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AN EXPLORATIVE EVALUATION OF THE CLIMATE DEBT¹

Climate change and global warming are often spoken of in the same breath as limited natural resources and the optimal way to manage the small amount that is still available. Understanding how we should use and share what is left in order not to put human life at risk is of cardinal importance, if not the cornerstone of nowadays debates. Despite all the pledges that have been made so far, both on the national and global stages, there is still a lot to be done before countries dedicate sufficient economic and political means to really tackle this issue.

The 24th Conference of Parties that will be launched on the 3rd of December in Katowice, Poland, is part and parcel of the traditional diplomatic apparatus aiming at promoting fruitful talks and agreements relative to this paramount topic. The location of this 24th summit is sufficient in itself to shed light on active fault lines of such negotiations. Indeed, Katowice is nothing but an example of how coal mining cities remain vital for some national European economies to stay away from deep crises. More specifically, it helps keeping in mind that entire economies, even in what is thought to be the “developed” world, still depends hugely on fossil fuels. Above all, this will surely be an additional occasion to realize that some countries are not especially welcoming structural changes in their energy mixes. To be more precise, it may be the place where countries will try and advocate one more time for differentiated historical responsibilities in the global warming phenomena currently happening as well as differentiated capabilities to address these issues. For instance, Katowice’s mayor has allegedly admitted that “it would be difficult to

1. All data, source code and spreadsheet files used to calculate elements in this chapter are available on request to xavier.timbeau@sciencespo.fr. Commercial data and software cannot be transmitted.

convince representatives of other countries to continue using energy from fossil fuels, but that he can't imagine the same to hold for Poland itself".²

In such a framework, it seems more urgent than ever to delineate countries' relative responsibilities and absolute contributions to emissions reductions in order to remain in line with the 2015 Paris Agreement. To do so, we outline in the subsequent work a methodology aiming at computing climate debts at the national and regional scales. In other words, we aim at developing monetized indicators that encapsulate the amount of efforts to be made by each country within the next decades if we want to keep the global temperature increase below 2°C (or 1.5°C in the best case scenario) above pre-industrial levels, proposing a measure of the distance to a sustainable pathway for the economy.

Our methodology relies on a two-step approach. First, we compute "carbon budgets" labelled in physical units, namely GtCO₂. These budgets correspond to the cumulative amount of carbon dioxide (CO₂) emissions permitted until the end of times to keep within a certain temperature threshold. Since these computations are subject to normative implications, we detail various alternatives to build those numerical entities. We carefully pay attention to the question of differentiated historical responsibilities among countries. Then, our goal is to associate a monetary price to these carbon budgets. To do so, we develop the concept of "climate debt". By "climate debt" we mean the amount of money that will have to be invested or paid by countries for them not to exceed their carbon budget. It means that we rely on previously computed carbon budgets on the one hand and a provisional emissions path on the other so as to determine which quantity of carbon will have to be abated. This allows us to compute the numbers of years before depletion of the carbon budget by country. We then rely on assumptions on the cost of abatement technologies in order to give a monetary value to these residual carbon emissions past the depletion date.

In the end, climate debts and years before depletion put emphasis on the urgency to mitigate climate change since numbers at stake are quite big. What's more, we find that there is a significant heterogeneity among countries within the European Union. However, we believe that these quantitative elements should not be interpreted as the proof that mitigating the climate is not undoable or too expensive. Rather, it sheds light on the fact that it is within our reach, making our failure to address it even more condemnable.

2. See <http://climatetracker.org/cop24-katowice-expect-polands-4th-un-climate-summit/>

III.1. Carbon budget, historical carbon adjustment and burden share

1.1. Historical construction and standard definitions

The 2015 Paris Agreement achieved a global consensus about the boundaries that should constrain greenhouse gases (GHG) emissions to prevent global warming. Nearly all countries agreed to cooperate in order to keep the increase in global temperature under 2°C above pre-industrial levels and to do whatever is in their power to get this global temperature change as close as possible to 1.5°C. Thus, countries have already committed to reduce their carbon emissions while designing and submitting their ***Intended Nationally Determined Contributions**** (also known as INDCs).³

In the light of the latest geophysical analyses, this implies that only a limited quantity of carbon dioxide can be emitted. Indeed, in the last decades, it has become widely acknowledged that global warming is almost linearly related to cumulative emissions of carbon dioxide (Allen *et al.*, 2009; Matthews *et al.*, 2009; Raupach *et al.*, 2011) complicating the setting of stabilization targets to avoid potentially dangerous levels of global warming. Similar problems apply to the carbon cycle: observations currently provide only a weak constraint on the response to future emissions. Here we use ensemble simulations of simple climate-carbon-cycle models constrained by observations and projections from more comprehensive models to simulate the temperature response to a broad range of carbon dioxide emission pathways. We find that the peak warming caused by a given cumulative carbon dioxide emission is better constrained than the warming response to a stabilization scenario. Furthermore, the relationship between cumulative emissions and peak warming is remarkably insensitive to the emission pathway (timing of emissions or peak emission rate). This is tantamount to say that there is no path specificity to global warming: as a first order approximation, only the cumulated quantity matters, regardless of the emissions trajectory.

Not only did this near-linear relationship between global warming and cumulative carbon dioxide emissions improve our understanding of climate change but it also amounted to a huge leap forward in terms of environmental policies design. Indeed, this simple link allowed the production of more accurate forecasts of future global warming and climate change. It enabled for instance to

3. Terms in bold with an asterisk are detailed in Chapter 3 final glossary.

conceptualize the indicator called Transient Climate Response to Cumulative Carbon Emissions (TCRE), which aims at quantifying the global average temperature change per units of emitted carbon dioxide. On the other hand, the quasi-linear relationship between temperature increase and carbon emissions can also be used in reverse in order to define the cumulative quantity of carbon dioxide than can be emitted until we reach a given global temperature change target.

This idea thus led to the development of *carbon budgets**, namely statistical indicators aiming at measuring how many tonnes of carbon dioxide can be released in the atmosphere before we cross given temperature change thresholds. According to the *Intergovernmental Panel on Climate Change** (thereafter the IPCC) Special Report on the impacts of global warming of 1.5°C above pre-industrial levels (SR1.5), the carbon budget is the “*estimated cumulative net global anthropogenic CO₂ emissions from preindustrial period to the time that anthropogenic CO₂ emissions reach net zero that would result, at some probability, in limiting global warming to a given level, accounting for the impact of other anthropogenic emissions*”.⁴ The IPCC SR1.5 also gives the most consensual and up to date evaluation of the global carbon budget.⁵

Table 17. Global Carbon Budget

Global warming since 1850-1900	Remaining carbon budget from 1.1.2018, GtCO ₂			Uncertainties				
	33%	50%	67%	Additional Earth system feedbacks	Non-CO ₂ scenarios variance	TCRE distribution uncertainty	Historical temp. uncertainty	Emissions uncertainty
+1.5 °C	1,080	770	570	+100	[-400:+200]	[+100:+200]	[-250:+250]	[-20:+20]
+2. °C	2,270	1,690	1,320					

Source: IPCC SR1.5 (2018).

Table 17 can be interpreted as follows: if we want to ensure a probability of 67% that global temperature change will remain below +2°C from preindustrial levels, we should not emit more than 1,320 billion tonnes (10⁹ tonnes) of carbon dioxide (GtCO₂) from now until the end of times globally. This limited cumulative emissions of carbon dioxide that can be released in the atmosphere falls down to 570 GtCO₂ if we consider the 1.5°C threshold instead.

4. See *Summary for Policymakers, IPCC SR1.5* p.26
5. Available here: www.ipcc.ch/report/sr15/

Of course, the computation of the carbon budget is always disputable as it relies on climate models which, in turn, depend on many assumptions and hypotheses that can be discussed. In particular, climate scientists keep improving climate models while bringing to light new physical properties of the Earth carbon cycle⁶. This is why the IPCC special report 1.5°C provides boundaries taking into account several uncertainties such as historical temperatures or the distribution of the TCRE in particular. More generally, the computation of the carbon budget can differ greatly between institutions not only because of the sensitivity of climate models but also due to the time frame considered, the scope of sectors under scrutiny (referring to the energy sector only or to all sectors) and the type of emissions accounted for (all greenhouse gases or carbon dioxide only).⁷

Nevertheless, although there is not a definitive consensus on how to compute global carbon budgets yet, the key issue lies elsewhere. More specifically, computing global carbon budgets remains less controversial than sharing these budgets between regions and countries.⁸

1.2. Normative implications of burden sharing

Deriving a global carbon budget is undoubtedly helpful when it comes to fueling the scientific debate on climate change. As far as national environmental public policies are concerned, it still needs to be broken down into smaller parts in order to enlighten decision makers and weigh in on public policy design. National budgets must be estimated to delineate countries' responsibilities and drive their emissions reductions. So far, the literature has underlined a continuum of burden sharing methods, whose two endpoints are the egalitarian approach on the one hand and full grandfathering on the other (Gignac and Matthews, 2015; Giraud *et al.*, 2017; Raupach *et al.*, 2014) on a spectrum of sharing principles that extends from continuation of the present distribution of emissions to an equal per-capita distribution of cumulative emissions. A blend of these endpoints emerges as the most viable option.

6. See for instance Comyn-Platt *et al.*, (2018) in "Carbon budgets for 1.5 and 2°C targets lowered by natural wetland and permafrost feedbacks".

7. For more details, see Sussams, (2018) in "Carbon budgets: where are we now?".

8. See Caney, (2013) in "Justice and the distribution of greenhouse gas emissions".

1.2.a The egalitarian approach

The first and most intuitive sharing method consists in allocating each and every human being the same right to emit carbon dioxide. Said differently, it means that the quota of CO₂ units per capita remains constant for a given reference year, regardless of considered country. It can be written as follows:

$$CB_c = CB_w \times \frac{pop_{c,t}}{pop_{w,t}}$$

with CB standing for “carbon budget”, pop for “population”, c (resp. w) for countries (resp. world) in year t . Thus, for a given year t , the more populated a country, the greater its carbon budget, no matter its level of economic development, degree of industrialization, cumulative past emissions, etc. This means that this approach is utterly blind to structural inequalities between countries⁹ and puts at the forefront present equality between people as a sharing principle. To some extent, it is a way to erase past differences between countries and hence make people equally responsible from now on when it comes to fighting global warming and climate change. As such, it could be interpreted as a way to impulse cohesion so as to trigger a global effort in designing efficient environmental public policies.

The strength of such a method is its relative simplicity as well as the transparency of its underlying hypotheses. Nevertheless, numerous shortfalls must be highlighted. The first one deals with the choice of reference year. The carbon budget allocated to each region or country can greatly vary depending on this choice. For instance, choosing 1990 as a baseline would be more favorable to the European Union than 2005 or 2015, since the ratio of the European population over the global population keeps decreasing.

Furthermore, ignoring past and remaining structural heterogeneities between countries—such as differences in countries’ access to renewable resources and in their weather and climate conditions—seems quite disputable. For instance, in countries where there are more cold days on average, it seems more likely that emissions per capita will be higher, all other things being equal. Allocating the same per capita carbon budget would implicitly mean that some people are constrained more than others since they are bound to do more efforts to keep their emissions within authorized boundaries. At some point, it goes against the idea that every individual is entitled the same rights and duties when it comes to their environmental impact.

9. At least, those that are not endogenous to population size.

1.2.b Grandfathering

The grandfathering method is the other endpoint of the continuum of burden sharing methods. While the egalitarian approach casts a blind eye to the past, the grandfathering approach seems on the contrary the most conservative sharing method to date. Indeed, it relies on the idea that the global carbon budget should be divided along the criterion of current carbon emissions. It means that the weight of each country in global emissions remains stable over time. In other words, countries that emit a lot will remain the major emitters while countries that release only a small quantity of carbon dioxide will keep being the smallest emitters, regardless of the absolute level of emissions considered.

This conservativeness can be interpreted to capture structural national elements that are only slowly modified or cannot be changed at all. This is for instance the case of the access to renewables or the exposure to particularly rough climate conditions, both linked to geographic location and physical features that cannot be changed at will.

It can be formalized with the following equation:

$$CB_c = CB_w \times \frac{ems_{c,t}}{ems_{w,t}}$$

with CB standing for “carbon budget”, ems for “emissions”, w for world, c indexing countries and t years. Once again, this method can be criticized due to its large dependency on the choice of the reference year. In this case, choosing 1990 as a reference year would favor the European Union more than 2005 or 2015 would do. Nonetheless the major problem of such a method lies on its normative implications rather than its disputable statistical robustness.

Indeed, it is worth highlighting that *“grandfathering is generally viewed as morally unacceptable, particularly in the developing world”* (Giraud *et al.*, 2017) since it is the exact opposite of the “polluter-pays” principle: emitting the greatest quantity of CO₂ ensures a country it will be allocated the greatest national carbon budget possible. In other words, the more you pollute, the less you are compelled to stop polluting: polluting gives you a right to pollute more than others in the future.

What’s more, such a measure leaves aside the issue of historical responsibility, and can be interpreted as “environmental colonialism” (Agarwal and Narain, 1991) to the extent that it impedes developing and poor countries to industrialize the way developed countries have industrialized before them, hence threatening them to fall into a wide open poverty trap. Even more importantly, it prevents developed countries from acknowledging they are largely respon-

sible for the climate change and should therefore be the ones undertaking costly actions.

