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The Illusion of a Green Transition in Slovenia by 2050

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This study analyzes the possibilities of phasing out fossil and nuclear energy sources for Slovenia by 2050. Alternative carbon-free sources include renewable energy sources (RES) i.e. electricity, synthetic fuels and hydrogen from water electrolysis. The model is based on the use of currently mature low-carbon technologies and is adapted to Slovenia's natural conditions. Photovoltaic panels (PV) and hydropower plants are used for the majority of renewable electricity generation. To bridge the winter period with minimal PV production, storage with a pumped storage power plant is planned. One of the assumptions of the national climate strategy has been incorporated into the model, which envisages zero growth in final energy consumption by 2050. The result of the paper is an assessment of what some of the basic characteristics of the Slovenian energy system would look like after the phase-out of fossil and nuclear energy sources. The estimated storage capacity required is 5.1 MWh/capita. Abandoning fossil fuels with the currently mature RES technologies is not realistically feasible for technical and economic reasons.
Keywords: phasing out fossil and nuclear energy sources, renewable energy sources, photovoltaic modules, pumped hydro storage, green transition

Highlights
- *The European Green Deal – to achieve a carbon neutral society in 2050.*
- *Primary and final energy in Slovenia; energy sources and consumption.*
- *The potential of renewable energy sources in Slovenia.*
- *Slovenia 2050 – illusion of energy self-sufficient, without fossil and nuclear energy using just mature renewable technologies.*

0 INTRODUCTION

The last United Nations Climate Change Conference - COP28 conference resulted in several agreements, including the commitment to phase out fossil fuels. The media, politics, and many international forums are full of plans, strategies, and commitments to reduce greenhouse gas emissions and prevent further warming of the planet. Environmentalists and young people have extremely ambitious demands to limit greenhouse gas emissions. The result of activism and vested interests are various plans for how humanity must change its habits in the near future, by 2050, so that the products of burning fossil fuels no longer harm the planet's climate. The European Union's (EU) very ambitious environmental plan is the "Green Deal" - it assumes that EU countries will achieve climate neutrality with zero emissions of greenhouse gases, by 2050 by abandoning fossil and nuclear fuels and switching to renewable energy sources (RES) [1]. On the surface, the plan is very tempting, but is it feasible with existing renewable technologies?

Slovenia's long-term climate strategies for 2050 [2] and [3] follow the European guidelines of the Green Deal [1] and the Paris Agreement in accordance with European Regulation EU 2018/1999. Slovenia's goal is to achieve climate neutrality by 2050. Circumstances will change considerably between now and 2050 and, given the various paths envisaged, there are still many unknowns, including in relation to future technologies – the use of hydrogen, the intensive use of energy storage, new types of nuclear power plants, etc. All the strategies and scenarios mentioned are written in a very populist and politically pleasing way, but are they feasible in reality, especially when the natural physical and thermodynamic laws of energy conversion and storage are taken into account? The promise made by politicians was that the price of energy would fall if the proportion of renewable energies increased. The reality does not live up to this promise. For example, the price of electricity for an average household in Germany (with an annual consumption of 2.5 MWh to 5 MWh) was 0.202 EUR/kWh in 2007, and 0.412 EUR/kWh in 2023 [4], with the share of renewable energy having risen steadily over the years. According to [5], the share of RES in Germany was 20 % in 2007 and 55 % in 2021. In the study on Switzerland's transition to renewable energy sources [6], it is shown that if energy production with photovoltaics (PV) systems exceeds 60 %, the need for surplus energy storage, interstate energy exchange and a simultaneous increase in the capacity of the transmission grid increases many times over. In 2023, the European Commission published two documents [7] and [8] on the urgent strengthening of transmission grids and the issue of energy storage. As variable renewable energy (VRE) continues to advance, energy surpluses increase, and

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without adequate storage systems, curtailment of VRE generation is necessary. The VRE curtailment rate for Ireland was over 11 % in 2020, and for Germany and the UK the average rate is around 4 % for the period 2017 to 2021 [9]. By strengthening the grid and increasing transmission capacity, China has reduced the curtailment rate from ~11 % in 2017 to below 3 % in just three years. The estimated annual growth of VRE in 2023 is 550 GW (~75 % PV, 25 % wind) [9]. The bottleneck for the full transition to renewables by 2050 is not only the production and installation of new sources, but also the capacity of the transmission grid and seasonal energy storage. As the share of VRE increases, storage capacity increases linearly in relation to output and exponentially in relation to stored energy [10]. A study on a real pumped hydro storage (PHS) system in Japan [11] concludes that problems arise in the existing grid configuration when the PV share exceeds 35 % and the same time the efficiency of PV decreases due to the storage of surpluses with PHS. A study [12] for the EU states that the need for storage increases with a higher PV share. The study [13], determines the optimum ratio between wind and PV for the US electricity system with as little storage capacity as possible.

