A transition analysis for a 1.5C Climate Vision

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Abstract

The Paris Agreement from December 2015 set an ambitious but necessary climate change goal: 1.5C global warming. The lack of effective climate change action up till now has led us to a very tight situation to comply with the 1.5C goal. As of today we miss a clear view of the feasibility and implications from a transition aligning our socio-economic system with the 1.5C goal without further diminishing the resilience from our systems when it will be mostly needed. We introduce a new transition analysis methodology based on transition rates which allows exploring and informing all the transition options and their implications, including the impact from structural changes. Integration requirements, within the energy system and beyond, as well as the role of equity in the transition are explored. RES deployment rates consistent with a climate sound transition are evaluated and found to be more than an order of magnitude higher than current values.

Key words: Climate Change, Transition, Mitigation, Renewables, Sustainability, Equity.

Abbreviations:

AR5	5th Assessment Report from the IPCC
B	Biomass
BAU	Business As Usual – Reference evolution pathway
BECCS	Bioenergy with CCS
CBW	Carbon Budget Wedge
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
COP	Conference Of the Parties from the UNFCCC
CSP	Concentrating Solar Power
DH	District Heating
EEM	Energy-Economy models
ER+	Advanced Energy [R]evolution scenario from Greenpeace
EV	Electric Vehicles
F-gases	Fluorinated greenhouse gases
FF	Fossil Fuels
G	Geothermal
GHG	Greenhouse Gases
GTP100	Global Temperature change Potential at 100 years

GWP100	Global Warming Potential at 100 years
IAM	Integrated Assessment Models
ICE	Internal Combustion Engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LUC	Land Use Change
NDC	Nationally Determined Contributions
NG	Natural Gas
NNE	Natural Negative Emissions
nonE	non-electricity final energy
PV	Photovoltaics
RCP	Representative Concentration Pathway
RES	Renewable Energy Sources
SDG	Sustainable Development Goals
ST	Solar Thermal
synF	Synthetic Fuel from Hydrogen
T/B	Transition to BAU ratio
UNFCCC	United Nations Convention on Climate Change

1 Introduction

The Paris Agreement, adopted by consensus during the COP21 in December 2015 and going into effect by November 2016 states the adopted global climate goal as: "Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change".

Although there is still much to be known about the incremental climate impacts when going from stabilizing the global climate heating from 1.5C to 2C, we already know enough as for having a very clear view of how important it is to manage climate stabilization at 1.5C. Indeed, stabilizing the climate at 2C instead of 1.5C means: A 50% increase in heat wave duration; up to 100% increase in the reduction of annual water availability in the Mediterranean basin; 43% increase in heavy precipitation intensity; 25% increase in global sea level rise in 2100; 41% increase in the fraction of coral reef cells at risk of long-term degradation; up to 100% increase in the productivity reduction from crops like maize and wheat in tropical regions; … **[1]**.

Moreover, between 1.5C and 2C several tipping points for non-return feedback mechanisms with potential climate impacts much beyond the incremental impacts described above could be surpassed, like unlocking a sea level rise of around 7 m because of Greenland's ice sheet melting at around 1.6C **[2]**.

In spite of all this, the Paris Agreement is undefined with regard to the adopted specific global warming goal. The dominant interpretation of the Paris Agreement's climate goal is limiting global warming to 1.5C with a 50% likelihood **[1]**, **[2]**, **[3]**, **[4]**, which already sounds a bit like playing Russian roulette with a half loaded revolver's cylinder, accepting an astonishing 50% chance of failure when what it's on the game is our Planet, and while any bank conditions investment decisions (for instance for RES plants) to a minimum of a 90% likelihood of exceeding expectations (RES plant's performance). But the lack of definition in the Paris Agreement with regard to the adopted climate goal leaves free way to speculators, which like IEA choose to interpret the Paris Agreement's goal as a 2C global warming with 66% likelihood **[5]** keeping true to its long term strategy of paving the way to burn up to the last possible fossil fuel droplet.

Another very important shortcoming from the Paris Agreement is the absence of a reference framework for applying equity and fairness principles to share between the different countries the required mitigation efforts, as well as the allocation of rights and obligations in terms of financing and support for mitigation and adaption, and the allocation of responsibilities for losses and harm due to climate change (including adaption costs) **[6]**. Without this framework it is almost impossible to articulate the kind of required transition within the available timeframe.

Even having underwritten the Paris Agreement, the aggregated today's mitigation commitments (NDC) from all the world governments are very far from attaining the 1.5C goal, in the best case leading to a 3.2C global warming with a 66% likelihood in 2100 **[3]**.

In fact, the lack of effective and significant climate action up to date has very important consequences, leading us to a very tight and urgent context: The climate boundary condition translates to a carbon budget (the amount of CO_2 that can still be emitted while staying within the climate goal of 1.5C global warming), which with the current emission rates (around 40 $GtCO_2/y$) would exhaust the available budget as of May 2017 in just 8 years if we aim to a 50% likelihood of success, and around 4 years if we increase the success likelihood requirement up to a still meager 66%.

The implications from the climate boundary condition are huge: For instance, with regard to the fossil fuel reserves, already in 2016, 85% of the overall known fossil fuel reserves and 60% of the already developed fossil fuel reserves should be left underground for aligning ourselves with the 1.5C at 50% likelihood climate goal **[7]**. This gives a clear idea of the huge amount of stranded assets even if as of today any new investment in fossil fuels would be stopped (which is not the case): The transition requires that those who have been speculating with the common good lose a significant fraction of their investments, and as a society we'll have to manage this situation in order to avoid that it keeps on being an unsurmountable transition barrier.

RES are breaking new records of installed capacity, dedicated investment and specific energy costs year after year, having become the dominating technological option for new capacity addition to the World's power system, in some cases even beating fossil fuel technologies in specific energy cost terms **[8]**, **[9]**, **[10]**. However, in spite of the euphoria that this advance of RES often produces, there is a lack of clarity and awareness of how far this RES deployment is from the transition requirements.

The analysis herewith presented is a novel transition rate analysis bypassing trending and structural limitations and focusing on potentials and its implications, which allows informing and exploring the implications of transition options currently not captured by other climate modeling exercises. It is a first of the kind analysis showing options to stay within 1.5C without resorting to false solutions, and providing detailed transition insight on the requirements and implications from such a transition, including the requirements for RES deployment.

2 Transition analysis methodology

The methodology used for the transition analysis herewith presented significantly differs from the methodology used in traditional scenario modeling exercises like those from Integrated Assessment Models (IAM) or Energy Economy Models (EEM).

We introduced a transition rate analysis methodology which cornerstone is the maximum transition rates that can be materialized in the different system elements/components. Therefore, transition rates become an input to the analysis instead of being an output as in the IAM and EEM approaches.

The aim of the transition rate analysis methodology is to overcome the limitations from IAM and EEM modeling exercises when it comes to capture the potential contribution of structural changes, providing additional transition insight, while being based on a very flexible methodology that allows an easy exploration of 'what-if' transition analyses.

Indeed, IAM and EEM methodologies heavily rely on past trends which do not include any information about the potential impact from structural changes. Moreover, the least-cost algorithms used in these modeling exercises fail to capture the full social costs, and therefore lead to scenarios that systematically exclude transition options more aligned with the socio-economic-environmental boundary conditions.