1.2.c Historical carbon adjustment

Considering historical accountability is thus at the heart of the carbon budget debates. It appears as the core concern and it is illustrated by the fact that the two endpoints of the methodological continuum seem to be polarized by the way they take into account past inequalities (*i.e.* not at all for the egalitarian approach and entirely for the grandfathering method). In order not to evade this issue, some authors such as H. Damon Matthews have suggested computing an additional measure of **historical carbon adjustment**^{*}. In his 2016 paper entitled “*Quantifying historical carbon and climate debts among nations*”, he relies on the following indicator:

$$HCA_c = \sum_{t=start}^{present} \left[ems_c(t) - ems_w(t) \times \frac{pop_c(t)}{pop_w(t)} \right]$$

with *HCA* standing for “historical carbon adjustment”.¹⁰ This methodology is based on an extrapolation of the egalitarian approach. More precisely, it is based on a preliminary computation of an annual quota of emissions that a country should not exceed, using the *start* date as the reference year. This quota consists in the sum of the individual emission rights over its population, which in turn are computed according to the egalitarian approach. Once this quota is defined, the historical carbon adjustment indicator aims at determining, for each year, whether countries have emitted more or less than their quotas and aggregates the deviations from the quotas over the time period extending from *start* to *present*.

Such a method enables to confront emissions released by a country to its theoretical carbon budget. It thus takes into account what can be called a “historical responsibility” of countries. Nonetheless, it still may be seen as an oversimplification of what is responsibility, all the more so as it is deeply rooted into the normative egalitarian framework. This means that we could compute historical carbon adjustments formalizing responsibility in a totally different way—for instance determining the quota of each country based on their past emissions.

10. In his 2016 paper, Matthews computes what he refers to as a “carbon debt” following the exact same definition. We believe calling it a “Historical Carbon Adjustment” enables us to be clearer in the presentation of our work, since we seek to avoid confusions between the concepts of “carbon debts” and “climate debts”.

To that extent, this formalization of historical responsibility should be interpreted cautiously, even though it helps previous methods in getting closer to a more realistic and consensual way of computing carbon budgets.

1.3. The European Union Carbon Budget

In this chapter, we aim at computing the carbon budget that can be spent by the European Union from now until the end of times. This is a first iteration of an exercise bound to be improved in the next few years and in the light of political negotiations on burden sharing rules. As such, we mostly try to produce clear indicators whose underlying hypotheses do not confuse the reader rather than develop highly complex measures that are not easily interpretable. That is why we focus on the two previously mentioned methods, namely the egalitarian approach and the grandfathering approach taking 2015 as a reference year. More specifically, we proceed following a two-step repartition: (i) first, we compute the carbon budget of the European Union (28 members) starting from the global carbon budget for 2018 and (ii) then, we break down the European carbon budget into 28 national carbon budgets.

Given the European focus of the present report, we consider in this chapter the climate issue through the European angle. We attempt to estimate the European Union's regional responsibility, in aggregate, in the decarbonization process. To do so, we first use the egalitarian approach—with 2015 as reference year—in order to compute the regional carbon budget at the European aggregate level. Then, we allocate to each member country its proper national budget using full grandfathering—based on emissions ratios of 2015 too.

Nonetheless, in order to consider differentiated national historical responsibilities since 1990, we compute in a second moment a *historical carbon adjustment* per country over the 1990-2017 period,¹¹ following Matthews' method as detailed earlier. 1990 is an arbitrary starting point to responsibility. It seems that for complex reasons, it is one of the focal points in international negotiations.¹²

11. Since we only have emissions data until 2015, we assume that 2016 and 2017 CO₂ emissions levels are the same as 2015 emissions levels.

12. To put it briefly, we must underline that there is a huge and paramount debate in the carbon budget literature when it comes to the choice of the starting date of historical responsibility. In particular, for some searchers and decision makers it seems fairer to take into account past emissions starting in 1750-1800, before developed countries started their industrialization process. Others argue in favour of 1990 claiming that it corresponds to the beginning of the global awareness and subsequent commitments to fight against climate change. This debate is made even more complex considering its interactions with the general debate about what "pre-industrial levels" means.

Finally, we compute and analyze **adjusted carbon budgets*** both at the regional and national scales. To the extent our baseline carbon budget computing method cashes in on both the egalitarian and the grandfathering methods, we thereafter call it the “hybrid” approach.

1.3.a Data

Our computations rely on three types of data: (i) the global carbon budget data, (ii) data on global and national emissions over the 1990-2015 period and (iii) data on national populations over the same period.

- i. The Global Carbon Budget is retrieved from the IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels released in October 2018. For the sake of clarity, we focus on the 67th percentile of the probability distribution to remain under a given temperature change threshold, namely either 1.5°C or 2°C. We only consider the core estimation of the remaining carbon budget, which means that we disregard uncertainties measures as underlined by the IPCC in their special report.
- ii. Emissions data are two-fold. On the one hand, when it comes to historic global emissions, we rely on the version 1.3 of the Historical Carbon Budget as computed by Le Quéré *et al.*, (2018),¹³ which includes emissions from fossil fuels and industry but also from land use change in GtCO₂ per year between 1990 and 2015. On the other hand, we use data on final demand content emission, in order to implement a consumer approach to emissions. We thus rely on data on CO₂ emissions embodied in consumption that are calculated by the OECD based on Input Output tables and imports from each region of the world for each country to take in account CO₂ emissions needed to produce goods and services consumed in a given country. Embodied emissions are added to direct emissions to calculate the consumer approach emissions.¹⁴
- iii. As far as population data are concerned, we exploit the 2017 revision of the United Nations World Population Prospects dataset, extracting data for the 28 member countries of the European Union between 1990 and 2015.¹⁵

13. <http://www.globalcarbonproject.org/carbonbudget/17/data.htm>

14. Data from 1995 to 2011 are used to correct national emissions. For emissions data before 1995 (resp. 2011), we use 1995 (resp. 2011) as a correction factor.

15. <https://population.un.org/wpp/DataQuery/>

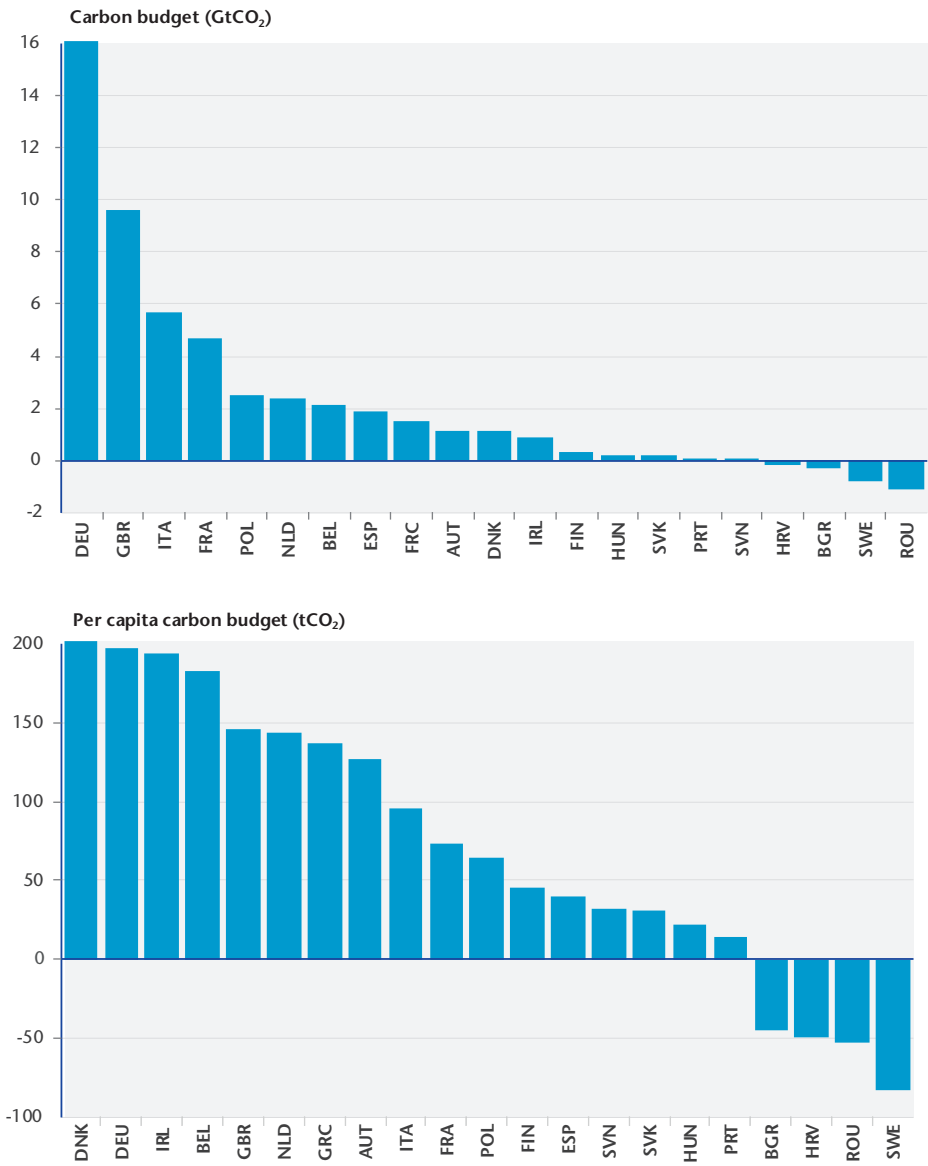
1.3.b Carbon budgets and historical carbon adjustment

Using the hybrid sharing method with 2015 as a reference year credits the European Union with a carbon budget of 91 GtCO₂ if we consider the +2°C scenario (Table 18). This amounts to approximately 30 more years if current emission levels remain unchanged. This budget falls down to 39 GtCO₂ in the case we scrutinize the +1.5°C scenario, that is to say a little bit more than 10 years. At the regional scale, the historical carbon adjustment since 1990 over the 28 member countries of the European Union amounts to 49.7 GtCO₂. This means that, updating previous results on the basis of historical carbon adjustments leads to a way smaller carbon budget for the European Union. More precisely, it falls down to 41 GtCO₂ for the +2°C scenario. Considering the +1.5°C scenario, these estimations lie at 11 GtCO₂.

Moreover, carbon budgets are quite dispersed among member countries. With the hybrid method for the +2°C scenario, the biggest carbon budget goes to Germany with 21 GtCO₂ while the smallest budget is for Malta with 0.04 GtCO₂. Considering the +1.5°C scenario does not change these two endpoints, granting Germany a budget of a little bit more than 9 GtCO₂ while the Maltese one is about 0.02 GtCO₂. Apart from Germany, the United Kingdom, France, Italy and Spain are the four countries with the more generous carbon allocations with budgets falling between 13 and 6.6 GtCO₂ for the +2°C scenario. This ranking remains unchanged while considering the 1.5°C scenario with budgets lying between 5.5 GtCO₂ for the United Kingdom and 2.8 GtCO₂ for Spain.

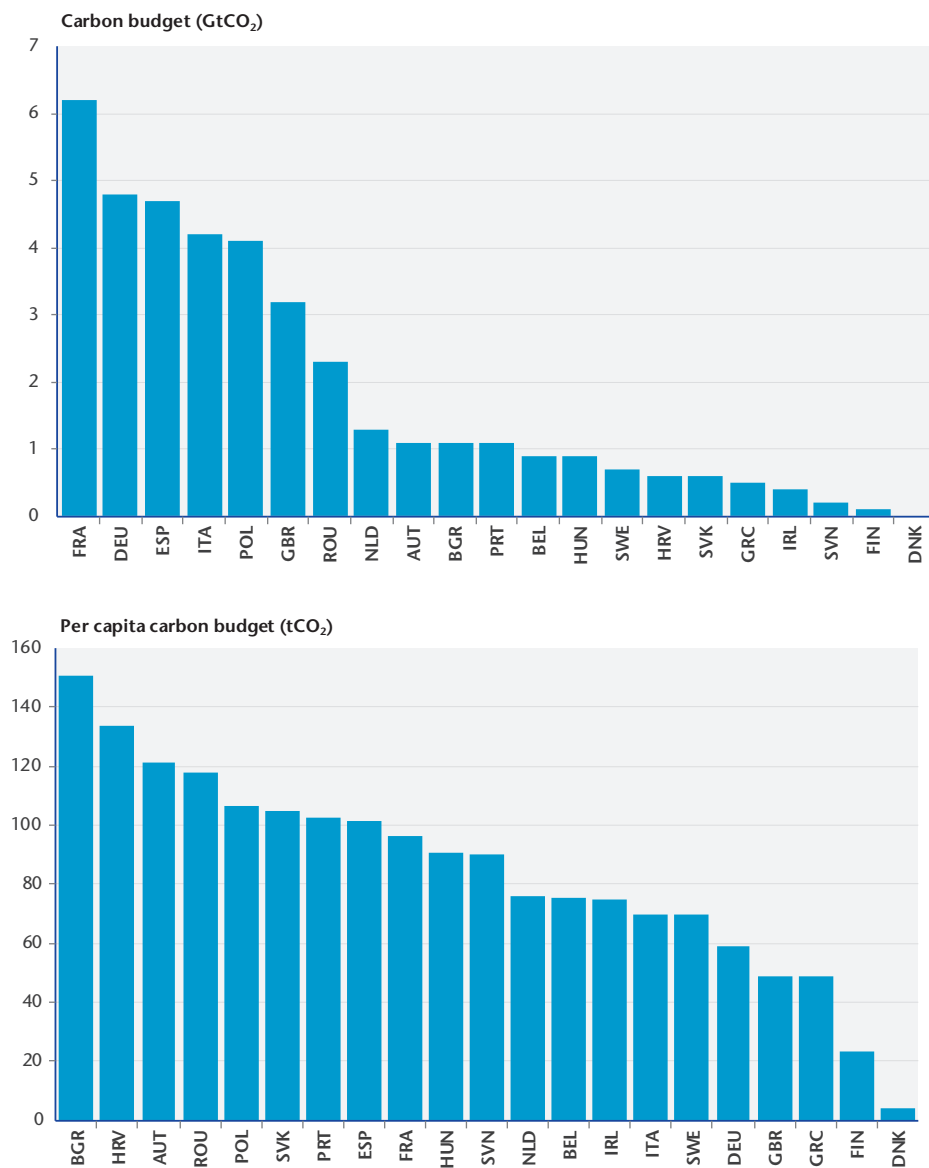
Nonetheless, taking into account adjusted carbon budgets changes quite a few things: in the framework of the 2°C scenario, computing hybrid budgets makes France the country with the most important carbon budget with 6.2 GtCO₂ while Germany goes down to the second position with an adjusted carbon budget of 4.8 GtCO₂ (as opposed to 21 GtCO₂ before adjustment). Spain, Italy and Poland follow. This is largely due to the fact that Spain and Poland have a small historical carbon adjustment while the United Kingdom's is the second biggest of the European Union, which makes it go out of the top 5. Denmark and Luxembourg are granted the smallest adjusted carbon budget with 0.02 GtCO₂. This order differs largely when considering the 1.5°C scenario, the first five countries being Romania, Spain, Sweden, Bulgaria and Portugal. More particularly, Germany's position shifts to the bottom with a negative carbon budget of 7 GtCO₂, just after the United Kingdom (-4 GtCO₂) and Italy (-1.5 GtCO₂).

