Mitigation strategies to enhance the ambition of the nationally determined contributions: an analysis of 4 European countries with the decarbonization wedges methodology

Sandrine Mathy, Philippe Menanteau

Abstract

Greater efforts are needed to bridge the emission gap between Nationally Determined Contributions and the objective to limit climate change below 2°C. This paper focuses on four European-Union countries: Germany, France, Poland and UK that represent on aggregate 55% of current EU emissions. It analyses national mitigation strategies produced by national research teams in the framework of the COP21_RIPPLES project and compatible with a long-term objective leading to a well below 2°C target either as part of an ambition in 2030 limited to that of the NDCs, or as part of more ambitious early action. We use the decarbonization wedges methodology, an advanced index decomposition analysis methodology for quantifying the contribution of different mitigation strategies. This makes it possible to assess the priorities for action to strengthen the NDCs. The article also highlights the impact sectoral growth dynamics have on the emission trajectories and the resulting necessary mitigation efforts.

Keywords: climate change; European Countries; mitigation strategies; LMDI; activity effect; Nationally Determined Contributions

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I. Introduction

The Paris Agreement aims at limiting the increase in the global average temperature to well below 2°C above preindustrial levels and to pursue efforts to limit this temperature increase to 1.5°C (Article 2.1 of the Paris Agreement, UNFCCC, 2015). It requires Parties to submit Nationally Determined Contributions (NDCs), representing voluntary commitments formulated by each country with a 10-15 years horizon in light of the above collective objective (Article 3 and 4.2). This framework has two direct implications. First, this hybrid approach demands an understanding of the domestic dimension of development pathways and their implications for emissions trajectories. Second, it raises the question of whether the NDC are in line with the global objective of the Paris Agreement.

Extensive literature has explored this issue, leading to the general conclusion that there is a global emissions gap between NDCs and 2°C trajectories: greater efforts will be needed to keep global warming below 2°C by the end of the century (den Elzen et al. 2016; Rogelj et al. 2016). Consequently, the NDC objectives for 2030 must be much more ambitious if the overall emission trajectory is to be in line with the 2050 target.

The present contribution aims to go beyond traditional gap analysis, in terms of aggregate emissions (UNEP, 2018), to provide a systemic analysis of the transformation gap between national NDC and well below 2°C scenarios. For this purpose, we use the decarbonization wedges (DW) methodology elaborated by Mathy et al. (2018). This entails index decomposition analysis (IDA), which allows quantifying the contribution of the various mitigation options in contrasting scenarios. The methodology splits forecast energy-related CO2 emissions up to 2050 into decarbonization wedges, on the demand side and on the supply side. The specificity of the DW approach is the focus on sectoral activity levels, that makes it possible to report on the impact contrasting sectoral growth dynamics have on the emission reduction strategies needed to achieve an emission reduction target.

Mathy et al. (2018) apply the DW methodology to the 16 largest GHG emitting countries and analyse mitigation strategies at the global level. This resulted in a typology of four groups of countries at the global scale according to their current level of economic development, and their current level of energy-related CO_2 emissions and four families of strategies.

Relying on this methodology, this paper focuses on European-Union (EU) countries. It analyses national mitigation strategies compatible with a long-term objective leading to a well below 2°C target either as part of an ambition in 2030 limited to that of the NDCs, or as part of more ambitious early action. This makes it possible to assess the priorities for action to strengthen the NDCs. The article also highlights the impact sectoral growth dynamics have on the necessary mitigation efforts. We apply the methodology to scenarios for four EU countries (Germany, France, Poland and UK) that have been produced by national research teams in the framework of the COP 21 RIPPLES project (cf. infra) and represent on aggregate 55% of current EU emissions.

In the second section, we describe the DW methodology and the scenarios to which we apply the methodology. The third section presents the results for the group made up of the four EU countries and the fourth section details the results for Germany, France, Poland and the UK. The fifth section discusses the results in a policy and a methodology perspective.

2. Methodology and national mitigation scenarios

The DW methodology (Mathy, *et al.,* 2018) goes beyond the traditional gap analysis by quantifying the contribution of different mitigation options. It splits prospective energy-related emissions into DW on the demand side and on the supply side.

2.1. Decarbonization wedges methodology

2.1.1. Specificities of the decarbonisation wedges methodology

Various methods are available for analyzing the factors explaining the evolution of emissions, such as econometric regression or decomposition analysis, but index decomposition analysis (IDA) is widely used for this type of study (Wang et al., 2005; Xu and Ang, 2013). The DW is an IDA that has been developed specifically to address three main issues related to the understanding and analysis of decarbonization strategies.

First, DW allows the comparison of prospective scenarios. In general the IDA decompositions are applied to understand past developments and are therefore based on full sets of observed data which is not possible for analysing prospective scenarios. Applying IDA to a forward-looking scenario can only be based on a limited set of variables (the ones used in the energy models, which generated the trajectories). When analysing prospective scenarios the breakdown is often limited to three effects: activity measured (GDP growth), the structural change effect (energy intensity), and a carbon intensity effect (carbon emissions per unit of final energy demand). Only very general conclusions can be drawn from such economy-wide analysis: improved energy efficiency (including end-use efficiency and structural changes in the economy) determines short to medium-term emissions reductions, with decarbonization of energy vectors becoming more important in the long term (Förster et al., 2013; Hanaoka, 2009, Marcucci and Fragkos, 2015). Such conclusions are limited in terms of policies required in specific sectors in each country.

Second, DW is based on sectoral activity indicators, contrary to what is usually done in IDA where the activity effect is represented by the evolution of GDP or value added of sectors. In many models, energy consumption in the residential or in the transport sectors or activity indicators in these sectors (number of m2 per inhabitant, number of km travelled each year per inhabitant) are represented with an increasing function of the evolution of GDP per inhabitant. The relationship between income and passenger-kilometres, or between industrial output and freight tonne-kilometres (Goodwin et al., 2004) has been documented through the assessment of elasticities. With such assumptions, a growth in GDP is necessarily accompanied by a growth in mobility or surface area per capita (unless a possible asymptote is reached) and it is not possible to project a decoupling between growth and sectoral evolutions. Conversely, the DW decomposition is based on sectoral-activity indicators (such as pass.km for passenger mobility, t.km for freight,…) in order to make explicit the assumptions about sectoral evolutions and their influence on resulting mitigation efforts

Third, DW attaches central importance to power-sector emission reduction options. An important issue for identifying drivers of emission reductions is the specific role of electricity as a main decarbonization pillar (William et al., 2012). In IDA methodologies, two alternative options are possible for the attribution of CO_2 emissions from the power sector. The first one attributes power-sector emissions directly to the specific sectors consuming electricity. The switch to low-carbon electricity end-uses is then integrated in the sectoral carbon-intensity factor. The other solution is to consider electricity consumed as a zero-emission energy-carrier at the end-use level and allocate CO_2 emissions separately, while considering the power sector as a specific sector. In this case, decarbonization of the power sector and the penetration of decarbonized electricity in end-use energy sectors can be considered as a separate wedge. Given the central role of decarbonized electrification of end-uses in deep decarbonization pathways, the DW methodology relies on the second option. As two-thirds of world electricity is still generated using fossil fuel, mostly coal, two main families of strategies are possible when choosing a decarbonization pathway in the power sector: either to organize a direct transition from CO_2 intensive conventional fossil fuels to low-carbon energy technologies, or to switch from coal to gas prior to full penetration of decarbonized energies. Low-carbon power generation technologies include renewables and nuclear energy that do not directly emit CO_2 and carbon capture and sequestration (CCS) with very low CO_2 emissions.

2.1.2. Description of the decarbonization wedges methodology

We have elaborated the DW methodology following Pacala and Socolow (2004) and relying on the Logarithmic Mean Divisia Index method (Wang et al., 2005). The elaboration of emission decomposition with DW methodology is described in Mathy et al. (2018) and summed up below.
At the economy-wide level, the variation of emissions C between year T and year 0 can be written:
$\Delta^{tot} = C_T - C_0 = \Delta^{ACT} + \Delta^{DS} + \Delta^{PS}$
with:
- Four activity effects that reports the evolution of sectoral activity, one in each end-use energy demand sector i.e. buildings (B), transport (T) and industry (I) and one in the power sector (E).
$\Delta^{ACT} = \Delta^{ACT\_B} + \Delta^{ACT\_T} + \Delta^{ACT\_I} + \Delta^{ACT\_E}$. Sectoral indicators are listed in Table 1.
- Six DW related to the final energy demand sectors (DS subscript), i.e. energy efficiency (*EFF_*) and decrease of the carbon content of energy carriers (*CARB_*) in buildings (residential + commercial), transport (passenger + freight) and industry
$\Delta^{DS} = \Delta^{EFF\_B} + \Delta^{CARB\_B} + \Delta^{EFF\_T} + \Delta^{CARB\_T} + \Delta^{EFF\_I} + \Delta^{CARB\_I}$
- Five DW specifically in the power sector (PS subscript): coal/gas substitution (*COAL_GAS*), renewables (*ENR*), nuclear (*NUKE*), carbon capture and sequestration (*CCS*) and the carbon-emission content of conventional fossil fuel plants (*CE_E*), which refers to the carbon content of primary fossil energy used to produce one unit of electricity. This last effect aggregates the energy-efficiency evolution of conventional fossil-fuel plants and the evolution of the carbon content of coal and gas that may differ according to region and time.

$$\Delta^{PS} = \Delta^{COAL\_GAS} + \Delta^{NUKE} + \Delta^{CCS} + \Delta^{ENR} + \Delta^{CE\_E}$$

Table 1: Sectoral activity indicators used in the DW methodology

Sectors	Sectoral activity indicators
Residential	Square meter in residential
Commercial sector	Square meter in the commercial sector (added value if not available)
Passenger transports	Total passenger.km
Freight transport	Total ton.km
Industry	Added value
Electricity	Total electricity generation

The decomposition can also be written according to the nature of the effect (activity, energy efficiency and evolution of the carbon content of energy): $\Delta^{tot} = \Delta^{ACT} + \Delta^{EFF} + \Delta^{CARB}$ with:

- The same four activity effects
- Four DW related to energy efficiency in end-use sectors and in the power sector

$\Delta^{EFF} = \Delta^{EFF\_B} + \Delta^{EFF\_T} + \Delta^{EFF\_I} + \Delta^{CE\_E}$

- Seven DW related to the carbon content of energy: three in end-use energy demand sectors and four in the power sector.

