Report

A renewable pathway for decarbonizing the electricity sector in Croatia and Slovenia

- Just Transition for an early coal and nuclear exit

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The study

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We inform on the sector transition, indicating technology trends of the so-called "Just Transition" scenario in comparison to a reference path where nuclear and coal maintain their dominance. The report also discusses how the electricity sector transition may affect the achievement of energy and climate commitments and informs on investment and cost impacts.

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1 Introduction

In light of the ambitious targets of the Paris Agreement and highly ambitious long-term decarbonisation goals set by the European Green Deal, a critical question for decision-makers is how to sustain a coal and lignite phase-out that is as swift as possible while also ensuring supply of affordable electricity, and a just transition in regions dependent on coal. Within Slovenia and Croatia electricity generation from nuclear power is often seen as a carbon-free alternative – but concerns on a safe and reliable operation of the nuclear power plant built at Krško question this generation asset and also the plans for a newly built second nuclear unit at the Krško site which may imply considerable cost (cf. Hinkley Point C, etc.).

This brief report sheds light on an alternative pathway for a just transition of the electricity sector of both countries, relying on a transition towards renewable energy forms as alternative to coal and nuclear. The aim of this report is to illustrate and describe how this alternative pathway may look like. We inform on the sector transition, indicating technology trends of the so-called "Just Transition" scenario in comparison to a reference path where nuclear and coal maintain their dominance. The report also discusses how the electricity sector transition may affect the achievement of energy and climate commitments and informs on investment and cost impacts.

1.1 Structure of this report

The structure of this brief report is as follows: Subsequently within chapter 2 we describe the approach taken and the key assumptions for the underlying analysis and modelling. Then chapter 3 is dedicated to inform on historic trends and the status quo of electricity demand and supply within Croatia and Slovenia, indicating the role of renewables as well as of coal and nuclear power for meeting the power needs in both countries. Chapter 4 introduces the available renewable energy sources within the region that may play a key role in the electricity sector in future, indicating the resource potentials at technology level. Next to that, chapter 5 describes the derived "Just Transition" pathway for a sector transition towards renewables. The description starts with a brief recap on energy and climate targets for 2030 that Member States (MS) of the European Union (EU) need to respect whereas all subsequent subsections are dedicated to introduce the transition scenario derived for both countries in further detail. That involves to analyse the anticipated change in the technology mix by assessing generation and capacity trends. Key results from the complementary power system analysis done for 2030 are also presented, serving as feasibility check that the electricity market can cope with rapid RES expansion. A closer look at impacts on CO_2 emissions related to electricity supply and on cost impacts conclude the assessment. The report concludes with a summary of key findings and recommendations on the way forward, cf. chapter 6.

2 Approach and key assumptions

2.1 The applied modelling system

This analysis builds on modelling works undertaken by the use of TU Wien's Green-X model, a specialised energy system model with a sound incorporation of various RES policy approaches, closely linked to the complementary power system model Balmorel. A brief characterisation of both models is given in Box 1 below.

More precisely, Green-X delivers a first picture of future RES developments under distinct energy policy trends and cost assumptions, indicating details on technology trends (investments, installed capacities and generation) and the geographical distribution of RES deployment as well as related costs (generation cost) and expenditures (capital, operation and support expenditures). For assessing the interplay between RES and the future electricity market, Green-X was complemented by its power-system companion, i.e. the Balmorel model. Thanks to a higher intertemporal resolution than in the RES investment model Green-X, Balmorel enables a deeper analysis of the electricity market integration of renewables, shedding light on the interplay between supply, demand and storage in the electricity sector.

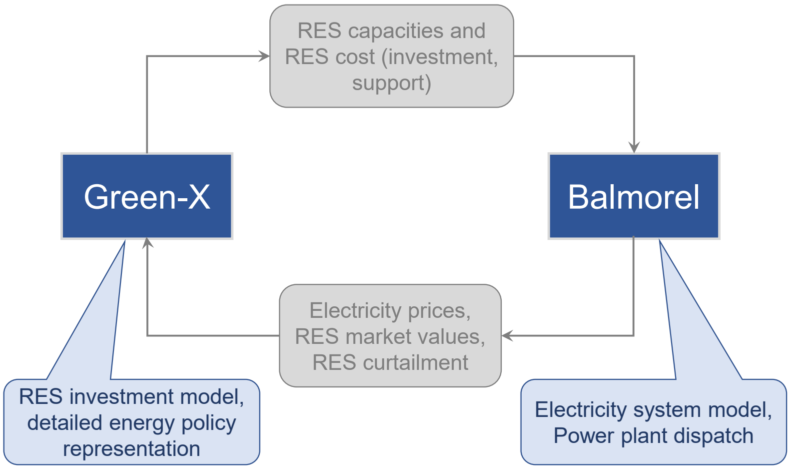
Box 1:Brief characterisation of the applied modelling system (Green-X in combination with Balmorel)

Green-X is an energy system model, developed by TU Wien, that offers a detailed representation of the potentials and the related technologies of various renewable energy sources (RES) in Europe and in neighbouring countries, including all EU Member States and all Contracting Parties of the Energy Community. It aims at indicating consequences of RES policy choices in a real-world energy policy context. The model simulates technology-specific RES deployment by country on a yearly basis, in the time span up to 2050, taking into account the impact of dedicated support schemes as well as economic and non-economic framework conditions (e.g. regulatory and societal constraints). Moreover, the model allows for an appropriate representation of financing conditions and of the related impact on investor's risk. This, in turn, allows conducting in-depth analyses of future RES deployment and corresponding costs, expenditures and benefits arising from the preconditioned policy choices on country, sector and technology level.

Balmorel (the **BALtic Model for Regional Electricity Liberalisation**) is an open-source partial equilibrium model, analysing the electricity and combined heat and power sector on various geographic levels. The analysis of further sectors via sector coupling (e.g. e-mobility, individual heating) is also possible via model add-ons. The model was originally developed by DTU and is now used and further developed by a wide range of institutions within Europe and worldwide, including TU Wien who is conducting also recent extensions in the course of this project. Balmorel is a deterministic bottom-up energy system model that is able to co-optimize energy dispatch and investments via linear (and for some applications mixed-integer) programming. For this, equations on electricity and district heat balance, capacity and energy constraints, production of dispatchable and non-dispatchable units, operational constraints, storage operation, transmission constraints, emission caps, and several more are considered. As a result, the model delivers energy conversion characteristics, fuel consumption, electricity exports and imports, emissions, investments in plants and transmission lines, prices on traded energy, and total system costs.

Figure 1 gives an overview on the interplay of both types of models. All models are operated with the same set of general input parameters, however in different spatial and temporal resolution. Green-X delivers a first picture of renewables deployment and related costs, expenditures and benefits by country on a yearly basis (2010 to 2030 and beyond). The output of Green-X in terms of country- and technology-specific RES capacities and generation in the electricity sector for selected years serves as input for the power-system analysis done with Balmorel. Subsequently, the applied power system model analyses the interplay between supply, demand, and storage in the electricity sector on an hourly basis for the given years. The output of the power system model is then fed back into the RES investment model Green-X. In particular, the feedback comprises the amount of RES that can be integrated into the grids, the electricity prices, and corresponding market revenues (i.e. market values of the electricity produced by variable and dispatchable RES-E) of all assessed RES-E technologies for each assessed country.

Figure 1: Model coupling between Green-X (energy policy analysis) and Balmorel (power system analysis) for an assessment of RES developments in the electricity sector. (Source: own development)



2.2 Assessed scenarios and key assumptions

The modelling undertaken in the course of this assessment serves to conduct **a feasibility check of an alternative pathway for a just transition of the electricity sector in Croatia and Slovenia**, indicating the perspectives for an early coal and nuclear exit in both countries. Since national electricity markets across Europe are closely interlinked, the **whole analysis is undertaken at a European scale**, by analysing the electricity sector transformation towards 2030 and beyond (2050) as well as the interplay of supply, demand and storage within the electricity sector of all EU Member States.

Two scenarios are in focus:

- On the one hand, modelling allows for identifying the needs arising from the European Green Deal for a stronger increase of RES overall in accordance with a strengthening of the climate ambition for 2030 and a full decarbonisation of the electricity sector (and the overall economy) by 2050. In our brief analysis undertaken within the course of this study we focus on assessing the contribution of RES electricity to that (**Just Transition scenario**). That scenario relies specifically for both target countries (Croatia and Slovenia) on a transition towards renewable energy forms as alternative to coal and nuclear which are assumed to be phased-out in the mid of this decade from the Croatian and Slovenian electricity sector.
- As reference we derived a second scenario where the planned RES uptake within the electricity sector of all EU Member States, including Croatia and Slovenia, was set in accordance with current national planning as postulated in National Energy and Climate Plans (NECPs) (**Reference scenario**), cf. (EC, 2020a).

Generally, a **least-cost approach is followed for allocating RES investments** post 2020 cost-effectively across technologies (and partly also geographically across the whole EU): The model-based selection of RES technologies in the period post 2020 follows within all assessed scenarios a least-cost approach, meaning that all additionally required future RES technology options are ranked in a merit-order, and it is left to the economic viability which options are chosen for meeting the presumed 2030 RES target. In other words, a least-cost approach is used to determine investments in RES technologies post 2020 across the EU. This allows for a full reflection of competition across technologies and to a limited extent also across countries from a European perspective. For the reference scenario we deviate from this general concept specifically for Slovenia and Croatia: here technology-specific RES use in the electricity was stronger aligned to the RES use stated in their NECPs.

Key assumptions on future energy price and carbon price trends were set in accordance with recent European modelling activities published by the European Commission, specifically the Climate Target Plan of the European Commission and the MIXED scenario published therein (EC, 2020b and EC, 2020c). That implies for example a carbon price of 44 €/tCO_2 by 2030 under both scenario.

The **future development of electricity consumption** was set in accordance with NECPs for the reference scenario whereas in the Just Transition scenario in the long-term (i.e. by 2050) an around 50% higher electricity demand (compared to reference) was presumed, driven by increases in sector coupling in accordance with decarbonisation needs.

3 Status quo of the electricity sector in Croatia and Slovenia

This chapter is dedicated to provide a brief overview on historic trends and on the status quo of electricity demand and supply within Croatia and Slovenia, indicating the role of renewables as well as of coal and nuclear power for meeting the power needs in both countries.

In this context, Table 1 provides a concise overview on historic trends in electricity consumption and fuel-specific supply in Croatia (left) and Slovenia (right).

As applicable from this table, renewables have already been in 2005 the largest contributor to meet domestic electricity demand in **Croatia**, accounting for a demand share of 41% by that point in time according to actual generation, or of 35% if normalised (hydro) production is taken into consideration. The normalised RES share has been steadily growing since then, achieving around 50% in 2019. Hydropower dominates renewable power supply but recent growth is caused by a rapid increase of wind onshore and to a smaller extent by the increase in bioenergy use. The share of fossil fuels has declined in turn, i.e. from 34% in 2005 to 23% in 2019, and also the underlying fossil fuel mix changed significantly: Croatia has managed to phase-out the use of oil and petroleum products and also coal use, accounted under solid fossil fuels in Table 1, has declined since then from 13% (2005) to 9% (2019) when measuring the coal share in relation to domestic gross electricity demand. As of today (2019), natural gas dominates fossil fuel supply in the Croatian electricity sector, achieving as demand share of 14% in 2019.

