Horizon 2020 Societal challenge 5:
Climate action, environment, resource efficiency and raw materials

COP21 RIPPLES

COP21: Results and Implications for Pathways and Policies for Low Emissions European Societies

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1. Changes with respect to the DoA

As of May 2018, we found a limited set of IAMs (Integrated Assessment Models) scenarios compatible with the long-term goal of the Paris Agreement. Recently, the first new systematic 1.5°C pathways have been published, though underlying data is not yet publicly available (Rogelj et al. 2018, Van Vuuren et al. 2018, Kriegler et al 2018 and Strefler et al. 2018).

Therefore, the quantitative analysis of this deliverable relied on (bottom-up) IEA/ETP 2017 scenarios, instead of (top-down) IAMs scenarios. Due to the different scope and nature of the IEA/ETP model compared to IAMs, the following changes have been made:

- We used the (additional) investment requirements under mitigation scenarios as an indication of the policy cost instead of GDP losses (as usually reported by Integrated Assessment models). The main reason for this is that the IEA/ETP 2017 assumes exogenous GDP projections (not changing across scenarios).
- Compared to IAMs, the IEA/ETP provides information on energy consumption and CO2 emissions at the sectorial level. However, it does not take into account non-CO2 emissions from other sectors (e.g. waste, CH4 emissions from agriculture etc.). Therefore, our analysis focused on selected sectors instead of the whole economy.
- For this reason, we did not compute the associated financial transfers by comparing least cost with "fair and equitable" pathways as the latter is available only for overall GHG emissions. In addition, the IEA/ETP provides limited information on the carbon price (for 2060 only), which is also needed to calculate the financial transfers.

In January 2019 we revised the deliverable by providing an assessment of the latest findings from the IPCC Special Report on 1.5°C and provide benchmarks to characterize 1.5°C pathways compared to 2°C in the short term. This analysis can be used to inform global modelling under WP3.

2. Dissemination and uptake

In this context, this deliverable reviewed publicly available 1.5°C and 2°C scenarios, collected in the project's Database D2.1, in order to provide insights to policy makers on how to reach the long term target of the Paris Agreement. Results can be used in the context of the facilitative (Talanoa) dialogue on how to improve the current level of ambition of NDCs. Results can also inform governments on how to design long term emission strategies in line with the Paris Agreement long term goal.

Under the COP21 RIPPLES project, the report identifies benchmarks that can be used to characterise narratives around 2°C and 1.5°C pathways. Those benchmarks can be used to inform global models under WP3, aiming at exploring the consequences of low-emission pathways for the major GHG emitters, including the EU and its member states. The analysis will provide critical input into D2.5 'Conclusions for the adequacy of pledges and pathways back to 2°C/1.5°C'.

3. Short Summary of results

This deliverable reviews the literature and publicly available data on 1.5°C compatible pathways. At the global level, recent papers based on Integrated Assessment Models (IAMs) and the IPCC SR 1.5C confirm the need for a rapid decarbonisation in the short term and the key role of energy efficiency improvements as enabling factor for 1.5°C. A number of 2030 benchmarks are identified to inform compatibility with 1.5°C pathways.

In order to be able to focus on the EU28 and rely on recent scenario data that tracks more up-to-date technological and policy developments, the quantitative analysis relies on the "beyond 2°C" pathway published by the IEA/ETP as a proxy for a Paris-compatible pathway. Note, however, that this pathway is aimed at a warming limit of 1.75°C and hence fails to achieve the 1.5°C limit of the Paris Agreement.

The assessment provides insights on how to enhance the level of ambition in selected EU countries, with a focus on the power and transport sectors. In general, our results show that a beyond 2°C scenario would require accelerated actions in all EU countries compared to a 2°C, or a reference technology scenario. The EU power sector should be completely decarbonised by around 2040-2050 and then go below zero in the second half of the century. By 2050, there will be virtually no fossil fuels-based power plants in operation in Europe. Countries currently strongly reliant on coal (like Poland) should quickly transform their power sector. Emissions in the transport sector should rapidly decrease over time with increased electrification rates.

4. Evidence of accomplishment

This deliverable is uploaded on the COP21 RIPPLES website.

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1. Introduction

The long-term temperature goal in Article 2 of the Paris Agreement is to hold global warming to well below 2°C and to pursue efforts to limit the temperature increase to 1.5°C. To achieve this end, as mentioned in Article 4 of the Agreement, global emissions should peak as soon as possible with rapid reductions thereafter, in order to achieve "a balance between anthropogenic emissions by sources and removals by sinks" in the second half of the century. In such a context, 1.5°C compatible emissions pathways should be based on best available science.

Before the Paris Agreement, science had focused mostly on "below 2°C" emission pathways, which highlights the need for further research in this area. The IPCC has published a special report on 1.5°C in October 2018.

The goal of this deliverable is twofold: 1) reviewing the literature on 1.5°C compatible pathway and highlight differences compared to the previous "hold below 2°C" goal and 2) analysing the transformation requirements in selected EU countries, with focus on the power and transport sector.

In the framework of the COP21 RIPPLES project we carried out a literature review of currently available 1.5°C emissions pathways to be used to inform global models (WP3) and the wedge decarbonisation analysis (Task 2.4), aiming at identifying the main drivers of decarbonisation. The literature review on low carbon-pathways is based on the IPCC SR 15 (Special Report) on 1.5°C and compares with previous findings from the IPCC AR5, largely focusing on 2°C scenarios. The report will shed light on how to characterise the COP21 RIPPLES storylines around 2°C and 1.5°C and provides benchmarks which could be used for the project's WP3.

Finally, the report will provide an in depth-analysis on how to decarbonise the European Economy in line with the Paris Agreement by using the results from a bottom-up IEA/ETP model. Since the IEA/ETP provides information only for the aggregated EU28 economy, this deliverable will downscale the results to the country level by using a reduced complexity integrated assessment model: SIAMESE (Simplified Integrated Assessment Model with Energy System Emulator) (Sferra et al 2019, forthcoming). The downscaling section will focus on the power and transport sectors for selected EU countries including Czech Republic, France, Germany, Italy, Poland, Spain and the United Kingdom. Those pathways are intended to support policy makers in the transition towards a low-carbon pathway, while taking into account country-specific characteristics.

The deliverable concludes by providing an estimate of the investments requirements in the power sector at the country level, in line with 2C and 1.5C.

2. Literature review

Under WP2, we carried out a literature review of 1.5°C emissions pathways based on the AR5 IPCC database and the IEA's scenarios. Those scenarios can be used to inform global models in WP3 and the decarbonisation wedges analysis in WP2.

The Paris Agreement refers to only one long-term goal ("Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C (…) "). However, its interpretation is not unambiguous. For example, the IEA ETP 2017 recently released a "beyond 2°C" scenario which is consistent with a long-term temperature goal of 1.75°C warming with a 50% probability. The IEA does not clarify if this scenario will lead to a temporary overshoot of the 2°C goal before 2100. If this is the case, this scenario is not consistent with the long-term temperature goal of the Paris Agreement (Schleussner et al. 2016[1]).

Keeping in mind the lack of consistency between pathways in the literature and the Paris Agreement temperature and emissions goals, we consider only pathways that lead to at least 66% chance of staying below 2°C throughout the whole century and a 50% chance staying below 1.5°C by 2100, in line with best available science.

The AR5 IPCC database contains the scenarios published under the 5th Assessment Report of WG3 of the IPCC. The database comprises of 1184 scenarios based on 31 models. However, we found that only five pathways are compatible with a 1.5°C temperature increase, based on only two models: GCAM and IMAGE[2].

Regarding the regional coverage, IPCC data is mostly available at the global level and for five IPCC regions (OECD90, Latin America, Asia, Middle East and North Africa, Reforming Economies). A few model runs also provide data at the country level, namely for the USA, EU27, China, India, Indonesia, Japan, and Korea. Data at the country level, are not directly available from the AR5 IPCC database, but can be accessed from their specific "model comparison projects" websites (e.g. Asian Modelling Exercise database).

[1] Schleussner, C.-F., Lissner, T. K., Rogelj, J., Fischer, E. M., Knutti, R., Licker, R., Levermann, A., Frieler, K., Schaeffer, M. and Hare, W. (2016) "Science and policy characteristics of the Paris Agreement temperature goal", Nature Climate Change 6, 827–835, doi:10.1038/nclimate3096.

[2] We excluded from our analysis a 1.5°C pathway based on the MERGE model, due to implausible high emissions of aerosols leading to air pollution and cooling that is off-setting warming by greenhouse gases, so that this model leads to anomalously high carbon budgets for a specified limit of temperature increase.

Model and Scenario	2°C maximum exceedance probability throughout the 21st century	1.5°C exceedance probability in 2100	Policy constraints	Technology constraints
GCAM 2.0 AME CO2 price $50 (5% p.a.)	16%	48%	P1	T0
GCAM 3.0 EMF27-450-Conv	11%	46%	P1	T2
GCAM 3.0 EMF27-450-LimBio	12%	46%	P1	T2
GCAM 3.0 EMF27-450-NoCCS	13%	49%	P1	T3
IMAGE 2.4AME 2.6 W/m2 OS	15%	49%	P1	T0

Table 1: Summary of AR5 IPCC scenarios. See text for explanation of Policy and Technology constraints P1, T0, T2, T3.

Table 1 shows an overview of 1.5°C compatible emissions pathways available from the AR5 IPCC database. Those scenarios are consistent with at least a 66% probability of holding global warming below 2°C throughout the whole century and at least a 50% probability of not exceeding 1.5°C warming by 2100. As shown in table 1, all of those scenarios are characterised by an immediate adoption of "idealised" climate change policies across all countries (P1), such as the introduction of a global carbon price.

Two out of the five scenarios assume a "full technological availability" (T0). Other scenarios consider some technological restrictions (T2), but nonetheless allow for negative emissions. Finally, only one model (GCAM) can reach 1.5°C without negative emissions (T3), but with very large carbon sequestration by the land sector (afforestation and reforestation).

It is also important to note that some of those scenarios (e.g. GCAM EMF27) rely on substantial negative CO_2 emissions from the land-use sector, leading to deep overall CO_2 emission reductions already in 2020 (Figure 1).

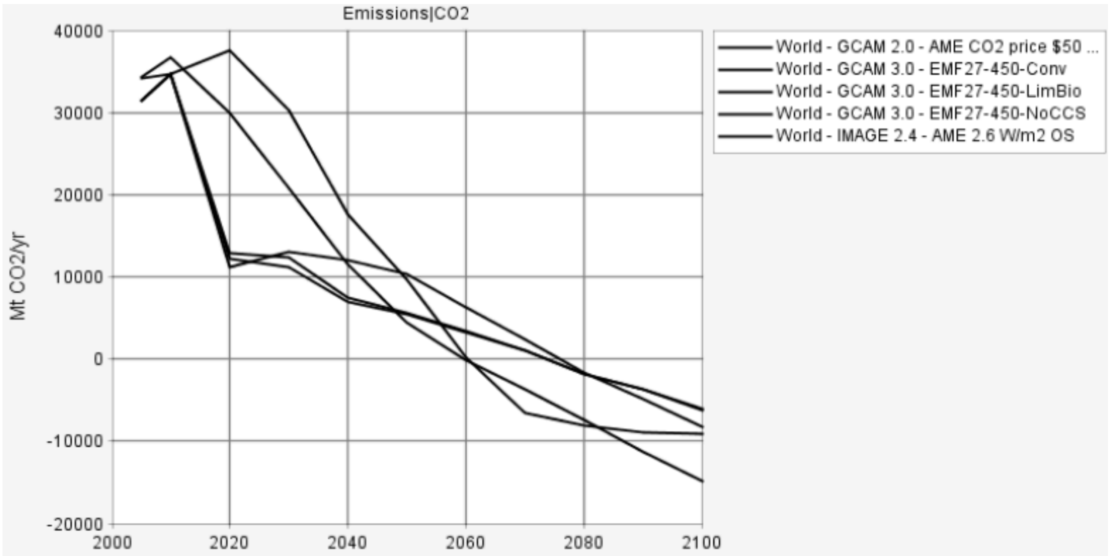


Figure 1: Global CO2 emissions under a 1.5°C target (source IPCC database).

Recently a new paper on 1.5°C (Rogelj et al 2018) confirmed previous findings in terms of a rapid and deep decarbonisation in the short term with global CO2 emissions reaching zero between 2045 and 2060. This study also confirms the key role of energy efficiency improvements in the short term as enabling factor for 1.5°C.

