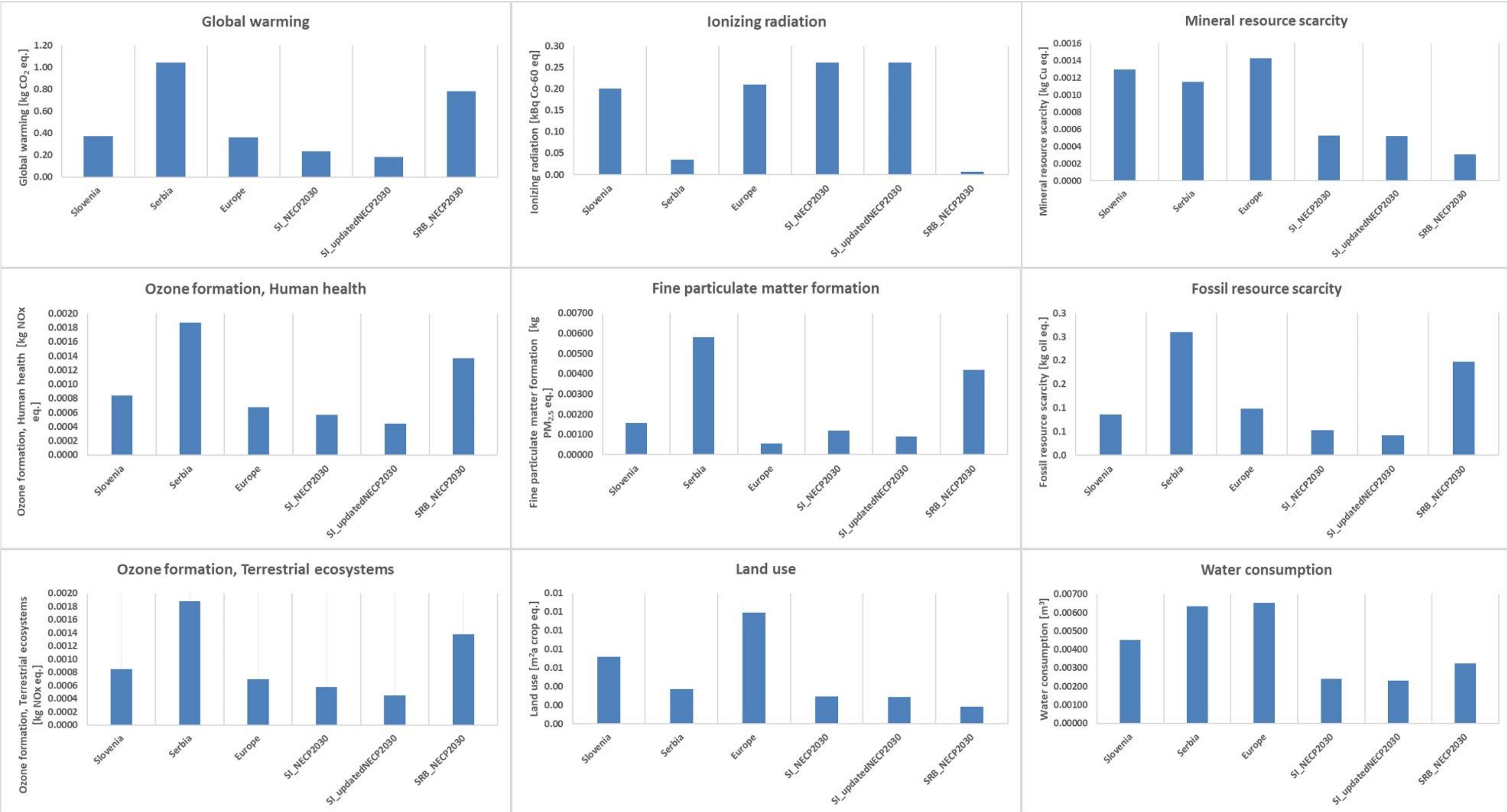

Figure 2: Environmental impact assessment in selected impact categories of 1 MJ of heat generated from ground-source heat pumps (GSHP) with electricity production mix scenarios for Slovenia, Serbia, and the 2030 NECP scenario.

4. Conclusions

The transition to low carbon energy future requires decarbonization of electricity and heating sector simultaneously as together with transportation they are interconnected via electricity. Heat pumps are considered one of the most energy efficient and environmentally friendly technologies, however the environmental impact of the heat generated from heat pumps differs from country to country due to different electricity production sources and its shares. The results show that use of air-water heat pumps resulted in higher impacts for all impact categories considered in all the modelled scenarios which can be attributed to a better COP of ground-source heat pumps and lower use of electricity and subsequently lower environmental impact.

The results showed that the use of heat pumps in Serbia has a higher impact in categories global warming, fine particulate matter formation and fossil resource scarcity than Slovenia. Serbia still has a large share of coal-based sector which is not being planned to be completely phased out resulting in the 84.7 % higher value of impact category global warming for 1 MJ of heat produced by ground source heat-pump in Serbia (0.080 kg CO_2 eq) compared to Slovenia (0.033 kg CO_2 eq) and 85.9 % higher value compared to Europe (0.032 kg CO_2 eq). Decarbonization of the electricity sector is an important contributor to the decrease in the environmental impact of the use of heat pumps. The reduction in the impact category global warming in NECP 2030 scenarios that model reduction in coal and increase solar PV can be observed in both countries (-17.1% Serbia; -28.6 % Slovenia). Additionally, reduction in the impact in the categories fine particulate matter formation (-18.1 % Serbia, -38.2 % Slovenia) and fossil resource scarcity (-18.4 % Serbia, -31.3 % Slovenia) can be also observed in NECP 2030 scenarios. The results showcase that electricity of the system has repercussions on its sustainability and effectiveness of decarbonization goals. One of the limitations of the study is that does not take into consideration the wide variation of the actual power generation mix on both seasonal and daily basis which can lead to over- or underestimation of the impacts of the electricity in the related sector. In the case of high-RES penetration, the spatiotemporal aspect should be analyzed and further elaborated.

The widespread adoption of heat pumps still faces several technical and socio-economic challenges as the addition of heat pumps to the existing network may lead to an increase in peak demoing and heat pumps can efficiently replace conventional heating systems in old buildings only if they are well-insulated, which increases the overall costs of retrofitting. Lack of understanding of costs and environmental benefits arising from HPs may also influence the uptake rate of heat pumps.

The study demonstrates that LCA provides a powerful tool to consider GHG emissions reduction and other environmental impacts such as land use and mineral resource scarcity and can be used in supporting decision makers dealing with future national energy plans and decarbonization strategies. For a holistic assessment of the impact of green transition scenarios, aspects beyond the environmental perspective can be included, namely life cycle costing and social LCA, to obtain a life cycle sustainability assessment.

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