The results of economic studies on the transition to VRE are also interesting. Increasing the proportion of VRE causes a cannibalistic effect, while energy storage reduces this effect [14]. The result of the study evaluating the cost of replacing nuclear energy with RES for Sweden [15] showed that this is neither economical nor environmentally friendly.

In this article, we want to show how some of the basic characteristics of the Slovenian energy system would look like after the phase out of fossil and nuclear energy sources and the transition to VRE in 2050. The system of photovoltaics in combination with pumped hydro storage is chosen as the basic model for the replacement of fossil and nuclear energy sources. This type of system was chosen, primarily because it is currently the most technologically mature for utilizing the natural conditions of the Slovenian landscape.

1 METHODOLOGY

Fossil and nuclear energy still represent the main source of energy in Slovenia, more than 80 %. Compared to 2003, a restructuring can be observed, the share of coal has decreased significantly due to the increased use of wood fuels, Table 1 [16]. Total primary energy consumption has increased by only 4.5 % in the period 2003 to 2019, while total CO_2 emissions have decreased by 16 %, Fig. 1. This indirectly shows the success of measures to reduce CO_2 emissions and increase energy efficiency in all sectors.

Table 1. *Primary energy consumption in Slovenia in 2003 and 2019* [16]

Energy source	2003		2019	
	Energy consumption		Energy consumption	
	[PJ]	share [%]	[PJ]	share [%]
Coal	63.8	25.8	47.3	18.3
Petroleum products	95.5	38.6	98.5	38.1
Natural gas	38.0	15.3	30.3	11.7
Nuclear heat	27.1	10.9	31.5	12.2
Hydro energy	10.5	4.3	16.9	6.6
Renewables	11.4	4.6	31.4	12.2
Industrial waste	1.0	0.4	2.5	1.0
Total	247.3	100.0	258.5	100.0

Renewable energies are primarily intended to replace fossil and nuclear energy. A more detailed analysis of the consumption of fossil fuels by sector was carried out [17] and the technological parameters of replacement were assumed (fossil/electric ratio). Where the use of electricity does not make sense or is technologically impossible, the use of synthetic fuels is envisaged to replace conventional oil derivatives or natural gas. Taking into account the natural conditions of the Slovenian landscape, PV modules and existing hydropower plants are planned as the basic source of production. PHS pumped-hydro power plants are planned as daytime storage for the nighttime and also as a seasonal storage system for surplus energy in summer, which can be used in winter when PV production is minimal. PHS systems of this type can achieve corresponding outputs of up to several GW with potentially achievable storage capacities of several TWh [18] and [19]. This technology was chosen primarily because it is currently the most technologically mature.

The calculation is based on the national energy balance of primary energy [16]. The year 2019 is considered the base year for Slovenia's energy balance. Fig. 1 shows Slovenia's greenhouse gas (GHG) emissions over the last 35 years. The emissions are proportional to the consumption of fossil fuels and also to economic activity. There is a clear trend towards increasing transport emissions and decreasing industrial emissions (use of fossil fuels and process emissions from industry). For 2014, there is a sharp decline in the energy sector, which is due to the replacement of the old coal-fired thermal power plant with a new one. The trend in total emissions also shows the effects of various crises, e.g. a significant drop in emissions in 2009, as the global crisis began in 2008. A similarly pronounced decline in emissions also occurred in 2020 due to the Covid-19 pandemic, which was immediately followed by the war in Ukraine. The year 2019 was therefore the last year in which the impact of the global crises on energy consumption was minimal, which is why it was chosen as the starting/reference year for the further calculations.

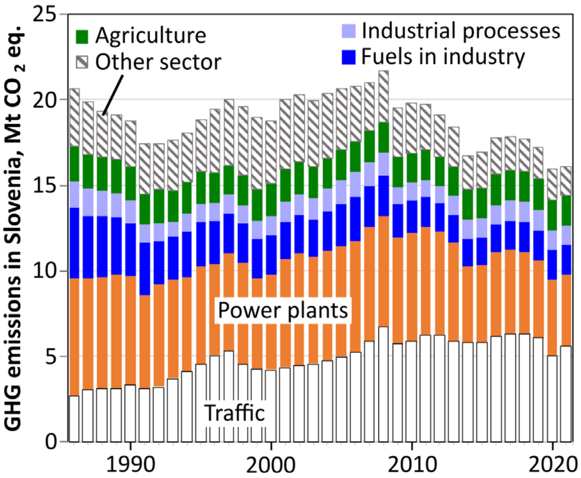

Fig. 1. *Greenhouse gas (GHG) emissions in Slovenia in period 1986 to 2021* [20]

The green transition assumes that energy consumption will decrease in the future due to greater energy efficiency. The scenario forecasts until 2050 are taken from the National Energy Climate Plan (NECP) [3] and the Long-term Climate Strategy up to 2050 [2]. Fig. 2 shows 4 basic scenarios for the development of final energy consumption according to the forecast measures: 1 – no measures, 2 – basic measures, 3 – additional measures and 4 – intensive additional measures.