The IPCC Special Report on 1.5°C, published on October 2018, provides new insights on how to achieve the Paris Agreement's long term goal. The report assesses the technological and economic feasibility of achieving 1.5°C more in depth than any other previous IPCC report. IPCC findings are largely based on IAM (Integrated Assessment Models), which provide least cost pathways under a set of idealised condition (including a global carbon price, and perfect markets). These energy-economic models describe an internally consistent and calibrated way to get from current developments to meeting long-term climate targets like 1.5°C. Models reflect technological potentials, structural change, autonomous and price-induced energy efficiency changes, energy resources, reserves, inter-fuel substitutions, economies of scale, imports, exports, etc. all affecting prices and "optimal" prioritisation of mitigation options. Models find optimal least cost pathways by choosing the timing of deployment of mitigation options based on technological development and prices, that is inherently uncertain (Hare, Brecha and Schaeffer 2018).

Based on recent scientific literature, the IPCC SR 1.5°C finds the 1.5°C goal to be within reach under a range of socioeconomic, technological and economic assumptions (as identified by the SSP – Shared Socioeconomic Pathways – storylines, O'Neill et al 2014, Fricko et al 2016, Bauer et al 2016, Riahi et al 2017, Dellink et al 2017). Compared to AR5 mitigation pathways (largely focusing on below 2C scenario), the new 1.5C IPCC pathways are characterised by greater mitigation efforts on the energy demand side.

However, the 1.5C goal pushes IAMs to their limits in both structural and scientific terms, as virtually any known mitigation option has to be deployed. In this context model assumptions such as SSP storylines play

an important role as they represent varying socio-economic challenges to adaptation and mitigation. SSPs can be combined with a set of climate policy assumptions that together would lead to emissions and concentration outcomes consistent with the RCPs. SSPx-1.9 are 1.5°C compatible by 2100. Broader literature includes other concepts like Sustainable Development Pathways, climate-resilient development pathways, etc. that can also be 1.5°C scenarios.

New 1.5C emissions pathways are generally in line with sustainable development storylines (SSP1 – "sustainability") or with historical technological patterns (SSP2 – "middle of the road"). Other storylines characterised by lack of international cooperation or regional rivalry (SSP 3), inequality (SSP4) and fossil fuel development (SSP5), are generally less compatible with Paris Agreement's long term goal.

Under 1.5C pathways global GHG emissions should be in the range of 25-30 MtCO2eq by 2030 (Allen et al 2018). The IPCC SR 1.5C finds that stronger emissions reduction by 2030 lead to a higher change of limiting warming below 1.5C without (or with limited) overshoot. To this end, emissions should decline sharply in the coming decade with the goal of achieving net zero emissions by mid-century.

Typical Paris Agreement compatible pathways show that the energy sector should be decarbonised in the near-term, with coal phased out globally by 2050 (by 2040 in China and 2030 in the OECD countries). Energy efficiency and other demand-side measures are crucial enabling factor and deployed 5-10 years sooner than in 2°C pathway. As a result, total Primary Energy demand is lower due to higher efficiency across sectors. Substantial mitigation efforts especially in industry, buildings and transport sectors are needed to achieve deep reductions by mid-century. The power sector plays central role in decarbonizing those other sectors through electrification and full decarbonisation in the power sector itself (Rogelj et al. 2018, Strefler et al 2018, van Vuuren et al 2018, Kriegler et al 2018).

Deeper emissions reductions in 2030 (driven by energy efficiency and decarbonisation measures) reduce the need for CDR (Carbon Dioxide Removal) technologies, which should be developed at scale in the second half of the century to compensate for the lack of current ambition and the rise in global GHG emissions during the last decade. The two main CDR options employed by IAMs are in the land sector (trough afforestation/reforestation) and the energy sector via bioenergy in combination with CCS (BECCS). CDR deployment vary across models and largely depends on the assumptions made (e.g. SSP storylines).

Those pathways exclude geoengineering technologies such as Solar Radiation Management (SRM) which are not in line with the UNFCCC goal (aiming at preventing dangerous anthropogenic interference in the climate system). Finally, SRM does not help in reducing or balancing net GHG emissions, and does not help in achieving the Article 4 goal of the PA.

The IPCC SR1.5 SPM (Summary for Policy Makers) identified upper limits on BECCS and afforestation/reforestation potential by 2050 based on sustainability and economic constraints: BECCS should be lower than 5 GtCO2/year and afforestation/reforestation lower than 3.6 GtCO2eq/year. Consequently, we focus on both 1.5°C and below 2°C compatible pathways with these limits.

The underlying literature basis for the SR1.5 SPM statements (Fuss et al 2018) show that the economic potential post 2050 (e.g. 2100) of CDR technologies (incl. afforestation and BECCS) is far larger but does not include sustainability considerations beyond 2050.
However, because pathways generally exhibit quite rapid changes in these afforestation and BECCS indicators around 2050, we use average numbers over the period 2040-2060. Based on those average values around mid-century, we filter out those pathways that exceed the sustainability constraints on average over that time period.

The table below show key 1.5°C metrics across for IPCC 1.5°C SR scenarios that meet the CDR sustainability criteria for mid-century. The table shows key indicators until 2030, including GDP, population, emissions and energy consumption.

VARIABLES	**2030 global median (and interquartile range)**
GDP Market Exchange Rate 2010$ (Index, *where 2010=1*)	1.84 (1.83-2.07)
Population (Million)	8262 (8262-8262)
Total primary energy consumption (EJ/yr)	481 (452-498)
Total final energy consumption (EJ/yr)	370 (346-386)
GHG Emissions, using AR4 100-year GWPs (MtCO2e/yr)	27332 (25863-28933)
CO2 Emissions from Energy Demand (MtCO2/yr)	10502 (9397 – 12434)
Of which CO2 Emissions from Transport (MtCO2/yr)	6131 (5606-6697)
Of which CO2 Emissions from Industry (MtCO2/yr)	3371 (2519-4107)
Of which CO2 Emissions from Residential and Commercial (MtCO2/yr)	1407 (1368-1859)
CO2 Emissions from Energy Supply (MtCO2/yr)	8912 (6642 – 10256)
Of which CO2 Emissions from Electricity (MtCO2/yr)	5199 (2623-6887)
Carbon sequestration from AFOLU (MtCO2/yr)	137 (61-2601)
Carbon Sequestration Biomass with CCS (MtCO2/yr)	18 (2-167)

A key difference between 1.5°C and 2°C scenarios relates to the rate of decarbonisation in the short term. Pathways limiting warming to 1.5°C (no low overshoot) require a much faster energy system transformation? in the next two decades compared to 2°C pathways (Allen et al 2018). To this end, energy demand is usually met with lower energy use (though energy efficiency), along with a higher share of renewables until 2050 (meeting around 70-85% of the energy mix).
Coal power plants should be virtually phased out by 2050 under 1.5C pathways. New IPCC 1.5°C SR15 scenarios show higher renewable energy development compared to previous model findings, along with a higher electrification rate across sectors.

Important insights from comparisons studies often identify higher mitigation potentials in bottom-up assessments than IAMs in the near term, particularly in the industry, buildings, and transport sectors. Bottom up studies are in general more tied up to specific sectors and regions, and ideally reflect more up to date policies and prices. As a result, sectorial decarbonisation could be faster in near term than identified in SR1.5. For this reason, this deliverable relies on the IEA ETP B2DS pathway for a deeper analysis of short-term emissions reduction in the EU28 in the transport and power sector. The IEA/ETP provides up to date pathways in terms of policies in place and energy prices developments.

The IEA (ETP 2017) estimate that the B2DS pathway leads to a peak global warming of 1.75°C with a 50% probability. A Climate Action Tracker analysis (CAT 2018) along with the IPCC SR 1.5°C confirm that it provides important insights on how to realistically decarbonise the global economy up to at least 2050. The IEA/ETP 2017 provides only energy-related CO2 emissions, whereas land-use and non-CO2 GHG emissions are not reported. While estimating the 1.75°C warming the IEA found that non-CO2 emissions add about 0.35°C to the CO2 only warming.

A study from the Climate Action Tracker (CAT 2018) based on the carbon-cycle/climate model MAGICC (Meinshausen, Raper, and Wigley 2011), shows that the B2DS reaches a peak warming of 1.6°C above pre-industrial level by 2060 (by assuming an RCP 2.6 pathway for non-co2 GHG). The same study shows that if we extend negative CO2 emissions comparable to those in 1.5° C compatible pathways, the B2DS would lead to peak warming dropping below 1.5°C.

The IPCC SR15 has also compared the B2Ds with the IAMs 1.5°C consistent pathways (Chapter 2, section 2.4.3 and Figures 2.18, 2.19 and 2.20). The IPCC confirms that the B2DS scenario is consistent with 1.5°C pathways in terms of emissions up to 2060. A closer look at the sectorial level shows that while emissions intensity by 2050 in the power and industry sectors are above those typical for 1.5°C pathways, B2DS emissions intensity is lower in the buildings and transport sectors. The IPCC SR15 concludes that "… although its [B2DS] temperature rise in 2100 is below 1.75°C rather than below 1.5°C, this scenario can give information related to 1.5°C consistent overshoot pathway up to 2050."

The B2DS scenario until 2060 is confirmed to provide reliable insights on how to decarbonise the economy in line with the Paris Agreement. The rest of this deliverable focuses on the IEA/ETP results globally and for the EU28 in relation to overall and sectorial carbon emissions.

3. EU and Member State-level transformation (based on IEA/ETP 2°C and Beyond 2°C scenarios)

In 2017 the IEA/ETP (Energy Technology Perspective) published a "beyond 2°C" scenario (B2DS) with a 50% chance of limiting warming to 1.75 °C (IEA, 2017a). This scenario leads to a 1.75°C warming in 2100 and thus does not seem to be compatible with the Paris Agreement long-term goal for two reasons. First, their temperature target has a 50% probability of holding global warming to below 1.75°C in 2100, instead of 1.5°C. Second, the IEA report does not clarify what is the "maximum" temperature reached throughout the whole century (and its associated probability), which might also violate the "well-below" 2°C target, as referenced in the Paris Agreement.

Despite this B2DS scenario is not fully consistent with the Paris Agreement's 1.5 °C temperature goal, its global CO_2 emission pathway for both the transport and power sector until 2050 appear to be roughly in line with the least-cost 1.5 °C emission pathways (with a >50% probability by the end of the century) from IAMs (integrated assessment models) (Rogelj et al., 2015 ; Rogelj et al., 2018). IAMs prescribe emissions from electricity sector to reach zero before 2050 and then go below zero in the second half of the century, thus leading to zero GHG emissions by 2050. Regarding the transport sector, emissions should be reduced by roughly a third compared to 2010 according to both IAMs and the IEA B2DS scenario.

The IEA/ETP 2017 scenarios are more technology-oriented than IAM scenarios and takes into account more up-to-date expectations on innovation developments, which makes it suitable in particular for short and medium-term projections. In its beyond 2°C scenario, the IEA/ETP aims for maximizing the mitigation potential associated with existing technologies, and for this reason it can provide useful insights on how to realistically increase the level of ambition in the short/medium term.

The IEA/ETP 2017 can provide useful benchmarks for the 2025 and 2030 milestones in the upcoming round of NDC revisions and submissions. Indeed, the current level of ambition of NDCs is currently not in line with the PA and would likely lead to 3.2°C warming by the end of the century (CAT 2017).

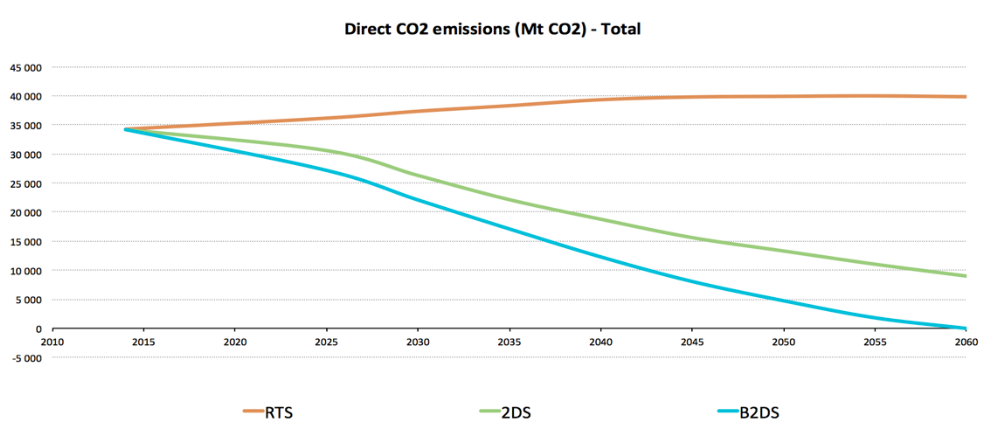


Figure 2: Global Direct global CO2 emissions under a Reference Technology Scenario (RTS), 2°C scenario (2DS) and Beyond 2°C scenario (B2DS). Source: IEA Energy Technology Perspective 2017.

