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Transparent and cross-sectoral assessment of possible pathways towards climate-neutral economy in Croatia until 2050

Description of the scenarios

Zagreb, June 2022

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Description of the scenarios

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Zagreb, June 2022

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Executive summary

As part of the global efforts to climate change mitigation, the European Union aims to achieve a climate-neutral economy by 2050. This ambition is a driver of the European Green Deal and part of the EU's commitments under the Paris Agreement. On the road to climate-neutrality, all Member States have to transform their economies. However, there are different transition pathways possible.

Under this project, a model for a transparent and cross-sectoral assessment of possible pathways towards climate-neutral economy in Croatia until 2050 is created, and different scenarios assessed. The model is conceived as energy accounting model extended to materials, products, land and food systems. The model is based on a series of levers that allow modelling of technological developments as well as changes in societal organisation and behavioural patterns. A key feature of the model consists in transparent presentation of the possible decarbonisation options, thereby offering a broad view on the challenges of the transition. It allows understanding of series of trade-offs between sectors and fields of activity.

The model allows creation of almost infinite number of scenarios, but six representative scenarios are created for the Republic of Croatia and presented in this report, as follows:

- REF scenario – scenario with existing measures, based on the official national scenario;
- NECP scenario – scenario with additional measures, based on published national scenario presented in National Energy and Climate Plan;
- S-NECP scenarios – scenario based on the NECP scenario, but with the increased ambition that could reflect the recent events led by the EU Green Deal and the EU's response to the war in Ukraine accelerating the decarbonization in the EU;
- NZ scenario – scenario for reaching the net-zero in 2050, based on the national net-zero scenario;
- B-NZ scenario – scenario for reaching the net-zero in 2050, focusing on behavioural measures;
- T-NZ scenario – scenario for reaching the net-zero in 2050, focusing on technological advances.

The results provide a lot of insights for the policy makers, and the following 20 key messages are highlighted:

Transversal

1. Model results point out that reaching climate neutrality is technically feasible in Croatia by 2050. Range of policy options imply different possible trajectories. Current national reference (with existing measures) scenario and scenario with additional measures are not on track to climate neutrality.
2. Hardest to abate sectors are the industry and agriculture. Buildings, transport and power sectors could be almost completely decarbonised by 2050. The remaining emissions can be annulled by the GHG sequestration through the land-use sector, and carbon capture, use and storage technologies.

3. Energy demand is driven by opposing factors and projections show stagnation or only graduate decrease until 2030, and steeper decrease afterwards. Societal changes can provide key effects towards cost-effective demand decrease.
4. Fossil fuels in final energy demand have to be gradually phased out and compensated by carbon-free or carbon neutral energy sources. The remaining fossil fuels are predominantly used in industry and are candidates for CCUS.
5. Decarbonization requires low carbon investments in infrastructure in all sectors. Total capital expenditures can nevertheless be significantly reduced when the demand for the related energy services is reduced through behavioural changes and circular economy levers. Fuel cost reductions tend to compensate capital expenditure increases. The price and consumption levels of hydrogen and e-fuels, including as feedstock use, then become an important determinant of the total energy bill.

Buildings

6. More ambitious national effort regarding building stock renovation and decarbonization of heating technologies (both space heating and hot water) is required.
7. Phasing out natural gas, decreasing biomass consumption in heating sector and replacing it with more efficient technologies can lead to energy savings and increased energy security.
8. Empowering district heating sector in urban areas with high heat demand density to decrease losses and utilize new technologies can contribute to power system optimization and fuel savings.
9. Support the higher integration of PV in buildings, both residential and commercial.

Transport

10. Behavioural change and technology development leads to lower personal vehicle fleet and energy demand.
11. Ambitious electrification process, with special focus on personal cars fleet, public transportation and costal and river waterways should be the priority. Modes of transport which are more difficult to electrify will depend on alternative fuels, primarily hydrogen and advanced electrofuels with lower shares of biofuels.
12. More ambitious rail expansion, both in infrastructure and quality, leads to higher modal and intermodal switch. Advanced public transport schemes, followed by decarbonization technologies uptake.

Industry

13. Applying circular economy has the potential to drastically reduce materials demand, energy use and greenhouse gas emissions.
14. Technological developments and energy and feedstock switches are key to reducing GHG emissions in industry. However, a significant level of CCUS is required in the net-zero scenarios.
15. Electrification is part of the solution in industry but plays a smaller role than in other sectors. Application of synthetic and biofuels are required to decrease oil and natural gas use, and decarbonise a large part of the energy supplied.

Energy production

16. Reaching climate neutrality by 2050 requires, in most scenarios, a higher electricity production level than the current trend. The share of carbon neutral hydrogen and synthetic fuels produced domestically has a critical impact on total electricity demand.
17. Even in some high electricity demand scenarios (NZ and B-NZ), 100% E-RES is achievable for the domestic generation provided that intermittency is adequately managed.

Agriculture, Forestry and Others

18. Changes towards healthier and more plant-based diets can significantly reduce the food-related GHG footprint in Croatia, including food waste along the supply chain, from farm to consumer.
19. Changes in the agricultural model could have a strong impact on land-use and thereby on carbon sequestration possibilities. Progressive but transformative changes in agricultural practices are required in order to reach significant emission reductions by 2050.
20. To achieve climate neutrality within the framework of sustainable land management and forestry, it is necessary to develop a national land information system and guidelines for land management with the aim of increasing the carbon sink in the Republic of Croatia, due to the fact the trend of sink reduction has been recorded in these sectors.
21. Reducing paper and plastic packaging, reducing food waste and adopting more sustainable consumption patterns leads to a reduction of the related production and distribution activities and thereby on GHG emissions.

1 Introduction

The European Union (EU) aims to achieve a climate-neutral economy by 2050 [1]. This ambition is at the core of the European Green Deal [2] and in line with the EU's commitment to global climate action under the Paris Agreement [3]. To reach such a target, all Member States will have to make substantial contributions and transform their economies.

Surface-wise and population-wise, the Republic of Croatia belongs to smaller EU Member States. Croatian economy is service-based and at around 60% of EU GDP per capita average [4]. On the other hand, Croatia is currently above the EU average in share of renewable energy sources (RES) in gross final energy consumption [5] and has less greenhouse gas (GHG) emissions per capita than European Union average [6]. As most of the EU Member States, the Republic of Croatia is in process of energy planning and developing of a long-term low-carbon development strategy. In this process, besides the common goals of increasing RES share, reduction of GHG emissions, and growth in energy efficiency in order to contribute to reduction of GHG emission and support to commitments of the EU, Croatia aims to provide impetus for faster economic development. To achieve transition to climate-neutral economy, Croatia has different pathways at its disposal. Implementation of smart policy and measures could encourage research and development, decrease cost of energy transition and increase benefits in terms of new jobs, and development of industrial competitiveness and know-how.

Therefore, the aim of this project is to develop a user-friendly climate and energy model for Croatia. The model is developed using Pathways Explorer modelling tool [7]. A development of such a model for the Republic of Croatia, and making it publicly available, will provide policymakers and NGOs with a tool based on which an argumentative discussion can be conducted. Further, in this project, the several possible pathways will be modelled, and their impacts on achieving the climate and energy goals quantified. The resulted comprehensive overview of actions needed, as well as expected costs and benefits for different pathways, will provide valuable insights that can serve as orientation for policymakers in Croatia and beyond. The project will integrate modelling of the following sectors: Energy production, Buildings, Transport, Industry, and Agriculture, forestry and land-use (AFOLU) sector. The modelling activities are conducted in cooperation with CLIMACT [8], who are the administrators and technical support for the development of the model.

2 Methodological approach and input data

To allow transparent and cross-sectoral assessment of possible pathways towards climate-neutral economy in Croatia until 2050, the energy and climate model are created, and different scenarios assessed. In this section, the model and scenarios are described.

2.1 Pathways Explorer Model

The model is available online [7], including the description of the model methodology [9]. In brief: "the Pathways Explorer is a web-based tool which enables the development of country energy transition scenarios based on realistic and transparent assumptions. Simulations can be performed in real time offering a direct understanding of the key levers of the low carbon transition. The exploration scope encompasses the energy system and its dynamics, all GHG emissions, and the associated resources and socio-economic impacts. Behind the web interface, a step-by-step process equips organizations with a robust analytical foundation, enabling them to explore possible futures and assess the implications and trade-offs of their choices" [9].

A relation of the Pathways Explorer to other modelling tools is depicted in Figure 2-1. As shown in the figure, modelling tools can be classified in three categories, based on their focus: (1) synthesis, transparency, user friendliness and communication; (2) comprehensive energy system/sector interactions; and (3) cover more detailed sector specific issues. Focus of the Pathways Explorer is on synthesis, transparency, user friendliness and communication. However, it also aims to have important features of other approaches – allows modelling policies and zooming in sectoral details to certain extent.

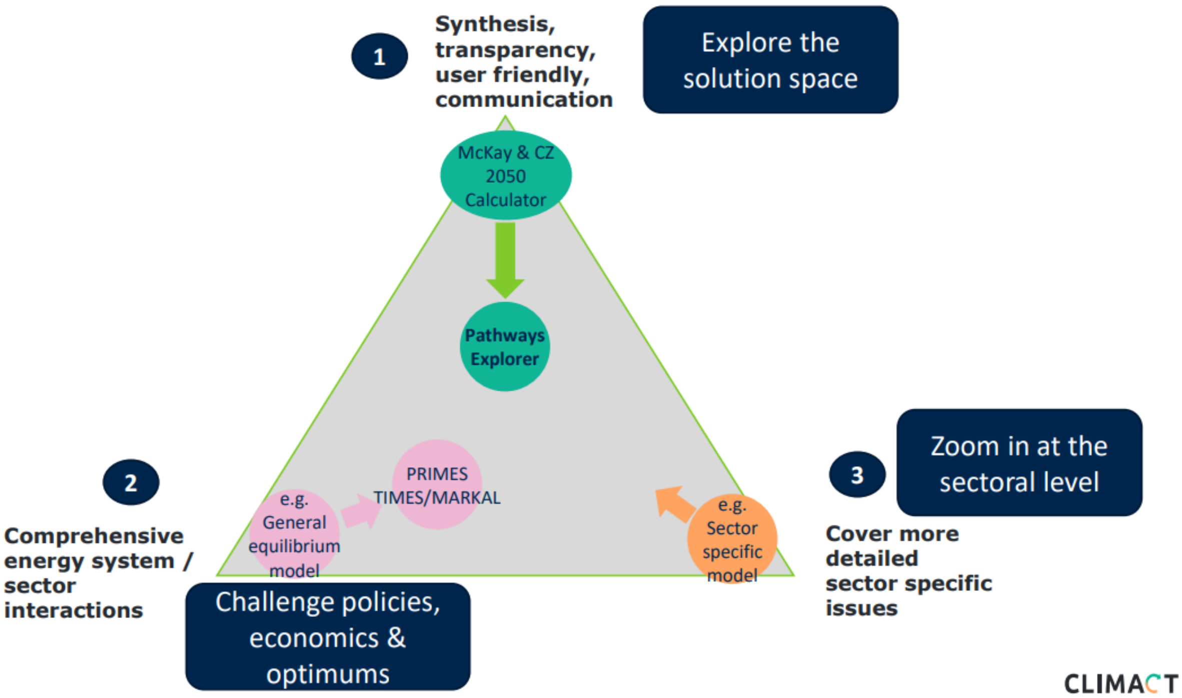

Figure 2-1: Relation of Pathways Explorer to other models [9]

The overview of the main features as well as limitations of the model is shown in Figure 2-2. This simulation tool captures insights on the trade-offs and implications of implementing energy transition scenarios. However, it is no-way a forecast tool, or a cost-optimization model.

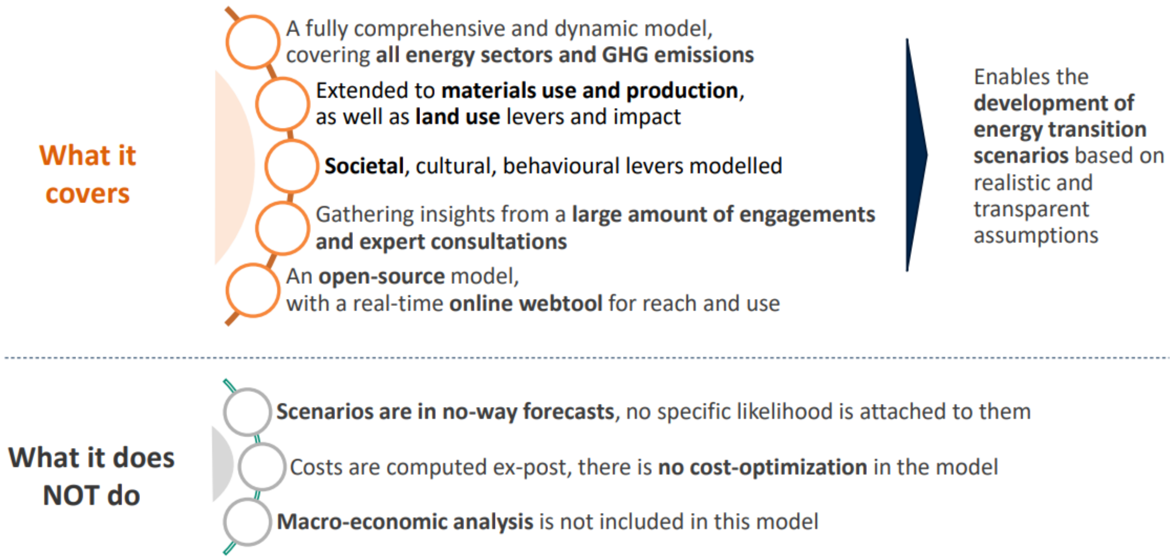

Figure 2-2: Features and limitations of the model [9]

The overview of the modelling process is shown in Figure 2-3. Here, countries follow a rigorous process to ensure analytical robustness.

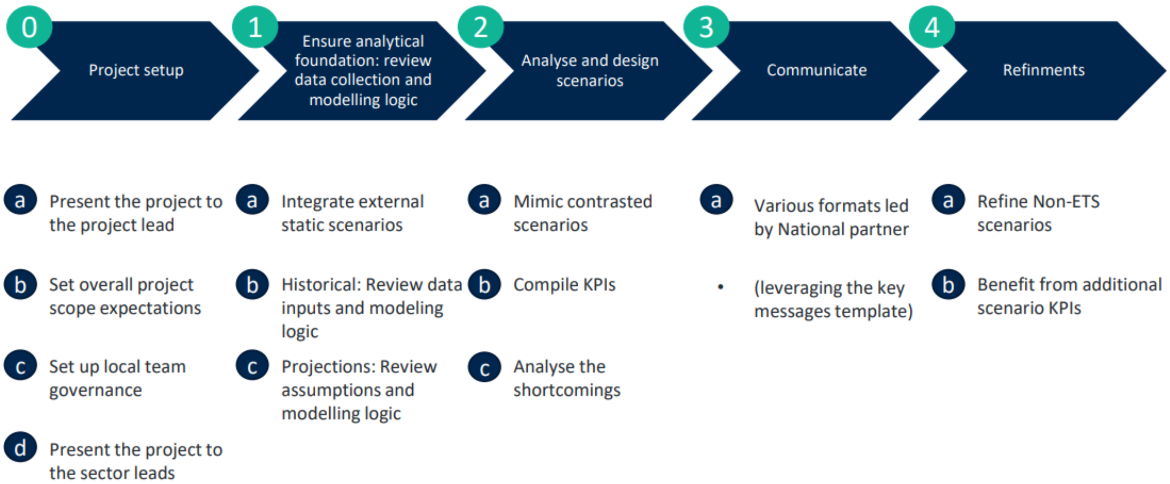

Figure 2-3: Modelling process [9]

The interface of the Pathways Explorer tool is shown in Figure 2-4, as available at https://pathwaysexplorer.climact.com/ (Release v22.23, 13/06/2022) [7].