Table 1: Historic trends in electricity consumption and supply (by fuel) in Croatia and Slovenia (Source: Eurostat, 2021a and Eurostat, 2021b)

Historic trends in electricity demand and supply in TWh	Croatia				Slovenia			
	2005	2010	2015	2019	2005	2010	2015	2019
Gross electricity demand	17.5	18.8	18.0	18.8	14.8	14.1	14.8	15.6
RES generation (normalised)	6.1	7.0	8.2	9.4	4.2	4.6	4.8	5.1
RES share (in % of consumption)	35.2%	37.5%	45.4%	49.8%	28.7%	32.2%	32.7%	32.6%
Gross electricity generation	13.2	14.9	11.4	12.8	15.1	16.4	15.1	16.1
Net import	4.3	3.9	6.6	6.0	-0.3	-2.3	-0.3	-0.5
RES generation (actual)	7.2	9.4	7.7	8.5	3.6	4.9	4.6	5.2
Solid fossil fuels	2.3	2.4	2.3	1.6	5.3	5.3	4.4	4.5
of which lignite	0.0	0.0	0.0	0.0	4.8	4.8	4.0	4.2
Natural gas	1.8	2.6	1.2	2.6	0.3	0.5	0.4	0.5
Oil and petroleum products	1.9	0.6	0.2	0.0	0.0	0.0	0.0	0.0
Nuclear	0.0	0.0	0.0	0.0	5.9	5.7	5.6	5.8

A slower transformation of the electricity sector has taken place in **Slovenia**. Similar to Croatia, also in Slovenia an increase of the use of renewables is applicable, but the uptake from 29% (2005) to 33% (2019) when comparing normalised RES generation with domestic electricity demand is less pronounced than in Croatia. Renewable supply is dominated by hydropower where also throughout the last decade a strong increase has been achieved. On second place follows photovoltaics (PV), and on third bioenergy.

Electricity supply in Slovenia is currently dominated by nuclear power, contributing 37% in 2019 to meet domestic demand, followed by renewables as discussed above. The share of solid fossil fuels (lignite and coal) has been slowly declining in the period 2005 to 2019, i.e. from 36% in 2005 to 29% in 2019 when comparing supply with demand. Thus, as applicable from Table 1, as of today (2019) lignite and to a minor extent coal still play an important role in Slovenian power supply.

4 Renewable Energy Sources – a closer look at available potentials in Croatia and Slovenia

This section provides a concise overview on the potentials of renewable energy sources applicable in both countries in focus. In this context, Table 2 provides a concise overview on domestic potentials for electricity generation from RES in Croatia (left) and Slovenia (right). This table combines information gained from an intense literature review performed in an ongoing EU study (cf. Resch et al. (2021)) with the outcomes of an own GIS-based analysis of the available resources across European countries. The latter has been conducted for wind energy and solar electricity (photovoltaics) using meteorological data and land use datasets at a high geographical and temporal resolution. For both on- and offshore as well as for PV land use restrictions were incorporated into the analysis in order to identify cost-effective generation sites that could be exploited in future years. The incorporation of restrictions implied for example to exclude environmental protection areas and to consider distance rules to the built environment in the case of onshore wind. Complementary to Table 2, a graphical illustration of the outcomes of the GIS-based assessment is provided by Figure 2 for solar PV, showing a map for global solar irradiation, and by Figure 3 for onshore wind, indicating site conditions for those areas where wind energy can be used under the incorporated land use restrictions. Figure 4 complements the above with a map for offshore wind use in the whole of Southern and Eastern Europe.

Table 2: Domestic potentials for electricity generation from RES in Croatia and Slovenia (Source: Eurostat (2019a) and own assessment, based on DLR (2006), Heaps (2009), IRENA (2017) and Neubarth (2018))

Potentials for electricity generation from RES (in GWh)	Croatia				Slovenia			
	Historic use (2019)	Literature survey on technical/economic potentials: Min	Literature survey on technical/economic potentials: Max	Own GIS-based assessment	Historic use (2019)	Literature survey on technical/economic potentials: Min	Literature survey on technical/economic potentials: Max	Own GIS-based assessment
Bioenergy	970	340	5,743		246	84	1,420	
Geothermal	0	450			0	540		
Hydropower	6,897	8,919	12,000		4,528	5,148	9,000	
Photovoltaics	83	4,355	4,356	22,997	303	447	1,459	6,582
Wind onshore	1403	2,600	29,153	54,837	6	300	2,273	10,275
Wind offshore	0	n.a.	n.a.	ca. 900	0	n.a.	n.a.	n.a.

As outlined in chapter 2, historically hydropower has been the dominant renewable energy source in the electricity sector of both Croatia and Slovenia but here the future uptake appears limited considering available potentials (cf. Table 2) and environmental concerns. In contrast to hydropower, significant future potentials are applicable for PV and wind onshore. Here the outcomes of our own GIS based analysis point out that available domestic resources would allow for meeting and exceeding current electricity needs of both Croatia and Slovenia. Summing up the identified technical potentials of both countries together corresponds to an annual generation volume that is almost three times as high a current electricity demand. Due to the country size and the topographical location potentials for both PV and wind onshore are however significantly higher in Croatia than in Slovenia. As shown in Table 2, apart from solar and wind also bioenergy offers techno-economic potentials at a relevant magnitude that may help to balance the weather-dependent variable electricity supply from hydro, wind and PV.

Figure 2: **Map of solar (global) irradiation in Croatia and Slovenia, indicating site conditions for photovoltaics (Source: own assessment)**

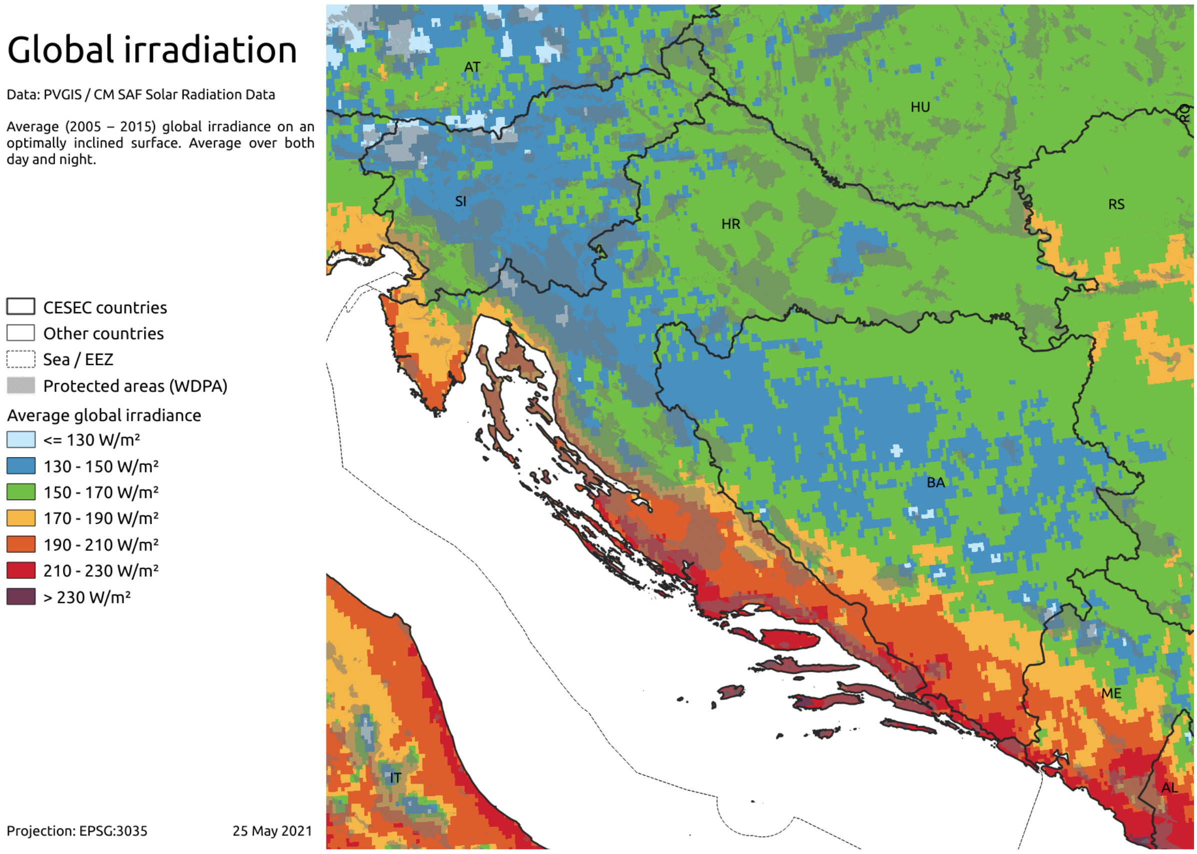


Figure 3: **Wind map of Croatia and Slovenia, indicating site conditions (full load hours) for wind onshore (Source: own assessment)**