Figure 43. 1990 Historical carbon adjustment



Source: iASES (formerly iAGS) 2019 computations, based on IPCC SR1.5, OECD emissions data, Le Quéré et al. (2018) Historical Carbon Budget (version 1.3) and UN World Population Prospects (2017 revision); consumer approach.

Figure 44. Adjusted hybrid carbon budgets (consumer approach)



Source: iASES (formerly iAGS) 2019 computations, based on IPCC SR1.5, OECD emissions data, Le Quéré *et al.* (2018) *Historical Carbon Budget* (version 1.3) and UN World Population Prospects (2017 revision); adjusted carbon budgets take into account the Historical Carbon Adjustment (see Figure 43, 1990 Historical carbon adjustment for assumptions) and are calculated for +2°C 2/3 probability, hybrid share and consumer approach.

Table 18. Hybrid carbon budgets, historical carbon adjustment and adjusted carbon budgets

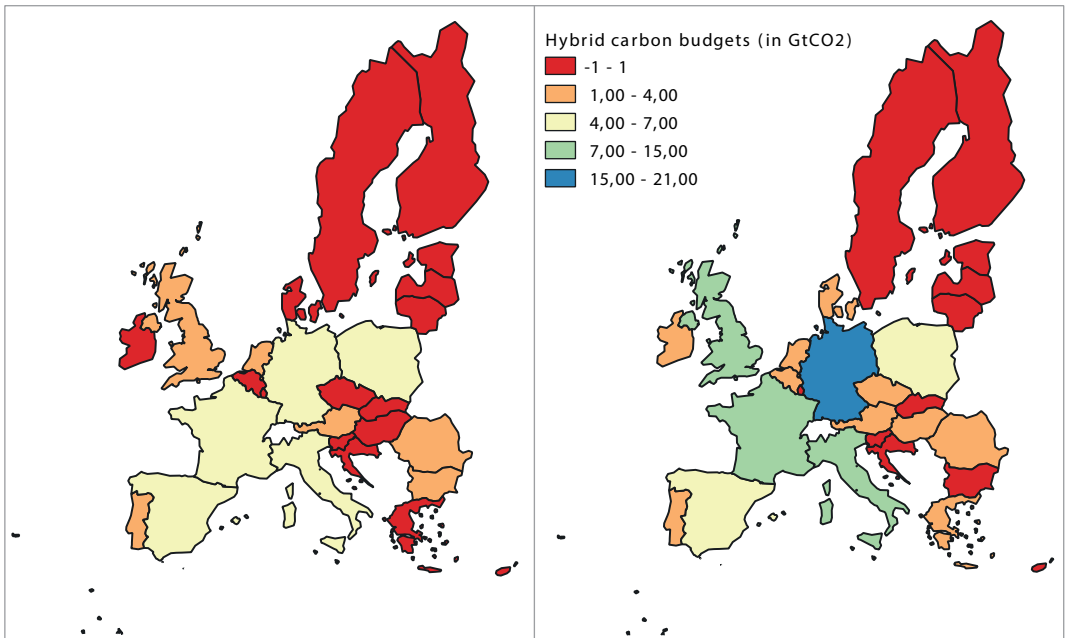
	Hybrid carbon budget (2015 reference year)	Historical carbon adjustment (1990-2017)	Hybrid adjusted carbon budget (2015 reference year) (C = A – B)	Per capita hybrid adjusted carbon budget (2015 reference year) C/POP
	(A)	(B)		
EU-28	90.7	49.7	41.0	96.5
AUT	2.16	1.11	1.05	121.5
BEL	2.92	2.07	0.85	75.7
BGR	0.76	-0.32	1.08	151.0
HRV	0.36	-0.21	0.57	133.5
CYP	0.21	0.11	0.10	84.6
CZE	2.15	1.56	0.59	55.6
DNK	1.17	1.15	0.02	3.8
EST	0.26	0.19	0.07	50.6
FIN	0.38	0.25	0.13	23.2
FRA	10.93	4.71	6.22	96.5
DEU	20.96	16.13	4.84	59.2
GRC	2.09	1.54	0.55	48.7
HUN	1.10	0.22	0.89	90.6
IRL	1.26	0.91	0.35	74.6
ITA	9.88	5.72	4.15	69.8
LVA	0.23	-0.28	0.51	255.6
LTU	0.23	-0.13	0.36	122.3
LUX	0.17	0.15	0.02	43.3
MLT	0.04	0.01	0.03	73.7
NLD	3.73	2.44	1.29	76.1
POL	6.54	2.46	4.09	106.8
PRT	1.21	0.14	1.07	102.6
ROU	1.28	-1.06	2.34	117.8
SVK	0.74	0.17	0.57	105.0
SVN	0.25	0.07	0.19	90.4
ESP	6.58	1.87	4.70	101.3
SWE	-0.13	-0.81	0.68	69.7
GBR	12.75	9.55	3.20	48.9

Source: iASES (formerly iAGS) 2019 computations, based on IPCC SR1.5, UNFCCC emissions data, Le Quéré et al. (2018) Historical Carbon Budget (version 1.3) and UN World Population Prospects (2017 revision). Calculated for +2°C 2/3 probability, hybrid share and consumer approach.

In those numbers a “population size” effect remains, even while sharing the European budget between member countries using full grandfathering. The level of emissions is correlated to the number of people living in a given country. In other words, two differently populated countries with the same levels of emissions per capita will have different aggregate levels of emissions, hence different carbon budgets. This is why it is also instructive to cast a glance at per capita results, which largely redistribute emissions rights within the European Union. More precisely, Bulgaria, Croatia, Austria, Romania and Poland then appear to have the greatest carbon budgets per capita. France ends up at the 9th position while Germany and the United Kingdom respectively hold the 17th and 18th positions.

The maps on Figures 45 aim at summarizing carbon budgets and adjusted carbon budgets for the 2°C scenario using the hybrid approach with embodied emissions data:

Figure 45. Maps of carbon budgets



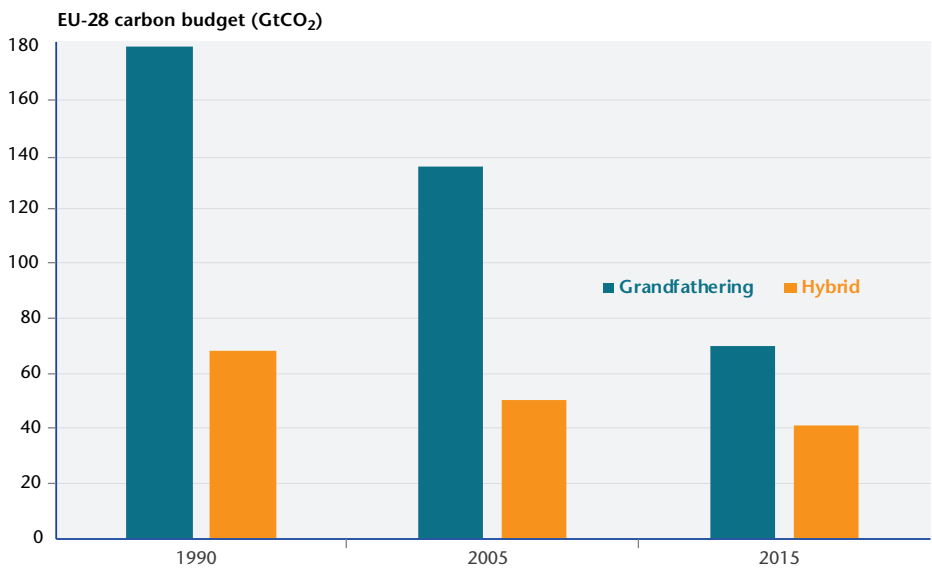
Source: iASES (formerly iAGS) 2019 computations, based on IPCC SR1.5, UNFCCC emissions data, Le Quéré *et al.* (2018) *Historical Carbon Budget* (version 1.3) and UN World Population Prospects (2017 revision); on the left handside are displayed national adjusted carbon budgets for EU28 member countries; on the right handside are displayed national carbon budgets (before historical carbon adjustment) for the same countries. Calculated for +2°C 2/3 probability, hybrid share and consumer approach.

1.3.c Sensitivity analysis

The previous section detailed the result of our baseline scenario, namely hybrid carbon budgets with a consumer approach to emissions data. We first wonder whether these results are greatly sensitive to the sharing approach used. When it comes to the grandfathering method, computed carbon budgets appear to be bigger, with 119 GtCO₂ (resp. 52 GtCO₂) for the European Union for the +2°C scenario (resp. +1.5°C). Furthermore, at the regional scale the hybrid method and the egalitarian method lead to the same results, by construction of the former.

As underlined in the first section, sharing methods might be very sensitive to the choice of the reference year and this also goes hand in hand with normative implications. In particular, there seems to be great differences depending on the reference year used when we rely on the grandfathering sharing method: the 1990 computed budget is 2.5 times bigger than the 2015 budget. On the other hand, the egalitarian approach seems more robust and shows less variation due to the choice of the reference year. That being said, 2015 is the reference year that leads to the smallest differences between the two sharing methods at the regional scale.

Figure 46. Grandfathering versus hybrid EU adjusted carbon budgets



Source: iASES (formerly iAGS) 2019 computations, based on IPCC SR1.5, UNFCCC emissions data, Le Quéré *et al.* (2018) *Historical Carbon Budget* (version 1.3) and UN World Population Prospects (2017 revision); adjusted carbon budgets take into account the Historical Carbon Adjustment (see Figure 43 for assumptions) and are calculated for +2°C 2/3 probability, hybrid share and consumer approach.

At the national scale, results are a little bit more sensitive to the implemented method in absolute terms. Nevertheless, in relative terms, the three methods lead to very robust results. The top 5 ranking does not vary hugely while considering the grandfathering allocation method, the egalitarian approach or the hybrid one. Nonetheless, it is worth underlining that adjusting budgets for the historical carbon emissions lead to substantial differences between these three approaches.

Table 19. Ranks of countries under various assumptions

	Grandfathering budget	Egalitarian budget	Hybrid budget	HCA-adjusted grandfathering budget	HCA-adjusted egalitarian budget	HCA-adjusted hybrid budget
1	DEU	DEU	DEU	DEU	FRA	FRA
2	GBR	GBR	GBR	FRA	ESP	DEU
3	FRA	FRA	FRA	ITA	ITA	ESP
4	ITA	ITA	ITA	GBR	ROU	ITA
5	ESP	ESP	ESP	ESP	POL	POL

Source: iASES (formerly iAGS) 2019 computations, based on IPCC SR1.5, UNFCCC emissions data, Le Quéré *et al.* (2018) *Historical Carbon Budget* (version 1.3) and UN World Population Prospects (2017 revision); budgets are calculated for +2°C 2/3 probability, hybrid share and consumer approach.