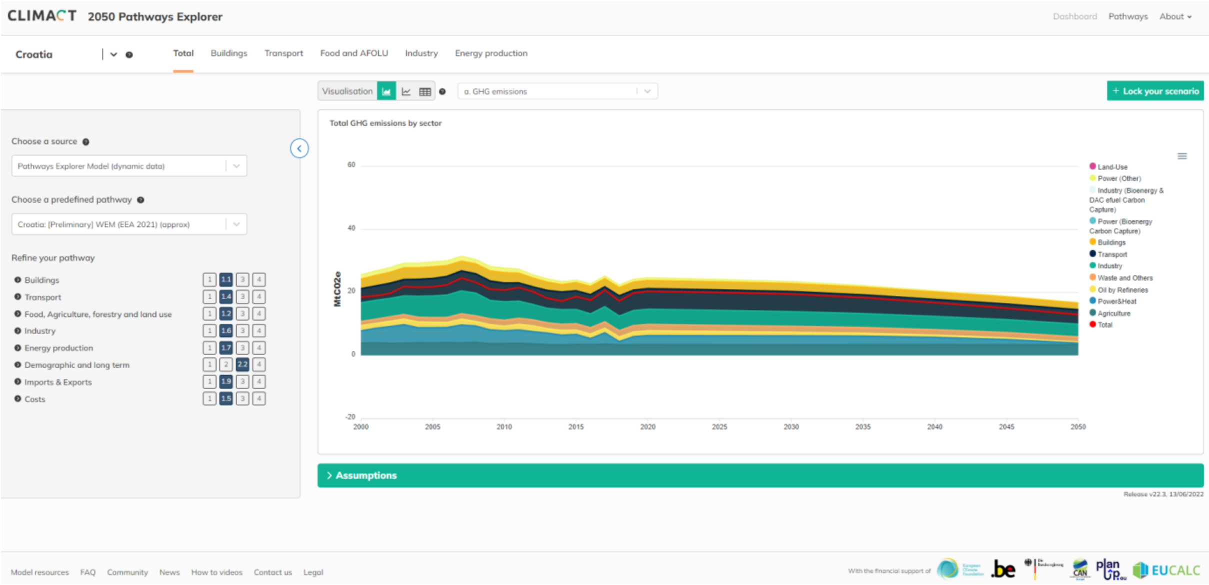

Figure 2-4: Interface of the Pathways Explorer tool

2.2 Scenarios

To assess different pathways for the Republic of Croatia, several scenarios were created. Three scenarios are modelled to achieve results as in the official nationally published scenarios. This report includes mimicking of the following nationally published scenarios:

- Scenario REF - Corresponds to scenario S0 from Green Book of Energy Strategy [10], scenario S0 from the Low-carbon Development Strategy [11] and as submitted to European Environment Agency (EEA) [6] under the 2021 projections in scenario with existing measures (WEM);
- Scenario NECP - Corresponds to scenario 2 from Green Book of Energy Strategy [10] and scenario S1 from Low-carbon Development Strategy [11] and as submitted to the EEA [6] under the 2021 projections in scenario with additional measures (WAM). This scenario is also submitted in Croatian Energy and Climate Action Plan (NECP) [12].
- Scenario NZ – Corresponds to the scenario presented in Scenario for Achieving Climate Neutrality by 2050 [13], where climate neutrality is reached until 2050 – Net zero scenario.

Graphical overview of projections of GHG emissions in different scenarios is shown in Figure 2-5. It is visible that WEM2020 and WAM2020 scenarios submitted to EEA under 2020 reporting cycle were not aligned with NECP. The reporting in 2021 was aligned to final NECP submitted to the European Commission.

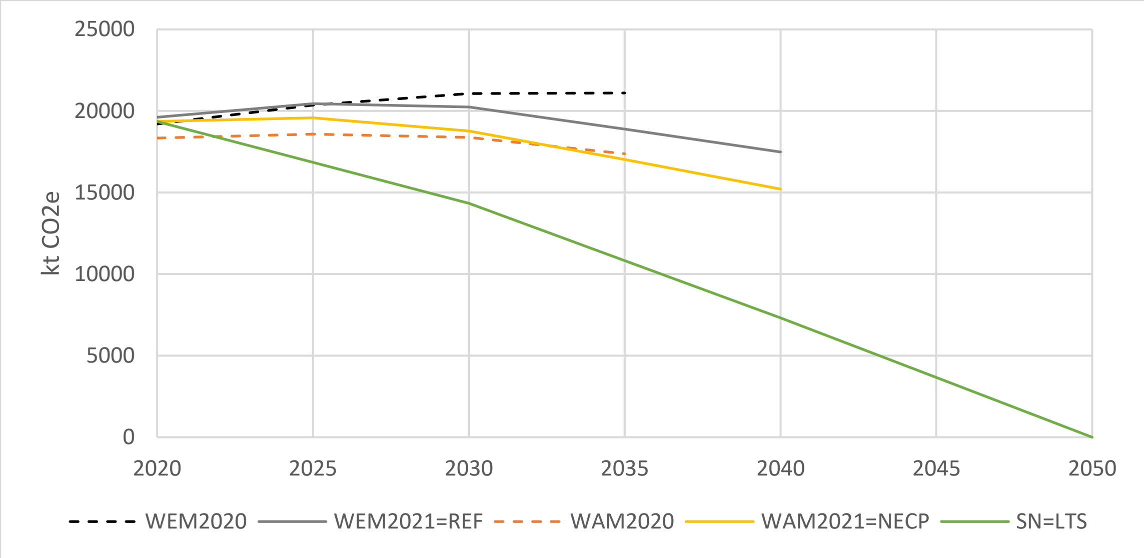

Figure 2-5: Total GHG emissions with Land Use in nationally published scenarios

The simulations are done using the techno-economic model for time horizon from 2015 until 2050 where all forecasted data in simulations are harmonized with listed scenarios. However, where additional data was available for the period 2015-2020 historical data were inserted, meaning scenarios differ after 2020, which is in line with official projections.

In the listed scenarios, official scenarios are replicated in a model created in the Pathways Explorer tool. Here, study considers important aspects which define the Croatian emission sources in all sectors. Even though official projections submitted to EEA are done until 2040, the model incorporates the data that is available until 2050 in listed documents for REF and NECP scenarios.

In addition to the mimicking of the official scenarios, additional three scenarios are created:

- Scenario Suggested NECP (S-NECP) - The scenario is a suggestion for the next revision of the NECP and WAM scenario, considering the increased EU policy ambition for faster decrease of GHG emissions and decrease of fossil fuel consumption.
- Behaviour Net-Zero (B-NZ) - The scenario is developed with an aim to reach climate neutrality but with a focus on achieving as much as possible contributions from the changes in key consumption behaviours and lifestyle changes, easing the burden on technological changes.
- Technology Net-Zero (T-NZ) - The scenario is developed with an aim to reach climate neutrality but with a focus on development and implementation of extensive span of new technologies, meaning a need for additional behaviour and lifestyle changes could be minimized.

The illustration of the modelled scenarios considering the ambition for GHG emission mitigation and time horizon is shown in Figure 2-6. Here, existing nationally published scenarios are marked blue, and newly created scenarios are marked green.

Further, a summary description of all six scenarios with notes on more details and deviations are listed in Table 2-1.

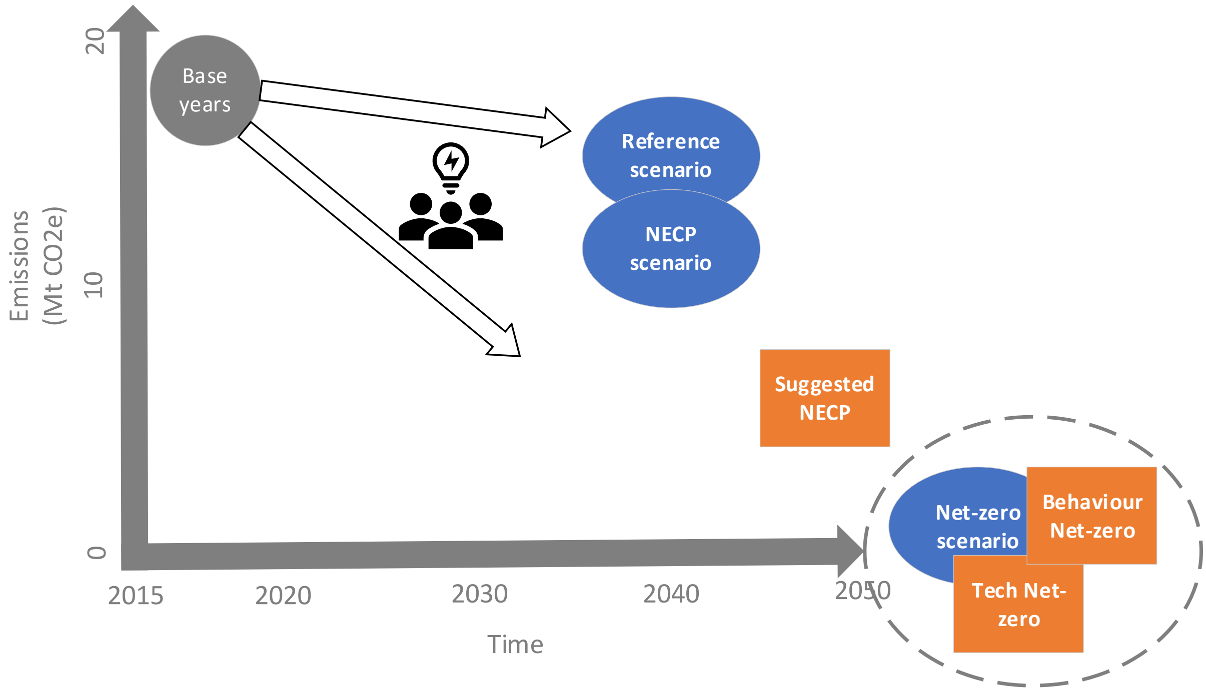

Figure 2-6: Total GHG emissions with LULUCF in nationally published scenarios

Table 2-1: Scenarios available in Pathways Explorer

Name	Description and notes
Croatia: WEM (EEA 2021) (approx)	The scenario is the approximation of the Croatian reference (with existing measures, WEM) scenario, as submitted to EEA in 2021 official national projections and in line with: - Scenario NUR (Reference scenario) from the Low-carbon Development Strategy of the Republic of Croatia until 2030 with a view to 2050 (OG 63/2021), - Scenario S0 (With existing measures scenario) from the Energy Strategy of the Republic of Croatia until 2030 with a view to 2050 (OG 25/2020), - Scenario WEM (With existing measures scenario) from the Integrated National Energy and Climate Plan for the Republic of Croatia for the period 2021-2030 (final, Dec 2019). Notes on deviations: - We prioritise matching in historical years and 2050, years between are not always matching. Emissions are only available up to 2040 but energy is available up to 2050. - On Buildings and Agriculture energy (CRF 1.A.4), there are remaining gaps between the official WEM and its approximation, because the official scenario is judged too unambitious. Fuel mixes are more or less appropriate. - In Buildings; Green gas and Green liquids Leaver 1 is to ambitious and creates an increase of those fuels in 2050, although official scenarios are without those fuels (Gas synthetic, H2, biomethane). - On LULUCF emissions (CRF 4), the official WEM scenario is judged not ambitious enough. - For historical LULUCF emissions, CRF values have been used in the model. They slightly differ from EEA 2021 values provided for the WEM scenarios. - Transport sector : 2050 Pathways explorer separates Transport energy demand and International bunkers so they are modelled separately. In some national references they are combined. - Energy Supply : Renewable energy production [TWh] in line with the reference values from official Croatian scenario, high level of imports due to the insufficient levels of

Name	Description and notes
	renewable production in order to meet emission targets, rapid and massive switch from gas to biogas for heating (again to meet the emission targets)
Croatia: WAM (EEA 2021) (approx)	The scenario is the approximation of the Croatian with additional measures (WAM) scenario, as submitted to EEA in 2021 official national projections and in line with: - Scenario NU1 (Gradual transition scenario) from the Low-carbon Development Strategy of the Republic of Croatia until 2030 with a view to 2050 (OG 63/2021) - Scenario S2 (Moderate energy transition scenario) from the Energy Strategy of the Republic of Croatia until 2030 with a view to 2050 (OG 25/2020), - Scenario WAM (With existing measures scenario) from the Integrated National Energy and Climate Plan for the Republic of Croatia for the period 2021-2030 (final, Dec 2019). Notes on deviations: - We prioritize matching in historical years and 2050, years between are not always matching. Emissions are only available up to 2040 but energy is available up to 2050. - On LULUCF emissions (CRF 4) and Agriculture (CRF 1.A.4.c-3), the official WAM scenario is judged not ambitious enough. - In Buildings; Green gas and Green liquids Leaver 1 is to ambitious and creates an increase of those fuels in 2050, although official scenarios are without those fuels (Gas synthetic, H2, biomethane). - For historical LULUCF emissions, CRF values have been used in the model. They slightly differ from EEA 2020 values provided for the WAM scenarios. - Transport sector notes: 2050 Pathways explorer separates Transport energy demand and International bunkers so they are modelled separately. In some national references they are combined. The focus is set on the energy (that goes to
Croatia: National Scenario for achieving climate-neutrality (approx)	The scenario is the approximation of the Croatian climate-neutral scenario, as presented in Scenario for Achieving Climate Neutrality in Croatia by 2050 (published by Ministry for Economy and Sustainable Development, 2021) Notes on deviations: - We prioritize matching in historical years and 2050, years between are not always matching. -Transport sector notes: 2050 Pathways explorer separates Transport energy demand and International bunkers so they are modelled separately. In some national references they are combined.
Croatia: Suggested NECP (FER)	The scenario is a suggestion for the next revision of the NECP and WAM scenario, considering the increased EU policy ambition for faster decrease of GHG emissions and decrease of fossil fuel consumption. Main differences compared to current NECP: - In Buildings: Higher electrification in heating and hot water sector. Slightly higher renovation effort. Slightly lower biomass intake for heating purposes. Higher district heating share. Initial step towards green fuels. - In Transport: Higher electrification of marine/IWW/aviation and automation of LDVs. Better utilization and load factors in freight transport. More efficient modal switch and passenger distance. - In Industry: reduced use of paper and plastic in packaging, a higher share of electrification and use of hydrogen instead of natural gas, introduction of CCS for part of the emissions in cement, steel, lime, ammonia production after 2030 - In AFOLU: less intensive agricultural practices (optimization of fertilizer use), slightly more ambitions change in animal feed to alternative protein sources, improved energy efficiency in agricultural practices (more switching to renewable energy or bioenergy); increased carbon sinks (in particular in biomass storage / carbon accumulation on forests

Name	Description and notes
	areas) due to management practices in the forestry and agricultural sector that apply measures to mitigate and adapt to climate change; more ambitious changes in the people lifestyle regarding dieting and decreasing food waste (lower calories consumption per capita, lower meat consumption and more plant based dieting). - In Energy production: increased switch from gas to biogas for heating, increased switch in electricity production from natural liquid to bio-liquid, additionally, stronger switch in electricity production from natural solid to bio-solid and in refineries strong energy carrier switch away from fossil fuels; 10% increase in installed capacity of RES power plants by 2050 leading to less installed gas power plants (2.5 times); higher carbon capture in electricity production - 64% of GHG emissions by 2050
Croatia: Behaviour Net-Zero (FER)	The scenario is developed with an aim to reach climate neutrality but with a focus on achieving as much as possible contributions from the changes in key consumption behaviours and lifestyle changes, easing the burden on technological changes.
Croatia: Technology Net-Zero (FER)	The scenario is developed with an aim to reach climate neutrality but with a focus on development and implementation of extensive span of new technologies, meaning a need for additional behaviour and lifestyle changes could be minimized.

3 Transversal results

In this section, the transversal results are presented. The key performance indicators (KPIs), key messages as well as graphical overview of the chosen results are shown with extended explanations and discussion.

The transversal KPIs are shown in Table 3-1. Total GHG emissions with and without sequestrations, and share of fossil fuels, electricity, alternative fuels, and biomass in final energy demand are pinpointed.

Table 3-1: Transversal KPIs

KPI	2015	REF scenario		NECP scenario		Suggested NECP	
		2030	2050	2030	2050	2030	2050
Total GHG [MtCO2e]	18.70	17.35	11.78	16.97	7.61	14.98	3.49
Sequestration [MtCO2e]	-5.12	-3.57	-3.37	-3.76	-4.12	-4.04	-4.29
Total GHG w/o sequestration [MtCO2e]	23.82	20.92	15.15	20.73	11.73	19.02	7.78
Fossil fuels [% of final energy]	59.1	56.8	49.9	55.2	30.2	41.3	32.3
Electricity [% of final energy]	20.6	23.0	27.1	23.7	33.1	24.3	34.4
Alternative fuels [% of H2+e-fuels in final energy]	0.0	0.4	1.3	0.4	0.9	1.2	9.7
Biomass [% of final energy]	17.2	16.1	16.2	17.4	17.3	17.0	13.4
KPI	**2015**	**Net-zero scenario**		**Behaviour Net-zero**		**Technology Net-zero**	
		2030	**2050**	**2030**	**2050**	**2030**	**2050**
Total GHG [MtCO2e]	18.70	12.85	0.0	11.37	0.00	10.46	0.00
Sequestration [MtCO2e]	-5.12	-3.38	-3.58	-3.74	-3.95	-4.22	-5.56
Total GHG w/o sequestration [MtCO2e]	23.82	16.23	3.58	15.11	3.95	14.68	5.56
Fossil fuels [% of final energy]	59.1	48.7	19.9	47.3	23.6	33.7	14.1
Electricity [% of final energy]	20.6	25.8	43.3	25.3	40.9	25.9	34.9
Alternative fuels [% of H2+e-fuels in final energy]	0.0	1.7	16.2	1.8	14.4	3.9	19.2
Biomass [% of final energy]	17.2	21.0	18.2	22.8	18.8	30.4	21.3

3.1 Greenhouse gas emissions

The overview of the GHG emissions across the scenarios is shown in Figure 3-1. The total (net) GHG emissions range from 11.8 Mt CO_2e in REF scenario to zero in net-zero scenarios in 2050.

The actual national scenarios are reflecting the existing and additional measures. However, they were created before recent developments that include the European Green Deal [2], implications of the war in Ukraine, or long-term effects of the COVID-19 pandemic. Planned revisions of NECP can include those changes.

Key message 1
Model results point out that reaching climate neutrality is technically feasible in Croatia by 2050. Range of policy options imply different possible trajectories. Current national reference (with existing measures) scenario and scenario with additional measures are not on track to climate neutrality.