The updated version of the NECP calls for the most intensive measures to achieve climate neutrality by 2050, i.e. scenario 4 with a reduction of final energy consumption to ~70 % of 2005 consumption by 2050. These targets are in line with EU Directive 2023/1791 (September 23, 2023), which foresees final energy savings of ~25 % in 2030 compared to peak consumption in the EU in 2005 (Fig. 3). The projected increase in energy efficiency is overly optimistic, exceeds thermodynamic limits and will not be technically achievable with the same standard of living and economic growth.

The basic aim of this article is not to forecast energy consumption in 2050, but to assess the feasibility of Slovenia's energy self-sufficiency in the event of a complete transition to renewable energy sources. Since the focus is on demonstrating the complexity of the green transition, zero growth in energy consumption is predicted. The prediction of future consumption represents an additional unknown.

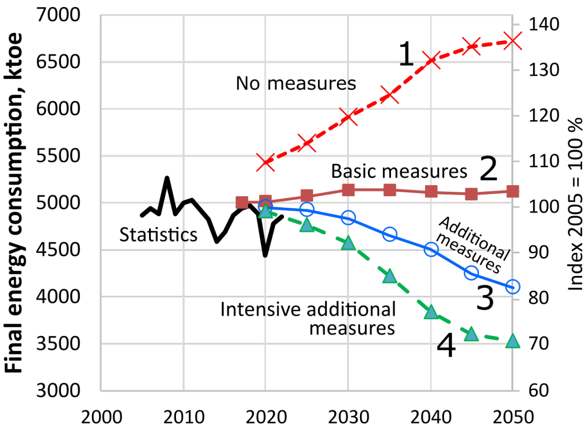

Fig. 2. *Scenarios for the development of final energy consumption in Slovenia until 2050* [2] *and* [3]

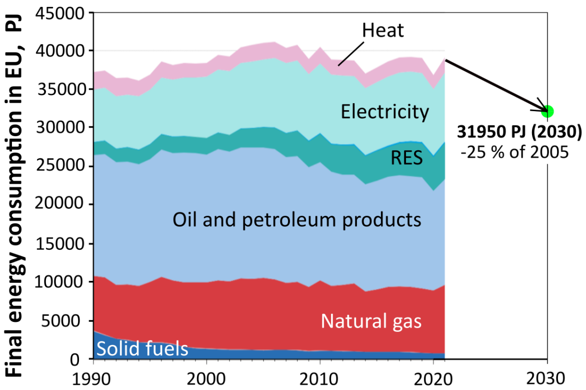

Fig. 3. *Projected reduction of EU final energy consumption by 2030 due to increased energy efficiency – EU Directive 2023/1791* [21]

The result obtained can be used as a basis for assessing the feasibility of higher or lower consumption in 2050. The same assumption of zero growth in energy consumption is also used in some other similar studies dealing with the possibility of moving away from fossil resources on a global scale by 2050, e.g. [22]. Finally, the forecast of zero growth in energy consumption can be considered very optimistic (Scenario 2, Fig. 2). Never in history has energy consumption fallen in the long term, it has always risen due to technological progress, demographics and economic growth.

2 CALCULATION OF THE REPLACEMENT RES ELECTRICITY

2.1 Boundary Conditions and Energy Balance of Slovenia

The following boundary conditions were taken into account in the calculations for the projected energy consumption in 2050:

- zero CO_2 emissions, or complete abandonment of fossil fuels and nuclear energy,
- 100 % energy self-sufficiency (currently ~35 %),
- increase in food self-sufficiency from 40 % today to at least 80 %,
- final energy consumption in 2050 is the same as in 2019,
- the storage of seasonal surpluses of VRE electricity takes place with PHS systems,
- very limited use of synthetic fuels for the needs of emergency services (e.g. police, rescue services, fire department, agriculture, etc.) and limited transit freight transport.

In Slovenia, the annual consumption of primary energy is around 260 PJ. The average annual consumption per inhabitant is ~130 GJ [16] (Slovenia has ~2 million inhabitants). Table 1 shows the consumption of primary energy in the base year 2019. A comparison of the structure in 2003 and 2019 shows a restructuring towards a reduction in coal and increase in renewable sources (wood fuels, hydro energy).

About one third of the required energy is provided from domestic sources, while two-thirds (65.4 %) of the energy is imported (in the national statistics, nuclear heat is considered a domestic source, although the nuclear fuel is imported).

2.2 Available RES Sources in Slovenia

Slovenia has quite limited opportunities when it comes to the use of some RES technologies. Wind energy does not have great potential. Currently, only three wind turbines with a total capacity of ~4 MW are installed. Most of the suitable sites for the use of thermal wind are located in 355 protected areas of "Natura 2000" [3] (which represent 37 % of the total county area), where all constructions and interventions in the space are prohibited due to environmental protection requirements. If the selected sites do not belong to the "Natura 2000" protected areas, the installation of wind turbines near urban areas is always strongly opposed by the local population.