IAM and EEM scenarios provide a very useful insight into what kind of evolution paths we would take if we do not manage to articulate socio-economic structural changes, but in a point in time when we face such strong challenges as the ones posed by climate change after all the lack of effective mitigation action along the last decades, we need to complement the outputs from IAM and EEM modeling exercises with insight from other transition options, so that we can lay down on the discussion and decision tables all the available evolution pathways in order to facilitate informed decisions. Indeed, standing in front of decision and discussion tables that only include results from scenarios based on the basic philosophy of 'let's manage to burn the last droplet of fossil fuels' (like the IEA's scenarios from the last decades up to today) won't allow articulating the right decision making when the uppermost imperative aligned with the climate boundary condition is stopping burning fossil fuels as fast as possible. Likewise, modeling results that fail to capture the full social cost impact of relying on uncertain and high impact correction measures like CCS or geoengineering, potentially truncating any sustainable transition option, shouldn't really be the single option laid down in the decision table if we want to have any chance to facilitate a sustainable and climate compatible evolution.

By bypassing all these limitations from current IAM and EEM modeling results, the transition rate analysis herewith presented can provide insight and inform future IAM and EEM runs so that they capture the potential impact from structural changes, contemplate other available transition options, and pay attention to the full social costs.

Therefore, the transition rate analysis seeks to explore the compatibility with the climate boundary condition of the transition options still available to us as of today, contributing to articulate an informed debate about the transition, exploring the impact from structural changes, and gaining insight on their transition implications.

The transition rate analysis can be applied with different levels of system resolution, from an overall single transition rate (overall GHG emissions), down to a detailed breakdown of transition rates for the different system components. The level of resolution into the different system components is directly linked to the insight to be obtained from the transition rate analysis. While applying the analysis to a single overall transition rate provides information on the requirements for the aggregated transition, it does not provide insight on the feasibility and implications for the different system components. For the transition rate analysis herewith presented we have considered around 70 system components with their associated transition rates, which provide a significant system resolution and therefore allows gaining significant sectorial transition insight.

The starting point from the transition rate analysis is to define the maximum transition rates that could be articulated into each of the considered system components. This becomes an iterative process when undertaking what-if analyses. The adopted component's maximum transition rates are subject to a feasibility check based on detailed sectorial analysis and evaluations of the sectorial impact of structural changes.

From the maximum transition rates, four transition paths are built to capture the spectrum of transition options that could be expected when materializing the maximum transition rates. Additional transition paths could be built to explore other transition aspects. In the current results two criteria have been considered when building these four transition paths:

- Delay on undertaking the transition (transition starting in 2017 versus in 2020). This provides a direct feedback on the implications of delaying an effective transition until 2020 as is the current situation under the Paris Agreement.

- Gradualism in articulating the maximum transition rate (instantaneous versus a 10-year window with linear increase in transition rate up to its maximum value). This gives a direct feedback on the impact of the transition ambition.

By combining these 4 transition options, four different transition paths are evaluated which are likely to provide the boundary conditions of any transition path that would articulate the considered maximum transition rates:

- Transition-A: Starts in 2017 and instantaneously articulates the maximum transition rate.
- Transition-B: Starts in 2020 and instantaneously articulates the maximum transition rate.
- Transition-C: Starts in 2017 and linearly articulates the maximum transition rate along a 10-year time window.
- Transition-D: Starts in 2020 and linearly articulates the maximum transition rate along a 10-year time window.

The only transition rate which is not an input but an output from the transition analysis is the RES deployment rate into the power sector. Indeed, the RES deployment rate is the closure of the transition analysis to match the power requirements from each transition path. The resulting RES deployment rate for each transition path provides direct insight on the requirements to articulate the transition, and can be directly compared with the current rates of RES deployment.

3 Main inputs to the transition analysis

Herewith we summarize the main inputs used for the transition analysis.

In general terms, for each one of the system's components considered for the transition we have considered a maximum transition rate and a saturation of the transition process.

The transition analysis results herewith presented is a first iteration where initial values have been assumed for the system component's maximum transition rates. Specific sectorial analysis can be used to refine each one of the system component's maximum transition rates to update the transition analysis results. Likewise, the implemented methodology facilitates undertaking what-if analysis that provides a quantification of the impact from modifying the maximum transition rate from each one of the system components. However, this first iteration already provides very interesting transition insights.

The maximum transition rate for each system component (which will then be modulated by the four transition paths), is subject to a feasibility check based on expert judgement. One criterion that has been used is capping transition rates to maximum values in the order of 3-5 %/y representative of other transition processes we have witnessed along history, except when evidence already exists of other more ambitious commitments already in place (like the goal of stopping deforestation in 2020 included in the SDG). Still, most of the transition rates considered for this first iteration of the transition analysis are well below this cap.

The saturation of the transition process is an estimate of the end point for the transition of each one of the system components, and it has been obtained from estimates of the potential coming from more detailed sectorial analyses.

For the carbon budgets we used the IPCC AR5 **[11]** for the carbon budgets as of 2011, and updated them to 2016 values with the global CO_2 emissions reported by **[12]**, **[13]** and **[14]**.

The reference non-CO_2 GHG emissions used to evaluate the Carbon Budget Wedges (CBW) are those used in the climate model simulations that lead to the carbon budgets presented in the IPCC AR5 **[11]**, and as indicated in **[11]** are those corresponding to the RCP8.5, which are documented in **[15]** and **[16]**. In order to evaluate the CBW associated to mitigation of non-CO_2 GHG emissions with respect to the RCP8.5 values, we used the GTP100 metrics (Global Temperature change Potential at 100 years) to evaluate the $CO_{2\text{-equivalent}}$, and more specifically the GTP including climate-carbon feedbacks, instead of using the more common GWP100 values (Global Warming Potential at 100 years), since the GTP is better aligned with the climate goal we are aiming at (1.5C global temperature increase). The GTP conversion factors have been obtained from **[17]** and **[18]**.

The starting point for informing the estimates for mitigation and Natural Negative Emissions (NNE) from forests are obtained from **[19]**, **[20]** and **[21]**. For the forest's NNE saturation we assumed a 75% - 62% of the potential reported in **[19]** depending of the transition path (transitions A and B having the higher value).

The starting point for informing the estimates for mitigation and NNE from agriculture is obtained from **[21]**. The transition dimensions considered in the agriculture sector are: improving fertilizer use, reducing biomass burning, improving rice production and diet change (which leads to reduced livestock CH_4 and N_2O emissions as well as NNE). The diet change herewith considered is an evolution towards a so-called healthy diet, which includes about a 50% reduction in consumption of beef, pork and poultry relative to BAU, with dairy remaining the same as BAU **[22]**. An evolution towards a plant based diet could unlock almost twice the mitigation and NNE potential than the healthy diet, but would be far more complex to materialize because of requiring a significantly higher behavioral change. The considered transition GHG emissions saturation with regard to a BAU evolution, in terms of the transition-to-BAU ratio are around 10% for improved fertilizer use, 40% for improved rice production, 0% for biomass burning, and 60% for diet change.

With regard to F-gases emissions, the recent Kigali agreement already represents a significant emissions reduction **[23]** compared with the reference RCP8.5 emissions **[15]** considered to derive the current carbon budgets, and therefore would already generate a CBW. However, in an integrated approach to address climate change and comply with the 1.5C climate boundary condition, the level of ambition on F-gases mitigation could be still increased beyond the Kigali Agreement requirements. We consider in our transition analysis a maximum transition rate in F-gases mitigation corresponding to a complete F-gases phase-out in year 2035 for transition-A.