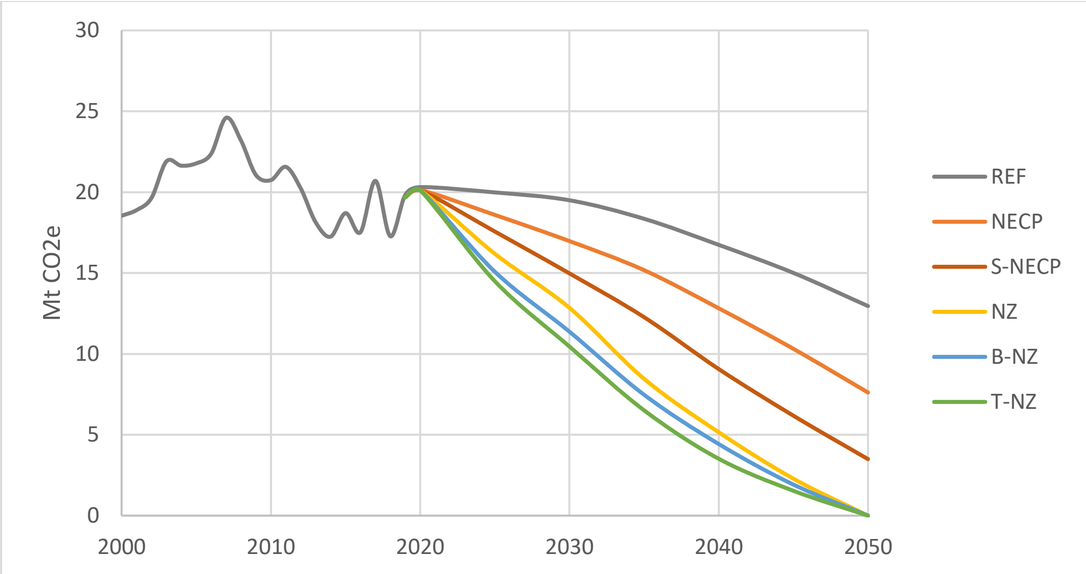

Figure 3-1: Total GHG emissions in analysed scenarios

From the technical and behavioural perspective considering the current and foreseeable state of the technological development, there is a wide range of options across the sectors. The sectoral GHG emissions in 2015 and in 2050 for all the scenarios are shown in Figure 3-2.

Key message 2
Hardest to abate sectors are the industry and agriculture. The buildings, transport and power sectors need to be almost completely decarbonised by 2050. The remaining emissions can be annulled by the GHG sequestration through the land-use sector, and carbon capture, use and storage technologies.

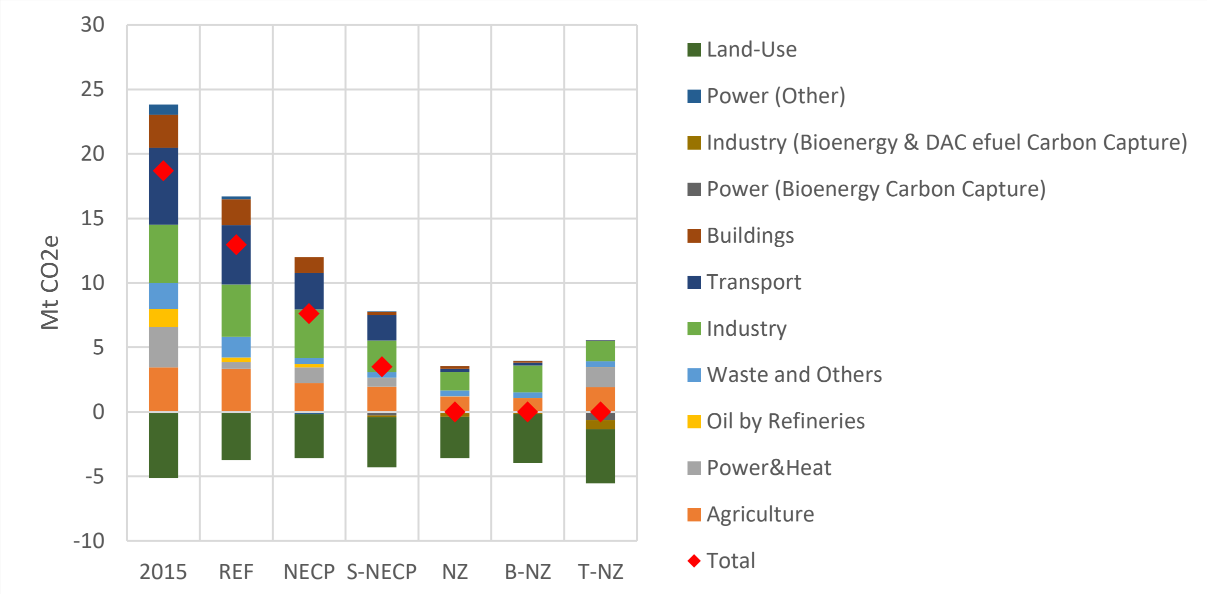

Figure 3-2: Sectoral GHG emissions in 2050 for all scenarios, and historical in 2015

3.2 Energy

Final energy demand per sectors is shown in Figure 3-3, and per vectors in Figure 3-4. In all scenarios except REF, the energy demand decreases until 2050. However, the trajectory and amount depend on the scenarios. Due to the previous recession after 2009 in Croatia that led to substantial decrease in energy consumption until 2014. Afterwards a upward trend is evident due to the recovery of industry, transport and tourism activities. This trend could be maintained, as energy demand falls below 2014 levels in the period between 2025 and 2035 across the scenarios. Deepest decrease is evident in B-NZ scenario where big changes in behaviour lead to biggest decrease in energy consumption.

Key message 3
Energy demand is driven by opposing factors and projections show stagnation or only graduate decrease until 2030, and steeper decrease afterwards. Societal changes can provide key effects towards cost-effective demand decrease.

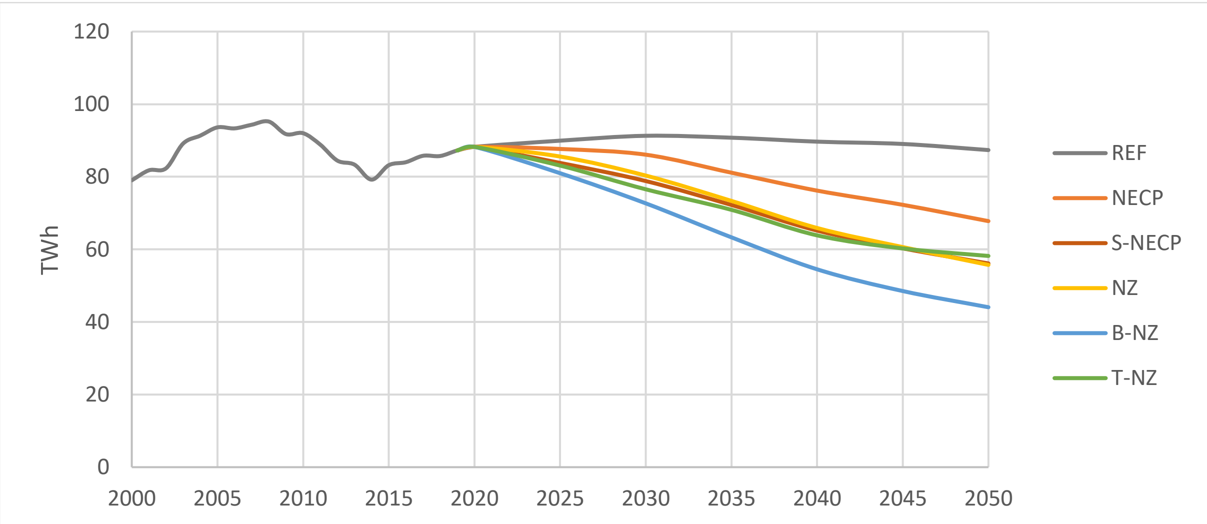

Figure 3-3: Final energy demand until 2050 in all scenarios

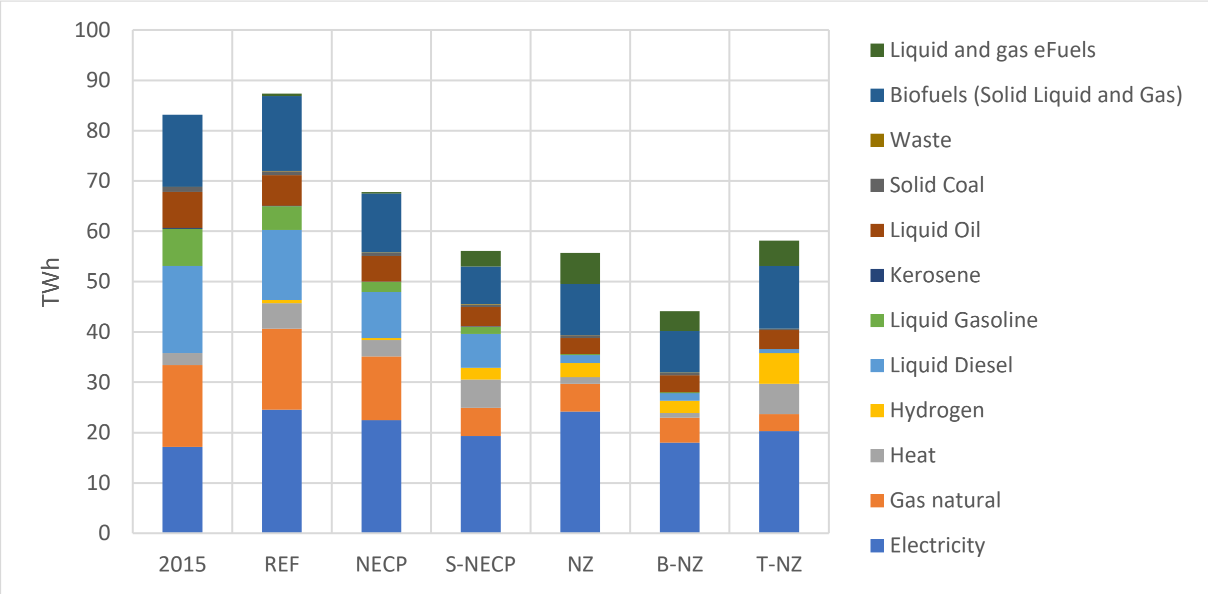

Figure 3-4: Final energy demand in 2050 for all scenarios, and historical in 2015

Reducing use of fossil fuels, namely oil and natural gas in final demand is a necessary lever towards the decarbonization of the economy. The share of renewable energy in final energy is shown in Figure 3-5. It is visible that the uptake of RES is necessary for deeper decarbonization.

Key message 4
Fossil fuels in final energy demand have to be gradually phased out and compensated by carbon-free or carbon neutral energy sources. The remaining fossil fuels are predominantly used in industry and are candidates for CCUS.

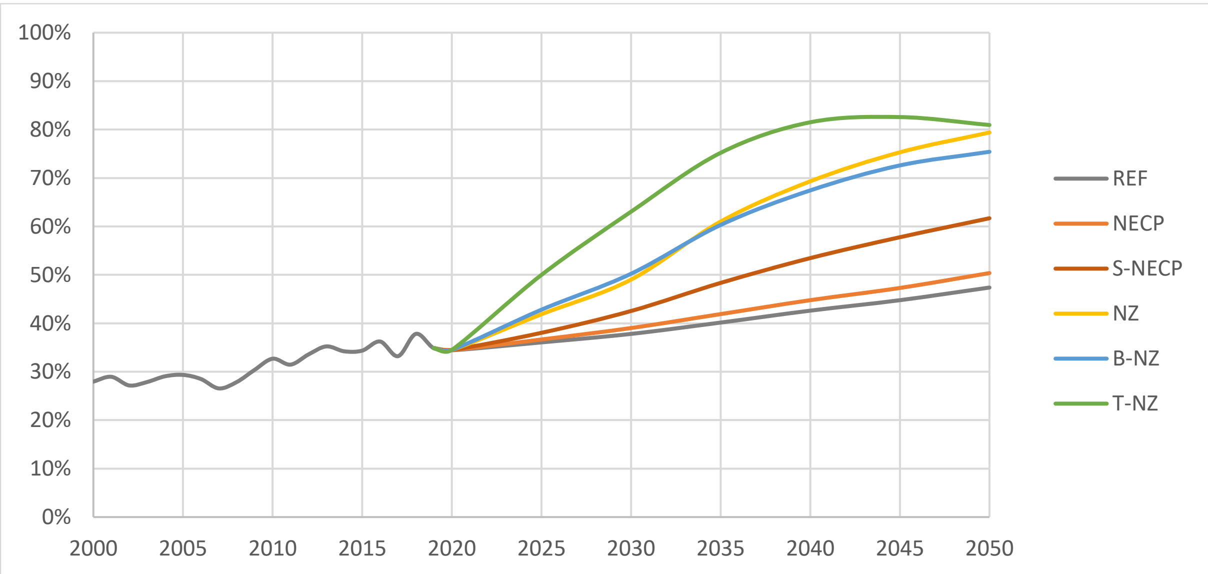

Figure 3-5: RES share in final energy demand until 2050 in all scenarios

3.3 Costs

The total costs of the system from the final energy perspective are shown in Figure 3-6 and sectoral in Figure 3-7. The costs include energy system only costs that add up across different sectors and by different actors (households, private actors, governments). In the final energy perspective, the energy costs of the demand sectors cover the final energy demand, the energy costs of the supply sector covers the energy losses. Energy exports are associated with a negative price. Modelled scenarios show that energy transition is economically feasible, and savings can compensate for additional investments needed (compared to WEM scenario). The B-NZ scenario show the lowest cost due to the fact that behavioural change does not need an material investment (any promotional or educational costs are not included).

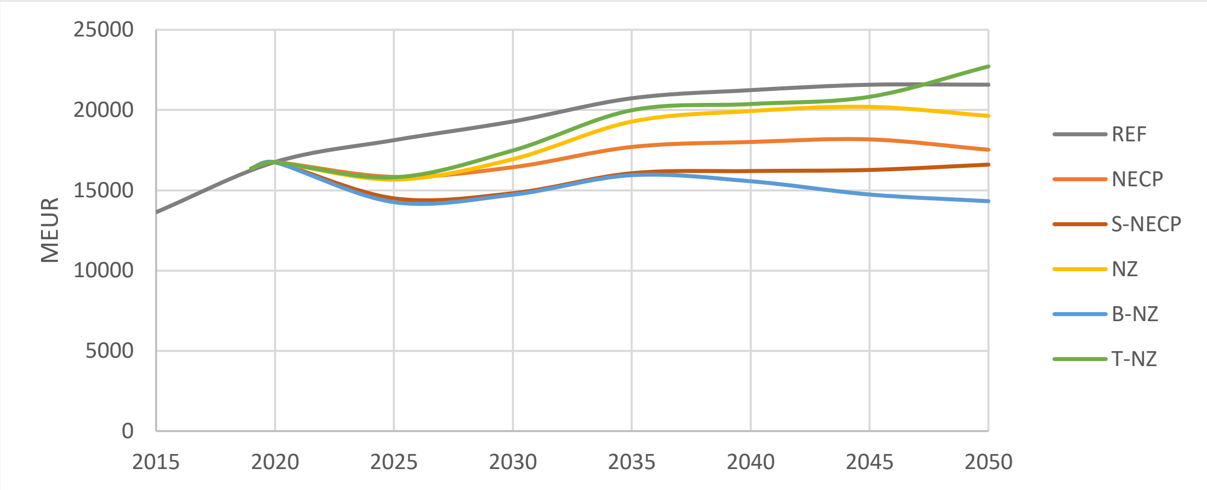

Figure 3-6: Costs until 2050 in all scenarios

Key message 5
Decarbonization requires low carbon investments in infrastructure in all sectors. Total capital expenditures can nevertheless be significantly reduced when the demand for the related energy services is reduced through behavioural changes and circular economy levers. Fuel cost reductions tend to compensate capital expenditure increases. The price and consumption levels of hydrogen and e-fuels, including as feedstock use, then become an important determinant of the total energy bill.

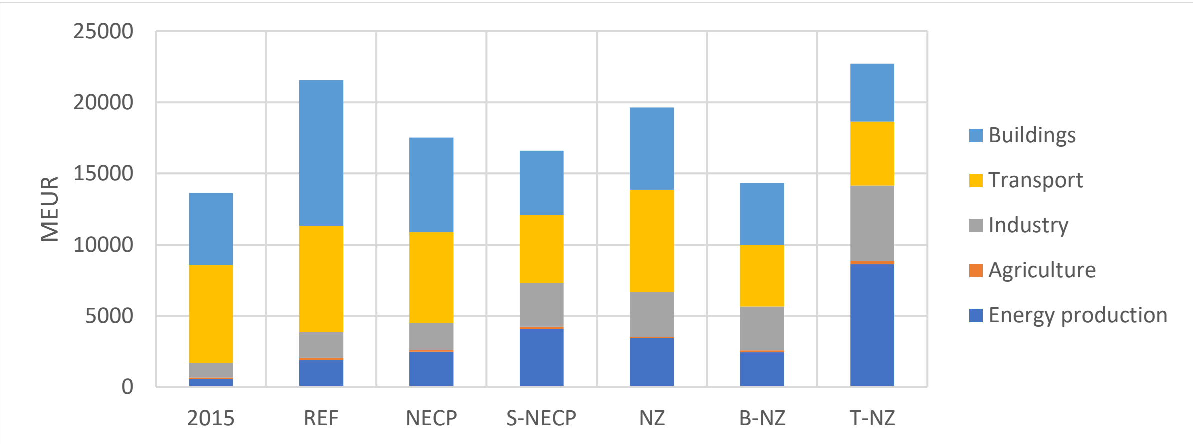

Figure 3-7: Sectoral costs in 2050 for all scenarios, and historical in 2015

4 Sectoral results

4.1 Buildings

Buildings sector presents a challenge in the Croatian strategic energy plannings since it is characterized with relatively old and inefficient buildings stock which is heavily relied on natural gas and biomass. Nevertheless, in the following paragraph a few key messages are identified, which would lead to decarbonization process and bring the buildings towards carbon neutrality.