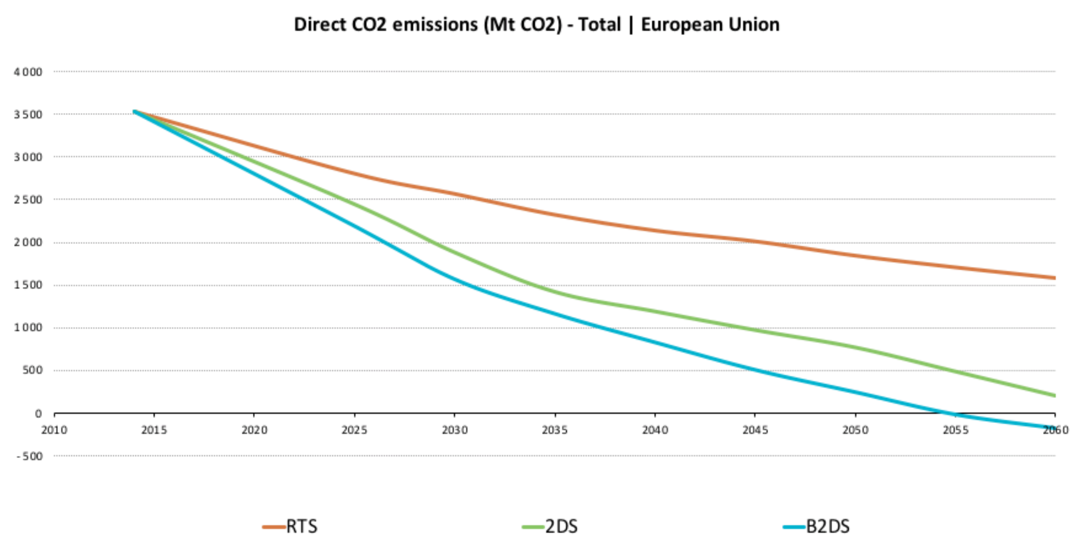
Figure 2 shows global direct CO2 emissions from the IEA/ETP across scenarios: Reference technology scenario (RTS), 2°C (2DS) and a beyond 2°C scenario (B2DS). Apart from global emissions, the IEA/ETP 2017 offers a wide range of indicators at the sectorial level and for the main global emitters[3].

Like other IAMs, the IEA/ETP considers the European Union as a single economic aggregate. Assessing the implications of the Paris Agreement at the country level is crucial in order to keep track of actual mitigation actions and compare them against the transformation requirements.

In the next section we downscale the IEA/ETP 2017 scenarios at the country level, with a focus on the power and transport sectors. The literature clarifies that decarbonizing the power sector is an enabling factor for achieving 1.5°C (Rogelj et al 2015). Moreover, the electricity sector is expected to become increasingly connected to the transport sector, due to the expected higher demand in the road transport sector for clean power generation to charge batteries or produce other energy carriers (e.g. hydrogen, synfuels etc.).

3.1. Decarbonising the EU economy

The IEA/ETP relies on the TIMES model for future energy results under different scenarios. Figure 3 shows Direct CO2 emissions across scenarios in the EU28, during the time period 2014-2060. The IEA/ ETP explores a Reference technology scenario (RTS), 2°C (2DS) and a beyond 2°C scenario (B2DS). The reference technology scenario assumes a continuation of current pledges and commitments, including NDCs. This scenario represents current level of climate ambition, and therefore, it not consistent with the Paris Agreement, despite entailing a significant deviation compared to a business-as-usual scenario.



[3] Namely: Brazil, China, European Union, India, Mexico, Russia, South Africa and the United States

Figure 3: Direct CO2 emission in the EU28 power sector across scenarios: Reference technology (RTS), 2°C (2DS), and beyond 2°C (B2DS). Source IEA/ETP 2017.

The 2°C scenario sets out an emission pathway that is even not in line with the previous Cancun Agreement "hold below 2°C" goal, as it has only a 50% chance to hold warming below 2°C. It entails a rapid decarbonisation of the EU economy, but not as fast as for a 1.5°C temperature limit. Even the beyond 2°C pathway it is not fully consistent with the Paris Agreement long-term temperature goal as it aims for a 1.75°C warming. However, this pathway appears to be – in the first half of the century – roughly in line with IAM scenarios compatible with 1.5°C regarding the power and transport sector.

3.2. Transformation requirements in selected EU countries

In this section, we downscale the IEA/ETP 2017 scenarios at the country level by using a simplified model: SIAMESE Simplified Integrated Assessment Model with Energy System Emulator (Sferra et al. 2019 forthcoming).

3.2.1. Method

This deliverable employs a model-based approach to downscale the IAM results to the country level: SIAMESE (Simplified Integrated Assessment Model with Energy System Emulator).
SIAMESE is essentially a reduced complexity Integrated Assessment Model, which allocates energy consumption (and emissions) to the country level by maximising welfare in all countries belonging to the same region (e.g. EU28).

SIAMESE provide pathways consistent with IAM results at the regional and global level, under a common set of assumptions (e.g. common SSP storylines, technological availability). To this end, SIAMESE takes into account expected GDP and population growths at the country level, based on SSP storylines (Fricko et al 2016, Dellink et al 2017, SSP database).

SIAMESE is calibrated to replicate the historical energy consumption at the base year (e.g. 2014). This calibration process is intended to reflect current infrastructures and resources availability at the country level, while introducing inertia in the transition towards low carbon pathways.

In absence of specific policies in place, SIAMESE allocates energy consumption at the country level by equalising the marginal cost of energy for each technology in all countries, under a welfare maximisation approach. SIAMESE can also take into account specific policy in place or other constraints at the country level to provide policy-relevant scenarios. For example, we will consider current nuclear or coal-phase out policies in selected countries in the EU28

In terms of the equations, SIAMESE mimics the structure of IAMs, with a representative agent maximising welfare over time under a perfect foresight assumption. The sectorial GDP is a function of population (L), capital (K) and energy consumption (Q), by using a CES (Constant Elasticity of Substitution) production function.

$$Y_{t,j} = \gamma_{t,j}\left\{a_j\left(K_{t,j}{}^{s}L^{1-s}{}_{t,j}\right)^{\rho} + (1-a_j)\left[\left(\sum_f a_{j,f}Q_{t,j,f}{}^{1/\rho_e}\right)^{\rho_e}\right]^{\rho}\right\}^{1/\rho} \qquad (1)$$

Y is the GDP for each region (*j)* and time (*t)*. In order to provide realistic results, we employ the same population assumptions (*L*) as in the IEA/ETP 2017 scenarios for the EU28, that we proportionally[4] scale down to the country level based on the SSP2 "middle of the road" storyline (Fricko et al 2016, Dellink et al 2017, SSP database). In a similar manner we harmonise the GDP with the IEA/ETP projections, by calibrating the total factor productivity γ.
Energy consumption (*Q)* comprises different fuels type (*f*), in line with the sectorial resolution of the IEA/ETP 2017.

Capital for production of final goods (*K)* can be increased by means of dedicated investments (*I)* and it is subjected to depreciation rate (δ).

$$K_{t+1,j} = K_{t,j}(1-\ \delta)^{\Delta t} + I_{t,j}\ \Delta t \qquad (2)$$

Consumption of final goods is the remainder of the GDP after subtracting investment and energy expenditures:

$$C_{t,j} = Y_{t,j} - I_{t,j} - \sum_f Q_{t,f}\ P_{t,f} \qquad (3)$$

Then we make sure that the country-level results comply with the IEA/ETP results at the country level:

$$\sum_f Q_{f,j,t} = \bar{Q}_{f,t} \qquad (4)$$

At the same time, we compute the energy prices as the derivative of GDP with respect to energy consumption (for each fuel):

$$\frac{\partial Y_{j,t}}{\partial Q_{j,f,t}} = P_{f,t} \qquad (5)$$

Finally, the objective function for the time-dependent solution is represented in Equation 6, where W is the welfare to be maximised:

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[4] For example, if Germany represents x% of the EU28 population in a given time period (based on the SSP2 storyline), we apply the same percentage to IEA/ETP population for the EU28.

$$W = \sum_{t,j} (1 - d)^t \ L_{t,j} \log \frac{C_{t,j}}{L_{t,j}} \qquad (6)$$

In this deliverable, we employ SIAMESE to downscale these results at the country level for selected EU28 countries. While using SIAMESE we assume that the EU28 region of the IEA ETP-TIMES model can be decomposed into a number of (selected) inner economic countries: Germany, France, Italy, Spain, UK, Czech Republic and Poland. Therefore, we derive the energy at the country level based on 1) the IEA/ETP model results of the EU28 region and 2) socio-economic (GDP and population) projections for all the selected countries and the rest of the EU28 region.

We can apply the SIAMESE methodology to the overall economy (e.g. scaling down the overall primary energy consumption and emissions), or to individual sectors (e.g. transport and power).
However, since there are no specific GDP (or value added) projections at the sectorial level from the SSP storylines, we assume sectors (e.g. transport and power) at the country level will grow at the same rate of the overall GDP, based on the SSP2" middle of the road" storyline (Fricko et al 2016, Dellink et al 2017, SSP database). In a similar manner we also assume that labour employed in each sector will grow at the same rate of population.

The SIAMESE methodology allows for enhancing the regional resolution of the IEA/ETP 2017 model, by providing Paris Agreement compatible pathways at the country level, which are currently not available. If specific policies are not taken into account, SIAMESE implicitly assumes countries will equally contribute (from a cost optimisation perspective) towards achieving a given climate target (e.g. 2°C or 1.5°C). This assumption is particularly suitable under low carbon pathways, as countries are required to quickly converge towards low carbon policies.

However, there are still fundamental differences across EU28 countries in terms of energy and climate change policies. For example, countries like the UK, Poland and Czech Repoublic are planning to increase their electricity generation from nuclear power plants, whereas other countries like France and Germany are planning to phase out power plants. While downscaling the IEA/ETP results, we therefore take into account specific policies in place at the country level.

SIAMESE is also calibrated to replicate the observed data at the base year at the country level, which introduces some inertia in the transformation of the energy sector. Finally, we make sure that the sum at the sectorial level comply with the IEA/ETP results for the EU28.

3.2.2. Transport sector results

This section focuses on the transport sector results under a beyond 2°C pathway and compares with a 2°C and a reference technology scenario).

According to the ETP/IEA 2017, under a beyond 2°C scenario the European transport sector should be largely decarbonised by mid-century, with overall emissions declining by 85% compared to 2014 levels by 2050 (Figure 4, panel b and c).

Figure 4 panel a) shows the transformation requirements under a below 2°C pathway: from present day fossil fuel consumption to biofuels, electrification and hydrogen. The beyond 2°C scenario (continuous lines) requires accelerated actions compared to a 2°C scenario (dotted lines) in all the European countries. In particular, a beyond 2°C scenario would require higher electrification rates (hydrogen will play a limited role according to the IEA/ETP 2017). This pattern is clearly visible for France (green line) and Italy (orange line) but applies to all countries.