The water potential in Slovenia is already well exploited. There is still ~10 % (~2 PJ) available. As Slovenia is a rather forested region, a lot of wood biomass is also used as an energy source. Geothermal energy is not yet suitable for generating significant amounts of electricity in Slovenia.

Solar energy is best suited as a sufficiently large renewable primary source. For Slovenia, the use of PV is currently the most suitable. Classic (steam) thermal power plants with a solar steam boiler – concentrated solar energy are not suitable for Slovenia.

The characteristic of PV operation is the temporally unstable generation of electricity. As the proportion of irregularly timed production increases, so does the need for intermediate energy storage to ensure an uninterrupted supply for consumption [6] when production does not match consumption (e.g. at night, in winter). Large-scale electricity storage systems are currently one of the biggest technological barriers to the green transition. Electrical energy is a volatile form of energy and is not accumulated, such as potential energy. This problem is currently solved by converting electrical energy into another type of (accumulated) energy that can be stored. Technologically, there are several solutions/ possibilities - in the form of compressed air in caverns, batteries in the form of chemical potential, synthetic fuels, conversion to hydrogen, etc. [19]. As a technologically mature technology for long-term storage, the most suitable for Slovenia are pumped storage plants (PHS), where excess electricity is converted and stored in the form of potential water energy in the upper reservoir. In Slovenia, the Avče PHS on the Soča River has been in operation since 2012 with an output of 185 MW and a storage capacity of 2.4 GWh, with an efficiency of ~75 % [23].

2.3 Carbon Requirements for Synthetic Fuels

Replacing fossil fuels with electricity is not always possible or sensible. Therefore, a minimal use of synthetic fuels, such as synthetic methane, synthetic diesel, etc., is envisaged. The synthesis of fuels using the Fischer-Tropsch (FT) process is an energy-intensive process.

Table 2. *Comparison of the primary energy consumption for 1 km driving distance in well-wheel analysis of various synthetic fuels* [24]

Type of fuel	Primary energy [MJ/km]	Factor
BEV	0.75	1.0
Fuel cell	2.7	3.6
Methane	4.3	5.7
Methanol	4.4	5.9
Diesel	5.4	7.2

An example: If we use a vehicle powered by synthetic fuel instead of a battery electric vehicle (BEV), the primary energy consumption increases drastically, by a factor of 7.2, Table 2 [24]. It therefore makes sense that synthetic FT fuels should only be used for the most important and essential services, e.g. police, emergency services, agriculture, fire department, army, etc. Therefore, the majority of non-emergency traffic should be handled by BEVs.

We also need CO_2 to synthesize FT fuel. 1.7 million tons of carbon or 6.2 million tons of CO_2 would be required to synthesize the amounts currently used, which is equivalent to ~2 million tons of petroleum derivatives. However, such amounts of carbon or CO_2 are not available in Slovenia in the form of renewable energy, not even from biomass. In principle, CO_2 could be captured from the emissions of industrial processes, e.g. in the production of lime and cement (for which the use of electricity and hydrogen is envisaged in the future). Currently, these emissions amount to ~2300 tCO_2/d, and other industrial emissions to a further 700 tCO_2/d, a totaling ~1.1 $MtCO_2$/year [20]. It is shown that CO_2 sources are limited and it will therefore be necessary to synthesize only the necessary quantities of "classic" fuels with FT. The synthesis of natural gas (methane) requires slightly lower amounts of carbon, the mass fraction of carbon in methane is 75 %. There are many ways to extract and capture CO_2, but do they make sense? The energy consumption to extract 1 kg of carbon (or 3.66 kg of CO_2) from air is ~8 kWh, from seawater ~6 kWh [24]. This type of CO_2 extraction is indeed envisaged in various IEA strategies for green transition [25] and [26]. Perhaps in the future, methanol, obtained by the process of catalytic reduction of CO_2 at low temperature, will be establish itself as a less energy-intensive fuel compared to FT. A pilot plant for capturing CO_2 from flue gases has been set up at the Niederaussem thermal power plant (Germany, near Cologne). Several pilot projects for the useful reuse of captured CO_2 have also been carried out at the same site, including the European project LOTER.CO2M [27] for the catalytic synthesis of methanol at low temperatures (~100 °C).

2.4 Slovenian Energy Needs in 2050

According to the forecast of the selected scenario [2] and [3], total energy consumption in 2050 will remain at the 2019 level. As fossil fuels are replaced by renewable electricity, electricity consumption will increase significantly. In the following, the energy equivalents taken into account in the calculation are determined by field sector and fuel type.

2.4.1 Liquid Fuels

Agriculture. For 2050, it is predicted that food self-sufficiency in Slovenia will be at least 80 % (currently 40 % [3]) and therefore the consumption of liquid fuels in agriculture will double. In recent years, agricultural consumption has averaged around 70,000 tons of liquid fuels [16]. According to the scenario, the consumption of the agricultural sector will amount to 140,000 tons of liquid fuels in 2050 and will be synthesized by the FT process.