Table 4-1 presents the main key performance indicators which were used/calculated within the model in order to simulate certain energy policies. Total GHG emissions in the analysed scenarios in buildings sector are shown in Figure 4-1 and 4-2.

Table 4-1: Buildings KPIs

KPI	2015	REF scenario		NECP scenario		Suggested NECP	
		2030	2050	2030	2050	2030	2050
Total GHG [MtCO2e]	2.56	2.29	1.62	2.1	1.22	1.52	0.25
Renovation rate [% of stock per year]	1.6	1	1	1.8	1.8	2.5	2.5
Renovation depth [%]	0	5	5	25	25	29.7	29.7
Electricity [% of final energy]	32	38.2	39.7	39.3	43.9	40.9	51.4
District heating [% of final energy]	2.93	3.6	6.2	3.4	5.4	6.5	16.2
KPI	**2015**	**Net-Zero scenario**		**Behaviour Net-Zero**		**Technology Net-Zero**	
		2030	**2050**	**2030**	**2050**	**2030**	**2050**
Total GHG [MtCO2e]	2.56	1.55	0.21	1.35	0.12	0.86	0.02
Renovation rate [% of stock per year]	1.60%	2.6	2.6	3.5	3.5	3	3
Renovation depth [%]	0%	38	38	67	67	54	54
Electricity [% of final energy]	32%	42.3	60.7	42.5	68	41.7	51.7
District heating [% of final energy]	2.93%	2.6	1.9	2.6	1.5	8.4	20.9

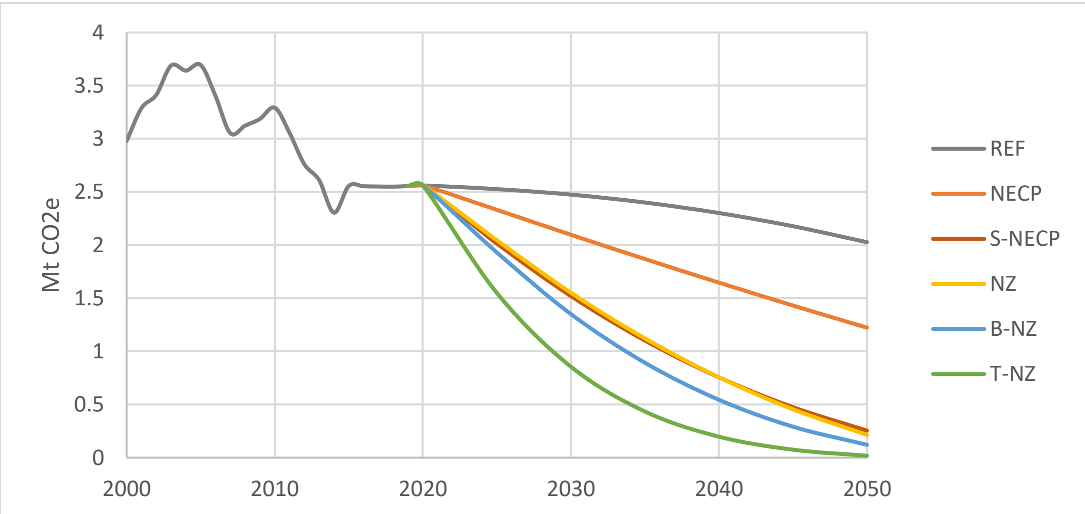

Figure 4-1: Total GHG emissions in analysed scenarios in buildings sector

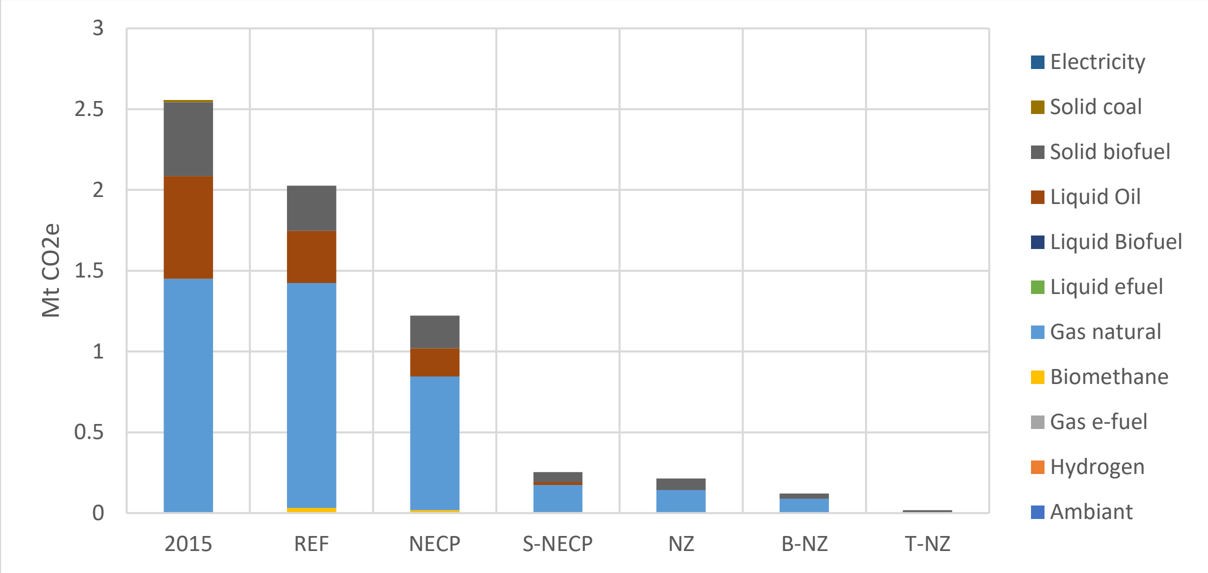

Figure 4-2: Buildings GHG emissions in 2050 for all scenarios, and historical in 2015

Key message 6
More ambitious national effort regarding building stock renovation and decarbonisation of heating technologies (both space heating and hot water) is required.

As previously mentioned; one of the main challenges in the decarbonisation process of Croatian buildings sector is an old and inefficient buildings stock and the efforts that would lead to quicker renovation paste. This process has proven to be challenging, and even though the renovation process has picked up a paste in the last few years it is still not sufficient for achieving the long-term climate targets. This process presents a certain prerequisite for technology decarbonisation. Long term EU perspective, together with national strategy, gives us guidelines for additional efforts in the renovation process, which will lead to significant decrease of overall energy demand. In the Net-zero scenarios special focus was given to those measures since the intention was to show how behavioural change and technology development can lead to energy demand and GHG decrease. Very ambitious renovation rates were tested (Level 3 and above). By lowering useful energy demand per square meter, low carbon and low heat energy technologies become more favourable, both from technical and financial point of view. Regarding useful floor areas; residential sector is modelled relatively conservative with an increase of 12% till 2050, while non-residential area was modelled with much higher increase of 31% till 2050. This increase in non-residential sector is driven with high expansion in the tourism sector, which is expected till 2050.

The energy demand in the analysed scenarios is shown in Figure 4-3 and Figure 4-4 per energy vector.

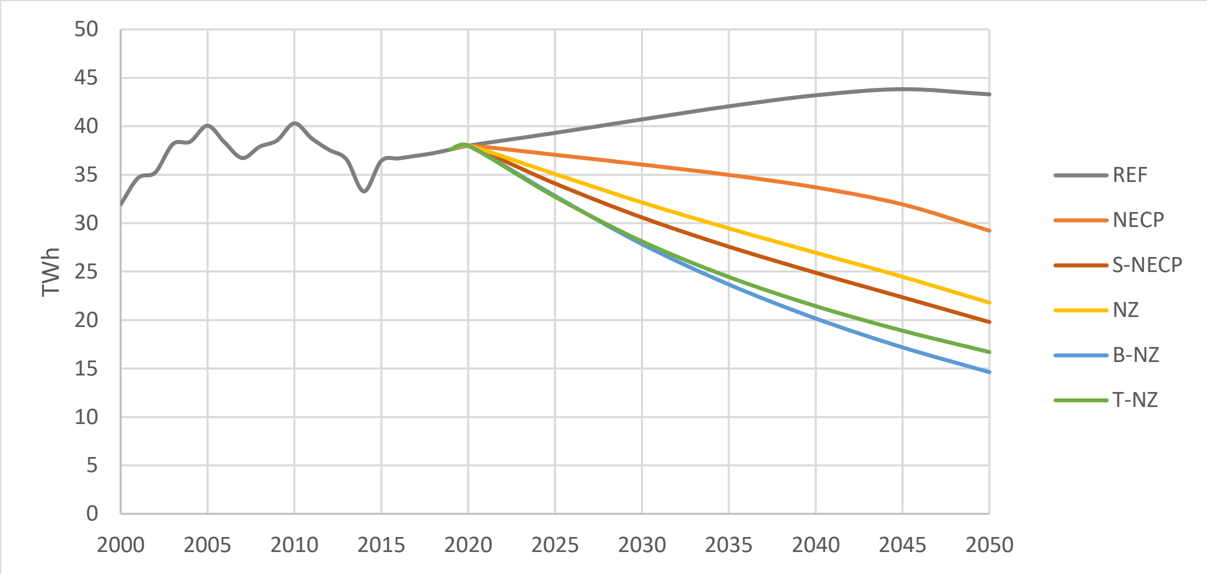

Figure 4-3: Total energy demand in analysed scenarios in buildings sector

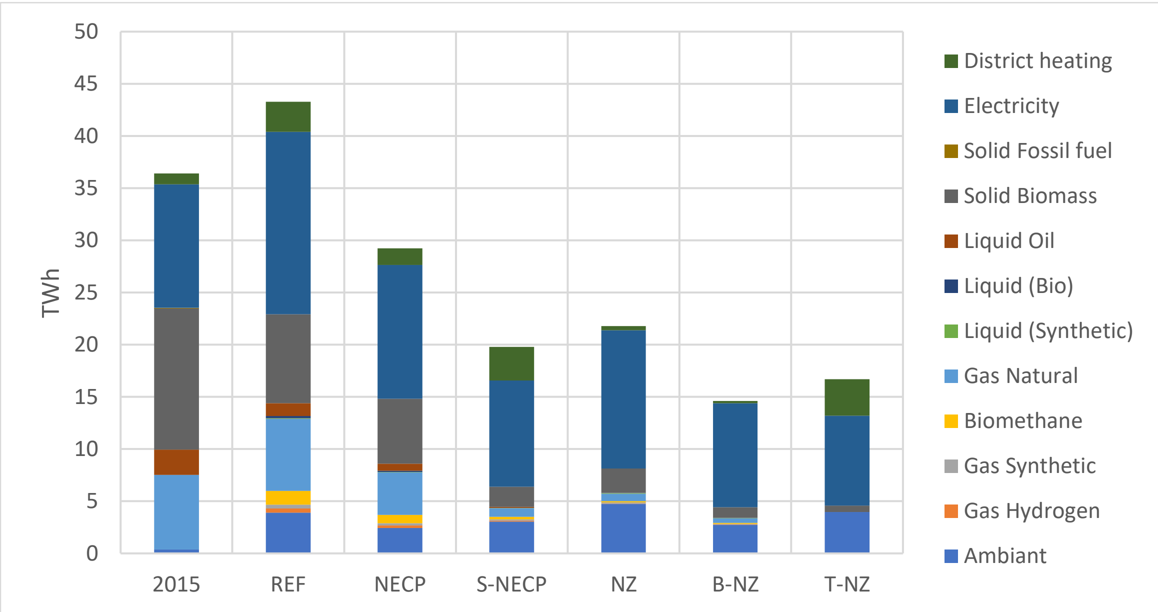

Figure 4-4: Buildings energy demand in 2050 for all scenarios, and historical in 2015

Key message 7
Phasing out natural gas, decreasing biomass consumption in heating sector and replacing it with more efficient technologies can lead to energy savings and increased energy security.

Considering current EU geopolitical context; one of the main challenges for Croatian buildings sector is decreasing dependence on foreign fossil fuel, primarily natural gas which is used in space heating and covering hot water demand. Having that in mind, one of the crucial energy policies would be defining the phase out of natural gas heating boilers for all new buildings. At the same time biomass is widely used in space heating, especially in rural surroundings. Although biomass presents a more favourable heating solution in comparison to natural gas, it still presents a problem from sustainability point of view and should not be pushed long term as a space heating fuel.

One of the main energy sources in the upcoming period for the Croatian buildings sector is electricity. This does not relate only to space heating, but all other end-use categories, like cooking and hot water. Electrification of space heating is primarily focused on heat pumps, especially rural areas and urban areas with relatively low heating demand density.

Key message 8
Empowering district heating sector in urban areas with high heat demand density to decrease losses and utilize new technologies can contribute to power system optimization and fuel savings.

One of the most interesting demand response technologies today is power to heat, which is primarily utilized in district heating systems. Croatia has a relatively good starting point but with some inherited problems. District heating systems are relatively old and inefficient (those based on heat only boilers.) and a certain push needs to be done in order to proceed towards 5th generation district heating systems. By doing so higher renewable energy integration could be done cross sectoral (integration of electricity and heating sector) and at the same time low temperature heat sources could be used.

Current NECP does not recognize the importance of district heating systems, in the future energy system, so additional energy policies were modelled through Suggested NECP and Net-Zero scenarios (with Leaver starting at 3, which corresponds to 30% of space heating demand in 2050). It needs to be said that district heating solutions are primarily focused on urban areas with relatively high space heating demand density.

Key message 9
Support the higher integration of PV in buildings, both residential and commercial.

One of the main conclusions in this modelling process is an overall electrification in the buildings sector. Having that in mind, the position of PV and different integration models (eg. prosumers) becomes one of the key issues. Overall electrification pushes a building towards a concept of a "power plant" which also correlates to the EU's push towards nearly zero energy buildings. One of the long-term strategies for Croatian building sector should be be higher integration of PV in residential and non-residential sector. This process would be also beneficial in the democratization of Croatian energy sector and empowerment of smaller energy community approach.

4.2 Transport

Croatian transport sector is characterized with high focus towards road transport (energy and GHG emission wise) and relatively low developed rail and public transportation in general. With this starting point it is clear that majorities efforts in the decarbonisation process will be focused on modal switch as decarbonisation of various powertrain technologies. The overview of KPIs in the transport sector is shown in Table 4-2.

Table 4-2: Transport KPIs

KPI	2015	REF scenario		NECP scenario		Suggested NECP	
		2030	2050	2030	2050	2030	2050
Total GHG [MtCO2e]	6.31	6.36	3.97	6.32	2.98	5.53	2.09
Passenger Car fleet size [# cars in Millions]	1.5	1.54	1.48	1.54	1.48	1.34	0.942
Modal share passenger [% of passenger.km by car]	68.67	68.44	70.7	68.44	70.7	66.35	59.48
Tech share passenger [% vehicle.km electric]	0.01	1.44	16.5	4.5	42.86	3.8	38.45
Modal share freight [% of ton.km by truck]	40.23	45.48	47.62	45.34	47.68	43.35	42.8
Tech share freight [% truck.km electric]	0.06	1.58	23.62	4.17	40.9	3.78	39.42
KPI	**2015**	**Net-Zero scenario**		**Behaviour Net-Zero**		**Technology Net-Zero**	
		2030	**2050**	**2030**	**2050**	**2030**	**2050**
Total GHG [MtCO2e]	6.31	5.04	0.27	3.87	0.27	2.32	0
Passenger Car fleet size [# cars in MIllions]	1.5	1.54	1.48	1.08	0.458	1.26	0.733
Modal share passenger [% of passenger.km by car]	68.67	68.44	70.7	61.68	43.61	62.87	46.87
Tech share passenger [% vehicle.km electric]	0.01	7.33	43.35	3.1	31.06	13.11	47.95
Modal share freight [% of ton.km by truck]	40.23	45.3	48.38	41.36	37.43	41.53	37.75
Tech share freight [% truck.km electric]	0.06	7.6	32.01	3.59	34	14.2	55.51

Since the transport sector will have to reach (almost) 100% GHG emission reductions, in order to ensure climate neutrality in 2050, significant efforts needs to be implemented. This is reflected in both the decreased demand to travel and the need to decarbonize vehicle fleets across all end-use categories. Compared to WAM scenario one of the main ambitions in suggested NECP and Net-zero scenarios included increased urban and non-urban bike, rail and bus demand with lower car demand. In the freight demand an overall focus on rail increase is one of the main policies, primarily long distance while last mile is bike focused. However, significant GHG reduction is not possible only by behavioural change and various modal switches. A clear and strong effort is necessary in decarbonisation of various vehicle fleets (electricity, hydrogen, biofuels and electrofuels).