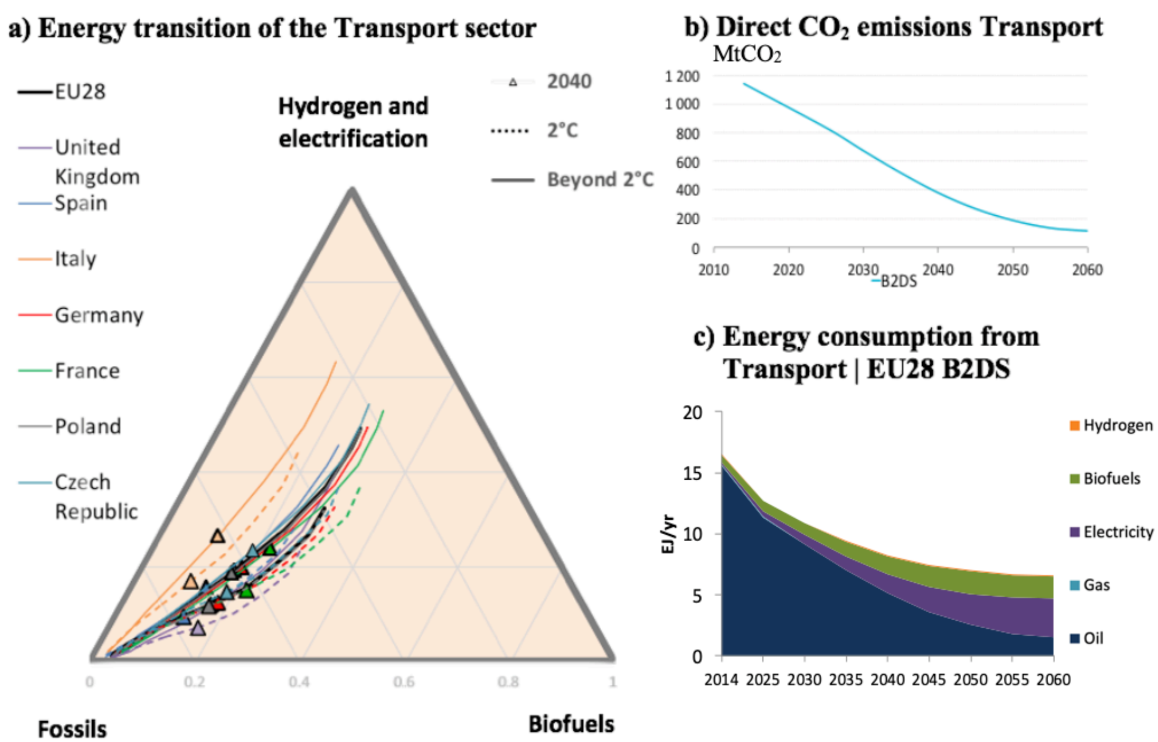


Figure 4: Transformation requirements in the EU28 Transport sector. Panel a) shows the Energy structure of the transport sector under a beyond 2°C scenario (continuous line) and 2°C scenario (dotted lines). Coloured lines represent country-level results (source: SIAMESE), whereas the black lines denote the EU28 results (source IEA/ETP 2017). Panel B) shows direct global CO2 emissions under Beyond 2°C scenario (B2DS) for the EU28 (source IEA/ETP 2017). Panel C) shows energy consumption in the transport sector (source IEA/ETP 2017).

Figure 5 shows a comparison of energy consumption across different countries and scenarios. Results show that overall transport energy consumption is expected to decline over time compared to 2014 levels, in all scenarios. The deepest decline is achieved under a beyond 2°C pathways, which highlight the need for enhanced energy efficiency. In particular, oil is set to decrease over time in all scenarios.

Under a reference technology scenario gas consumption is expected to slightly increase over time, whereas it will virtually disappear from the energy mix under a 2°C and beyond 2°C scenario.

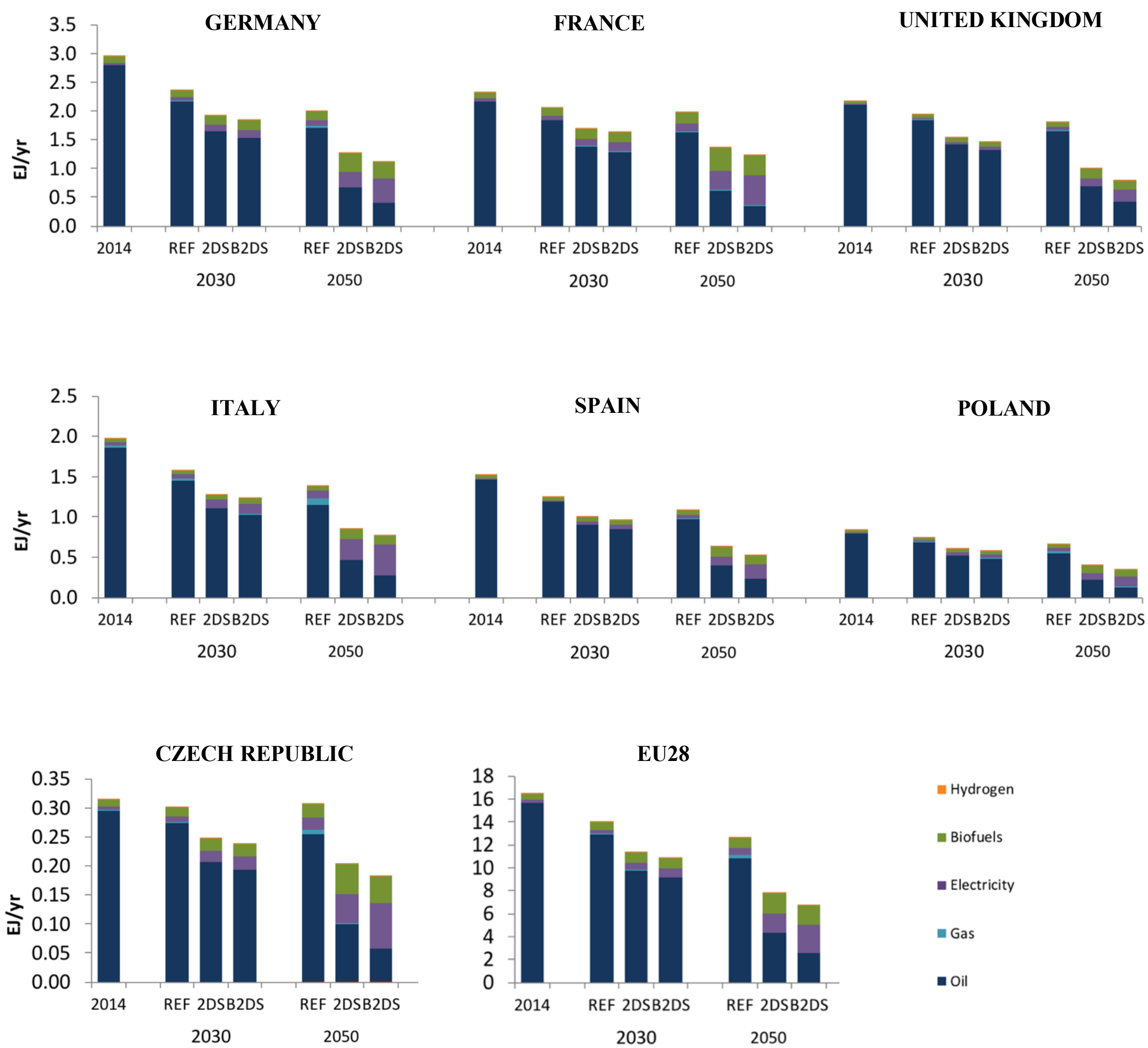


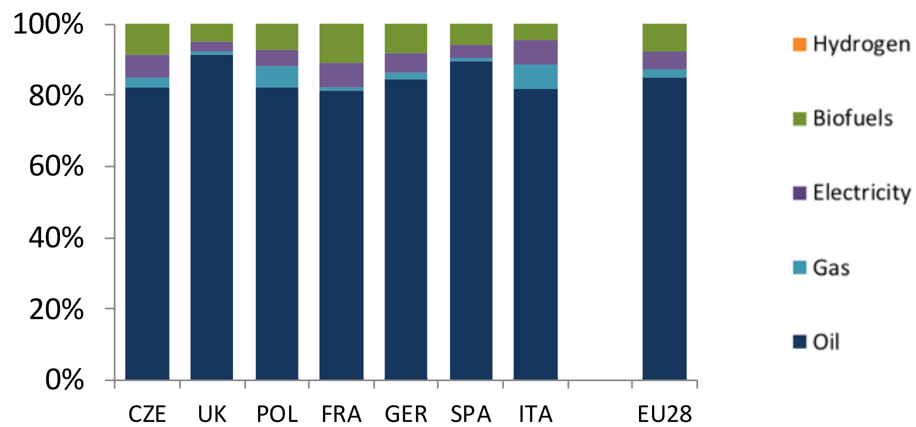
Figure 5: Energy consumption of the Transport sector in selected European countries, across scenarios: Reference technology (REF), 2°C scenario (2DS) and beyond 2°C (B2DS). Data show consumption at the base year (2014) and then 2030 and 2050. Source SIAMESE downscaling and IEA/ETP 2017.

By mid-century, more than half of total transport energy demand is projected to be met by electricity and biomass (Figure 6) under a beyond 2°C scenario. For Italy, France and the Czech Republic, electricity share

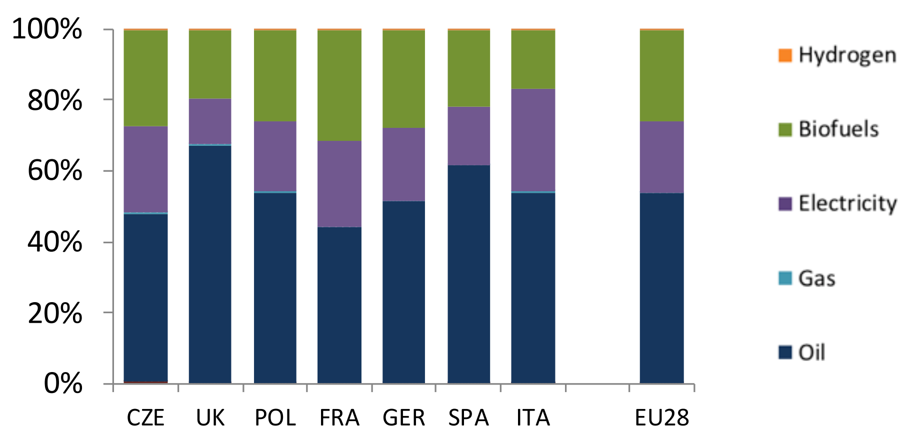
is higher than average by 2050, while bioenergy reliance reaches highest levels in France, Germany and the Czech Republic. Overall fossil-fuel reliance is lowest in France and the Czech Republic, roughly half the share compared to the UK. Spain and the United Kingdom are expected to be the countries with the highest reliance on fossil fuels by mid-century, although in a beyond 2°C scenario it would cover less than half of the total transport demand.

Under a beyond 2°C scenario, energy demand is expected to drop in most of the countries by roughly a half compared to 2014 levels. France is expected to reach the highest level of energy consumption in the transport sector among the (selected) EU countries by 2050, by largely replacing oil with both biofuels and electricity.

a) Reference Technology | 2050



b) 2°C scenario | 2050



c) **Beyond 2°C Scenario | 2050**

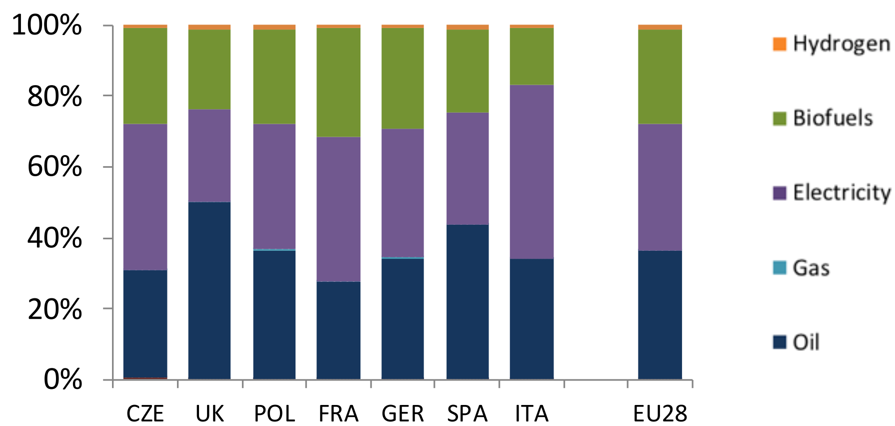


Figure 6: Energy consumption in the transport sector in 2050 across EU countries and scenarios: Reference Technology Scenario (panel a), 2°C scenario (Panel b) and beyond 2°C scenario (Panel c). Source: SIAMESE downscaling based on IEA/ETP 2017.

Unfortunately, the IEA/ETP does not provide detailed results for all transport modes. As most of current policies in place in the transport sector focus on road passengers transport, we were not able to include these policies in our modelling exercise (focusing on overall transport). Conceivably, higher electrification rates should be expected in road transport passengers, whereas in the freight, bunkers and aviation modes we could expect somehow lower decarbonisation rates. Regarding freight, in May 2018 the EU Commissions proposed to reduce the average CO2 emissions from new trucks by at least 30% by 2030 below 2019 levels. A study from the Climate Action Tracker (Sferra et al 2018) showed that this is a first step in the right direction although not yet in line with what is needed for the Paris Agreement.

