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Climate action, environment, resource
efficiency and raw materials

COP21 RIPPLES

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1. Changes with respect to the DoA

Original delivery date for D3.2 was M19 (June-18). The delivery was re-scheduled for M25 to be able to include 1.5°C scenarios in the analysis.

2. Dissemination and uptake

The first part of this study, scenario modeling, provided data for the COP21 RIPPLES D2.4 deliverable and for the policy brief "A Sectoral Perspective To Embark on Transformative Pathways". The scenarios may be used to inform upcoming policy briefs. The second part, the actual energy security analysis, builds on the energy security indicators that was previously identified in Milestone 3.1. The research report is going to be disseminated through the Consortium's research networks and websites. It will be translated into a specific policy brief on energy security to enhance dissemination across policymakers and key influencers. This brief will be a main input into the first Policy Dialogue of the Project.

3. Short summary

The main goal of this contribution is to evaluate the possible impacts of ambitious climate mitigation policies on future European energy security. We consider four dimensions of energy security: availability of energy sources, energy affordability, electricity and sustainability. In total, we use 13 indicators to evaluate these four dimensions. Relying on the POLES model, five prospective scenarios have been built: a reference scenario consistent with the NDCs in 2030 and without enhanced ambitions, two 2°C scenarios distinguished by the start date of enhanced climate policy, and two 1.5°C scenarios representing different levels of final energy demand. These scenarios provide highly detailed data regarding energy systems. They are used to derive energy security indicators at EU and national level. At the aggregated EU level, our analysis shows that ambitious climate policies improve the level of energy security dimensions related to the share of residential energy expenditure in GDP, total (households and economic sectors) energy costs in GDP, and energy intensity of GDP. Nevertheless, these positive effects must be qualified for the Central and Eastern European countries in particular, which appear to be much more vulnerable than the EU15 countries. This work also reveals points of vigilance that must be taken into account. The first weakness concerns security of natural gas supply since Russia is by far the main supplier for a number of countries, including in the most ambitious mitigation scenarios, even if quantities imported are much lower. A second element concerns grid stability issues in light of the decarbonisation of the electricity mix and the required rise in intermittent renewables. The country-level scenario analysis was also supplemented by a country case study for Bulgaria and Poland. The focus on these countries is critical, as energy security is a key socio-economic objective closely linked with climate and energy policy in the CEE region.

4. Evidence of accomplishment

Report submitted and uploaded onto the COP21 RIPPLES website.

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Introduction

There is broad consensus in the literature that climate policies have a positive impact on fossil fuel dependency due to reductions in consumption. However, energy security is a much broader concept than mere fossil fuel dependency (APERC, 2007; Hughes, 2009; Sovacool, Mukherjee, 2011; Cherp, Jewell, 2014) which should also take into account the availability of supply (dependency, diversity, energy reserves), the ability of the economy to deal with energy risks, energy affordability and sustainability issues. If all of these dimensions are included in the analysis, climate policies can have a positive impact on some dimensions and a negative impact on others. This is shown, for example, in the article by Sovacool and Saunders (2014) comparing policy packages in order to explore trade-offs between energy security and sustainability. Half of them reveal a contradiction between energy security and sustainability objectives. Bollen et al. (2010) study how the combination of energy security, climate and pollution mitigation policies affects GHG emissions, pollution and oil consumption in OECD countries. The authors show that, in some cases, a climate policy can be inconsistent with the reduction of pollution and would simply delay peak oil consumption. Other authors point out additional potential weaknesses: reduction in supply diversity (Victor et al., 2014; Jewell et al. 2014), increasing energy dependency (Bazilian et al. 2011) etc.

All these studies were published before COP21. The goal of COP21 RIPPLES project task 3.1 is to analyse European energy security issues in light of the Paris Agreement. As a first step, a literature review was carried out in order to define the relevant dimensions for our energy security analysis and the specific indicators to be used for reporting purposes (Stolyarova et al. 2017). The second step involved developing scenarios corresponding to a limitation of global warming to 2°C and 1.5°C. The POLES model was used for this. In total, four mitigation scenarios plus a reference scenario were produced. Two 2°C scenarios were developed, one being compatible with the NDC ambitions of the Paris Agreement, the other incorporating an enhanced ambition starting in 2020. Two 1.5°C scenarios were also produced. They are differentiated in terms of level of final energy demand. In the last stage of this work, this allowed us to analyse the energy security challenges facing the European Union and major economies in each of these scenarios. The energy security analysis is complemented by country case-study for Bulgaria and Poland. This report focuses on the last two stages of the work, the first of which resulted in a Milestone 3.1 in 2017.

In this deliverable, we first review the energy security concept and the indicators used (Section 1). Then we describe the five prospective scenarios produced with the POLES model and present the main results (Section 2). Section 3 assesses the impact of these scenarios on energy security at EU level, while Section 4 provides a more detailed analysis at country level. The last section sets out our conclusion.

1. Evaluating energy security in a prospective scenario

The extensive in-depth review of energy security indicators we carried out as part of Milestone 3.1 (Stolyarova et al., 2017[1]) shows there is neither a common definition of energy security nor a list of suitable energy security indicators. For the purposes of the COP21 RIPPLES project, we define energy security using a multidimensional approach, following the advice of Cherp and Jewell (2014), Hippel (2011) et al. and Leung et al. (2014):

- Scope and purpose of energy security definition. The scope of the study is to evaluate energy security in prospective scenarios focusing on EU countries. The first vulnerability is future availability of energy sources. In addition to energy availability, the most extensively studied dimension of energy security, we will also analyse energy affordability. In Milestone 3.1, we investigated potential future vulnerabilities of the EU in the case of an ambitious climate policy. Moreover, there are two specific features: the future security of natural gas consumption given the high level of dependence of some European countries on this energy, which could potentially be a transition energy towards a low-carbon mix, and security of the electricity grid in a context of high renewable energy deployment.
- Selection of energy security indicators. The next step was to select the most appropriate energy security indicators. We identified 46 energy security indicators in Milestone 3.1. At first sight, 24-35 of them seemed to be calculable and useful to our analysis. However, only 13 indicators (**Table 1**) are computable with the POLES model and relevant to this analysis.

Given the scope of the study and the energy security indicators used in our analysis, the IEA definition of energy security[2] suitably summarizes the concept of energy security that we use:

"Energy security is the uninterrupted availability of energy sources at an affordable price. Energy security policy should cover and reduce the risks that affect the energy sector and should be sustainable".

In the following section, we describe the indicators we used to analyse energy security in the EU. For ease of reading, we have sorted them into four categories: availability of primary energy, energy affordability, electricity security and sustainability.

The first dimension is **energy availability**. We analyse availability of primary energy sources through nine indicators sorted in three sub dimensions:

- Diversity of energy sources. The first meaning of this indicator refers to the fact that the greater the diversity of the energy mix the lower the vulnerability to a risk of supply disruption. However, another dimension that needs to be kept in mind is the fact that, all other things being equal, the less vulnerable a poorly diversified mix will be if total energy consumption is low.

[1] See https://www.cop21ripples.eu/resources/milestone-3-1/
[2] https://www.iea.org/topics/energysecurity/

- Energy dependency on energy imports (imports of oil, coal and natural gas) and the energy dependency of the whole economy.
- Focus on natural gas security[3]: we use two additional indicators to evolve the security of natural gas supply in the EU: share of Russian gas in imports and international gas prices.

There are two widely used energy diversity indicators: the Shannon diversity index (SDI) and the Herfindahl–Hirschman index (HHI). The SDI refers to the diversity in energy sources in the energy mix: the higher the SDI, the greater the diversity is, i.e. the share of energy used is the same for all energy sources. The HHI evaluates the level of competition, it decreases rapidly when some agents, companies or energy sources in our case have a large market share. The HHI ranges from 0 (infinite number of sources with low shares) to 10,000 (single supplier). Lower HHI means better diversity (the opposite compared to SDI).

The formulae for both diversity indicators are as follows:

$$SDI = -\sum_{i=1}^{I}(s_i \times \ln s_i)$$

$$HHI = \sum_{i=1}^{I}(s_i \times 100)^2$$

where s_i is the share of each source, gas importer or technology in total energy, imports or technology mix. $I = \{1,2, \dots, i, \dots I\}$ is the total number of sources, importers or technologies.

We use the SDI to evaluate the diversity of energy sources and natural gas importers, and the HHI only to evaluate diversity among natural gas importers. As mentioned in Milestone 3.1, this indicator is not useful for evaluating the energy mix, in particular the diversity of the electricity mix. A company, energy source or electricity technology with a very large share does not imply that energy is less available. For example, in the electricity sector, peak electricity suppliers are crucial for managing peak load. However, their market share is never high.

Table 1: Energy security indicators

No.	Indicator	Dimension	Sub-dimension	EU level	Country level
1	Shannon Diversity Index	Availability	Diversity	✓	✓
2	Herfindahl-Hirschman Index	Availability	Diversity	✓	
3	Oil dependency	Availability	Dependency	✓	✓
4	Coal dependency	Availability	Dependency	✓	✓
5	Gas dependency	Availability	Dependency	✓	✓
6	Share of Russian gas	Availability	Natural gas	✓	
7	International gas prices	Availability	Natural gas	✓	
8	Energy intensity	Availability	Dependency	✓	✓
9	EU energy net imports (in value) compared to GDP	Availability	Dependency	✓	✓
10	Total energy expenditure in GDP	Affordability		✓	✓
11	Energy bill per dwelling	Affordability		✓	✓
12	Share of VRE	Electricity		✓	✓
13	Share of RES	Sustainability			✓

[3] As there is a single market for oil, issues related to security of oil supply are different, and the same analysis for oil would make less sense.

Other dimensions of energy availability are listed in the **Table 1**. The energy intensity of GDP evaluates the level of energy dependency of the whole economy, while dependency on oil, coal and natural gas is determined by the proportion of imports in total consumption. In the case of natural gas, we also measure the Russian contribution to EU imports. The share of fossil fuels net imports in GDP is also an important indicator to be considered in mitigation scenarios.

The second dimension of energy security is **affordability** of energy supply. This dimension refers in particular to the energy bills of the various economic actors (households, industries, tertiary sector, and agriculture) but also to the challenges of fuel poverty for the poorest households. However, since the POLES model does not describe household behaviours for each income class and does not consider income distribution within a country or region, it cannot compute the level of fuel poverty of households in the country or region. The analysis relies thus on two proxies:

- The share of total energy expenditures[4] for final energy consumption (households + economic sectors) divided by the total GDP in PPP represents energy affordability of the economy.
- The energy bill per dwelling (defined as the ratio between energy expenditure in the residential sector and the number of dwellings). This indicator is considered here as a proxy of fuel poverty. We analyse the evolution of energy bill in each mitigation scenario compared to BAU. Furthermore, to ease country level analysis we will compare the energy bill evolution to the increase of GDP PPP.

Energy security issues related to **electricity** generation are analysed with three indicators: the diversity of energy sources and the diversity of technologies used to generate electricity (measured by SDI in the availability dimension), and the share of variable renewable energy (VRE). Looking at the diversity of technologies, we consider that a high number of technologies is better, because technologies may be complementary. Concerning the share of VRE, if this is too high, it may decrease electricity security because of network stability issues.

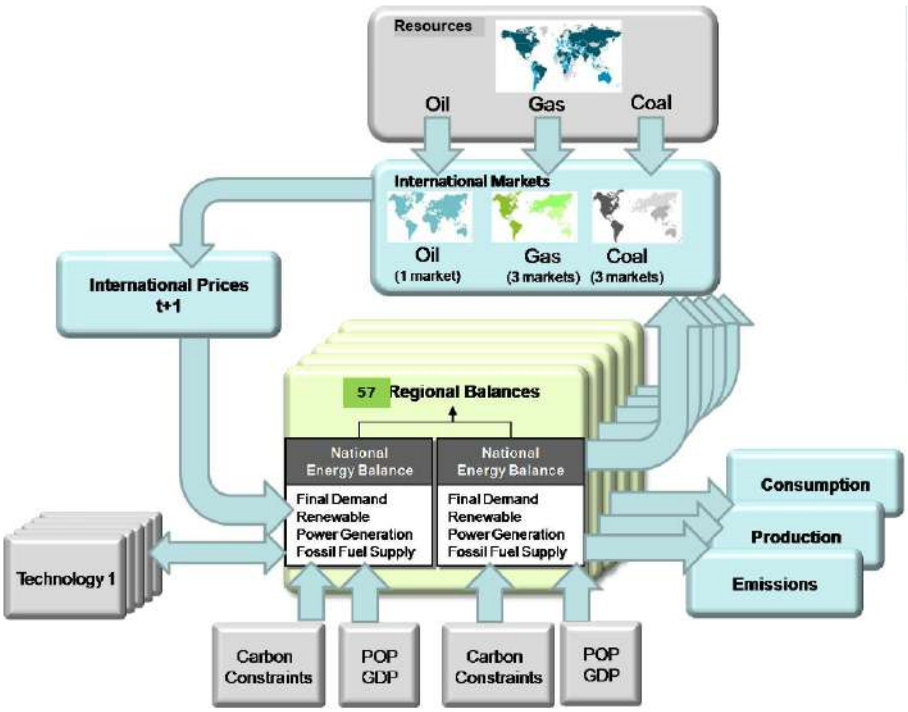
The last dimension, **sustainability**, is analysed only with regard to the share of renewable energy sources (RES) because the POLES model does not compute pollution emissions, deforestation rate, etc.

2. Overview of scenarios

The quantification of energy security indicators relies on the POLES (Prospective Outlook on Long-term Energy Systems) model. POLES is a long-term recursive simulation model (up to 2100) for energy supply, demand and prices. It is a partial equilibrium bottom-up world model, based on 57 national sub-models, which allows the balancing of energy supply and demand with endogenous prices. The model allows projections of energy demand and supply in each country or region, as well as CO_2 emissions generated. The scenarios provide energy and emission data for 46 countries and 11 regions worldwide, 14 fuel supply sectors and 15 final demand sectors. Economic growth assumptions are exogenous to the model, while the set of variables that structure energy demand, supply and prices are endogenously simulated for each country or region and market. **Figure 1** shows the interactions between variables and parameters in the POLES model.

[4] Unit : constant 2005 US$

Figure 1: Presentation of the POLES model



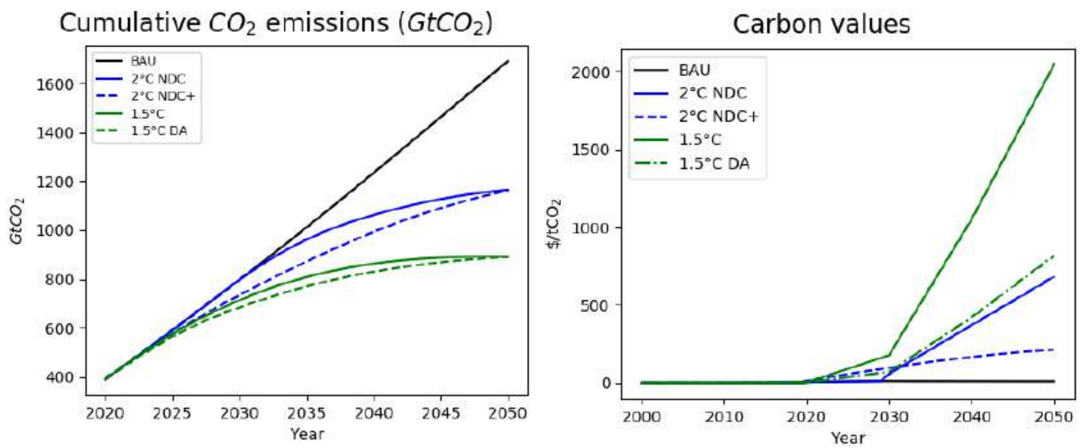
Source: authors

In this section, we first define the main features of the scenarios computed with the model. Then, we will present the energy and emission trajectories of each scenario.

2.1. Definition of scenarios

To evaluate energy security issues related to deep decarbonisation, we have built five prospective scenarios simulated using the POLES model: one Business as Usual scenario and four mitigation scenarios following RIPPLES narratives. All of them rely on the same socio-economic assumptions (Kitous et al. 2017). The scenarios are sorted into three categories according to carbon budget (**Figure 2**, left-hand graph): (i) reference scenario, (ii) 2°C scenarios and (iii) 1.5°C scenarios. Additional climate policies start in 2020 and are implemented in POLES through "implicit carbon values", as summarized in **Table 2** for all scenarios. A carbon value can be associated to each mitigation objective. This carbon value is not necessarily a pure price instrument, but should be considered as a proxy of the different instruments and constraints that will impact the energy system. This value corresponds to a shadow cost imposed to all CO2 emitting activities. In the model, the carbon value defined at regional or national scales is set according to the carbon constraints. These implicit carbon values are exogenous, adjusted by the modeller to follow a given emission trajectory. **Figure 2** (right-hand graph) gives the evolution of implicit carbon values for each of the five scenarios.

Figure 2: Carbon budget and average global carbon values



Source: POLES results

Table 2: Carbon budget and implicit carbon values in 2050 for the five scenarios

Scenario	Carbon budget ($GtCO_2$) 2010-2050	CO_2 emissions from energy uses and industrial process ($GtCO_2$) 2030	2050	Carbon value in 2050
BAU	1,625	41.5	45.6	2030: National values from 0€/tCO2 to 60€/tCO2. On average: 11.15 $/tCO_2$ Same over the period 2030-50
2°C NDC	1,130	41.5	5.4	Convergence from national values of BAU in 2030 toward 680 $/tCO_2$ in 2050 on average
2°C NDC+	1,130	29.4	12.6	3 regional carbon prices: 520 $/tCO_2$ high-income countries in 2050 260 $/tCO_2$ middle-income countries in 2050 130 $/tCO_2$ low-income countries in 2050
1.5°C	890	24.0	-0.6	One world carbon price reaching 2,050 $/tCO_2$ in 2050
1.5°C DA	890	19.6	2.9	One world carbon price reaching 818 $/tCO_2$ in 2050

Source: POLES results

2.1.1. Reference scenario

The ***BAU*** scenario depicts a world in which the ambition of climate policy is limited to compliance with Nationally Determined Contributions (NDC) in 2030. In such a context, national carbon values are exogenously adjusted to reach national objectives of the NDCs in 2030. They vary from 0 to \$60.5/tCO_2 in 2030. The global average carbon value is only \$11.15/tCO_2 in 2030. After 2030, we assume that the national implicit carbon values remain unchanged between 2030 and 2050.

2.1.2. 2°C scenarios

Relying on COP21 RIPPLES narratives, the two 2°C scenarios represent a global effort by all countries to reduce GHG emissions and limit climate change to 2°C. Both scenarios have the same carbon budget,

i.e. 1,130 $GtCO_2$ from energy use and industrial process for the period from 2010 to 2050. The 2°C scenario narratives are common to the whole RIPPLES project.

The ***Current-NDC (or 2°C NDC)*** scenario is consistent with NDCs for the 2020-2030 period and follow the same pathway as the BAU scenario. In the second period (2030-2050), countries need to implement a very strong climate policy to comply with the 1,130 $GtCO_2$ carbon budget established for the period between 2010 and 2050. CO_2 emissions from energy use and industrial process reach 40 $GtCO_2$ in 2030. For 2020-2030, national implicit carbon values are the same as in the BAU scenario. For the second period, 2030-2050, national implicit carbon values increase sharply and they all converge towards $680/tCO2 in 2050.

In the early action ***Enhanced NDC*** scenario (or ***2°C NDC+***), the ambition of climate policy is higher than in the 2°C NDC scenario before 2030, but the same carbon budget as in 2°C NDC is reached up to 2050. We follow the logic used in the GECO 2017 report (Kitous et al., 2017) by dividing countries and regions into three groups[5] and applying three different implicit carbon values. The carbon value for middle-income countries is half the value for high-income countries, while the carbon value for low-income countries is one quarter of this value, i.e. $520/tCO2, $260/tCO2 and $130/tCO2 in 2050. The additional 10 years for enhanced ambition between 2020 and 2030 compared to the 2°C NDC scenario have two main outcomes. First, low carbon technologies and energy efficiency have more time for implementation and to penetrate the technical and economic system at an earlier stage. This results in lower carbon dependency of the energy system after 2030, compared to the 2°C NDC scenario. Second, they lead to lower CO_2 emissions from energy use and industrial process in 2030: 27 $GtCO_2$ in 2030, compared to 40 $GtCO_2$ in the 2°C NDC scenario.

2.1.3. 1.5°C scenarios

1.5°C scenario relies on the third RIPPLES narrative. The carbon budget resulting from energy combustion and industrial process is equal to 891 $GtCO_2$ for 2010-2050, i.e. 240 $GtCO_2$ lower than in the ***2°C NDC*** and ***2°C NDC+*** scenarios. This reduction in the carbon budget requires very high implicit carbon values. The regional implicit carbon values[6] converge rapidly to 2050, a value 10 times higher than in the ***2°C NDC+*** scenario and three times as high as in the ***2°C NDC*** scenario. Moreover, GHG emissions in ***1.5°C*** for 2010-2050 require a high amount of negative emissions in the second period (2050-2100) in order to comply with the carbon budget of 370 $GtCO_2$ from energy combustion. In total, this scenario corresponds to the third illustrative pathway (P3) in the last IPCC special report on 1.5°C scenarios (IPCC, 2018).