Electrification will have a strong impact on lowering final energy consumption due to efficiency difference of internal combustion engines and electric motors. However, this will have a significant impact on primary energy used in the power sector; both for electricity production or some of power2X technology (like hydrogen or electrofuels). Long term perspective of biofuels should be observed rather carefully, due to sustainability constraints and availability of advanced biofuels that are not in competition with food production.

The GHG emissions in the analysed scenarios in transport sector are shown in Figure 4-5.

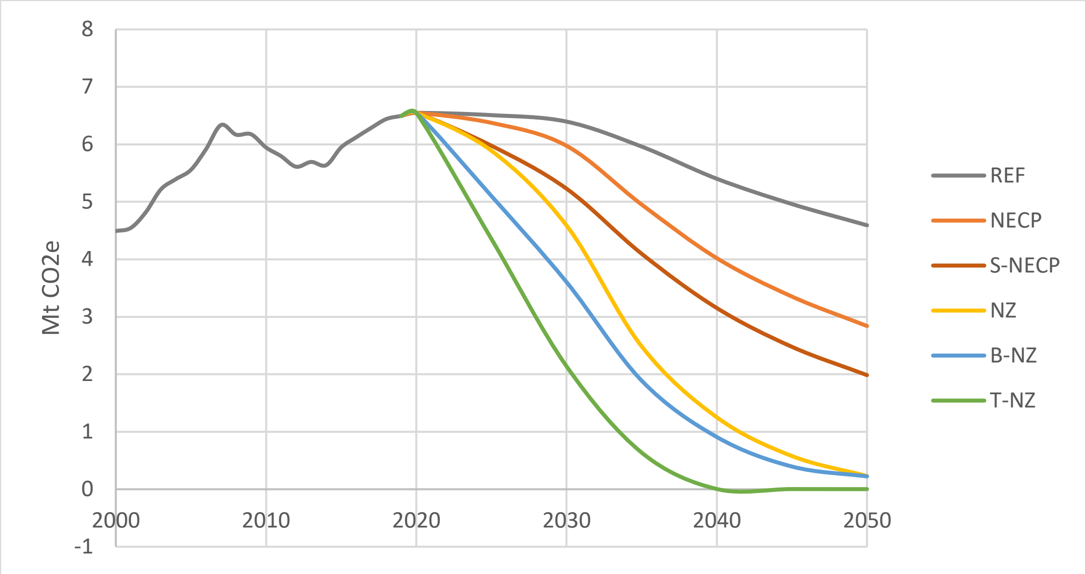

Figure 4-5: Total GHG emissions in analysed scenarios in buildings sector

Key message 10
Behavioural change and technology development leads to lower personal vehicle fleet and energy demand.

Through the modelling process certain boundary conditions significantly impacted the energy demand and GHG emissions of Croatian transport sector. On one hand Croatia expects a significant population decrease till 2050 (from 4.22 Million to 3.38 Million) which should be followed by significant behavioural change regarding vehicle usage (load factors, car ownerships etc.). As a result, decrease in personal vehicle population is expected in all alternative scenarios (suggested NECP and Net-zero scenarios). One of the most significant leavers in these scenarios is the occupancy (pkm/vkm), which highly influences the total amount of personal vehicles in the system. Total energy demand in analysed scenarios in transport sector is shown in Figure 4-6.

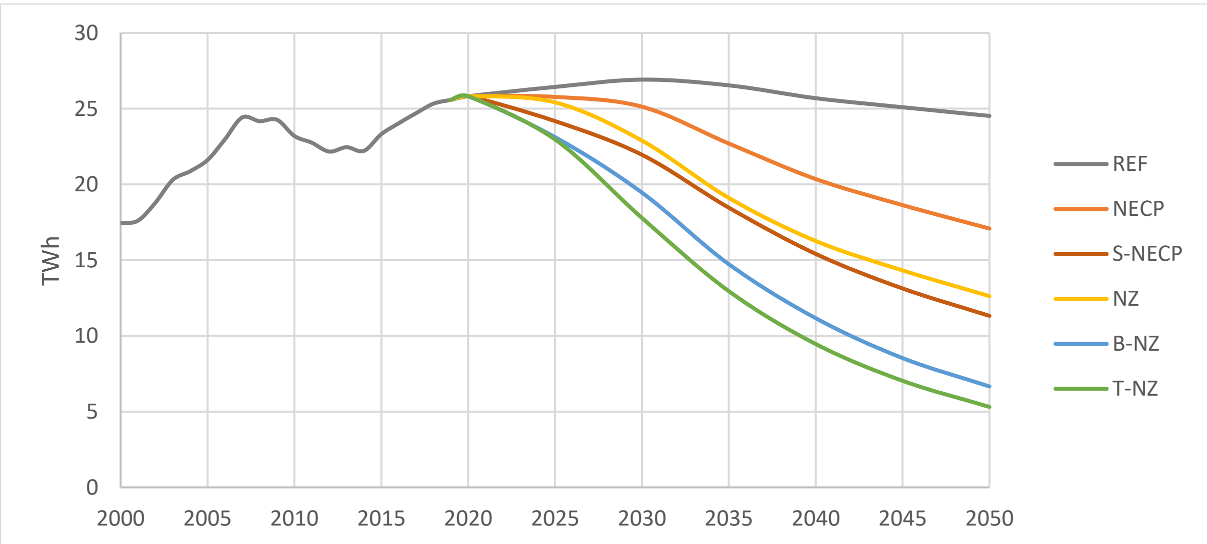

Figure 4-6: Total energy demand in analysed scenarios in transport sector

Key message 11
Ambitious electrification process, with special focus on personal cars fleet, public transportation and costal and river waterways should be the priority. Modes of transport which are more difficult to electrify will depend on alternative fuels, primarily hydrogen and advanced electrofuels with lower shares of biofuels.

Electrification process is of high importance because it allows higher long term integration of renewable energy sources. In the forthcoming period more advanced schemes of charging (smart charging and vehicle2grid) will allow more flexibility and higher uptake of RES electricity to the power grid. In parallel, long term power sector decarbonisation will allow significant GHG decrease in the transport sector. Croatia is rather specific with its long costal line which is an excellent opportunity for the electrification of short-sea navigation sector, together with river waterways and public transportation. At this point there are still parts of the transportation sector that are very difficult to electrify, such as heavy duty, air and long distance sea transport. In the proposed scenarios hydrogen and electrofuels are dominantly use to cover this energy demand. As stated for the electricity, crucial question will be defined within the power sector on how the hydrogen and electrofuels would be produced. It is clear that this also presents an opportunity for the increased penetration of renewable energy sources. Transport energy demand in 2050 for all scenarios is shown in Figure 4-7.

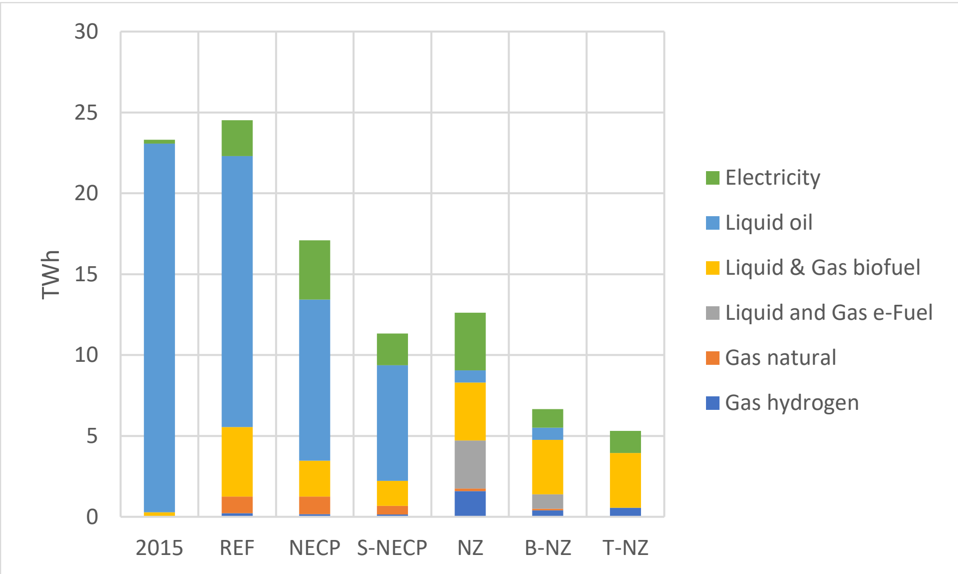

Figure 4-7: Transport energy demand in 2050 for all scenarios, and historical in 2015

Key message 12
More ambitious rail expansion, both in infrastructure and quality, leads to higher modal and intermodal switch. Advanced public transport schemes, followed by decarbonization technologies uptake.

Another specific Croatian constraint is its geographical shape which is excellent for a developed rail infrastructure. Unfortunately, years of neglect in infrastructure and vehicle fleet has led to a relatively small total numbers in traffic (bot passenger and cargo). In line with the EU and national strategy regarding rail infrastructure expansion and modernization this presents a significant potential for modal shift between energy intensive modes (road and air) to rail.

Decarbonisation and electrification within the rail sector would also require modernization towards two way tracks and electrification.

4.3 Industry

Emissions in industry sector include emissions from fuel combustion and emissions from industrial processes, and combined they contribute to about 24% of total net emissions in Croatia. The overview of the KPIs for the industry sector is shown in Table 4-3.

Table 4-3: Industry KPIs

KPI	2015	REF scenario		NECP scenario		Suggested NECP	
		2030	2050	2030	2050	2030	2050
Total GHG [MtCO2e]	4.53	4.66	4.04	4.55	3.75	4.35	2.34
Production volume [Mt]	10.12	11.29	12.17	11.29	12.17	10.97	11.21
Technology [% electric in final energy excl feedstocks]	20	20.5	21	20.7	23.2	21.3	24.2
Sequestration [MtCO2e]	0	0	0	0	-0.01	0	-0.12
KPI	**2015**	**Net-Zero scenario**		**Behaviour Net-Zero**		**Technology Net-Zero**	
		2030	**2050**	**2030**	**2050**	**2030**	**2050**
Total GHG [MtCO2e]	4.53	4.2	1.07	4.34	1.92	4.13	0.87
Production volume [Mt]	10.12	11.29	12.16	11.12	11.66	11.5	12.8
Technology [% electric in final energy excl feedstocks]	20	21.6	26.3	21.3	24.8	20.8	23.8
Sequestration [MtCO2e]	0	0	-0.39	0	-0.16	0	-0.73

The industry material production across the scenarios is shown in Figure 4-8. In the applied model, material production is specified exogenously - meaning that the domestic demand in other sectors are not endogenously reflected in the industry sector. Production volume is considered to rise in all scenarios, with the highest values in T-NZ scenario that implies strong technological development and application of increased industrial production.

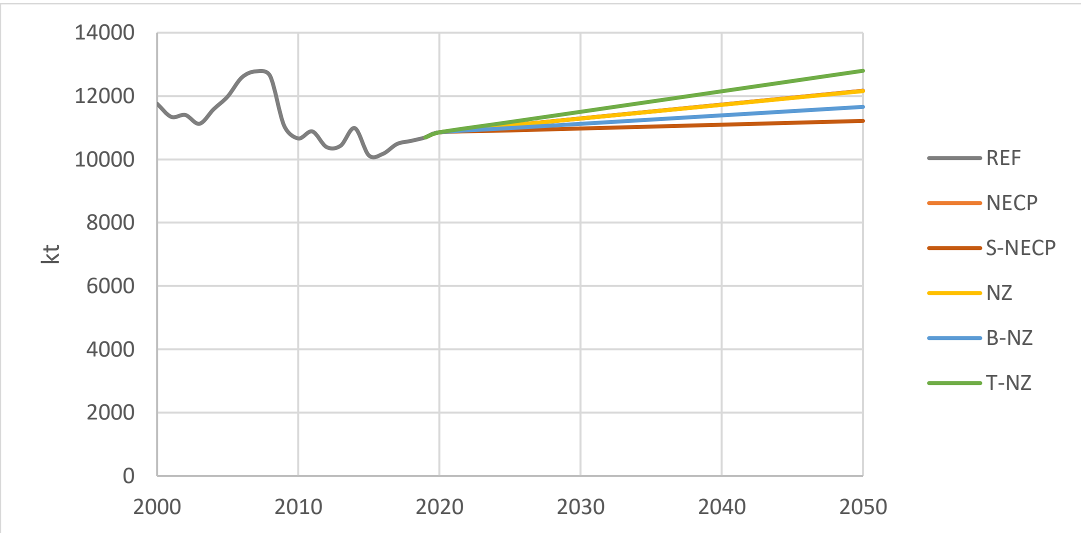

Figure 4-8: Industry material production in all scenarios

Application of circular economy principles has the potential to decrease material consumption and therefore GHG emissions. This effect can further be enhanced under the single EU market with ETS and considering the measures to prevent carbon leakage and development of carbon pricing mechanisms across the globe. The leading example is Carbon Border Adjustment Mechanism set by the EU [14].

Key message 13
Applying circular economy has the potential to drastically reduce materials demand, energy use and greenhouse gas emissions.

The GHG emissions across the scenarios are shown in Figure 4-9. The emissions range from staying at nearly constant levels in REF scenario, to significant reductions in NZ scenarios. Even though there are solutions that can be applied, decreasing emissions in industry sector remains a challenge considering the needed cost-competitiveness.

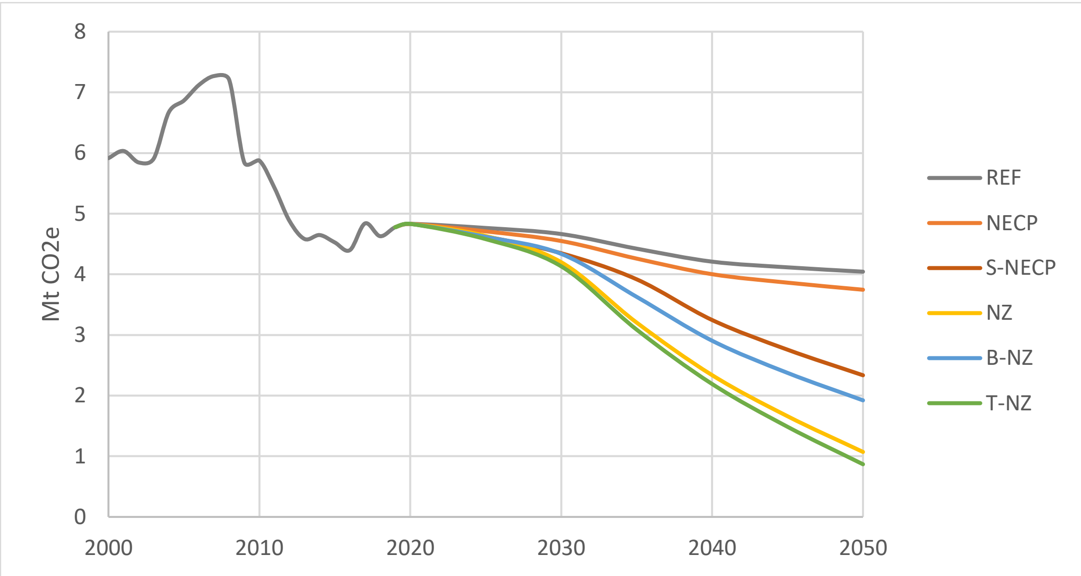

Figure 4-9: Industry GHG emissions for all scenarios

The subpectoral distribution of emissions is shown in Figure 4-10. Emissions from cement and chemical (ammonia) production present highest emitters and application of CCUS technologies are seen as part of the solution in net-zero scenarios.

Key message 14
Technological developments and energy and feedstock switches are key to reducing GHG emissions in industry. However, a significant level of CCUS is required in the net-zero scenarios.