Industry emissions are comprised by energy-related GHG emissions (which we account for within the energy sector emissions), and non-energy process GHG emissions. Typical examples of industrial process emissions are steel and cement manufacturing process emissions, which would be there even if all energy used for these industrial processes would come from renewable energy sources (full transition in the energy sector).

For the Industry process emissions, as in **[7]** we consider the BAU evolution of product demand as given by the average growth rate from the cement scenarios developed in **[24]**. From here we consider a reduction in demand (recycling, circular economy, shared economy, with a saturation of 70% of the BAU reached in 2040 for transition-A, and on top of it an industrial technology shift to zero-emission technologies to be completed in year 2040 for metals and 2060 for cement (all in the transition-A pathway).

The energy sector is the one for which a higher resolution has been considered in this transition analysis. In general terms, the BAU scenarios are those from the IEA used in **[25]** for the Energy [r]Evolution study, while the potentials for efficiency, integration and technology shift have been extracted from the Energy 3.0 study **[26]**. The Energy 3.0 study is a very detailed bottom-up transition analysis for the overall energy sector, with high resolution in the different energy sub-sectors, capturing the impacts of energy system integration and smartness deployment, including the impacts of structural changes like the evolution towards collaborative and participative techno-economic systems. Table 1, Table 2, Table 3 and Table 4 present the maximum transition rates and transition saturation points[1] considered for the different energy sector's components captured by the transition analysis.

Sector	***Element***	***Transition rate***		***Transition saturation***		
		d(T/B)/dt	***dφ/dt***	***T/B***	***φ***	***phase-out***
energy-transport	efficiency and demand attenuation	-3.50 %/y		20%		
energy-transport	electrification	2.50 %/y		60%		
energy-transport	biomass to fuel ratio		2.00 %/y		30%	
energy-transport	H_2 & synF to fuel ratio		3.70 %/y		70%	
energy-transport	FF fuels share		-5.70 %/y		0%	2035
bunkers marine	efficiency and demand attenuation	-1.25 %/y		57.5%		
bunkers marine	FF share		-5.26 %/y		0%	2035
bunkers aviation	efficiency and demand attenuation	-1.50 %/y		49.0%		
bunkers aviation	FF share		-4.17 %/y		0%	2040

Table 1: Maximum transition rates and transition saturation point considered for the different components from the demand transport subsectors from the energy sector. 'Energy-transport' includes all transport modes except international 'bunker' transport. Phase-out year makes reference to Transition-A. FF phase-out from energy-transport is an output and not an input to the analysis, but is added here for completeness. T/B = ratio transition to BAU; φ = fraction or share; FF = fossil fuels; synF = synthetic fuel (from H_2).

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[1] In some cases, the saturation point presents two values. The first one corresponds to the fossil fuel phase-out year, and the second one to the value around 2050 when the use of biomass is minimized because of its sustainability issues, and the installed capacity from some technologies absorbs the full impact of the efficiency deployment.

Sector	***Element***	***Transition rate***		***Transition saturation***		
		$d(T/B)/dt$	***$d\varphi/dt$***	***T/B***	***φ***	***phase-out***
energy-industry	efficiency and demand attenuation	-2.00 %/y		48.0%		
energy-industry	electrification	2.00 %/y		60%		
energy-industry	coal to nonE ratio		-2.44 %/y		0%	2030
energy-industry	oil to nonE ratio		-1.78 %/y		0%	2025
energy-industry	NG to nonE ratio		-2.37 %/y		0%	2030
energy-industry	ST to nonE ratio		1.78 %/y		25% -> 34%	
energy-industry	B to nonE ratio		1.09 %/y		25% -> 0%	
energy-industry	G to nonE ratio		1.21 %/y		17% -> 23%	
energy-industry	DH to nonE ratio		0.23 %/y		10%	
energy-industry	H_2 to nonE ratio		1.64 %/y		23% -> 33%	

Table 2: Maximum transition rates and transition saturation point considered for the different components from the demand industry subsector from the energy sector. T/B = ratio transition to BAU; φ = fraction or share; nonE = non-electricity energy demand; NG = natural gas; ST = solar thermal; B = biomass; G = geothermal; DH = District Heating.

Sector	***Element***	***Transition rate***		***Transition saturation***		
		$d(T/B)/dt$	***$d\varphi/dt$***	***T/B***	***φ***	***phase-out***
energy-other	efficiency and demand attenuation	-4.50 %/y		20%		
energy-other	electrification	2.80 %/y		75%		
energy-other	coal to nonE ratio		-1.01 %/y		0%	2022
energy-other	oil to nonE ratio		-2.10 %/y		0%	2025
energy-other	NG to nonE ratio		-2.02 %/y		0%	2030
energy-other	ST to nonE ratio		0.64 %/y		15% -> 28%	
energy-other	B to nonE ratio		-0.60 %/y		23% -> 0%	
energy-other	G to nonE ratio		0.04 %/y		2% -> 4%	
energy-other	DH to nonE ratio		0.005 %/y		7%	
energy-other	H_2&synF to nonE ratio		3.71 /%y		52% -> 61%	

Table 3: Maximum transition rates and transition saturation point considered for the different components from the demand other subsectors from the energy sector. T/B = ratio transition to BAU; φ = fraction or share; nonE = non-electricity energy demand; NG = natural gas; ST = solar thermal; B = biomass; G = geothermal; DH = District Heating; synF = synthetic fuel (from H_2).

Sector	***Element***	***Transition rate***		***Transition saturation***		
		$d(T/B)/dt$	***$d\varphi/dt$***	***T/B***	***φ***	***phase-out***
energy - power	nuclear share		-0.69 %/y		0%	2035
energy - power	hard coal share		-2.06 %/y		0%	2030
energy - power	lignite share		-0.92 %/y		0%	2025
energy - power	oil share		-0.25 %/y		0%	2030
energy - power	diesel share		-0.08 %/y		0%	2025
energy - power	NG share		-1.37 %/y		0%	2030
energy - power	H_2&synF share		0.11 %/y		2%	
energy - power	wind share of non-hydro&B RE		-1.79 %/y		46%	
energy - power	PV share of non-hydro&B RE		0.52 %/y		27%	
energy - power	CSP share of non-hydro&B RE		1.19 %/y		18%	
energy - power	G share of non-hydro&B RE		-0.13 %/y		6%	
energy - power	Ocean share of non-hydro&B RE		0.21 %/y		3%	
energy - CHP	efficiency and demand attenuation	-3.30 %/y		39%		

energy - CHP	hard coal share		-3.40 %/y		0%	2030
energy - CHP	lignite share		-0.60 %/y		0%	2025
energy - CHP	oil share		-0.23 %/y		0%	2025
energy - CHP	NG share		-2.78 %/y		0%	2030
energy - CHP	B share		2.09 %/y		35% -> 25%	
energy - CHP	G share		2.13 %/y		30%	
energy - CHP	H_2 & synF share		2.50 %/y		35% -> 45%	
energy - DH	coal share		-2.76 %/y		0%	2030
energy - DH	oil share		-0.69 %/y		0%	2030
energy - DH	NG share		-3.45 %/y		0%	2030
energy - DH	B share		1.20 %/y		20% -> 0%	
energy - DH	ST share		1.57 %/y		22% -> 33%	
energy - DH	G share		1.42 %/y		20% -> 30%	
energy - DH	heat pumps share		2.71 %/y		38%	

Table 4: Maximum transition rates and transition saturation point considered for the different components from the generation subsectors from the energy sector. T/B = ratio transition to BAU; φ = fraction or share; NG = natural gas; CSP = concentrating solar power; PV = photovoltaics; ST = solar thermal; B = biomass; G = geothermal; DH = District Heating; synF = synthetic fuel (from H_2)

4 Aiming for a sustainable and resilient transition

This analysis explores the feasibility and implications from a sustainable and resilient transition aligned with the climate boundary condition.