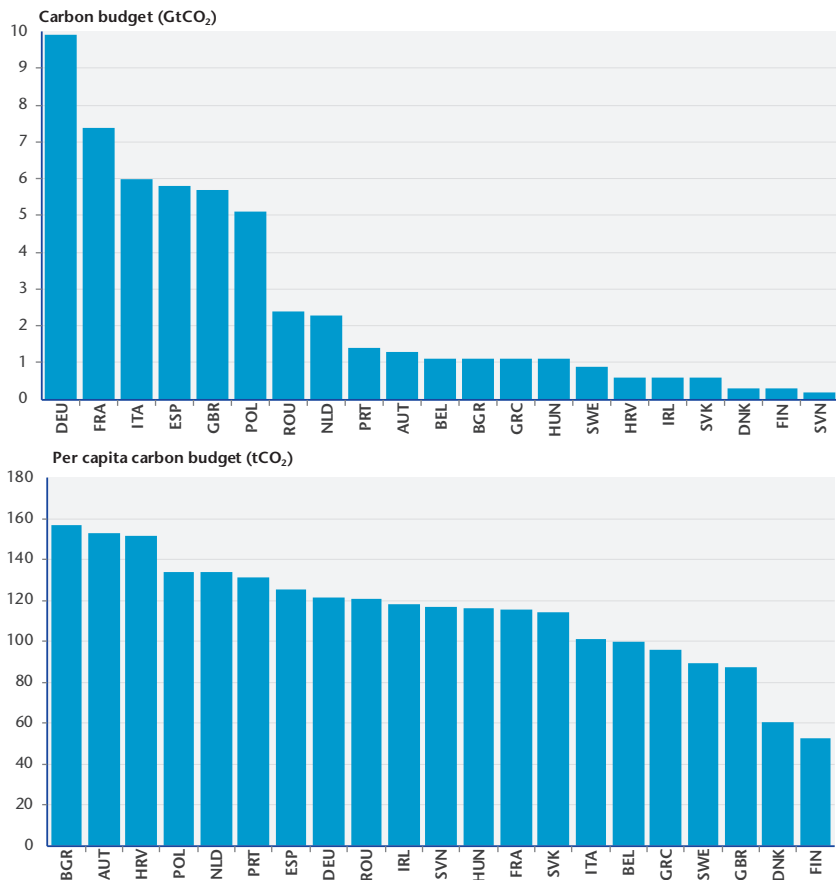
These discrepancies between methods might be largely due to the fact that they do not take into account countries' structural inequalities in the same way. A solution to tackle these heterogeneity issues would be to estimate econometrically the idiosyncratic part of each country explaining their levels of emissions. It would thus allow to use the egalitarian approach in a first moment and modify the results in a second moment applying the estimated idiosyncratic factor in order to redistribute budgets with respect to structural differences between countries.

Finally, computed results may also be sensitive to the type of emissions data considered.¹⁶ We have sought to understand to what extent considering producer emissions data would modify our results. Hence, we use the United Nations Framework Convention on Climate Change (UNFCCC) total carbon

16. The consumer approach imputes the emissions to the consumer, accounting for direct carbon emissions and embodied carbon emissions in goods or services. The producer approach accounts for carbon emitted on a territory, using for instance fuel consumption for final demand and production processes. The producer approach overstates the responsibility of highly industrialized countries where production activities have been located. The consumer approach appears to be more satisfactory even though the calculation needed for the imputation can be complex and rely on assumptions, subject to criticism.

dioxide emissions (with land use, land use change and forestry) time series of the Annex I countries from 1990 to 2015. In relative terms, results are a bit different as compared to the consumer approach but Germany, France, Spain, Italy, Poland and the United Kingdom remain at the top of the ranking, just as in the consumer approach. However, the producer approach to emissions leads to bigger adjusted carbon budgets for European countries. Germany and the United Kingdom have a 10 GtCO₂ and 5.7 GtCO₂ budget (Figure 47) as compared to a 4.8 and 3.2 GtCO₂ with the consumer approach (Figure 44). France’s budget remains quite identical in both cases with 7.4 GtCO₂ (producer) and 6.2 GtCO₂ (consumer).

Figure 47. Adjusted hybrid carbon budgets (producer approach)



Source: iASES (formerly iAGS) 2019 computations, based on IPCC SR1.5, OECD emissions data, Le Quéré et al. (2018) Historical Carbon Budget (version 1.3) and UN World Population Prospects (2017 revision); adjusted carbon budgets take into account the Historical Carbon Adjustment (see Figure 43 for assumptions) and are calculated for +2°C 2/3 probability, hybrid share and producer approach. Assessing the current path for emissions.

The estimation of the EU countries carbon budgets performed in the first part provides information on the total amount of CO₂ emissions that can be emitted before reaching a threshold (in this case, the probability to keep the temperature increase below +1.5°C and +2°C) but without indication on the pace at which it will be exhausted. In order to tackle this issue, one needs to associate it to an emissions reduction scenario.

We propose to combine several approaches to reconcile the short-term considerations on the emissions level with the long-term objective of reaching a Zero-Net Emissions (ZNE) state. The first part aims at providing a methodology for bridging the gap between the emissions data availability and the existence of contemporaneous estimated indicators. The second presents the long-term emissions pathways scenarios used in the process of calculating indicators on climate debts.

1.4. Estimating current emissions through nowcasting

Ascertaining the current level of greenhouse emissions is a key prerequisite to estimate the trajectory of future emissions. However, country-level emissions data is released with a significant lag (generally several years) by major statistical bodies, both at the national and multilateral levels. This calls for implementing new methods of emissions tracking (See Box 1). This stands in stark contrast with the prevailing timeliness of macroeconomic data, which is almost estimated and released in real time. Table 20 illustrates this lag for the main organizations reporting greenhouse gas emissions worldwide. European countries' climate targets call for aggressive emissions reductions, which—if implemented in practice—should lead to rapid change in the level of their emissions on a yearly basis. This strengthens the need for more up-to-date emissions data.

Table 20. Latest year of emissions data currently available

Agency	Year
UNFCCC	2016
International Energy Agency	2015
European Environmental Agency	2016
U.S. Environmental Protection Agency	2016

Source: iASES (formerly iAGS) 2019 computations.

Box 1. Nowcasting Emissions

We propose to compensate the publication gap in the data on emissions through the use of nowcasting. More specifically, we introduce a simple econometric methodology aiming at estimating current emissions level from available contemporary macroeconomic data—GDP in particular. We provide a brief outline of this approach in the rest of this section. For reference, a complete description is also provided in Appendix.

Our main design objective is to yield a parsimonious model providing the best possible emissions data from a small set of widely available macroeconomic data. This has driven our choice of a simple VAR approach.¹⁷ We then took inspiration from the Kaya decomposition to choose the endogenous variables:

$$GHG_t = GDP_t \frac{E_t}{GDP_t} \frac{GHG_t}{E_t}$$

With GHG_t the current level of greenhouse gas emissions, GDP_t the current annual GDP, and E_t the total primary energy supply. Our main specification thus links GHG emissions to GDP and the share of non-fossil fuels in primary energy supply.¹⁸ We supplement this core set of variables with an additional endogenous covariate, industry's share of value added, and exogenous variables driving energy consumption and by extension emissions: international oil prices, heating and cooling degree days.¹⁹

This yields the following straightforward specification:

$$Y_t = A Y_{t-1} + B X_t + \varepsilon_t$$

With Y_t the vector of the endogenous variables listed above, X_t the vector of the aforementioned exogenous variables and ε_t an error term. Parameters A and B are estimated separately for each country on data collected from 1974 until 2015. The oil shock of 1974, which led to a major change in the energy mix of European countries and their carbon intensity, motivates the exclusion of earlier data. Still, we control for country-specific shocks that affected the dynamic of emissions during the estimation period. Examples include the rapid expansion of nuclear power in France in the early 1980s, or the Great Recession of 2009. We also allow for the possibility of a structural break in the evolution of each country's emissions borne by decarbonization efforts. The occurrence and eventual timing of this structural break is estimated through an information criterion.²⁰

Once the model estimated for each country, we can proceed with emissions nowcasting. The procedure is as follows: all of the variables included in our speci-

17. Vector AutoRegression is a tool to estimate a system of endogeneous variables including lags of those variables and exogenous variables.

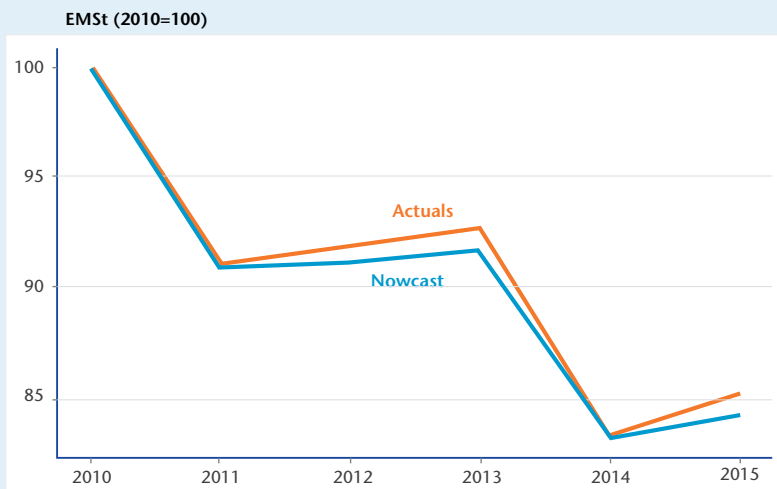
18. Alternatively, we also test the inclusion of the share of coal or natural gas in primary energy supply.

19. Heating and cooling days are days were heating or cooling systems are supposed to be used, based on the temperature reached that day and accounting for the difference between current temperature and a threshold. Threshold temperatures are different for each country.

20. The structural break year yielding the best fit on the data is elicited. See the Appendix for further details.

fication are observed in near-real time, save for emissions themselves. We therefore substitute each observed endogenous and exogenous variable for its current observation, and deduce the level of emissions implied by the model.²¹ The use of observed data for the majority of our model's variables significantly improves the performance of our nowcasting algorithm when compared with a simple one-step ahead VAR projection. For illustration purposes, Figure 48 compares the performance of the nowcasting projection of French emissions between 2011 and 2015 with the actual measured data.²² The root mean square error achieved in this case is below 1%, and remains below 2% for most European countries tested in our sample.

Figure 48. Nowcast performance for French emissions (2011-2015)



Source: iASES (formerly iAGS) 2019.

To strengthen the robustness of our nowcasting projection, we implement this procedure with several distinct specifications including different subsets of endogenous and exogenous variables selected among those listed previously. We then combine the results of these various model specifications into a single predicted value (Timmermann, 2006) simple combinations that ignore correlations between forecast errors often dominate more refined combination schemes aimed at estimating the theoretically optimal combination weights. In this chapter we analyze theoretically the factors that determine the advantages from combining forecasts (for example, the degree of correlation between forecast errors and the relative size of the individual models' forecast error variances).

21. See the Annex for an explicit derivation.

22. The model used in this example is the simple 3-variable VAR model including GDP, share on non-fossil energy and emissions, along with Brent oil price, heating and cooling degree days. It should be noted that to perform this nowcasting test on the period 2011-2015, the model's estimation period had to be restricted to 1974-2010.

The results of this nowcasting exercise for the six largest European emitters is presented in Table 5 of chapter 1.

1.5. Establishing the long-term path of emissions

The choice of a scenario is a comprehensive task in the sense that it needs to draw an emissions reduction pathway onto the next decades²³ based on our current knowledge on different parameters such as the set of available technologies, public policies implemented, demography, economic structure, GDP growth rate, etc.

An easy way would be to use a business-as-usual scenario (BAU), projecting the current trend of emissions reduction until the exhaustion of the carbon budget. This approach, despite having the advantage of being straightforward, appears not to be satisfying for several reasons. On one hand, it eludes the market penetration of already emissions mitigation or energy efficiency technologies and the long-term effects of existing public policies, on the other hands, it raises the question of the historical period on which the trend is projected.

One another approach is to simulate a scenario with a model that allows encompassing different dynamics on the supply and the energy use. Such a model allows producing scenarios depending on different dynamics in an integrated and consistent framework. For the sake of this exercise, we decided to choose the *Ener-Blue* scenario from the *Enerfuture* Emissions forecast issued by Enerdata (2018) and simulated with the POLES model (Keramidas *et al.*, 2017), see Box 2.

Box 2. The Energy model POLES

The POLES Model (Prospective Outlook on Long-Term Energy Systems) developed since the beginning of the 1990s by ENERDATA, the applied economics laboratory GAEL from the Grenoble University and the Joint Research Center from the European Commission is a world techno-economic energy supply-use model. It assesses equilibria for each period and for each of the 46 regions the energy flows in physical units as well as the price dynamics for each energy vectors. Technical progress is also included through an endogenous process for energy related technologies, on both the energy transformation side and the energy use sectors. 50 key-technologies are accounted and represented by learning-by-doing and learning-searching curves (Research & Development expenses). It also includes a

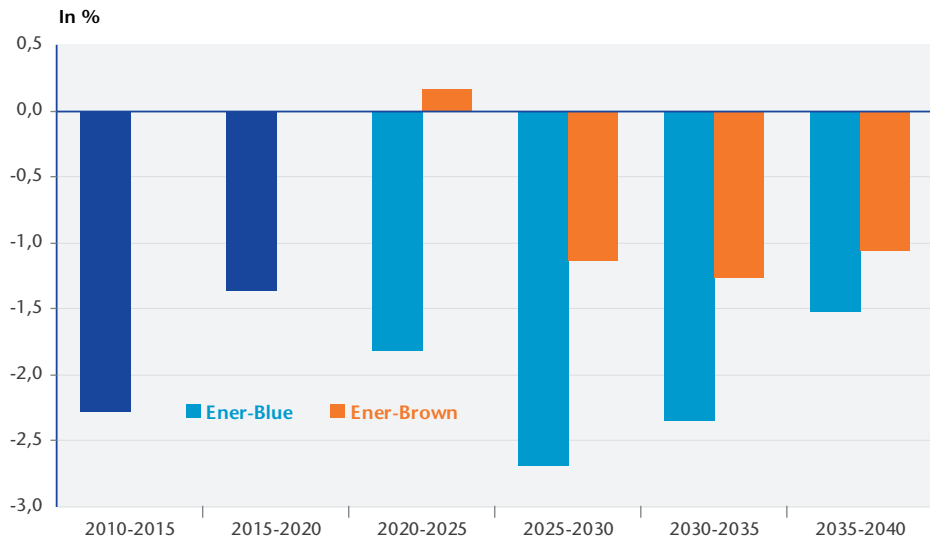
23. Ideally up to 2200, considering this period as the end of time.

resource constraint module for all the fossil-fuels in order to fully explicit the price formation as well as precisising the strategy associated to their management.