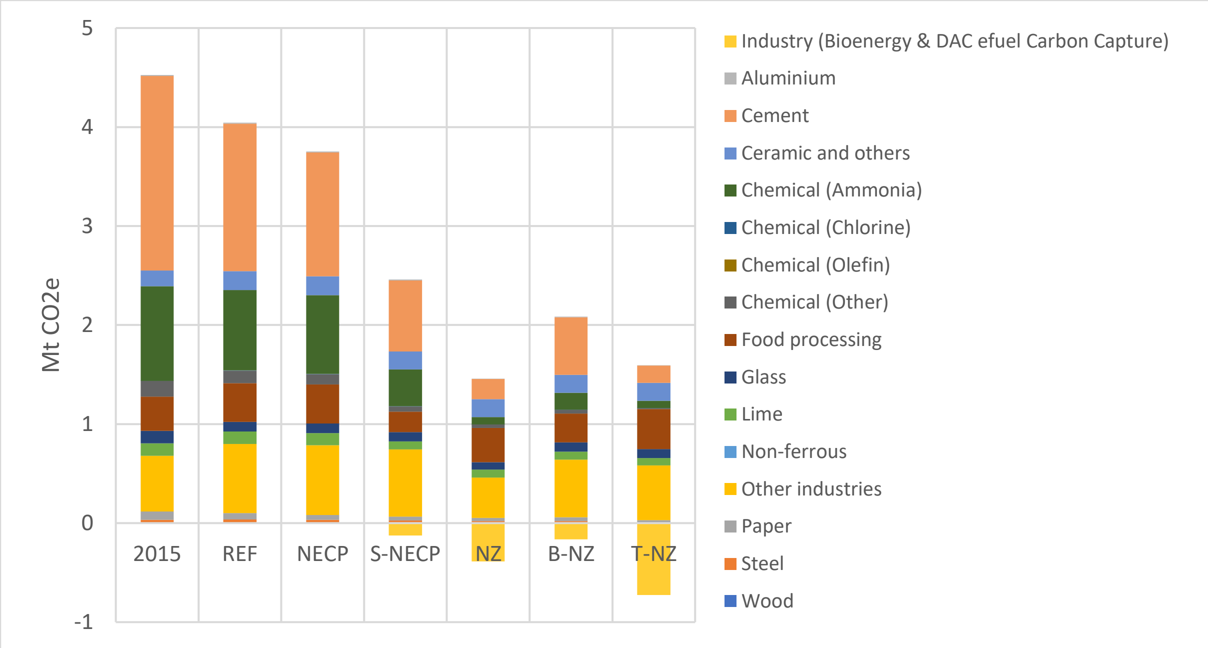

Figure 4-10: Industry GHG emissions in 2050 for all scenarios, and historical in 2015

The energy consumption trends are shown in Figure 4-11 in the industry, and distribution by the vectors and scenarios is shown in Figure 4-12. It is evident that energy consumption remains approximately at the level as in 2015 even though production increases. The exception is the T-NZ scenario where strong increase in production and energy demand is foreseen. In this scenario emissions are compensated by the strong application of CCUS technologies.

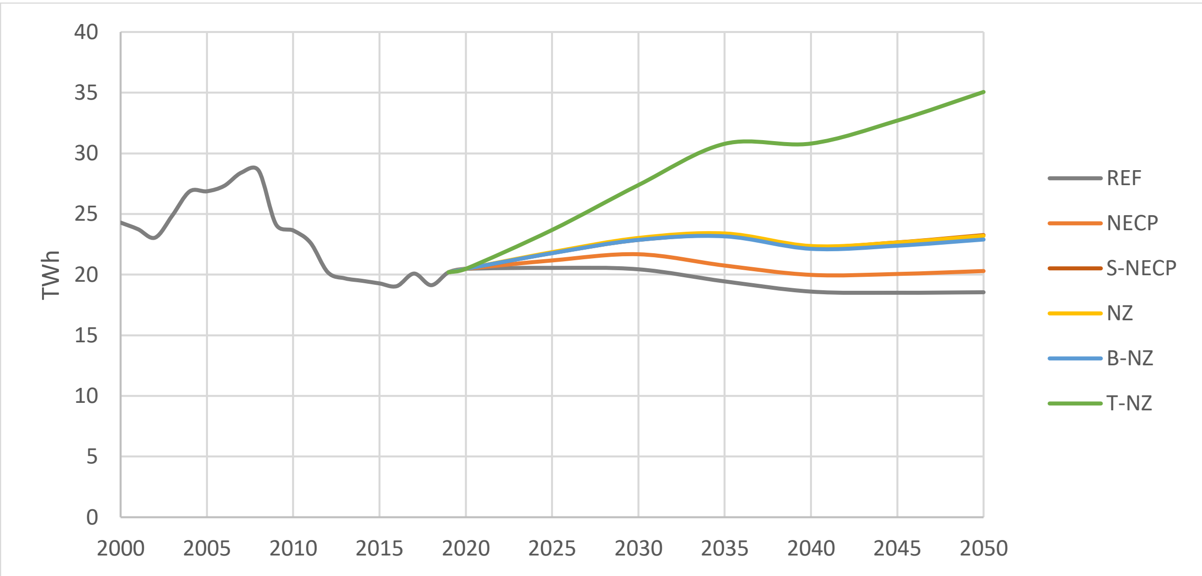

Figure 4-11: Industry energy consumption in all scenarios

In the pursuit of the deep carbonization in industry sector decreasing use of natural gas presents a considerable challenge as electrification is not expected to play such a big role as in other sectors. Here, development and application of hydrogen, e-fuels and biofuels will be required.

Key message 15
Electrification is part of the solution in industry but plays a smaller role than in other sectors. Application of synthetic and biofuels are required to decrease oil and natural gas use, and decarbonise a large part of the energy supplied.

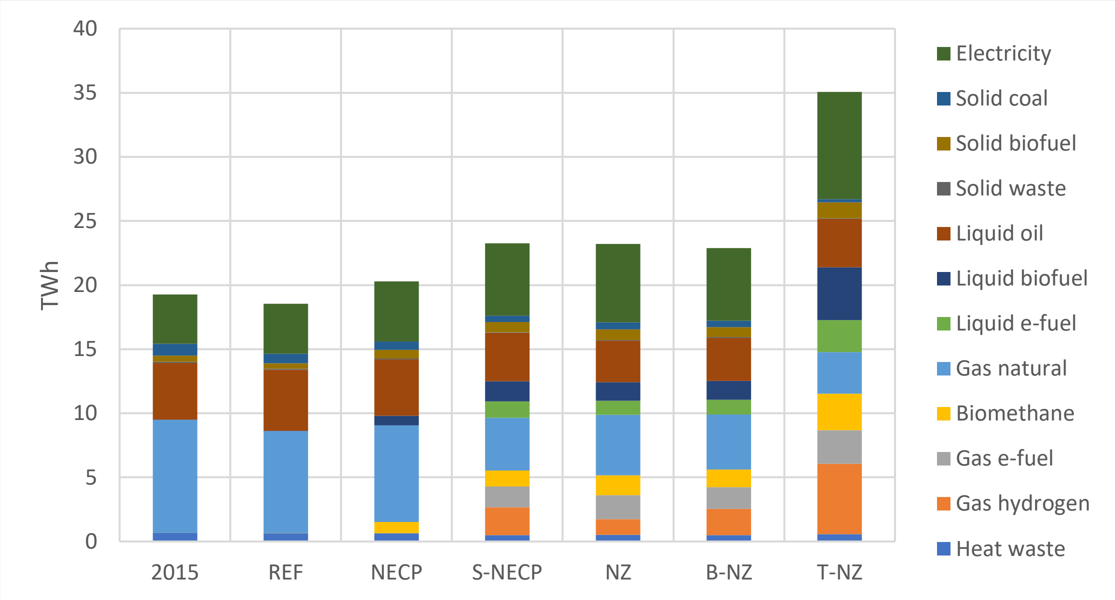

Figure 4-12: Industry energy demand in 2050 for all scenarios, and historical in 2015

4.4 Energy production

The main KPIs related to the energy production are shown in Table 4-4. The KPIs are total GHG emissions in MtCo2-eq, percentage of renewable energy production in final electricity supply, and percentage of coal power plants production in final electricity supply. The KPIs are presented for all 6 scenarios for years 2030 and 2050 and for a base year 2015.

Table 4-4: Scenarios available in Pathways Explorer

KPI	2015	REF scenario		NECP scenario		Suggested NECP	
		2030	2050	2030	2050	2030	2050
Total GHG	5.35	4.62	1.07	3.69	0.78	3.61	0.73
RES [% in final electricity supply]	43.21	50.96	67.26	57	85.24	66.54	92.76
Coal [% in final electricity supply]	8.98	6.37	0	5.36	0	0	0
KPI	**2015**	**Net-Zero scenario**		**Behaviour Net-Zero**		**Technology Net-Zero**	
		2030	**2050**	**2030**	**2050**	**2030**	**2050**
Total GHG	5.35	1.89	0.08	1.84	0.08	3.3	1.62
RES [% in final electricity supply]	43.21	68.4	94.33	72.32	98.04	81.23	96.89
Coal [% in final electricity supply]	8.98	0	0	0	0	0	0

From the Table 4-4 it can be observed that the coal power plants are foreseen to be decommissioned in all scenarios by the year 2050. Additionally, in S-NECP and B-NZ scenarios the coal power plants are foreseen to be decommissioned even by the year 2025.

As it can be seen in Figure 4-13 that in all scenarios, but T-NZ, the GHG emissions are lower than in the REF scenario.

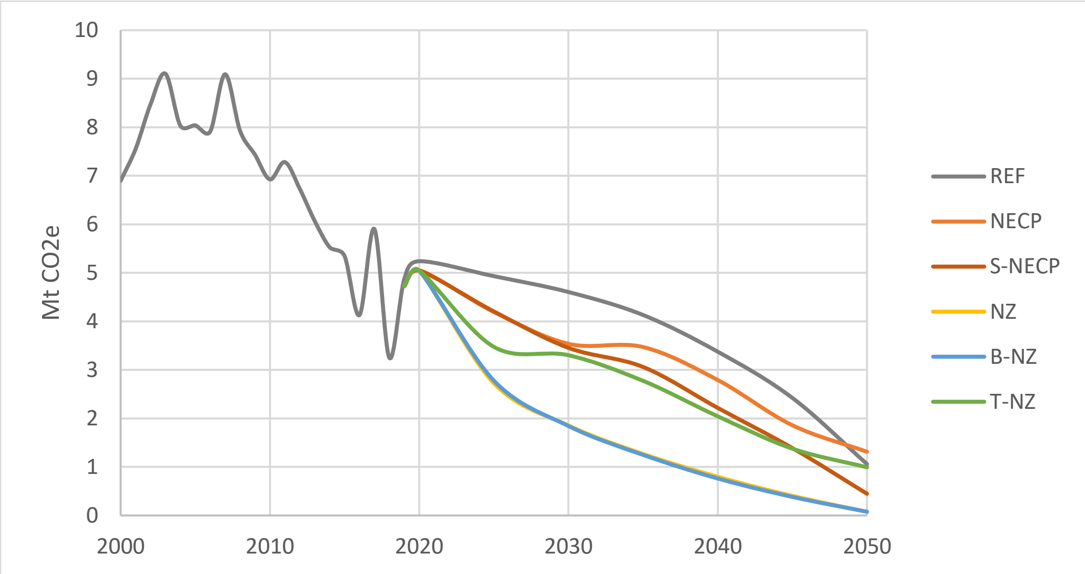

Figure 4-13: Energy production GHG emissions in all scenarios

Key message 16
Reaching climate neutrality by 2050 requires, in most scenarios, a higher electricity production level than the current trend. The share of carbon neutral hydrogen and synthetic fuels produced domestically has a critical impact on total electricity demand.

Total electricity demand depends not only on the direct electricity demand of the buildings, industrial sectors and transport, but also on the electricity required to produce hydrogen (both for sector demand and e-fuels) especially in climate neutral scenarios. Given the large demand for hydrogen and e-fuels in all climate neutral scenarios (NZ, B-NZ, and T-NZ), assumptions made on the level of domestic production (vs import) of these energy vectors play a key role in determining total electricity demand.

Total electricity demand per sector and net exports are shown in Figure 4-14.

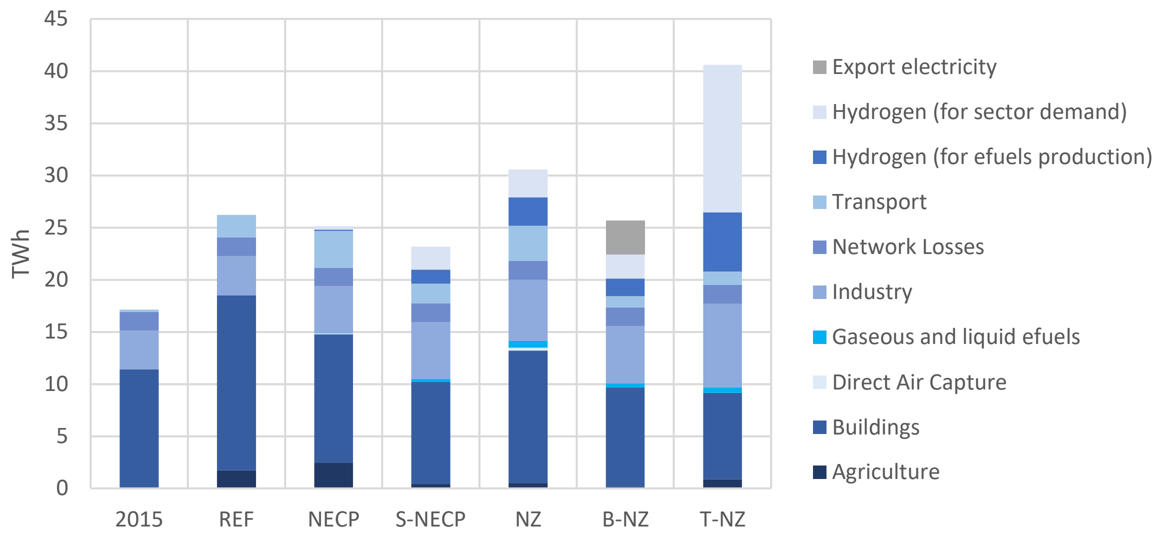

Figure 4-14: Total electricity demand per sector and net exports (in TWh)

The share of hydrogen/e-fuels supply that is produced in Croatia (via the technologies to produce them in a climate neutral manner), rather than imported from abroad, therefore plays a crucial role on the electricity demand (and therefore also on electricity production) in Croatia. The electricity production per source and net imports are shown in Figure 4-15.

Key message 17
Even in some high electricity demand scenarios (NZ and B-NZ), 100% E-RES is achievable for the domestic generation provided that intermittency is adequately managed.

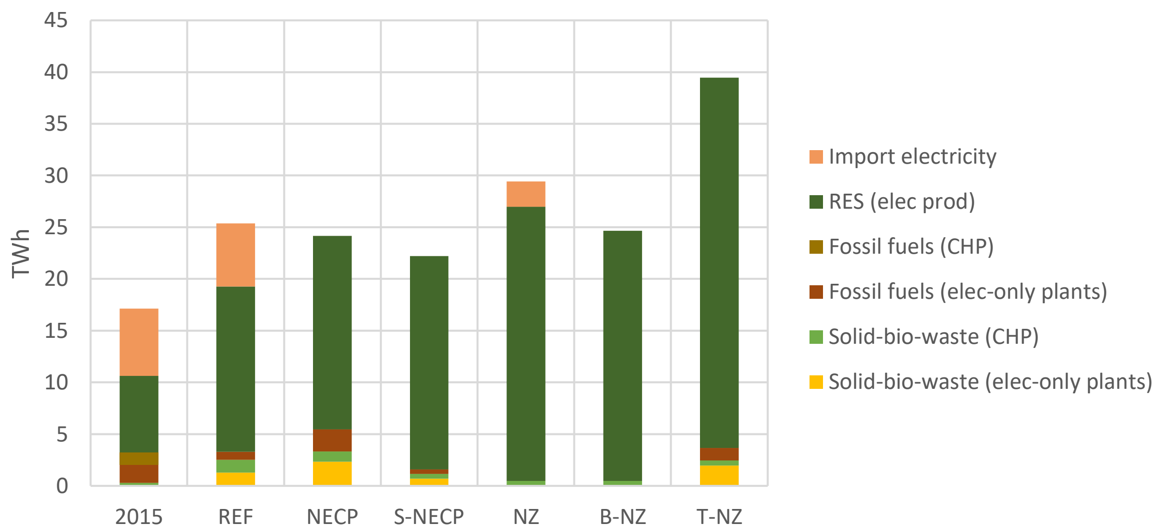

Figure 4-15: Electricity production per source and net imports (in TWh)

In this context, as it can be seen in Figure 4-14, the electricity demand under NZ scenario is higher than in the REF scenario in year 2050 (around 15 %). The B-NZ scenario on the other hand, has slightly lower electricity demand (2%) and additionally, compared to T-NZ much lower electricity demand (around 37%). Although the NZ scenario has higher electricity demand, the demand is covered by renewables and some imported amount (around 8%). To enable this to happen, this scenario is characterized by increased switch from gas to biogas for heating; increased switch in electricity production from natural liquid to bio-liquid additionally; stronger switch in electricity production from natural solid to bio-solid and in refineries strong energy carrier switch away from fossil fuels; 10% increase in installed capacity of RES power plants by 2050 leading to less installed gas power plants (2.5 times); higher carbon capture in electricity production (- 64% of GHG emissions by 2050).

In the B-NZ scenario all the electricity demand can be covered only by renewable energy (**Error! Reference source not found.**), also omitting the import (**Error! Reference source not found.**). In order for this to happen, the solar PV installed capacity reaches 7.1 GW by 2050. Onshore wind capacity reaches 3.98 GW and no off-shore wind power plants are foreseen in this scenario. Hydroelectric power plants reach 3.33 GW od installed capacity by 2050 and the rest of the installed capacity is in geothermal power plants 100 MW and 155 MW in solid biomass and waste.

Regarding the scenarios with high level of renewable production, the management of intermittent renewable energy sources will be the key. Indeed, the reliability of the energy system will need to be ensured through efficient grid management, improved storage capacities and other flexibilities. The integration of renewable energy will be facilitated through decentralized and large-scale storage, different types of demand response and also partly through gas fired power plants fuelled by synthetic gas or biogas. Electricity production per fossil fuels is shown in Figure 4-16.