When the 1.5C climate goal was adopted during COP21 in Paris at the end of 2015, after the failure along the last decades on articulating any effective transition progress, and given the limited availability of mitigation scenarios aligned with the 1.5C climate goal, significant doubts arouse about the feasibility to attain that climate goal without resorting to so called ‘false solutions’. These doubts still persist as of today, and the transition analysis herewith presented aimed at providing some additional insight on that regard.

By ‘false solutions’ we mean those technological options that pretend to provide a fix to the climate change crisis but that due to their uncertainty and intrinsic nature in fact would take us far away from a sustainable and resilient transition pathway, while at the same time having a very high likelihood of finally failing to sort out the climate crisis itself. At this point in time, ‘false solutions’ would be CCS, geoengineering and nuclear power.

Because of the very tight situation we currently face due to the lack of effective climate action along the last decades, we assist to a surge in ‘false solutions’-based proposals to tackle the climate change crisis. Indeed, the stabilization scenarios (most for 2ºC) presented in the IPCC AR5 all rely heavily in CCS, and even after refining the IAMs and EEMs to better capture the options of renewable energy the scenarios for 2C and 1.5C climate stabilization generated by the ADVANCE project **[4]** still present a very heavy reliance on CCS for attaining the 1.5C climate goal.

Hence, appropriate management of ’false solutions’ expectations and implications becomes a must, since it is just at this tight critical times when their impact can be the worst, taking away the scarce resources available to articulate the transition and severely impacting de development of resilience into our systems.

Current 2C and specially 1.5C mitigation scenarios heavily rely on CCS, and particularly BECCS. With regard to the CCS part of it, it is a technological option still not available and with doubts about its reliable availability in the future for offering the stability and permanence of the carbon storage. Therefore its implementation would take away scarce transition resources that could not be directed to ‘real solutions’, and the materialization of their uncertainties in a failure to fulfil their expectations in the future would leave us in a far more critical position because of having locked in higher cumulative emissions.

Beyond that, BECCS requires a use of biomass for energy production that goes far beyond the available sustainable biomass resources, which would have a very strong impact on our system’s resiliency, specially impacting food production capacity, on which we already expect strong climate change impacts.

Any geoengineering practice can bring about ‘side effects’ of comparable magnitude to climate change, impacting both our resilience and out capability to progress towards sustainable development. Moreover, our current socio-economic-politic systems are very poorly posed for effectively addressing and dealing with the potential negative impacts from these global inferences. Indeed, we can consider climate change itself as the first unintended geoengineering practice, and after almost half a century of having a clear identification of its negative impacts we are still struggling to articulate an effective way to tackle it and avoid the most catastrophic of its impacts. What we least need while we are still busy on effectively tackling climate change is to unleash additional global impacts of potentially comparative magnitude.

Nuclear power, besides its higher costs than renewable energy, presents many drawbacks (waste management, operational security, nuclear weapons proliferation,…) that render it completely inappropriate as a building block of a global sustainable transition pathway. In fact, the characteristics of nuclear power (operational stiffness –lack of flexibility, its lack of social governance, its centralized corporate structure preventing social participation,…) go just in the opposite direction of the sustainable transition pathway (flexible generation to complement renewables, direct social involvement and participation, distributed generation and governance,…), and therefore are completely unsuited for contributing to the transition. Moreover, in the current urgency time-framework, the huge time requirements to develop nuclear power would on their own disqualify this technology as meaningful transition contributor.

It could be that ‘false solutions’ would become at a certain point in time the only desperate apparent alternative to try to align our socio-economic system with the climate boundary condition, and as time goes by without articulating any effective transition, this point in time comes closer.

But on the one hand this is still not the case, since other transition options, and very specifically those associated to the articulation of structural changes, are currently not included into the scenarios used to inform decisions. The transition analysis herewith presented was aimed to add some light on this regard, and its results show that there is still room to articulate a climate compatible transition which does not resort to 'false solutions'.

And on the other hand, even if that point in time would be reached, we need to seriously challenge the illusion offered by 'false solutions', since once their 'false' attribute would materialized, they would leave us even in a significantly worst condition to navigate the future ahead, specifically seriously impacting our system's resilience.

Although trying to align our socio-economic systems with the 1.5C climate boundary condition is of paramount importance and we have to do all our best to attain this goal, we do not have to lose sight of the even higher priority goals of deploying resilience and introducing sustainability. Indeed, whatever the outcome from out attempts to stabilize our climate at 1.5C we'll have to tackle with the requirements to adapt to the resulting climate change, while simultaneously pursuing the SDGs, which will require a significant increase of resiliency deployment.

Therefore, the transition analysis herewith presented does not consider 'false solutions', and explores the options and implications of articulating a 'false solutions'-free transition which would ultimately contribute to increasing our resiliency and provide sustainability to our development path.

5 Beyond energy system mitigation

The CO_2 emissions from the energy system have been up to now the main contributor to climate change.

In the past, deploying appropriate mitigation strategies in the energy system would have allowed us to stay within the climate boundary condition.

However, the lack of effective climate action along the last decades has brought us to a very tight situation, leaving us with a meager remaining carbon budget to stay within the climate boundaries. Under these conditions, the transition analysis herewith presented shows us that mitigation within the energy system, even if instantaneously deployed at its maximum feasible transition rate, it is no longer able on its own to align us with the climate boundary condition (to keep us within the available carbon budget).

Therefore, an integral transition approach, dealing with all GHG emissions from all the sectors, is the only transition option we have available at this point in time for addressing the climate change challenges.

The transition analysis herewith presented evaluates the multisectoral integrated transition potential, and shows us that we still have chances to articulate a transition that aligns us with the climate boundary condition, but that for attaining this goal we need to get the best from the transition potential in all the different sectors, and articulating the transition without any further delay.

With regard to CO_2 mitigation, beyond that on the energy sector, mitigation in the non-energy industrial sector (process emissions), agriculture and forests needs to be articulated.

But the transition needs to go beyond CO_2 mitigation in order to have chances of staying within the climate boundary conditions. In this transition analysis we considered two additional transition components:

- Natural Negative Emissions (NNE), which are the CO_2 sequestration capacity from forests and agriculture associated to enhancing natural sustainable practices. NNE differ from other negative emissions approaches (like BECCS) in that they only consider sustainable carbon sequestration processes. NNE include reforestation and ecosystem restoration, as well as the impact from different sustainability agriculture strategies (diet change, crop land and grazing land management, restoration of cultivated degraded lands and biochar), with the main contributor (diet change) being strongly socially driven.
- Carbon Budget Wedges (CBW), which are the impact into the carbon budget from agriculture and F-gases non-CO_2 GHG mitigation. Agriculture non-CO_2 GHG mitigation includes improving fertilizer’s use (N_2O mitigation) and rice production (CH_4 mitigation), as well as the diet change impact into livestock emissions (N_2O and CH_4).