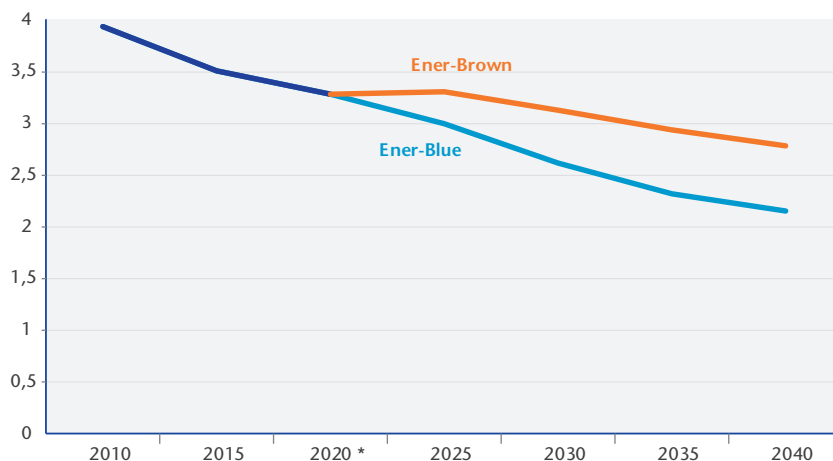
This model allows sketching energy scenario up to 2050 and can provides results on the world GHG emissions in an integrated and consistent framework.

This scenario corresponds to an INDC-compatible trajectory up to 2040 (extrapolated up to 2200) and which leads to a global average rise in temperature between 3 and 4°C. Whereas GHG emissions are reaching a peak in 2020 and follows then a near-stabilization pathway around 42 Gt CO₂eq, fossil-fuels are still the main energy source with a primary energy mix share of 70% (with respect to a current 81% share). Despite a stabilized level of GHG emissions at the world level, OECD-countries experience a constant decrease of them at a 0.6% yearly rate. Concerning European Union countries, we observe a constant decrease of their emissions, in the wake of the observed dynamic from the past decade (Figure 49 and Figure 50). The range of the yearly average CO₂ emissions reduction per 5-years period remains in an interval from 1.4% to 2.6%, close to the observed trend for the period 2010-2015 where this rate was 2.3%. We also consider an alternative scenario called *Ener-Brown*, which leads to a +5°

Figure 49. Compound annual decline rate of CO₂ emission



Sources: European Environmental Agency (2010,2015), Enerdata (2025-2040), 2020 is extrapolated using a moving average mean on the last five known years (2016-2011).

Figure 50. CO₂ Emissions from EU countries in the *Enerfuture* scenarios (Gt)

Sources: European Environmental Agency (2010,2015), Enerdata (2025-2040), iASES (formerly iAGS) 2019 computations.

rise in temperature. In this scenario the INDC's pledges are not fulfilled; the use of fossil fuels is still rising, spurred by the unconventional fossil resources extraction like shales gas or coal tar and with energy efficiency improvement remaining modest.

1.6. Abating emissions with a backstop technology

We assume in our estimations that only a backstop technology can remove the remaining CO₂ in the atmosphere from the carbon budget depletion date and until reaching a zero net emissions state. This backstop technology does not replace a potential investment. It is only aiming at reducing emissions, in the sense that it does not provide any other benefit than removing CO₂. Such Carbon Dioxide Removal (CDR)²⁴ technologies are currently experimented in some places—Climeworks, Carbon Engineering being active companies in that field.²⁵ It is assumed to be more expensive than any other option and with a

24. We do not consider here the use of Solar Radiation Management (SRM) technologies or, more generally, of geo-engineering since such technologies imply irreversibility and uncertainties far beyond what is acceptable.

25. See "[Sucking CO2 out of the atmosphere explained](#)" on vox.org by Umair Ifran for a quick survey. Websites of [Climeworks](#) and [Carbon Engineering](#) provide commercial information. Some peer reviewed papers are published (Keith *et al.* (2018), *Joule* 2, 1573–1594).

high enough potential capacity to achieve the targeted reduction, as the limit is physical only. The ability to scale up the deployment of such technologies is controversial, as well as the cost per tonnes of CO₂ removed from the atmosphere. The ability to store CO₂ underground definitively and the potential capacity to do so is also disputed. Current cost estimations are mostly industry side estimations with only prototype or experimental projects to back up over optimistic announcements.

The set of assumptions around the existence of such a backstop technology is undoubtedly questionable, but from our viewpoint, it has the advantage of translating a physical metric (carbon budget in Gt) into a monetary one (expressed in €₁₈). The sensitivity tests surrounding the backstop price are attempts at reducing the uncertainty via the definition of a confidence interval around its estimated value [250€:500€]

1.7. The Climate debt

The areas under the emissions pathways serve as the basis for the valuation. As it is a flow with a complex time pattern, it is necessary to use a net present value to transform it into a stock. We use a standard discounted sum with a discount rate representing the social rate of time preference, and potentially, an effect of technical progress on this backstop and the uncertainty on future technological progress. The discount factor we use there has no implication on intergenerational equity, a point that was central to the Stern Review, and is therefore simpler to quantify.

With r the discount rate, \bar{T} the number of years before the carbon budget is exhausted $CO_{2,\bar{T}}$ the present value of emissions at the date \bar{T} , at which the budget is exhausted,—that is to say the total cost of meeting ZNE given the current policy path— climate debt can be expressed as:

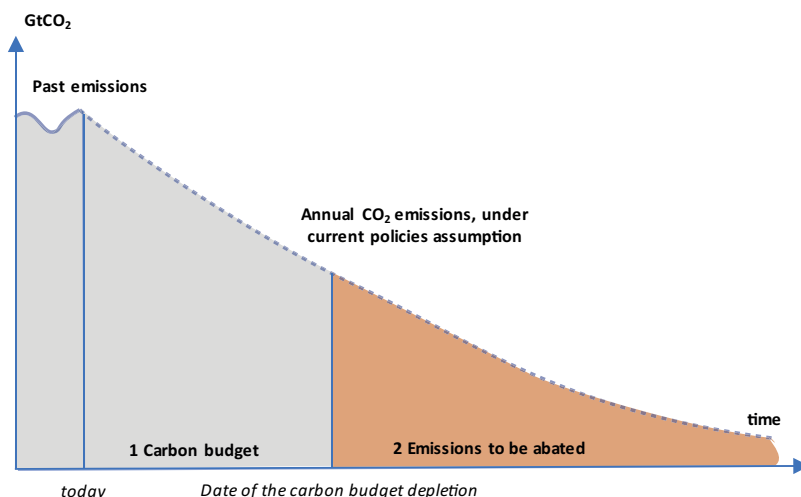
$$ClimDebt = \frac{1}{(1+r)^{\bar{T}}} \times \frac{CO_{2,\bar{T}} \cdot p^{BS}}{r}$$

$e^i(t)$ being the annual flow at date t of CO₂ emissions under the scenario i used as a path for current policies, the $CO_{2,\bar{T}}$ quantity is then calculated as:

$$CO_{2,\bar{T}} = \sum_{t=\bar{T}}^{\infty} \frac{e^i(t)}{(1+r)^t}$$

The Figure 51 illustrates the principle of the calculation:

Figure 51. Discounting climate debt



Source: iASES (formerly iAGS) 2019.

Observed emissions are projected with current policies scenario. Once the carbon budget is exhausted—area 1 in gray on Figure 51—, at some date in the future, the remaining annual flow of emissions has to be fully abated—area 2 in brown—. Discount rate r is applied to the cost of abatement every year (the cost of abatement times the emissions to abate) and summed to get the net present value today of those future costs.

There may be a special case if the date of the carbon budget depletion has already occurred. It is the case for one country in the +2°C, under the baseline assumptions and for many in the +1.5°C scenario. Burden sharing with less favorable bases than the ones of the baseline scenario (for instance adjusting for historical emissions since 1980 or 1970) would push more countries in the exhausted carbon budget zone. In that case, as argued below, countries still emitting past the depletion date are borrowing to other countries or to the Climate their current emissions. To repay those emissions they will have in the future to pay back and possibly, because it will cause the climate to overshoot the +2°C scenario, they will have to abate more than the overshooting of emissions.²⁶

26. This could be represented as a « geo-physical » interest rate. If that rate is superior to the discount rate (probable) it is profitable not to overshoot. It would be better (same outcome for a lower cost) to postpone emissions reduction and overshoot on global temperature if the cost in term of supplementary emissions is low enough (unlikely). We are not able to compute this parameter without access to climate models.

III.2. Years before depletion of Carbon Budget and Climate Debts

Here, we present the results of this exploration of the concept of *climate debt*. It is important to distinguish what relies on physical units (the carbon budget, the year of the depletion of the carbon budget) and the differences between countries from what relies on a monetary evaluation. A monetary evaluation needs to be done to add hypotheses and shortcuts which are going to pile up on all the hypotheses done before. Piling up hypotheses does increase the fragility of the evaluation or, evenly, the range for the final quantification.²⁷ Nevertheless, a monetary valuation of the debt is necessary as it provides an alternative metric to the underlying problem—how far are we from the +2°C—in a unit that pins the potential trade-offs in a universally understandable way. A euro value of the distance to the +2°C target is more striking than a distance expressed in tonnes of CO₂. Moreover, modifying the metric is not only a question of the striking power of the unit in which it is expressed. It is also a question of the ability to weigh more some dimensions of the problem and thus to give less weight to some others. Using a discount rate for instance puts more weight on the present and the near future compared to a more distant horizon. This reduces the impact of hypotheses about the far future, which speculative nature is irreducible, and allows for, may be, an easier interpretation. Expressed in monetary units, distance to targets will also make comparisons between countries more meaningful, by taking into account various elements such as levels of development, country sizes or current levels of emissions.

2.1. Years to depletion

Starting with physical unit Table 22 displays the number of years left before depleting the entire carbon budget. This number encapsulates both the share of the global carbon budget that was allocated to a given country and the current policies emissions pathway. The lower the budget, the shorter the time before the carbon budget is depleted. The quicker the emissions reductions due to current policies, the higher the number of years before depletion. Hence, a country implementing an ambitious policy to reduce emissions in the near future can postpone significantly its depletion date.

27. As Mark Twain (supposedly quoting Benjamin Disraeli) put it a long time ago, “there are three kinds of lies: lies, damned lies and statistics”. Quantification of extrapolated scenarios may be the fourth kind. Doing such a quantification and being honest impose thus to be highly transparent about the methodology.

2.1.a Baseline and alternative scenarios (political, speculative and technical)

To assess the mere possibility of quantifying the distance to the climate target, we need to calculate that distance using various assumptions and judge for consistency. This is a way to identify the sensibility of the final number to chosen parameters and shed light on underdevelopments of the modelling needing further improvements. We define a baseline scenario. Alternative scenarios are modifications of this baseline. More precisely, each alternative scenario only differs from the baseline due to the modification of one very specific hypothesis (see Table 21).

The baseline is defined for the +2°C target and what we deem to be a middle point in the burden sharing question, that is to say the previously details “hybrid” sharing method. Different views on the way to share the burden will lead to different allocations of the global carbon budget. Those are moral or political hypotheses and we are not to decide which ones are the right ones.

Among the hypotheses needed, some are forecasts. For instance, the current policies pathway, further reductions of emissions past that date, the price of the backstop technology or future MACC are by definition speculative. No matter how subtle your understanding of the problem is, it remains impossible to guess future realizations of technologies, of the evolution of the environment, the feedbacks, positive or negative that can appear one day. Just like any other sustainability concern, the climate change issue cannot be analyzed without relying at some point on long term forecasts. Our choice has been here to define the simplest approach possible in order to warrant perfect transparency and to use consensual scenarios whenever possible (IPCC, ENERDATA).

Finally, technical hypotheses are also at stake. We display every time we can plausible ranges for those hypotheses, always keeping in mind transparency as a guiding rule. However, for those hypotheses, a sophistication of our analysis may provide a better estimate, in the sense that we could reduce the range of the estimation. This calls for more research and work so as to discard as many uncertainties as possible. In other words, alternative scenarios to the baseline have different interpretations (political, speculative, technical, see Table 21 for a qualification of each hypothesis).

Table 21. Hypotheses of baseline and alternative scenarios

	Baseline assumption	Alternative assumption	Comment
Producer vs Consumer approach	Consumer	Producer	Consumer approach accounts for embodied carbon and direct emissions by the final consumer. Producer approach accounts for emissions by final consumers and firms in a country. (moral).
Historical carbon adjustment	HCA	no HCA	Historical carbon adjustment corrects the carbon budget of emissions since a given date (1990 in our case). It is equivalent to consider a 1990 carbon budget and calculate the date of depletion including observed emissions since 1990 up to 2017. No HCA starts the carbon budget in 2018. (moral).
EU population vs emissions share	Emissions shares	Population	Carbon budget is shared between the world and EU following the egalitarian principle. Emissions shares are used to share the carbon budget between EU countries willing to take in account specific reasons (climate, industrial structure) mutualized between similar countries. The alternative is the full egalitarian principle. (moral).
+1.5°C target versus +2°C	+2°C	+1.5°C	The target is to limit climate change to no more than +2°C (or +1.5°C) increase of global surface land and sea temperature as compared to pre-industrial times. Emissions compatible with targets are reviewed and selected by the IPCC. (moral).
TCRE 50th vs 67th percentile	67 th	50 th	This number is the (estimated) probability to meet the target chosen for climate change (+1.5 or +2°C) given the uncertainties in our knowledge of the climate. (moral and technical).
Ener-brown vs Ener-Blue scenario	Ener-blue	Ener-brown	Ener-blue is a scenario for future carbon emissions (from 2017 to 2040) following INDCs. Ener-brown is a scenario with less emissions reduction leading to a +5°C increase of global temperature. (speculative).
Discount rate (annual)	4%	3%	The discount rate is used to discount flow of future costs and calculate a net present value (aka debt). The discount rate add a standard real discount factor of 2% and a 2% or 1% rate of decrease for the cost of future abatement technologies (divided by 2 every 35 years for 2%, 70 years for 1%) (speculative and technical).
Price of backstop (annual)	250€/tCO ₂	500€/tCO ₂	The initial (before discount) price of the backstop is crucial for the quantification of the climate debt. It has been chosen on the basis of expert knowledge. (speculative and technical).
Extrapolation of emissions after 2040	2020-2040 trend extrapolation	emissions of the year 2040	Extrapolation is used to extend scenarios beyond 2040. Trend extrapolation leads to zero emissions in most countries at some date. (speculative).