$\Delta^{CARB} = \Delta^{CARB\_B} + \Delta^{CARB\_T} + \Delta^{CARB\_I} + \Delta^{COAL\_GAS} + \Delta^{NUKE} + \Delta^{CCS} + \Delta^{ENR}$

Figure 1 illustrates this methodology. In the fictive scenario described, the initial level of emissions during the base year is 1000 Mt. Activity effects corresponding to hypotheses of this scenario (in transport, building, industry, power sector) would lead emissions to 1600 Mt in 2050. DW in final energy demand sectors (building, transport and industry) would bring back emissions to around 1000 Mt and DW in the power sector would represent around 400 Mt additional emission reduction. According to the type of analysis, DW can also be grouped into their category (activity, energy efficiency or carbon content of energy carrier). Emission reductions due to gains in energy performance (energy efficiency) on the one hand, and decrease of the carbon content of energy sources (energy decarbonisation) on the other hand, make it possible to reduce overall emissions to 600 Mt.

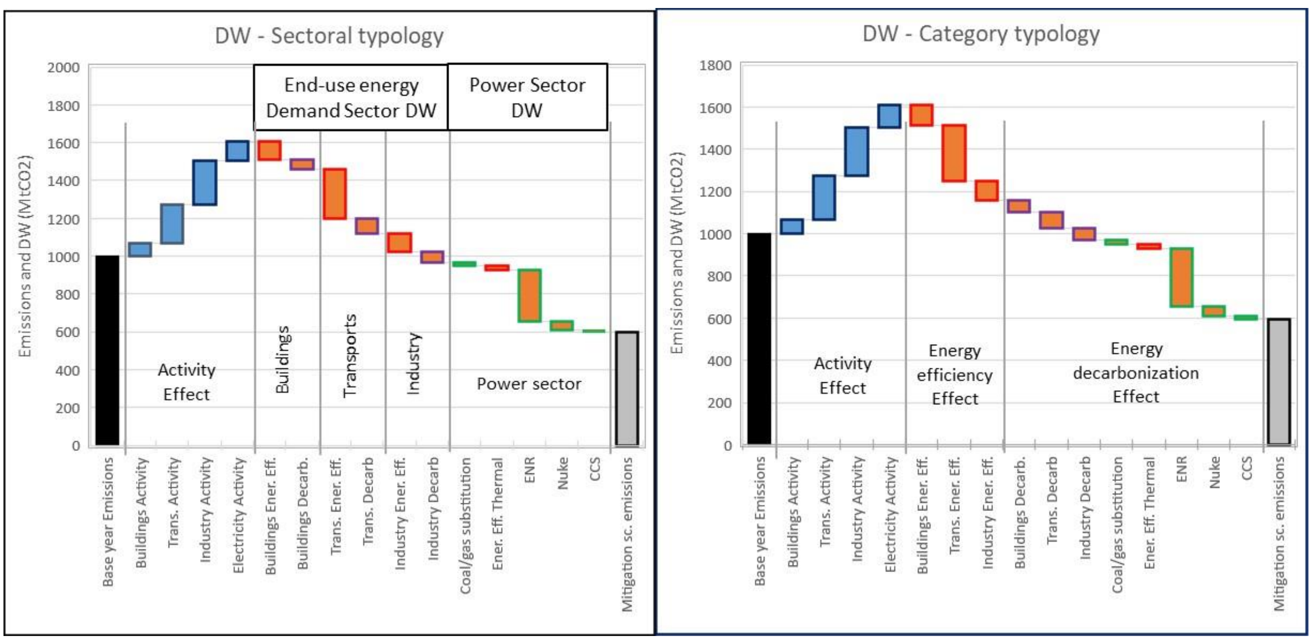


Figure 1 : DW classification and categories based on an example of mitigation scenario

The particularity of the DW method is that it does not rely on a baseline scenario but on a fictitious counterfactual scenario that is the projection of CO_2 emissions considering the evolution of sectoral activity (number of square metres in buildings, passenger.km, etc.) while energy efficiency and the energy mix in each sector would remain unchanged compared to the base year. This is different from what is usually called a baseline or reference scenario which take into account autonomous technical change and price-induced technical progress leading to improved energy efficiency, penetration of new technologies and changes in the energy-mix.

This counterfactual method is helpful for comparing strategies between two countries, which do not have the same level of development or standard of living. Indeed, it reveals the impact that the evolution of sectoral activities would have on emissions, without emission reduction option and therefore it reveals the impact on the required emission reductions compared to counterfactual emissions. Figure 1 illustrates this point. Let's consider, for example, a developed economy with a high level of equipment, and a high standard of living. The future evolution of sectoral indicators (passenger.km or square-meter per capita) will be lower (bottom figure) than in a less developed, or even emerging country, in which the expected growth of the main demographic, socio-economic and macro-economic indicators are high (upper figure). For this reason, counterfactual emissions will be higher in these latter countries than in wealthier economies and more efforts, i.e. a higher volume of emission reductions will be needed if the same level of emissions is to be reached in the future.

The same reasoning would apply between two scenarios for the same country if one of the scenarios (top figure) projects a weak evolution of the sectoral indicators (number of km travelled each year, residential area...) and the second one a strong growth of these same sectoral indicators (top figure). Thus this methodology makes it possible to account for factors that are rarely explicit in modelling, i.e. changes in consumption styles and development patterns.

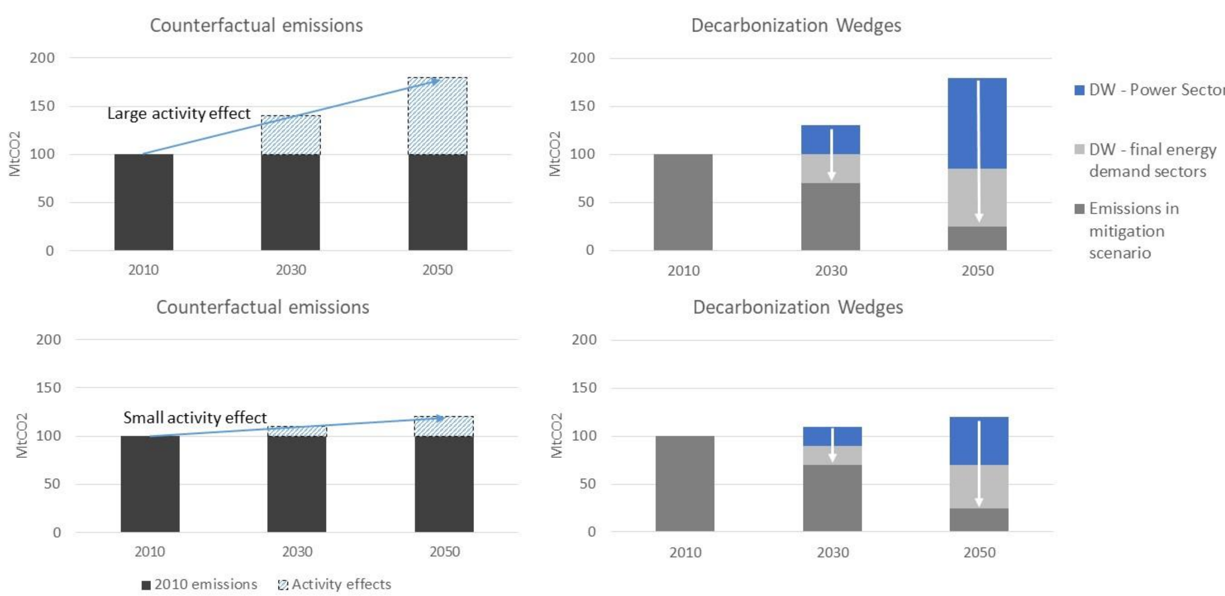


Figure 2 : Schematic representation and interpretation of the counterfactual scenario and of the decarbonization wedges

2.2 Typology of national scenarios

We apply the DW methodology to a set of national mitigation scenarios for four EU countries taking part in the RIPPLES project: France, Germany, Poland and United

Kingdom. All the scenarios considered are consistent with at least a 2°C long-term target (cf. next section) and are grouped into two main families[1].

1. the *Current_NDC* family corresponds to scenarios which emissions pathways are consistent with the EU NDC objective in 2030 and compatible with a 'well below 2°C' (UNFCCC, 2015) target in 2050.
2. the *Enhanced_NDC* family corresponds to scenarios which pathways are also consistent with the long term 'well below 2°C' target but integrate much more ambitious reduction emission targets in 2030.