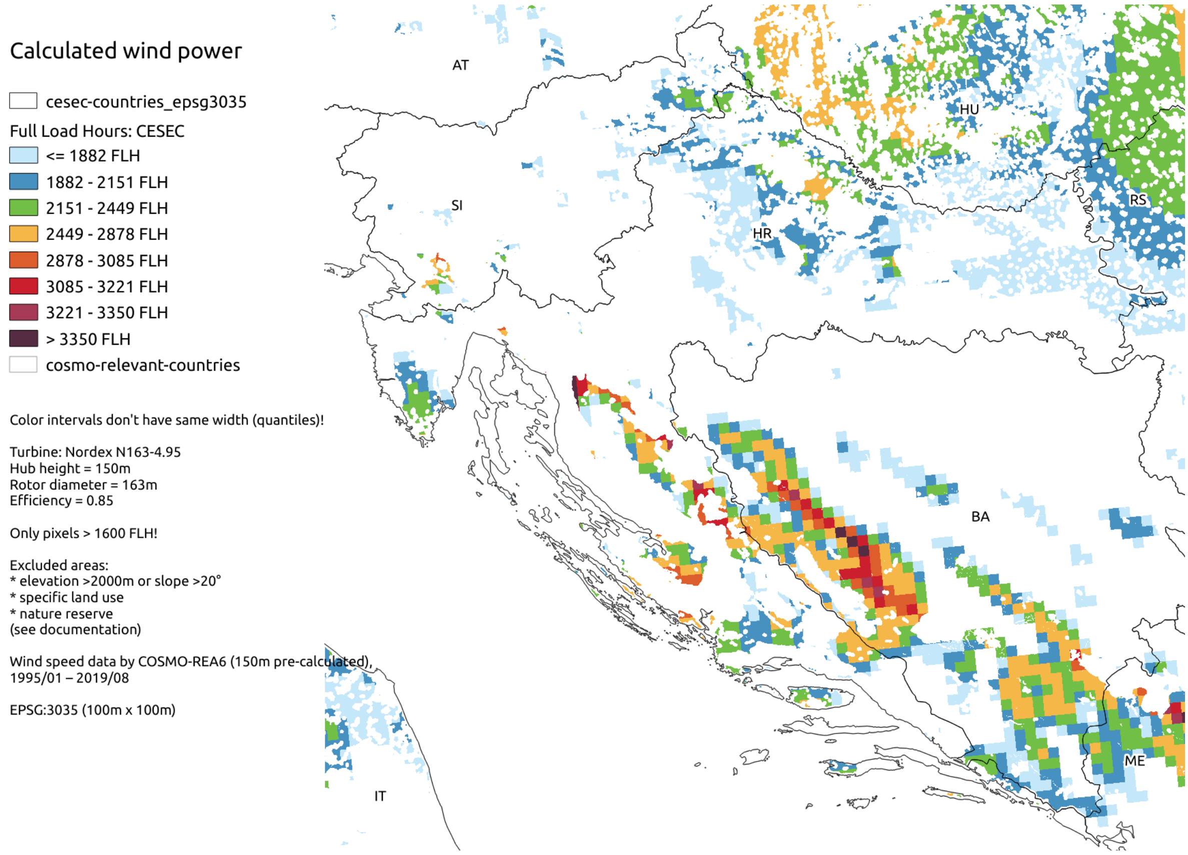
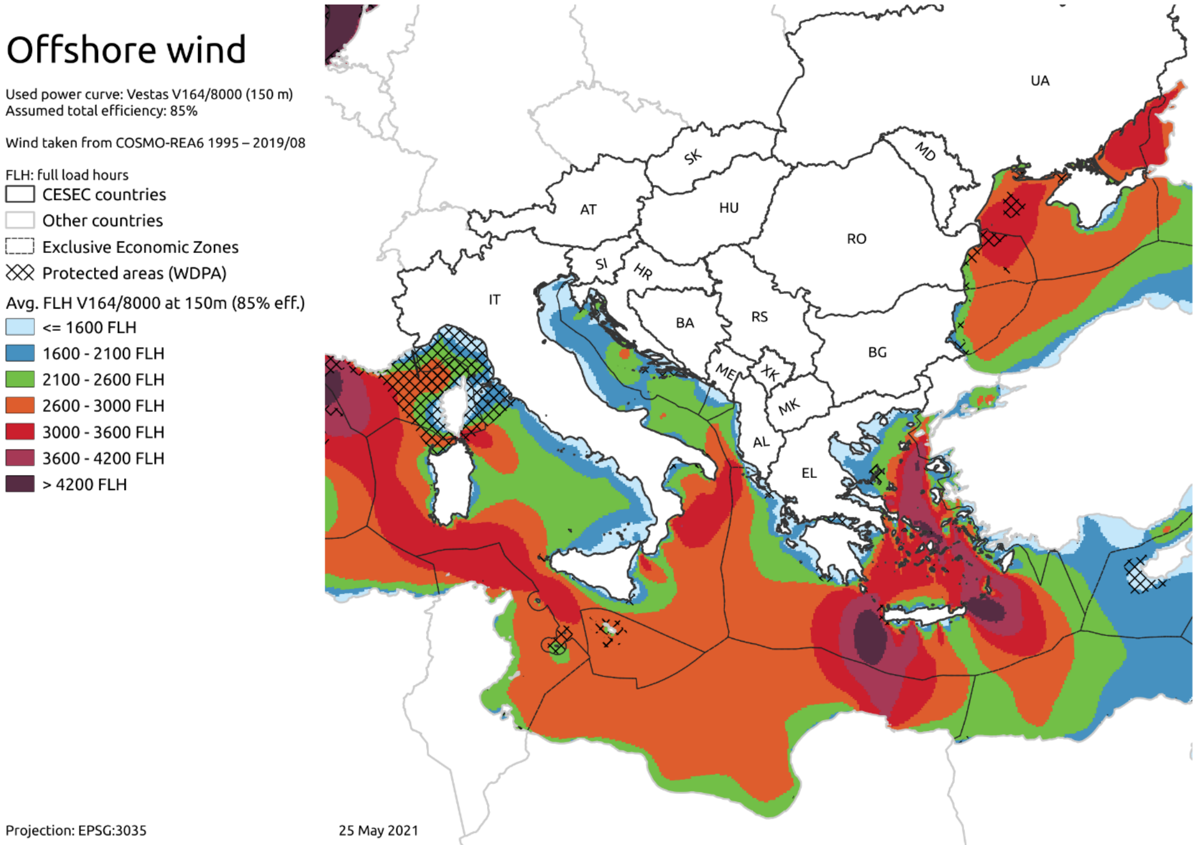


Figure 4: Wind map of sea areas in Southern Europe, indicating site conditions (full load hours) for wind off-shore (Source: own assessment)



5 Just Transition: a renewable pathway for decarbonising the Croatian and Slovenian electricity sector

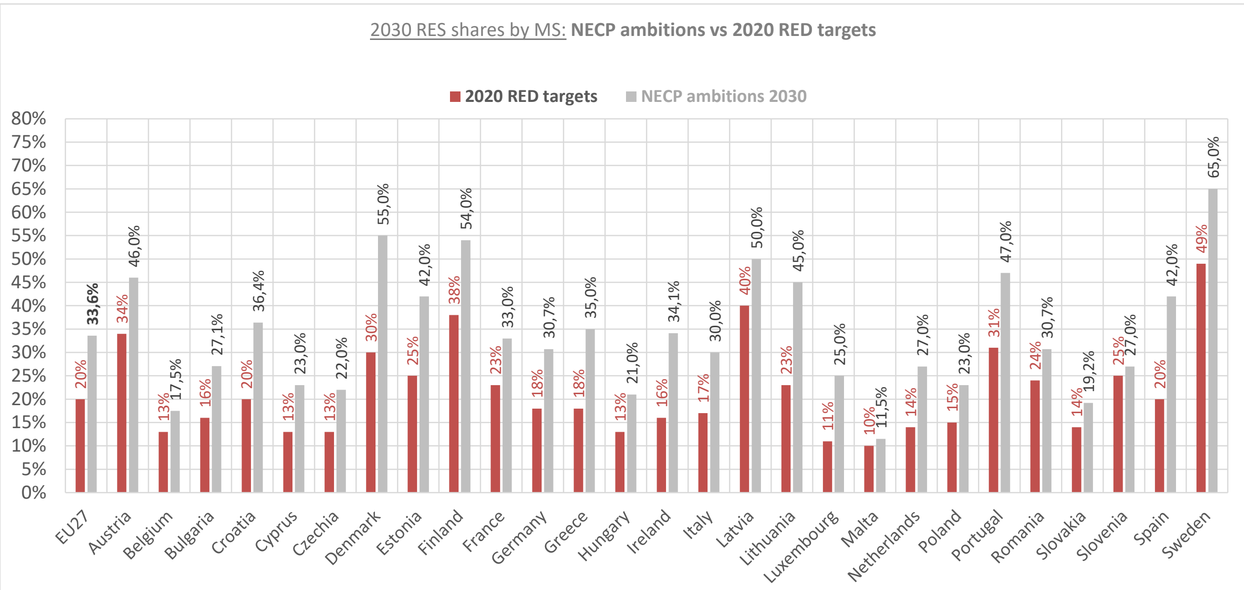
This chapter sheds light on the outcomes of our brief model-based assessment for a decarbonization of the Croatian and Slovenian electricity sector. As outlined in detail in chapter 2, two complementary models were used to assess energy policy needs and impacts (Green-X) and to conduct a techno-economic feasibility check from a power system point of view (Balmorel). The modelling undertaken served to derive an alternative pathway for a just transition of the electricity sector in Croatia and Slovenia via an enhanced use of renewable energy sources (**Just Transition scenario**), indicating the perspectives for an early coal and nuclear exit in both countries. A Reference scenario that builds on current energy and climate planning within Croatia and Slovenia, where coal and nuclear maintain their dominance, helps to contrast the outcomes of the derived Just Transition scenario. Since national electricity markets across Europe are closely interlinked, the whole analysis was undertaken at a European scale, by analysing the electricity sector transformation towards 2030 and beyond (2050) as well as the interplay of supply, demand and storage within the electricity sector of all EU Member States.

Below we start with a brief recap on 2030 RES targets for the whole EU and its Member States. Next to that the uptake of renewables in the electricity sector is discussed, putting Croatia and Slovenia into the spotlight. In subsequence, key aspects of an enhanced RES market integration are then illustrated, assessing the interplay between supply, demand and storage in the electricity market at a high temporal resolution.

5.1 Recap on 2030 RES targets

The role of RES in National Energy and Climate Plans

Figure 5: 2020 RES targets vs. 2030 RES shares by EU MS according to NECPs (Target Scenario) (Source: NECPs and own analysis)



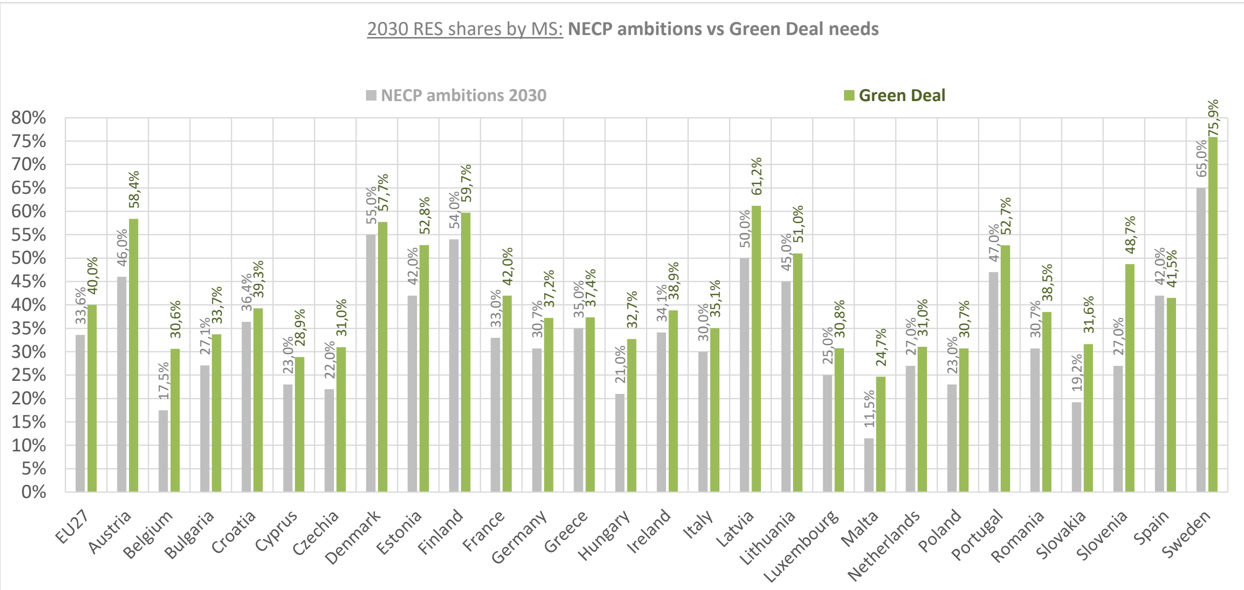
Throughout the last years, EU MSs have agreed upon 2030 energy and climate targets. In the field of renewables the current framework implies at EU level an increase of the RES share from 20% by 2020, as set by the original RED (EU, 2009), to (at least) 32% by 2030, in accordance with the recast of the RED (EU, 2018a). In order to facilitate this energy transition, EU MSs had to provide National Energy and Climate Plans (NECPs) by the end of

2019, indicating how to contribute to the overall 2030 EU energy and climate targets. Thus, MSs have to increase their RES shares (well) above their 2020 RES targets in order to contribute to the overall EU RES target of (at least) 32% by 2030, and, as applicable from Figure 5, they are aware of that: Summing up the nationally planned RES shares (and where reported demand projections) for 2030 leads to an EU RES share of approx. 33.6%. The RES ambition however differs to a large extent across MSs: at the lower end, MSs like Malta, Slovenia, Belgium and Slovakia plan for increasing their RES share until 2030 less than 6 percentage points compared to their 2020 RES target, which is less than half of the RES share increase imposed at EU level during the same period in time. At the upper end, Denmark, Lithuania, Spain and Ireland aim for increasing their RES share until 2030 by more than 18 percentage points which is well above the EU RES share increase (12 percentage points) agreed upon.