Transportation. All emergency services (police, rescue services, agriculture, etc.) will require 5 PJ of synthetic liquid fuels in 2050. International freight transport, with a current liquid fuel consumption of 30 PJ to 35 PJ, accounts for more than 10 % of national consumption [17]. As rail transport will account for a significantly larger share in 2050, it is assumed that the consumption of international freight transport will fall to 10 PJ of synthetic fuels and 10 PJ of electricity for rail transport [17]. All other transportation will be electrified. The total consumption of synthetic fuels in transport will amount to 15 PJ or 360,000 tons of oil equivalent (toe) in 2050, of which 120,000 toe of liquid synthetic fuels for emergency services and 240,000 toe of synthetic methane LNG (liquefied natural gas) for international freight transport. The consumption of ship transport is taken into account in international freight transport. According to the IEA scenarios [25], the use of synthetic ammonia is assumed for ship transportation in 2050.

The remaining consumption of liquid fuels in domestic transportation, ~40 PJ, corresponds to 40 PJ × 0.25 = 10 PJ of mechanical work (on wheels), which is replaced by electricity. Taking into account the overall efficiency of 0.6 [24] charging, discharging, and the efficiency of the electric motor in battery vehicles, 16.6 PJ of electricity are needed to replace 40 PJ of fossil energy.

Air traffic. The annual consumption for air traffic is on average 1.5 PJ or ~36,000 tons of kerosene.

Heating (service sector, households, and industry). In the service sector and in households, liquid fuels are used for heating, and therefore the consumption of 6.3 PJ is replaced by 3.15 PJ of electricity for heating with heat pumps with a coefficient of performance (COP) of 2. The industrial consumption of liquid fuels amounts to an additional 1 PJ.

2.4.2 Gaseous Fuels

Slovenian natural gas consumption amounts to ~9 TWh or 775,000 toe (ton of oil equivalent) on an annual basis. Industry also consumes 170,000 toe of solid fuels [16] and [28] and ~480,000 toe of gaseous fuels. It is largely possible to replace fossil fuels with electricity, in principle also for the production of water steam, which is required in various technological processes. For high-temperature processes in which chemical reactions also take place at the same time, e.g. reduction of metal oxides, calcination of minerals, glass melting, etc., there are still no suitable technologies for complete substitution by electricity. The use of hydrogen is envisaged for these high-temperature processes. Natural gas consumption in households will be replaced by electricity (heating with heat pumps, electric stoves, etc.).

The total consumption of liquefied petrol gas (LPG) is relatively low at 3.8 PJ, most of which is used for heating in households and the service sector. If we replace this with heat pumps (coefficient of performance, COP = 2) and electricity, this means an electricity consumption of ~0.5 TWh to replace LPG.

2.4.3 Hydrogen in Industry

Replacing natural gas with hydrogen is potentially feasible, but intensive use on large scale poses a technological and safety challenge [29] and [30]. The use of hydrogen also leads to a sharp increase in primary energy consumption for water electrolysis, storage and transportation [31]. Hydrogen is not a fuel, but a technologically extremely demanding energy carrier. For industrial consumption of fossil fuels, it is envisaged that 2/3 of natural gas consumption will be replaced by electricity (516,000 toe), with the remaining 259,000 toe of energy being replaced by hydrogen. The remaining natural gas consumption in households and the service sector (375,000 toe), which is mainly used for heating will be replaced by electricity to drive heat pumps with 180,000 toe of electricity. The long-term storage of hydrogen in the order of several TWh is currently still a major technological challenge. In order to avoid the energy consumption for storage (compression to higher pressures, liquefaction, etc.), it is assumed that the hydrogen will be produced during operation by electrolysis of water.

2.4.4 District Heating

In 2019, 2.2 TWh of district heating [32] was distributed in Slovenia, mostly from fossil fuels. There are also some district heating systems with wood biomass, the total share of RES in district heating was 15.4 % [32]. District heating is replaced by electricity and heat pumps with an average COP of 2, which corresponds to 1.1 TWh of electricity.

2.5 Electricity Demand 2050

Due to the substitution of fossil fuels with electricity, hydrogen, and synthetic fuels, electricity demand will increase significantly in 2050, even if it is assumed that final energy consumption remains the same as in 2019. In the substitution calculations, the conversion efficiencies of electricity to synthetic fuels and hydrogen are listed in Table 3, summarized according to [24].

Table 3. *Energy yields of conversions to synthetic fuels* [24]

Source energy	Transformation	Product	Efficiency
Electricity	electrolysis	hydrogen	0.75
Electricity	FT synthesis	methane	0.48
Electricity	FT synthesis	diesel, petrol	0.29

Tables 4 to 7 show the quantities of electricity required to replace fossil fuels. The amount of electricity required to replace liquid fossil fuels is 26.3 TWh, (Table 4). 12.6 TWh are required to replace natural gas and LPG (Table 5). To replace the current fossil and nuclear electricity sources (without taking losses into account), 9.8 TWh are required (Table 6). The total final value of electricity consumption in 2050 is predicted to be 57.9 TWh (Table 7).