Source: iASES (formerly iAGS) 2019 computations

2.1.b The EU carbon budget is nearly exhausted

The first result of Table 22 is that for the 6 main European Union member countries, the +2°C budget is nearly exhausted. On average for EU countries, there are only 10 years left. It means that current stocks of capital—productive capital, residential buildings, tertiary buildings, means of transportation, etc.—are partly stranded under the +2°C constraint: the capital stock is far too polluting, it needs to be zero net emission in 10 years from now and its average lifespan is probably longer than 10 years, leaving a share of it unsuited to meet the climate target. It means that current policies are not sufficient to meet the +2°C target and that some of this already built capital stock will need to be seriously retrofitted or decommissioned before the end of its full depreciation. The extent to which it is stranded and the cost of resolving that are difficult to estimate. We attempt to do lead such an evaluation in the next section (Section 2.2).

Table 22. Years remaining before the Carbon budget is exhausted, EU-6 largest countries

	DEU	GBR	FRA	ITA	ESP	NLD	EU-6
Baseline (see note for definition)	5	7	16	10	16	8	10
Producer approach (vs Consumer)	15	20	32	22	27	14	22
No historical carbon adjustment (vs HCA)	40	41	31	32	26	29	35
EU population share (vs EU emissions share)	0	4	17	12	25	3	10
+1.5°C target (vs +2°C)	-6	-6	0	-2	2	-4	-3
TCRE 50th percentile (vs 67th)	14	17	25	19	25	16	19
Ener-brown scenario (vs Ener-Blue)	5	6	13	9	15	7	9
Constant post 2040 (vs trend extrapolation)	5	7	16	10	16	8	10

Note: scenarios are described in Table 21. A 0 means that the carbon budget is exhausted before the year 2018. EU6 is the aggregation of the 6 largest economies (2017 GDP).

Source: iASES (formerly iAGS) 2019 computations, based on IPCC SR1.5, OECD emissions data, Le Quéré et al. (2018) *Historical Carbon Budget* (version 1.3) and UN World Population Prospects (2017 revision), AMECO online (11/2018) for 2017 GDP.

If the years before depletion were 0, it would mean that the concerned country is borrowing some carbon emissions (rights) to other countries (which have not reach their depletion date yet) or to the “Climate”, because it will lead to overshooting in emissions and to meet finally the climate target, compensation in the future—in the form of more negative emissions—will be needed to meet the target in the long term.

This situation of an already exhausted scenario would undoubtedly constitute a situation of “*excessive climate deficit*”, implying a warning and a strict monitoring from surveillance bodies. The use of the Stability and Growth Pact vocabulary is intentional. The spillover effect coming from not respecting climate by one European country on the other member states are better identified than the ones implied by public debt.

The baseline scenario shows that there are important differences between countries. The metric used to compare those differences is key as linearity and quantification can lead to very different relative appreciations. However, the number of years before depletion indicates that the emergency of taking seriously the climate targets varies among countries. Germany, with no surprise, is facing a very near climate cliff and is close to the implicit borrowing point. This cliff is the closest of all, even closer than the ageing population one, the under-investment in infrastructure one or the public debt one.

That being said, even the least stranded countries are stranded. France and Spain have less than two decades to reach zero net emissions.

2.1.c Sensitivity analysis: a wide range of estimation

Sensitivity analyses suggest that the political or moral hypotheses may completely change the perspective, pointing at a much-needed agreement on how to share the burden. With no Historical Carbon adjustment, emissions from 1990 to 2017 are forgotten and the national budget is based on the 2018 global budget shared proportionally to population ratios. This gives a larger share to strong emitters and postpone the date of depletion by 25 years on average for EU6 countries. Using a producer approach increases the EU Carbon budget since the EU is a carbon net importer overall²⁸.

The +1.5°C target, which the IPCC recently advocated for since it is the only way to avoid a lot of costly and irreversible consequences of climate change,

28. According to OECD embodied CO₂ emissions, net imports of CO₂ (of exports of CO₂) for EU as a whole are equal to 20% of CO₂ emissions on the EU territory.

would put EU countries in an “*excessive climate deficit*” situation. Under the constraint of +1.5°C, all countries except Spain have exhausted their allocated carbon budget, some of them since a few years. Relaxing the constraint, by using the 50th percentile and risking a 50% probability to miss the +2°C target, is postponing the depletion date.

Under a less “optimistic” evaluation of the current policies pathway (namely the *Ener-Brown* scenario), the years left before depletion are lower although the order of magnitude is close. The same applies for the way extrapolation is conducted but with little change for most countries as the extrapolation date is after the depletion date.

What’s more, sensitivity analyses show a large impact of political and moral considerations. The hierarchy between European member states, at least for the largest ones is fairly robust to different assumptions. Yet, we will see that the euro metric of climate debt may qualify this interpretation.

We have chosen not to display in the main text data for smaller countries. The reasons are that imputation of carbon emissions for small countries, even in the consumer approach is a sensitive topic and is currently done on an unsatisfactory basis. For instance, small countries that have a large tourist inflow may be imputed a rather large amount of fossil fuels due to transportation or tourists. Current data do not allow for a correct imputation of tourism, because of the lack of data on the origin of tourists. For large countries, this matters less, because it is mixed with other sources of emissions large enough to cover those difficulties. This even may be the case for countries whose commercial transport activities are important respective to the size of their economy and may explain the rather dire situation of the Netherlands.

Moreover, we need to consider subtler ways to share the burden. Basing the allocation of the carbon budget on factors such as the level of economic development (less developed countries may have more) or geographic endowments (north countries are colder in the winter, denser countries need less fossil transportation) can change a lot the budget for each country. Larger countries however are quite close in structure, which makes imputation issues less sensitive.

2.2. Climate debts

The climate debt for a given country is calculated by estimating the cost of a specific scenario. Once the carbon budget is exhausted, in order to fulfil its pledge, the country implements overnight and for the following years, abatement techniques that shrink its remaining emissions down to zero. The point is not the realism of such a scenario in technical terms. There is no denying that if

the emissions to abate are large, building overnight negative emissions capacities or retrofitting existing capitals would be impossible. The point here is to estimate the underlying cost of procrastination. This cost could be then claimed by other countries whose carbon budget is not exhausted yet. This claim could be materialized as a transfer. Carbon emitted past the depletion date could also be borrowed to the “Climate” by a commitment to remove CO₂ from the atmosphere in the distant future, conditionally on the fact that the country compensates fully the consequences of overshooting the target (in terms of more removal of CO₂ from the atmosphere, see note 26). This cost can also be interpreted as the cost that should have been paid in the past to meet the target but has not been paid and thus must be at the depletion date. Hence the thought experiment scenario we are using is an abstraction of complex realistic scenarios, giving a crude but coherent estimate of those scenarios.

Interestingly, each of these scenarios would have macroeconomic consequences, because of multiplier effects of the climate spending, crowding out effects of financing that investment (depending on the way it is financed) or distortion effects due to taxes needed to induce the transition. At this stage, we completely ignore these considerations, not caring for instance on whom is going to fall the cost and what would be the distributional issues. The point of such an abstraction is not to say that these issues are not important, especially as we, all along the previous iAGS and in the first chapter of this report, have asserted that those macroeconomic and distributional issues are of cardinal importance. The point is rather that, in order to understand the challenges, one needs to have a clear view of what lies ahead, and a good starting point is to assert the “core” cost of more real-world scenarios.

2.2.a Valuation of Climate debt depends on some assumptions

Once the carbon budget is allocated, the debt valuation is dependent on the quantity of CO₂ still emitted at the depletion date. A country committed on a successful decarbonization path will have a lower emissions flow than one still postponing the transition to zero net emissions. It will also be dependent of the date of depletion of the carbon budget. As the climate debt is the net present value of the investment needed to fulfill the pledges, the latter the depletion, the latter will be the investment and the more discounted will be the cost. Countries with time before depletion can adjust slowly. Our conviction is that adjusting slowly is going to be less costly and less stressful on the social and political levels. Hence the justification of the discount rate can be based on that interpretation of the time left before the cliff. This of course could be estimated in a subtler way.

The role of the abstraction is to give an order of magnitude and to escape the perils of valuating the incommensurable. The valuation of the climate debt also depends on a third important element, namely the price of the backstop. It is impossible to define with certainty such a price. Industry promises costs as low as 100€/tCO₂ abated, when estimates of cutting-edge abatement technologies points to costs per abated ton close to (still under) 1,000€. We have chosen in the baseline a value of 250€/tCO₂ incorporating some wishful thinking about technical progress and an alternative scenario of 500€/tCO₂. The wide range will have an immediate consequence: a wide range in the valuation of the climate debt. Because of that, our quantification is indicating the importance of the problem we are facing rather than aiming at being a guide for public finance. This is one reason among others why we consider that climate debt should not be added to public debt. The discount rate used in the calculation is also changing a lot the valuation. Indeed, a lower discount rate increases the value of the debt by giving more weight to the future or expecting less progress in the evolution of the abatement technologies.

Table 23. Climate debts, EU-6 largest countries

	DEU	GBR	FRA	ITA	ESP	NLD	EU6
Baseline (see note for definition)	66	53	37	51	41	62	53
Producer approach (vs Consumer)	29	20	11	18	17	49	22
No historical carbon adjustment (vs HCA)	4	8	17	12	22	20	12
EU population share (vs EU emissions share)	95	63	35	45	23	81	61
+1.5°C target (vs +2°C)	145	125	92	117	99	123	120
TCRE 50th percentile (vs 67th)	35	30	24	29	23	40	30
Ener-brown scenario (vs Ener Blue)	80	80	67	66	57	79	73
Backstop 500€/tCO₂ (vs 250€/tCO ₂)	86	61	46	69	61	73	67
Discount rate 3% (vs 4%)	132	105	74	102	82	123	105
Constant post 2040 (vs trend extrapolation)	86	68	53	66	56	81	68

Note: scenarios are described in Table 21. EU-6 is the aggregation of the 6 largest economies (2017 GDP).
Source: iASES (formerly iAGS) 2019 computations, based on IPCC SR1.5, OECD emissions data, Le Quéré et al. (2018) *Historical Carbon Budget* (version 1.3) and UN World Population Prospects (2017 revision), AMECO online (11/2018) for 2017 GDP.

In the baseline scenario, the EU Climate debt is close to 50% of GDP. This quantification is high and reveals that the climate issue is far from being a small one. The interpretation of that number must be done carefully. It is the net present value of costs to be paid in order to reach the +2°C target, without any consideration on how to do it. Smart policies, early enough, although it is a bit late for that today, could produce a less costly reduction of emissions. However, nothing in our current policies indicates that we are caring to do such smart and careful policies. Hence, the cliff scenario is more likely. The debt figure is a stock. One can understand it better as a flow. Using a 2 or 3% interest rate (which is a different concept than the discount rate used for the climate debt calculation), based on market value of risk-free interest rates, this stock can be converted to a 1 to 1.5% of GDP flow of investment in Climate change from now until the end of times. This is a large flow, meaning for instance a reduction in consumption by the same amount, but it is an amount that rich societies can afford without any difficulties.

That number comes with a wide range given the piling up of assumptions—some heroic and speculative—and interpretation of data sets—with some uncertainties and inconsistencies. The range for climate debt for the 6 largest EU economies is from a little more than 20% to nearly 200%: EU6 climate debt lies between [22%:193%] of GDP depending on the discount rate [3%:4%], the price of the ton of CO₂ abated with the backstop [250€:500€], a riskier targeting [50th:67th] and the range between Ener-brown and Ener-blue. This forces to a careful use of climate debt figures and asks for more work to better assess this important notion.

To the specific uncertainties of the valuation of climate debt, one has to add the elements pointed in the previous sections. The burden sharing can lead to very different carbon budgets and hence to very different climate debts. Table 23, using the same methodology than Table 22, displays what can change when you change the burden sharing principles. The extent of implicit transfers between countries, comparable in size and in structure is also important. For instance, the historical carbon adjustment modifies the climate debt gap between France and Germany by more than 40% of (France) GDP. Such differences are not really a transfer in the usual sense of the word, but it illustrates that relative differences of a macroeconomic magnitude can be driven by the principles in the burden sharing.

A decisive conclusion is that climate issue is important but is not a catch-22 situation. No one should find reasons to give up the project of mitigating climate change and to consider that the responsibilities towards future generations are beyond reach. Even the 1.5°C is still doable (Table 23). The costs are undoubt-

edly larger than for the +2°C target—more than twice, reaching 120% of GDP for the EU6—but they are still in the acceptable and possible bounds. Our methodology does not incorporate the costs of adaption; those costs are surely lower for the +1.5°C objective than for the +2°C one.