The ***1.5°C decoupling activity (1.5°C DA)*** scenario is based on fourth RIPPLES narrative. We follow the same logic as in the "Low Energy Demand (LED)" scenario described in Grübler et al. (2018)[7] allowing for lower level of activity in all sectors than in the ***1.5°C scenario*** described above. This scenario

[5] Countries are grouped as follows: high-income countries (EU28, Switzerland, Norway and Iceland, USA, Canada, Japan, Australia, New Zealand, South Korea); middle-income countries (Turkey, Russia, Brazil, rest of South America, China and South Africa); low-income countries (rest of the world).
[6] Unit : constant 2005 US$/tCO2
[7] The article presents narratives of a 1.5°C scenario named "Low Energy Demand (LED)". It considers major transformations in energy supply through social, business and technological innovations without relying on negative emissions.

corresponds to the first illustrative pathway (P1) in IPCC report (IPCC, 2018). POLES is a partial equilibrium model and the activity levels in all sectoral demands are derived from GDP, population levels and energy demand elasticity, except for residential sector. All three variables are exogenous to the model. To build a low activity scenario, we reduce the level of demand elasticity by 50%. In the residential sector, activity level is defined in terms of surface area (m²). In the residential sector, we change exogenously the residential area per capita that converges to 30 m²/cap in 2100 in all countries and regions. This assumption is less stringent than in the LED scenario, where this level is reached as early as 2050. In other sectors, energy demand elasticity is twice as low in 2030 compared to the ***1.5°C*** scenario. This scenario adjusts carbon value in order to reach the same carbon budget as in the ***1.5°C*** scenario. The carbon value is \$818/tCO_2 in 2050, i.e. two-fifths of the carbon value reached in the ***1.5°C*** scenario.

All these characteristics relating to the carbon budget and implicit carbon values are described in the **Table 2**. The **Table 3** summarizes sectorial assumptions for both 1.5°C scenarios.

Table 3: Sectorial assumptions for 1.5°C scenarios

	Region	Carbon budget 2010-2050	Carbon value \$/tCO_2	Industry, services, agriculture Energy demand elasticity by sector i and year t		Road transport Total Gkm		Freight Total Gtkm		Residential m²/cap	
				2020	2030-2050	2030	2050	2030	2050	2030	2050
1.5°C	World	890GtCO_2	2,050	$DE_{i,t}$	$DE_{i,t}$	25,058	31,227	35,488	50,036	25	31
1.5°C DA	World	890GtCO_2	818	$DE_{i,t}$	$0.5 \times DE_{i,t}$	13,869	17,857	18,694	26,130	21	22
1.5°C	EU28	91GtCO_2	2,050	$DE_{i,t}$	$DE_{i,t}$	3,229	3,116	2,622	2,973	40	44
1.5°C DA	EU28	80GtCO_2	818	$DE_{i,t}$	$0.5 \times DE_{i,t}$	1,671	1,804	1,319	1,513	36	34

Source: POLES results

2.2. Description of Global and EU energy and carbon content in the prospective scenarios

Figures 3 and **4** show the development of primary energy consumption and CO_2 emissions worldwide and in the EU.

In the BAU scenario, global primary energy consumption increases twice as fast as the related CO_2 emissions: even without coordinated and ambitious climate policies, the CO_2 intensity of energy use improves. Global primary energy consumption is equal to 20 Gtoe in 2050 in the BAU scenario compared to 14-16 Gtoe in the 2°C scenarios and 12-13 Gtoe in the 1.5°C scenarios. At EU level, in the BAU scenario, primary energy consumption remains stable while CO_2 emissions decrease.

In terms of carbon budget, both 2°C scenarios are equivalent, by construction. The pathway of global primary energy consumption in the ***2°C NDC*** scenario can be divided into three periods after 2020:

- 10 years of growth until 2030.
- 10 years of dramatic decline in 2030-2040 due to a sharp increase in implicit carbon values.
- 10 years of slight increase, because international oil and gas prices in 2040 are half those of 2030 (Figure 5) due to a fall in oil and gas demand in all countries.

In the ***2°C NDC+*** scenario, a more ambitious climate policy starts as early as 2020. These 10 extra years of significant carbon prices allow the countries to shift to a low-carbon economy without shocks on energy markets. It is the only mitigation scenario in which primary energy consumption continues to increase after 2030 at global level.

At global level, the energy and emission pathways of the two 2°C scenarios are quite different. In 2050, primary energy consumption is 30% and 18% lower in ***2°C NDC*** and ***2°C NDC+***, respectively, compared to ***BAU,*** while CO_2 emissions are 81% and 63% lower in ***2°C NDC*** and ***2°C NDC+*** than in ***BAU***. On the other hand, at EU level, primary energy consumption and CO_2 emissions for the two 2°C scenarios are less contrasted. Primary energy consumption is 18% (14%) lower in the ***NDC*** (***NDC+***) scenarios than in ***BAU***, and the same goes for CO_2 emissions: 72% (64%).

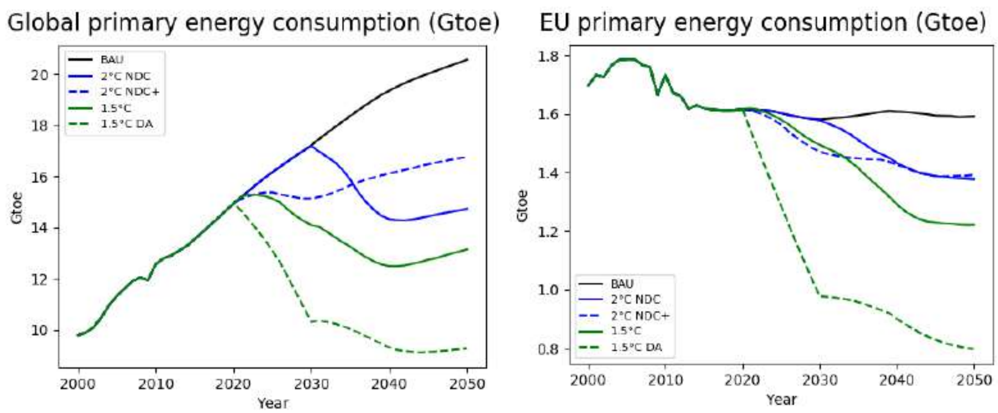
The most noteworthy aspect of 1.5°C scenarios is the difference in CO_2 emissions at global and EU level. At global level, CO_2 emissions stay throughout the entire period 2020-50 below emission pathways of the 2°C scenario and reach -0.7 $GtCO_2$ in ***1.5°C*** and -0.2 $GtCO_2$ in ***1.5°C DA*** in 2050. In the EU, emissions remain positive and are only 25-50% lower than in the 2°C scenarios. This modelling result has one main explanation: the limited potential of biomass in the EU and so the limited potential for implementing negative emissions in EU. As we will see in the following sections, the contribution of bioenergy with carbon capture and storage (BECCS) to the energy mix in Europe is low compared to other countries and regions.

However, it is important not to interpret these emission trajectories for the EU as an equitable distribution of effort. First, these trajectories result from the assumptions made in the construction of the 1.5°C scenarios, using a uniform global carbon price, which minimises the mitigation cost at the global level. Thus, this in no way prejudges the "burden sharing" between countries and in particular the EU's effort, since the emission trajectories produced in these simulations show the domestic reductions under this cost minimization assumption without taking into account an EU contribution to international financing for emission reductions or to the purchase of emission reductions in other countries.

The second important point in the 1.5°C scenarios is the drastic reduction in primary energy consumption and CO_2 emissions in the ***1.5°C Decoupling Activity*** scenario between 2020 and 2030. This decrease is almost exclusively due to the 50% reduction in activity level[8] during this period. Thus, the implicit carbon values have a low impact on energy consumption and related CO_2 emissions. Even if the implicit carbon values are 2.5 times lower in ***1.5°C DA*** than in ***1.5°C***, CO_2 emissions are only 35% higher. The implicit carbon values in ***1.5°C DA*** are also lower than in ***2°C NDC+*** for the same period. However, they do not lead to higher energy consumption and CO_2 emissions. On the contrary, they are 28% lower in ***1.5°C DA*** compared to ***2°C NDC+*** in 2030.

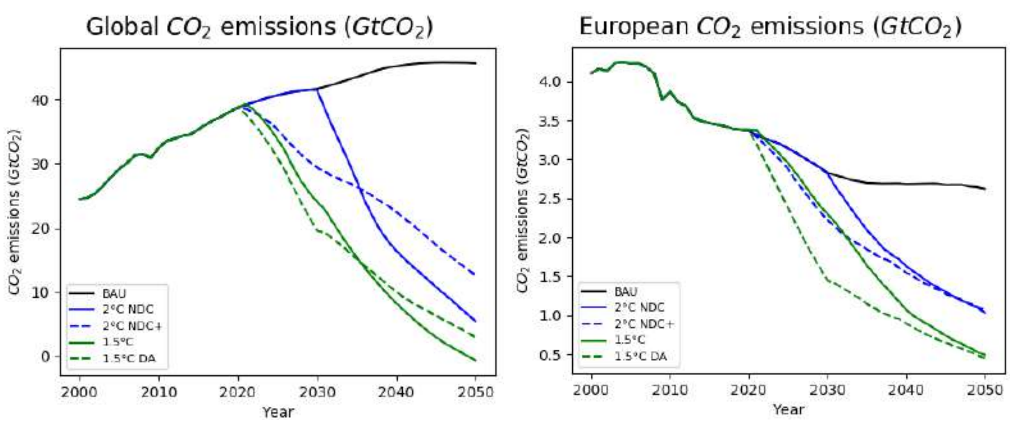
[8] Activity level related to energy consumption. As explained in previous section, this reduction is implemented exogenously to the model.

Figure 3: Primary energy consumption



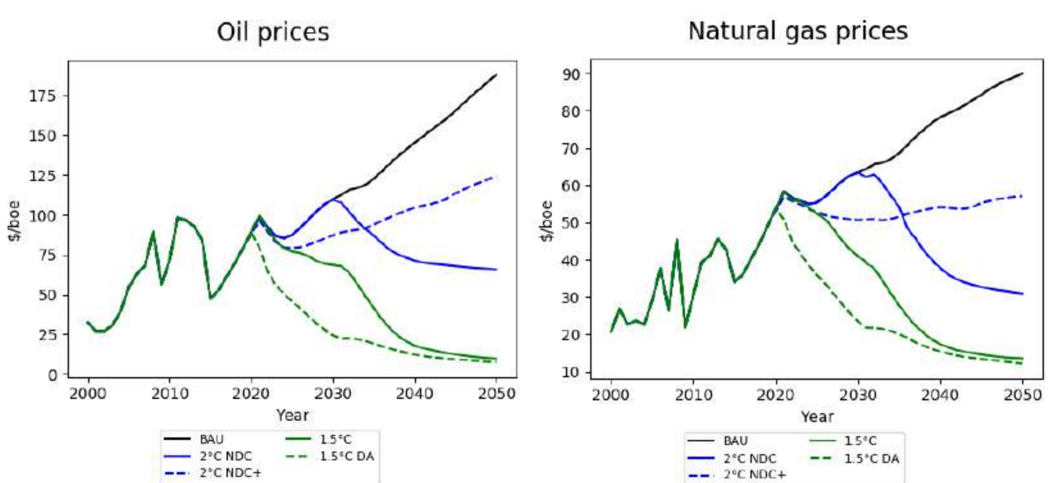
Source: POLES results

Figure 4: CO_2 emissions



Source: POLES results

Figure 5: International oil and natural gas prices



Source: POLES results

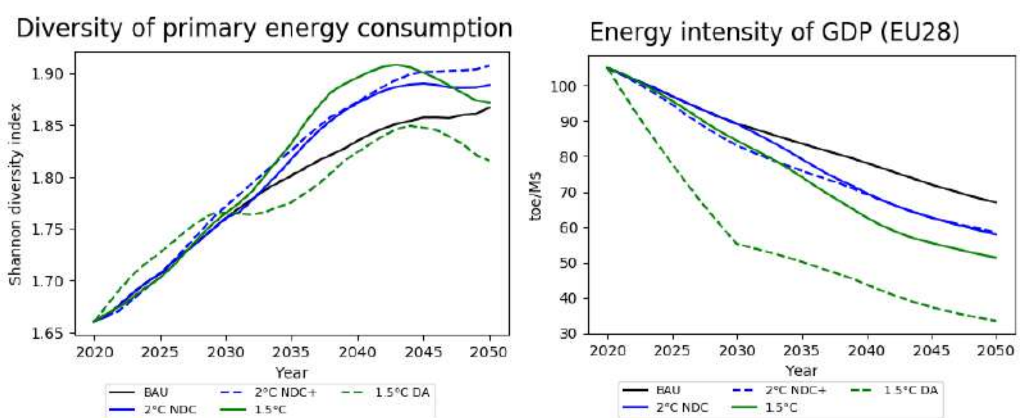
3. Impact of mitigation scenarios on EU energy security

3.1. Energy availability

In this section, we analyse the availability of energy in the EU via five indicators: diversity of primary energy sources, energy intensity of the economy and dependency on coal, natural gas and oil imports.

The **diversity of primary energy sources** is measured by the **Shannon Diversity Index (SDI)**. **Figure 6** shows changes in the SDI measuring the diversity of the energy mix in the EU (for the energy mix see Figures 33-34 in the appendices). Diversity improves over time in all scenarios until 2050, except in the 1.5°C scenarios, where diversity decreases from 2045 onwards.

Figure 6: Diversity of primary energy sources and energy intensity of GDP in the EU



Source: POLES results

Diversity is always higher in the 2°C scenarios than in the BAU. This also applies to 1.5°C scenario until 2043. On the contrary, in the 1.5°C DA scenario, the diversity is higher at the beginning of the period (2020-2030) because the early reduction of activity level reduces the share of fossil fuels in the energy mix, leading to a more balanced energy mix. After 2043, diversity in all 1.5°C scenarios starts to decrease due to a high penetration of renewable sources and the reduction in fossil fuel consumption. In 2050, 1.5°C scenario's diversity reaches the BAU level, while SDI in 1.5°C DA scenario is below the BAU scenario SDI.

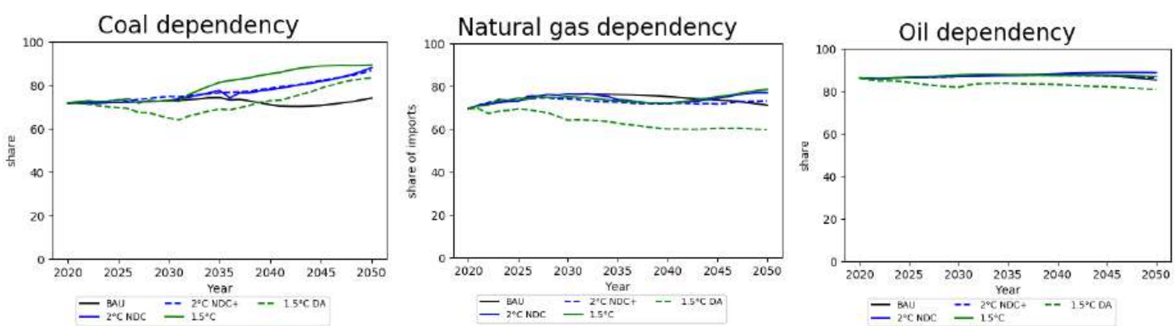
Using SDI to evaluate diversity, the two scenarios with the highest level of diversity in 2050 are 2°C NDC and 2°C NDC+. In these scenarios, the use of fossil fuels is not marginal and climate policies encourage the deployment of low-carbon sources contrary to 1.5°C where countries have to rely a lot on renewable sources to meet policy's objectives.

The second indicator, **energy intensity of GDP PPP**, measures the whole economy's dependency on energy. Not surprisingly, energy intensity is below BAU levels in all of the mitigation scenarios. However, there is no significant difference between the 2°C NDC+ scenarios and 1.5°C scenario in

2020-2035 and both 2°C scenarios in 2040-2050 due to the model assumptions. This shows that the emission reductions achieved in the 2°C scenarios and 1.5°C scenario result mainly from the decarbonisation of the energy mix.

On the contrary, and by construction of sectoral activity levels, energy intensity in 1.5°C DA scenario sharply decreases from 2020. As soon as 2030, energy intensity in these scenario is already lower than the level as the energy intensity reached in 2°C scenarios in 2050. In the 1.5°C DA scenario, energy intensity is halved over the 2020-2030 period and halved again over the 2030-2050 period. The gap between the 1.5°C DA scenario and other scenarios shows the relatively low sensitivity in the POLES model of sectoral final energy consumption compared to the increase in final energy prices.

Figure 7: Share of coal, natural gas and oil imports in European primary energy consumption



Source: POLES results

The last three indicators measure the level of **coal, oil** and **gas imports dependency**. According to **Figure 7**, the EU continues to import on average over 80% of its oil and coal consumption in all scenarios.

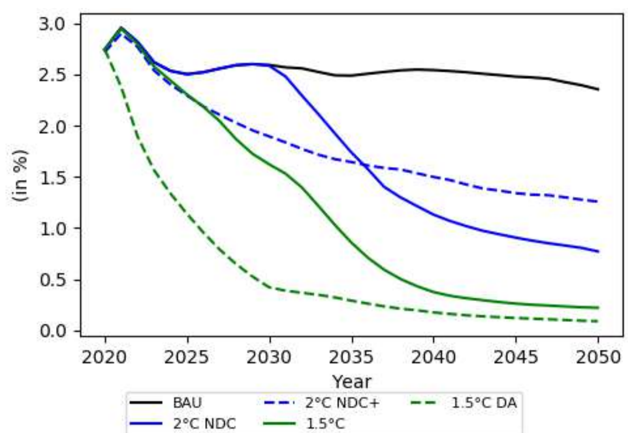
Coal import dependency decreases slightly between 2020 and 2030 in 1.5°C DA scenario. However, this decrease is temporary. Coal dependency is 7% higher in the 2°C NDC, 2°C NDC+ and 1.5°C scenarios than in the 1.5°C DA scenario. There is no significant difference between scenarios in terms of dependency on oil imports. Dependency on natural gas imports is the only one to decrease at the long-term in the 1.5°C DA scenario: the level of gas imports in natural gas consumption accounts for 60% in the 1.5°C DA scenario against 75%-80% in other scenarios. The reduction of natural gas demand in the 1.5°C DA scenario halves gas imports from Russia. Even if the coal, oil and natural gas consumption decrease in mitigation scenarios, the security of energy supply may decrease due to the high level of imports.

The high share of imports needs to be explained, as one could consider that given the much lower quantity of fossil fuel consumed in mitigation scenarios, it would be possible to reduce the share of imports, and to rely more on domestic sources. Our scenarios show that it does not happen. The first reason is the limited natural gas and oil reserves in the EU. Second, oil and natural gas extraction becomes unprofitable in mitigation scenarios due to very low international prices. It is cheaper to import them.

Such results concern the share of imports but not the quantity of fossil fuels imported. The costs of coal, oil and natural gas imports in $2005 represents 2.8% of GDP PPP $2005 in 2020 (**Figure 8**). The

import (net of exports) expenditure reaches 3% of GDP in 2023 and remains above 2.3% in the BAU scenario. On the contrary, in the 2°C NDC + scenario, the expenditure decreases to attain 50% of BAU import level in 2050. In term of total import expenditure over 2020-2050, the early action 2°C NDC+ scenario shows better savings than the 2°C NDC scenario in which, after 2030, import expenditure decreases faster than in the NDC+ scenario to compensate later implementation of implicit carbon values. Overall, the total expenditure over 2020-2050 in the NDC, NDC+, 1.5°C and 1.5°C DA scenarios is, respectively, 33%, 31%, 58% and 79% lower than in the BAU scenario.

Figure 8: EU energy net imports (in value) compared to GDP PPP



Source: POLES results

Tables 4 and **5** summarise the level of availability dimension indicators in 2030 and 2050 (best values in green bold). Energy is more available and less dependent in the 1.5°C DA scenario for both years, which shows the best values for five out of the six indicators. The main positive impact of mitigation scenarios concerns the share of energy imports in the GDP PPP, particularly in 1.5°C scenarios.

Such results nevertheless raise questions about the relevance of these indicators for assessing energy availability. Indeed, the diversity of the energy mix (assessed with the SDI indicator) decreases in the mitigation scenarios and this is all the more so for the 1.5°C scenarios due to the massive penetration of renewable energies. In less ambitious mitigation scenarios, the energy diversity is less impacted because a mix composed by fossil fuels and renewables persists. The corollary question is therefore: is it better in terms of security of supply to have a diversified energy mix based on renewables and fossil fuels (and therefore on energy imports for Europe), or to have a mix based almost exclusively on renewable energies, which have a strong potential for job creation at local level as macroeconomic assessments show.

Nuances must also be made with regard to the use of the import share for each fossil energy consumed. Indeed, vulnerability is not the same, considering a given import share for a fossil energy, in two scenarios, if in one of these scenarios, 10 times more of this fossil energy is consumed than in the other.