To conclude, the 2°C pathway entail a deeper transformation compared to the reference technology scenario. Biofuel consumption is expected to increase over time along with increased electrification rates. Under a beyond 2°C pathway the electrification rate should increase even further covering more than half of total energy consumption demand by 2060. Overall transport energy demand is set to decline in all countries, which confirms previous literature findings that energy efficiency is an enabling factor for the Paris Agreement long term temperature goal (Rogelj et al 2015). Results from the SIAMESE model suggest that the transformation path would be relatively similar in all EU countries, with increasing demand for electric mobility. However, some differences emerge, including a higher electrification rates in Italy, France and Czech Republic. In the United Kingdom, oil is expected to meet half of the overall transport demand by 2050 under a beyond 2°C scenario, above the EU average. Despite the UK's announcement of a plan to ban fossil fuels cars by 2040[5] for passenger transport (the Guardian 2017), oil will conceivably continue to fuel other transport modes including aviation, maritime and to some extent freight transport. Additional

[5]Similar plans have been also announced by France and Germany (Bloomberg 2017). However, our analysis focused on overall transport due to lack of data for each transport mode from the IEA/ETP 2017 report. Therefore, these plans have not been explicitly included in SIAMESE.

technologies not covered by the IEA/ETP 2017 report might accelerate the transition to low-carbon transport, which emphasises the need for additional research and R&D investments.

3.2.3. Power sector results

This section focuses on the power sector results under a beyond 2°C pathway and compare with a below 2°C and reference technology scenario.

While downscaling the EU28 results with SIAMESE, we include specific policies in place at the country level (please see appendix A for a detailed list). We also assume that those policies are implicitly taken into account by the IEA/ETP 2017 results while providing the results for the aggregated EU-28 region (so that country-level results are fully consistent with the IEA/ETP 2017 scenarios for the EU region).

According to the ETP/IEA 2017, under a beyond 2°C scenario the European power sector should be completely decarbonized by around 2040-2050, with emissions going below zero in the second half of the century (Figure 7, panel b, c).

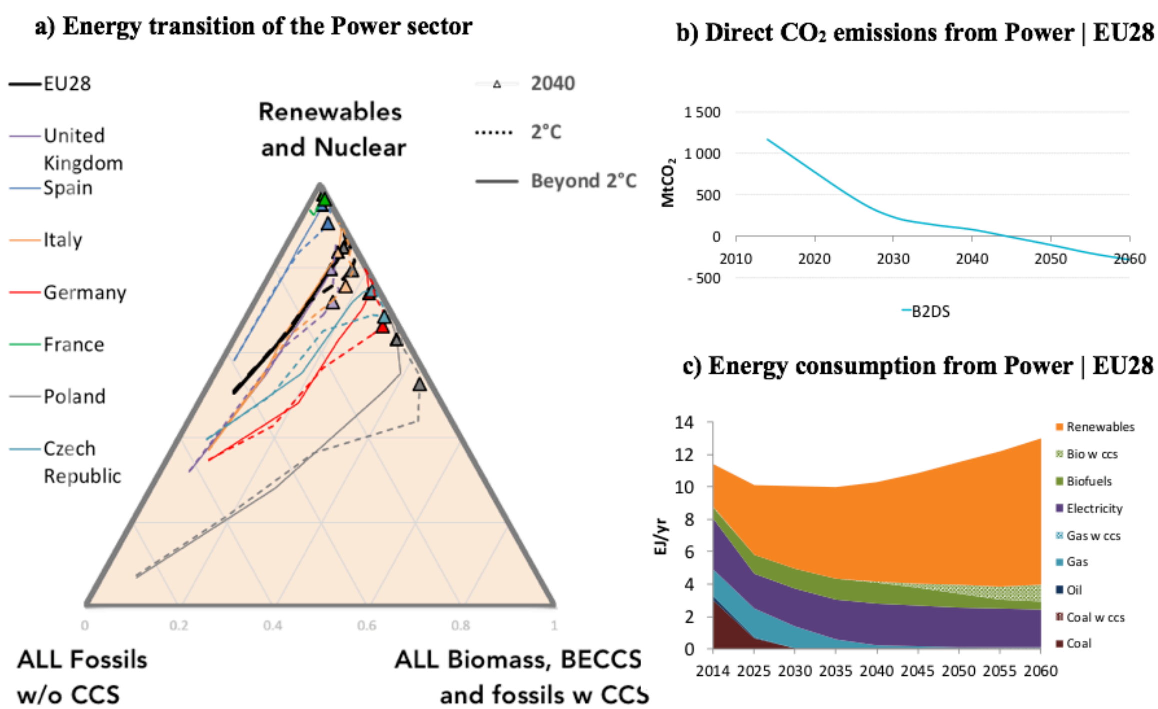


Figure 7: Power sector transformation requirements under a Beyond 2°C scenario (2014-2060-time horizon). Panel a) shows the transformation requirements under a 2°C (dashed lines) and below 2°C pathways (continuous lines): from present day fossil fuel consumption to biofuels, electrification and hydrogen. The black solid lines show data for the EU28 (source IEA/ETP 2017). Coloured lines show the downscale IEA/ETP 2017 results at the country level (source SIAMESE). Triangles represent 2040 data points for each country. Panel b) shows direct global CO_2 emissions under Beyond 2°C scenario (B2DS) for

the EU28 (source IEA/ETP 2017). Panel c) shows the energy consumption in the transport sector, under a beyond 2°C scenario for the EU 28 (source IEA/ETP 2017).

As shown in the previous section, under a beyond 2°C scenario, all countries should substitute fossil fuels in the transport sector with increased electricity consumption. This confirms the role of decarbonized power sector as enabling factor to achieve further emission reductions in other sectors (Rogelj et al 2015).

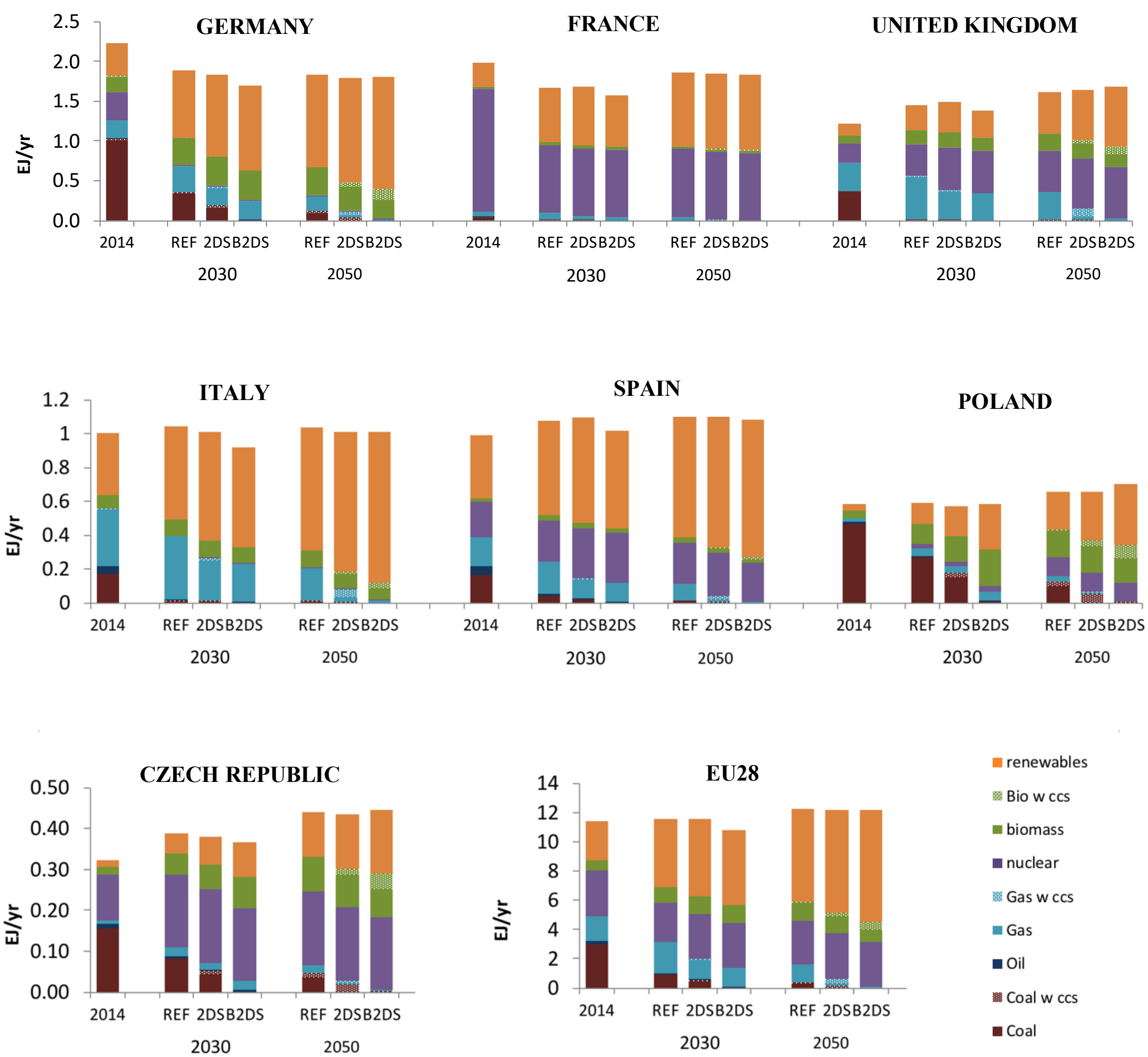


Figure 8: Electricity mix across countries and across scenarios (Reference Technology, 2°C and beyond 2°C), in 2014, 2030 and 2050.

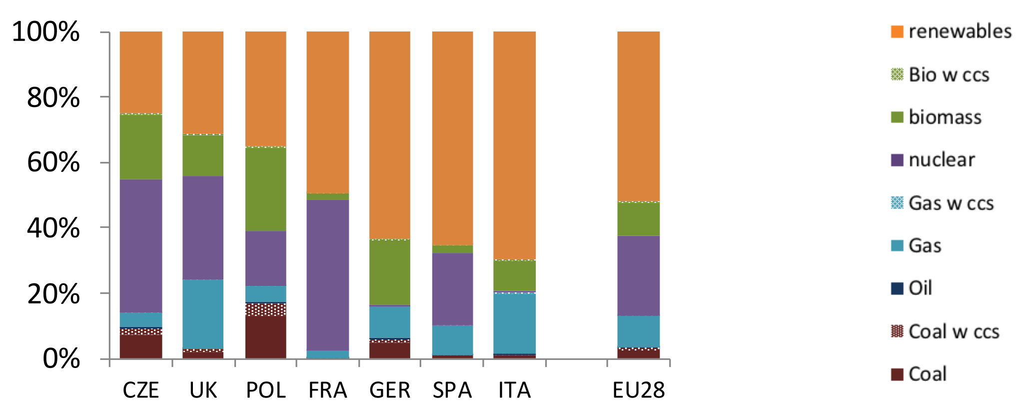
Figure 8 shows that a beyond 2°C scenario entails a lower energy consumption in 2030 compared to a 2°C and reference technology scenario in virtually all countries, highlighting the need for energy efficiency improvements in the short term.

Fossil fuels with CCS seems to be unnecessary in a beyond 2°C scenario, whereas all countries are required to deploy biomass with CCS to achieve negative emissions by mid-century. To achieve this, clear policy signals are needed, including support for negative emission technologies like BECCS.

In many European countries, including Italy, Spain and Germany, non-biomass renewable will supply more than half of the electricity demand in all scenarios (with highest values reached under a beyond 2°C pathway). Countries heavily reliant on coal, like Czech Republic and Poland would need to quickly transform their power sector. The transformation need to be quicker under a beyond 2°C pathway compared to a Reference technology scenario. Coal plants would be replaced mostly by renewable energy, biomass and nuclear energy. Other countries like Spain and the UK would substitute fossils with nuclear and renewables. Germany and France which already decided to reduce or abandon nuclear energy would need to enhance energy efficiency while investing in renewable energy.