Some scenarios were computed with national modelling tools during the Deep Decarbonization Pathways Project (DDPP, 2015), when others were specifically built during the COP21 RIPPLES project by national country teams or at GAEL laboratory with the POLES global energy model. The description of these mitigation scenarios is available on the COP21_RIPPLES website:
https://www.cop21ripples.eu/wp-content/uploads/2018/07/RIPPLES_D2.1-v3.pdf

Box 1: the COP21 RIPPLES project

The COP21 RIPPLES consortium, led by the Institute for Sustainable Development and International Relations (IDDRI), is comprised of 18 international institutes. This COP21 RIPPLES project has four overarching objectives:
1. To assess the adequacy of the NDCs submitted at COP21 in light of the global temperature target of limiting warming to 2°C/1.5°C.
2. To assess the implications of NDCs and deeper mitigation pathways on other European socio-economic objectives, related to innovation and technology deployment; trade and competiveness; investment, financial flows and economic growth; and global energy markets and energy security.
3. To assess the adequacy of the outcomes of COP21, and the implications and opportunities emerging from ongoing UNFCCC negotiations.
4. To provide policy recommendations for EU climate policy and climate diplomacy.
The COP21 RIPPLES project has received funding from the European Union's Horizon 2020 research and innovation programme

[1] All the assumptions of these families of scenarios are given in the scenarios narratives from COP21 RIPPLES.

Table 2 : Typology of national scenarios within EU and modelling tools used

	France		Germany		Poland		UK	
	Current_NDC	Enhanced_NDC	Current_NDC	Enhanced_NDC	Current_NDC	Enhanced_NDC	Current_NDC	Enhanced_NDC
Comments	Global Current_NDC scenario built with the POLES model. The French Current_NDC scenario is the national extraction of this scenario.	French scenario from the Deep Decarbonization Pathway Project - Mathy et al. 2015.It corresponds to the EFF scenario in the report and is built with Imaclim-R France	Global Current_NDC scenario built with the POLES model. The German Current_NDC scenario is the national extraction of this scenario.	From study commissioned on behalf of the German Federal Ministry for the Environment prepared by „Öko-Institut“ and „Fraunhofer ISI“	The model used is MEEP: Micro-foundations based Energy and Emissions Projection model	The model used is MEEP: Micro-foundations based Energy and Emissions Projection model	From Pye et al., 2017 Current_NDC scenario for UK is the national extraction of the global scenario “1240 Inertia” realized with Times	From Pye et al., 2017 Enhanced_NDC scenario for UK is the national extraction of the global scenario “1240 Equity” realized with Times
Emissions in 2050	Endogenous	Exogenous: -75% Compared to 1990	Endogenous.	Exogeneous : -81% in 2050 compared to 2010	Exogeneous : -93% in 2050 compared to 2010. Same carbon budget as Enhanced_NDC Polish scenario	Exogeneous : -89% in 2050 compared to 2010. Same carbon budget as Current_NDC Polish scenario	Allocation of the global budget (1240 GtCO2) to the UK according to an “inertia” principle	allocation of the global budget (1240 GtCO2) to the UK according to an “equity” principle
Sectoral structures and behavioral change	No behavioral change, no structural and sectoral change	Moderate decrease in individual mobility; decoupling between freight and GDP	No behavioral change, no structural and sectoral change	No behavioral change, no structural and sectoral change	Low potential of behavioral shift - no change in sectoral structures	Low potential of behavioral shift - no change in sectoral structures	Projections for energy service demand levels lead to low demand reduction	Projections for energy service demand levels lead to high demand reduction. Strong decoupling between freight and GDP

Energy efficiency	No particular emphasis compared to other mitigation options	Strong policies on energy management (ambitious thermal renovation of the building stock in 2050) leading in 2050 to -50% in final energy consumption	No particular emphasis compared to other mitigation options	Strong policies on energy management (ambitious thermal renovation of all the building stock in 2050, modal shift in transport)	No emphasis on energy efficiency, technology-focused mitigation effort	No emphasis on energy efficiency, technology-focused mitigation effort		
Low carbon technologies	All available and endogeneous: competition between technologies	70% renewables in the power sector in 2050 (exogenous)	All low carbon technologies available	Early and consistently strong expansion of renewable energies. renewable energy share of gross electricity consumption equal to 50 % by 2030.	Diversified portfolio of technologies, including nuclear and CCS	high availability of low-carbon technologies in industry, transport and buildings sector		High bioenergy potential and imports
CCS	Available and endogeneous: competition between technologies	Exogenous: No CCS	All low carbon technologies available	No CCS	CCS available in 2040	CCS available in 2030	CCS considered commercially available only after 2040	Nearly no CCS even if available
Nuclear	All low carbon technologies available	Exogenous (-25% /2012) decrease in nuclear generation	All low carbon technologies available	Exogenous: phase-out of nuclear energy by 2030	Diversified portfolio of technologies, including nuclear	Diversified portfolio of technologies, including nuclear	Significant nuclear development	Massive nuclear development

Note: POLES: Global Current_NDC scenario built with the POLES model to achieve a well-below 2°C target in 2050 with a carbon budget for the period 2010 to 2050 equal to 1,130 GtCO2 (IPCC, 2014). The scenario is implemented through national carbon values required to reach the carbon budget and to be consistent with NDCs on 2025 or 2030

3. European strategy regarding NDC (*Current_NDC*) and accelerated NDC (*Enhanced_NDC*)

The emissions of the four European countries have been aggregated to create an EU-4 group. This group represent 55% of 2010 EU28 energy-related CO_2 emissions. The evolution of aggregated emissions presented in Figure 3 shows two different profiles. In both scenarios, the final level of emission reductions compared to 1990 is approximately the same (-85% in *Enhanced_NDC* and -87% in *Current_NDC*). This is consistent with the recommendations required for Annex 1 countries from IPCC AR4 (Box 13.7, 2007) to reach a greenhouse gas reductions between -95 and -80% in 2050 compared to 1990 in order to comply with a 450 ppm CO2eq stabilisation concentration level[2]. In the *Current_NDC* scenario, emission reduction in 2030 compared to 1990 is equal to –38% which is very close, but lower than the EU NDC target to reach at least -40% GHG domestic reduction by 2030. This implies that the rate of emission reduction in other EU countries and for non CO_2 energy-related emissions will have to compensate. In the *Enhanced_NDC* scenario, CO_2 energy-related emissions are 52% lower compared to 1990 EU-4 emissions. The carbon budget on the period 2011-50 is also 10% higher in the *Current_NDC* scenario than in the *Enhanced_NDC* scenario.

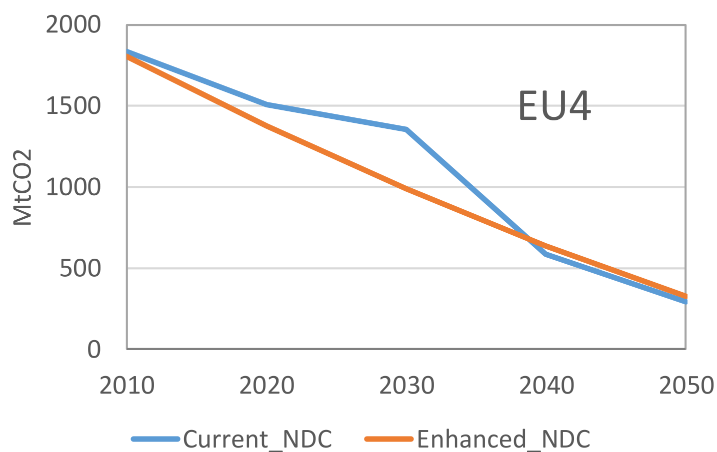


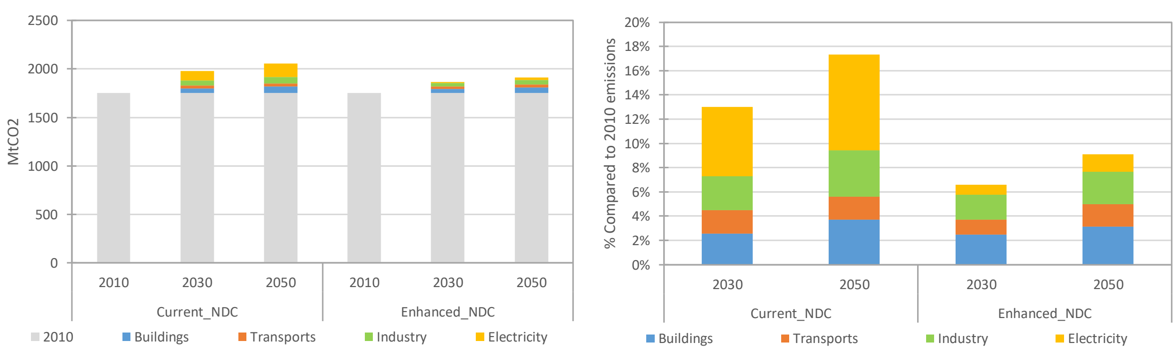
Figure 3: Aggregation of emissions in the EU-4 region for *Current_NDC* and *Enhanced_NDC* scenarios

[2] Although non-CO2 energy emission reductions are considered more costly than CO_2 energy reductions and more weight should be given to CO2 energy emission reductions than to other gases, it can be considered that such CO2 energy related emission reductions for the EU-4 in 2050 are consistent with 2°C long-term objective.

3.1. Contrasted assumptions about sector activity between *Current_NDC* and *Enhanced_NDC*

As explained above, the counterfactual scenario of CO_2 emissions takes into account the evolution of sectoral activity but no improvement in energy efficiency or change in the energy mix. The different assumptions about sectoral activity (housing area, mobility, industrial activity…) from one scenario to another result in contrasted emission trajectories: in the *Current_NDC* counterfactual scenario, the increase in emissions compared to 2010 would be 13% in 2030 and 17% in 2050, while it would only be 6% and 9% respectively in the *Enhanced_NDC* scenario (Figure 4).