If the current share of hydro energy increases slightly, to ~5.5 TWh, an additional 52.4 TWh must be generated with new carbon-free sources. On a daily (nighttime) and annual (winter months) level, at least 70 % of the 57.9 TWh assumed for PHS must be stored. If the efficiency of PHS systems (75 %) is taken into account, the annual production of all sources amounts to ~68 TWh, while the storage losses with PHS amount to up 10.1 TWh. The projected consumption of ~68 TWh (245 PJ) means that electricity consumption will more than quadruple after the phase out of fossil and nuclear fuels compared to the base year 2019. The result achieved is in line with the result of a comparable study at global level [22], which indicates a six-fold increase in electricity consumption as a result of substitution.

Table 4. *Electricity required for synthetic fuels and electrified transport, assuming the conversion efficiencies from Table 3*

Sector	Fuel	Energy equivalent	Electricity [TWh]
Agriculture*	synthetic diesel	0.14 Mtoe 1.6 TWh	5.6
Urgent services*	synthetic petrol, diesel	0.12 Mtoe 1.4 TWh	4.8
International cargo traffic*	synthetic LNG - methane	0.24 Mtoe 2.8 TWh	5.8
Aviation*	synthetic kerosene	35 ktoe 0.4 TWh	1.4
Other use (all sectors)	electricity	4.2 PJ	1.2
Other traffic	electricity	27.4 PJ wheel energy	7.6
TOTAL			26.3

*an additional 430,000 tonnes of carbon or 1,550,000 tonnes of CO_2 are required for FT synthesis

Table 5. *Electricity required to replace natural gas and LPG*

Sector	Fuel	Energy equivalent [ktoe]	Electricity [TWh]
Industry	hydrogen	259	4.0
Industry, services, households	electricity	516+180 = 696	8.1
All sectors	LPG	91	0.5
TOTAL			12.6

Table 6. *Current losses and production sources of electricity (annual electricity consumption corresponds to ~15 TWh)*

Production source	[TWh]
Hydro + other RES	~4.5
Losses	~0.7
Thermal + nuclear + import	~9.8

Table 7. *Electricity demands in 2050 after the phase out of fossil fuels and nuclear energy*

Electricity needs	[TWh]
Liquid fuels synthesis	26.2
Gaseous fuels synthesis	12.6
District heating	1.1
Electricity	15
Additional losses	3
TOTAL	57.9

3 SOURCES FOR CARBON-FREE ELECTRICITY

The annual consumption of 68 TWh of electricity means an average annual output of ~7.8 GW. As production with PV modules is extremely volatile over time, large installed capacities and large system storage are required. The calculation of the required area of PV modules is carried out for the Primorska region (coastal region on the Adriatic Sea), which is the sunniest region in Slovenia. The average annual solar radiation on the Slovenian coast is 3.94 kWh/m² per day, i.e. 1.44 MWh/m² per year **[33]**. With an average PV system efficiency of 15 %, 216 kWh of electricity is generated per 1 m² per year. For 62.5 TWh of annual PV energy (relevant production of hydropower plants, 68.0 TWh – 5.5 TWh = 62.5 TWh), the area of PV modules is ~290 km², i.e. the side of the square area corresponds to 17.0 km. In reality, the required area of PV modules would be much larger, as the modules are not ideally placed. The estimated peak power of photovoltaic modules at a specific power of 150 W/m² is 43.4 GW (~53 % of the power of installed PV systems in Germany, which is ~81.8 GW, January 2024 **[34]**).

Surplus electricity produced in summer needs to be stored for the winter period when PV production is at its lowest. Currently, the most reliable and mature technology for storing large amounts of electricity is PHS. Switzerland and Austria have the most such systems in Europe. The current energy consumption for pumping is 6.4 % of annual consumption in Switzerland, 7.1 % in Austria and 2.1 % **[35]** in Slovenia (PHS Avče).

Fig. 4. *The size of the upper reservoir on the Karst rim for the storage of 10.2 TWh*

It is typical for the Slovenian coastal area that solar radiation in July is on average 5.6 times higher than in December. Therefore, it is necessary to systematically store at least 11 %, preferably at least 15 % of the annual electricity consumption **[36]**, which corresponds to ~10.2 TWh (the capacity corresponds to ~4200 PHS Avče). The amount of water that would have to be pumped daily through the PHS exceeds the water capacity of Slovenian rivers, and therefore the only way to realize the PHS is to use the sea and pump seawater to the Karst rim, which is geodetically ~400 m higher, ~10 km from the sea and where 1 m³ of seawater stores ~1 kWh of electricity. For 10.2 TWh, a water volume of 10.2 km³ is required, i.e. a circular reservoir with a diameter of 20.8 km and an active height of 30 m. The proportionality of the extent of accumulation in relation to Slovenia is shown in Fig. 4.