The transition analysis results show how important NNE and CBW are for providing chances to stay within the climate boundary condition. However, both NNE and CBW have significant associated uncertainties, and therefore should never be used to reduce the CO_2 mitigation effort, but rather to increase the likelihood to stay within a given climate goal.

Indeed, all the NNE and CBW elements considered in the transition analysis herewith presented have positive sustainability implications on their own beyond their climate change impact, increasing our system’s resiliency, and therefore should be pursued even without factoring in climate change considerations. Their very important climate change contribution should ideally be used to increase the likelihood of staying within the climate boundary condition after deploying our best mitigation transition potential.

6 Structural changes

Our socio-economic-political systems' trending evolution has led us to a limit situation where we face climate change impacts able to collapse these socio-economic-political systems themselves. Therefore whatever we do, we face a fundamental change of these systems, the options being waiting for their chaotic crumbling by climate change impacts, or actively addressing fundamental structural changes on them that provide us the tools to successfully address the climate change challenges and the resiliency to properly and sustainably navigate the future.

The current socio-economic-political systems are unable to successfully address the climate change challenge, especially within the very narrow time window available for effective response. It could be that they played their necessary role along history (tough probably we could have done better…), but right now they are structurally unfit for the climate and sustainability challenges.

Our disregard for addressing structural changes in these systems has led to a race downhill, being unable to articulate any significant transition, and leaving us in an extremely tight situation where the time window to effectively address dangerous climate change has almost closed.

Today's transition requirements are far more demanding of what they were just 10 years ago. As time went by without articulating any effective transition, today we need significantly higher transition rates that the ones we would have needed to address the transition in the past. The current socio-economic-political systems were unable to come even close to any effective articulation of the much lower transition rates required in the past, so we clearly cannot count on them for articulating the significantly higher transition rates required today. Moreover, going beyond the current requirement for high transition rates, we desperately need to build in sustainability and resiliency into our systems, and the current set out accelerating downhill is nowhere close to being able to provide these. Both the articulation of high transition rates and building sustainability and resiliency require implementing structural changes.

Articulating high transition rates on a trending context seems highly unfeasible. However, structural changes are the key to unlock step changes in transition rates.

For instance, energy system integration is a clear structural change that unlocks a huge potential to increase transition rates by providing direct access to all these synergies between system components that were inaccessible under the current non-integrated context: Fast mitigation in diffuse sectors (transport, buildings) by their smart RES-based electrification while simultaneously providing huge flexibility for the integration of RES into the power system.

Another example is the economic system evolution from individual ownership to collective ownership and collaborative economy, with a clear exponent in the transport sector's transition beyond its electrification with EVs to a radical reduction on the number of vehicles in the roads, with all its efficiency implications (and the associated manufacturing requirements reduction), by the deployment of smart and organic collectively owned EVs transport networks, able to make far more flexible the other public transport modes (an therefore increase their modal share).

Perhaps the main element underpinning structural changes is the evolution from representative to participative socio-economic-political set-ups. Representative approaches, where most of the population delegates their direct participation to a handful of stakeholders is inherently very limited and inefficient by building in all the personal, corporate and institutional limitations from the very few representative stakeholders, and by giving priority to these individual's interests and goals over the ones of the society as a whole. Probably the representative approach was the only one we could follow in the past with the available technology and development status, but as of today the tools and means (smart communication, blockchain based peer to peer interaction,…) already exist to articulate the full society's participation, with all its richness and capabilities, into the definition and operation of our systems, overcoming the limitations of very few and biased representative stakeholders.

There are many fronts where this representative to participative structural change component can contribute to the transition, from political, social, economic and financing structures. Few specific aspects relevant to this discussion are:

- Energy system definition and operation. Direct and smart involvement of the demand side and distributed generation on the definition and operation of the energy system, aligning the energy system with the social services it provides, including its climate compatibility, overcoming the current dominance of corporate minority interests stepping on top of social interests.
- Transition financing. Articulating the high RES deployment rates required to materialize the transition (§9) within the available time window requires direct participation from the population, building social financing initiatives capable to underpin the transition and address all its equity and fairness implications, as well as its requirements for sustainability.

The transition analysis herewith presented provides a first estimate of the impact from these structural changes on the feasible transition rates that could be articulated, building on the results from former analysis addressing these issues **[26]**. However, further work is required to better identify, potentiate and facilitate the structural changes needed to materialize the transition.

Still, tough feasible, we don't have to fool ourselves: This potential for change is on the table, but it won't be easy for us to articulate it overcoming the inertias that have been created into all our socio-economic-political systems. Materializing this potential for change will require very conscious, firm and comprehensive action to articulate the required structural changes, with strong governance elements on place to prioritize social interests.

Looking at a very simple example provides a direct feeling of the challenge: The current lack of smartness in the distribution and organization of work. Certainly we have the tools available for an appropriate matching of the needs and capabilities to perform different tasks and works to fulfill our society’s needs while observing environmental, sustainability and social boundary conditions, especially in a transition context. However, we still leave the matching of needs and capacities to highly underdeveloped markets or central planning, speckled of huge limitations and inefficiencies, where work needs are with a very low likelihood assigned to close to optimal capabilities, where huge capability potential remains idle (unemployed) while simultaneously tasks are extremely poorly performed, where communication and interaction (smartness) between needs and capabilities is extremely limited and subject to corporate and personal interests and limitations from a few representative stakeholders,… There seems to be certainly huge room for improvement, and still we keep on operating without untapping any of this potential within a dimension with such a high social relevance.

7 Energy system’s integration

Energy system integration is a key component to unlock the transition potential: Both structural changes and efficiency deployment are facilitated and enabled by energy system integration.

Up till now, the different energy system’s dimensions have evolved following highly non-integrated patterns, with the only significant link among them being the price of fossil fuel resources. Within each of the energy system’s subsectors, isolated and self-standing approaches have been used to match a passive and non-responsive demand with unidirectional offer side approaches, disregarding intersectoral synergies.

The deployment of smartness allows articulating a rich communication between demand and offer, both within a subsector and among different subsectors, unlocking a huge potential for synergic interaction.

Electrification becomes the main instrument for energy system integration, both in terms of direct and indirect (through hydrogen or synthetic fuels produced from electricity) electrification. By ‘*speaking the same language: electricity*’ the potential for synergic interaction between the different energy system’s subcomponents increases drastically, providing the grounds for step change potential. Likewise, the integration of renewables into the whole energy system is greatly amplified by electrification, since demand’s access to renewable generation is hugely facilitated in all the energy subsectors. Electrification also facilitates the deployment of efficiency (EVs versus ICEs, heat pumps versus boilers,…).

Smartness and electrification allow for a direct and comprehensive two-way communication between demand and generation, embracing all the dimensions from the energy sector, and unlocking a huge potential for synergic and active participation from all the components of the energy system.

Integration provides access to a whole bunch of flexibility mechanisms for the operation of a RES-based energy system, which in turn facilitates the further integration of RES into the power system. The access to demand side response from all the energy subsectors, and specially the distributed part of it, with its storage potential (batteries from EVs, thermal inertia from buildings,…), brings about a complete change of paradigm in the operation of the power system and its capability to integrate RES-based generation. Indirect electrification of some parts of demand sectors not able to be directly electrified provides further flexibility.