The contribution of demand-side sectors is slightly higher in the *Current_NDC* compared to the *Enhanced_NDC* scenarios and almost balanced between buildings (residential and services), transport (passenger and freight) and industry. The power sector accounts for the main difference between counterfactual emissions trajectories as explained in section 3.3.



NB: The left-side figure refers to emissions in $MtCO_2$, the right-side figure to the increase in emissions in the Current_NDC and Enhanced_NDC counterfactual scenarios compared to 2010.

Figure 4 : Impact of sectoral activity effects on *Current_NDC* and *Enhanced_NDC* counterfactual emissions - EU-4 aggregated level in 2030 and 2050 compared to 2010

3.2. The key role of energy decarbonization for the *Current_NDC* scenario in the second period

As explained earlier, DW in relation to 2010, are split into two main categories:

- energy efficiency in the final energy consumer sectors (residential and tertiary buildings, passenger and freight transports, and industry) and in the power sector;
- reduction of the energy content of energy carriers in demand-side sectors and in the power sector (coal/gas substitution, renewables, nuclear, carbon capture and sequestration).

In the Figure 5, the DW and activity effects are grouped into two periods, 2010-30 and 2030-50, and over the whole period 2010-50 as well. Each of the effects considered over each period is represented in such a way as to assess the impact it has on the evolution of emissions compared to 2010.

The energy efficiency DW is quite comparable from one scenario to another while the DW related to the carbon content of energy is highly differentiated between *Current_NDC* and *Enhanced_NDC*. In both scenarios, the energy efficiency effect provides higher emission reductions before 2030 than afterwards. On the contrary, the impact of reducing the carbon content of energy is much contrasted. Efforts to decarbonize energy carriers are not significant in the first period of the *Current_NDC* scenario, and for this reason, energy decarbonization must be significantly accelerated after 2030 to reach the long-term mitigation objective: in the *Current_NDC* scenario, the DW related to the decrease of the carbon content of energy represents 53% of 2010 emissions, in the second period, compared to 19% only in the first period. It is around 30% of 2010 emissions for both periods in the *Enhanced_NDC* scenario. This DW related to the carbon content of energy appears as playing the role of an adjustment variable in order to bridge the gap in emission reduction required. The degree of realism of such a feature for the *Current_NDC* scenario is really questionable because the economy has not been prepared to this acceleration. On the other hand, the efforts towards energy decarbonization are much better distributed between the two periods in the *Enhanced_NDC* scenario.

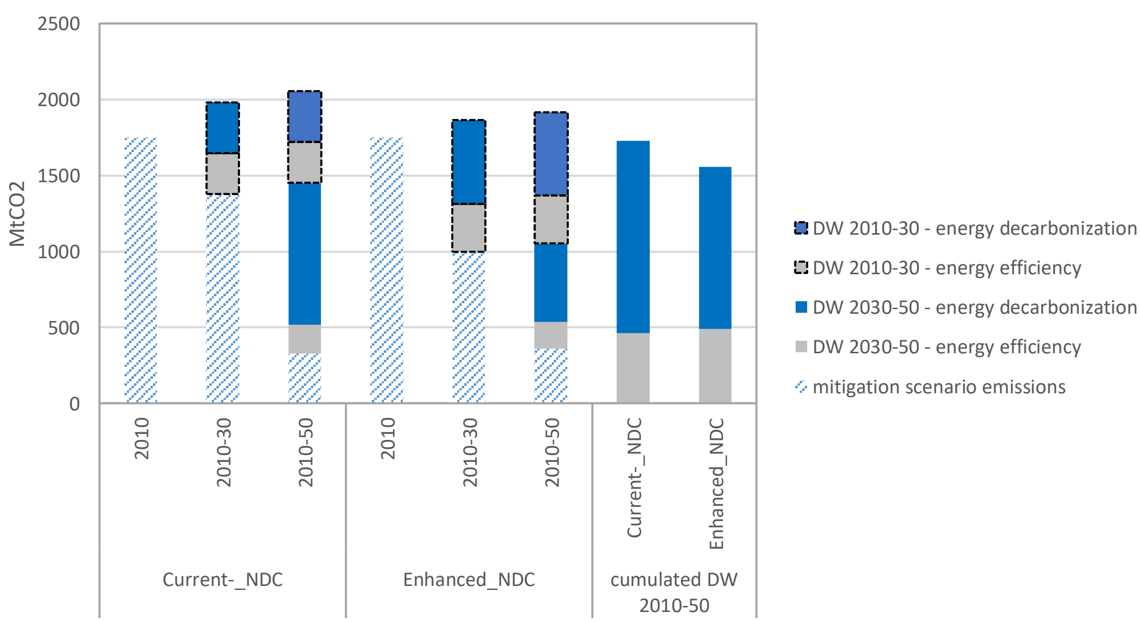
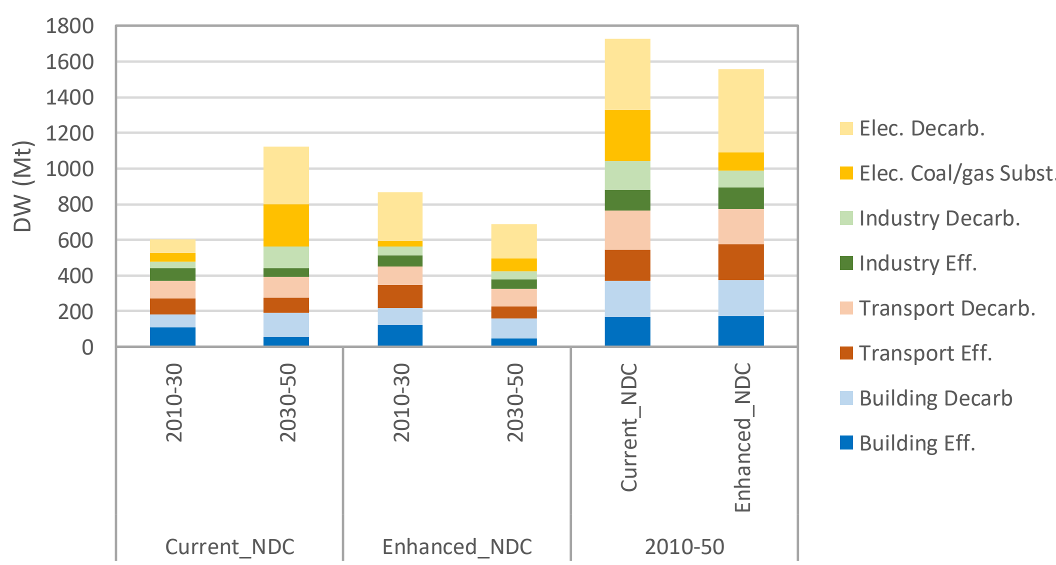


Figure 5 : Activity effect and DW related to energy efficiency and to energy decarbonization in *Current_NDC* and *Enhanced_NDC* scenarios - EU-4 aggregated level

The contributions of different technologies and sectors to emission reductions are detailed in Figure 6. Throughout 2010-50, the total volume and structure of DW in final energy demand sectors are not very different. Buildings (residential and tertiary) and transport (passenger and freight) are the main contributors with a similar contribution to DW (around 200 Mt CO2 in each period for each sector). Differences between the two scenarios are more pronounced for industry but remain limited. The most important differences between the two scenarios are in the power sector and, particularly, because of the additional wedges from coal/gas substitution. They largely explain the higher total DW in *Current_NDC* compared to *Enhanced_NDC*.

The distribution of DW over time is also contrasted. In the *Enhanced_NDC* scenario, most of the effort is made before 2030, but the reductions achieved in the second period are quite comparable in structure and volume. In the *Current_NDC* scenario, on the other hand, the limited volume of reductions produced before 2030 requires a very strong catch-up in the second half. The structure of reductions is also different with a considerable effort in the electricity sector: development of decarbonized vectors and especially coal/gas substitution.

The socio-technical feasibility of such volumes of DW which correspond to a massive penetration of carbon-free energies may be questioned. Especially since the learning by doing will remain limited in the *Current_NDC* scenario due to a moderate penetration of these low carbon technologies in the first period. As a result, the cost of these technologies will be higher and the diffusion more constrained in the post-2030 period, compared to the *Enhanced_NDC* scenario (Criqui et al., 2015).



NB: The DW between 2030 and 2050 are additional to the one observed between 2010 and 2030

Figure 6 : Sectoral decarbonization wedges - EU-4 aggregated level

3.3. DW in the power sector: decarbonisation of the electricity and electrification of end-uses *versus* demand control

The assumptions on the evolution of electricity demand and consequently on electricity supply are radically different between the two scenarios (Figure 7). In the *Current_NDC* scenario, demand is growing, in particular but not only, to meet the development of new uses in the consumer sectors. On the other hand, demand and therefore electricity production are stabilized in the *Enhanced_NDC* scenario to accelerate the decrease in emissions (25% growth for power generation in 2050 compared to 2010 in *Current_NDC* versus -7% in Enhanced_NDC). The penetration of electricity for final energy uses (electrification rate) in *Current_NDC* reaches 52% in 2050 with a sharp increase after 2030 compared to 36% in *Enhanced_NDC*.

Important differences in the electricity mix are also observable in Figure 7. Electricity production from fossil sources continues until 2030 in the *Current_NDC* scenario, while it decreases from 2020 in *Enhanced_NDC*. To partially limit coal and gas emissions, CCS has to be developed from 2040 for *Current_NDC* while it is nearly absent from *Enhanced_NDC*. And as mentioned above, other carbon-free technologies play a major role in both scenarios after 2030 (the contribution of renewable energy is even higher in *Current_NDC*) but their deployment is progressive in *Enhanced_NDC* while it is very sudden in *Current_NDC*. Generation capacities corresponding to 1020 TWh of additional low-carbon electricity (CCS, nuclear and renewable energies) must be built between 2030 and 2050 in the *Current_NDC* scenario compared to 410 TWh in the *Enhanced_NDC* scenario, in addition to the renewal of end-of-life generation capacities in this period.