Table 4: Comparison of availability indicators in 2030 (EU28)

	SDI PE	*Energy intensity of GDP (toe/M$)*	*Coal imports*	*Gas imports*	*Oil imports*	Share of energy imports/GDP
BAU	1.78	89.27	73%	76%	87%	2.6%
2°C NDC	1.79	89.27	73%	76%	87%	2.6%
2°C NDC+	**1.81**	83.14	75%	74%	87%	1.9%
1.5°C	1.80	83.14	73%	75%	88%	**1.6%**
1.5°C DA	1.77	**54.34**	**65%**	**64%**	**82%**	**0.4%**

Source: POLES results

Table 5: Comparison of availability indicators in 2050 (EU28)

	SDI PE	*Energy intensity of GDP (toe/M$)*	*Coal imports*	*Gas imports*	*Oil imports*	Share of energy imports/GDP
BAU	1.87	66.99	**81%**	71%	86%	2.4%
2°C NDC	**1.89**	57.94	90%	77%	**83%**	**0.8%**
2°C NDC+	**1.91**	58.59	92%	73%	**84%**	**1.3%**
1.5°C	1.87	51.41	89%	79%	87%	**0.2%**
1.5°C DA	1.82	**33.67**	**83%**	**60%**	**81%**	**0.1%**

Source: POLES results

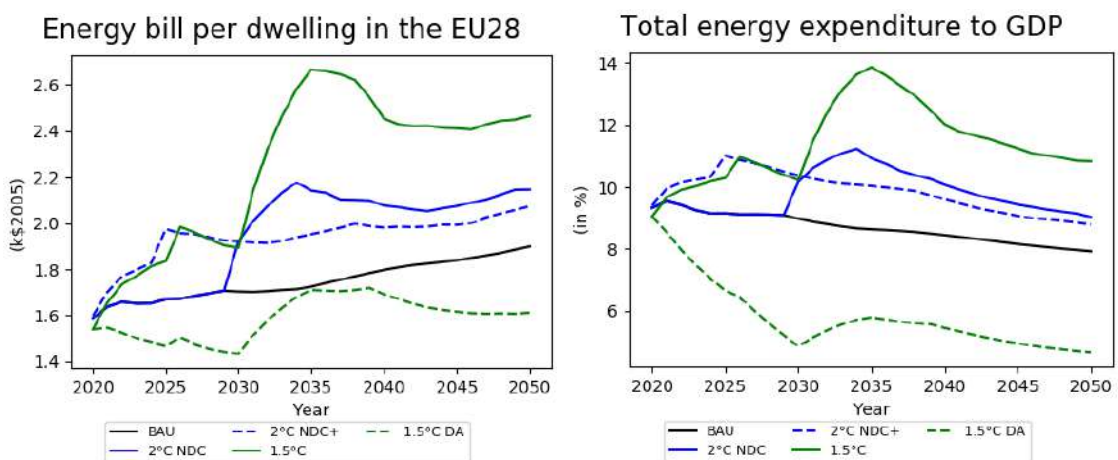
3.2. Affordability

Figure 9 (left-hand graph) shows the level of **energy bill per dwelling**. In the BAU scenario, the yearly energy bill per dwelling increases from $1,600 to $1,900 over 2020-2050, i.e. an increase of 18%. That is lower than the increase of GDP $2005 and GDP PPP $2005 on the same period (+55%). In the three mitigation scenarios without a decoupling activity, the energy bill per dwelling increases sharply due to the increase in implicit carbon values. The implicit carbon values are so high that the decrease of energy demand and the fall of international energy prices do not compensate for this increase and final energy prices increase. In 2°C NDC, the energy bill increases by 35% over 2030-2035 and then remains stable until 2050. The increase is lower in 2°C NDC+ scenario than in 2°C NDC: +23% from 2020 to 2025 and +30% over 2020-2050. Even if the bill per dwelling increases in both 2°C scenarios, the GDP increases faster. Thus, the share of energy bill for households in their income decrease under the assumption that household income follows the same evolution as GDP. There is a positive outcome of such mitigation scenarios. Unlike the 2°C scenarios, the raise of expenditure in the 1.5°C is higher than the increase of GDP: +60% for energy bill per dwelling against +55% for GDP. The share of the energy bill for households in their income increases. This is the only mitigation scenario considered here to present such an outcome.

In the 1.5°C DA scenario, the energy bill per dwelling is lower than in the BAU scenario in 2050 thanks to the reduction of the activity level in the residential sector (number if square meters). This scenario is the only one in which household energy bill in dwellings is, all over the period, lower than in the BAU scenario.

The second indicator of affordability is the share of total energy expenditure in $2005 (households and economic sectors) in GDP PPP $2005 (**Figure 9** right-hand side). The ratio is 9% in 2020 and decreases slowly in the BAU scenario to reach 8% of GDP in 2050. At the long-term, the high implicit carbon values do not impact the share of energy expenditure in GDP in 2°C scenarios: the share increases at the beginning due to the increase of implicit carbon values and then the share decreases to reach the level of 2020 in 2050. The 1.5°C scenario is the only one in which the energy expenditure increases as a percentage of GDP. This share reaches 14% of GDP in 2035, followed by a decrease to 11% in 2050. Finally, in 1.5°C DA, the share of energy expenditure in GDP decreases from 9% in 2020 to 5% in 2050 due to the drop of activity level related to energy. As a conclusion, the high implicit carbon values in mitigation scenarios do not deteriorate the energy affordability of the economy on the long term, but particular attention should be paid in the medium term in scenarios with very high carbon value levels, if the increase in final energy prices is not quickly offset by a decrease in energy demand in all economic sectors.

Figure 9: Energy expenditure per dwelling (left) and share of energy expenditure in GDP (right) in the EU



Source: POLES results

1.5°C DA is the best scenario from an affordability point of view, followed by 2°C NDC+. The enhanced action pre-2030 in the 2°C NDC+ scenario results on more affordable energy prices in 2050 compared to 2°C NDC in which climate action starts in 2030.

Such results must be considered bearing in mind that the carbon value is a proxy for sectoral climate policies. In terms of policy instruments, results from the modelling exercise suggests that to overcome the social acceptability problems complementary tools such as performance standards or niche-market requirements for low emission options should accompany carbon pricing (Jaccard, 2016; Mathy et al., 2016).

On the contrary, in the 1.5°C DA scenario, the energy consumption reductions induced by the scenario assumptions of these "decoupling activity" scenario are achieved "free of charge" by changes in behaviour. It would therefore be of crucial importance for the representation of such ambitious scenarios to better understand the mechanisms of economic policies, regulation and infrastructure in behavioural change, and the underlying economic and welfare costs.

3.3. Natural gas

At present, the EU is highly dependent on fossil fuel imports, which amount to 90% for crude oil, 66% for natural gas, 42% for solid fuels and 40% for nuclear energy. Natural gas imports are the most vulnerable due to the combined effect of high dependency in some countries, the nature of contracts and political tensions with some importers. In addition, Russia provides over 50% of natural gas consumption to seven EU countries and is the sole supplier in six others[9]. For these reasons, we have paid special attention to the security of natural gas consumption in the EU.

The POLES model sorts countries and regions into 14 natural gas markets. The European gas market includes the EU countries, Norway, Switzerland, Iceland, Turkey and the Balkan states. The model assumes the share of each importer is the same in each country on this market. This is a strong modelling assumption, but not an observed fact. International gas prices are endogenously computed to adjust supply and demand.

We rely on five indicators to measure energy security of natural gas imports in the EU: the overall dependency rate, the share of Russian gas, international prices and the importer mix measured by the SDI and HHI. EU natural gas consumption decreases in all mitigation scenarios and in all sectors: by 27-30% in the 2°C scenarios and by 40% in 1.5°C scenario compared to the BAU scenario in 2050 (**Figure 10**). The reduction in final energy demand doubles the decrease in consumption: -64% in 1.5°C DA scenario in 2050 compared to BAU. Moreover, **dependency on gas imports** in 1.5°C DA scenario is lower than in other scenarios, in terms of both share and volume of imports. In fact, the share of imports in 2°C NDC, 2°C NDC+ and 1.5°C is similar to BAU or higher (73-79% compared to 71% in BAU), while the share of imports in 1.5°C DA scenario is 60% only. We can see that domestic production cannot replace all imports even in the 1.5°C DA scenario in which the gas consumption is 2.7 times lower in 2050 compared to BAU scenario. First, we observe that the BAU scenario is the most advantageous scenario for natural gas producers (90 $2005/boe in 2050), while the prices are around 12-14 $2005/boe in the 1.5°C scenarios. Such prices spur domestic producers to reduce gas extraction from 106 Mtoe in the BAU to 75-81 Mtoe in the 2°C and to 59-65 Mtoe in the 1.5°C scenarios. Second, domestic gas production cannot cover European natural gas demand. The natural gas demand is equal to 155 Mtoe in the 1.5°C DA scenario, there is more than EU gas production in the BAU scenario.

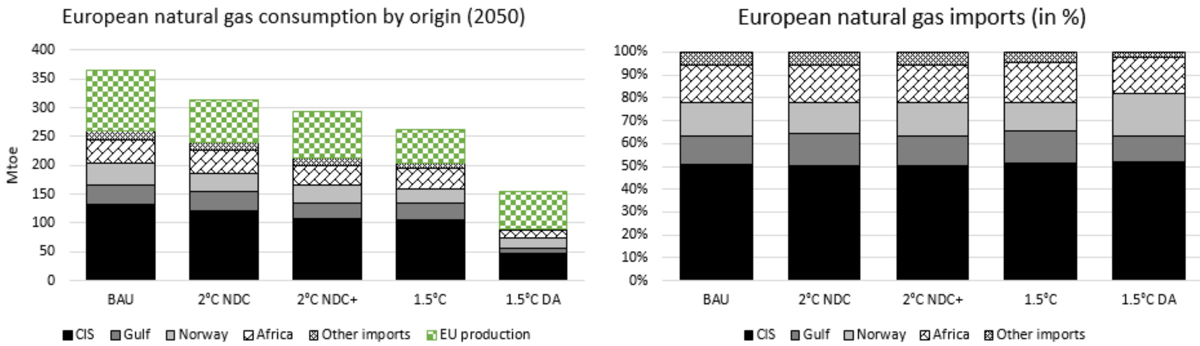
There are 34 natural gas exporters in POLES. Ten of them exported natural gas to the EU in 2010. The number of EU importers increases in all prospective scenarios from 10 in 2010 to 21-28 in 2050. This is principally due to the model assumption about a single gas market for EU countries, which is not the case now due to the physical strains, the lack of EU single market for natural gas and the different long-term contracts between several EU countries and Russia. Even if number of natural gas suppliers increases, 75-93% of gas imports come from four countries only: Russia, Qatar, Norway and Algeria. We use **SDI** and **HHI** to measure the diversity of importers in different scenarios. Both indicators show that implicit carbon values do not improve the diversity of importers in the EU. Furthermore, diversity decreases in the 1.5°C DA scenario. Even if consumption is half that of BAU, half of this consumption depends on Russian gas. It reflects also that Russian natural gas is cheaper than other imports.

[9] Czech Republic, Slovenia, Greece, Poland, Austria, Hungary, Germany, Estonia, Latvia, Lithuania, Bulgaria, Slovakia and Finland

The last indicator, **international gas prices**, measures tension on gas markets. Here, we suppose that high international prices reduce the bargaining power of EU countries with importers, particularly in Central and Eastern Europe that relies on imports from Russia and has to pay higher price than, e.g., Germany. **Figure 5** shows movements in gas prices and **Table 6** shows the level of gas prices in 2050.

In the BAU scenario, gas prices increase throughout the period, reaching $64/ktoe in 2050. In the enhanced 2°C NDC + scenario, international natural gas prices level off at $39/ktoe.

Figure 10: European gas consumption by production origin in 2050[10]



Source: POLES results

Table 6 summarizes the level of all indicators in 2050. We use bold green type to highlight the best values for each indicator. The only major difference between BAU and 2°C scenarios is the level of international gas prices, where 2°C scenario prices in 2050 are close to 2012 prices. A 2°C carbon value trajectory applied in NDC and NDC+ scenarios neither improves nor degrades European gas security. Regarding the 1.5°C target, the decoupling activity scenario is better than BAU in respect of three indicators: international prices, share of imports and share of Russian gas. In the case of diversity of importers, SDI diverges from HHI. The best diversity according to SDI is when all importers contribute at the same level, i.e. when their shares of imports are equal. HHI, on the other hand, penalizes a situation where one or more importers have high market shares. SDI in the 1.5°C DA scenario is 1.68 instead of 1.9, because the share of imports from Norway increases from 11-12% to 18%, while the share of "other importers" decreases from 4-6% to 1%. However, Norway is a neighbouring country and a reliable partner of the EU. A higher share of imports from Norway is more convenient for the EU than higher imports from other countries.

Table 6: Comparison of natural gas security indicators in 2050 (EU28)

	Price ($/ktoe)	***HHI***	***SDI***	***Share of imports***	***Russian gas***
BAU	64	2717	**1.92**	71%	48%
2°C NDC	27	**2629**	**1.94**	77%	47%
2°C NDC+	39	**2676**	**1.91**	73%	48%
1.5°C	**14**	2734	**1.88**	79%	49%
1.5°C DA	**12**	3085	1.68	**60%**	51%

Source: POLES results

[10] CIS stands for Commonwealth of Independent States, the union of 12 ex-URSS countries.

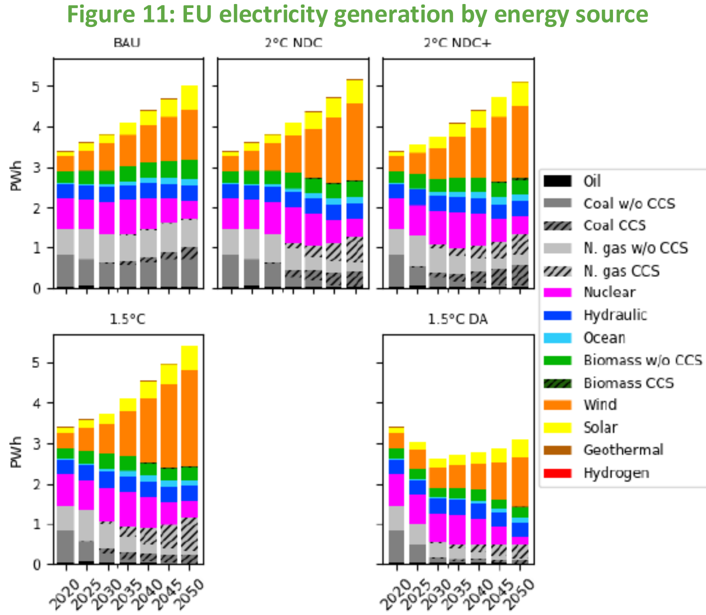
Once again, these results must be balanced by the overall decrease in the quantities consumed and imported, in mitigation scenarios, but more particularly in 1.5°C scenarios.

3.4. Electricity generation

Figure 11 shows the development of the European electricity mix in the six scenarios (for more details, see Figures 20-21 in the appendices). **Table 7** summarises electricity security indicators. As end-use electrification is a major decarbonisation wedge, the increasing total electricity consumption is similar in the BAU, 2°C and 1.5°Cscenarios, reaching around 5 PWh in 2050. This results from the combined effect of the decrease in primary energy consumption in mitigation scenarios, compensated by the increase of the share of electricity in final consumption (from 38% in the BAU scenario to 44-54% in mitigation scenarios). On the other hand, electricity consumption is stable in 1.5°C DA scenario: 3 PWh in 2050, because the effect of the decrease in energy consumption is higher than the electrification effect.

The share of all renewables (RES) rises to 69% in 2050 in the BAU scenario, 74% in 2°C scenarios and 80-91% in 1.5°C scenarios. In mitigation scenarios, fossil fuel consumption decreases from 43% in 2020 to 10-30% in 2050, gradually switching from coal and gas power plants without CCS to power plants with CCS. By 2050, all coal power plants are fitted with CCS. The use of GGS instead of gas power plants without CCS depends on the scenario. In 2°C scenarios, 50-70% of gas plants are fitted with CCS in 2050, while in 1.5°C scenarios, almost 100% of gas plants have CCS.

Figure 11: EU electricity generation by energy source



Source: POLES results

BECCS technology also emerges at global level after 2030, but there is almost no BECCS in the EU countries. BECCS is the only negative-emission technology that is expected to become competitive by the end of the century with high implicit carbon values[11]. The reason for the limited development of

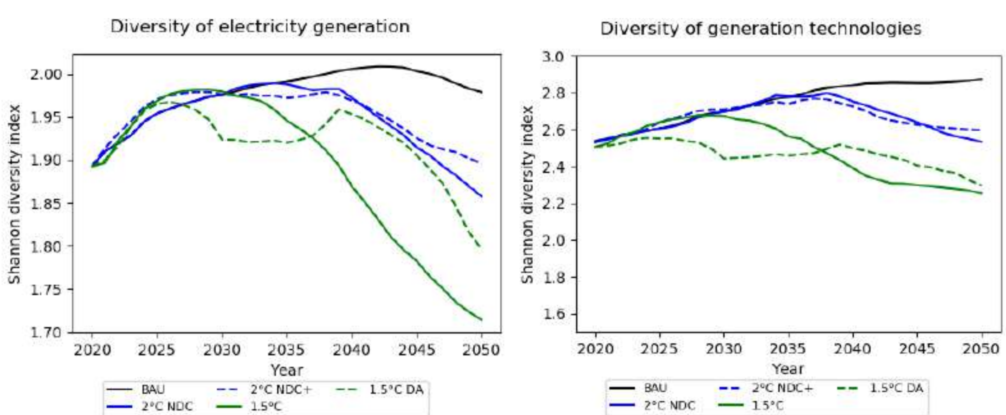
[11] Compared to other technologies such as Direct Air Capture

BECCS in Europe in mitigation scenarios is the limited biomass potential in the EU and the increasing demand in the rest of the world. In the EU, the amount of biomass used to generate power increases by 28% at the most between 2030 and 2050. At global level, on the other hand, the electricity generation from biomass is 3-6 times higher in 2050 than in 2030, while the share of BECCS in biomass generation is between 43% and 78% in 2050.

We use two SDI indicators to evaluate the electricity generation mix. **Diversity of energy sources in electricity generation** remains stable in the BAU scenario and decreases slightly in the two 2°C scenarios and in the 1.5°C DA scenario (**Figure 12**, left-hand graph). On the other hand, diversity in the 1.5°C scenario is 15-20% below the BAU level. Such figures are a direct result of the increase in the share of renewables in the energy mix, particularly in the 2°C scenarios and even more so in the 1.5°C DA scenario.

The second indicator measures the **diversity of technologies used to generate electricity**. There are 38 technologies in the POLES model, 20 of which were already used in the EU to produce electricity in 2010. This figure increases in all scenarios (between 27 and 35) up to 2050. **Figure 12** (right-hand graph) shows SDI for technologies. As for energy sources, the highest SDI is in the BAU scenario. Diversity of technologies in the mitigation scenarios starts to decrease in 2035 for the 2°C scenarios, in 2027 for the 1.5°C scenario and in 2023 for the 1.5°C DA scenario. These developments are logical, since the goal of climate policies is to reduce the use of fossil fuel plants and increase the share of renewables. The version of POLES used for this analysis does not include smart grids and some other technologies like as grid storage. A version of the model with even more low carbon technologies would increase the diversity induced by mitigation policies.

Figure 12: Diversity of electricity mix



Source: POLES results

Not surprisingly, **the share of variable renewables** (VRE, i.e. solar and wind) increases from 15% in 2020 to 30%-63% in 2050. Such results are of course dependent upon technology costs, and learning rates assumptions. A more detailed analysis may require a sensitivity study on these parameters. Research carried out in Germany and France suggests that, with current demand profiles, when VRE accounts for more than 40% of output, significant surplus production starts occurring (Grand *et al.*, 2014). However, such results are country specific and should not be generalized. Nevertheless, in our scenarios, the share of VRE exceeds 40% in the 2°C scenarios after 2042 and in the 1.5°C scenarios

after 2038 to attain 63% in the 1.5°C scenario and around 50% in all other mitigation scenario. Even if such levels are higher than 40%, it is far from 80-100% of VRE in electricity generation.

In conclusion, the main stumbling block to energy security issues for the electricity sector is the diversity of the production mix, and particular attention should be paid to the level of penetration of VRE in the technology mix for power generation.

A complete analysis of the network stability issues would require the integration of a complete representation of the network at European level and of network management technologies into the modelling.

Table 7: Comparison of electricity security indicators in 2050

	Energy SDI	*Technology SDI*	*VRE share*	*RES share*
BAU	2.00	2.87	30%	69%
2°C NDC	1.95	2.53	35%	74%
2°C NDC+	1.97	2.60	36%	74%
1.5°C	1.71	2.25	55%	80%
1.5°C DA	1.79	2.29	53%	86%

Source: POLES results

3.5. Concluding remarks

In **Section 3,** we have analysed energy security at EU level relying on 13 indicators.

In terms of availability, three indicators out of six are improved in the mitigation scenarios. The first is energy intensity of GDP PPP, which represents the EU economy's dependency on energy. However, this is a direct result of mitigation. Energy decarbonisation is the main driver of the decrease in energy intensity in non-low activity scenarios. The "decoupling activity" assumption in 1.5°C DA scenario leads to an additional huge decrease in energy consumption. The second concerns, in the case of the 1.5°C scenario, the reduction in the share of natural gas imports from 76%-81% in other scenarios to 60% in the 1.5°C DA without degrading other indicators. The main positive outcome concerns the very significant decrease in the energy bill of imports. The share of fossil fuel imports in GDP PPP is twice lower in 2°C NDC+ scenario than in the BAU scenario. This share becomes close to zero in the 1.5°C scenarios.

Three other indicators, diversity of primary energy consumption and the share of coal and oil imports in consumption, remain comparable to BAU scenario.

Concerning affordability, two indicators used in this study show that the affordability is either similar to the BAU scenario or improved. First, implicit carbon values lead to an increase of energy bills in dwellings. However, if we compare the energy bill to the raise of GDP PPP on the same period, the GDP increases faster. The energy in dwellings becomes more affordable in all mitigation scenario, except in the 1.5°C scenario. In this scenario, the level of GDP increases by 55%, while the energy bill increased by 60% in 2050. Second, the share of total energy expenditure (households + economic sectors) in GDP PPP represents 8%-10% in 2050 in the BAU and in the 2°C scenarios, i.e. the same level as in 2020.

The share is twice lower in the 1.5°C DA scenario than in the BAU. As for the energy bill per dwelling, the second indicator increases only in the 1.5°C scenario and is relatively small: from 9% in 2020 to 11% in 2050. Once again, 1.5°C DA is the best scenario among mitigation scenarios.

At this stage, it would be necessary to deepen the evaluation work on two dimensions: the challenges of fuel poverty and, beyond the implicit carbon values considered as proxies for climate policies, to better understand the impact of both price and non-price sectoral policies, on final prices and on consumer behaviour.