2.2.b *Climate debts differences between countries are important*

Table 23 displays important differences between countries. EU6 average is 53% for the baseline scenario, Germany climate debt is 66% and France one is 37%. Part of it comes from the historical adjustment (as discussed above). The rest is related to a more carbon intensive energy mix in some countries than in others. It is a strong divide between Germany and France. Recent transition of Germany towards renewable energy has not been enough to compensate for the exit from nuclear energy. Our point is not to promote one energy mix over another one. It is to acknowledge that our methodology amplifies existing state of the economies.²⁹

Industrial structures—more industry in Germany, much less in France—play definitively a role, except in the baseline scenario where the consumer approach is taken. Without this approach, the relative climate debts of France and Germany are in the 1 to 3 range instead of less than 1 to 2. Again, methodological choices, based on moral or political considerations, can lead to a very different appreciation of the situation.

The speculative nature of the *Enerfuture* scenarios we have used for climate debt valuation and carbon budget calculations have also an influence on differences between countries. Failing to take in account fully the impact of renewable investment in Germany on future emissions may increase the estimated value of climate debt. We believe those scenarios to be middle ground and solid interpretation of current policies, but we will know for sure not until some time.

2.2.c *How climate debt and public debt do relate?*

We have mentioned above that climate debt should not be added to public debt because of the uncertain nature of the evaluation. Public debt is the result

29. Climate debt is a quantitative indicator which cannot deal with every question in the choices to mitigate climate change. For instance, nuclear energy is a low carbon energy, hence improving climate debt when deployed, but implies a set of moral choices related basically to safety not involved in the debt quantification. Environmental policies should not be designed only based on emissions reduction targets. As safety concerns go over borders, at least a European Safety Agency for Nuclear Energy would be a necessary requirement to different paths for energy mix.

of a contract between two parties with a well-defined flow of payments of interest and principal. One can follow the evolution of public debt as the accumulation or decumulation of such contracts. Climate debt is a different notion, being the net present value of a flow of investment needed under an extreme scenario, where you choose to respect commitments but have done nothing so far to respect them.

Therefore, climate debt depends on the discount rate used and the price of the backstop considered. There are no equivalent hypotheses for public debt. Calculating net present value of public debt, using the same discount rate would be a first step toward an uniformization of the definition. However, it would not be enough: the discount rate incorporates possibilities about the future price of the backstop, decreasing because of technical progress and learning by doing. The discount rate applied to flow of interest payment on public debt cannot be assimilated to this discount rate.

The macroeconomics of climate debt are different. Climate debt looks a lot like a negative shock to productivity. This stimulate spending in climate transition, may have multiplier effects or distortionary effects in the economy through taxes needed to trigger the transition. Distributional issues are raised by whom is going to pay for or own the negative productivity shock. Macroeconomics of public debt are way different. Public debt is a transfer between agents inside an economy. When public debt is held by foreigners, then it is a transfer between a country (or agents in a country) and the rest of the world. Sovereign rates are changing and may impact the whole spectrum of rates. The mechanisms are different.

For those reasons it is a bad idea to add public debt figure and our valuation of climate debts. Nevertheless, in order to diagnose the situation of an economy, we strongly suggest that climate debt is a complement to other macroeconomic imbalances. A country may seem in a sustainable and prudent situation – a low public deficit, a public debt stable at a low ratio to GDP – but may be facing a wall due to climate change unpreparedness. A scoreboard failing to inform on that would be inappropriate. Moreover, the EU committed to climate change targets and insuring that all countries take their shares in that commitment is necessary to avoid unwanted transfers.

III.3. Main conclusions

Climate debt and years before depletion concepts shed light on the urgency to mitigate climate change. As a rich and developed area, EU is now facing that cliff. We have exhausted our procrastination capital and the amount of debt is significant, in the range of 20% to 200% of GDP for the +2°C, our point estimate being close to 50% of GDP. For the more constraining +1.5°C, the number is much higher, the point estimate being close to 120% of GDP. However, the quantification of the climate debt should not fuel excuses to despair in front of the responsibility ahead. Mitigating the climate is not undoable or too expensive. It is within our reach, making our failure to address it even more condemnable.

The quantification of years before depletion and debt are sensitive to various assumptions and hypotheses. Some of those assumptions are in the field of *moral position and politics*. They deal with burden sharing methods. It is not our task, in this report, to decide on those rules. Nevertheless, we have shown that the quantifications are very different for each scenario. That means that, implicitly, important transfers are done when you do not address those issues politically.

Some assumptions are *technical issues*, some others are related to the use of *long-term forecasts*. It means that the quantification is partly *speculative* in nature and that little can be done to reduce that unpleasant characteristic. This uncertainty has to be understood when discussing the burden sharing issue on the political point of view.

As for technical issues, we have to admit that some more work and further research are needed to refine the quantifications and provide a better information for the instruction of the political and moral debate about the burden sharing (see Box 3). Considering the importance of the problem stated by our tentative quantifications, this task should not fall only on us but should be the concern of administrative bodies, member states governments, national representations and civil society.

They are three policy conclusions to our tentative estimation:

1. It is imperative to act to address mitigation of climate change. The procrastination capital is nearly exhausted for the +2°C scenario. It is completely exhausted for the +1.5°C one and EU is running a massive climate deficit.
2. Surveillance mechanisms, policy recommendations should focus much more on climate and more generally on sustainability issues. Public debt is

for sure one element of general sustainability. But it is far from being the only one. It may not be the most important one. A change in EU governance is needed to shift from the narrow vision to a broader one. Investment in quantifications and tools to appreciate sustainability has to be urgently delivered.

3. A consensus on the way to share the burden is necessary. Climate change mitigation is a deeply structural change so some time is left to decide on the extent of responsibility of each country. However, as we have shown, already some countries, may be the EU as a whole, could be close or past to the exhaustion of their allocated budgets. Solving this issue is necessary before the *fait accompli* is the new rule.

Box 3. How to better estimate the climate debt

The evaluation presented here is based on a large number of assumptions, sometimes heroic. Such shortcuts are however necessary to show that the concept is useful, that the order of magnitude is relevant to policy conclusion and that there are some lessons to be drawn from international comparisons. We acknowledge and shoulder the limitations. To produce a better estimation of the climate debt, one needs to go further on several points.

1. Improve the MACC and use an integrated modelling to understand the links between technologies. This would also allow to represent scenarios for the energy mix and energy vectors more realistic and more holistic. Soberness could be incorporated in the framework, whereas an estimation of the welfare loss (and not only of the technical cost) of that solution would have to be included.
2. Improve the current policies scenario and the long term of emission reduction. We have used and extrapolated scenarios up to 2040. Such an extrapolation is fragile and has produced for some countries current policies paths with little or no emission reduction. This is clearly overstating the climate debt in some countries whereas being overoptimistic in others.
3. Backstop technologies are crucial to our estimation because the inventory of non-CDR technologies is limited. Cost and capacity of backstop technologies is difficult to estimate and as time and deployment of CDR technologies go on, we may be able to have more reliable figures in the future.
4. For backstop technologies as for MACC in general, the effect of technical progress on future cost is important. Incorporating more flexible hypothesis there may lower the estimation of the Climate debt. However, uncertainty should be incorporated in the analysis.
5. The line of reasoning we have adopted is that each country is responsible for a certain target of emission reductions (the carbon budget, adjusted by historical emissions). However, without disregarding this responsibility, it may be

possible for a country to buy emission reductions elsewhere, especially if the cost of this abatement is lower than the national one. That could be an important element in the medium run as some developing countries have still important carbon budget. Developed countries could access in the next decades to cheaper ways to meet their commitment through ambitious trade schemes. The idea is not to define a possible scheme to trade emission rights, but to incorporate in the analysis the positive impact it could have by reducing the climate debt of some countries.

6. The possibility to borrow to the Climate, by overshooting the carbon budget in the medium term and then compensating that overshooting by more negative emissions may be a rational way to deal with the constraint. However, climate science does not give today a real cost to do so. One can imagine it would lead to impose an overall lower cumulated emission and that would come with nonlinear effects, limiting the extend of that dangerous game with climate change consequences. Nevertheless, this could be incorporated in the analysis, especially for already exhausted carbon budgets.

References

- Agarwal, A., and Narain, S. (1991). *Global warming in an unequal world: a case of environmental colonialism*. New Delhi, India: Centre for Science and Environment.
- Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M., and Meinshausen, N. (2009). "Warming caused by cumulative carbon emissions towards the trillionth tonne." *Nature* 458(7242): 1163–1166.
- Caney, S. (2009). Justice and the distribution of greenhouse gas emissions. *Journal of Global Ethics* 5(2): 125-146
- Comyn-Platt, E., Hayman, G., Huntingford, C., Chadburn, S. E., Burke, E. J., Harper, A. B., Collins, W. J., Webber, C. P., Powell, T., Cox, P. M., Gedney, N., and Sitch, S. (2018). "Carbon budgets for 1.5 and 2 °C targets lowered by natural wetland and permafrost feedbacks." *Nature Geoscience* 11(August): 1–6.
- Enerdata (2018). *Global Energy Scenarios to 2040: Understanding our Energy Future 2018 Edition*.
- Gignac, R., and Matthews, H. D. (2015). "Allocating a 2°C cumulative carbon budget to countries." *Environmental Research Letters* 10(7).
- Giraud, G., Lantremange, H., Nicolas, E., and Rech, O. (2017). "National Carbon Reduction Commitments: Identifying the Most Consensual Burden Sharing." *Documents de travail du Centre d'Économie de la Sorbonne*.

- Keith D.W., Holmes G., St. Angelo D., and Heide K. (2018). "A Process for Capturing CO₂ from the Atmosphere." *Joule* 2(8), 1573–1594.
- Keramidas, K., Kitous, A. G., Després, J., and Schmitz, A. (2017). *POLES-JRC model documentation* (No. ISBN 978-92-79-71801-4). (Publications Office of the European Union, Ed.). Luxembourg.
- Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A. C., et al. (2018). "Carbon cycle-Global Carbon Budget 2017." *Earth System Science Data* 1010333739(10): 405–448.
- Matthews, H. D. (2016). "Quantifying historical carbon and climate debts among nations." *Nature Climate Change* 6(1): 60–64.
- Matthews, H. D., Gillett, N. P., Stott, P. A., and Zickfeld, K. (2009). "The proportionality of global warming to cumulative carbon emissions." *Nature* 459(7248): 829–832.
- Raupach, M. R., Canadell, J. G., Ciais, P., Friedlingstein, P., Rayner, P. J., and Trudinger, C. M. (2011). "The relationship between peak warming and cumulative CO₂ emissions, and its use to quantify vulnerabilities in the carbon-climate-human system." *Tellus, Series B: Chemical and Physical Meteorology* 63(2): 145–164.
- Raupach, M. R., Davis, S. J., Peters, G. P., Andrew, R. M., Canadell, J. G., Ciais, P., Friedlingstein, P., Jotzo, F., Van Vuuren, D. P., and Le Quéré, C. (2014). "Sharing a quota on cumulative carbon emissions." *Nature Climate Change* 4(10): 873–879.
- Sussams, L. (2018). Carbon budgets: where are we now?
- Timmermann, A. (2006). Chapter 4 Forecast Combinations." *Handbook of Economic Forecasting* 1: 135–196.

GLOSSARY

* ***Adjusted carbon budget***: a carbon budget minus the historical carbon adjustment. It aims at producing a carbon budget which would take into account the national differentiated historical responsibilities in global warming and climate change.

* ***Carbon budget***: the cumulative amount of carbon dioxide (CO₂) emissions permitted until the end of times to keep within a certain temperature threshold.

* ***Historical carbon adjustment***: national deviation—in tCO₂—from the carbon budget allocated to a specific country thanks to the egalitarian approach over a given period of time.

* ***Intergovernmental Panel on Climate Change***: created in 1988, it is an international group of scientists and experts mandated by the United Nations in order to document climate change not only from a geophysical point of view but also in terms of economic and political impacts.

* ***Intended National Determined Contributions***: emissions reduction targets submitted by the Annex I countries of the UNFCCC in the wake of the 2015 United Nations Climate Change Conference. These targets concern mainly emissions levels by 2030 as compared to those of 2005.

APPENDIX. DATA AND SUPPLEMENTARY MATERIAL

Table A1. Egalitarian carbon budgets, HCA and adjusted carbon budget

GtCO ₂	Egalitarian carbon budget (2015 reference year)	Historical carbon adjustment (1990-2017)	Egalitarian adjusted carbon budget (2015 reference year)
EU28	91	49.7	41.0
AUT	1.6	1.1	0.4
BEL	2.0	2.1	0.0
BGR	1.3	-0.3	1.6
HRV	0.8	-0.2	1.0
CYP	0.2	0.1	0.1
CZE	1.9	1.6	0.3
DNK	1.0	1.1	-0.1
EST	0.2	0.2	0.0
FIN	1.0	0.3	0.7
FRA	11.5	4.7	6.8
DEU	14.6	16.1	-1.5
GRC	2.0	1.5	0.5
HUN	1.7	0.2	1.5
IRL	0.8	0.9	-0.1
ITA	10.6	5.7	4.9
LVA	0.4	-0.3	0.6
LTU	0.5	-0.1	0.7
LUX	0.1	0.1	0.0
MLT	0.1	0.0	0.1
NLD	3.0	2.4	0.6
POL	6.8	2.5	4.4
PRT	1.9	0.1	1.7
ROU	3.6	-1.1	4.6
SVK	1.0	0.2	0.8
SVN	0.4	0.1	0.3
ESP	8.3	1.9	6.4
SWE	1.7	-0.8	2.6
GBR	11.7	9.6	2.1

Source: iASES (formerly iAGS) 2019 computations, based on IPCC SR1.5, UNFCCC emissions data, Le Quéré *et al.* (2018) *Historical Carbon Budget* (version 1.3) and UN World Population Prospects (2017 revision). Calculated for +2°C 2/3 probability, egalitarian share and consumer approach.