These changes in the electricity mix are also observed in the volume and structure of the DW (Figure 8). The volume of DW required to compensate for the increase in electricity consumption is 800 Mt CO_2 for *Current_NDC* compared to only 620 Mt CO_2 for *Enhanced_NDC*. Moreover, most of the reductions are obtained by the development of renewables in *Enhanced_NDC* whereas the *Current_NDC* scenario requires a strong contribution from coal/gas substitution and, as indicated above, a significant share of CCS. It can also be seen that the greater decline in nuclear energy between 2010 and 2030 in *Current_NDC* requires a larger volume of DWs[3]. Considering the combined effect of DWs and of the activity effects in the power sector, the volume of emission reduction is negligible in 2030 in *Current_NDC*. Despite much higher DWs in *Current_NDC* than in *Enhanced_NDC*, the effects of activities lead to lower cumulative reductions than in *Enhanced_NDC*.

[3] The decline in nuclear generation stems from nuclear targets in France and Germany.

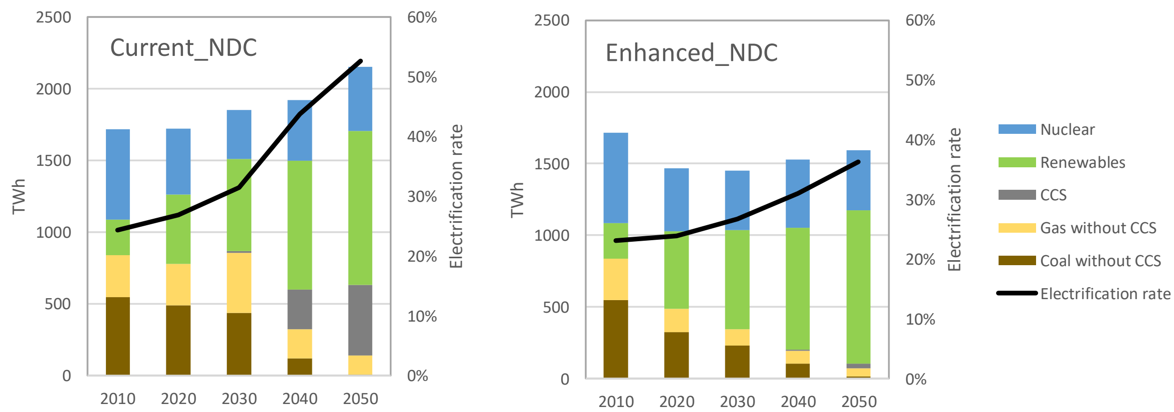


Figure 7: Energy mix in the power sector and electrification rate in *Current_NDC* and *Enhanced_NDC* scenarios – EU-4 aggregated level

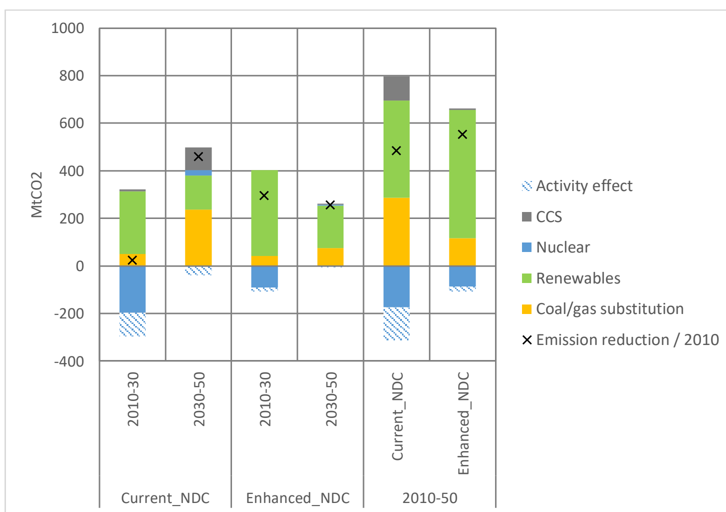


Figure 8: DW in the power sector, activity effect and emission reduction in the power sector compared to 2010 total emissions– EU-4 aggregated level

4. Differentiated national strategies within EU

In this section we analyse in more detail the specificities of the scenarios for each country.

The detailed analysis of the national scenarios reveals clearly differentiated strategies for France, Germany, Poland and the UK. In all these countries, the emissions in 2030 in the *Current_NDC* scenario are higher than *Enhanced_NDC* scenarios. A clear acceleration of emission reductions is required after 2030 in the *Current_NDC* scenario to compensate for this higher trend. At the end, the cumulated CO_2 emissions during the period 2010-50 for France, Germany and Poland are close in both families of scenarios, but they remain lower for *Enhanced_NDC*. In UK, the carbon budget is clearly lower for *Enhanced_NDC* compared to *Current_NDC*.

These emission trajectories are associated with differentiated mitigation strategies but also, as revealed by the DW method, with very distinct sectoral activity hypotheses.

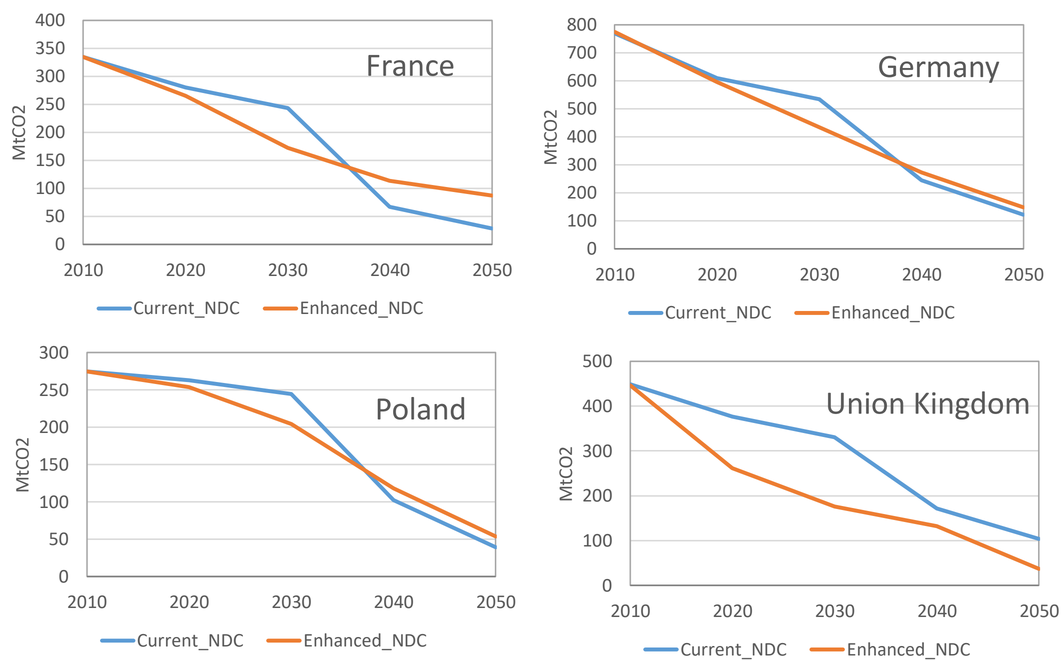


Figure 9: Emissions in national mitigation scenarios for France, Germany, Poland and the UK

4.1. Distinct national assumptions for sectoral activity

The counterfactual emissions induced by the evolution of sectoral activity indicators are presented in Figure 10.

Although in different proportions, Germany, France and UK have specific counterfactual emission profiles for the two scenarios. This reveals that different assumptions have been made about the evolution of activity indicators in each scenario and also that two distinct models have been used for the *Current_NDC* and the *Enhanced_NDC* for Germany. For Poland, the differences between the counterfactual emission profiles in the two scenarios are also important but they come from the electricity sector alone as the same exogenous evolution of activity indicators for buildings, transport and industry are considered.

Counterfactual emissions are particularly contrasted in Poland compared to other countries; they are about 30% higher in 2030 compared to 2010 in all scenarios when the difference is closer to 10% in other countries. The growth of activity in all the sectors explains this evolution but it is even more pronounced in the power sector, which is very carbon intensive compared to other countries. This needs to be considered when analysing mitigation strategies, because such sectoral dynamics will make it necessary to implement more extensive mitigation efforts compared to other countries with a smoother evolution of sectoral activities.