The size of the upper reservoir is therefore astronomical (up to 1.7 % of national territory). The PV modules could ideally be installed floating and rotating on the surface of the upper reservoir. The installed peak capacity of the PHS pumps would be approximately ~43.4 GW, which is about ~31 times the capacity of existing Slovenian hydropower.

4 DISCUSSION

The main objective of this article is not to predict the energy consumption in Slovenia in 2050 as accurately as possible, but to provide a realistic assessment of what the Slovenian energy system would look like in 2050 if fossil and nuclear fuels are abandoned (and technologically mature RES technologies are used). The results presented show that the construction of such megalomaniacal systems would be completely unfeasible in reality. The reasons for the rejection are manifold and range from the fundamental safety risk (earthquakes, natural disasters, operating errors, etc.), the extreme technical complexity and the unimaginable investments to public resistance in their own country and in neighboring countries.

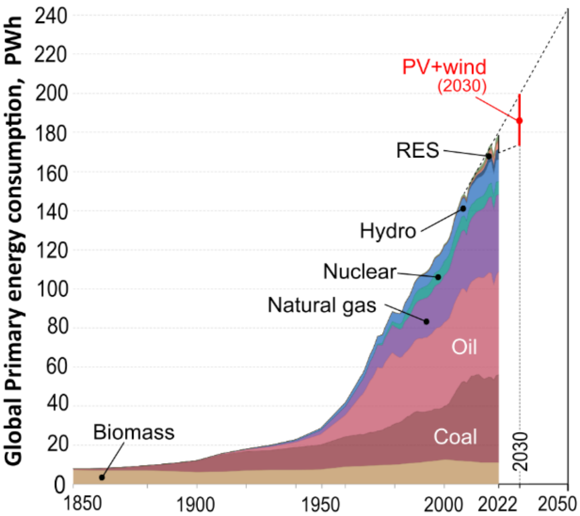

Fig. 5. *Global primary energy consumption by source* [37]

The assumption that final energy consumption in 2050 will be at the level of 2019 (also used in [22]) is realistically very optimistic. Based on past energy consumption (Fig. 5), it is clear that we cannot expect consumption to decrease due to increasing energy efficiency and policy preferences.

In the International Energy Agency (IEA) report Renewables 2023 [38], even the IEA admits that of all types of renewable energy sources, only PV and wind are still viable for the future; the others, the upper limit has more or less already been reached. Fig. 5 shows the predicted tripling of PV and wind energy by 2030 according to the IEA Net Zero scenario [38]. As can be seen, this will not even be enough to cover the increase in consumption, let alone reduce the consumption of fossil resources. The message of Fig. 5 is also that from 2020 to 2050 we will have consumed almost half of all fossil fuels used so far and that achieving global climate neutrality in 2050 is a complete illusion. The IEA has already recently admitted that all these megalomaniacal VRE installation projects will only partially mitigate the increase in fossil fuel consumption, with the additional condition that there will not be too much of a cannibalistic effect due to the physical production of all these VRE systems, which are produced from fossil energy and freshly mined minerals.

By 2050, technologies can continue to improve. Currently, RES systems (with the exception of hydropower plants) use low energy density sources, which means huge losses for the end consumer during conversion. A technically viable solution for eliminating fossil fuels requires a completely new technology with a completely new paradigm based on completely different principles. Current technological developments in this area are expected to produce new results from known and old technologies [39].

For the industrial sector, it is expected that part of the energy from fossil fuels will be replaced by hydrogen. As far as the widespread use of hydrogen is concerned, the opinions of experts are very divided, both for and against. Some researchers who have worked with hydrogen throughout their careers are very sceptical about the widespread and mass use of hydrogen [31], [40] and [41]. The use of hydrogen is technologically very demanding. Hydrogen is not a fuel, but an energy consumer. One may ask why the fuel cell, which was discovered as early as 1838 [42], has not yet become established. The use of hydrogen will increase electricity consumption enormously. For example, in order to decarbonize the production of 6 million tons of steel per year at Voestalpine Stahl (Austria) with hydrogen, 20.5 TWh of electricity will be required, i.e. 30 % of Austria's electricity consumption [43].

The planned storage capacity of 10.2 TWh is enormous. Currently, the largest PHS capacity is several tens of GWh. Of course, a combination of various smaller systems can also be installed. The largest Li-ion battery system, for example is currently in operation in California, with a maximum output of 750 MW and a capacity of 3 GWh [44]. However, the estimates of the costs of the storage systems are interesting. According to [45], the average cost of the PHS system is 47 EUR/kWh, while the cost of the Li-ion battery system is 346 EUR/kWh. The capacity of 10.2 TWh means a specific capacity of 5.1 MWh per inhabitant in Slovenia. The costs per inhabitant for the installation of a PHS system would amount to EUR 268,000, and for a Li-ion system even EUR 1,980,000. There is no country in the world that is so rich that it could finance something like this. The battery system has a ~5 times shorter lifetime (50 years hydro, 10 years Li-ion) and is ~7.4 times more expensive. In a similar study for the UK [46], the required storage capacity is given as 66.6 TWh, which means a specific capacity per inhabitant of ~1 MWh. The reason why the estimate of the required specific capacity in [46] is significantly lower is that the UK has a lot of wind in winter, while the model for Slovenia is primarily based on production with PV modules, which have the lowest production in winter. The calculation for the UK is done for 85 % wind and 15 % PV. The cost estimate for building storage capacity for 55 TWh of hydrogen and 11 TWh of compressed air (CAES) in [46] is extremely optimistic and is only ~3000 EUR/inhabitant.