Our results show that under a beyond 2°C scenario there will be virtually no fossil fuels-based power plants in operation in Europe by 2050 (with the exception of a few gas fired power plants) (Figure 9). SIAMESE projects a large share of renewables in Italy and Spain. Nuclear will continue to supply around half of total electricity demand in France (in line with current policies). Additional nuclear reactors are expected to come on line in Poland and Czech Republic. Those results are mainly driven by the higher nuclear energy demand projected by the IEA/ETP 2017 under a beyond 2°C scenario in the EU28. Allocation of this overall higher demand to individual countries by SIAMESE is affected by the current power plants infrastructures, but crucially also determined by the projected GDP and population growth in these countries and the relative costs of nuclear energy compared to low-carbon alternatives. In short, SIAMESE allocates energy consumption by equalizing the marginal cost of energy in all countries. In addition, SIAMESE takes into account current policies in place at the country level, such as plans to build new reactors (e.g. Czech Republic, Poland and the UK) or to limit or abandon nuclear energy (e.g. France and Germany).

a) Reference Technology | 2050



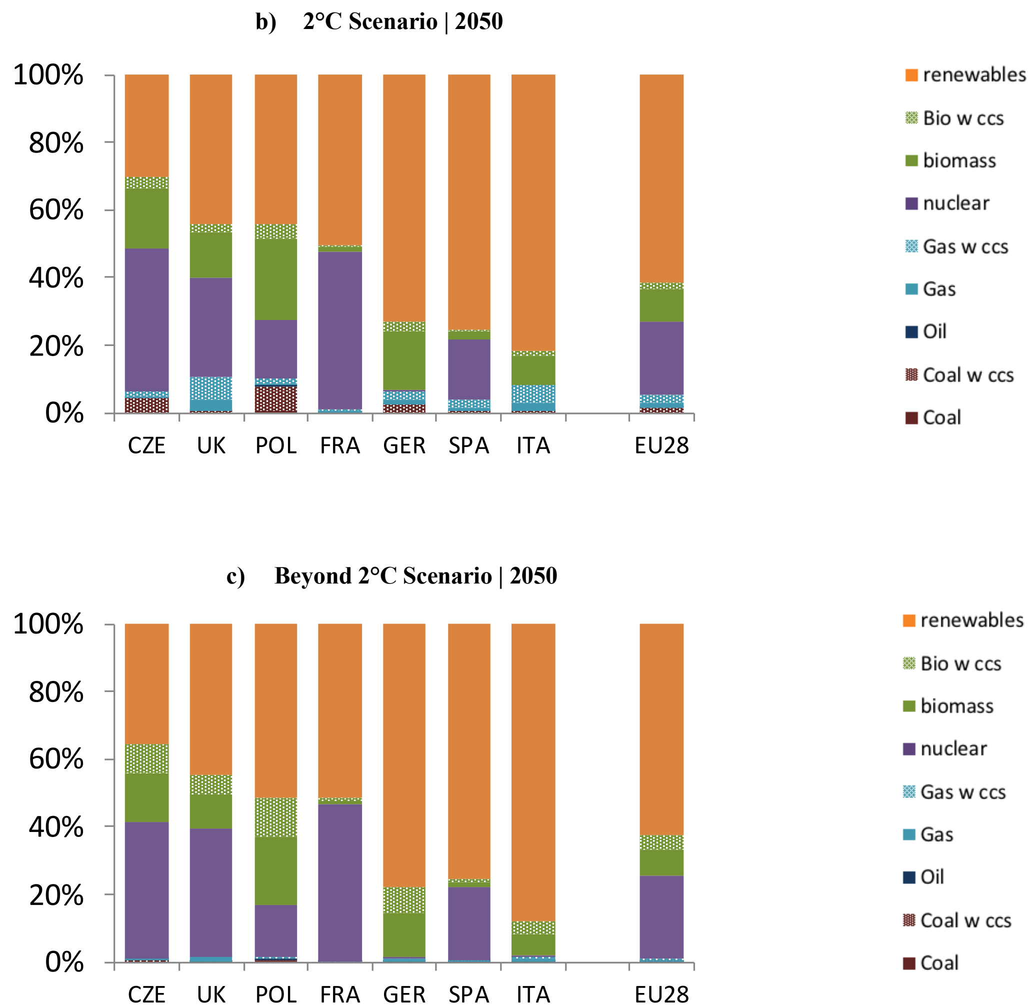


Figure 9: Electricity mix in 2050 across EU countries and scenarios: Reference Technology Scenario (panel a), 2°C scenario (Panel b) and beyond 2°C scenario (Panel c). Source: SIAMESE downscaling based on IEA/ETP 2017.

Coal power plants would need to be phased out in all countries by 2030. Poland, for example, is currently heavily reliant on coal and needs to face a quick transformation of the power sector. More than half of installed power plants in Poland need to be replaced by non-biomass renewables by 2030. The remaining plants can be replaced by biomass-based plants and – to some extent – nuclear energy (in line with current policies in place). In the short term, energy efficiency measures are pivotal to ensure the transition to a low-carbon economy (also considering the expected increase in power demand from the transport sector). To achieve this, clear policy signals are needed, including support for renewables and negative emission technologies like BECCS.

However, other authors (Ecke et al 2017) suggest a phase out by 2030 in Poland would be problematic given the very large current share of coal in the energy mix. A somewhat slower pace with a phase out even just a few years later appears to facilitate a much smoother and feasible transition.

Investments requirements in the power sector

In this section we estimate the amount of investments associated with electricity generation presented above. As the current version of SIAMESE does not explicitly include investments, we calculate the energy investments requirements ex-post (see additional explanations in annex).

Estimating the amount of power investments, we would require information on: 1) the retirement schedule of power plants, 2) the load factor (annual utilization rate of plants) and 3) the capital cost of different power technologies. The IEA/ETP only provides data on the load factor in the EU 28: (we compute it by dividing electricity generation by installed capacity). Then we apply the same load factor of the EU28 to all member states.

However, the IEA/ETP does not provide detailed information on the investment cost assumptions nor the retirement schedule (or depreciation rate). Therefore, we had to rely on external data and assumptions. The investment cost assumed in our analysis, are based on the AMPERE inter-comparison project (Riahi et al. 2014, Kriegler et al. 2014, Capros et al. 2014) which provides the capital costs assumptions ($ per KW installed) for each technology, based on IAMs data. For CCS technologies we assume a markup of 20%. However, for renewables, we use more recent capital cost data from IRENA 2018. We assume that these costs remain constant over time, except for renewables, where the capital cost will decline according to a 20% learning rate. This would reduce the investment cost of renewables by roughly a half by 2060 compared to 2014 levels (table 2) under all scenarios (a bit less in a Reference Technology scenario).

While using a methodology in line with IAMs, we derive the additional investments capacity by using some capital accumulation equations (see annex). We assume that the additional installed capacity is a function of: 1) the GW installed in the previous time period, subjected to a depreciation rate, and 2) the capital cost of technologies. The depreciation rate reflects the average technical lifetime of power plants (a lower depreciation rate entails a higher lifetime).

Assumptions	Capital cost ($/KW)	Learning rate	Annual Depreciation rate of installed capacity
Coal w/o ccs	1800	-	2.0%
Oil	500	-	5.0%
Gas w/o ccs	500	-	3.5%
Nuclear	5000	-	1.5%
Bio w/o ccs	1250	-	3.5%
Renewables	2067	20%	5.0%
Coal w ccs	2160	-	2.0%

Bio w ccs	1500	-	3.5%
Gas w ccs	600	-	3.5%

Table 2 Capital cost assumptions at the base year, learning rate (capital cost reduction for each doubling of cumulative installed capacity) and depreciation rate of installed capacity

However, for nuclear power plants, we enhanced our calculation by taking into account the expected decommissioning years of existing power plants (e.g. UK, Czech Republic) (IAEA, World Nuclear Association). In absence of specific data on this, we derived the shutdown schedule of current power plants based on the date of commercialisation, assuming an average technical lifetime of 60 years. New installed nuclear plants projected by SIAMESE after 2014 are subjected to depreciation rate (Table 2).

Our results show that renewables will dominate investments plans in the near future (Figure 11), although some countries – in particular the UK and Czech Republic – are also planning to expand their nuclear generation capacity or substitute old reactors (World Nuclear Association, 2018). Poland and Spain are also set to likely invest in nuclear energy. Poland announced the construction of new reactors that are expected to come on line around 2035 (IAEA 2018, World Nuclear Association, 2018), whilst the future of Spain's policies on nuclear generation is more uncertain. Currently there is no power plants under construction in Spain, even though nuclear investments are expected before 2030.

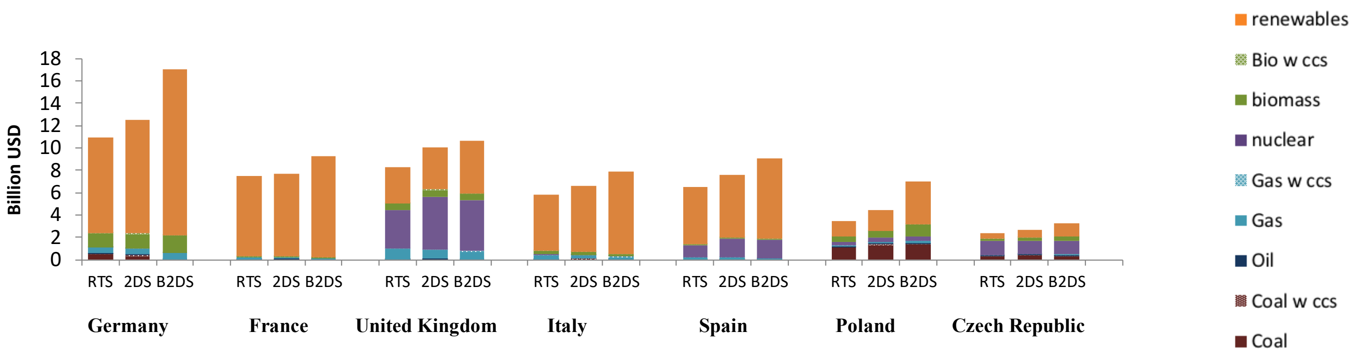


Figure 10: Average annual investments in electricity generation during the period 2014-2030 under a Reference technology scenario (RTS), 2° scenario (2DS) and beyond 2°C scenario (B2DS). Source: own calculations based on SIAMESE model results

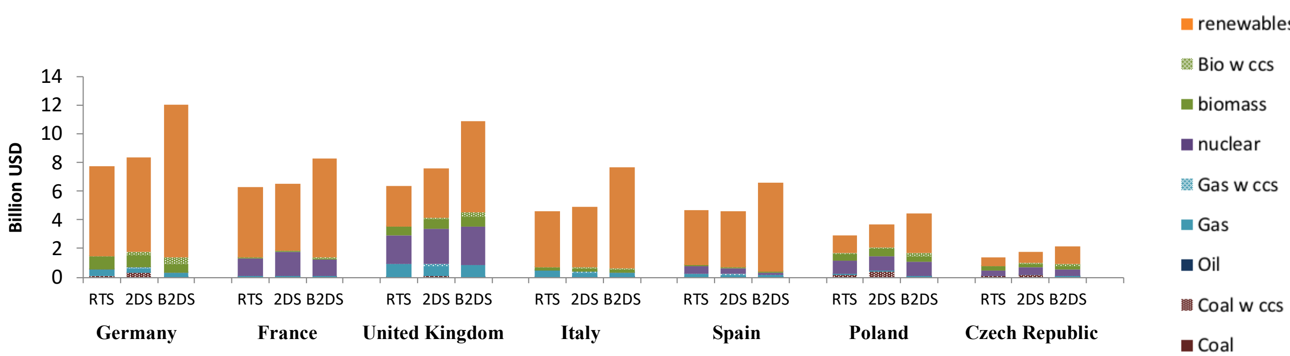


Figure 11: Average annual investments in electricity generation during the period 2030-2050 across scenarios: Reference technology (RTS), 2° scenario (2DS) and beyond 2°C scenario (B2DS). Source: own calculations based on SIAMESE model results

Annual investments from 2014 to 2030 are on average higher than in the period 2030-2050. This is not a coincidence: in the short-term renewables are expected to become increasingly competitive in all scenarios by phasing out installed coal plants or by reducing their utilization rate.

Investments in coal during the period 2014-2030 mainly reflect decisions taken in the past (Figure 10). Indeed, all of our scenarios suggest that 2025 would be the end date for investments in unabated coal plants in the EU. However, it is important to note that the Reference Technology Scenario is somehow more ambitious than a current policy scenario (as published for example by the IEA/WEO 2018) as it takes into account both current policies and pledges. As some coal power plants are currently under construction in the EU, countries are required to revise their plans and accelerate climate actions in line with their pledges to avoid an unnecessary (and costly) lock in carbon-intensive infrastructures.

Decarbonising the power sector would require additional investments, especially in countries that are currently heavily reliant on coal plants. In Poland, for example, under a beyond 2°C scenario investments from 2014 up to 2030, would be twice as much as those required in a Reference Technology scenario. This transformation is challenging and requires clear policy signals to foster the development of renewables and other low or negative emission technologies. Despite the additional investments, the transition to a decarbonized power sector can lead to significant co-benefits including additional job opportunities and air quality improvements. At the same time, Poland and other countries can take advantage of the expected declining cost in renewable energy, which is likely to reduce the investments requirements in a longer time period up to 2050 as shown in Figure 11.