Unlike other forms of final energy, electricity is probably the only one whose consumption levels are likely to increase under ambitious mitigation scenarios. Therefore, the power sector poses specific energy security challenges that are rarely studied in the context of scenarios without climate policies or with moderate policies. No mitigation scenario shows an improvement in energy security indicators related to the electricity sector compared to the BAU scenario. The large penetration of VRE deteriorates energy diversity, but the VRE share reach at most 63% (in the 1.5°C scenario). Further research should evaluate if such levels only involve a limited stake in terms of grid stability.

Overall, at EU aggregated level, implicit carbon values consistent with 2°C and 1.5°C objectives improve energy security in different areas. The main outcome in term of energy security of ambitious climate policy is a decrease in energy consumption, which allows economies to reduce the quantity and the value of energy imports. Nevertheless, issues regarding affordability of households and energy costs in economic sectors should be central to scenario assessments that are consistent with the long-term objective of the Paris Agreement. This applies in particular in our analysis to 2°C NDC+ and 1.5°C that consider unchanged behaviour and high implicit carbon values.

At this stage, the assessment allows us to study energy security issues only for the EU at aggregate level without taking into account the specificities of each of its constituent countries. In the following, we analyse the consequences of the scenarios at the level of European countries, as well as for some countries such as Norway, USA, Canada, China, India, Brazil and South Africa.

4. Energy security: country analysis (EU and major non-EU countries)

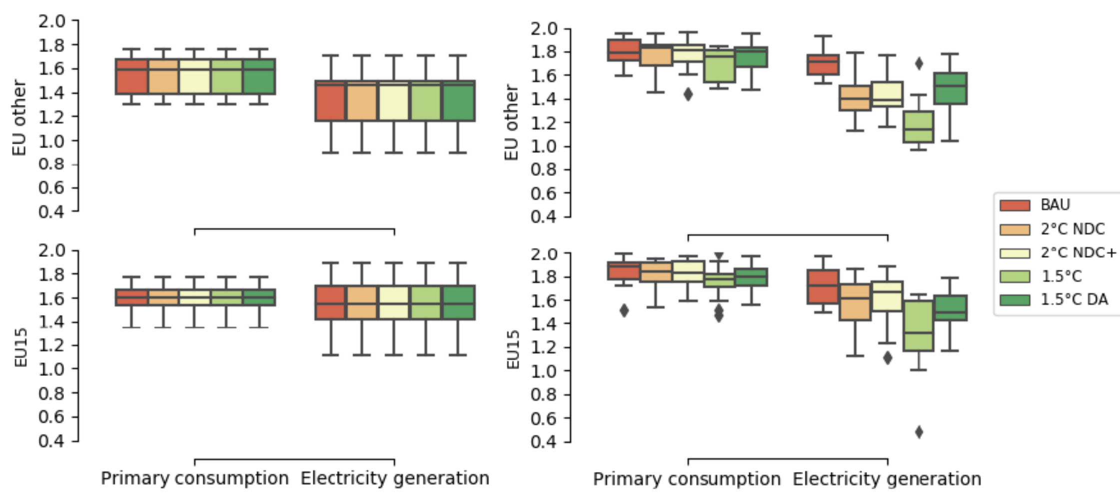
4.1. Energy availability

The European **primary energy SDI** increases in all scenarios between 2020 and 2050, on average from 1.5 in 2020 to 1.8 in 2050 (BAU). **Figure 13** shows the dispersion of primary energy mix SDI within EU countries and gives more detail than the simple average at the EU level. First, the median of SDI is slightly higher than the average. For example, in all 1.5°C scenarios, at the end of the period, the SDI is 1.76 or higher for a half of EU countries, while the average index is only 1.70. The boxplot also shows that in the mitigation scenarios the dispersion of index is higher than in the BAU. In UK, Bulgaria, Italy, Belgium, the Netherlands and Hungary, the high implicit carbon values improve the diversity of primary energy consumption in two 2°C and 1.5 scenarios compared to the BAU. The common point of all these countries is a very high share of fossil fuels in energy mix in 2020 or/and the possibility to rely on domestic production. On the contrary, in Germany, Denmark, Czech Republic, Baltic countries and Ireland, the SDI is around 1.5 in the 1.5°C scenario against 1.6-1.8 in the BAU. The similar pattern of these countries is a very high share of solar and wind energy in primary energy consumption. As solar

and wind energy are used only in electricity generation, it is also interesting to compare both the SDI of primary energy consumption and the SDI of electricity generation. We can observe on the **Figure 13**, that the diversity of electricity generation is particularly low in the 1.5°C scenario because of the high share of renewables that reduce the diversity of the energy mix in electricity and, probably, the stability of the grid. We will focus on it in the next sub section.

Outside the EU, we observe the same features. In the countries with a high share of fossil fuels in 2020 (US, China, Russia and South Africa), the SDI of primary energy consumption is higher in the 2 °C and even for some countries in the 1.5°C scenarios than in the BAU. The SDI is low in the case of countries with high share of renewables (Norway and South Korea).

Figure 13: Boxplot of energy diversity for EU countries in 2020 (left) and 2050 (right)



Source: POLES results

The next three indicators are **coal, natural gas and oil import dependency** (**Figure 14**, left-hand graph). In 2020, the share of oil imports is 100% for half of the EU countries and 80-100% for the other half. There is also very high dependency on coal imports, except for EU coal producers. The situation in 2020 is better for natural gas consumption in EU15: imports account for 90-100% in half of the EU countries and 50-70% in a quarter of the countries. Non-EU15 countries are more dependent on gas imports.

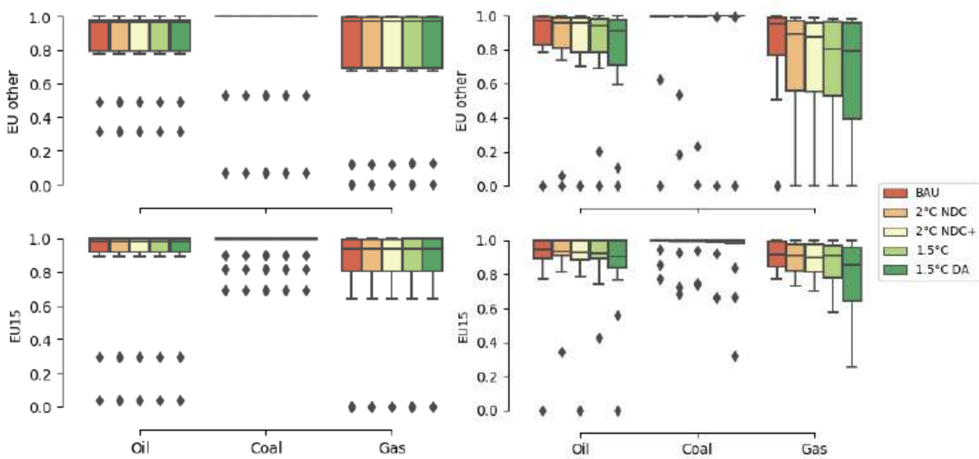
Figure 14 (right-hand graph) presents the dispersion of import dependency in 2050 by scenario. The level of coal dependency remains the same as in 2020, but oil and natural gas dependency decreases by 2050 for some countries, especially in mitigation scenarios. The results presented in the previous section show that the share of oil imports in the EU remains high. However, it is clear that this is not the case for all countries. Oil dependency decreases more sharply in non-EU15 countries than in EU15. Among non-European countries, dependency on oil imports decreases in USA and China in all 1.5°C scenarios and in India in the 1.5°C DA scenario.

Regarding EU15, the median dependency on natural gas imports in 2050 is comparable to the figure observed in 2020 in the BAU, 2°C NDC, 2°C NDC+ and both 1.5°C scenarios. For half of the countries, strong climate policy does not improve the situation. However, the boxplot shows that, for the other

half, the share of gas imports decreases from 60%-90% to 55%-85% and 30-80% respectively in the 1.5°C and 1.5°C DA scenarios.

For other EU countries, the reduction in gas import dependency is greater than in EU15. This is due to a single European gas market in 2050. In 1.5°C and 1.5°C DA scenarios, the share of gas imports in gas consumption is only 0-50% versus 70-90% in the BAU and 2°C scenarios.

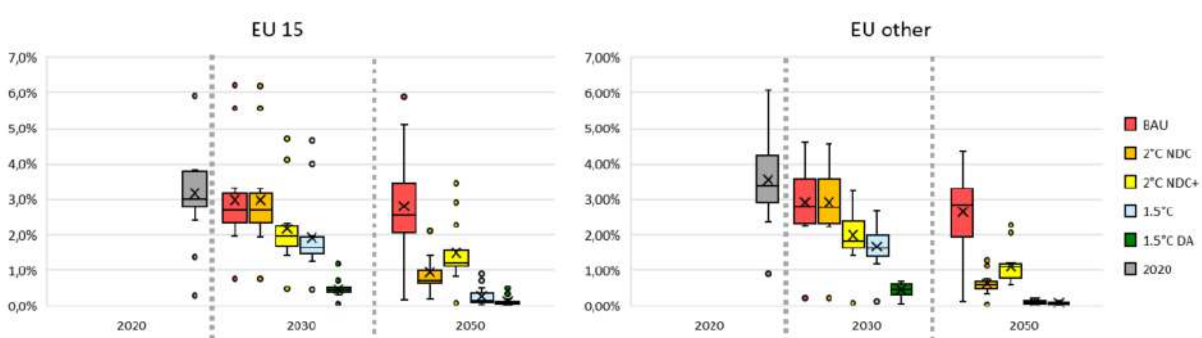
Figure 14: Boxplot of EU countries' import dependency in 2020 (left) and 2050 (right)



Source: POLES results

As in the **Section 3.1**, the share of imports in total consumption should be compared to **the import expenditure**. **Figure 15** shows the value of net energy imports compared to GDP PPP both for the EU15 (left-hand side) and for the rest of EU countries (right-hand side). The share of imports in GDP decreases with the increase of implicit carbon values, especially in 2050. In the EU15, the share is below 2% in the 2°C scenarios and close to zero in 1.5°C scenarios. The share of import expenditure is lower in other EU countries than in the EU15 in the BAU and mitigation scenarios.

Figure 15: share of net energy imports ($) in GDP PPP



Source: POLES results

The last indicator is **energy intensity of GDP**. We do not present the results here, because the reduction in energy intensity follows the same trajectory as CO_2 emission reductions.

4.2. Affordability

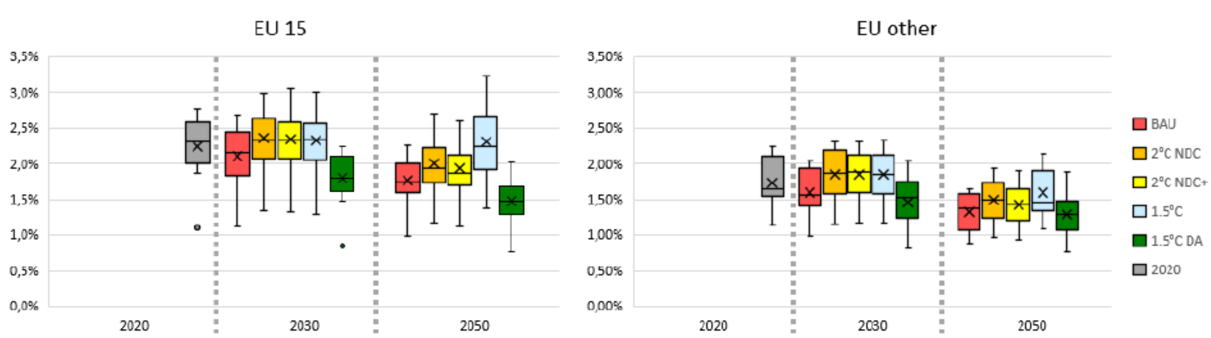
In this section, the analysis relies on two indicators of affordability. First, we use the energy expenditure in residential sector in $2005 relative to GDP PPP $2005 (**Figure 16)**. Second, we analyse the share of energy expenditure for households and all economic sectors in GDP PPP (**Figure 17**). Both indicators show similar patterns. First, the median and the average coincide. That means that the affordability indicators at EU level give an accurate description. Second, the 1.5°C scenario is the worst from an affordability point of view.

In 2030, the reduction of final energy demand leads to a moderate increase or decrease of **residential expenditure** in the EU15 countries compared to the BAU scenario at the same period or in 2020. The same would applied to 2050. Such effects are not observable in other EU countries and in the BRICS (**Table 8**). In Eastern Europe, the share of residential bill for all mitigation scenarios are either equal to the BAU or higher in both 2°C scenarios and in the 1.5°C scenario. However, the share is lower than in the EU15. As **Table 8** shows, the low final energy demand in the 1.5°C DA scenario do not always compensate the high implicit carbon values. In fact, for BRICS countries the best mitigation scenario for energy affordability in residential for households is the 2°C NDC+ in which the implicit carbon values in the middle income countries are half as high compared to high income countries.

In conclusion, we observe the lowest increase of residential energy expenditure relative to GDP in the 1.5°C DA scenario for all EU countries, except Romania, followed by BAU scenario. However, in other mitigation scenarios, the share of residential expenditure in GDP PPP is higher than in the BAU scenario. Such results indicate how important is the change of behaviour to reduce the negative impact of high implicit carbon values in dwellings.

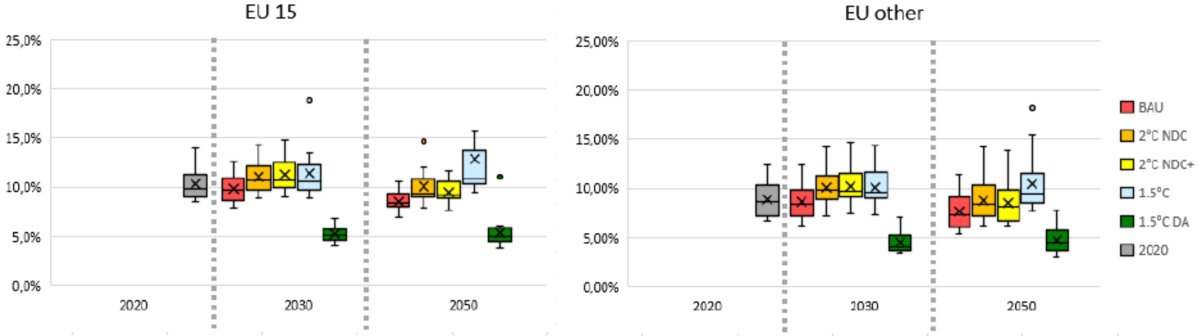
If we look on the share of **energy expenditure from all sectors** in GDP PPP, the high implicit carbon values and the reduction of energy demand allow dividing the share by two in 2050 in the 1.5°C DA scenario compared to the BAU scenario (**Table 9**). On the contrary, the 1.5°C scenario leads to an increase of the share, especially in EU15 countries. This is also true for some Eastern countries: Bulgaria, Lithuania, Slovenia, and Romania, as well as in all BRICS countries, where the share of total energy expenditure in GDP is above 10%. In all these countries, the unacceptability of high energy expenditure can jeopardise the implementation of an ambitious climate policy that would focus on raising the price of energy through the introduction of carbon taxes without accompanying policies to reduce the effects on the purchasing power and competitiveness of companies.

Figure 16: boxplots of energy expenditure in dwellings relative to GDP PPP in the EU



Source: POLES results

Figure 17: boxplots of total energy expenditure relative to GDP PPP



Source: POLES results

Table 8: Share of residential energy expenditure in GDP PPP

	BAU	2°C NDC	2°C NDC+	1.5°C	1.5°C DA
FRA	2,09%	2,31%	2,24%	2,54%	1,72%
DEU	1,74%	1,93%	1,87%	2,13%	1,48%
GBR	1,90%	2,18%	2,12%	2,66%	1,56%
BGR	1,19%	1,45%	1,38%	1,46%	1,26%
POL	0,95%	1,06%	1,00%	1,28%	0,82%
ITA	2,26%	2,71%	2,60%	3,23%	2,03%
AUT	1,74%	1,84%	1,78%	1,98%	1,29%
BEL	2,10%	2,50%	2,35%	3,01%	1,78%
LUX	0,99%	1,17%	1,12%	1,37%	0,76%
DNK	2,00%	2,13%	2,04%	2,58%	1,62%
FIN	1,56%	1,71%	1,68%	1,91%	1,35%
IRL	1,58%	1,85%	1,79%	2,25%	1,20%
NLD	1,85%	2,22%	2,13%	2,75%	1,52%
SWE	1,64%	1,71%	1,70%	1,89%	1,29%
ESP	1,60%	1,74%	1,70%	1,92%	1,39%
GRC	1,91%	2,12%	2,07%	2,41%	1,68%
PRT	1,63%	1,86%	1,79%	2,09%	1,47%
HUN	1,59%	1,65%	1,58%	1,77%	1,30%
CZE	1,38%	1,50%	1,43%	1,46%	1,02%
SVK	0,88%	0,98%	0,93%	1,09%	0,77%
EST	1,45%	1,66%	1,55%	1,87%	1,50%
LVA	1,19%	1,36%	1,31%	1,45%	1,18%
LTU	1,29%	1,41%	1,37%	1,40%	1,29%
SVN	1,66%	1,83%	1,81%	1,95%	1,44%
mlt	0,95%	1,12%	1,10%	1,23%	1,13%
cyp	1,55%	1,93%	1,91%	2,14%	1,73%
ROU	1,59%	1,81%	1,70%	2,03%	1,89%
HRV	1,56%	1,64%	1,59%	1,60%	1,48%
NOR	1,66%	1,79%	1,77%	1,91%	1,41%
USA	1,11%	1,11%	1,05%	1,17%	0,87%
CAN	1,51%	1,69%	1,59%	1,71%	1,10%
CHN	0,56%	0,99%	0,80%	1,14%	0,79%
RUS	1,10%	1,95%	1,49%	2,00%	1,67%
BRA	0,90%	1,04%	0,98%	1,18%	1,00%
IND	0,78%	1,11%	0,85%	1,38%	0,91%
ZAF	0,99%	1,18%	1,05%	1,32%	1,15%
MEX	0,61%	0,67%	0,59%	0,82%	0,63%
KOR	1,02%	1,29%	1,23%	1,55%	1,03%

Source: POLES results

Table 9: Share of total energy expenditure in GDP PPP

	BAU	2°C NDC	2°C NDC+	1.5°C	1.5°C DA
FRA	8,20%	9,09%	8,93%	10,13%	4,55%
DEU	7,62%	8,83%	8,62%	10,59%	4,52%
GBR	7,07%	7,90%	7,78%	9,47%	3,96%
BGR	7,04%	8,35%	8,13%	9,16%	4,25%
POL	6,08%	6,42%	6,30%	7,75%	3,02%
ITA	9,39%	10,86%	10,51%	13,40%	5,88%
AUT	8,40%	9,31%	9,20%	10,30%	4,54%
BEL	9,76%	11,97%	11,47%	15,61%	6,09%
LUX	9,59%	14,68%	10,63%	27,53%	11,09%
DNK	8,40%	9,26%	9,00%	10,75%	4,84%
FIN	10,55%	11,85%	11,69%	13,66%	5,99%
IRL	6,89%	7,85%	7,67%	10,04%	3,83%
NLD	8,45%	10,30%	9,94%	13,19%	5,37%
SWE	8,80%	9,95%	9,70%	10,75%	4,95%
ESP	8,08%	9,04%	8,96%	10,78%	4,68%
GRC	8,18%	9,30%	8,89%	12,35%	5,23%
PRT	8,87%	10,51%	9,94%	13,85%	5,69%
HUN	6,96%	7,09%	6,94%	8,47%	3,68%
CZE	7,33%	8,51%	8,17%	9,27%	3,99%
SVK	6,03%	7,33%	6,98%	8,49%	3,56%
EST	8,94%	9,56%	9,07%	11,17%	5,42%
LVA	7,53%	8,41%	8,15%	9,88%	4,57%
LTU	10,02%	11,00%	10,87%	11,89%	5,99%
SVN	9,16%	11,21%	10,53%	15,45%	6,38%
mlt	5,33%	6,24%	6,23%	7,70%	3,47%
cyp	11,38%	14,25%	13,90%	18,19%	7,75%
ROU	6,05%	7,29%	6,42%	9,56%	4,77%
HRV	7,50%	8,55%	8,25%	9,47%	4,67%
NOR	7,90%	8,84%	8,69%	10,10%	4,97%
USA	5,89%	6,71%	6,30%	7,74%	3,39%
CAN	9,36%	10,94%	10,55%	12,40%	5,44%
CHN	4,85%	7,93%	6,64%	9,82%	4,83%
RUS	6,18%	11,38%	8,74%	12,59%	7,10%
BRA	8,07%	10,74%	9,81%	12,86%	5,63%
IND	3,51%	5,14%	3,99%	6,62%	2,90%
ZAF	8,60%	9,97%	8,97%	11,74%	5,98%
MEX	5,73%	6,74%	5,56%	9,54%	3,43%
KOR	8,47%	10,79%	10,28%	13,65%	6,11%

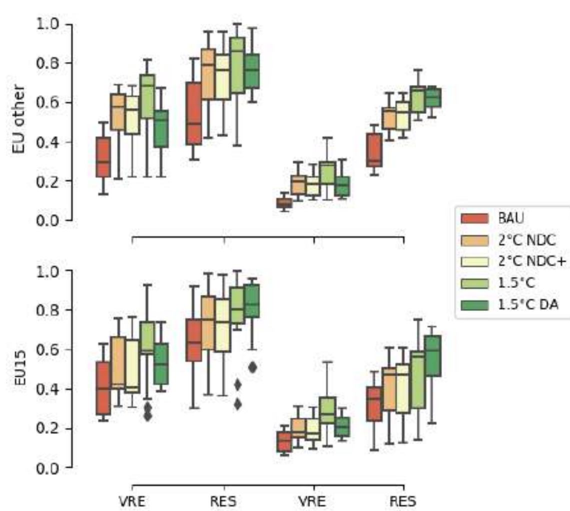
Source: POLES results

4.3. Electricity

Figure 18 shows the dispersion of the technology diversity in electricity generation. In 2020, electricity generation SDI is higher in EU15 (1.2-1.9) than in "Other EU" countries (0.8-1.8) according to scenarios. The median diversity increases in the BAU and in the 2°C scenarios between 2020 and 2050. The two 1.5°C scenarios lead to a reduced electricity mix diversity, especially in non-EU15 countries. This is a direct outcome of the rising shares of renewables in the electricity mix.