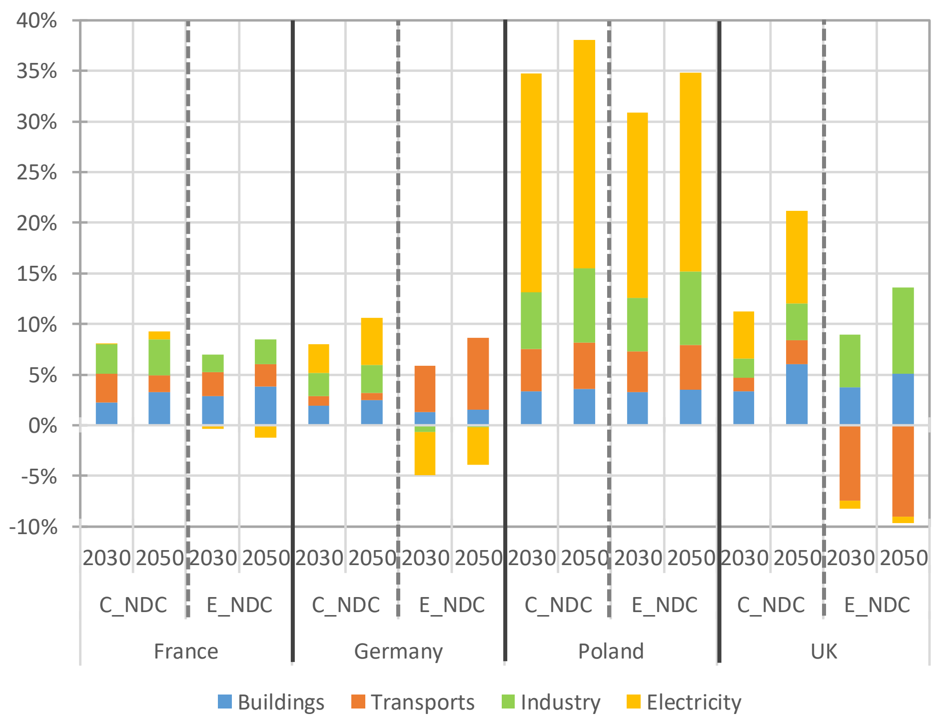


Figure 10: Sectoral activity effects on counterfactual emissions in 2030 and 2050 (/2010)

Except industry in UK, the evolution of sectoral activity is much lower in other countries. In France, the contribution of each sector is balanced and particularly low for the power sector, compared to other countries, as it is already largely carbon-free. The slightly negative contribution of the power sector in *Enhanced_NDC* in both periods refers to the decline of nuclear generation capacity compared to 2010.

In UK, sectoral activity indicators are highly contrasted between *Current_NDC* and *Enhanced_NDC*. In *Current_NDC*, the evolution is similar to France or Germany but with a higher contribution of the power sector for UK. In *Enhanced_NDC*, on the contrary, the contribution of the power sector and particularly of the transport sector (reflecting assumptions of moderation of mobility and of freight needs) to the counterfactual emissions is negative in UK.

In Germany the main difference is due to the contribution of the power sector, which is large and positive in *Current_NDC* but negative in *Enhanced_NDC*. Contrary to the UK, this *Enhanced_NDC* scenario projects a strong growth in demand for freight and mobility reflecting a specific vision that is not shared by the others European countries.

4.2. Analysis of DW in *Current_NDC* and *Enhanced_NDC* national scenarios within EU-4

The contribution of the DWs according to their nature (energy efficiency and decrease in the carbon content of energy) and of activity effects to emission reduction compared to 2010 is illustrated in Figure 11.

For the four countries, we find the same results as those observed at the aggregate level for EU-4, i.e. the strong imbalance of DWs between the two periods in the *Current_NDC* scenario compared to a constant effort for *Enhanced_NDC*. While the effort devoted to energy efficiency is relatively stable, for both periods and both scenarios, the lower effort to reduce the carbon content of energy during the first period of *Current_NDC* compared to *Enhanced_NDC* has to be caught up during the second period, leading to extremely high levels.

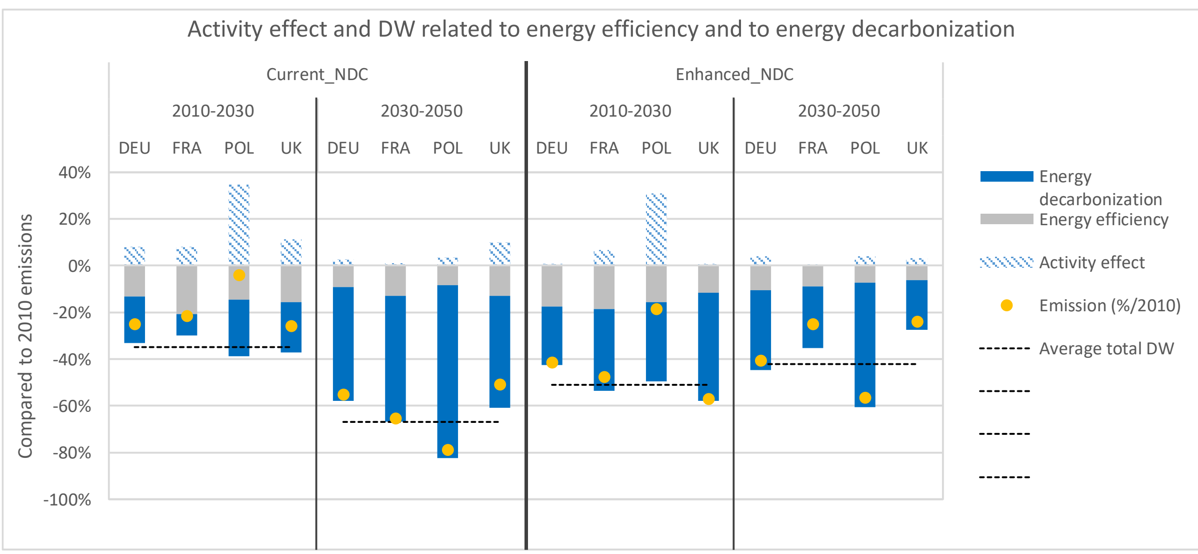


Figure 11: Activity effect and DW related to energy efficiency and to the reduction of the carbon content of energy. Emission reductions (/2010 emissions) between 2010 and 2030 and between 2030 and 2050 in *Current_NDC* and *Enhanced_NDC* national scenarios

If we look at the countries in more detail, the specificity of the trajectory for Poland, based on a strong activity effect in the first period, appears clearly. As a consequence, even if efforts on energy efficiency and on the decrease of the carbon content of energy are comparable to what is observed in the UK (in both scenarios), the resulting emission reduction is much lower in Poland in 2030 and the catch-up observed in 2050 is only possible thanks to a massive effort on the reduction of the carbon content of energy carriers, and especially electricity.

On contrary, the moderation of activity effects observed for example for Germany and UK during the first period in the *Enhanced_NDC* compared to *Current_NDC* combined with significant DWs contributes to the achievement of ambitious emission reductions.

As mentioned above for the UK, the activity effects are much smaller in the *Enhanced_NDC* scenario compared to the *Current_NDC* scenario mainly due to the effect of behavioural changes in the mobility sector. This allows in the *Enhanced_NDC* scenario to achieve very high levels of emission reductions, particularly during the first period, while limiting the volume of DWs needed mainly during the second period.

Further analysis at the level of each of the sectors is instructive.

Figure 12 compares the contribution of activity effects and of DW on energy efficiency and on the carbon content of energy, to emissions reductions in each sector, for each scenario family and country.

Emission reduction strategies in the buildings sector appear similar from one country to another. Energy efficiency and reduction of carbon content each contribute about 10% to emission reductions compared to 2010 national emissions. The final level of emission reductions achieved in this sector depends, however, on assumptions about the activity effects (growth of the building stock). This growth which is marked for Poland and the UK, offsets the gains in energy efficiency.

In the industrial sector, the reduction strategies appear more contrasted from one country to another and for the same country between *Current_NDC* and *Enhanced_NDC*. For Poland, activity effects fully absorb the impact of DW on emission reductions. Gains in terms of energy efficiency appear relatively small compared to the contribution of the decrease in the carbon content of energy for France and Germany. Only in the UK is the emission reduction potential offered by energy efficiency gains higher than the decrease in the carbon content of energy. Nevertheless, considering activity effects, the resulting emission reductions from the industrial sector in the UK remain low compared to France and Germany.

Finally, the transport sector shows by far the greatest diversity in the contributions of the different components of the DW method. For Poland, we find the same conclusion as for the industrial sector: activity effects fully absorb the impact of DW on emission reductions. This result is in contrast to France, for which the sum of DW on energy efficiency and decarbonation of energy sources is much higher than the increase in activity effects. The UK profile of *Enhanced_NDC* is also very interesting: it projects a decrease in activity effects, notably through a decoupling of freight from GDP growth and a decrease in individual mobility; this contributes almost half of the decrease in emissions in this sector (which, with 37% decrease in emissions compared to UK emissions in 2010, is the largest decrease observed over the 4 countries). Surprisingly, we observe that no assumption of gain in energy efficiency is made for this the transport sector in *Enhanced_NDC* scenario ; also surprising is the fact that in France and Germany, assumptions about the activity effects of *Enhanced_NDC* are higher than those of *Current_NDC*.