The necessary increase of the RES ambition in accordance with the European Green Deal

The EU Green Deal and the corresponding increase in the 2030 climate ambition (approximately 55% instead of 40% GHG reduction) raises the need for a stronger uptake of renewables. Within the underlying model-based analysis the assumption was taken that the EU 2030 RES target would consequently be increased from (at least) 32% to (at least) 40%. Subsequently, a fair effort sharing across MSs was calculated, expressing national contributions for the EU RES target in accordance with an approach for doing so as described in the EU Governance Directive (EU, 2018b)[1], cf. Figure 6. Except for Spain where national planning shows a higher RES ambition, this implies in general a strong increase of the RES ambition in the forthcoming decade. Following that approach would imply highest increases of the 2030 RES share (above 10 percentage points) for Slovenia, Malta, Belgium, Austria, Slovenia, Latvia, Hungary, Sweden and Slovakia, whereas a comparatively small increase (below 3 percentage points) would result for Greece, Denmark and Croatia.

Figure 6: 2030 RES shares by EU MS according to NECP planning (Reference Scenario) vs Green Deal needs (Just Transition scenario) (Source: NECPs and own analysis)



1 The question arose how to distribute the increased overall RES effort at EU level across individual MSs. Annex II of the EU Governance Directive (EU, 2018b) introduces for that purpose a methodology for establishing benchmarks concerning the national contributions for the RES share in gross final energy consumption in the 2030 context at EU level. This approach follows an integrated concept that takes into account the differences in economic development, the potential for cost-effective RES deployment and the interconnection level in the European Network of Transmission System Operators for Electricity (ENTSO-E) across the EU and its MSs, respectively.

5.2 The future uptake of renewables in the electricity sector

This section sheds light on the future RES uptake proclaimed for the electricity sector in Croatia, Slovenia and the remainder of the European Union. Here modelling provides a sound basis for that since derived pathways of RES deployment provide, on the one hand, insights on the planned RES uptake within the electricity sector in accordance with NECP planning (**Reference scenario**). On the other hand, modelling also allows for identifying the needs arising from the Green Deal for a stronger increase of RES overall, and on the contribution of RES electricity to that (**Just Transition scenario**). For Croatia and Slovenia that goes hand in hand with the presumed phase-out of coal and nuclear during this decade.

A closer look at the EU level

Before digging into details for the countries in focus within this study, a closer look is taken at the RES uptake in the EU electricity market.

Key results derived from this analysis are:

- At EU level we see a moderate RES uptake in the electricity sector if NECP planning is considered (57% RES-E share 2030 according to the Reference scenario), and
- a strong increase of RES deployment in the electricity sector if the Green Deal perspective is followed (ca. 66% by 2030 in accordance with the Just Transition scenario);
- New RES installations within this decade (up to 2030) will by 2030 have to provide slightly less than half of total electricity generation from RES (i.e. 46% of total) under NECP planning. The required contribution of new installations has to increase to 55% of the total RES-E volumes considering Green Deal needs.

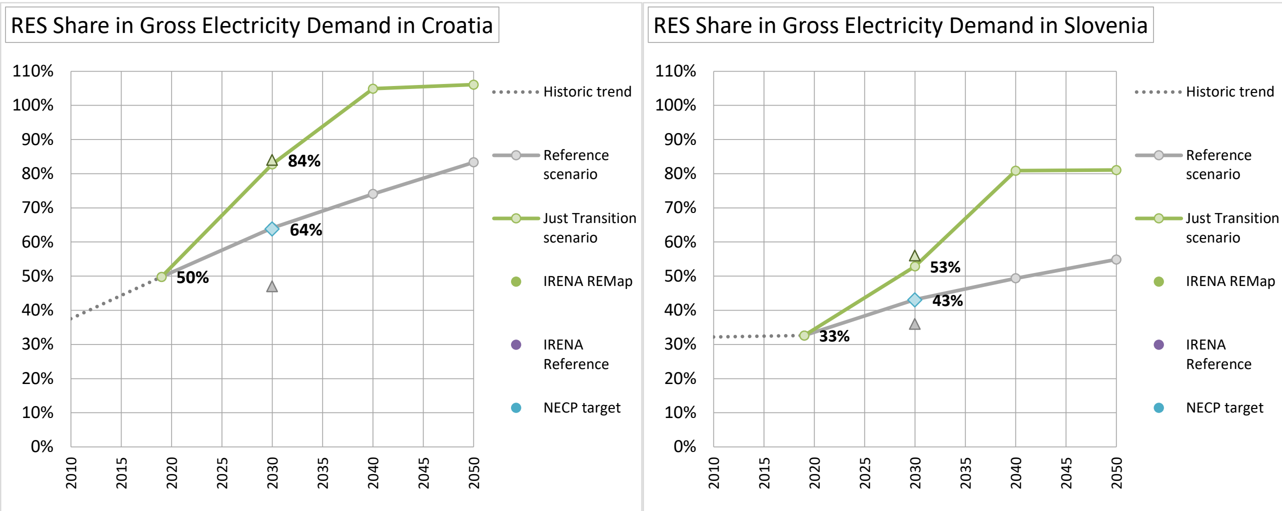
5.2.1 Spotlight on Croatia and Slovenia: Changing the electricity mix

Within Croatia and Slovenia renewables are already at present a key contributor to meet the demand for electricity. According to latest statistical data available (Eurostat, 2021a), RES achieved a share of ca. 50% in gross electricity demand by 2019 in Croatia, and the RES demand share in Slovenia was 33% (2019). Historically, the RES share was steadily growing over the past decade, with differences across both countries, cf. chapter 3. This growth needs to be accelerated in future years, given the policy commitments taken and the needs arising from a transformation of the energy sector in order to combat climate change while phasing out coal and nuclear.

Electricity generation and corresponding RES share in gross electricity demand

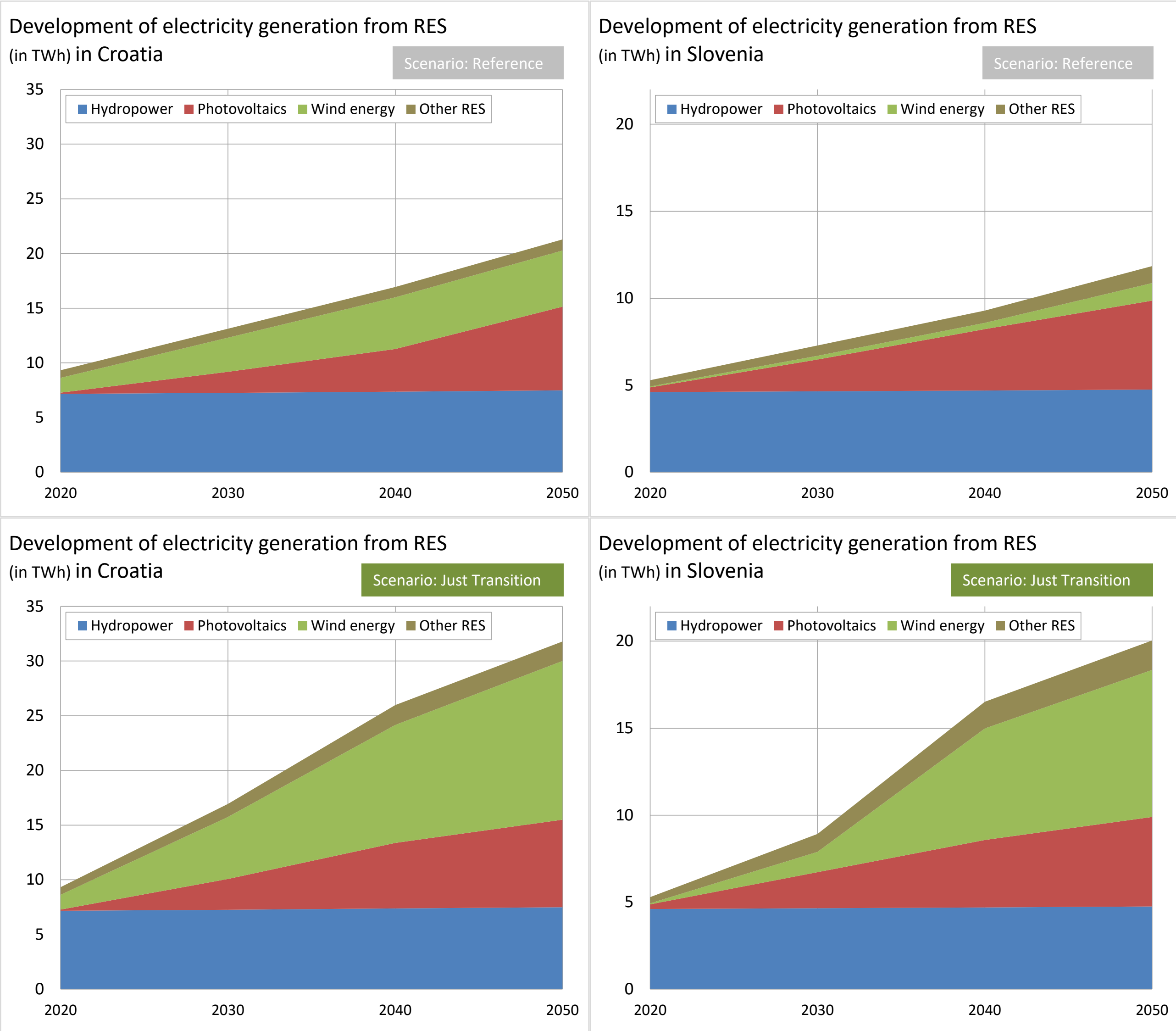
As a starting point for our analysis of the future uptake of renewables in the Croatian and Slovenian electricity sector, Figure 7 shows the development of the country-specific RES shares in gross electricity demand in the period up to 2050 according to derived scenarios (Just Transition and Reference). Apart from depicting our own modelling results Figure 7 also offers a comparison to NECP planning, indicating the targeted RES-E share for 2030; as well as to other modelling works in this topical context, indicating 2030 RES shares according to a recent study published by the International Renewable Energy Agency (IRENA) on "Renewable Energy Prospects for CESEC" (IRENA, 2020). As applicable from Figure 7, according to NECPs (Reference scenario) a steady growth of RES is planned in future years in Croatia and Slovenia. That would allow Croatia to increase its RES share from 50% (2019) to 64% by 2030, and, assuming that the underlying policy ambition remains constant in the period post 2030, to ca. 83% by 2050. National planning (Reference scenario) indicates for Slovenia a moderate increase of the RES share from 33% (2019) to 43% by 2030, and a RES share of 55% by 2050 (assuming the RES policy ambition is maintained post 2030). A more proactive approach is followed in the Just Transition scenario, indicating decarbonisation needs in accordance with the European Green Deal. Under this pathway the RES share in the electricity sector would grow more rapidly within both countries, reaching 84% in Croatia and 53% in Slovenia already by 2030, respectively. In the long-term (2050) RES would generate more than domestically needed in Croatia at an annual balance (i.e. a RES share of 106% by 2050) which, in turn, helps Slovenia to fill the gap needed for a carbon-free power supply by that point in time. For Slovenia modelling shows that a RES share of ca. 81% in 2050 appears feasible and makes economically sense, considering RES cooperation with neighbouring countries as fruitful alternative to meet domestic power needs. Finally, it can be stated that our modelled 2030 RES shares match well with the outcomes of the IRENA study (IRENA, 2020) and reflect for the Reference scenarios national planning, cf. Figure 7.