8 Energy system's transition results

The conditions for the energy system's transition under the climate boundary condition are today significantly tighter than just ten years ago.

Ideally we would first have pursued the power sector's decarbonization before starting a deep transition in the demand sectors requiring high electrification, but there is no longer an option for such a sequential approach. The delay in effective transition action up till now forces a parallel transition of generation and demand, which as this analysis shows could easily produce internal peaks in emissions due to simultaneous power system decarbonization and sectorial demand transition.

Figure 1 shows the conceptual development of potential internal transition peaks in electricity demand, FF consumption and emissions due to the parallel transition of demand and generation. Indeed, as transition progresses in parallel, we assist simultaneously to two opposing trends:

- a decreasing FF share in the power system and final energy demand (red curve)
- an increasing electrification and integration (blue curve)

The resulting effect of these two opposing trends is an internal transition peak of electricity demand, fossil fuel's electricity generation and emissions, as illustrated by the black dashed curve in Figure 1. Not all these peaks need to materialize along the transition, but their avoidance imposes additional constraints on an already tight transition process. For instance, as we will see, avoiding an internal peak in fossil fuel's electricity generation would require still higher rates of RES deployment.

These internal transition peaks should be properly managed, since they can impose additional transition barriers. For instance, an internal peak in fossil fuel's electricity generation would lead to additional fossil fuel stranded assets in the transition process, which can easily develop into transition barriers through lobby driven regulation impacts. Smart transition management, with for instance appropriate staggering of biomass, indirect-electricity, and power sector overcapacity for regulation purposes, can greatly contribute to minimize the impact from these internal transition peaks.

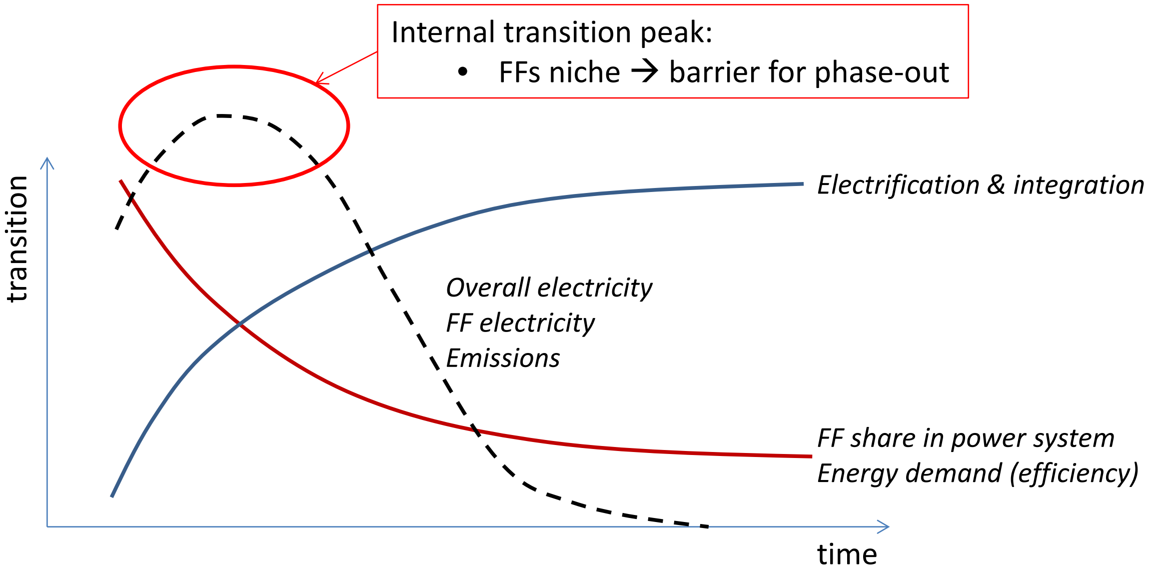

Figure 1: Conceptual deployment of internal transition peaks in FF use and emissions.

Figure 2 presents the evolution of the total final energy demand for the four transition paths (A, B, C and D). For reference purposes, we present also the BAU scenario (IEA projections) and advanced energy [r]evolution (ER+) scenario from **[25]**. The ER+ scenario started the transition in 2012. As we can see in Figure 2 the potential for efficiency and demand attenuation from the BAU and even the ER+ scenarios is very significant at the end of the transition process. However further delays in undertaking the transition easily lead to internal peaks in final energy demand, with transition-D's energy demand being above the ER+ scenario demand until 2030.

Figure 3 presents the cumulative CO_2 emissions from the energy sector and the process industry, as well as their breakdown, for the different scenarios, compared with the available CO_2 budget for a 50% likelihood of staying within 1.5C global warming. We can see in this figure how in spite of the very significant improvement over the BAU and even the ER+ scenarios, the energy sector's cumulative emissions of the four transition paths are above or very close to the overall 1.5C carbon budget, and cumulative emissions from the transition in other sectors still need to be added up before having a meaningful benchmarking against the carbon budget. Indeed, when adding up the energy sector and industry process emissions, only transition-A manages to provide cumulative CO_2 emissions below the carbon budget. A single 3-years delay in undertaking the transition (transition-B) leads to energy sector's cumulative CO_2 emissions almost equal to the overall 1.5C carbon budget, and when adding the industry process emissions would already overshoot the available carbon budget (even before adding up other sector's emissions). Transitions C and D significantly overshoot the available carbon budget just with the energy and process industry sectoral emissions, providing a very direct feedback on the impact of gradual transition rate deployment.

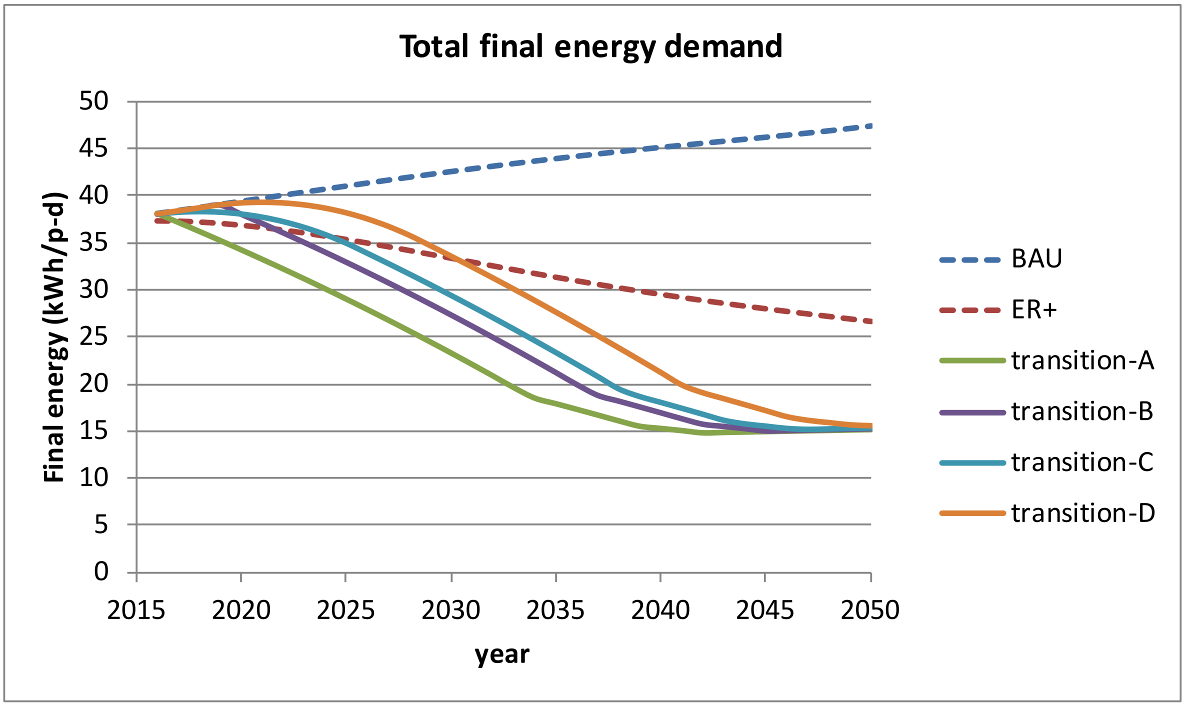

Figure 2: Evolution of total final energy demand from the overall energy sector. Results are presented for the four transition paths (A, B, C and D), the BAU and the advanced energy [r]evolution scenario (ER+) from [25].