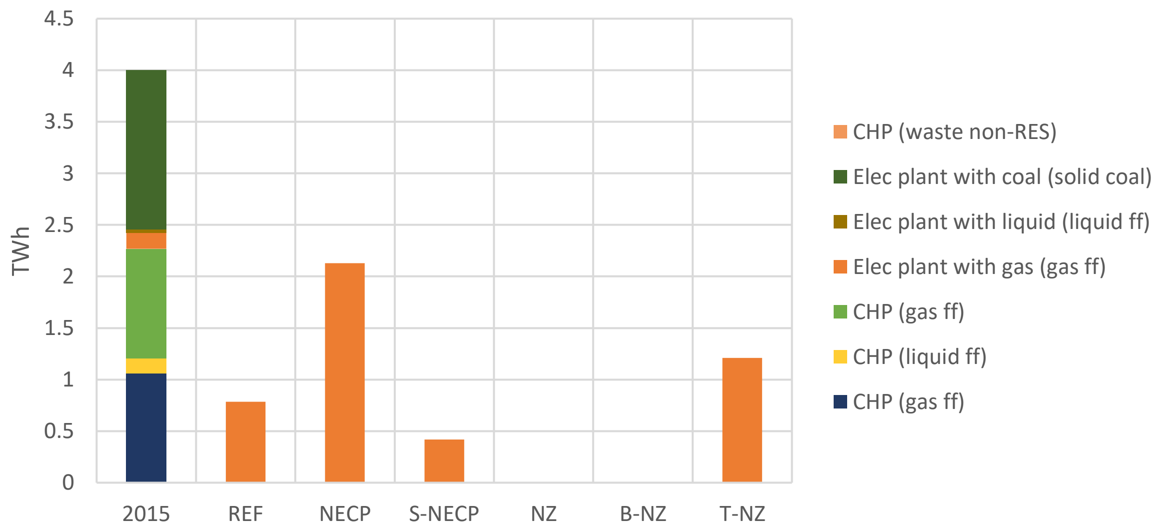

Figure 4-16: Electricity production per fossil fuels (in TWh)

The assumption made in the presented scenarios is that 0 to 20 % of electricity is imported to cover the demand (only in REF and NZ scenarios the import is modeled as higher than 0 %). The model allows making different assumptions, which will of course also impact the levels of required production and production mix in Croatia.

4.5 Agriculture, forestry and other

In the AFOLU sector (agriculture, forestry and land use), all scenarios suggest that gradual and significant changes of agricultural practices and consumption patterns are required to reach climate neutrality by 2050. Besides agricultural and land use practices, Pathway Explorer AFOLU module also considers the impact of human lifestyle on food demand, food waste management, as well as bioenergy from other sectors, and the food production is the priority of this module[1]. The overview of the KPIs for the AFOLU sectors is shown in Table 4-5.

Key message 18
Changes towards healthier and more plant based diets can significantly reduce the food-related GHG footprint in Croatia, including food waste along the supply chain, from farm to consumer.

Table 4-5: AFOLU KPIs

KPI	2015	REF scenario		NECP scenario		Suggested NECP	
		2030	2050	2030	2050	2030	2050
Agriculture GHG [$MtCO_2e$]	3.44	3.34	3.35	2.93	2.23	2.83	1.96
Land use GHG [$MtCO_2e$]	-5.12	-3.86	-3.73	-3.61	-3.4	-3.88	-3.89
Calories consumption [kcal/cap/day]	1.14	1.19	1.26	1.15	1.12	1.14	1.09
KPI	**2015**	**Net-Zero scenario**		**Behavior Net-Zero**		**Technology Net-Zero**	
		2030	**2050**	**2030**	**2050**	**2030**	**2050**
Agriculture GHG [$MtCO_2e$]	3.44	2.61	1.35	2.41	0.8	2.73	1.8
Land use GHG [$MtCO_2e$]	-5.12	-3.45	-3.26	-3.72	-3.8	-4.19	-4.13
Calories consumption [kcal/cap/day]	1.14	1.08	0.93	1.05	0.84	1.16	1.17

Two key behavioural levers related to a change in human diet are distinguished in the model across all scenarios. The first lever concerns food calories consumption, whereby we consider that by 2050, calories consumption could decrease the most in the B-NZ scenario by more than 30% comparing to REF. The second lever controls the type of diet, specifically the quantity of meat consumed and the share of ruminant meat (bovine, sheep etc.) compared to other meat types (pigs, poultry etc.) in total meat consumption. Decrease in the meat consumption is most significant in 2050 in B-NZ scenario, with the share of ruminant meat decreasing from by more than 50% as compared to 2015.

[1] The AFOLU modul is consisted of next levers: 1. Key behaviours - Diet, waste and others (1.1 Calories consumption, 1.2 Type of diet, 1.3 Food waste at farm and post-farm), 2. Agriculture practices (2.1 Crop extensification degree, 2.2 Alternative Protein Source, 2.3 Livestock management extensification degree, 2.4 Emissions from energy use in agriculture), 3. Land-use (3.1 Land management (3.1.1. Settlement and other lands, 3.1.2 Afforestation of freed-up lands, 3.1.3 Deployment of energy crops and natural prairies on remaining freed-up lands), 3.2 Forest degradation, 3.3 Forestry management) and 4. Bioenergy (4.1 DDC and agricultural products, 4.2 Agricultural co-products, wastes and co, 4.3 Energy crop share)

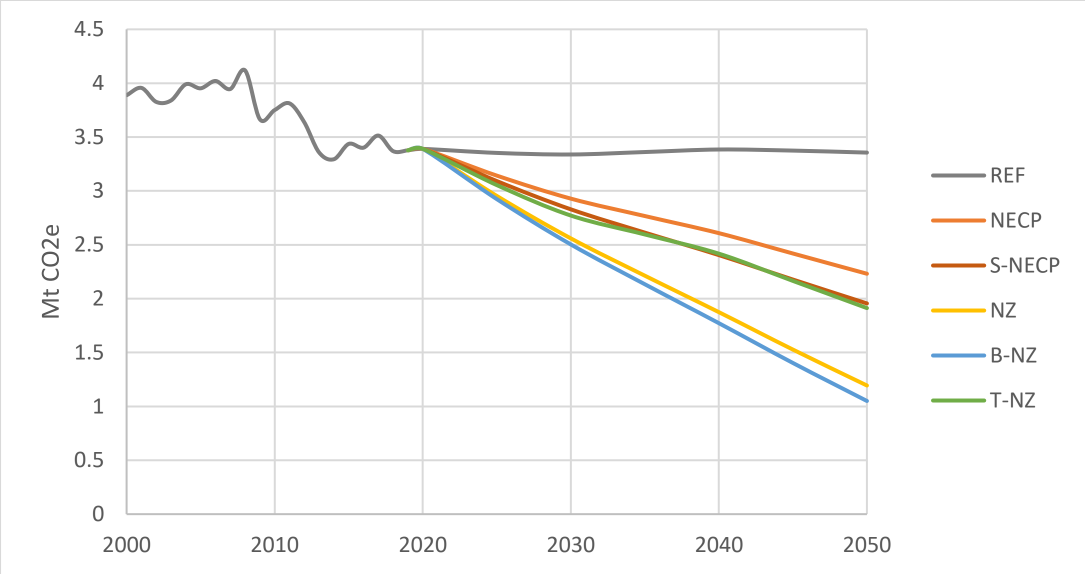

Figure 4-17: Agriculture GHG emissions in all scenarios

Agricultural activities today account for approximately 11% of total national greenhouse gas emissions in Croatia. By 2050, total GHG emissions form agricultural activities decrease in the five main scenarios illustrated in Figure 4-17, when compared to the Reference scenario. The most significant GHG emission reductions in 2050 in agricultural sector of 2.5 $MtCO_2e$ comparing to the reference scenario is obtained in B-NZ scenario, suggesting the possibility for achieving significant reductions in emissions from the changes in key human behaviours and lifestyle.

Changes in human nutrition, such as less calories consumption, less meat and more plant-based dieting, vegeterian or vegan lifestyle especially have a positive effect on the emissions in the agriculture - both due to decreased use of mineral fertilizers (and consequently less nitrogen compounds) required for animal feed production, and also due to the reduction of methane emissions from the intestinal fermentation of livestock. The additional benefits are significantly lower water and fuel consumption in agricultural production. Diet changes indeed lead to a reduction of the required feed crops and thus of related surfaces. They also reduce the area needed for livestock pasture.

Key message 19
Changes in the agricultural model could have a strong impact on land-use and thereby on carbon sequestration possibilities. Progressive but transformative changes in agricultural practices are required in order to reach significant emission reductions by 2050.

All scenarios imply that agricultural practices need to evolve towards agroecology practices for all crops by 2050 in order to achieve sectoral GHG reductions and improved trends in carbon sequestration sinks. It is also important to optimize mineral fertilizer application and replace the use of the nitrogen-based intrants and pesticides. Application of organic fertilizers and limestone materials, together with and treatment, are crucial in the overall solution of the problem of agricultural soils management because of the need to correct the excess acidity of soils in many agricultural holdings. The most ambitious reductions are achieved in T-NZ scenario, by lever suggesting the decrease by 20% in the use of NPK fertilizers in 2050.

More action is also required to reduce methane emissions from intestinal fermentations and the extraction of methane and nitrogen from manure management through changes in diet and changes in the composition of animal feed, such as replacing share of the animals feed by alternative proteins sources requiring no crops (e.g. insects or algae). This lever is the most ambitious in T-NZ scenario where on average 3% of animals feed will be replaced by alternative proteins by 2050.

Livestock management extensification degree lever stays the most ambitious in REF scenario. It suggests the higher the share of pasture in animals feed, the results in more extensive livestock is on pasture and the lower animals yields. Higher levels also favour leaving manure on pasture or applying it on cropland (which will reduce the need for synthetic fertilizers) which reduces the availability of manure for biomethane production. In REF scenario, CH_4 emissions due to better management of manure decreases by almost 30% in 2050 compared to 2015.

Energy efficiency (improved equipment maintenance, energy monitoring and technology improvement) and switching to renewable energy are the most ambitious in the NZ and T-NZ scenarios, suggesting almost the complete reduction of the agriculture energy induced emissions by 2050. This scenario assumes national policy improvements in favouring anaerobic digestion (of silage and renewable lignocellulosic raw materials, organic byproducts of the food industry and slaughterhouses, biodegradable solid waste fractions and microbial biomass) and biogas production for production of electricity and heat and fuel for internal combustion engines.

Consumption of crops products to produce bioenergy is far more ambitious in S-NECP and T-NZ comparing to other scenarios. Energy exploitation of post-harvest residues is one of the most significant ways of producing biomass energy in the Republic of Croatia. Except agricultural co-products and residues, this includes the remnants of the winter harvest of horticultural species and fast-growing energy-producing crops that are planted / sown for the biomass production and its conversion to energy. However, starting from the fact that Croatian farms are the smallest in the EU and that the biomass market is still on its way to be developed in Croatia, this scenarios could be improved later in future, following the application of the recommendations of the EU Common Agricultural Policy.

The emission reductions achieved through these agricultural practice levers of about 1.1 $MtCO_2e$ to 2.5 $MtCO_2e$ in 2050 when compared to the REF scenario, are also the result of intersectoral interactions within the model. To conclude, the modelling showed that in the process of decarbonisation, the agricultural sector plays an important role - both in the context of its own emissions and in the context of its contribution to the use of renewable sources.

The land use and forestry sector differ from other sectors in that it contains both sources and sinks of greenhouse gases. The sources or emissions to the atmosphere are given as positive values; the sinks, or removals from the atmosphere, are given as negative values. In the segment of land use, most of the official scenarios using this model have been judged not ambitious enough what is in line with current state of national policy in this sectors.[2]

[2] By 2027 and legal obligations, it is necessary to develop a Land Management Strategy of the Republic of Croatia. Resource: https://mingor.gov.hr/UserDocsImages/klimatske_aktivnosti/odrzivi_razvoj/NUS/lts_nus_eng.pdf

Key message 20
To achieve climate neutrality within the framework of sustainable land management and forestry, it is necessary to develop a national land information system and guidelines for land management with the aim of increasing the carbon sink in the Republic of Croatia, due to the fact the trend of sink reduction has been recorded in these sectors.

Following Figure (4-18), it is possible to observe that trends in Land Use significantly differ. Levers modelled in the scenario NZ seems to result in significant loss in carbon sinks. Here in 2050 removals in this sector reach value of -3.26 $MtCO_2e$ in 2050. Comparing to the historical value in 2015, removals decreased for 1.86 $MtCO_2e$. Scenario T-NZ assumes the most ambitions and almost continuous value of removals (-4.13 $MtCO_2e$ in 2050). Comparing the values from this 2 scenarios, is seems that the difference in removals in 2050 is almost 1 $MtCO_2e$. Interestingly, S-NECP and REF scenarios suggest the same trend. Other important thing to emphasize is that a trend of sink reduction has been recorded.

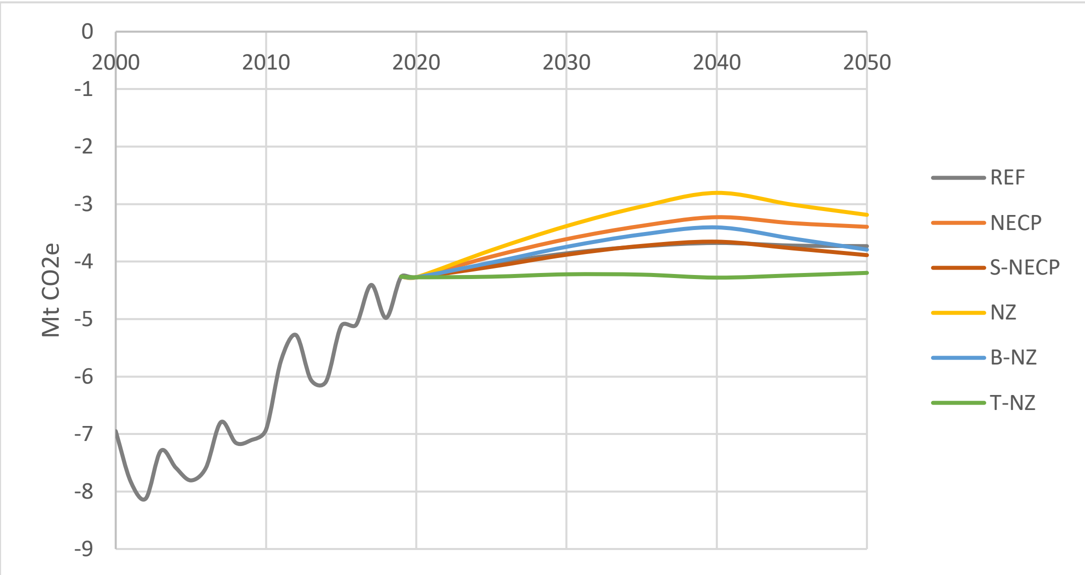

Figure 4-18: Land Use GHG emissions in all scenarios

The biggest reason for this is the lack of implementation of prescribed forest management practices on all forest areas, during the Croatian War that took place in Croatia from 1990 to 1998. The war and the consequences of the war caused a disruption of the structure of forest stands and led to a decrease in forests growth, due to the lack of timely implementation of the prescribed cultivation interventions (absence of logging). In the Republic of Croatia, it is still necessary to implement land management practices that have so far resulted in sinks[3]. To ensure this, Croatia develop a National Forestry Accounting Plan (NFAP)[4].

[3] The works envisaged by the Forest Management Plan of the Republic of Croatia for the period 2016-2025, should lead to the establishment of an appropriate structure of stands, for which it is necessary to carry out all works that were not carried out in time in stands that were in war-affected areas, as well as in areas affected by post-war events (e.g. mined and mine suspected forest areas).

[4] In accordance with Article 8, paragraph 3 of Regulation (EU) 2018/841 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, the Republic of Croatia, like all other Member States of the European Union, had an obligation to develop a National Forestry Accounting Plan (NFAP) for the period from 2021 to 2025, which was submitted to the European Commission on 31st December 2018. The mentioned plan also proposes the Forest Reference Level (FRL) for the

Within the framework of sustainable land management and forestry, the introduction of new management practices, should be implemented. In the way to achieve climate neutrality, if emissions will not be able to be reduced in some sectors, it could be done by measures to increase sinks. Some of the forestry practices that could be implemented and that are in line with the levers suggested in Pathways Explorer Webtool are additional biomass accumulation in forests, afforestation[5], reduction of timber exports, reduction of biomass use for energy purposes, increasing production of furniture and other wood products, agroforestry, additional carbon storage in soil and in grasslands land use areas, reduction of the emissions on the croplands. Land management practices that can affect emissions and removals, for example in soil storage, are: soil treatment methods, plantation/crop life (rotation period) and crop / plantation type, fertilizer application, residue management, erosion control, application of irrigation systems etc. Activities in a climate and environmentally beneficial manner should be promoted and technological measures for carbon capture, use and storage.

Waste GHG emissions in all scenarios are shown in Figure 4-19.