Figure 7: Development of the share of electricity generation from RES in gross electricity demand up to 2050 in Croatia (left) and Slovenia (right) according to assessed scenarios (Just Transition and Reference) (Source: Green-X modelling)



Details on the underlying technology mix in RES-based electricity generation are applicable from Figure 8. This graph illustrates the development of electricity generation from RES in Croatia (left) and Slovenia (right) for the Reference (top) and for the Just Transition (bottom) scenario. According to modelling, within all scenarios the dominance of hydropower in electricity supply is expected to diminish. Solar electricity (from PV systems) and wind power (onshore wind) will become the major contributor to future electricity supply. Of interest, as applicable from the results of the Reference scenario, wind energy gains currently comparatively little policy attention under current planning, specifically in Slovenia – i.e. here the current policy emphasis is on solar PV. Modelling results of the Just Transition scenario however make clear that wind energy could contribute significantly to the decarbonisation objective and may become the dominant power source in future (2050) within both Croatia and Slovenia. Apart from wind energy also bioenergy may deserve more policy attention, contributing to balance variable RES generation from hydro, wind and PV systems.

Figure 8: Development of electricity generation from RES up to 2050 in Croatia (left) and Slovenia (right) according to assessed scenarios (Just Transition (bottom) and Reference (top)) (Source: Green-X modelling)



Installed capacities

This section complements the above by taking a closer look at capacity trends in the modelled RES transition within Croatia and Slovenia. As a starting point, Figure 9 provides a comparison of the differences in cumulative installed RES capacities for all assessed scenarios within both countries by 2030 (left) and by 2050 (right). Next to that, insights on the anticipated changes in the country-specific technology mix of installed RES capacities at present (2020) and in future (2030, 2050) are shown in Figure 10 for all EU MSs, exemplified here for the Just Transition scenario.

Key results derived from these depictions are:

- As discussed above, the comparatively strong RES ambition is confirmed by the capacity trends: The cumulative installed RES capacity in Croatia (Slovenia) has to increase by a factor of six (eight) compared to today (2020).
- The changes in power technology mix across the whole EU can be branded as “solar revolution”: Both decentral and central PV systems are expected to become the largest contributor to power supply in

capacity terms in almost all countries, including Croatia and Slovenia – the contribution to power supply in energy terms is however smaller, cf. Figure 8.

Figure 9: Installed cumulative RES capacities in Croatia and Slovenia by 2030 (left) and by 2050 (right) according to assessed scenarios (Just Transition and Reference) (Source: Green-X modelling)

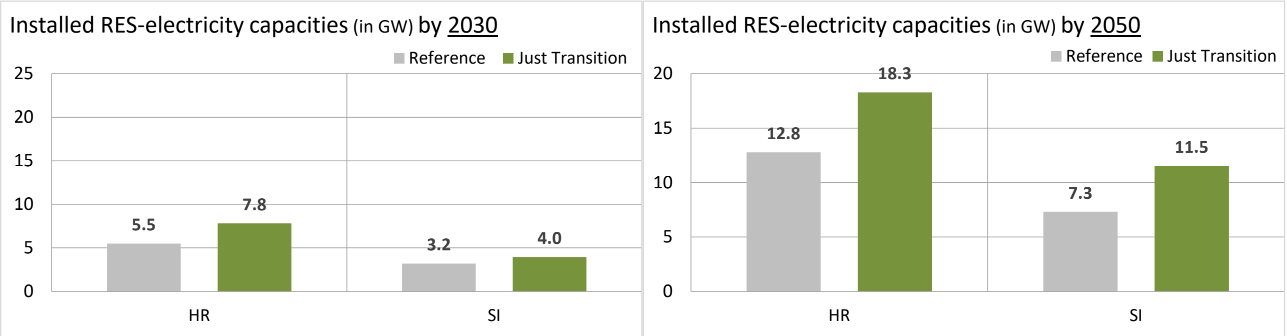
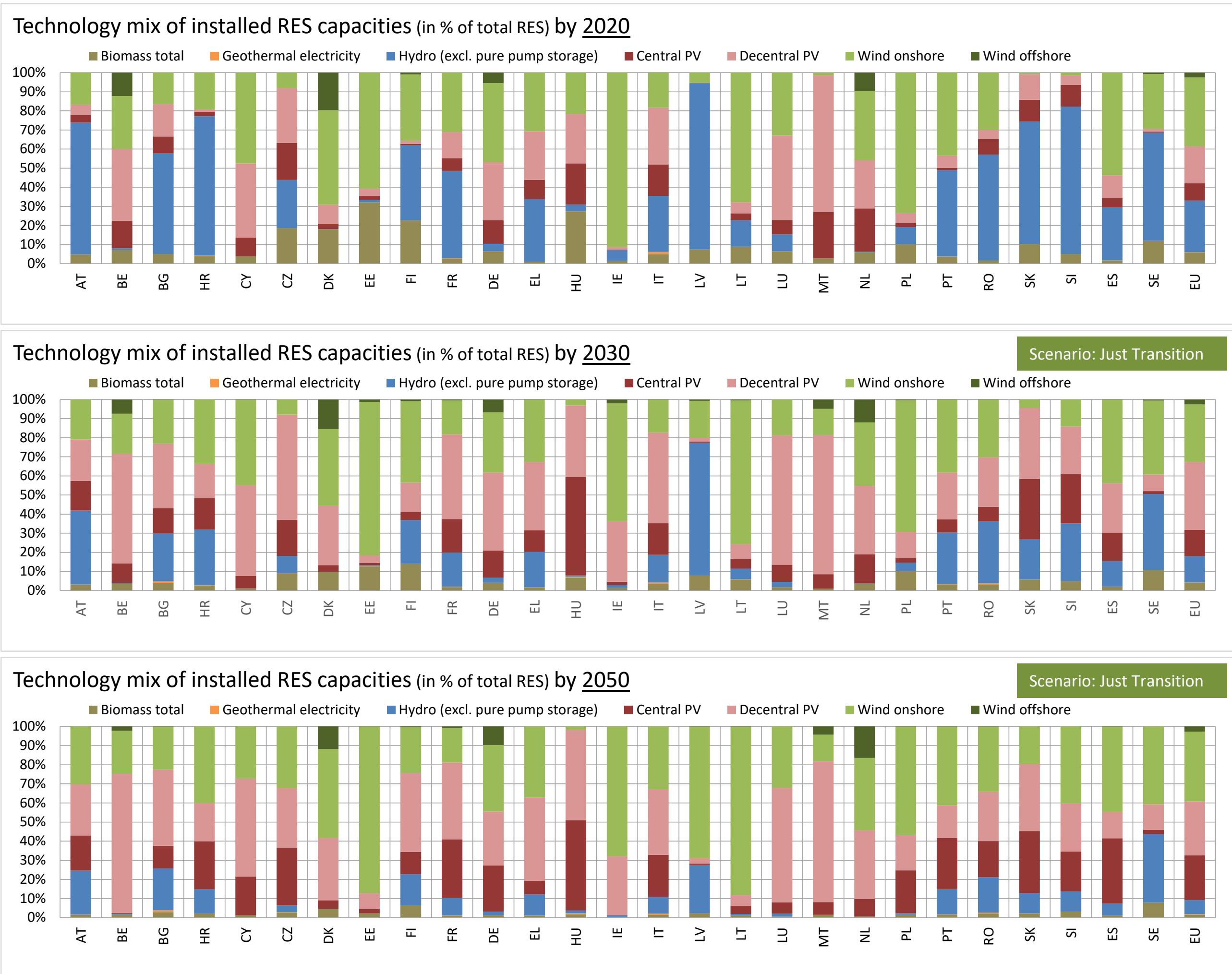


Figure 10: Country-specific technology mix of installed RES capacities at present (2020) and in future (2030, 2050) of all EU MSs, exemplified for the Just Transition scenario (Source: Green-X modelling)



Mapping of RES installations

This section aims to inform on the details in the geographical distribution of the anticipated RES uptake in Croatia and Slovenia in future years which may, in turn, help to identify promising sites as well as infrastructural prerequisites. For doing so, we have undertaken a detailed geographical mapping of the previously discussed modelling results on the future uptake of renewables in both countries. This mapping exercise was performed for all key RES technologies from a current and forward-looking perspective, comprising hydropower, photovoltaics and wind energy. The graphs below, Figure 11 to Figure 13, illustrate the development over time (2020 to 2050) for all key RES technologies identified, exemplified for the Just Transition scenario.