Engineers have always focused on increasing production, increasing performance and increasing efficiency. But we never ask why we need more and more energy and where all this energy is going [47]. What will be the ultimate impact of a society with ever increasing energy consumption? Everyone has their own helicopter and goes on vacation in space, as Trainer asks in [48]. In general, even technically educated people are not aware of how much physical effort is required to generate 1 kWh of energy through their own physical labor. The amount of energy generated during a whole day of hard work, e.g. of a construction worker or a miner, corresponds to "only" 0.5 kWh to 0.6 kWh [49] (0.5 kWh is the energy needed to lift 100 kg 1800 meters). In general, the price of electricity seems to be high. But if you know that the equivalent for a whole day of physical work with renewable energy (0.5 kWh) costs a few dozen cents (including grid fees and taxes), then the price of electricity is no longer (too) high. Because it is (too) cheap, we consume it in large quantities, which can be explained by the Jevons paradox. In general, people would get a better sense of what "current leisure consumption" of energy means, if they had to charge their cell phone battery with their own work (the RES way) to understand it themselves. For a typical cell phone battery capacity of "only" ~15 Wh, you would have to physically generate 15 Wh / 0.8 = 18.75 Wh yourself, which means lifting the mass of 100 kg by a whole 67.5 m.

Even the food we eat every day is generally assumed to be (almost) a completely renewable source of energy. In reality, bread contains up to 1/3 fossil energy (artificial fertilizers, tillage, harvesting, milling, baking, transport) [50].

Can we assume that we will do without fossil fuels in the future? Certainly not with this level of energy consumption. The price of abandoning fossil and nuclear fuels is too high with the known renewable energy technologies, and if the price of energy rises sharply due to the transition to renewable energy, economic growth will also come to a standstill and there will be no surplus money for investment in renewable energy. One of the predictions for the future is the transition to a so-called "symbiotic economy" [51], in which the economy will be in symbiosis with the environment and society. Social progress will no longer consist in economic growth, but in increasing the quality of life, which is still a rather utopian idea at the moment.

5 CONCLUSIONS

The article shows the increase in the use of renewable resources in Slovenia to the extent that fossil and nuclear resources could be replaced by 2050. The results obtained show the technical (in)feasibility and relative absurdity of such intentions. In principle, however, renewable energy sources will only be half of the solution to the problem. There is still the problem of where new raw materials are to be extracted from the finite planet Earth.

By switching to RES, we are trying to find a second kind of perpetual motion machine. This means that mechanical work is extracted from the environment while the environment does not change. The second law of thermodynamics teaches us that every activity, energy conversion causes an increase in the entropy of the universe and an approach to the heat death of the universe. Do we currently assume that as soon as we have an infinite amount PV and wind power, we can also afford infinitely low conversion efficiencies?

Where can we look for a solution to the problem? A relatively simple but inconvenient technical solution is to reduce productivity and increase the amount of physical labor people do in producing (and maintaining) more durable and useful necessary goods. This would reduce the consumption of energy and raw materials, and "green jobs" would take the place of highly productive manufacturing. Why the decline in productivity? The increase in productivity increases profits linearly, but energy consumption exponentially [52]. In the mentioned study, a very clear comparison is made between manual and mechanical milking of a cow. With mechanical milking, energy consumption increases ~400-fold, the working time spent with a single cow decrease from 110 hours/year to 12 hours/year, which means that productivity only increases by a factor of $110/12 = 9.1$. A decrease in productivity means more employees for the same economic effect and, of course, lower revenues as a result. The introduction and spread of "green" jobs are exactly that, a reduction in the productivity of energy systems, which makes renewable energy increasingly more expensive than conventional fossil energy [52]. Currently, various subsidies and the carbon tax further distort economic conditions and the reality of energy prices. Although the share of renewable energy sources is increasing, electricity prices in the EU have risen significantly in the last two years, affecting the competitiveness of European economies. What is the cause of this? Is it due to neglecting the physical facts? Unfortunately, politicians (and green activists) cannot influence or change physical laws [31], but they can simply be ignored for a limited time - probably until the first pan-European blackout.

The application of the above inconvenient technical solution is absolutely not possible in a free market economy where economic growth is the top priority. The philosophy of ecology and the free-market economy are diametrically opposed. Solutions must be found in the movement for better ideas, values and social systems [48].

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