In EU15 countries, the share of VRE in electricity generation is 15-55% in BAU, 18-70% in 2°C scenarios and 40-90% in 1.5°C scenarios (**Figure 18**). The share is the highest in the 1.5°C scenario. Several differences between EU15 and other European countries are observed. First, the share of VRE remains moderate (15-40%) in BAU and 2°C scenarios and increases dramatically in 1.5°C scenarios. In fact, in half of these countries, VRE represent 70-85% of the mix. The share of VRE is over 79% in Ireland (93% in 1.5°C scenario), South Africa (all 1.5°C scenarios), Greece (84% in 1.5°C), Lithuania (82% in 1.5°C), USA (80% in 1.5°C DA) and Denmark (79% in 1.5°C DA). In these countries, electricity system stability would be an important issue in the 1.5°C scenarios.

Figure 18: Share of VRE and RES in electricity generation and primary energy consumption (2050)



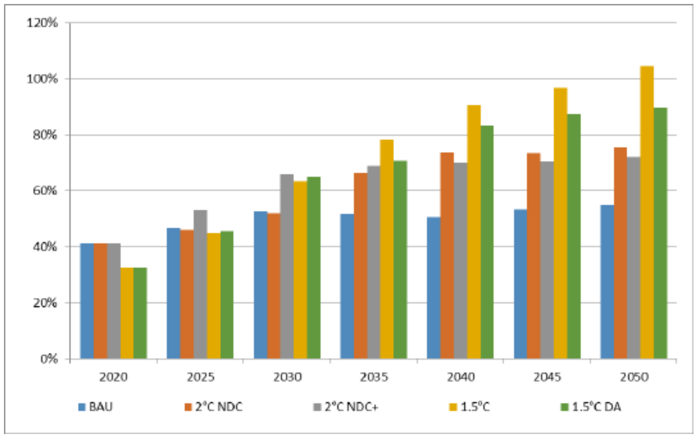
Source: POLES results

5. Case study: Bulgaria – energy security until 2050

The scenarios must be checked against the already defined, selected energy security indicators: import independency[12]; energy intensity of GDP; average energy expenditure; energy and CO_2 intensity; electricity export dependency; share of variable renewable energies (VRE) in the energy mix.

[12] The import independency rate is the inverse of dependency rate. If country export coal (oil or natural gas), then the independency rate is higher than 100%.

Figure 19: Total energy independence of Bulgaria, % (2020-2050)



Source: POLES results

As noted in the literature review of energy security indicators for Bulgaria (Stolyarova et al. 2017), the country is a net energy importer and the main local sources of energy are nuclear power (with imported Russian fuel), lignite and RES (mostly hydro-capacities).

The projections for Bulgaria's energy independence until 2050 (Figure 19) show that the largest share of energy independence in 2050 could be achieved through the 1.5°C scenario (104.6%). This is the preferable scenario, since it provides high energy independence early on and would have the largest cumulative effect on energy imports for the whole period after 2020.

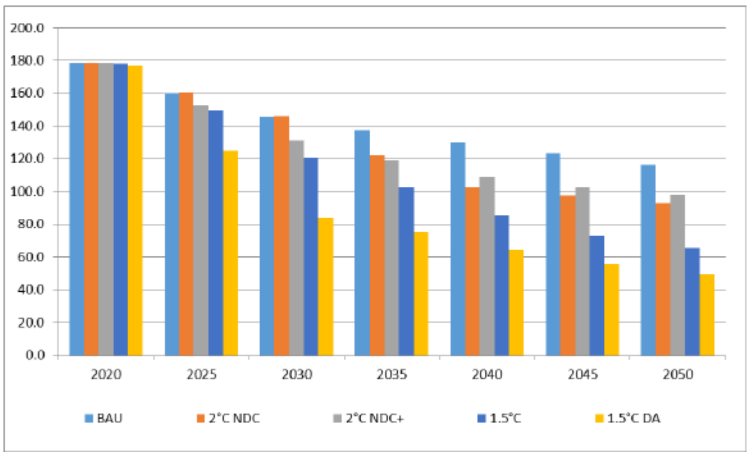
One of the related sub-indicators is gas import independence. The POLES model provided results between 20% and 31% independence, i.e. 69% to 80% dependence, in 2050. The results are better than the baseline scenario, where the dependence in 2050 is more than 82%. The largest gas independence is displayed in the 1.5°C scenario – 31% with cumulative effect right after 2030. The prospects for local production of gas are still low, as shale gas is under moratorium, and offshore exploration works have not given yet a positive result.

Regarding nuclear energy, all scenarios show several times less energy from nuclear in 2050 than in 2020 (falling to between 3.4 and 5.0 TWh p.a. in 2050 from the starting point of 12.9 TWh in 2020). This effect may be attributed to the rising share of renewables in the electricity sector and the crowding out of larger generating capacities. However, other studies like SEERMAP have projected a slight rise in nuclear for Bulgaria in the period after 2030, which is also in line with Bulgaria's national policy to keep at least 2 nuclear plants of 1 GW capacity each operating, meaning extending the life of the current reactors at Kozloduy, and gradually adding a few more units and replacing the existing ones.

In the BAU scenario, coal keeps more than half of its 2020 share in electricity production in 2050 (16.5 TWh in 2050) but this share decreases in all four other scenarios. The largest reductions occur in the 1.5°C DA scenario – coal electricity generation shrinks from 24.9 TWh to 1.5 TWh. In all scenarios, the lower share of electricity produced from coal is related to the higher share of renewable technologies – wind and solar, in combination with a slight rise in hydro, biomass and other RES.

As noted before, Bulgaria has the highest energy intensity in the EU at the beginning of the 21st century, as measured in terms of gross energy consumption and GDP[13]. The prospective scenarios for Bulgaria (Figure 20) show that energy intensity in 2050 is lowest in the 1.5°C scenarios, in which economic players reduce energy demand. The 1.5°C DA scenario leads to early fall in energy intensity of GDP.

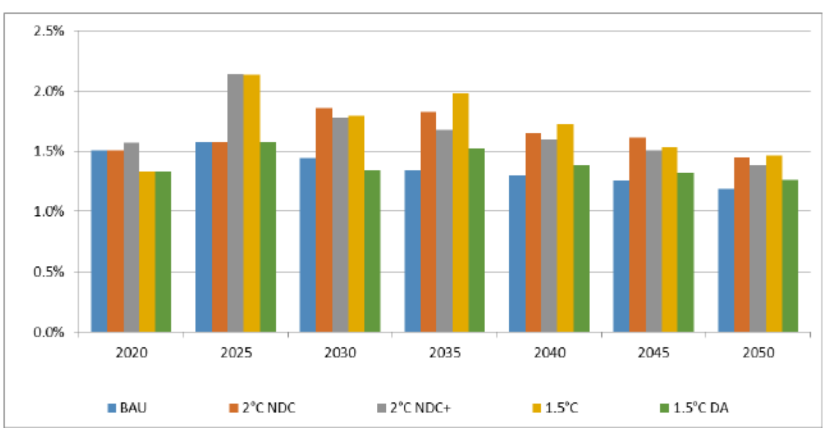
Figure 20: Energy intensity of GDP (primary energy) for Bulgaria, toe/M$ (2020-2050)



Source: POLES results

In terms of energy poverty, a proxy indicator could be used, i.e. the share of energy bills in general and the share of residential energy bills in GDP for the period 2020-2050. The scenarios show that the best cumulative effect for diminishing household energy bills in relative terms is provided by the 1.5°C DA scenario (Figure 21).

Figure 21: Energy expenditure in residential sector $2005 / GDP PPP $2005 (%) for Bulgaria, 2020-2050

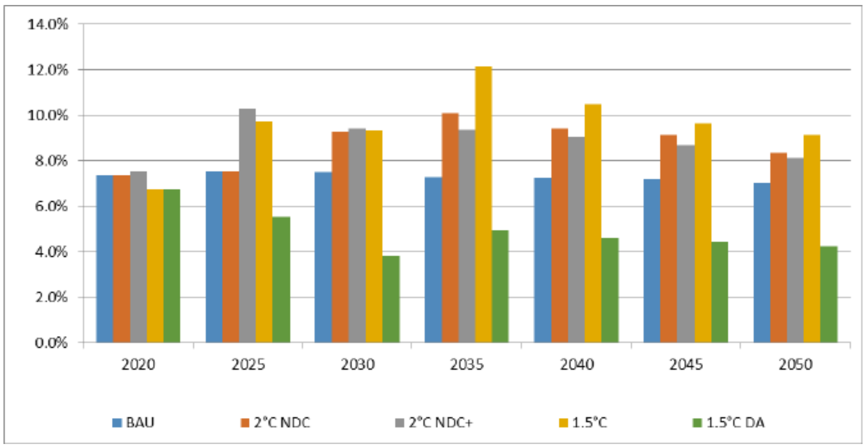


Source: POLES results

[13] Eurostat (2015) Energy intensity of the economy. http://ec.europa.eu/eurostat/en/web/products-datasets/-/TSDEC360

When the overall energy expenditure of the economy is considered, the 1.5°C DA provides even lower energy bills, bringing costs for the business consumers lower as well. All other scenarios lead to up to 2 times higher share of the energy bills as part of the GDP in 2050, putting at risk the economy of the country (Figure 22).

Figure 22: Total energy expenditure \$2005 / GDP PPP \$2005 (%) for Bulgaria, 2020-2050



Source: POLES results

Both 1.5°C and 1.5°C DA scenarios provide better indicators for 2050 in terms of energy security. The 1.5°C DA scenarios is the one, which provides lower costs measured as share of GDP, while providing similar energy security indicators.

6. Case study: Poland – energy security until 2050

GDP and population

Macroeconomic and demographic trends contribute to dynamics of the energy demand, indirectly affecting energy security indicators. Demographic projections indicate that the population of Poland will significantly decline in the next decade: from current 38 million people to 35 million people in 2050. The rate of decline will accelerate over time. In the period 2030-2050 it is expected to be twice as fast as in 2015-2030.

Table 10: GDP and population indicators, Poland 2000-2050

	Levels				CAGR		
	2000	***2015***	***2030***	***2050***	**2000-2015**	**2015-2030**	**2030-2050**
Population, million	38	38	37	35	0.04%	-0.18%	-0.37%
GDP per capita (PPP), k\$2005 per capita	12	20	30	41	3.51%	2.70%	1.60%

According to the baseline macroeconomic projection applied in the POLES model, Polish GDP growth rate will gradually decline from robust levels exceeding 3.5% which were observed between 2000 and 2015. While demographic decline contributes significantly to the decline in the total GDP growth in Poland in the long-term, the key driver is a deceleration of the rate of GDP per capita growth. However,

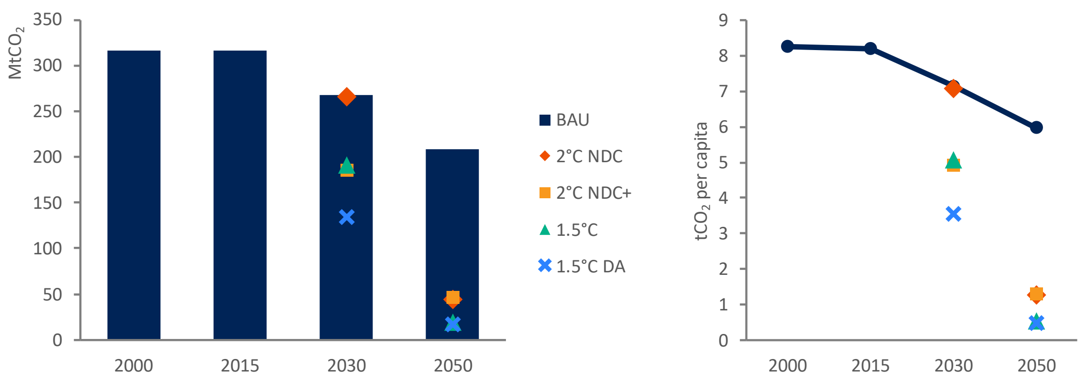
even despite such decline, projected GDP per capita in Poland doubles over the 2015-2050 period. The total size of the economy grows by 85% by mid-century, putting pressure on domestic energy demand and CO2 emissions.

GHG emissions

The BAU scenario results in a decline in total CO_2 emissions by 15% by 2030 and by 34% in 2050 compared to 2015. NDC scenario results in similar emission reduction by 2030 (16%) and then accelerates to deliver 86% reduction by 2050. NDC+ leads to the same long-term result while achieving substantial reductions (by 42%) earlier – already by 2030. 1.5°C scenario results in 40% emission reduction in 2030 and 94% by 2050. The most rapid and deepest CO_2 cuts appear in 1.5°C Decoupling Activity scenario (-58% by 2030 and -95% by 2050).

Regarding emissions per capita, NDC and NDC+ scenarios result in a drop from over 8 tonnes CO_2 per person in 2015 to 1.3 tonnes by 2050. In both 1.5°C scenario, Poland reaches 0.5 tonnes of CO_2 per capita by mid-century. For comparison, the EU average in 2016 stood at ca. 7 tonnes per capita. In the BAU scenario, Poland does not reach this threshold until the mid-2030s, with CO_2 emissions per capita declining for the first time below 6 tonnes in the late 2040s.

Figure 23: Total CO2 emissions (left) and emissions per capita (right), Poland 2000-2050

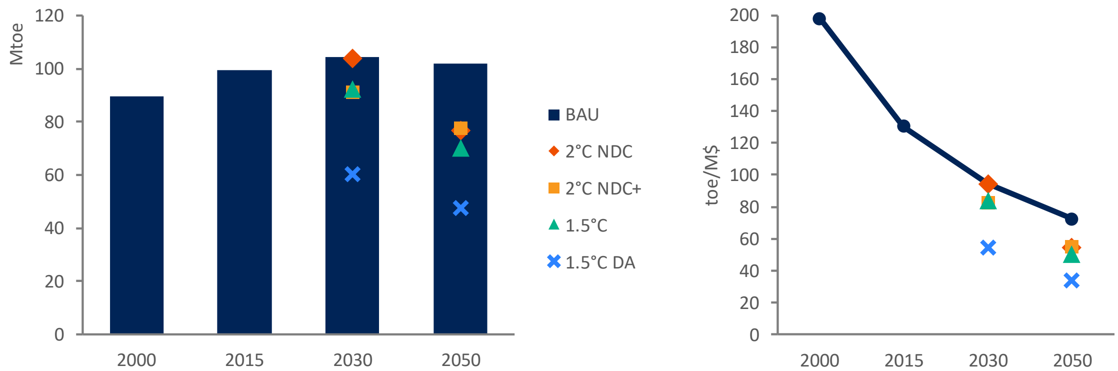


Source: POLES results

Primary and final energy intensity

In the BAU scenario, demand for primary energy plateaus in the long run. In other scenarios it significantly decreases by 2050, with 1.5°C DA reaching 39% reduction compared to 2015 levels already by 2030 and 52% by 2050. NDC and NDC+ achieve comparable energy demand reductions by 2050 (22-23%), although this requires significant acceleration of energy efficiency improvements in NDC scenario after 2030.

Figure 24: Total primary energy (left) and primary energy intensity of GDP (right), Poland 2000-2050

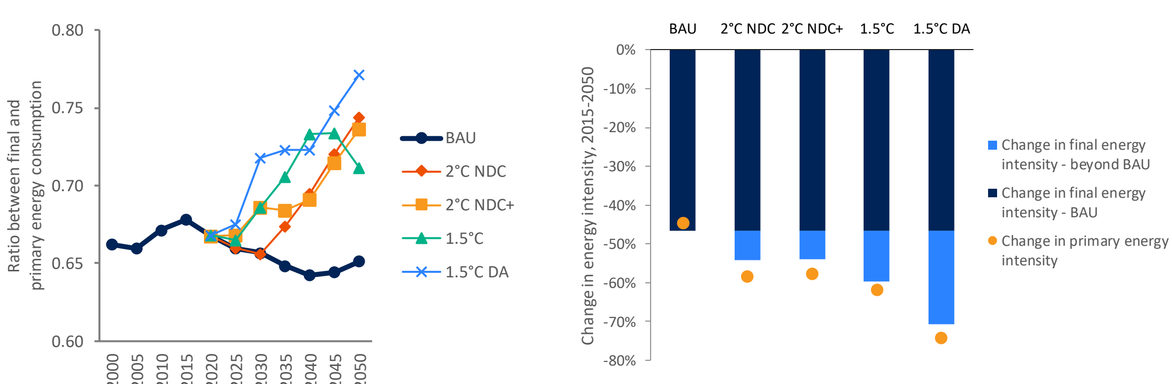


Source: POLES results

Projected declines in energy intensity of GDP follow the historical trend, with all scenarios achieving significant improvements in energy efficiency. By 2030, primary energy intensity is lower by at least 30%, with values ranging between 55 toe/M$ and 94 toe/M$. In 1.5°C DA scenario it reaches a value as low as 34 toe/M$ in 2050, implying almost four times higher economic output per unit of energy compared to 2015.

Final energy consumption intensity follows similar trends to primary energy consumption intensity in each scenario. Thus, differentiation in improvements in the energy efficiency among final users across the scenarios is the key driver of overall differences in demand observed between the scenarios. Nevertheless, divergent trends in energy transformation losses also contribute to the differentiation between the scenarios. In particular, the BAU scenario leads to a decrease in the ratio between final and primary energy consumption. All other scenarios see a decrease in transformation losses in the long term, even though in most of them the losses increase in the 2020s. Thus, in 2°C and 1.5°C scenarios, factors decreasing losses of primary energy (such as increased share of wind and solar in energy mix) outweigh technological shifts which may increase the transformation losses (e.g. adding CCS installations to power plants).

Figure 25: Ratio between final and primary energy consumption (left) and comparison of primary and final energy intensity dynamics (right) in Poland up to 2050



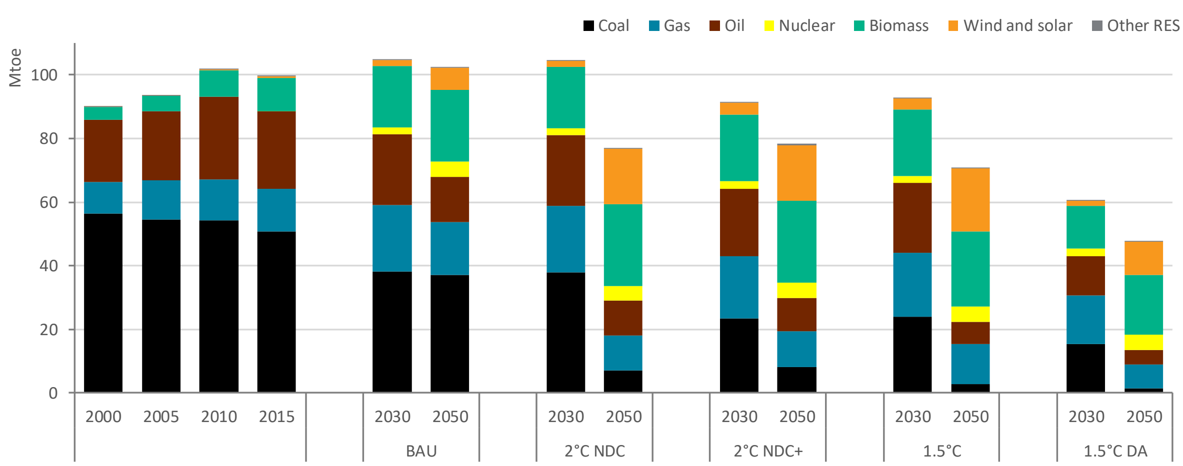
Source: POLES results

Diversity of primary energy consumption and electricity generation mix

Despite gradual diversification observed in 2000-2015, coal still dominates Polish energy mix. This applies both to the structure of total primary energy consumption (share of coal over 50%) and electricity supply (share of coal over 80%). Historically, the diversification of Polish energy mix was driven primarily by the fact that increasing demand was covered by non-coal energy sources, while the volume of coal consumption has seen only moderate declines and coal-based electricity output has been stable. This trend is largely maintained in BAU scenario in the long run: while absolute coal consumption decline accelerates in 2015-2030, it remains stable afterwards. The difference between the relative and absolute drop in coal use is especially evident in the case of the electricity sector. It is driven by robust electricity demand growth, which significantly exceeds projections provided in the draft National Energy and Climate Plan presented by the Polish government in early 2019, as well as expectations of other stakeholders in Poland.

Scenarios that assume more ambitious climate action result in an accelerated decline in coal share by 2030, which persists up to 2050. While in BAU scenario coal share in primary energy use exceeds 1/3 in 2050, it drops to ca. 10% in 2°C scenarios and 2-4% in 1.5°C scenarios. This rapid decline implies increased diversity of Polish primary energy mix compared to BAU scenario up to 2040s when the decline in fossil fuel use and increasing share of renewable sources leads to decrease in diversity indices in all decarbonisation scenarios. By 2050, BAU becomes the most diversified scenario, while 1.5°C DA scenario which assumes deep reduction in energy demand is characterised by the lowest levels of primary energy source diversity. Nevertheless, in every scenario Polish primary energy mix diversity remains above current levels.