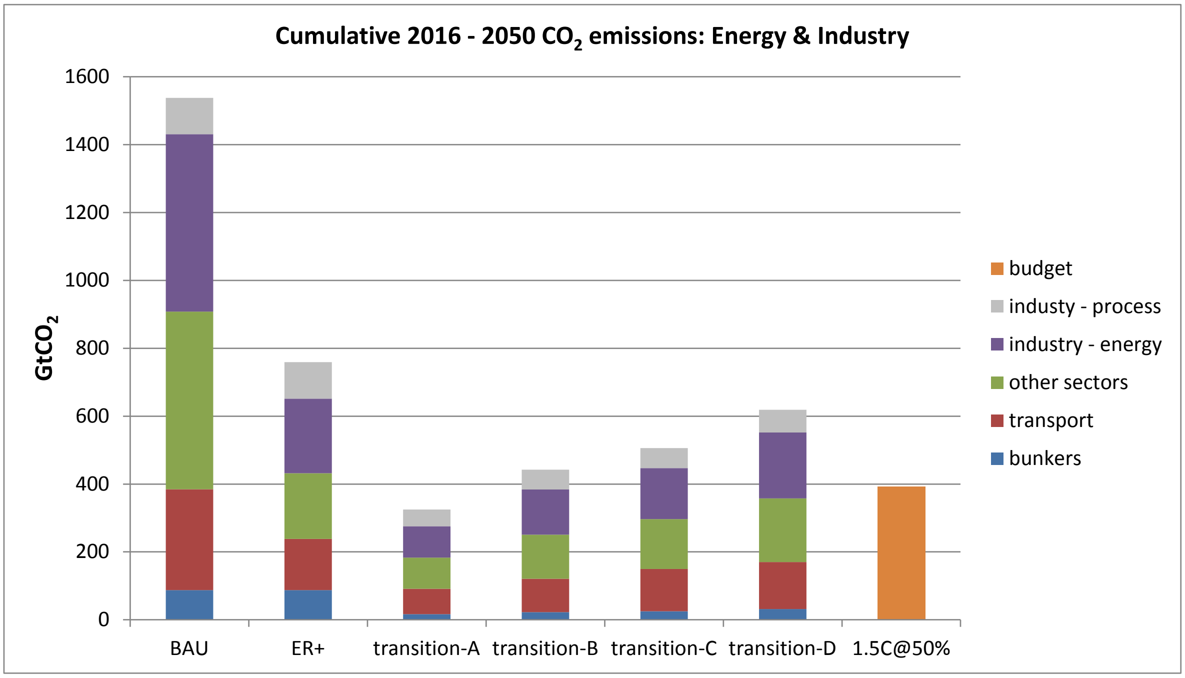

Figure 3: Cumulative CO_2 emissions from 2016 to 2050 for the overall energy sector (with break down between subsectors) and process industry emissions. Results are presented for the four transition paths (A, B, C and D), the BAU and the advanced energy [r]evolution scenario (ER+) from [25]. The carbon budget for 50% likelihood of staying within 1.5C global warming (1.5C@50%) is also presented for reference.

9 Renewable Energy deployment requirements

RES deployment rates are the closure of the transition rate analysis: Once transition rates have been applied for each one of the energy system components, the resulting electricity demand is compounded, and after introducing fossil fuel and nuclear phase-out transition rates into the power sector, the resulting requirements for RES deployment close the transition analysis.

Therefore, unlike all the other component's transition rates which are an input to the transition analysis, the rate of RES deployment is an output from the transition analysis and provides a direct feedback on the requirements and implications for RES deployment to support the transition.

Figure 4 presents the resulting overall gross electricity demand in the different transition paths. Unlike the BAU and advanced energy [r]evolution (ER+) scenarios from **[25]**, which present a monotonous growing and non-saturated electricity demand, the four transition paths developed in this transition analysis display a very clear internal peak in electricity demand, and while at the end of the considered scenario's time window the resulting electricity demand is even lower than in the ER+ (in spite of a higher electrification), the internal peak reached between 2025 and 2035 (depending on the transition path) has higher electricity demand.

This internal peak in electricity demand leads to overcapacity issues, which can be both in terms of deployed RES capacity and in terms of FF or nuclear electricity generation capacity.

There might be room to further minimizing this internal peak by appropriate management of the transition, for instance by staggering biomass and direct/indirect electrification in the different subsectors, and by minimizing RES installed overcapacity in the peak region. There may also be positive implications of this peak for the rest of the transition, like increased system flexibility, enhanced resilience to face unexpected transition evolutions, and an improved condition to address fairness and equity issues like the lack of convergence. But the potential internal peak is intrinsic to the parallel nature of the transition (Figure 1), and it is a clear signal to highlight the requirement for a smart planned and managed integrated transition.