Under a beyond 2°C scenario there will be virtually no fossil fuel investments beyond 2030, also including CCS. Some limited investments in fossil fuels investments with CCS would come online under a 2°C pathway, but not under a beyond 2°C. To some extent, fossil with CCS would conceivably lead to unintended “carbon leakage”, and it is therefore unlikely that they would capture 100% of carbon emissions. It is probably for this reason that fossil fuels with CCS do not come online in the EU28 under a beyond 2°C pathway (source IEA/ETP 2017), and therefore appear to be not in line with a Paris compatible pathway.

4. Conclusions

In this deliverable we have reviewed the literature on 1.5°C compatible pathways. We found that the IPCC AR5 database contains only a few scenarios compatible with the long term goal of the Paris Agreement (1.5°C warming with at least 50% probability by the end of the century, and at least 66% probability of staying below 2°C throughout the whole century).

New IAMs scenarios compatible with 1.5°C have been published in 2018 (Rogelj t al. 2018, Van Vuuren et al. 2018, Kriegler et al 2018 and Strefler et al 2018). New literature confirmed earlier findings regarding the need for rapid decarbonisation in the short term and the key role of energy efficiency (Rogelj et al. 2018). Unfortunately, only a few data from this new IAM scenarios are publicly available (as of May 2018).

Due to the lack of published data on 1.5°C compatible pathways, our analysis relied on a "beyond 2°C scenario" published by the IEA/ETP 2017. Although this pathway entails a median global warming of 1.75°C by the end of the century, its global emission trajectory for the first half of the century is roughly in line with the IAMs 1.5°C compatible range. Also, it contains up-to-date assumption on expected technological developments, and can provide realistic benchmarks for the 2030 milestone of NDCs.

In this deliverable we provide least-cost pathways at the country level by using the SIAMESE model, with the aim to provide insights to policy makers on how to enhance current policies and pledges. Those pathways are the outcome of a downscaling methodology based on the IEA/ETP 2017 result for the EU28. Our analysis focused on the power and transport sector. In general, the results show that a beyond 2°C countries would require accelerated actions in all EU countries compared to a 2°C or reference technology scenario.

In the transport sector we find that emissions need to be considerably reduced over time under a beyond 2°C scenario, although it is unlikely that emissions would approach zero in the first half of the century (with expected technology developments). Additional technologies beyond those covered in the IEA/ETP 2017 could accelerate the decarbonisation process, which emphasizes the need for R&D investments.

Oil consumption is expected to decline in all countries and scenarios, with the lowest values reached under a beyond 2°C target. According to the IEA/ETP 2017, batteries and enhanced electrification would be required to decarbonise the EU transport sector. Hydrogen is likely to remain a niche market in all scenarios, covering around 1% of the EU28 transport demand by 2050 (although a key source of uncertainty lies in the future cost of fuel cell technologies).

Results from the SIAMESE model suggest that the transformation path of the transport sector would be relatively similar in all EU countries, with increasing electrification rates between now and 2050. Higher electrification rates are expected in Italy, France and Czech Republic, whereas bioenergy reliance reaches highest levels in France, Germany and the Czech Republic. Overall fossil-fuel reliance is lowest in France and the Czech Republic, roughly half the share compared to the UK which is likely to rely on oil for roughly

50% of its energy transport needs. This is not a coincidence as France and Czech Republic are expected to maintain relatively high energy consumption by 2050, which is enabled by higher decarbonisation rates. Instead the UK is likely to remain more reliant on oil: hence overall transport demand would need to be reduced by more than half by 2050 compared to 2014 levels (more than the EU average).

Finally, significant differences between a Reference Technology scenario and a beyond 2C scenario suggest that current policies and pledges in the European transport sector fall short of what is needed under a Paris agreement compatible pathway. Additional policy signals are needed such as the introduction of sustained carbon prices or carbon taxes. According to the IEA/ETP 2017, under a beyond 2C pathway the carbon price would reach around 540 \$/tCO2 by 2060. This would correspond to a fuel (tax) increase of roughly 1.5 USD per litre (IEA/ETP 2017).

In the power sector, current policies and pledges seems to be more in line with a Paris compatible pathway, although decarbonisation should occur at a faster rate. In particular, coal power plants would need to be phased out in 2030, whereas by 2050 there will be virtually no fossil-fuel power plants in operation in Europe (beyond 2°C scenario). The power sector needs to be completely decarbonized in all countries by 2050 and go below zero in the second half of the century. Negative emission technologies in the power sector would need to be deployed around 2040. Those negative emission technologies will partly compensate for residual emission in the other sectors, including transport.

Renewable generation is set to increase over time in all countries and under all scenarios. In Italy, Spain and Germany, non-biomass renewables are expected to meet more than half of the electricity demand by 2050 in all scenarios, with the highest values reached under a beyond 2°C pathway.

Nuclear energy is expected to increase over time in Poland, Czech Republic, United Kingdom and, to a minor extent, in Spain. Other countries like Germany and France which decided to reduce or abandon nuclear energy by 2025, would need to enhance energy efficiency while investing in renewable energy.

Currently installed coal-based power plants are likely to become costlier than renewables leading to an early phase out or declining utilization rates. In particular, countries that are currently heavily reliant on coal, like Czech Republic and Poland would need to quickly transform their power sector.

Our analysis also provides estimates on the investment requirements in the power sector (excluding transmission and distribution). Results show that renewables will represent the bulk of investments in the near term. In all countries, fossil fuels with CCS (Carbon Capture Sequestration and Storage) appears to be unnecessary under a beyond 2°C scenario. However, some investments with CCS would come online in the less ambitious 2°C scenario.

Decarbonising the power sector would require additional investments compared to a reference technology scenario especially in countries currently heavily reliant on coal such as Poland. Therefore, countries that are currently investing in unabated coal plants should revise their plans as this would lead to stranded assets and to higher costs than appear necessary. At the same decarbonisation would likely lead to significant co-benefits, including reduced air pollution and additional jobs in the renewables industry.

Our investment analysis is based on data and assumptions from the IEA/ETP as well as other sources (IAEA, World Nuclear Association, IRENA, AMPERE). For this reason, we do not expect our estimates to match those of the IEA/ETP if they were to be published. For example, the IEA/ETP only provides regional estimates on the amount of cumulative nuclear investments required under a Beyond 2°C scenario (from 2014 to 2060). As a comparison, the IEA/ETP envisions 0.7 trillion USD of cumulative investments in the EU28 in nuclear energy, whereas our estimate is lower: around 0.5 trillion. This might be related to a higher capital cost assumption in the IEA/ETP report, or to lower technical lifetime assumptions of existing power plants. On the other hand, our investment estimates up to 2030 appear to be roughly in line with earlier estimates for the EU from the IEA/WEIO 2014 report (see appendix A).

Finally, in our investments analysis we consider non-biomass renewables as an aggregated technology, even though, the capital cost can vary across different types of renewables. For example, onshore wind is currently significantly cheaper than offshore wind (IRENA 2017). For this reason, renewables investments might be underestimated in countries (e.g. the United Kingdom) with a higher offshore wind potential compared to the EU28 average. For this reason, our investment estimates are more suitable for comparison across scenarios rather than across countries.

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Appendix A: Downscaling method

Figure A1 shows the production function of SIAMESE, where GDP is a function of Captal and Labour (KL) and energy consumption (Energy). SIAMESE was originally designed to downscale the regional primary energy results of IAMs at the country level. For this deliverable, we employed it to downscale the IEA/ETP results at the sectorial level. We assume that sectorial GDP growth will follow GDP projections for the whole economy (based on IEA/ETP assumptions for the EU region and harmonized SSP2 projections at the country level).

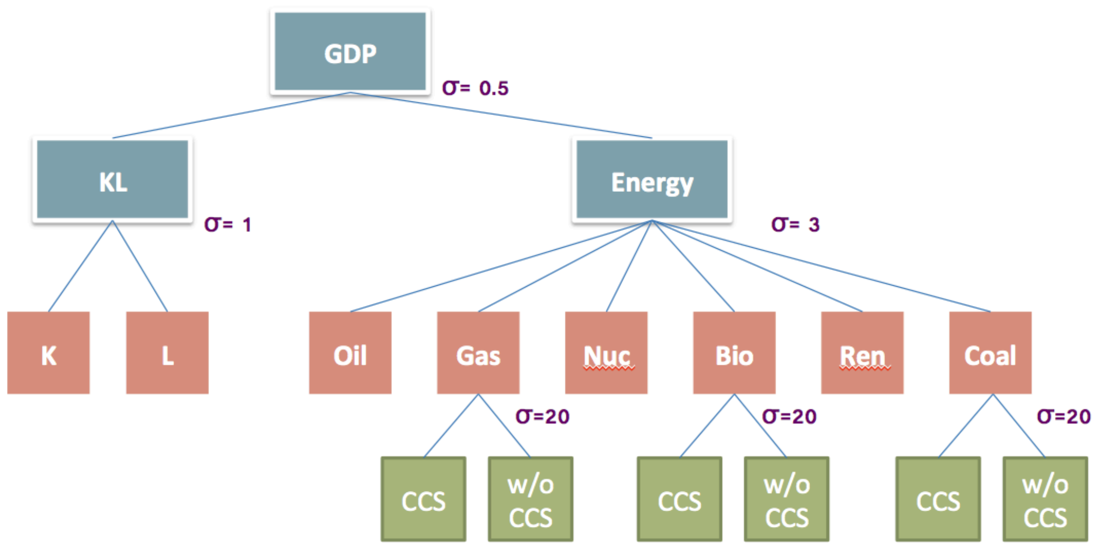

Figure A1: Production function of the SIAMESE model.

At the same time, SIAMESE can take into account specific policy in place at the country level. Therefore, it can provide insights to policy makers on how to realistically improve current policies and pledges in line with the Paris Agreement long term target. Table A1 provides a list of policies and energy targets included in the SIAMESE model

Country	Policies
Poland	Nuclear: ▪ At least 1.3 GW by 2030 and ▪ 4.5 GW by 2040
France	Nuclear: ▪ Less than 50% in the power mix by 2025 Renewables: ▪ At least 40% in the power mix by 2030 Coal:

	▪ Phase out by 2025
Spain	Nuclear: ▪ No capacity additions until 2025 (no nuclear plants currently under construction)
Italy	Coal: ▪ Phase out by 2025
United Kingdom	Coal: ▪ Phase out by 2025
Czech Republic	Nuclear: ▪ Additional 20 TWH (0.07 EJ) by 2030
Germany	Nuclear: ▪ Phase out by 2022 Renewables (incl. biomass): ▪ At least 40% in the power mix by 2025 ▪ At least 55% in the power mix by 2035 ▪ At least 80% in the power mix by 2050

Table A1: List of policies included in the SIAMESE model (in all scenarios)

Based on the SIAMESE model results, we estimate the amount of investments in the power sector across countries and scenarios We calculate investment requirements by employing capital accumulation equations, in line with IAMs approach (e.g. Bosetti et al 2007):

$$KW_{f,j,t+1} = KW_{f,j,t}\,(1-\delta_f)^{\Delta t} + \Delta t\,\frac{I\_power_{f,j,t}}{Capital\ cost_{f,j,t}}$$

The main idea behind this equation is that it would be possible to increase the capacity installed (KW) by means of dedicated investments (I_power), which are driven by the capital cost for each technology (Capital cost). Installed power plants from the previous time period (t) are subjected to a depreciation rate (δ) which reflect the expected lifetime for each type of power plants (f).

With this approach future investments pathways tend to be a bit smoother compared to real world developments, as the decommissioning of power plants is a fixed fraction of the installed capacity in the previous year. In the real world, though, decommissioning of power plants usually follow a step-wise curve, as technologies remain online for some years (expected lifetime) and then drop to zero. For most of technologies we were unable to determine the exact retirement schedule of existing power plants at the country level.