Figure 26: Primary energy consumption by source, Poland 2000-2050

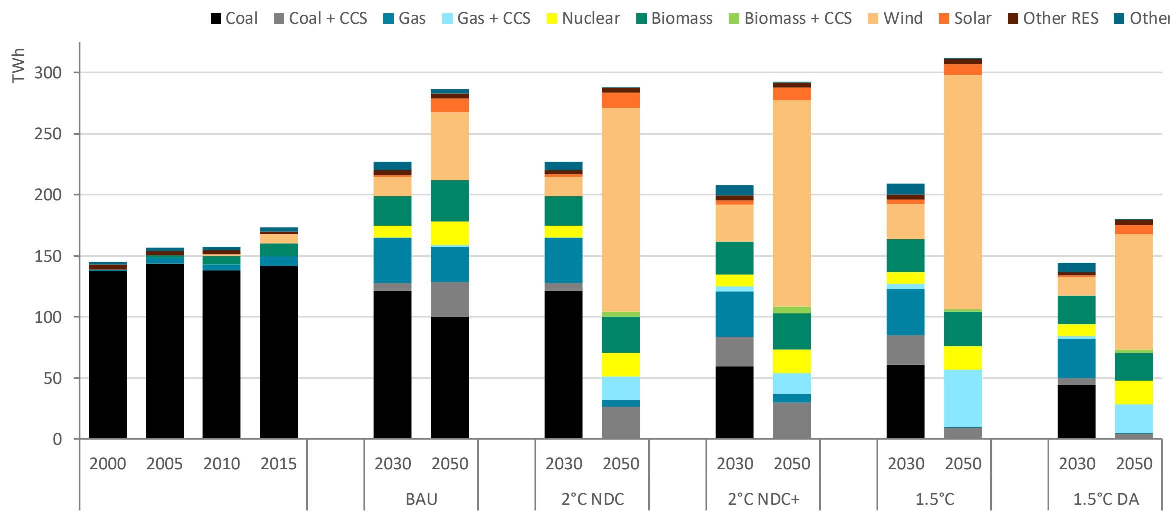


Source: POLES results

The diversity dynamics is somewhat different for electricity production. While each deep decarbonisation scenario leads to the emergence of wind as a new dominant primary energy source for electricity production in Poland (53%-62% share in total production), it does not reach as high share as currently observed for coal. Rather, wind farm electricity output is supplemented by other low-emission plants (nuclear, biomass and fossil fuel + CCS, with the limited role of solar and biomass +

CCS). As a result, all decarbonisation scenarios provide higher diversity compared to BAU over the whole assessed period.

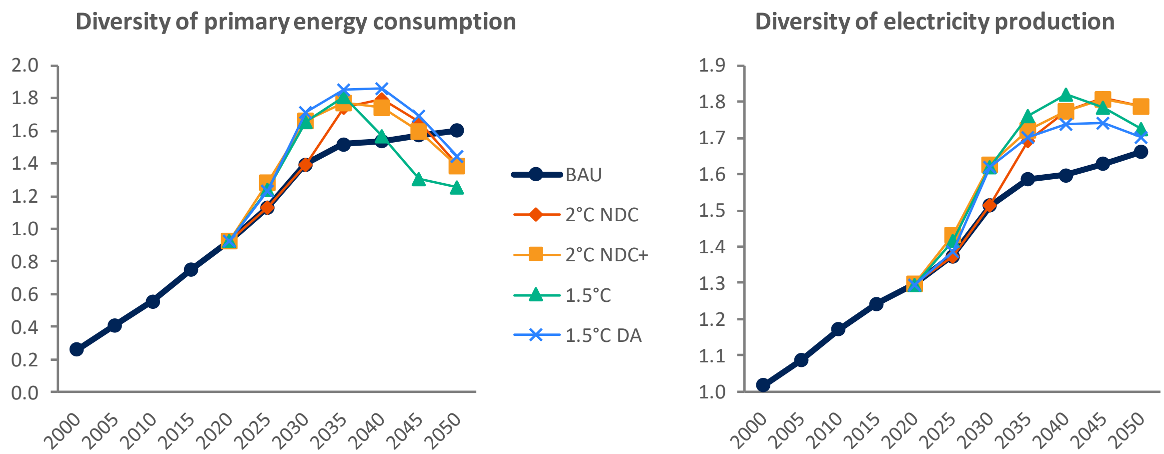
Figure 27: Electricity generation mix, Poland 2000-2050



Source: POLES results

The results suggest that while in the 2020s and 2030s deep decarbonisation scenarios lead to increased diversity and improved resilience of energy mix in Poland, more careful consideration should be given to ensuring successful completion of final stages of energy transition towards the low-carbon system. The POLES model indicates that it will be highly dependent on utilising the potential of a single energy source (wind). Delays in deployment of wind farms or technical problems with integrating very high shares of variable RES in the Polish grid may be difficult to compensate by alternative low-carbon energy sources. Furthermore, given delays in Polish nuclear power programme and lack of deployment of CCS technologies on an industrial scale in Poland up to date, actual dependence of Polish energy system on wind power to deliver required levels of decarbonisation may be even higher than indicated by the modelling results.

Figure 28: Shannon diversity index for primary energy consumption (left) and electricity production (right), Poland 2000-2050



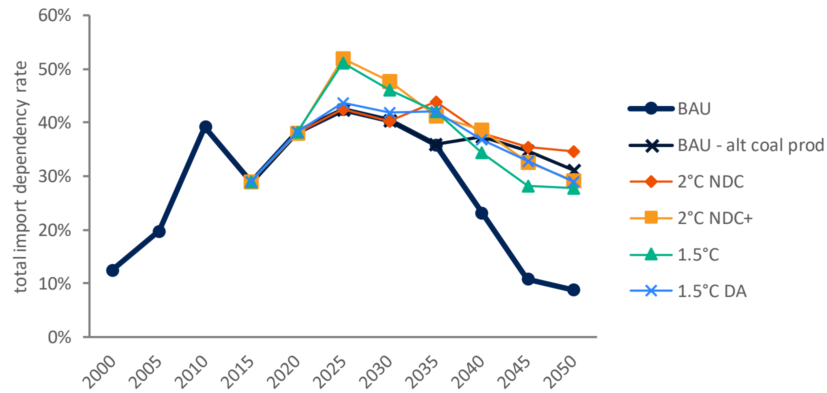
Source: POLES results

Import dependency

Although the dependency of the Polish energy system on fuel imports decreased between 2010 and 2015, all of the scenarios envisage an increase in total import dependency in the 2020s. Only BAU scenario envisages that in 2050 it will decrease below the 2015 values. It should be noted, however, that rapid decrease in import dependency rate in BAU scenario after 2035 is driven by a single factor: a significant increase in domestic coal production and exports in Poland. This is dependent on the POLES model assumption that long-term mining costs in Poland will converge to c.a. $14 per tonne of coal. Assuming miners' wage increases in line with GDP per capita growth, annual labour cost per miner in Poland will exceed $50,000 by 2050. This would require achieving extraction productivity exceeding 4000 tonnes per worker per year, i.e. over five times higher than current domestic average and over twice higher than the current best practice in Polish hard coal mining[14]. Such improvements would go significantly beyond currently observed trends, i.e. gradual productivity growth not fully offsetting increasing wage pressure, leading to declines in employment and hard coal extraction levels in Poland. Thus, the import dependency rate for Poland was calculated for an additional, illustrative scenario (*BAU alt coal prod*) which assumes stable domestic coal production after 2035. The result indicates that under less optimistic assumptions on domestic hard coal mining potential, all 1.5°C scenarios and 2°C NDC+ scenario lead to lower total import dependency in the long run. Given that domestic coal production in *BAU – alt coal prod* scenario stabilises on a rather high level (2/3 of output in 2015), a further decline of Polish coal mining would result in an import dependency rate which would be even higher relative to decarbonisation scenarios.

[14] For a review of costs and productivity trends in Polish hard coal mining sector, see Bukowski et al (2015).

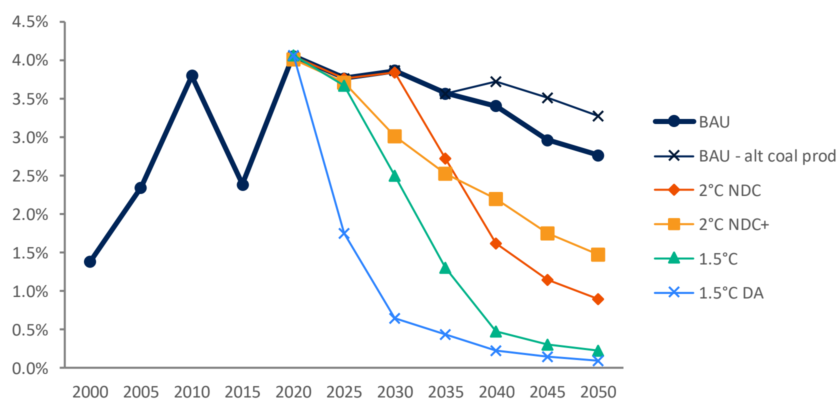
Figure 29: Import dependency rate, Poland 2000-2050



Note: BAU – alt coal prod *scenario assumes constant domestic coal production in 2035-2050*
Source: POLES results, WiseEuropa calculations for BAU – alt coal prod *scenario*

While projected developments in coal production are crucial for import dependency rate, their impact on total fossil fuel import bill is more limited. This is explained by the fact that the unit price of coal is significantly below the unit price of both gas and oil. Furthermore, as 2°C and 1.5°C scenarios result in a decrease in global fuel prices, the decline of the Polish fuel import bill is driven both by a decrease in volumes of imported oil and gas as well as deep fall in their price. Thus, a more ambitious climate policy scenario leads to a significant reduction in fossil fuel import bill for Poland, even compared to BAU scenario with high levels of coal production. In particular, in both 1.5°C scenarios, fossil fuel import bill becomes negligible from the macroeconomic perspective by 2050, declining below 0.5% of Polish GDP.

Figure 30: Total net fossil fuel import bill relative to GDP, Poland 2000-2050

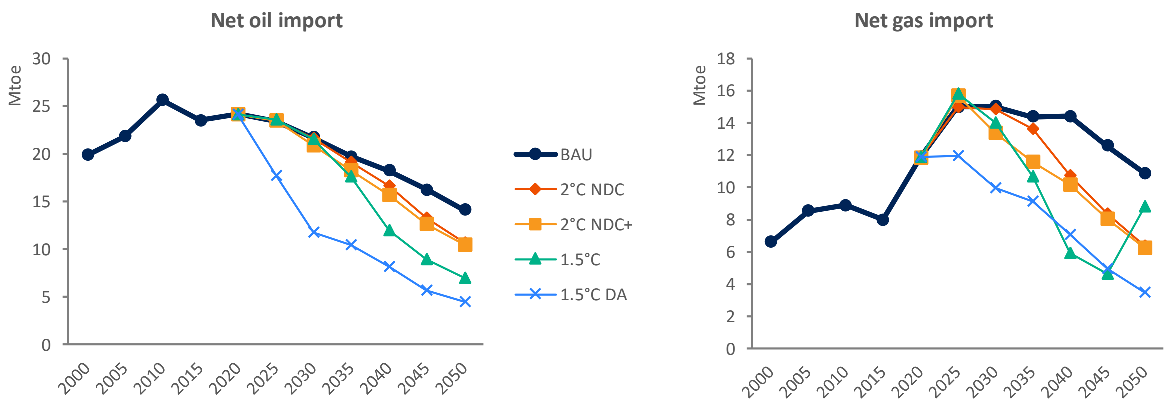


Note: BAU – alt coal prod *scenario assumes constant domestic coal production in 2035-2050*
Source: POLES results, WiseEuropa calculations for BAU – alt coal prod *scenario*

As climate policy impact on fossil fuel import bill depends on actions of all countries participating in the international market, the volume of imported fuels is a more robust indicator for assessing the impact of domestic climate action on energy security. A closer look at projected oil and gas net import volumes for Poland confirms that more ambitious climate action leads to decreased dependence on external supplies of these two types of fossil fuels. The results for gas import dynamics are particularly significant, given high current dependence of Poland on one supplier. The POLES model confirms that gas demand in Poland will increase by 2025 in all scenarios, even 1.5°C DA which is characterised by

significant total energy demand reduction. Gas imports do not decrease below 2015 levels until the 2030s for 1.5°C scenarios and until the 2040s for 2°C scenarios. This indicates that enhancing the security of supply in case of Polish gas imports requires supply-side infrastructure investments ensuring diversification of supplies even under most ambitious climate policy scenarios. At the same time, in 2°C NDC and 1.5°C scenarios, higher climate policy ambition before 2030 results in a temporary increase of gas imports in the 2020s. However, this increase is very limited (+5% of total projected gas imports relative to the BAU scenario) and is fully offset by 2030.

Figure 31: Net oil and gas import volumes, Poland 2000-2050

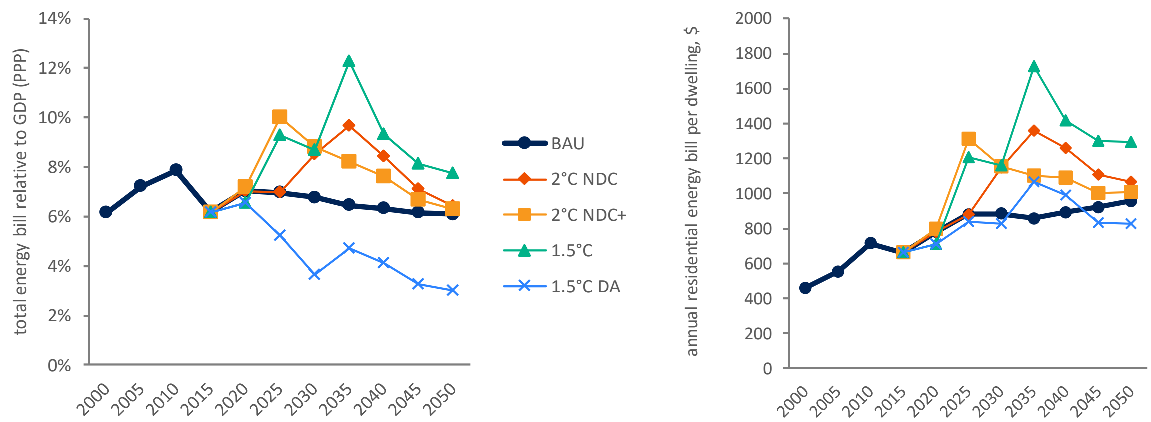


Source: POLES results

Affordability of energy

The POLES modelling results indicate that without behavioural shifts leading to decreased energy demand which are assumed in 1.5°C DA scenario, moving towards more ambitious climate action results in an increase in total energy expenditure across all the sectors. Furthermore, residential energy bills paid by households will also significantly increase already in the 2020s. While earlier action in 2°C NDC+ scenario decreases the costs of transition in 2030-2050, the sudden increase in total energy bill relative to GDP in 2025 is comparable to the one observed in 2°C NDC scenario in 2035. Furthermore, supply-side focused 1.5°C scenario results in doubling of the total energy bill in the 2030s. While 2°C gradually converge to BAU scenario by 2050, the cost difference between 1.5°C and BAU scenarios does not disappear. The scale of increase in energy bill indicated by the modelling is significant from macroeconomic perspective, with maximum deviation from BAU amounting to 6% of GDP in case of 1.5°C scenario and 3% of GDP in 2°C scenarios. At the same time, 1.5°C Decoupling Activity scenarios result in halving of the total energy bill in the long run.

Figure 32: Total energy bill relative to GDP (left) and residential energy bill per dwelling (right), Poland 2000-2050



Source: POLES results

It should be noted that the energy bill indicators reported by the POLES model include the impact of carbon taxation on all the fuels used in the economy. This implies significant carbon revenues raised by the government, which may be used to mitigate the impacts of increases in energy bills. In 1.5°C scenario, these revenues are equivalent to 60% of total energy expenditure in Poland, while in the BAU scenario this ratio is only 8.5%. If the sum of carbon revenues were subtracted from total energy consumption bill, the BAU bill would be 30-50% higher compared to 2°C scenarios and 80% higher compared to 1.5°C scenario.

Table 11: Total energy bill and carbon revenue, Poland 2050

	BAU	2°C NDC	2°C NDC+	1.5°C	1.5°C DA
Total energy bill ($ bn)	86	91	89	109	43
Carbon revenue ($ bn)	7	38	29	66	19

Source: POLES results

Overall, the modelling results show that ensuring affordability of energy during the low-carbon transition in Poland is possible, but it would require careful policy design, including utilisation of carbon revenues to mitigate sudden shocks affecting energy bills. It should also be noted that other policy measures, such as bans of emission-intensive technologies or energy efficiency norms, may allow Poland to reach similar levels of decarbonisation with lower levels of direct emission taxation.

Implications of higher GDP growth

The baseline GDP growth projections applied in the POLES model are significantly lower than the pathway required to catch up with most developed countries by 2050. An additional GDP scenario was modelled to explore implications of higher growth for energy security.

Table 12: Selected energy security indicators for two GDP growth scenarios, Poland 2030-2050

	Baseline GDP growth		Higher GDP growth		Difference: higher GDP vs baseline GDP	
	2030	2050	2030	2050	2030	2050
GDP per capita (PPP), k$2005 pc	30	41	33	55	4 (+13%)	14 (+36%)
Primary energy consumption, Mtoe						
BAU	104	102	113	123	8.6 (+8%)	21.1 (+21%)
2°C NDC	104	77	113	93	8.6 (+8%)	15.9 (+21%)
2°C NDC+	91	78	98	94	7.3 (+8%)	16.5 (+21%)
1.5°C	93	70	100	86	7.4 (+8%)	15.8 (+22%)
1.5°C DA	60	47	65	55	4.4 (+7%)	7.6 (+16%)
Total energy dependency, %						
BAU	40%	9%	44%	22%	3.8 p.p (+9%)	14 p.p (+157%)
2°C NDC	40%	35%	44%	43%	3.8 p.p (+9%)	8 p.p (+24%)
2°C NDC+	48%	29%	51%	38%	3 p.p (+6%)	9 p.p (+30%)
1.5°C	46%	28%	49%	38%	3.1 p.p (+7%)	11 p.p (+38%)
1.5°C DA	42%	29%	45%	32%	3 p.p (+7%)	3 p.p (+9%)
Gas imports volume, Mtoe						
BAU	15.0	10.9	17.4	16.1	2.4 (+16%)	5.2 (+48%)
2°C NDC	14.9	6.4	17.2	13.1	2.4 (+16%)	6.7 (+106%)
2°C NDC+	13.3	6.2	15.7	11.5	2.3 (+18%)	5.2 (+84%)
1.5°C	14.0	8.8	16.4	16.8	2.4 (+17%)	8.1 (+92%)
1.5°C DA	9.9	3.5	11.3	5.2	1.4 (+14%)	1.7 (+48%)
Total net import bill, % GDP						
BAU	3.9%	2.8%	3.8%	2.8%	-0.1 p.p. (-2%)	0.02 p.p. (+1%)
2°C NDC	3.8%	0.9%	3.8%	0.9%	-0.1 p.p. (-2%)	0.04 p.p. (+4%)
2°C NDC+	3.0%	1.5%	3.0%	1.5%	-0 p.p. (-2%)	0.03 p.p. (+2%)
1.5°C	2.5%	0.2%	2.5%	0.3%	-0.03 p.p. (-1%)	0.06 p.p. (+29%)
1.5°C DA	0.6%	0.1%	0.6%	0.1%	0.004 p.p. (+1%)	0.002 p.p. (+2%)
Total energy bill, % GDP						
BAU	6.8%	6.1%	6.4%	5.3%	-0.4 p.p. (-6%)	-0.8 p.p. (-13%)
2°C NDC	8.5%	6.4%	8.1%	5.6%	-0.4 p.p. (-5%)	-0.8 p.p. (-12%)
2°C NDC+	8.8%	6.3%	8.4%	5.5%	-0.4 p.p. (-5%)	-0.8 p.p. (-12%)
1.5°C	8.7%	7.8%	8.3%	6.6%	-0.4 p.p. (-5%)	-1.2 p.p. (-15%)
1.5°C DA	4.4%	3.4%	4.1%	2.8%	-0.3 p.p. (-6%)	-0.6 p.p. (-17%)

Source: POLES results

In the higher growth scenario, Polish GDP is 36% higher in 2050 compared to the baseline. This translates into 21-22% higher energy consumption in all scenarios except 1.5°C Decoupling Activity scenario (+16%). However, in absolute terms, additional economic growth leads to the highest increase in primary energy consumption in the BAU scenario, with more ambitious climate policy leading to lower additional energy needs. Similarly, increased climate policy ambition leads to a lower impact of higher GDP growth on dependency ratio. The results are more nuanced for gas imports. While 1.5°C Decoupling Activity scenario sees much lower additional demand for imported gas in Poland, 1.5°C and 2°C result in either similar or higher additional demand driven by higher GDP growth compared to BAU. For 2°C scenarios, total gas import volumes are still lower than in BAU scenario. However, additional

GDP growth results in the 1.5°C scenario becoming the one with the highest demand for imported gas. This is driven inter alia by high volumes of this fuel required in CCS power plants. Similarly, the impact of additional economic growth on the increase in total import bill is highest for 1.5°C scenario. While faster economic growth leads to higher import bill relative to GDP, it also decreases the ratio between total energy bill and GDP.

Conclusions

Increasing concerns over both energy security and the environmental impact of anthropogenic energy emissions feeds the necessity to enhance our understanding of the climate and energy security nexus. In this perspective, we overview the potential impact of climate policies in line of the Paris Agreement on European energy security through a model based analysis of scenarios produced with the POLES model. We rely on a multidimensional approach to energy security that considers energy availability, energy affordability, supply security of natural gas consumption and issues related to the security of the electricity supply. These dimensions are captured through 13 indicators.