Figure 11: Mapping of current (2020) (left) and future (2030 (middle), 2050 (right)) hydropower installations in Croatia and Slovenia according to modelling (Just Transition scenario) (Source: own assessment)

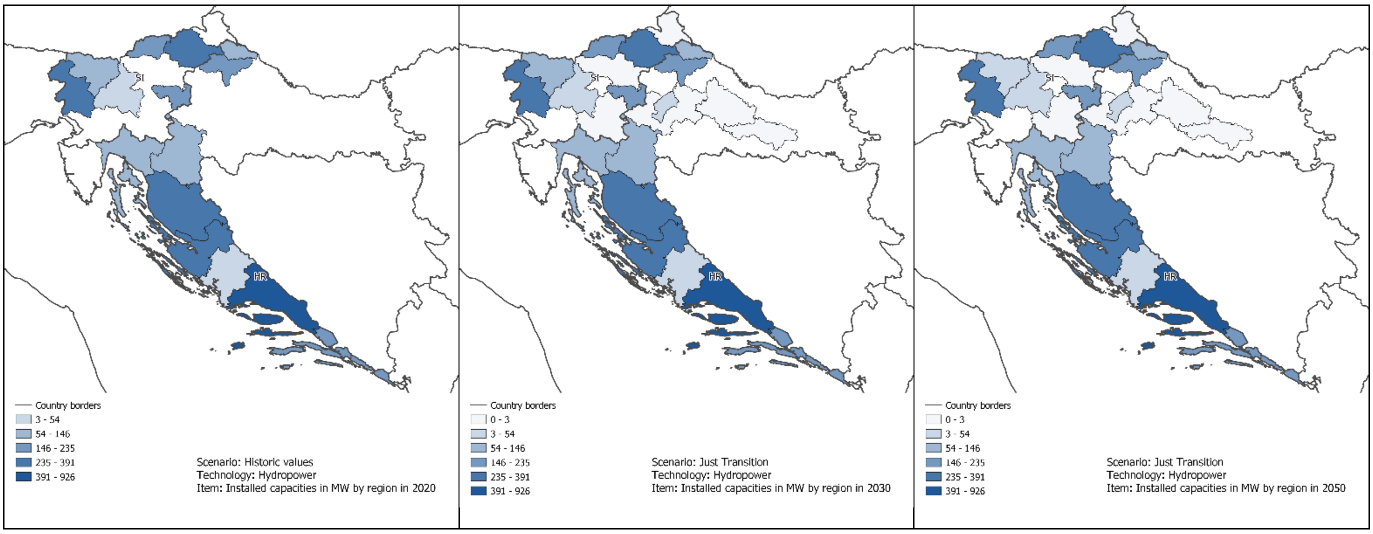


Figure 12: Mapping of current (2020) (left) and future (2030 (middle), 2050 (right)) photovoltaic installations in Croatia and Slovenia according to modelling (Just Transition scenario) (Source: own assessment)

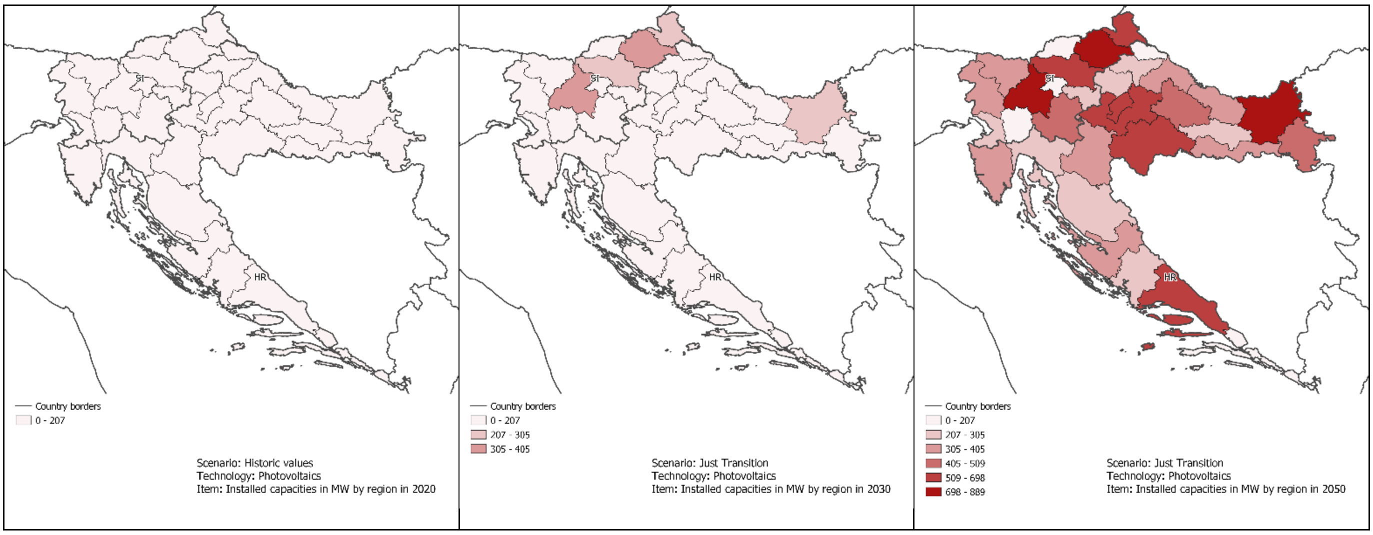
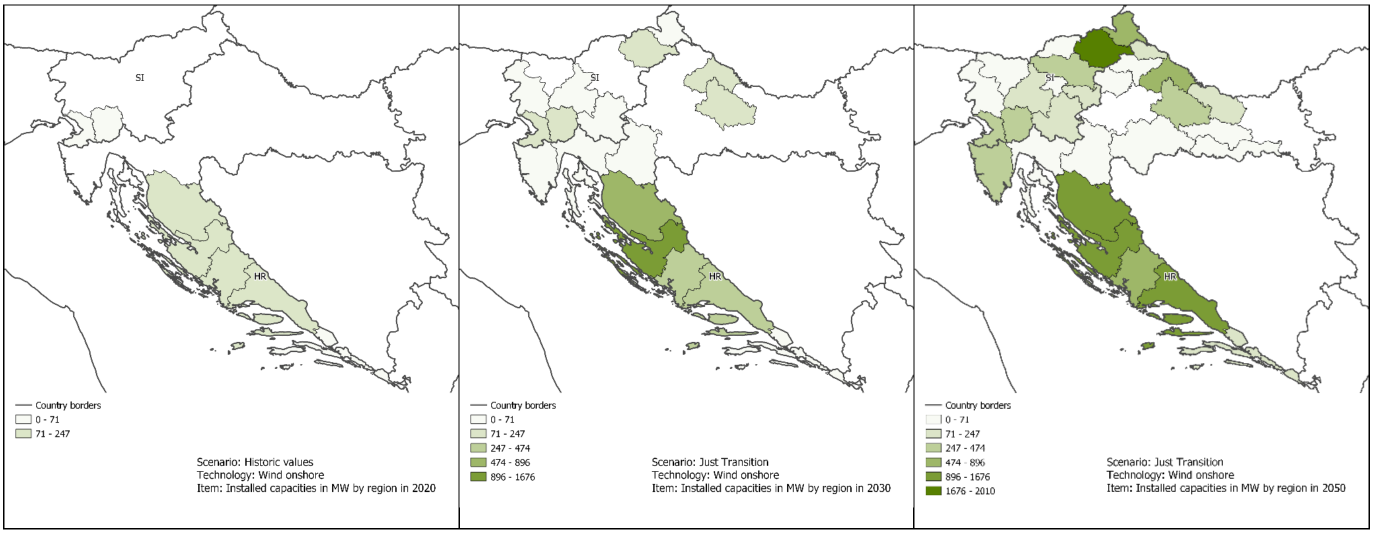


Figure 13: Mapping of current (2020) (left) and future (2030 (middle), 2050 (right)) wind onshore installations in Croatia and Slovenia according to modelling (Just Transition scenario) (Source: own assessment)



5.3 Power System Analysis: Feasibility check for 2030

Complementary to the above, a power system analysis has been undertaken for 2030 at European scale, serving as feasibility check that the electricity market in Croatia and Slovenia as well as in the remainder of the EU can cope with the anticipated rapid RES expansion as presumed in the Just Transition scenario. As outlined in chapter 2 of this report, the power system analysis was done by use of the open-source model Balmorel, offering a sound representation of the European power system, clustered into country nodes that are interlinked via transmission lines in accordance with ENTSO-E planning (i.e. TYNDP 2018), at a high temporal resolution[2]. Modelling indicates the power plant dispatch in order to achieve a match between demand and supply, including storage and other flexibility options to a limited extent.

The analysis proves that the European electricity system can cope well with the anticipated strong RES uptake in the period up to 2030. Below we take a closer look at the resulting generation mix for representative weeks and at a yearly balance. The latter served to also identify CO_2 emissions that stem from fossil electricity generation as reported subsequently.

Hourly power plant dispatch in Croatia and Slovenia for representative weeks

Figure 14 and Figure 15 illustrate the hourly power plant dispatch in the regional market of both Croatia and Slovenia during a typical summer week (Figure 14) as well as during a typical winter week (Figure 15) of the year 2030 for both assessed scenarios. The strong uptake of renewables in the Just Transition scenario translates into significantly higher generation volumes in comparison to the Reference scenario. PV systems contribute to cover a high share of total demand during the summer period whereas wind power contributes slightly more during the winter period. Weather-dependent fluctuations in electricity supply from all forms of variable RES are observable but the power system can cope well with these. Since coal and nuclear remain in the power plant fleet in the Reference scenario their contribution to electricity supply is also applicable in the Reference scenario.

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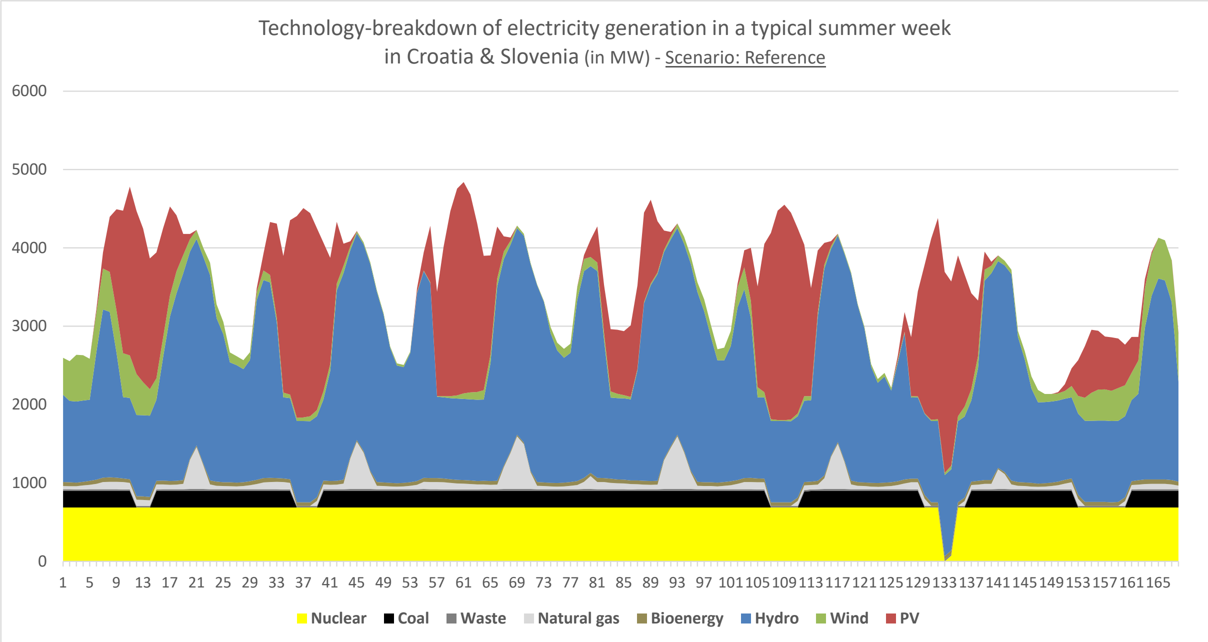
2 The modelling was done at an hourly basis for the whole year 2030.