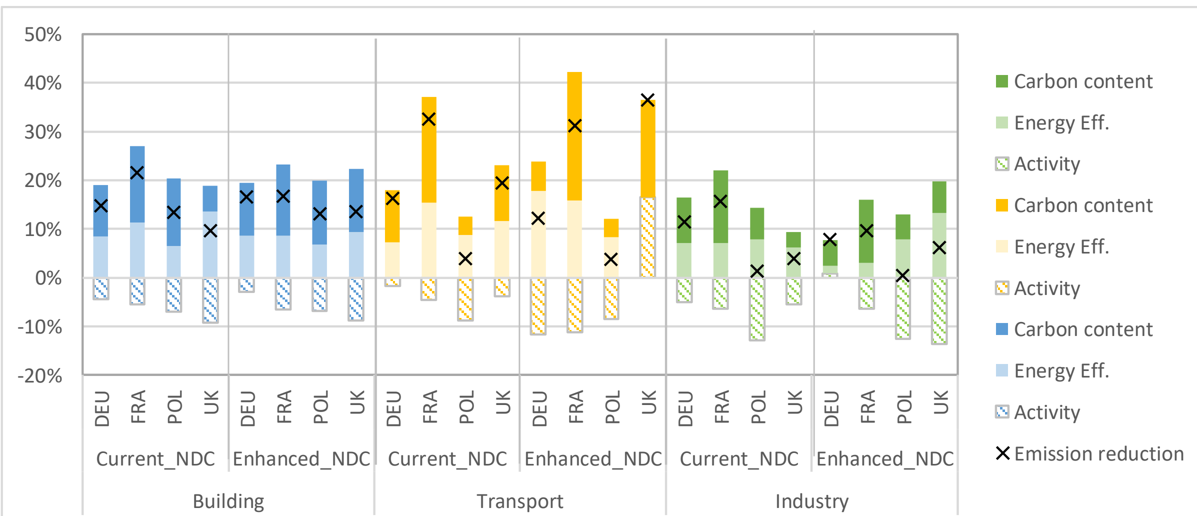


Figure 12: Cumulated 2010-50 activity effect, decarbonisation wedges related to energy efficiency and to the decrease of the carbon content of energy and emission reductions in building, transport and industrial sectors compared to 2010 national emissions

4.3. A closer look at the power sector

The detailed country-by-country analysis reveals the influence of national electricity mixes and prospects associated with a particular technology on strategic choices in the power sector (Figure 13) and the resulting impact on emissions reduction (Figure 14). It is worth noting that for each country and scenario, the power sector achieves a total decarbonization by 2050.

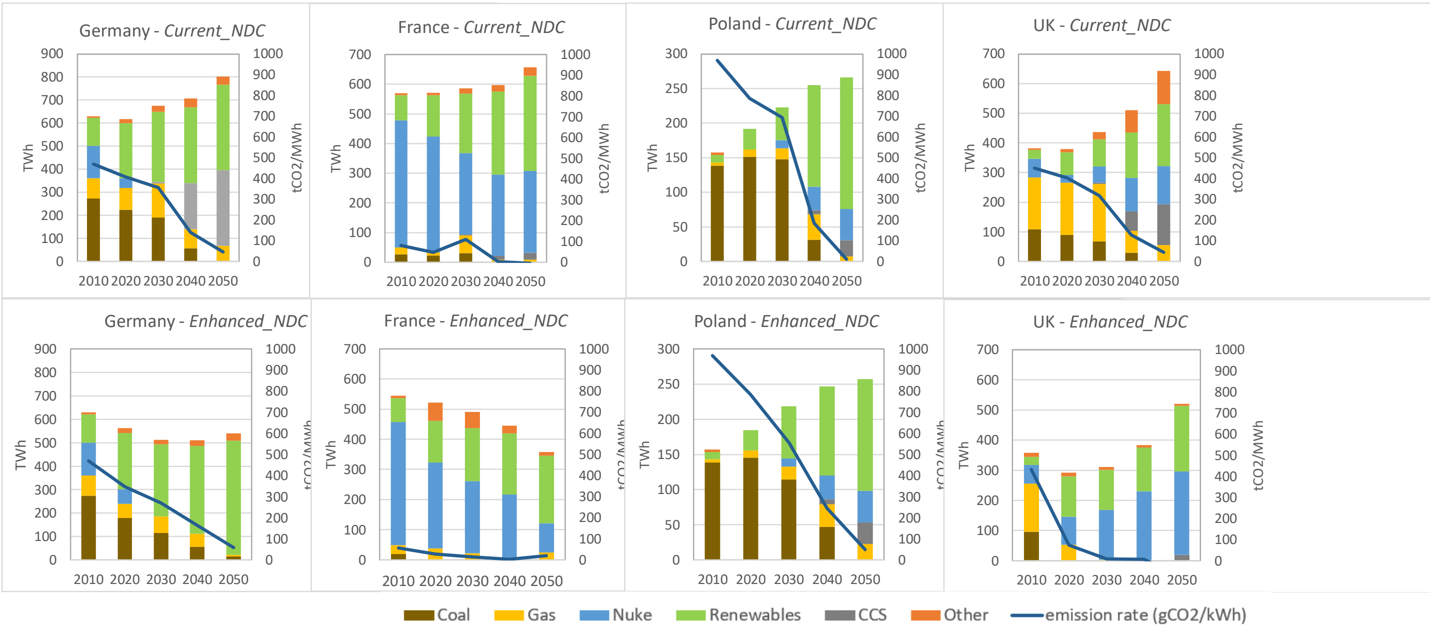
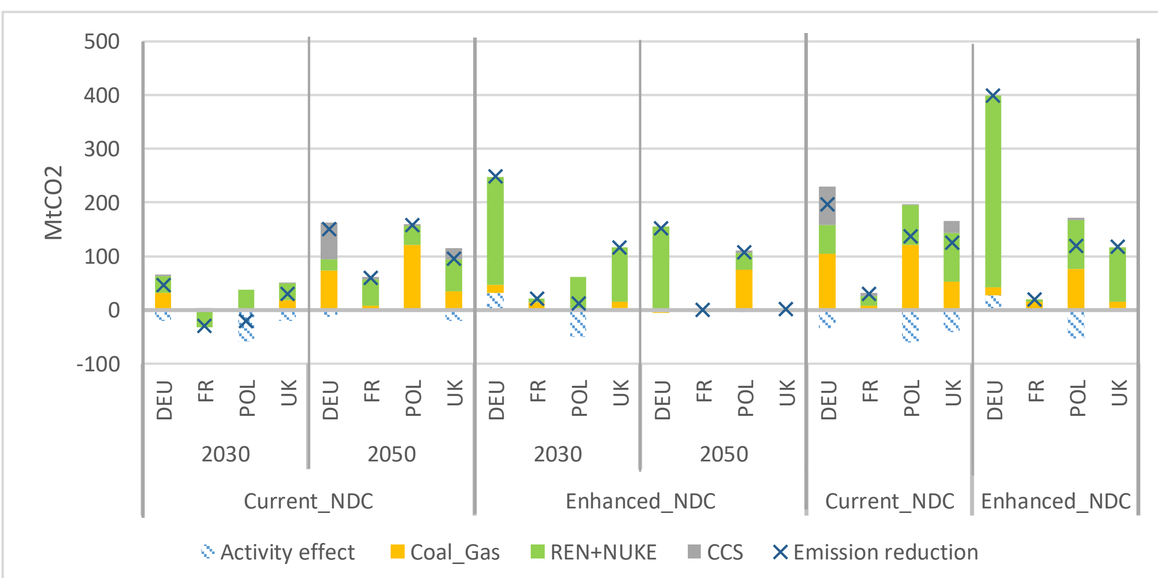


Figure 13: Energy mix in power generation and CO2 emission rate in the power sector in *Current_NDC* and *Enhanced_NDC* scenarios



NB: "Emission reduction" corresponds to the volume of emission reduction (MtCO2) taking 2010 as the base year for the first period and 2030 for the second period.

Figure 14 : DW in the power sector

Poland is the only one of the 4 countries to show little difference in the evolution of the power sector in the two scenarios. Some differences appear among the power production technologies but they are limited to a more important coal/gas substitution during the second period in *Enhanced_NDC*, the final mix in 2050 being very similar. As explained earlier, in Poland, coal generation decreases earlier and more gradually in *Enhanced_NDC* than in *Current_NDC* scenario. The consequence is a sharp decrease in coal generation in the *Current_NDC* scenario, after 2030, which may be politically and socially difficult given the number of people working directly or indirectly in the production and exploitation of coal. In addition this will lead to stranded assets and increase the cost of the scenario (Spencer et al., 2018). Similarly, the very strong growth in renewable electricity production expected before 2030 in *Enhanced_NDC* scenario, or after 2030 in *Current_NDC* can be questioned.

Poland is also the only country to show a negative contribution of the activity effect on emission reduction in *Enhanced_NDC.* Indeed, in the three other countries (Germany, France end UK), this scenario relies on a significant reduction in electricity consumption which leads to a negative activity effect, *i.e*. a decrease of emissions. Conversely, in *Current_NDC*, electricity production is strongly increasing in all 3 countries and the activity effect contributes negatively to emissions reduction. This leads to an important development of CCS after 2030 for the UK and Germany, in the *Current_NDC* scenario, whereas it is very low and mainly limited to Poland in *Enhanced_NDC*.

The case of France stands out with very low emission reductions due to an already highly decarbonised electricity system. The transition is much more complex for UK and Germany, two coal-producing countries. In the *Current_NDC* scenario, the emission reduction strategy is significantly based on a coal_gas substitution. On the other hand, such a substitution does not take place in the *Enhanced_NDC* scenario, giving way to a direct transition to decarbonized technologies.

5. Discussion

5.1. Priorities for action

As already observed in Mathy *et al.* (2018), the highly differentiated socio-economic growth prospects lead to very heterogeneous counterfactual emission trajectories in the main regions of the world. These differences are also found within EU, where contrasted projections of sectoral activities across countries have strong implications for the analysis of mitigation strategies.

In France, Germany and UK, low expected population and economic growth leads to lower activity effect than in Poland where sectoral activity is evolving more dynamically to catch up with the standard of living in Western European countries. Taking into account these contrasted activity effects, the emission reductions achieved in Poland are lower than those observed in the United Kingdom, despite comparable mitigation efforts considering the total volume of DW. This evolution is particularly marked during the first period when the differences between the activity factors are more pronounced.

The time profile of the contribution of energy efficiency appear similar whatever the scenario family : higher during the first period than during the second. Whatever the strategy chosen, very ambitious policies to improve energy efficiency in building, industry and transportation are required on the short term.