Energy security issues are analysed through a family of four prospective COP21 RIPPLES narratives and a counterfactual baseline scenario to which stronger policy cases are compared.

The Business as Usual scenario (BAU) depicts a world in which climate policy ambition is limited to compliance with Nationally Determined Contributions (NDC) in 2030 and the level of ambition in the BAU does not increase after 2030. The second set of scenarios comprises 2°C scenarios. Relying on COP21 RIPPLES narratives, the 2°C NDC and 2°C NDC+ scenarios represent a global effort by all countries to limit climate change to 2°C. Both scenarios have the same carbon budget for the 2010-2050 period. The 2°C NDC scenario is consistent with NDCs for the 2020-2030 period, but after 2030, countries need to implement a very strong climate policy to comply with the 2°C carbon budget. In the enhanced NDC 2°C scenario (2°C NDC+), climate policy ambition is higher than in the 2°C NDC scenario before 2030. Two stringent scenarios limiting global warming to 1.5°C are also developed in order to test the consequences of a more fuel efficient behaviour in a decoupling activity scenario (1.5°C DA) compared to well-known 1.5°C scenario. Stringent climate cases not only help to understand the efforts needed to respect the requested range of mitigation but also describe the complex interactions of climate policies with energy security issues.

The high dependency on energy imports and the huge gap between energy consumption and production capacity makes the European Union (EU) vulnerable to crises in the energy markets. However, the analysis shows that under such stringent climate policies, Europe may benefit of a significant double dividend: *(i)* in its capacity to develop a new cleaner and climate-friendlier energy model, and *(ii)* in a lower vulnerability by reducing the dependence on imported extra-European energy sources or supply shocks on the international energy markets. The share of net energy imports cost relative to GDP illustrates this positive outcome. In both 2°C scenarios, this share declines, but more quickly in the 2°C NDC+ because of the earlier implementation of ambitious climate policies that reduce the need for fossil fuel supply. In 1.5°C scenarios, this share reaches values close to zero. This result is an important outcome in terms of strengthening the energy independence of European countries.

One of the key concerns regarding the long-term energy security of Europe is its dependence in terms of gas supply. Natural gas is a key resource, with new perspectives introduced by non-conventional gas. Its environmental characteristics are rather favourable, especially in the context of GHG abatement policies, as gas-based electricity has a CO2 content twice lower than coal-based electricity (when no-carbon capture and storage options are considered). Natural gas also brings flexibility and diversification of energy supply at the transformation or end-use level. However, under the climate

effort constraint, the total gas demand of EU is lower after 2025 than in baseline scenario. To a large extent, this reduction of total demand weighs on traditional suppliers like Norway, Qatar and Algeria that would continue to play an important role in stringent scenarios. Russia seems, however, to keep a comparative advantage in the supply of Europe in both 2°C scenarios and in the 1.5°C scenario, at least until 2035, when Russia reach a level of about 160 Bcm representing around 50% of EU gas imports. The gas consumption is nearly halved in the 1.5°C DA scenario, which reduces even more supply tensions in the gas market.

Different instruments and constraints imposed to the energy system to decarbonize the final energy consumption send a powerful price signal that harnesses the invisible hand of the marketplace to steer economic actors towards a low-carbon future[15]. The increase of final energy prices leads to higher global energy bills in the residential, transport and industry sectors making affordability a difficult social and political problem. However, the acceptability of climate policies requires that climate effort revenues should be returned directly to EU citizens through direct compensations to increase the fairness and political viability of the important increase of the energy bill. The majority of European families, and particularly the most vulnerable, must benefit financially by receiving more “carbon dividends” than what they pay in increased energy prices. Other contributions to their budget can improve the people's acceptability and political viability of this unprecedented effort, i.e. through reduction of other taxes (including employer contributions on wages) or financing of transitional investments that will encourage technological innovation and large-scale infrastructure developments (Criqui, 2019). A border carbon adjustment system can also be established to prevent carbon leakage and to protect EU industry competitiveness. It would also create an incentive for other nations to adopt similar carbon pricing[16].

Investments on variable renewables (solar and wind) reduces the need for importing fossil fuels and direct electricity, which leverages the energy security at EU level. However, each EU country has a unique energy mix and applies different VRE promotion policies, which result in diverse share of VRE and consequently different grid stability issues. A high share of variable renewables can lead to outage if the electricity system is not adapted to a VRE penetration. The highest VRE shares are observed in 1.5°C scenarios, albeit not exceeding 63% in 2050 at the EU aggregated level. When looking more in detail for each EU country, a much higher share of VRE is projected in some countries like Germany, Denmark and the Netherlands which need to pay particular attention to grid stability. It is to be noted that such results depend on assumptions regarding the availability of flexibility options, learning rates of low carbon technologies and the possibility of relying on nuclear power, CCS and BECCS according the scenarios.

The country-level model-based analysis was supplemented with two country case studies in Bulgaria and Poland. The focus on these countries is critical for this assessment given the prominence of energy security as a key national socio-economic objective, and the strong links with climate and energy policies in the EEC region.

[15] ECONOMISTS’ STATEMENT ON CARBON DIVIDENDS. The Largest Public Statement of Economists in History. https://www.clcouncil.org/economists-statement/

[16] Ways of improving the affordability are not part of this study.

The Bulgaria case study confirms the findings related to energy affordability issues in Eastern Europe countries in the case of ambitious climate policies. The share that energy bill represents of the Bulgarian GDP increases. Energy bill would also increase more than the average EU level for the industrial sector in mitigation scenarios, which may lead to loss of competitiveness for the Bulgarian industrial sector. Among all the indicators evaluated, the only one that is positively impacted by more mitigation ambition compared to BAU is energy intensity of GDP. The 1.5°C DA scenario provides the best results for the country by improving energy intensity, CO_2 intensity and independence from energy imports from 2020 onwards.

The Polish case study also shows the importance of assessing model-based results with country-specific sectoral and policy context. For instance, the results indicate that Poland will require at least a temporary increase in gas imports compared to current levels even in the most ambitious climate policy scenarios. Furthermore, its overall energy dependency ratio will depend not only on climate policy developments but also the ability of domestic mining sector to improve its productivity (to offset the increasing labour costs) in the long run. The results also show that, while by the 2030s deep decarbonisation leads to diversification of Polish energy mix, afterwards it becomes dependent on several VRE technologies, in particular electricity generation from wind. If Poland fails to deliver very high share of RES (especially wind) on time (e.g. due to technical problems or grid investment delays) it will be difficult to balance the mix with alternative low-carbon sources in line with decarbonisation pathway. Finally, ensuring energy affordability under ambitious climate policy frameworks will be challenging. Increases in energy bills across the sectors may be mitigated by recycling carbon revenues as well as employing policy alternatives to price-based measures.

Last, it is important to note the limitations of the research undertook in this assessment when interpreting the results. Firstly, the dimensions of energy security are analysed according to the indicators that can be computed with the POLES model. As a consequence, fuel poverty, sustainability and grid stability-related analysis would benefit from additional tools. Secondly, the evolution of these 13 indicators for assessing energy security depend on the modelling assumptions necessary to project changes in final energy demand in different sectors (such as the learning rates of low-carbon technologies that drive their cost trends) which are all sources of great uncertainty.

References

APERC, 2007. A Quest for Energy Security in the 21st Century: Resources and Constraints. Asia Pacific Energy Research Centre.

Ang, B.W., Choong, W.L., Ng, T.S., 2015a. Energy security: Definitions, dimensions and indexes. Renewable and Sustainable Energy Reviews 42, 1077–1093. doi:10.1016/j.rser.2014.10.064

Bazilian, M., Hobbs, B.F., Blyth, W., MacGill, I., Howells, M., 2011. Interactions between energy security and climate change: A focus on developing countries. Energy Policy 39, 3750 – 3756. doi:10.1016/j.enpol.2011.04.003

Bollen, J., Hers, S., van der Zwaan, B., 2010. An integrated assessment of climate change, air pollution, and energy security policy. Energy Policy 38, 4021 – 4030. doi:10.1016/j.enpol.2010.03.026

Bukowski, M., Maśnicki, J., Śniegocki, A., Trzeciakowski, R., 2015. Whither are you headed, Polish coal? Development prospects of the Polish hard coal mining sector, Warsaw: WISE.

Cherp, A., Jewell, J., 2014. The concept of energy security: Beyond the four As. Energy Policy 75, 415 – 421. doi:10.1016/j.enpol.2014.09.005

Criqui P. (2019) Faisons encore mieux que les prix Nobel: rendons la taxe carbone à la fois écologique et social, https://www.telos-eu.com/fr/faisons-encore-mieux-que-les-prix-nobel-rendons-la.html

Grand, D., Le Brun, C., Vidil, R., & Wagner, F. (2016). Electricity production by intermittent renewable sources: a synthesis of French and German studies. The European Physical Journal Plus, 131(9), 329.

Georgiev, A., 2016. Shale and Eastern Europe (Bulgaria, Romania, and Ukraine), in Wang, Y. and Hefley, W.E. eds., The Global Impact of Unconventional Shale Gas Development: Economics, Policy and Interdependence, Springer International Publishing

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., ... & Cullen, J. (2018). A low energy demand scenario for meeting the 1.5° C target and sustainable development goals without negative emission technologies. Nature Energy, 3(6), 515.

Hughes, L., 2009. The four "R"s of energy security. Energy Policy 37, 2459 – 2461. doi:10.1016/j.enpol.2009.02.038

IPCC, 2018: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.

Jaccard, M., Hein, M., & Vass, T. (2016). Is Win-Win Possible? Retrieved from http://www.sustainablecanadadialogues.ca/pdf_2017/Jaccard-Hein-Vass_CdnClimatePol_EMRG-REM-SFU_Sep_20_2016-2.pdf

Jewell, J., Cherp, A., Riahi, K., 2014. Energy security under de-carbonization scenarios: An assessment framework and evaluation under different technology and policy choices. Energy Policy 65, 743 – 760. doi:10.1016/j.enpol.2013.10.051

Kitous, A., Keramidas, K., Vandyck, T., Saveyn, B., Van Dingenen, R., Spadaro, J., & Holland, M. (2017). Global Energy and Climate Outlook 2017: How climate policies improve air quality (No. JRC107944). Joint Research Centre (Seville site)

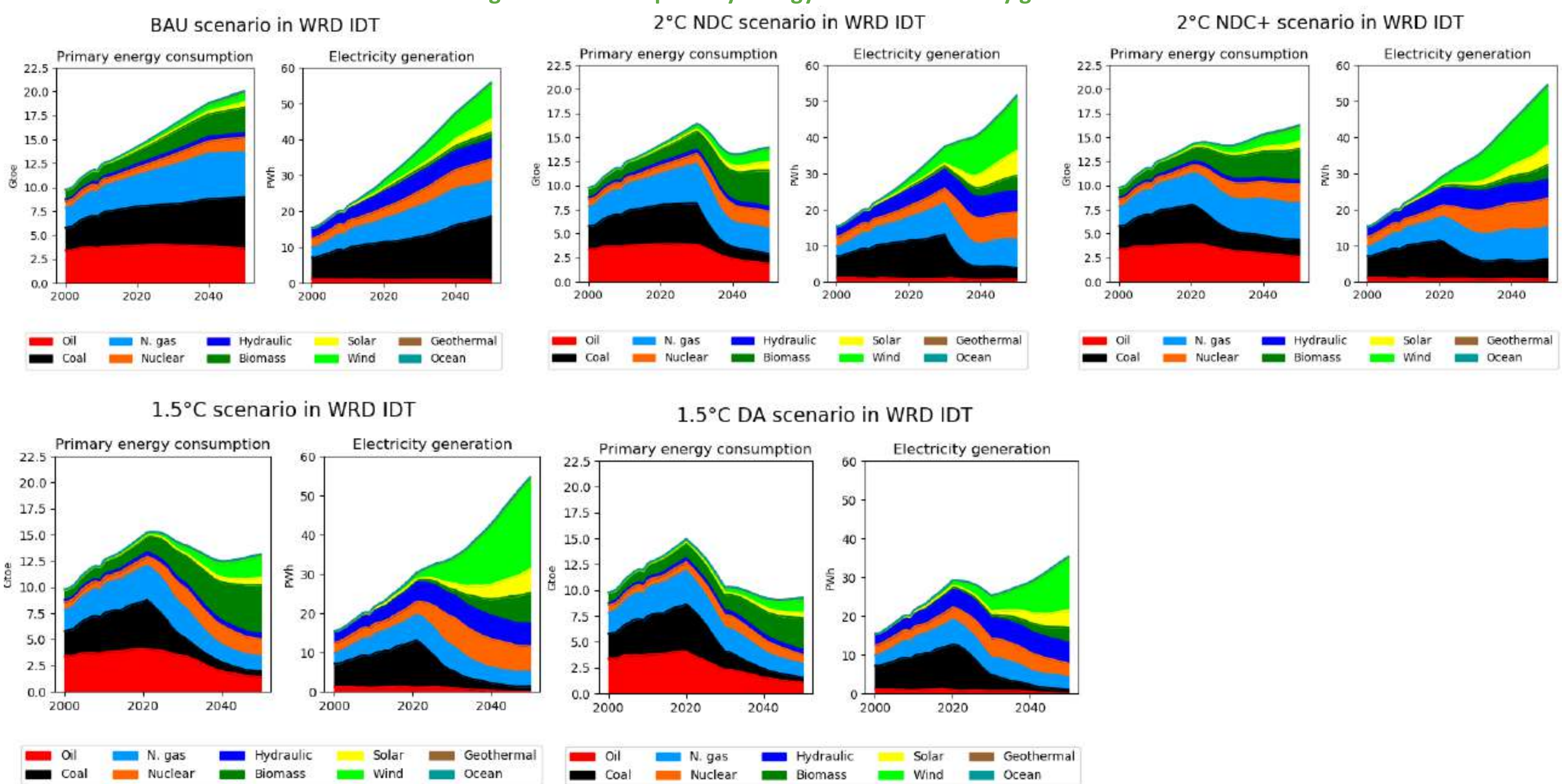
Leung, G.C.K., Cherp, A., Jewell, J., Wei, Y.-M., 2014. Securitization of energy supply chains in China. Applied Energy 123, 316 – 326. doi:10.1016/j.apenergy.2013.12.016

Mathy S, Criqui P, Knoop K, Fischedick M, Samadi S. (2016). Uncertainty management and the dynamic adjustment of Deep Decarbonization Pathways. Climate Policy. 16:47-62.

Pye, S., Dobbins, A., 2015. Energy poverty and vulnerable consumers in the energy sector across the EU: analysis of policies and measures, EU INSIGHTE project.
Sovacool, B.K., Mukherjee, I., 2011. Conceptualizing and measuring energy security: A synthesized approach. Energy 36, 5343 – 5355. doi:10.1016/j.energy.2011.06.043
Sovacool, B.K., Saunders, H., 2014. Competing policy packages and the complexity of energy security. Energy 67, 641 – 651. doi:10.1016/j.energy.2014.01.039
Stolyarova, E., Criqui, P., Mathy, S., Mima, S., Georgiev, A., Sniegocki, A., Bukowski, M., 2017. Literature Review of Energy Security Indicators. EU COP21 RIPPLES project.
Szabo, L., Mezosi, A., Pato, Z., Resch, G., Kovacs, M., Markovic, S., 2017. SEERMAP Bulgaria Country Report, SEERMAP Project
Victor, N., Nichols, C., Balash, P., 2014. The impacts of shale gas supply and climate policies on energy security: The U.S. energy system analysis based on MARKAL model. Energy Strategy Reviews 5, 26 – 41. doi:10.1016/j.esr.2014.10.008
von Hippel, D., Suzuki, T., Williams, J.H., Savage, T., Hayes, P., 2011. Energy security and sustainability in Northeast Asia. Energy Policy 39, 6719 – 6730. doi:10.1016/j.enpol.2009.07.001
Vrontisi, Z., Luderer, G., Saveyn, B., Keramidas, K., Reisa, L. A., Baumstark, L., Bertram, C., De Boer, H. S., Drouet, L., et al. (2018). Enhancing global climate policy ambition towards a 1.5° C stabilization: a short-term multi-model assessment. Environmental Research Letters, 13(4), 044039.