Table A2. Grandfathering carbon budgets, HCA and adjusted carbon budget

GtCO ₂	Grandfathering carbon budget (2015 reference year)	Historical carbon adjustment (1990-2017)	Grandfathering adjusted carbon budget (2015 reference year)
EU28	118.8	49.7	69.1
AUT	2.8	1.1	1.7
BEL	3.8	2.1	1.8
BGR	1.0	-0.3	1.3
HRV	0.5	-0.2	0.7
CYP	0.3	0.1	0.2
CZE	2.8	1.6	1.3
DNK	1.5	1.1	0.4
EST	0.3	0.2	0.1
FIN	0.5	0.3	0.2
FRA	14.4	4.7	9.7
DEU	27.6	16.1	11.5
GRC	2.8	1.5	1.2
HUN	1.5	0.2	1.2
IRL	1.7	0.9	0.8
ITA	13.0	5.7	7.3
LVA	0.3	-0.3	0.6
LTU	0.3	-0.1	0.4
LUX	0.2	0.1	0.1
MLT	0.1	0.0	0.0
NLD	4.9	2.4	2.5
POL	8.6	2.5	6.2
PRT	1.6	0.1	1.5
ROU	1.7	-1.1	2.7
SVK	1.0	0.2	0.8
SVN	0.3	0.1	0.3
ESP	8.7	1.9	6.8
SWE	-0.2	-0.8	0.6
GBR	16.8	9.6	7.2

Source: iASES (formerly iAGS) 2019 computations, based on IPCC SR1.5, UNFCCC emissions data, Le Quéré et al. (2018) *Historical Carbon Budget* (version 1.3) and UN World Population Prospects (2017 revision). Calculated for +2°C 2/3 probability, grandfathering share and consumer approach.

Table A3. Per capita hybrid carbon budgets, HCA and adjusted carbon budget

GtCO ₂	Per capita hybrid carbon budget (2015 reference year)	Per capita historical carbon adjustment (1990-2017)	Per capita hybrid adjusted carbon budget (2015 reference year)
EU28	169.6	98.0	96.5
AUT	248.9	127.4	121.5
BEL	258.6	183.0	75.7
BGR	106.3	-44.7	151.0
HRV	84.1	-49.4	133.5
CYP	180.7	96.1	84.6
CZE	203.1	147.5	55.6
DNK	205.3	201.5	3.8
EST	196.0	145.4	50.6
FIN	69.0	45.8	23.2
FRA	169.6	73.0	96.5
DEU	256.5	197.4	59.2
GRC	186.3	137.6	48.7
HUN	112.7	22.1	90.6
IRL	269.0	194.3	74.6
ITA	166.0	96.2	69.8
LVA	116.7	-138.9	255.6
LTU	79.0	-43.3	122.3
LUX	299.4	256.1	43.3
MLT	104.3	30.6	73.7
NLD	220.1	144.0	76.1
POL	171.0	64.2	106.8
PRT	116.3	13.7	102.6
ROU	64.6	-53.2	117.8
SVK	135.9	30.8	105.0
SVN	122.0	31.5	90.4
ESP	141.7	40.4	101.3
SWE	-13.7	-83.4	69.7
GBR	195.0	146.1	48.9

Source: iASES (formerly iAGS) 2019 computations, based on IPCC SR1.5, UNFCCC emissions data, Le Quéré et al. (2018) *Historical Carbon Budget* (version 1.3) and UN World Population Prospects (2017 revision). Calculated for +2°C 2/3 probability, hybrid share and consumer approach.

Table A4. Per capita egalitarian carbon budgets, HCA and adjusted carbon budget

GtCO ₂	Per capita egalitarian carbon budget (2015 reference year)	Historical carbon adjustment (1990-2017)	Per capita egalitarian adjusted carbon budget (2015 reference year)
EU28	178.8	98.0	80.8
AUT	178.8	127.4	51.4
BEL	178.8	183.0	-4.2
BGR	178.8	-44.7	223.5
HRV	178.8	-49.4	228.2
CYP	178.8	96.1	82.7
CZE	178.8	147.5	31.3
DNK	178.8	201.5	-22.7
EST	178.8	145.4	33.4
FIN	178.8	45.8	133.0
FRA	178.8	73.0	105.8
DEU	178.8	197.4	-18.6
GRC	178.8	137.6	41.2
HUN	178.8	22.1	156.7
IRL	178.8	194.3	-15.5
ITA	178.8	96.2	82.6
LVA	178.8	-138.9	317.7
LTU	178.8	-43.3	222.0
LUX	178.8	256.1	-77.3
MLT	178.8	30.6	148.2
NLD	178.8	144.0	34.8
POL	178.8	64.2	114.6
PRT	178.8	13.7	165.1
ROU	178.8	-53.2	232.0
SVK	178.8	30.8	148.0
SVN	178.8	31.5	147.2
ESP	178.8	40.4	138.4
SWE	178.8	-83.4	262.2
GBR	178.8	146.1	32.7

Source: iASES (formerly iAGS) 2019 computations, based on IPCC SR1.5, UNFCCC emissions data, Le Quéré et al. (2018) *Historical Carbon Budget* (version 1.3) and UN World Population Prospects (2017 revision). Calculated for +2°C 2/3 probability, egalitarian share and consumer approach.

Table A5. Per capita grandfathering carbon budgets, HCA and adjusted carbon budget

GtCO ₂	Per capita grandfathering carbon budget (2015 reference year)	Historical carbon adjustment (1990-2017)	Per capita grandfathering adjusted carbon budget (2015 reference year)
EU28	234.1	98.0	136.2
AUT	327.8	127.4	200.4
BEL	340.6	183.0	157.6
BGR	139.9	-44.7	184.7
HRV	110.8	-49.4	160.1
CYP	238.0	96.1	141.9
CZE	267.5	147.5	120.0
DNK	270.3	201.5	68.8
EST	258.2	145.4	112.8
FIN	90.9	45.8	45.1
FRA	223.3	73.0	150.3
DEU	337.8	197.4	140.5
GRC	245.4	137.6	107.8
HUN	148.4	22.1	126.3
IRL	354.2	194.3	159.9
ITA	218.6	96.2	122.4
LVA	153.7	-138.9	292.6
LTU	104.1	-43.3	147.3
LUX	394.2	256.1	138.2
MLT	137.3	30.6	106.8
NLD	289.8	144.0	145.9
POL	225.2	64.2	161.0
PRT	153.1	13.7	139.4
ROU	85.1	-53.2	138.3
SVK	178.9	30.8	148.1
SVN	160.6	31.5	129.1
ESP	186.6	40.4	146.2
SWE	-18.0	-83.4	65.4
GBR	256.8	146.1	110.7

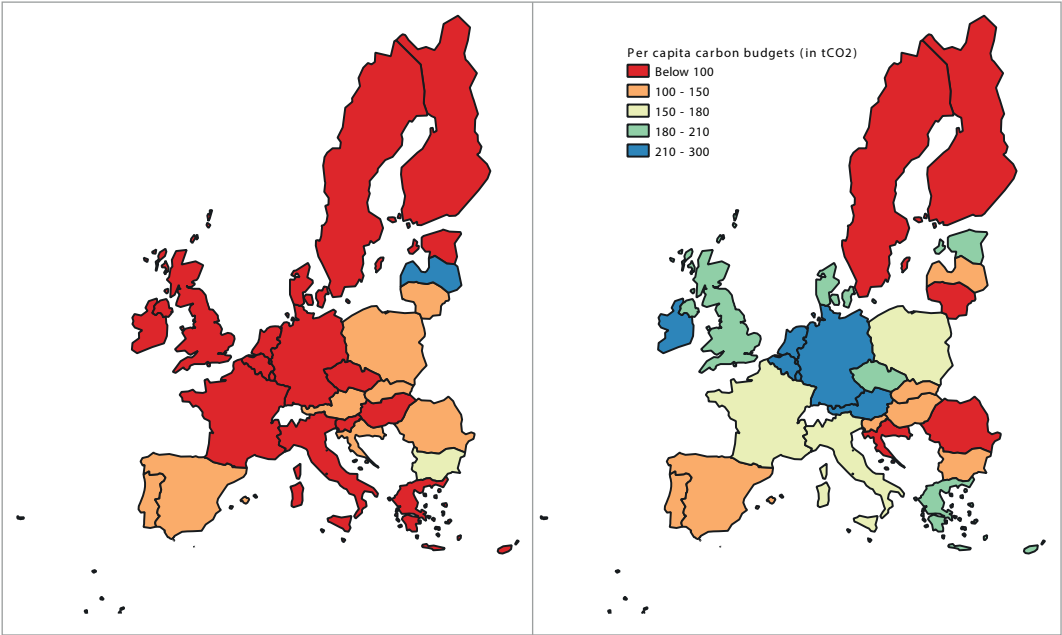
Source: iASES (formerly iAGS) 2019 computations, based on IPCC SR1.5, UNFCCC emissions data, Le Quéré *et al.* (2018) *Historical Carbon Budget* (version 1.3) and UN World Population Prospects (2017 revision). Calculated per capita based on 2015 population data for +2°C 2/3 probability, grandfathering share and consumer approach.

Table A6. Ranks of national per capita carbon budgets under various assumptions

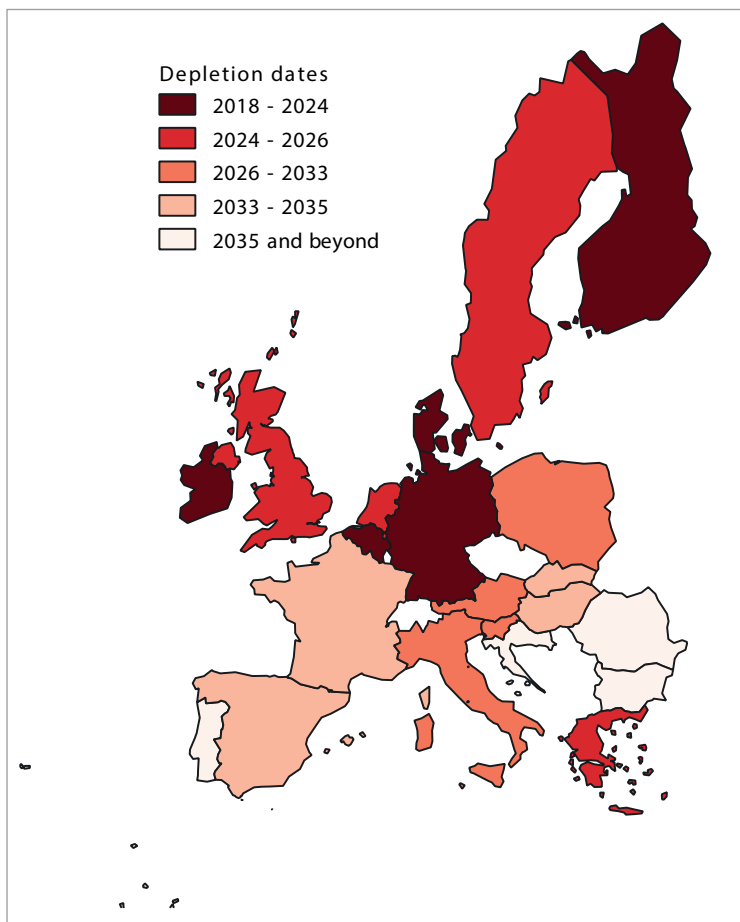
	Grandfathering per capita budget	Egalitarian per capita budget	Hybrid per capita budget	HCA-adjusted grandfathering per capita budget	HCA-adjusted egalitarian per capita budget	HCA-adjusted hybrid per capita budget
1	LUX	—	LUX	LVA	LVA	LVA
2	IRL	—	IRL	AUT	SWE	BGR
3	BEL	—	BEL	BGR	ROU	HV
4	DEU	—	DEU	POL	HRV	LTU
5	AUT	—	AUT	HRV	BGR	AUT

Source: iAGS, based on IPCC SR1.5, UNFCCC emissions data, Le Quéré et al. (2018) Historical Carbon Budget (version 1.3) and UN World Population Prospects (2017 revision); budgets are calculated per capita based on 2015 population data for +2°C 2/3 probability and consumer approach.

Graphique A1. Per capita carbon budgets before (right) and after (left) historical carbon adjustment



Source: iAGS, based on IPCC SR1.5, UNFCCC emissions data, Le Quéré et al. (2018) Historical Carbon Budget (version 1.3) and UN World Population Prospects (2017 revision); on the left handside are displayed national per capita adjusted carbon budgets for EU28 member countries; on the right handside are displayed national per capita carbon budgets (before historical carbon adjustment) for the same countries. Calculated for +2°C 2/3 probability, hybrid share and consumer approach.

Graphique A2. Maps for the years before depletion

Source: iAGS, based on IPCC SR1.5, UNFCCC emissions data, Le Quéré *et al.* (2018) *Historical Carbon Budget* (version 1.3), *UN World Population Prospects* (2017 revision), *AMECO online* (11/2018) for 2017 GDP. Calculated for +2°C 2/3 probability, hybrid share and consumer approach.