However, for nuclear power plants, we enhanced our calculation by taking into account the expected decommissioning years of existing power plants, based on the year of coming into operation of power plants and their expected technical lifetime (e.g. UK, Czech Republic) (IAEA, World Nuclear Association). In absence of specific data on this, we derived the shutdown schedule

of nuclear power plants currently in operation based on the date of commercialization, assuming an average technical lifetime of 60 years.
New installed nuclear plants (based on SIAMESE scenarios) coming into force after 2014 are subjected to depreciation rate (Table 2).

$$KWnuclear_{j,t+1} = KWold_{j,t+1} + KWnew_{j,t}\,(1-\delta)^{\Delta t} + \Delta t\,\frac{I\_power_{j,t}}{Capital\ cost_{j,t}}$$

We therefore made a distinction between power plants installed until 2014, which will remain online until the end of the economic lifetime (KWold), and new power plants installed after 2014 (KWnew), based on the SIAMESE results. In this manner we can provide a more realistic estimate of nuclear power plants investments.

A comparison with the IEA/WEIO 2014 shows that our average annual investments estimate for the EU28 appears to be in line with previous projections for the period 2014-2030.

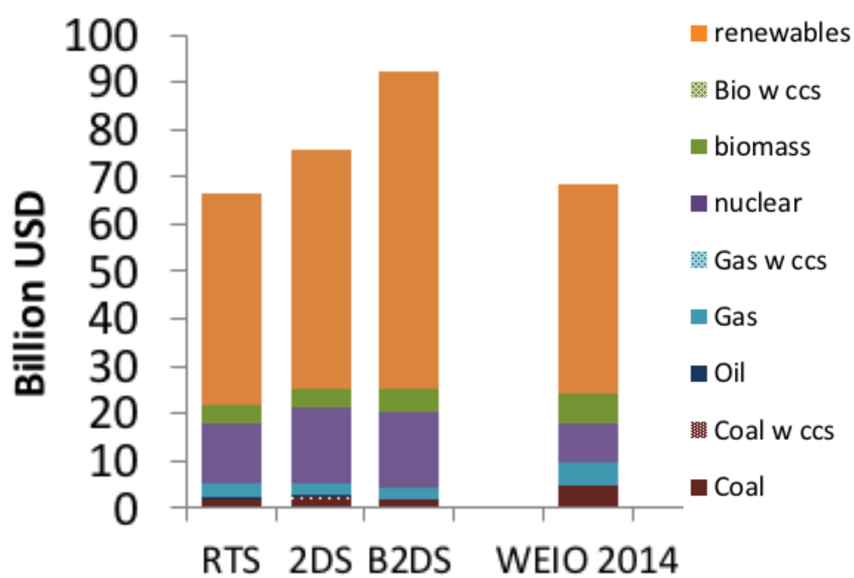

Figure A2: Average annual investments in the power sector of the EU28 from 2014 to 2030. The graph compares the results of our analysis (across scenarios: RTS, 2DS, B2DS) with previous projections from the IEA/WEIO 2014.

Our analysis envisions lower fossil fuels investments in a reference technology scenario because this scenario it is by definition more ambitious than historical business as usual or current trends projections. Our estimates for renewables are still in line with the WEIO 2014, as we take into

more recent data on the capital cost of renewables (IRENA 2017) which decreased substantially in the last few years.

When estimating investments, we consider renewables as an aggregated technology. Therefore, we derived the capital cost of renewables by using a weighted average for each technology, based on IRENA (2017). Weights are based on the share of each technology on total renewables in 2060 from the IEA/ETP (median across scenario).

Assumptions	Capital cost ($/KW)	Share in Renewables in IEA/ETP scenarios by 2060 (median)
Hydro	1535	19%
Solar PV	1388	12%
Solar CSP	5564	4%
Wind onshore	1477	41%
Wind offshore	4239	14%
Other	2000*	10%
Aggregated Renewables	**2067**	**100%**

* Assumption

Table A2 Capital cost of renewables (IRENA 2017) and share in total renewables (IEA/ETP 2017).

Appendix B – SIAMESE results dataset

	Electricity output by fuel (EJ/yr) - Reference pathway																				
	Germany			France			United Kingdom			Italy			Spain			Czech Republic			Poland		
Fuel / time	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050
Coal w/o CCS	1.02	0.35	0.10	0.05	0.01	0.00	0.36	0.01	0.01	0.17	0.01	0.01	0.17	0.04	0.01	0.16	0.08	0.04	0.47	0.27	0.10
Oil	0.02	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.05	0.01	0.00	0.05	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.00
Gas w/o CCS	0.22	0.33	0.18	0.05	0.08	0.04	0.36	0.54	0.35	0.33	0.37	0.19	0.17	0.19	0.10	0.01	0.02	0.02	0.02	0.05	0.03
Nuclear	0.36	0.00	0.00	1.56	0.85	0.85	0.24	0.41	0.52	0.00	0.00	0.00	0.21	0.25	0.24	0.11	0.18	0.18	0.00	0.03	0.11
Biomass w/o CCS	0.19	0.34	0.36	0.02	0.04	0.04	0.09	0.17	0.21	0.07	0.10	0.10	0.02	0.03	0.03	0.02	0.05	0.08	0.04	0.11	0.16
Renewables	0.42	0.85	1.15	0.31	0.69	0.92	0.16	0.32	0.52	0.37	0.55	0.73	0.37	0.56	0.73	0.02	0.05	0.11	0.04	0.12	0.22
Coal with CCS	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.03
Biomass with CCS	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gas with CCS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total electricity	2.23	1.89	1.83	1.99	1.66	1.85	1.22	1.45	1.62	1.01	1.04	1.04	0.99	1.08	1.11	0.32	0.39	0.44	0.58	0.59	0.66

	Electricity output by fuel (EJ/yr) - 2°C pathway																				
	Germany			France			United Kingdom			Italy			Spain			Czech Republic			Poland		
Fuel / time	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050
Coal w/o CCS	1.02	0.17	0.00	0.05	0.01	0.00	0.36	0.01	0.00	0.17	0.01	0.00	0.17	0.02	0.00	0.16	0.04	0.00	0.47	0.15	0.00
Oil	0.02	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.05	0.01	0.00	0.05	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.00
Gas w/o CCS	0.22	0.21	0.02	0.05	0.05	0.00	0.36	0.35	0.05	0.33	0.23	0.02	0.17	0.11	0.01	0.01	0.02	0.00	0.02	0.03	0.00
Nuclear	0.36	0.00	0.00	1.56	0.85	0.85	0.24	0.53	0.62	0.00	0.00	0.00	0.21	0.29	0.26	0.11	0.18	0.18	0.00	0.03	0.11
Biomass w/o CCS	0.19	0.37	0.30	0.02	0.03	0.03	0.09	0.18	0.19	0.07	0.10	0.08	0.02	0.03	0.02	0.02	0.06	0.08	0.04	0.15	0.16
Renewables	0.42	1.02	1.31	0.31	0.74	0.94	0.16	0.39	0.63	0.37	0.64	0.82	0.37	0.62	0.78	0.02	0.07	0.13	0.04	0.18	0.29
Coal with CCS	0.00	0.03	0.04	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.02	0.05
Biomass with CCS	0.00	0.00	0.05	0.00	0.00	0.01	0.00	0.00	0.04	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.03
Gas with CCS	0.00	0.01	0.05	0.00	0.00	0.01	0.00	0.02	0.10	0.00	0.01	0.05	0.00	0.01	0.02	0.00	0.00	0.01	0.00	0.00	0.01
Total electricity	2.23	1.83	1.79	1.99	1.68	1.84	1.22	1.49	1.64	1.01	1.01	1.01	0.99	1.10	1.10	0.32	0.38	0.43	0.58	0.57	0.66

	Electricity output by fuel (EJ/yr) – Beyond 2°C pathway																				
	Germany			France			United Kingdom			Italy			Spain			Czech Republic			Poland		
Fuel / time	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050
Coal w/o CCS	1.02	0.00	0.00	0.05	0.00	0.00	0.36	0.00	0.00	0.17	0.00	0.00	0.17	0.00	0.00	0.16	0.00	0.00	0.47	0.00	0.00
Oil	0.02	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.05	0.01	0.00	0.05	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00
Gas w/o CCS	0.22	0.23	0.01	0.05	0.04	0.00	0.36	0.34	0.02	0.33	0.22	0.01	0.17	0.11	0.00	0.01	0.02	0.00	0.02	0.06	0.00
Nuclear	0.36	0.00	0.00	1.56	0.85	0.85	0.24	0.53	0.64	0.00	0.00	0.00	0.21	0.29	0.23	0.11	0.18	0.18	0.00	0.03	0.11
Biomass w/o CCS	0.19	0.37	0.24	0.02	0.03	0.02	0.09	0.16	0.17	0.07	0.09	0.06	0.02	0.03	0.02	0.02	0.07	0.07	0.04	0.22	0.14
Renewables	0.42	1.06	1.41	0.31	0.65	0.94	0.16	0.35	0.75	0.37	0.59	0.89	0.37	0.58	0.81	0.02	0.09	0.16	0.04	0.27	0.36
Coal with CCS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass with CCS	0.00	0.00	0.14	0.00	0.00	0.01	0.00	0.00	0.10	0.00	0.00	0.04	0.00	0.00	0.01	0.00	0.00	0.04	0.00	0.00	0.08
Gas with CCS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total electricity	2.23	1.69	1.81	1.99	1.57	1.83	1.22	1.39	1.68	1.01	0.92	1.01	0.99	1.01	1.08	0.32	0.37	0.45	0.58	0.58	0.70

	Transport energy consumption by fuel (EJ/yr)– Reference pathway																				
	Germany			France			United Kingdom			Italy			Spain			Czech Republic			Poland		
Fuel / time	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050
Oil	2.79	2.16	1.70	2.17	1.84	1.63	2.10	1.84	1.65	1.86	1.44	1.14	1.47	1.18	0.98	0.29	0.27	0.25	0.79	0.68	0.55
Gas	0.01	0.02	0.04	0.00	0.01	0.02	0.00	0.01	0.02	0.02	0.04	0.10	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.01	0.04
Electricity	0.04	0.06	0.10	0.04	0.07	0.14	0.02	0.03	0.05	0.04	0.05	0.09	0.01	0.02	0.04	0.01	0.01	0.02	0.01	0.02	0.03
Biofuels	0.12	0.13	0.17	0.12	0.15	0.22	0.05	0.06	0.09	0.04	0.05	0.06	0.04	0.05	0.06	0.01	0.02	0.03	0.03	0.04	0.05
Hydrogen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	2.96	2.37	2.01	2.34	2.06	2.00	2.17	1.94	1.81	1.97	1.59	1.40	1.52	1.26	1.09	0.31	0.30	0.31	0.83	0.75	0.66

	Transport energy consumption by fuel (EJ/yr) – 2°C pathway																				
	Germany			France			United Kingdom			Italy			Spain			Czech Republic			Poland		
Fuel / time	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050
Oil	2.79	1.64	0.67	2.17	1.39	0.62	2.10	1.41	0.68	1.86	1.10	0.47	1.47	0.90	0.39	0.29	0.21	0.10	0.79	0.52	0.22
Gas	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Electricity	0.04	0.11	0.27	0.04	0.13	0.34	0.02	0.05	0.13	0.04	0.10	0.25	0.01	0.04	0.11	0.01	0.02	0.05	0.01	0.03	0.08
Biofuels	0.12	0.17	0.36	0.12	0.19	0.44	0.05	0.08	0.19	0.04	0.06	0.14	0.04	0.06	0.14	0.01	0.02	0.06	0.03	0.05	0.10
Hydrogen	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	2.96	1.93	1.31	2.34	1.71	1.41	2.17	1.54	1.02	1.97	1.28	0.87	1.52	1.01	0.64	0.31	0.25	0.21	0.83	0.60	0.41

	Transport energy consumption by fuel (EJ/yr) – beyond 2°C pathway																				
	Germany			France			United Kingdom			Italy			Spain			Czech Republic			Poland		
Fuel / time	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050	2014	2030	2050
Oil	2.79	1.53	0.39	2.17	1.29	0.35	2.10	1.32	0.41	1.86	1.03	0.27	1.47	0.84	0.23	0.29	0.19	0.06	0.79	0.48	0.13
Gas	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Electricity	0.04	0.14	0.42	0.04	0.16	0.52	0.02	0.06	0.21	0.04	0.12	0.39	0.01	0.05	0.17	0.01	0.02	0.08	0.01	0.04	0.13
Biofuels	0.12	0.18	0.32	0.12	0.20	0.39	0.05	0.08	0.18	0.04	0.07	0.13	0.04	0.06	0.13	0.01	0.02	0.05	0.03	0.05	0.10
Hydrogen	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Total	2.96	1.86	1.15	2.34	1.66	1.28	2.17	1.47	0.82	1.97	1.24	0.79	1.52	0.96	0.54	0.31	0.24	0.19	0.83	0.58	0.35