Figure 14: Hourly generation mix in Croatia and Slovenia for a typical summer week in 2030 according to the Reference (top) and the Just Transition (bottom) scenario. (Source: Balmorel modelling)



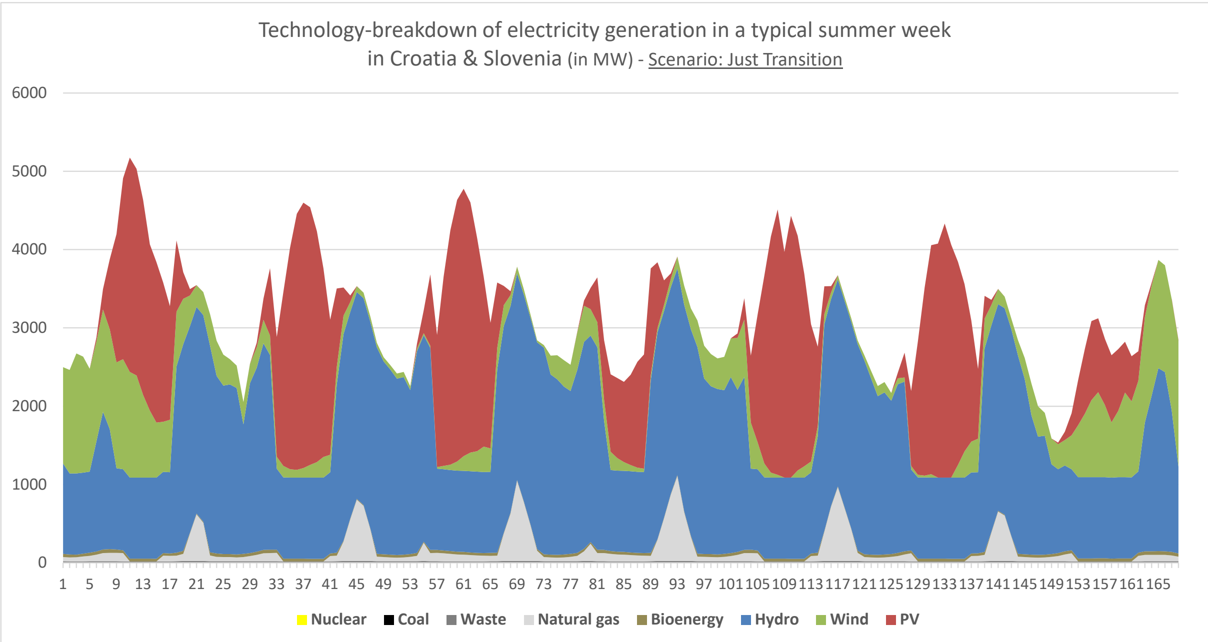
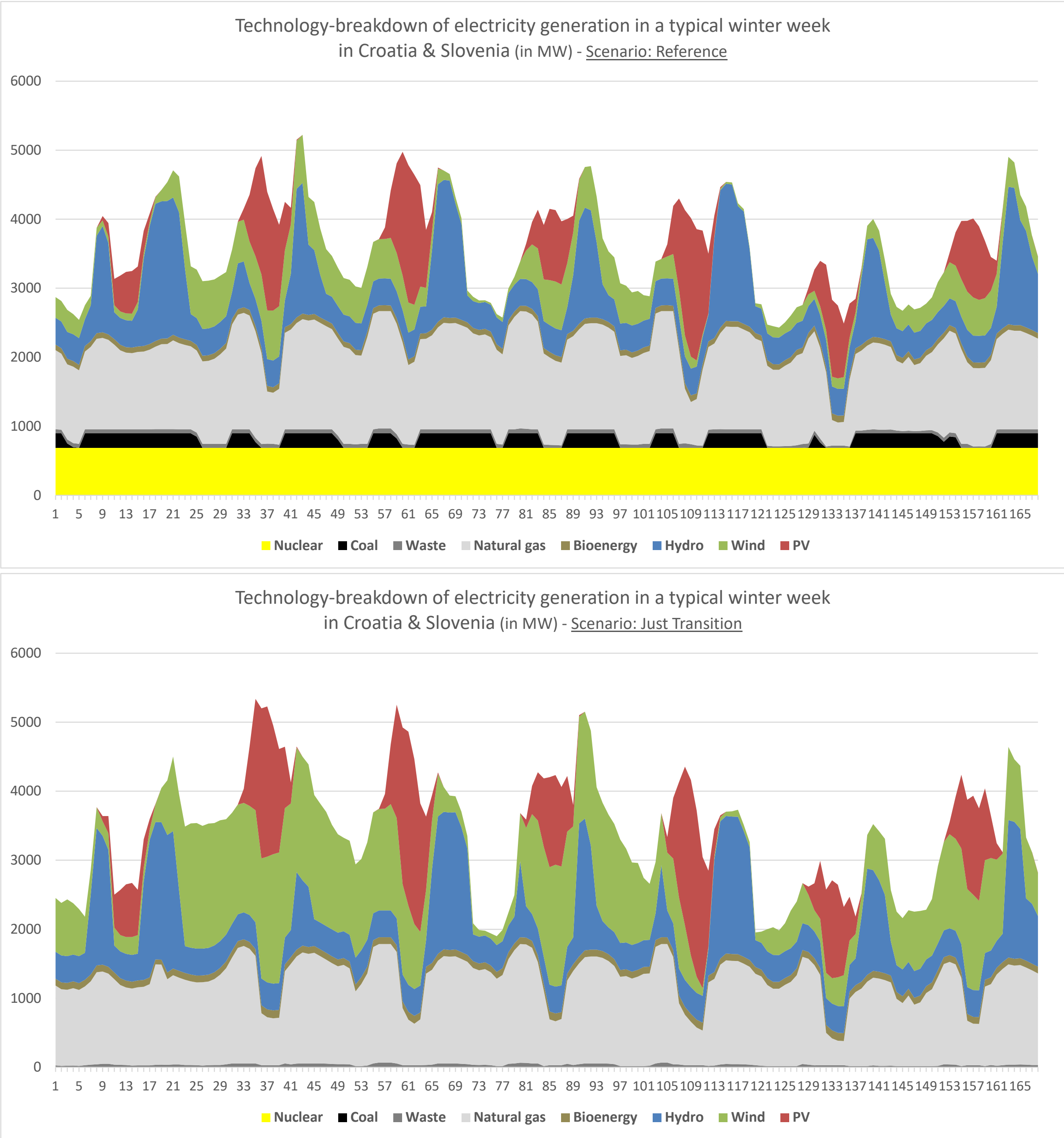


Figure 15: **Hourly generation mix in Croatia and Slovenia for a typical winter week in 2030 according to the Reference (top) and the Just Transition (bottom) scenario. (Source: Balmorel modelling)**



Changing the technology mix: Technology breakdown of electricity supply in Croatia and Slovenia at a yearly balance by 2030

Below we provide a technology breakdown of electricity supply in 2030 at a yearly balance for both Croatia and Slovenia in accordance with the assessed scenarios, cf. Table 3 (Reference scenario) and Table 4 (Just Transition scenario). As applicable also from the annual supply balance, the anticipated strong uptake of RES in both countries nicely compensates the supply gap arising from the early phase-out of coal and nuclear as presumed in the Just Transition scenario. The import ratio at regional level (i.e. Croatia and Slovenia as one region) increases slightly from 10% (in comparison to demand) in the Reference scenario to 14% in the Just Transition scenario. Natural gas does not contribute to compensate the gap at a yearly level but helps in providing flexible power when needed at a system level.

Table 3: Technology breakdown of yearly electricity generation (and comparison to demand) in Croatia and Slovenia by 2030 according to the Reference scenario. (Source: Balmorel modelling)

Yearly electricity generation in 2030 according to the Reference scenario (in TWh)	Nuclear	Lignite	Coal	Natural gas	Waste	Bioenergy	Hydropower	Wind	PV	Total Supply	Total Demand
Croatia	0.0	0.0	1.4	5.1	0.1	0.8	7.3	3.1	1.9	19.8	20.5
Slovenia	5.9	0.0	0.0	0.4	0.2	0.6	4.7	0.2	1.8	13.8	16.9
Total	5.9	0.0	1.4	5.5	0.3	1.4	11.9	3.3	3.8	33.6	37.3

Table 4: Technology breakdown of yearly electricity generation (and comparison to demand) in Croatia and Slovenia by 2030 according to the Just Transition scenario. (Source: Balmorel modelling)

Yearly electricity generation in 2030 according to the Just Transition scenario (in TWh)	Nuclear	Lignite	Coal	Natural gas	Waste	Bioenergy	Hydropower	Wind	PV	Total Supply	Total Demand
Croatia	0.0	0.0	0.0	5.2	0.1	1.2	7.3	5.7	2.8	22.2	20.5
Slovenia	0.0	0.0	0.0	0.3	0.2	1.0	4.7	1.2	2.1	9.3	16.9
Total	0.0	0.0	0.0	5.4	0.2	2.2	11.9	6.8	4.9	31.5	37.3

Impact on CO_2 emissions

The presumed early exit of coal has a positive impact on the GHG balance of the electricity sector in the focus region. Both in Croatia and Slovenia CO2 emissions related to domestic electricity supply in 2030 decline significantly. At regional level (i.e. Croatia and Slovenia as one region) this implies a decline by 42% under the Just Transition scenario in comparison to the reference, cf. Table 5.

Table 5: Yearly CO_2 emissions related to domestic electricity supply in Croatia and Slovenia by 2030 according to assessed scenarios. (Source: Balmorel modelling)

Yearly CO_2 emissions related to domestic electricity supply by 2030 (in Mt CO_2)	Croatia	Slovenia	Regional total
Reference scenario	3.3	0.5	3.8
Just Transition scenario	2.0	0.2	2.2

5.4 RES-related costs and expenditures: Investment needs and support expenditures

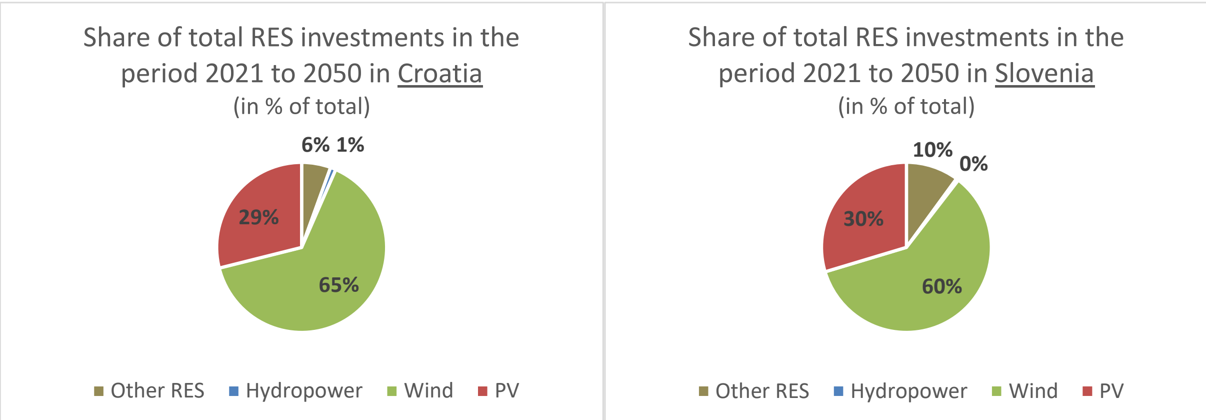
Investment needs

Strong investments in renewables are required to let the illustrated vision of a nuclear and coal-free power supply in Croatia and Slovenia become a reality. This is getting apparent when comparing the necessary yearly investments in RES technologies as shown in Table 6.