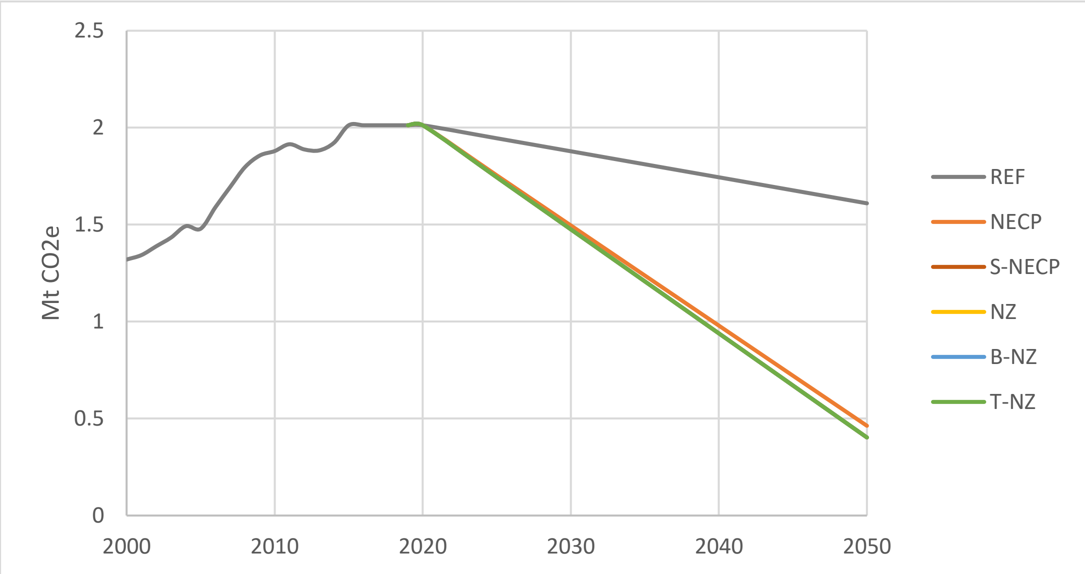

Figure 4-19: Waste GHG emissions in all scenarios

In the segment of waste management, most of the developed scenarios using this model have been judged too ambitious. Therefore, significant reductions in the GHG emissions can be observed through all models concerning this sector.

Republic of Croatia. An NFAP review has not been finished yet. https://mingor.gov.hr/nacionalni-racunski-plan-za-sumarstvo-ukljucujuci-i-predlozenu-referentnu-razinu-za-sume-za-razdoblje-od-2021-do-2025/5486

[5] Afforestation on non-forested areas (in terms of IPCC methodology and Pathways Explorer model) is an activity that generates carbon and reduces emissions. Due to the regulations in the field of nature protection governing the establishment of Natura 2000 sites, the Republic of Croatia is not able to dispose of all lawn areas (according to the national regulation: non-overgrown production forest land) for afforestation purposes. Considering that there are non-cultivated agricultural areas in the Republic of Croatia that have been neglected for many years, the problem of these areas must be adequately addressed when developing the Land Management Strategy.

Key message 21
Reducing paper and plastic packaging, reducing food waste and adopting more sustainable consumption patterns leads to a reduction of the related production and distribution activities and thereby on GHG emissions.

Regarding the waste from agricultural sector, one of the biggest aims is to reduce the amount of biodegradable fraction of waste disposed at landfills (especially agricultural co-products and post-harvest residues, remnants of the winter harvest of horticultural species etc.), which results in the reduced emissions of methane produced by anaerobic waste decomposition processes[6]. All scenarios try to show the possibility to reduce food waste (and meat waste in particular) along the supply chain, from farm to consumer. Most of the scenarios suggest the decrease in the quantity of food waste by food type. The most ambitious are B-NZ and T-NZ models which suggest the decrease of at least 60% of the waste in cereals production, 60% decrease for fruits waste, 70% for vegetables and meat waste at farm and post farm.

[6] In accordance with the Sustainable Waste Management Act, quantitative targets have been identified for reducing the share of biodegradable municipal waste disposed at landfills. By the end of 2020, the share of biodegradable municipal waste disposed of in landfills must be reduced to 35% of mass fraction of biodegradable municipal waste produced in 1997.

5 Conclusions and way forward

The EU's ambition towards climate neutrality until 2050 set the new policy context that any planning and development efforts should take into account. Under this work a model for transparent and cross-sectoral assessment of possible pathways towards climate-neutral economy in Croatia until 2050 is developed. To demonstrate the capabilities of the model six scenarios are created. Three that replicate the existing national scenarios (REF, NECP, NZ), and three that provide additional insight on different options (S-NECP, B-NZ, T-NZ) towards 2050. The analysis contributes to understanding and assessment of options towards transformation of the economy that can be achieved over next 30 years in Croatia. It allows policymakers to take more informed decisions and can engage wider public in consultation processes over upcoming strategies and action plans.

It is shown that reaching climate neutrality in Croatia by 2050 is technically feasible, even though it is particularly challenging and requires systemic changes. Activation of ambitious levers and options are needed to reach climate neutrality, out of which new technologies such as hydrogen, e-fuels, and CCUS, as well as new consumption and production patterns are needed. Furthermore, while GHG emissions in the buildings, transport and energy production sectors can be reduced to de facto zero, some harder to abate emissions in industry and agriculture sectors will need to be compensated with negative emissions through land use and CCUS.

The developed scenarios affirm the aspiration of the EU towards the phasing out of fossil fuels (oil and natural gas), not only to mitigate climate change but to increase energy security, which is particularly highlighted with current implications of the war in Ukraine. This can predominantly be achieved with the electrification of the demand sectors, followed up with a power system based entirely or almost entirely on renewable and energy sources. Sectors that are not possible to electrify have to be complemented with climate neutral fuels. Biomass potential remains significant but limited and is strongly linked to land use choices. Hydrogen and e-fuels could be a solution that could help in balancing of the intermittent renewable energy sources and close the gap in demand sectors, especially for use as industrial feedstocks. The share of the domestic production (vs import) of these fuels becomes an important factor for the dimensioning of the power system.

It is evident that economy transformation towards climate-neutrality requires additional capital investments in all sectors. However, those can be significantly reduced by behaviour and circular economy levers that can control the demand for energy-consuming activities, products or services. Capital investments are dominated by additional energy production facilities, grid expansion and storage in the power system, sectoral integration and investments in energy efficiency measures in buildings sector. On the other hand, those investments lead to decrease of fossil fuel expenditure to almost zero in the long run. That tend to compensate the additional investments (subject to future costs of technologies and fuels). The price of producing or importing of hydrogen and e-fuels, including for use as feedstock, then becomes a determinant element of the total energy bill.

The scenarios also highlight the importance of looking beyond the energy system to address the key aspects related to the use of resources and land. For instance, the massive renovation of buildings will be material-intensive, and the increased investments in renewable energy sources requires land use, which in case of biomass use has further impacts on GHG sequestration potential. The circularity of the resources together with material switches becomes an important issue in this context. The interlinkages between these different dimensions are strong and therefore important to take into account when designing policies. Further, the holistic and systematic approach can create efficient cross-sectoral solutions, for example integration of energy production and buildings through increased rooftop solar system installations can contribute to multiple benefits.

Finally, to transform the economy, systemic changes are required not only in terms of technological developments but also at the societal and cultural levels: rethinking the way we move, eat, consume, or use space will be crucial. In the transport sector, new mobility patterns based on mobility-as-a-service, modal shift, car sharing, and new freight transport modes can considerably reduce energy consumption and material use. New diets based on a lower consumption of proteins from animals together with decreasing the level of food waste are required for the drastic reduction of GHG emissions in an agricultural sector relying on novative agroecological ractices and the Common Agricultural Policy of EU. The development of the sharing economy and the economy of functionality allows to significantly reduce the need for materials and products and thereby contribute to the reduction of emissions in the production sectors. Housing behaviours, based among others on a rational use of space and heating, can present the 'low hanging fruits' and also significantly contribute to the decarbonisation.

The model as such provides a strong basis for additional analysis and simulations, and is meant to be used as a tool to foster the public awareness and argument-based debate on present and future policy directions. It can be complemented with additional sectoral or optimisation tools. Nevertheless, future work and improvements can be related to a more targeted analysis of the energy production system and intermittency challenges, specific implementation of decarbonisation policies in industrial sectors, the availability of biomass in the context of a bio-based economy, profitability of low carbon investments at a micro level in all sectors and the social and distributive impacts policy options from the jobs or health perspectives among the other possibilities.

Appendix

A.1 Key performance indicators

Table A-1: Key performance indicators for scenarios REF, NECP, and NZ

Sector	KPI	2015	REF scenario		NECP scenario		Suggested NECP	
			2030	2050	2030	2050	2030	2050
Transversal	• Total GHG [$MtCO_2e$] • Sequestration [$MtCO_2e$] • Total GHG w/o sequestration [$MtCO_2e$] • FF [% of final energy] • Electricity [% of final energy] • Alternative fuels [% of H_2+e-fuels in final energy] • Biomass [% of final energy]	• 18.70 • -5.12 • 23.82 • 59.1 • 20.6 • 0.0 • 17.2	• 17.35 • -3.57 • 20.92 • 56.8 • 23.0 • 0.4 • 16.1	• 11.78 • -3.37 • 15.15 • 49.9 • 27.1 • 1.3 • 16.2	• 16.97 • -3.76 • 20.73 • 55.2 • 23.7 • 0.4 • 17.4	• 7.61 • -4.12 • 11.73 • 30.2 • 33.1 • 0.9 • 17.3	• 14.98 • -4.04 • 19.02 • 41.3 • 24.3 • 1.2 • 17.0	• 3.49 • -4.29 • 7.78 • 32.3 • 34.4 • 9.7 • 13.4
Buildings	• Total GHG [$MtCO_2e$] • Renovation rate [% of stock per year] • Renovation depth [%] • Electricity [% of final energy] • District heating [% of final energy]	• 2.56 • 1.6 • 0 • 32 • 2.93	• 2.29 • 1 • 5 • 38.2 • 3.6	• 1.62 • 1 • 5 • 39.7 • 6.2	• 2.10 • 1.8 • 25 • 39.3 • 3.4	• 1.22 • 1.8 • 25 • 43.9 • 5.4	• 1.52 • 2.5 • 29.7 • 40.9 • 6.5	• 0.25 • 2.5 • 29.7 • 51.4 • 16.2
Transport	• Total GHG [$MtCO_2e$] • Passenger Car fleet size [# cars in Millions] • Modal share passenger [% of passenger.km by car] • Tech share passenger [% vehicle.km electric] • Modal share freight [% of ton.km by truck] • Tech share freight [% truck.km electric]	• 6.31 • 1.5 • 68.67 • 0.01 • 40.23 • 0.06	• 6.36 • 1.54 • 68.44 • 1.44 • 45.48 • 1.58	• 3.97 • 1.48 • 70.7 • 16.5 • 47.62 • 23.62	• 6.32 • 1.54 • 68.44 • 4.5 • 45.34 • 4.17	• 2.98 • 1.48 • 70.7 • 42.86 • 47.68 • 40.9	• 5.53 • 1.34 • 66.35 • 3.8 • 43.35 • 3.78	• 2.09 • 0.942 • 59.48 • 38.45 • 42.8 • 39.42
Industry	• Total GHG [$MtCO_2e$] • Production volume [Mt] • Technology [% electric in final energy excl feedstocks] • Sequestration [$MtCO_2e$]	• 4.53 • 10.12 • 20.0 • 0.00	• 4.66 • 11.29 • 20.5 • 0.00	• 4.04 • 12.17 • 21.0 • 0.00	• 4.55 • 11.29 • 20.7 • 0.00	• 3.75 • 12.17 • 23.2 • -0.01	• 4.35 • 10.97 • 21.3 • 0.00	• 2.34 • 11.21 • 24.2 • -0.12

Sector	KPI	2015	REF scenario		NECP scenario		Suggested NECP	
			2030	2050	2030	2050	2030	2050
Energy supply	• Total GHG • RES [% in final electricity supply] • Coal [% in final electriciity supply]	• 5.35 • 43.21 • 8.98	• 4.62 • 50.96 • 6.37	• 1.07 • 67.26 • 0	• 3.69 • 57.00 • 5.36	• 0.78 • 85.24 • 0	• 3.61 • 66.54 • 0	• 0.73 • 92.76 • 0
Agriculture. Forestry and Others	• Agriculture GHG [MtCO_2e] • Land use GHG [MtCO_2e] • Calories consumption [kcal/cap/day]	• 3.44 • -5.12 • 1.14	• 3.34 • -3.86 • 1.19	• 3.35 • -3.73 • 1.26	• 2.93 • -3.61 • 1.15	• 2.23 • -3.40 • 1.12	• 2.83 • -3.88 • 1.14	• 1.96 • -3.89 • 1.09

Table A-2: Key performance indicators for scenarios Suggested NECP, Behaviour Net-Zero, and Technology Net-Zero

Sector	KPI	2015	Net-Zero scenario		Behavior Net-Zero		Technology Net-Zero	
			2030	2050	2030	2050	2030	2050
Transversal	• Total GHG [MtCO$_2$e] • Sequestration [MtCO$_2$e] • Total GHG w/o sequestration [MtCO$_2$e] • FF [% of final energy] • Electricity [% of final energy] • Alternative fuels [% of H$_2$+e-fuels in final energy] • Biomass [% of final energy]	• 18.70 • -5.12 • 23.82 • 59.1 • 20.6 • 0 • 17.2	• 12.85 • -3.38 • 16.23 • 48.7 • 25.8 • 1.7 • 21.0	• 0.0 • -3.58 • 3.58 • 19.9 • 43.3 • 16.2 • 18.2	• 11.37 • -3.74 • 15.11 • 47.3 • 25.3 • 1.8 • 22.8	• 0.00 • -3.95 • 3.95 • 23.6 • 40.9 • 14.4 • 18.8	• 10.46 • -4.22 • 14.68 • 33.7 • 25.9 • 3.9 • 30.4	• 0.00 • -5.56 • 5.56 • 14.1 • 34.9 • 19.2 • 21.3
Buildings	• Total GHG [MtCO$_2$e] • Renovation rate [% of stock per year] • Renovation depth [%] • Electricity [% of final energy] • District heating [% of final energy]	• 2.56 • 1.6 % • 0 % • 32 % • 2.93 %	• 1.55 • 2.6 • 38 • 42.3 • 2.6	• 0.21 • 2.6 • 38 • 60.7 • 1.9	• 1.35 • 3.5 • 67 • 42.5 • 2.6	• 0.12 • 3.5 • 67 • 68 • 1.5	• 0.86 • 3 • 54 • 41.7 • 8.4	• 0.02 • 3 • 54 • 51.7 • 20.9
Transport	• Total GHG [MtCO$_2$e] • Passenger Car fleet size [# cars in MIllions] • Modal share passenger [% of passenger.km by car] • Tech share passenger [% vehicle.km electric] • Modal share freight [% of ton.km by truck] • Tech share freight [% truck.km electric]	• 6.31 • 1.5 • 68.67 • 0.01 • 40.23 • 0.06	• 5.04 • 1.54 • 68.44 • 7.33 • 45.3 • 7.6	• 0.27 • 1.48 • 70.7 • 43.35 • 48.38 • 32.01	• 3.87 • 1.08 • 61.68 • 3.1 • 41.36 • 3.59	• 0.27 • 0.458 • 43.61 • 31.06 • 37.43 • 34	• 2.32 • 1.26 • 62.87 • 13.11 • 41.53 • 14.2	• 0 • 0.733 • 46.87 • 47.95 • 37.75 • 55.51
Industry	• Total GHG [MtCO$_2$e] • Production volume [Mt] • Technology [% electric in final energy excl feedstocks] • Sequestration [MtCO$_2$e]	• 4.53 • 10.12 • 20.0 • 0.00	• 4.20 • 11.29 • 21.6 • 0.00	• 1.07 • 12.16 • 26.3 • -0.39	• 4.34 • 11.12 • 21.3 • 0.00	• 1.92 • 11.66 • 24.8 • -0.16	• 4.13 • 11.50 • 20.8 • 0.00	• 0.87 • 12.80 • 23.8 • -0.73

Energy supply	• Total GHG • RES [% in final electricity supply] • Coal [% in final electriciity supply]	• 5.35 • 43.21 • 8.98	• 1.89 • 68.40 • 0	• 0.08 • 94.33 • 0	• 1.84 • 72.32 • 0	• 0.08 • 98.04 • 0	• 3.30 • 81.23 • 0	• 1.62 • 96.89 • 0
Agriculture. Forestry and Others	• Agriculture GHG [MtCO_2e] • Land use GHG [MtCO_2e] • Calories consumption [kcal/cap/day]	• 3.44 • -5.12 • 1.14	• 2.61 • -3.45 • 1.08	• 1.35 • -3.26 • 0.93	• 2.41 • -3.72 • 1.05	• 0.80 • -3.80 • 0.84	• 2.73 • -4.19 • 1.16	• 1.80 • -4.13 • 1.17

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Abbreviations list

AFOLU – Agriculture, Forestry and Land Use
CCGT – Combined Cycle Gas Turbine
CCS – Carbon Capture and Storage
CCUS – Carbon Capture Use and Storage
CHP – Combined Heat and Power
ETS – Emission Trading Scheme
GHG – Greenhouse Gas Emissions
HPP – Hydro Power Plant
LTS – Long-term Strategy
NECP – National Energy and Climate Plan
NPP – Nuclear Power Plant
NPV – Net Present Value
OCGT – Open Cycle Gas Turbine
PHS – Pumped hydro storage
PV – Photo Voltaic
RES – Renewable Energy Sources
WPP – Wind power plant
WAM – With existing measures
WEM – With additional measures

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