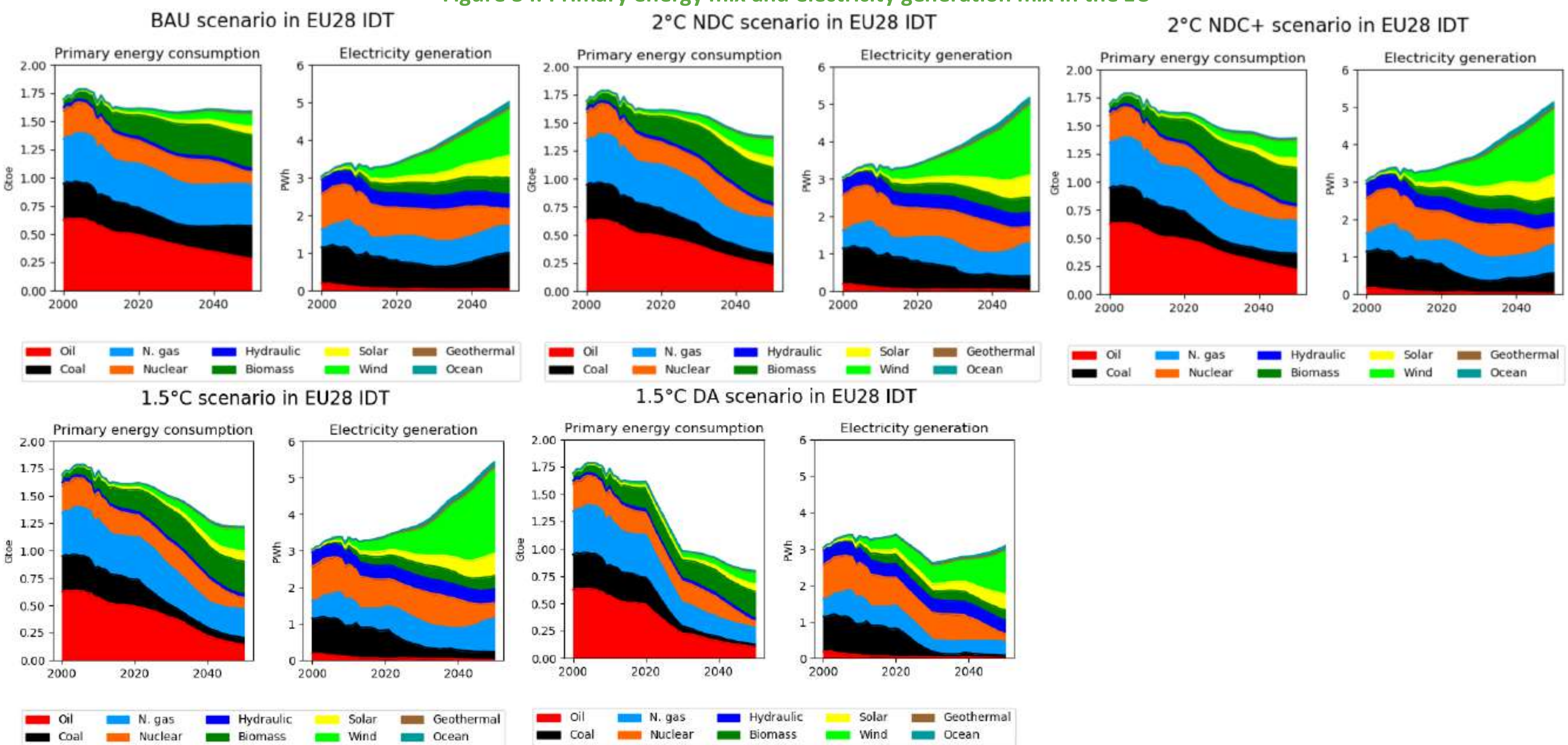
Appendices

Figure 33: Global primary energy mix and electricity generation mix



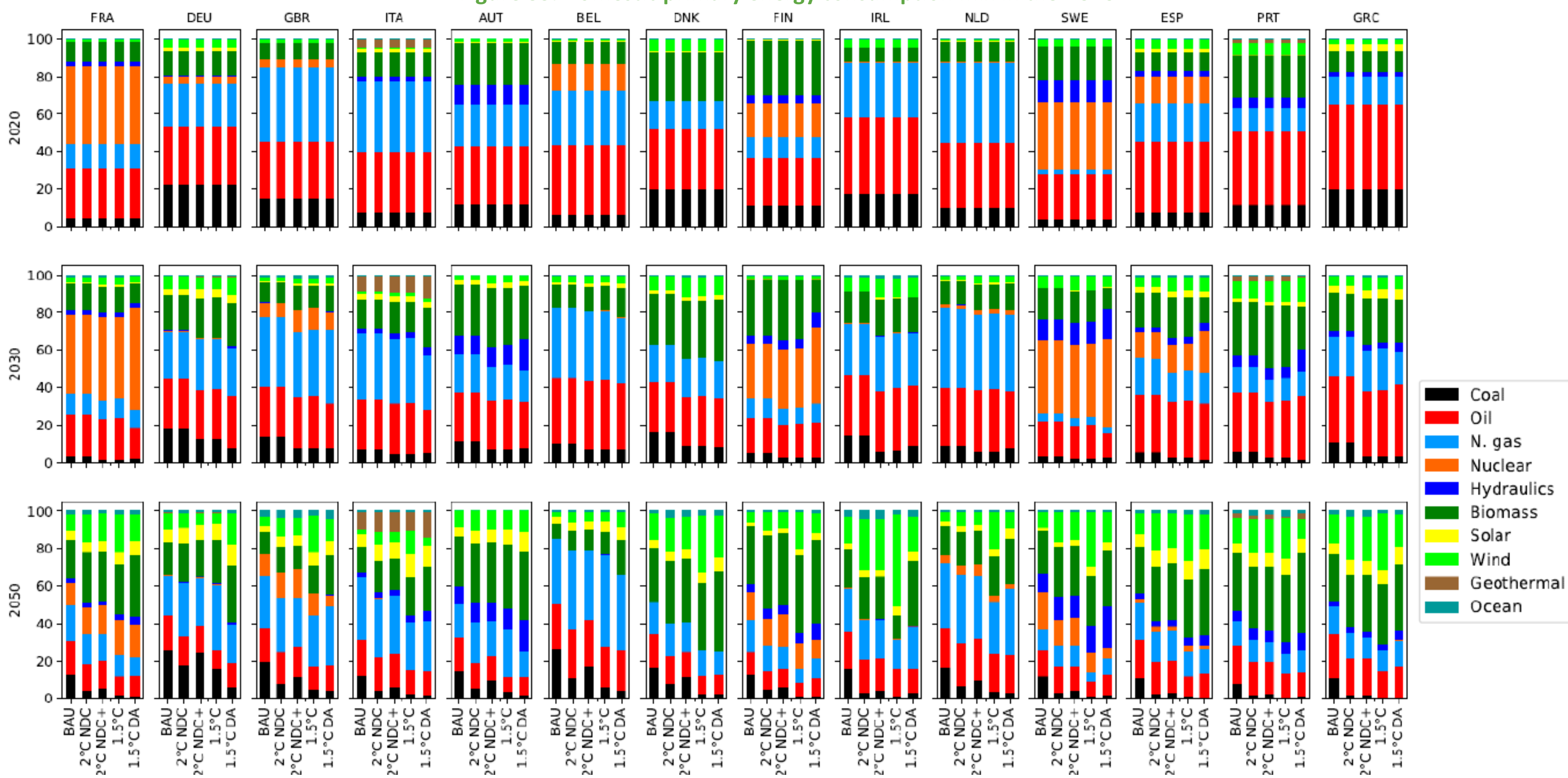
Source: POLES results

Figure 34: Primary energy mix and electricity generation mix in the EU



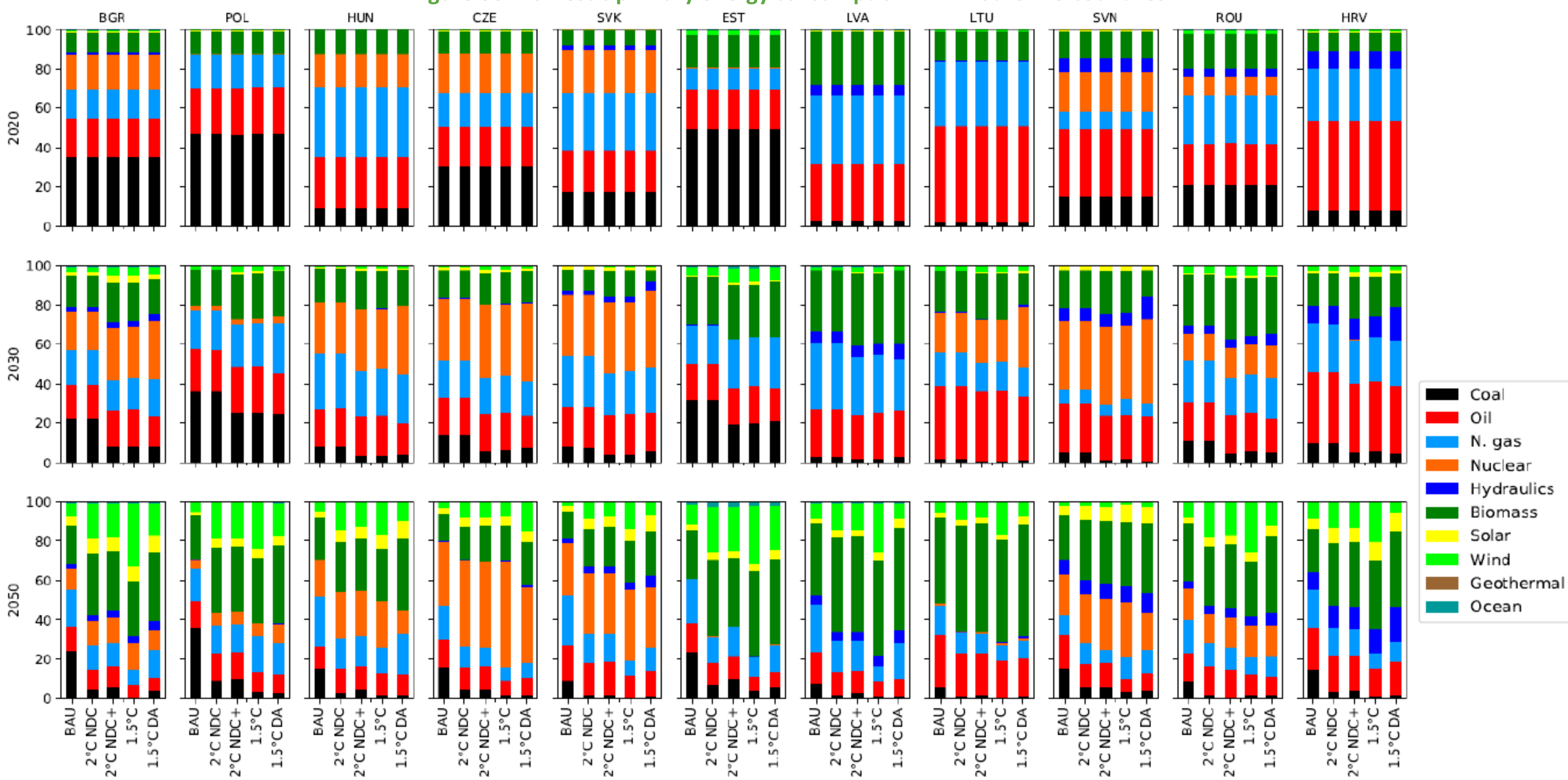
Source: POLES results

Figure 35: Domestic primary energy consumption mix in the EU15



Source: POLES results

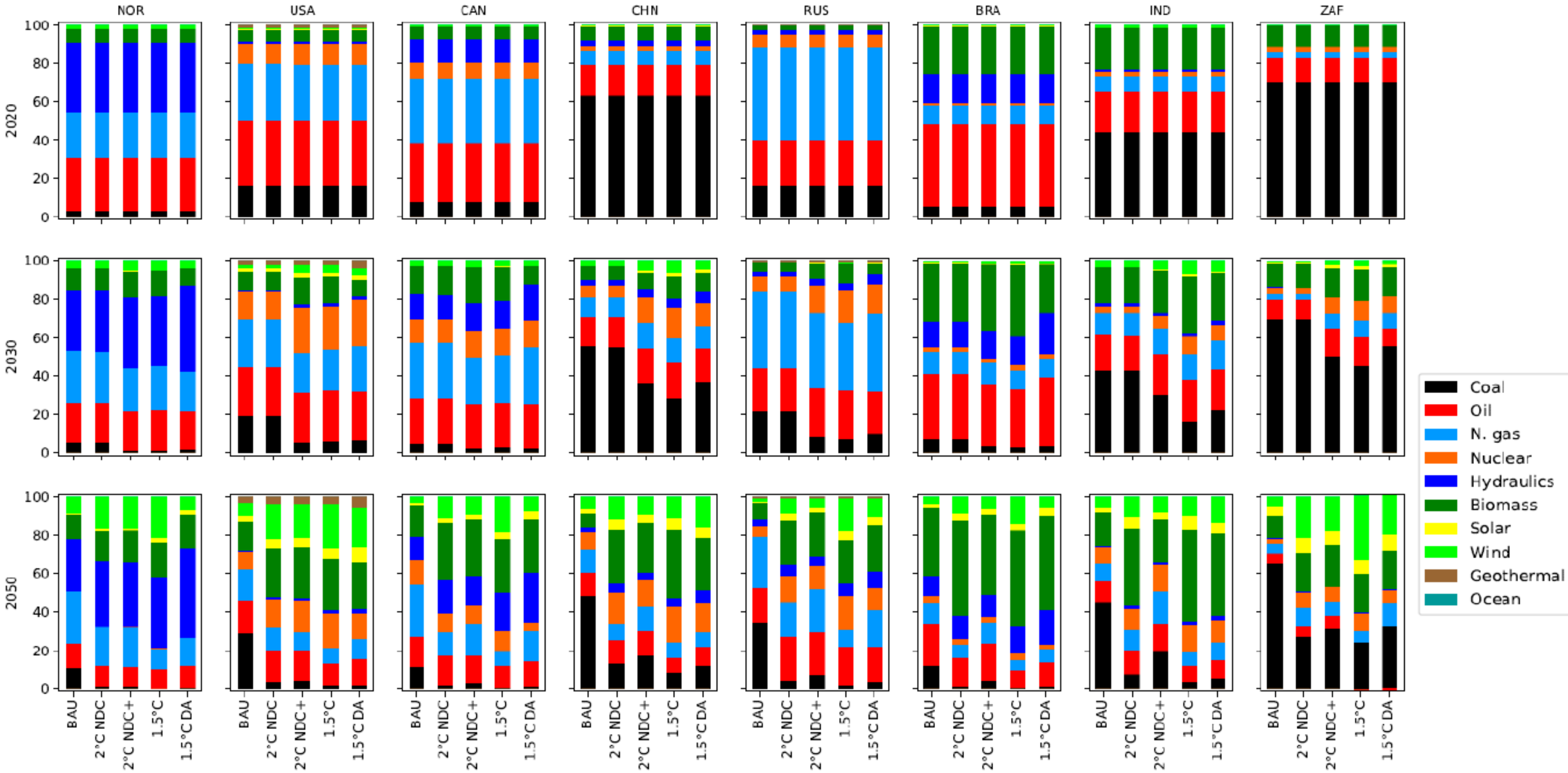
Figure 36: Domestic primary energy consumption mix in other EU countries



Source: POLES results

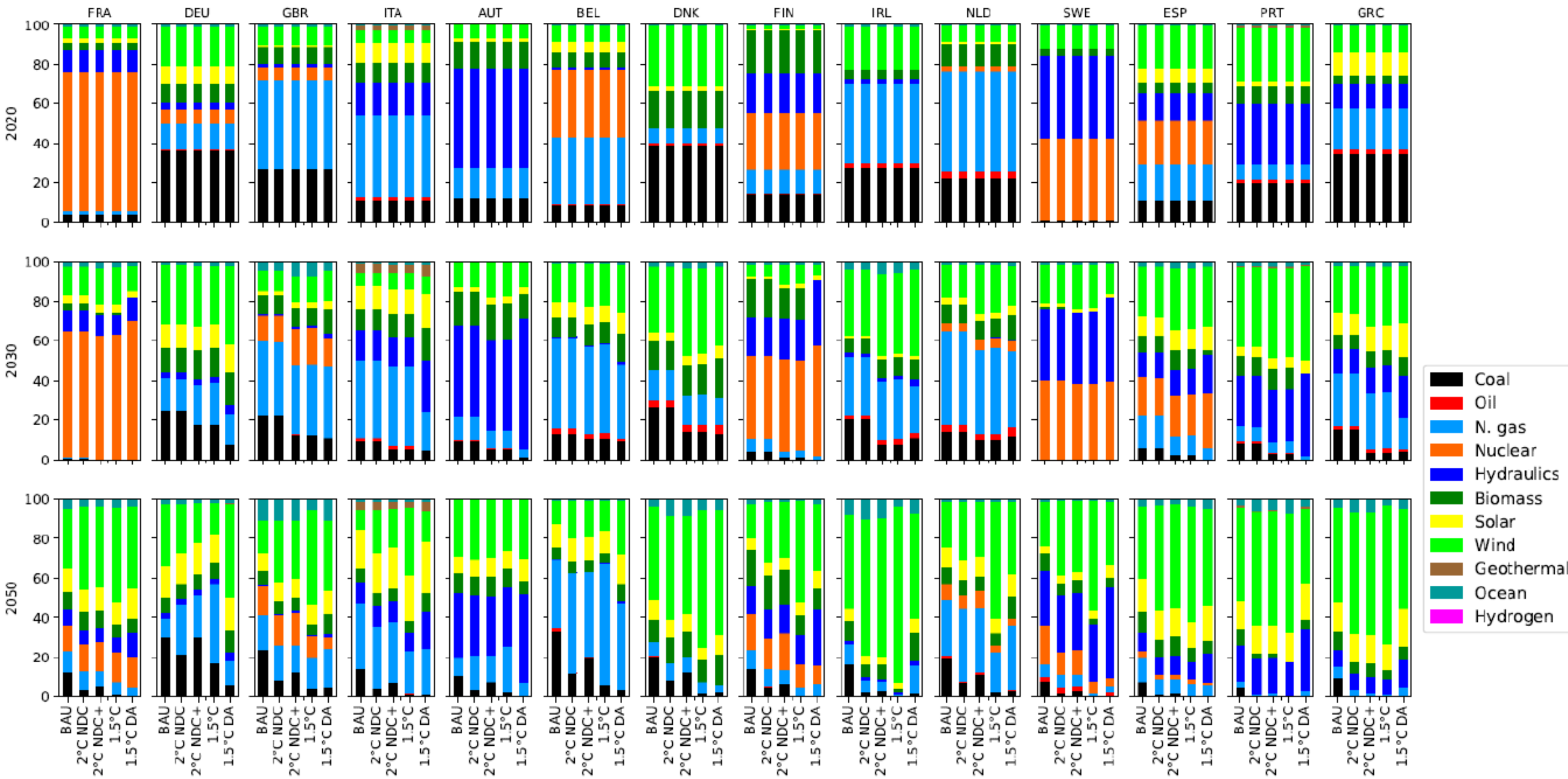
53

Figure 23: Domestic primary energy consumption mix in non-EU countries



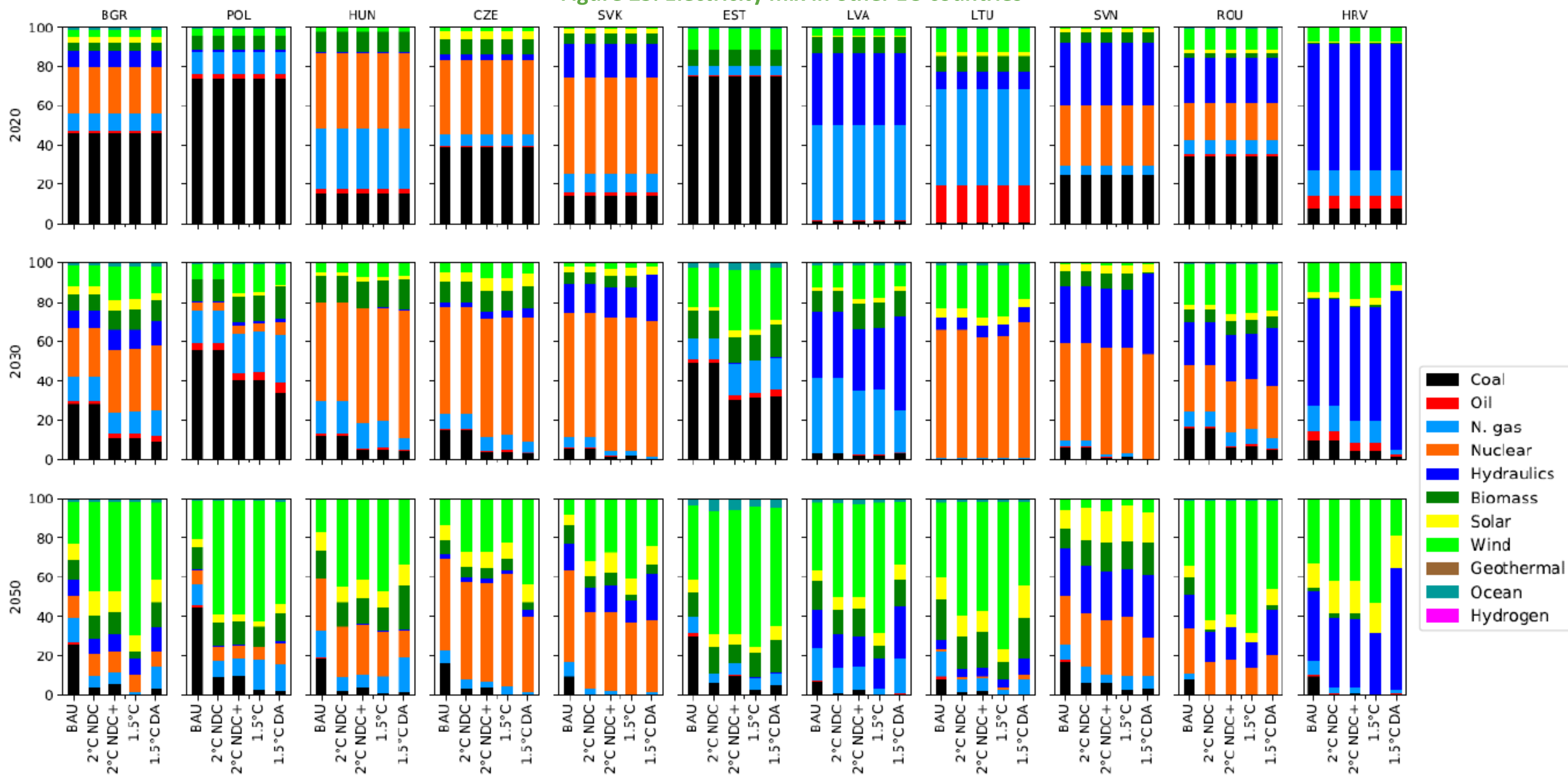
Source: POLES results

Figure 24: Electricity mix in the EU15



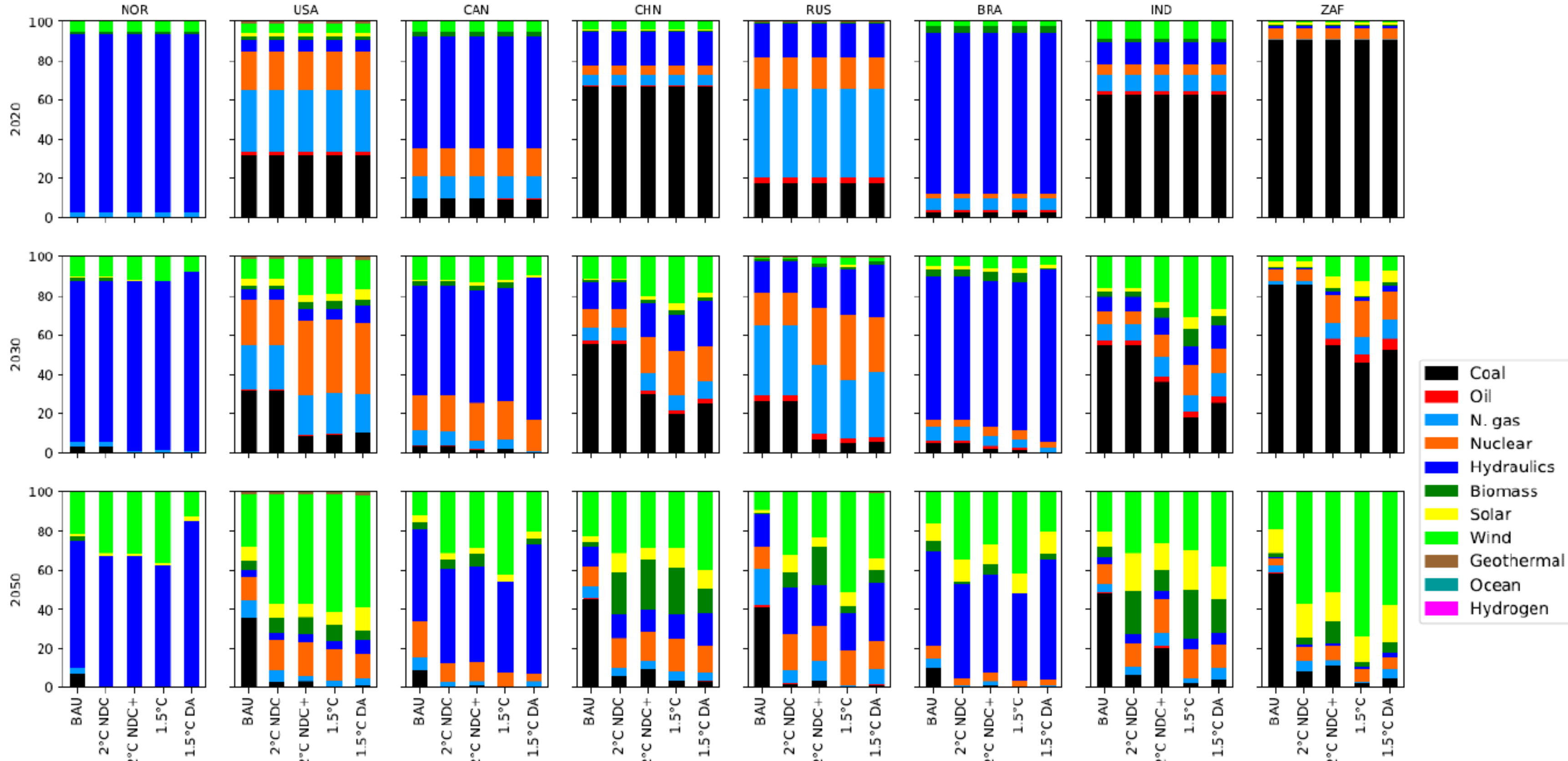
Source: POLES results

Figure 25: Electricity mix in other EU countries



Source: POLES results

Figure 26: Electricity mix in non-EU countries



Source: POLES results