Table 6: Average yearly investment needs for RES installations in the Croatian (left) and Slovenian (right) electricity sector in the period up to 2050 according to assessed scenarios. (Source: Green-X modelling)

Average yearly investment needs for RES installations (in Mio. €)	Croatia			Slovenia		
	2021-2030	2031-2040	2041-2050	2021-2030	2031-2040	2041-2050
Reference scenario	235	256	329	129	127	180
Just Transition scenario	495	605	553	230	519	291

Figure 16: Technology breakdown of total RES investments in the period up to 2050 in Croatia (left) and Slovenia (right) according to the Just Transition scenario. (Source: Green-X modelling)



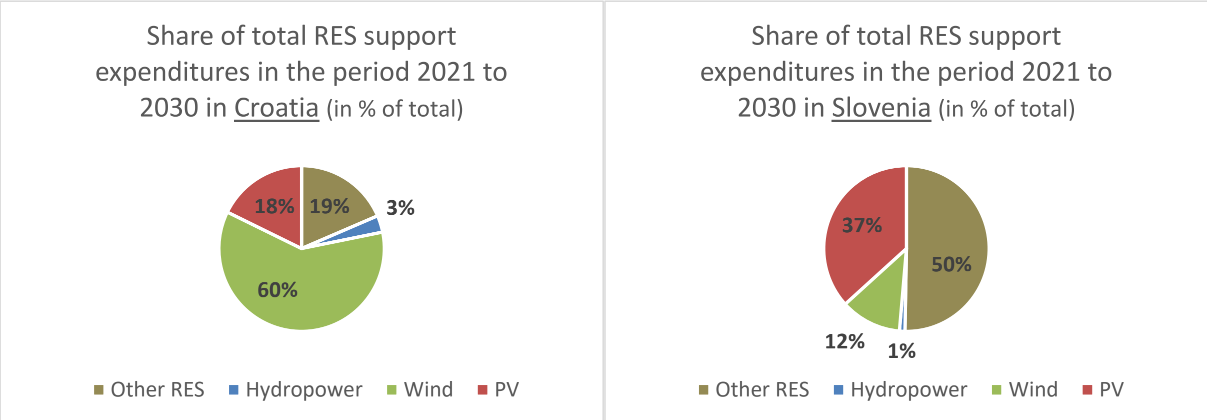
Impact on consumer cost

The strong uptake of renewables comes at cost – but the overall cost increase remains moderate as applicable from Table 7. At first glance, RES-related support expenditures appear to increase tremendously in this decade when comparing the results for the Just Transition scenario with the reference. But this increase is caused by the decline of electricity prices on the wholesale market as a consequence of the proactive phase-out of fossil electricity supply in Slovenia and Croatia as well as across the whole European continent. Variable renewables like hydropower, wind and solar PV have low operating cost which, in turn, leads to a drop of wholesale prices. In consequence, higher dedicated support is required for certain RES technologies to compensate the financing gap. The overall cost to consumer is however modest as applicable in the lower part of Table 7: Cost to consumer increase by ca.12% in Croatia and by 14% in Slovenia when comparing Just Transition with Reference.

Table 7: Average yearly support expenditures for electricity generation from RES (top) and yearly balance of cost impacts to consumer (by 2030 - bottom) in Croatia (left) and Slovenia (right) in the period up to 2030 according to assessed scenarios.
(Source: Green-X modelling)

Average yearly support expenditures for RES (in Mio. €)	Croatia 2021-2030			Slovenia 2021-2030		
Reference scenario	103			12		
Just Transition scenario	262			87		
Focus on 2030: Yearly balance of cost impacts to consumer (in €/MWh)	Wholesale price	RES Support expenditures	**Cost to Consumer**	Wholesale price	RES Support expenditures	**Cost to Consumer**
Reference scenario	60.9	6.3	**67.2**	60.8	1.3	**62.1**
Just Transition scenario	55.8	19.3	**75.1**	56.3	14.3	**70.6**

Figure 17: Technology breakdown of total RES support expenditures in the period up to 2030 in Croatia (left) and Slovenia (right) according to the Just Transition scenario.
(Source: Green-X modelling)



6 Summary of key findings

In light of the ambitious targets of the Paris Agreement and highly ambitious long-term decarbonisation goals set by the European Green Deal, a critical question for decision-makers is how to sustain a coal and lignite phase-out that is as swift as possible while also ensuring supply of affordable electricity, and a just transition in regions dependent on coal. Within Slovenia and Croatia electricity generation from nuclear power is often seen as a carbon-free alternative – but concerns on a safe and reliable operation of the nuclear power plant built at Krško question this generation asset and also the plans for a second nuclear unit at the Krško site.

This report sheds light on an **alternative pathway for a just transition of the electricity sector of Croatia and Slovenia, relying on a transition towards renewable energy forms as alternative to coal and nuclear**. The aim of this report is to illustrate and describe how this alternative pathway may look like. We thereby inform on the sector transition, indicating technology trends of the so-called "Just Transition" scenario in comparison to a reference path where nuclear and coal maintain their dominance.

Key findings from the analyses performed in the course of this study are:

► **A closer look at available potentials in Croatia and Slovenia reveals that domestic RES potentials may suffice well to compensate the supply gap arising from an early coal and nuclear exit.**
Building on an intense literature review performed in an ongoing EU study (cf. Resch et al. (2021)) and an own GIS-based analysis, we conclude that significant future potentials are applicable for PV and wind onshore. Here the outcomes of our own GIS based analysis point out that available domestic resources would allow for meeting and exceeding current electricity needs of both Croatia and Slovenia. Summing up the identified technical potentials of both countries together corresponds to an annual generation volume that is almost three times as high a current electricity demand. Due to the country size and the topographical location potentials for both PV and wind onshore are however significantly higher in Croatia than in Slovenia. Apart from solar and wind also bioenergy offers techno-economic potentials at a relevant magnitude that may help to balance the weather-dependent variable electricity supply from hydropower, wind and PV. In contrast to the above, future potentials for hydropower – currently the dominant renewable energy source – appear limited, considering available potentials as well as environmental concerns.

► **Recap on 2030 RES targets: the European Green Deals calls for a stronger uptake of renewables in the period up to 2030 across the whole continent.**
The European Green Deal and the corresponding increase in the 2030 climate ambition (approximately 55% instead of 40% GHG reduction at EU level) raises the need for a stronger uptake of renewables, from about 32-34% (in accordance with current Member State planning) to (at least) 40%. This may imply also for Croatia and Slovenia to revise their current energy planning as postulated in National Energy and Climate Plans at the end of 2019. Our derived "Just Transition" pathway may help well in that update process, offering a carbon-free reliable alternative to both coal and nuclear in electricity supply.

► **Spotlight on Croatia and Slovenia: Changing the electricity mix.**
Within Croatia and Slovenia renewables are already at present a key contributor to meet the demand for electricity. According to latest statistical data available (Eurostat, 2021a), RES achieved a share of ca. 50% in gross electricity demand by 2019 in Croatia, and the RES demand share in Slovenia was 33% (2019), respectively. Historically, the RES share was steadily growing over the past decade, with differences across both countries since a significantly stronger growth could be achieved in Croatia in comparison to Slovenia. This growth needs to be accelerated in future years, given the policy commitments taken and the needs arising from a transformation of the energy sector in order to combat climate change while phasing out coal and nuclear:

- According to the derived Just Transition pathway the RES share in the electricity sector would grow more rapidly within both countries compared to current national planning, reaching 84% in Croatia and 53% in Slovenia already by 2030, respectively. In the long-term (2050) RES would generate more than domestically needed in Croatia at an annual balance (i.e. a RES share of 106% by 2050) which, in turn, helps Slovenia to fill the gap needed for a carbon-free power supply by that point in time. For Slovenia modelling shows that a RES share of ca. 81% in 2050 appears feasible and makes economically sense, considering RES cooperation with neighbouring countries as fruitful alternative to meet domestic power needs.

- Just Transition imposes significant changes in the RES-based supply mix: According to modelling, within all scenarios the dominance of hydropower in electricity supply is expected to diminish. Solar electricity (from PV systems) and wind power (onshore wind) will become the major contributor to future electricity supply. As applicable from the results of the Reference scenario, wind energy gains currently comparatively little policy attention under current planning, specifically in Slovenia. Modelling results of the Just Transition scenario however make clear that wind energy could contribute significantly to the decarbonisation objective and may become the dominant power source in future (2050) within both Croatia and Slovenia. Apart from wind energy also bioenergy may deserve more policy attention, contributing to balance variable RES generation from hydro, wind and PV systems.

► **Power System Analysis: Feasibility check for 2030**

Complementary to the techno-economic policy-oriented analysis and modelling, a power system analysis has been undertaken for 2030 at European scale, serving as feasibility check that the electricity market in Croatia and Slovenia as well as in the remainder of the EU can cope with the anticipated rapid RES expansion as presumed in the Just Transition scenario. Modelling performed at an hourly temporal resolution indicated the power plant dispatch in order to achieve a match between demand and supply.

The analysis proofed that the European electricity system can cope well with the anticipated strong RES uptake in the period up to 2030. Results on the hourly dispatch show that PV systems contribute to cover a high share of total demand during the summer period whereas wind power contributes slightly more during the winter period. Weather-dependent fluctuations in electricity supply from all forms of variable RES are observable but the interconnected European power system can cope well with these by 2030.

In the long-term (2050), with increasing shares of variable RES, sector-coupling and a mobilising of the corresponding power system flexibility offered by e-mobility, e-heating & cooling and e-industry, combined with a broader roll-out of storage options and capacities as well as a further expansion of the grid infrastructure appear however necessary to safeguard a carbon-free electricity supply.

► **Just Transition may lead to a decline of CO_2 emissions in the electricity sector of both Croatia and Slovenia by 42% (in comparison to reference) already by 2030**

The presumed early exit of coal has a positive impact on the GHG balance of the electricity sector in the focus region. Both in Croatia and Slovenia CO_2 emissions related to domestic electricity supply in 2030 decline significantly. At regional level (i.e. Croatia and Slovenia as one region) this implies a decline by 42% under the Just Transition scenario in comparison to the reference.

► **A strong increase of investments into RES is necessary to let the vision of a nuclear and coal-free power supply in Croatia and Slovenia become a reality**

Modelling shows that the cumulative installed RES capacity in Croatia (Slovenia) has to increase by a factor of six (eight) compared to today (2020). Thus, a strong increase of investments in renewables is required to let the illustrated vision of a nuclear and coal-free power supply in Croatia and Slovenia become a reality.

► **The strong uptake of renewables comes at cost – but the overall cost increase remains moderate**

The strong uptake of renewables as postulated in the Just Transition scenarios leads to a decline of electricity prices on the wholesale market in future years, as a consequence of the proactive phase-out of fossil electricity supply in Slovenia and Croatia as well as across the whole European continent. Variable renewables like hydropower, wind and solar PV have low operating cost which, in turn, leads to the identified drop of wholesale prices. In consequence, higher dedicated support is required for certain RES technologies to compensate the financing gap. The overall cost to consumer is however modest: Cost to consumer increase by ca.12% in Croatia and by 14% in Slovenia when comparing Just Transition with Reference for the year 2030.

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