Energy efficiency strategies in the building sector are well identified. Nevertheless, the deployment of thermal renovation programmes in the housing sector implies carefully considering end-user consumption patterns, behavioural parameters, regulation design, awareness-raising campaigns and economic signals to disseminate low-carbon solutions and habits and solve the “energy-efficiency gap” problem (Jaffe et al., 1994; Hirst et al., 1990)

In industry, the strategies depend on the contrasting industrial context in each country. The magnitude of the identified wedges goes beyond the necessary generalization of energy efficiency improvements in all production processes (Bataille, 2020). The results need further investigations to better identify the transformation mechanisms at stake in each industrial subsector and particularly the role of disruptive innovations, based on robotics and digitalization, which we may expect in industry worldwide.

In transportation, beyond the many technological issues surrounding the deployment of engines that do not emit GHGs and air pollutants, results show the importance of making progress in understanding the determinants of mobility and freight transport in order to control their growth. Three main priorities for action emerge. First of all, it is important to make progress in understanding the levers of everyday mobility based on active modes (Mathy et al., 2020). Such mobility is in fact a strategy that leads to numerous co-benefits, particularly in terms of public health, due to the reduction in air pollution and induced physical activity (de Nazelle et al., 2011). On the other hand, it is also necessary to understand how to reduce long-distance transport and the use of low-cost air transport for both business and leisure travel. Finally, the decoupling of freight transport from GDP growth directly questions the organisation of production and supply chains and, beyond that, our lifestyles. In any case, it is clear that reducing individual mobility and freight transport are strategies that could constitute a strong pillar of GHG emission reduction strategies in this sector. These strategies will notably lead to numerous co-benefits in terms of health, limitation of road infrastructures, artificialization of soils and relocation of activities in particular.

Contrary to wedges related to energy efficiency in end-use energy demand sectors, the contribution and the time profile of wedges on the supply side (energy decarbonisation in final energy demand sectors and in the power sector) are really specific to the scenario family. In *Current_NDC*, it is necessary to wait for the second period for the penetration of low-carbon energy carriers (electricity, heat, fuels, etc.) to accelerate and become really significant because it necessitate time for decarbonisation, for the building of new infrastructure and for new technology development. In a general way but also in a detailed way for the 4 countries, delayed decarbonisation is made possible by a massive electricity decarbonation in parallel with an electrification of end-uses of final energy consumption after 2030. This sharp increase raises the question of socio- and techno-economic feasibility. From an economic point of view, the slow deployment of low carbon technologies during the first period in the delayed action scenario will necessarily slow down learning by doing in renewable technologies and increase the cost of renewables in the second period compared to earlier action scenario. No doubt the global cost of the delayed action scenario is much higher than the earlier action scenario.

The massive deployment of renewable energies needed in both strategies raises several issues particularly in *Current_NDC*. Renewable energies still depends on significant subsidies. Many electricity generation technologies using renewable energy sources have become much more cost-competitive in recent years, partly due to economies of scale driven by these selfsame subsidies. Nevertheless maintaining a high level of incentives for a rapid development of renewables can quickly become unsustainable unless cost-competitiveness is reached fairly rapidly. The penetration of high shares of renewable energies in the grid will also induce increasing system costs (transmission costs for connecting more widely dispersed generating plants, the buildup of reserve capacities, market restructuring, and re-optimization of the power plant fleet to minimize ramping costs). Increasing the share of variable renewable energy in the power generation mix also poses the problem of a structural mismatch, at certain periods of the year, between the grid demands and the power supplied. At times, they may produce a massive surplus and unless storage or increased transmission to other jurisdictions with unmet demand are implemented, large unused production would reduce the cost-effectiveness of variable renewable energies.

Another consequence of delayed action is the relatively high emission intensity of electricity production until 2030. Fossil electricity production, and in particular coal production, is higher in *Current_NDC* than in *Enhanced_NDC*, where electricity is already largely carbon-free at that date. This has several consequences. First, to avoid excessive stranded costs on then-existing coal-fired power plants, the use of carbon capture and storage takes a stronger role just after 2030 in *Current_NDC*, despite the high uncertainties about the availability of this technology at this time. On the other hand, because of the delay in learning by doing in renewables, gas might gain the upper hand over coal (too dirty) and renewables (still too expensive) for a couple of years. Finally, the rapid closure of many coal-fired power plants in the countries concerned (mainly Germany and Poland in the 4 countries considered) will inevitably lead to problems of employment and political acceptability. These three consequences are absent from *Enhanced_NDC (ie* earlier action scenario), which results in a continuous but significant decrease of coal in the energy mix and therefore does not use CCS or the substitution of coal for gas.

5.2. Prospects for future research on deep decarbonization pathway modelling

Beyond the analysis of national emission reduction strategies and of the impact of an early action on the reduction effort, this work helps to highlight the role that alternative consumption and living patterns or at least sobriety can play in emission reduction strategies. Indeed, the stronger the sectoral dynamics, the greater the effort required to reduce emissions and the greater the challenges posed by transition policies in order to properly coordinate the deployment of new carbon-free technologies (Mathy et al., 2016).

This is particularly true in the context of the Paris Agreement which aims at keeping the increase in global average temperature to **well below 2°C** and to pursue efforts to limit the temperature increase to 1.5°C. As pointed out by Wilson et al. (2012) global mitigation scenarios tend to focus on new energy supply technologies and underestimate the value of efficient end-use technologies. Many scenarios that limit global warming to 1.5°C do not hesitate to anticipate an ever-rising energy demand that requires the implementation of increasingly complex transformations in energy supply (Rogelj et al., 2018). Conversely, Grübler et al. (2018) developed a narrative of future change that quantifies changes in activity levels and energy intensity in the global North and global South for all major energy services and results global final energy demand by 2050 around 40% lower than today, despite rises in population, income and activity. Such low energy demand scenario shows that down-sizing the global energy system dramatically improves the feasibility of a low-carbon supply-side transformation.

Thus, from a methodological point of view, in support of energy-climate modelling, it would be necessary to systematize the modelling of low-carbon scenarios that are transparent on the assumptions allowing to project in the medium and long term the levels of sectoral activities and to better understand the determinants of behavioural changes towards alternative consumption patterns. From this point of view, the systematic scenario reporting approach through sectoral dashboards as developed in the Deep Decarbonization Pathways Project (Waisman et al., 2019) or in the COP21 RIPPLES is rich in lessons. It makes it possible to apply the DW methodology and thus to make visible the contribution of activity effects to the increase or reduction of emissions.

Finally, still from a methodological point of view, one of the advantages of the DW method is to provide a harmonised framework for analysing scenarios produced with different models. The method makes it possible to reveal and make visible different hypotheses but also the differences in complex internal dynamics existing between different models on the diffusion of energy efficiency, the penetration of low-carbon technologies and the impact of economic growth on sectoral dynamics. It is thus an appropriate tool for multi-model comparison exercises, if data are available, particularly data on sectoral activities. It would also be interesting if model comparison exercises were to be deployed in a context of harmonization on indicators of contrasting sectoral activity beyond harmonization on growth assumptions. These elements would be an integral part of the definition of scenario storylines.

6. Conclusion

In this paper, we provide systematic ex-post analysis of the national scenarios produced at a national level and collated in the COP21 RIPPLES project. For this purpose we use the decarbonization wedges (DW) methodology elaborated by Mathy et al. (2018). The methodology splits forecast energy-related emissions up to 2050 into decarbonization wedges related to energy efficiency and the decrease of the carbon content of energy carriers in buildings, transport and industry and in the power sector (coal/gas substitution, renewables, nuclear, carbon capture and sequestration (CCS)).

The present contribution goes beyond traditional gap analysis, in terms of aggregate emissions, to provide a systemic analysis of the transformation gap between NDC and well below 2°C/1.5°C national scenarios. The DW allows quantifiying the impact of contrasted sectoral development assumptions and potentiel structural change of the economy on mitigation strategy analysis. We apply the methodology to global mitigation scenarios and to four EU countries : Germany, France, Poland and UK that represent on aggregate 55% of current EU emissions.

The results show the diversity of mitigation actions between France, Germany and the United Kingdom on the one hand, and Poland on the other, where assumptions about the growth of economic and sectoral activities and the coal-intensive energy system raise major mitigation issues.

This analysis shows that expected contribution of energy efficiency in end use-sectors to emission reduction is significant and almost comparable to the contribution of the decrease of the carbon content of energy in the period 2010-30, but is slightly decreasing thereafter. Conversely, the contribution of energy decarbonization options (in end-use sectors and in the power sector) increases over time and takes a strategic role in emission reductions after 2030. This very strong growth in the second period is particularly remarkable for the *Current_NDC* scenario where an increase in effort is required to reach the 2°C trajectory. The technico-economic feasibility and realism of the assumptions for the diffusion of low-carbon technologies (renewable energies, CCS and coal/gas substitution) that are needed after 2030 in the *Current_NDC* scenarios is questionable.

This work clearly shows the advantages of the anticipated trajectory (*Enhanced_NDC*), which increases effort in the first period but significantly reduces it in the second period and does not require the use of too uncertain technical options. From that point of view, a strategy based on the moderation of sectoral dynamics, ambitious energy efficiency improvement programs in every end-use sectors, the penetration of renewables and an early but gradual decrease in coal capacity in the power sector before 2030, seems to be the most appropriate strategy to raise NDC ambition and limit the increase in the global average temperature to well below 2°C.

Finally, this work illustrates that it is not only possible but essential to take into account the assumptions about economic growth and changes in activity in the end-use energy sectors, in order to be able to compare the levels of effort required to combat climate change. In this respect, it can be seen that the strategies followed in terms of industry or mobility, for example, can differ greatly between countries. These policy choices need to be clarified to be more transparent and to allow for the development of alternatives on structural transformation assumptions.

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