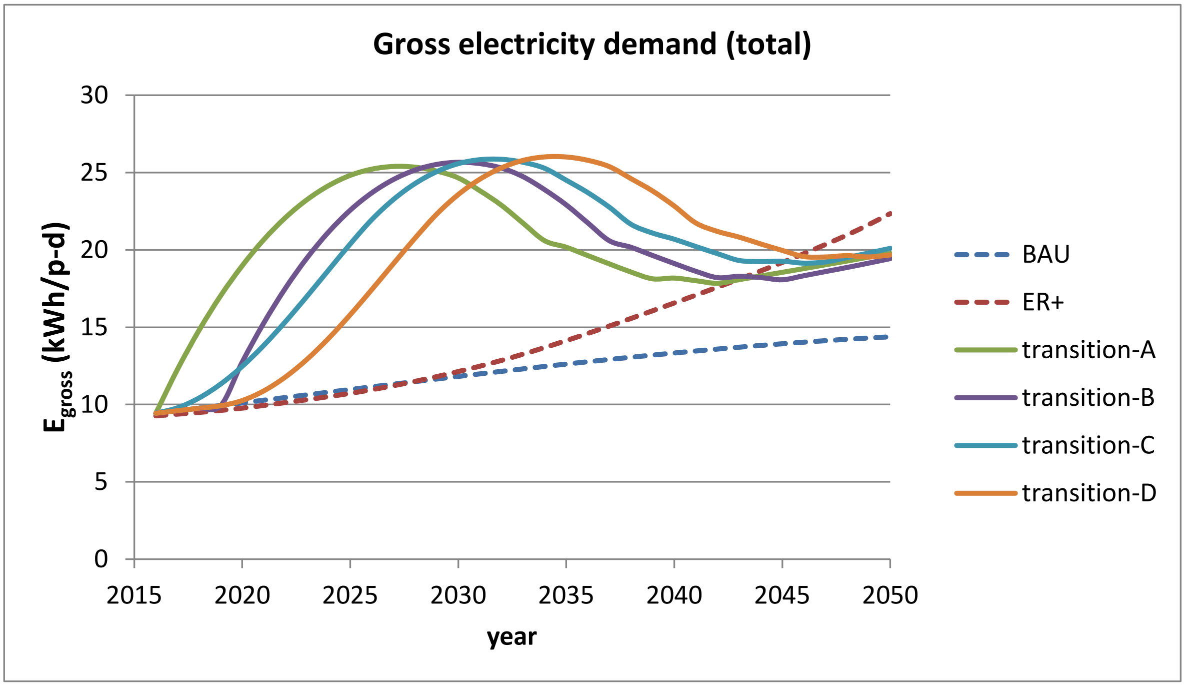

Figure 4: Evolution of per capita gross electricity demand in the four transition scenarios, compared with these from the BAU and advanced energy [r]evolution [25].

Many different RES-based power generation mixes could support a 100% RES energy system. In **[27]** we demonstrated this point for a power system with passive demand and no smartness and integration deployment. Even in this case, the regularizing effects of spatial dispersion and RES technology diversity, together with the intrinsic capabilities from the different RES technologies (including dipatchability from hydro, biomass and CSP) are enough to guaranty the proper dispatch of demand with many different RES-based mixes. When overall energy system integration is considered, the capabilities of demand response articulated, and smartness deployed, in **[26]** we found that power system flexibility is dramatically increased, and therefore it is even easier to dispatch demand all year through with almost any RES-based power system.

For this transition analysis we took a single RES energy mix balanced with current transition capabilities, and based on wind, PV, CSP, Geothermal, Ocean, Hydroelectric and biomass. Table 5 presents the generation and capacity shares from the different RES technologies from the considered generation mix at the end of the transition.

Technology	Generation share	Capacity share
Wind	42.6%	38.2%
PV	24.9%	44.7%
CSP	16.6%	7.5%
Hydro	7.5%	4.8%
Geothermal	5.5%	2.0%
Ocean	2.8%	2.5%
Biomass	0.0%	0.4%

Table 5: World RES mix at the end of the transition

The transition in the power system is characterized by the phase-out of fossil fuels and nuclear, although in the transition dynamics the lead corresponds to RES deployment, which has to overcome the transition barriers generated by the phase-out processes.

The first approach to the transition analysis was based on fossil fuel and nuclear phase-outs applied as decreasing rates of the share of these technologies in the generated electricity, defined by phase-out years between 2025 and 2030 for fossil fuels and 2035 for nuclear (transition-A). These phase-outs are significantly more aggressive than the most advanced transition scenarios proposed up to date (like the advanced energy [r]evolution scenario from **[25]**). However, they still lead to internal peaks of fossil fuel and nuclear electricity generation as a consequence of the coupling between a decreasing share in electricity generation and an internal peak in overall electricity demand. This is the direct impact of the huge transition delay we accumulated up till now, and the requirement to proceed in parallel in the transition (power sector decarbonisation, system integration and efficiency deployment). Essentially, for having a smooth transition, the power sector should already be almost fully decarbonized by now, but that’s still far from the present situation.

Internal peaks in fossil fuel and nuclear generation are no good for the transition, since they would produce additional transition barriers associated to these assets that would be stranded from the very onset. Also, regarding the transition dynamics, developing new fossil fuel and nuclear generation at this point in time would be counterproductive from all the financing, social, political and regulatory fronts. Therefore, it would be wise to avoid these internal peaks in fossil fuel and nuclear generation.

There could still be room to squeeze the smart transition management options beyond what has been done on this first iteration of the transition analysis: Appropriate staggering of multisector direct and indirect electrification, transitional use of biomass, accelerating efficiency deployment, increased use of non-electric RES technologies, transitional electricity services demand contraction, and many other strategies could be explored to minimize or eliminate this internal peak in fossil fuel and nuclear generation without requiring higher deployment rates of RES. In any case it is clear that detailed and smart transition planning and managing is a must to avoid the transition barriers that can arise as a consequence of the accumulated delay on undertaking effective transition.

The other option to avoid these internal peaks in fossil fuel and nuclear generation is increasing the RES deployment rates beyond the ones obtained in the first iteration of the transition analysis. This is the option we explored to inform the feasibility of addressing these transition barriers with increased RES deployment rates, and obtain a direct feedback of where we stand currently with relation to the transition requirements, since RES deployment in the power sector is currently the most advanced transition front.

Figure 5 presents the original results of the transition analysis in terms of the requirements for per capita RES deployment rates, when fossil fuel and nuclear phase-out are represented by a rate of change in their share of electricity generation leading to full phase-out of fossil fuels in 2025-2030 and of nuclear in 2035. As it can be seen, even under this conditions, the transition would require RES deployment rate peaks of around 300 W/p-y, an order of magnitude higher than current RES deployment rates (**[8]**, **[9]**, **[10]**), and significantly higher to those implemented in the most advanced transition scenarios up to date (like the advanced energy [r]evolution scenario from **[25]**), which provides a clear feedback of how far we still are from a climate consistent transition in terms of RES deployment rates. However these peak RES deployment rates are of the same order of magnitude than the deployment rates already achieved (190 W/p-y) in some of the countries that have introduced support for RES deployment **[27]**, even without the implementation of consistent climate policies or the articulation of structural changes. Therefore, it seems feasible to reach the RES deployment rates of Figure 5 required for a climate consistent transition, but reaching them globally in the time frames shown in Figure 5 certainly would require articulating structural changes.

However, with the RES deployment rates from Figure 5 the transition presents internal peaks in fossil fuel and nuclear electricity generation. Figure 6 shows the transitional internal peaks in fossil fuel electricity generation for the different transition paths, which go significantly above the BAU values for undertaking a step reduction after the peak, before completing the useful lifetime from the new installed generation infrastructure, and therefore generating stranded assets that would act as additional transition barriers.

Eliminating the internal peaks in nuclear electricity generation by increasing the RES deployment rates, would lead to a very slight increase of maximum RES deployment rates with regard to those presented in Figure 5, and therefore seems to be a feasible and appropriate transition strategy to eliminate internal transition peaks in nuclear electricity generation.

However, eliminating the internal peaks in fossil fuel electricity generation for transitions A&B would require initial peaks in RES deployment rates significantly higher than those from Figure 5, approaching 500 W/p-y. However, the required RES deployment rates evolve very fast towards those presented in Figure 5, and therefore wouldn't need to be maintained for long periods, which increases its chances to be feasible with the articulation of structural changes. In the case of the more gradual transitions (C&D), eliminating the internal peaks in fossil fuel electricity generation does not require RES deployment rates significantly above those presented in Figure 5, but as Figure 3 shows, transitions C&D are less aligned with the climate boundary condition.

Finally, Figure 7 presents the evolution of RES installed capacity for the different transition paths in the case of capping the peaks in fossil fuel and nuclear generation to the BAU values. The impact of capping the internal peaks in fossil fuel and nuclear electricity generation is the increased slope of the RES installed capacity at the beginning of the transition.

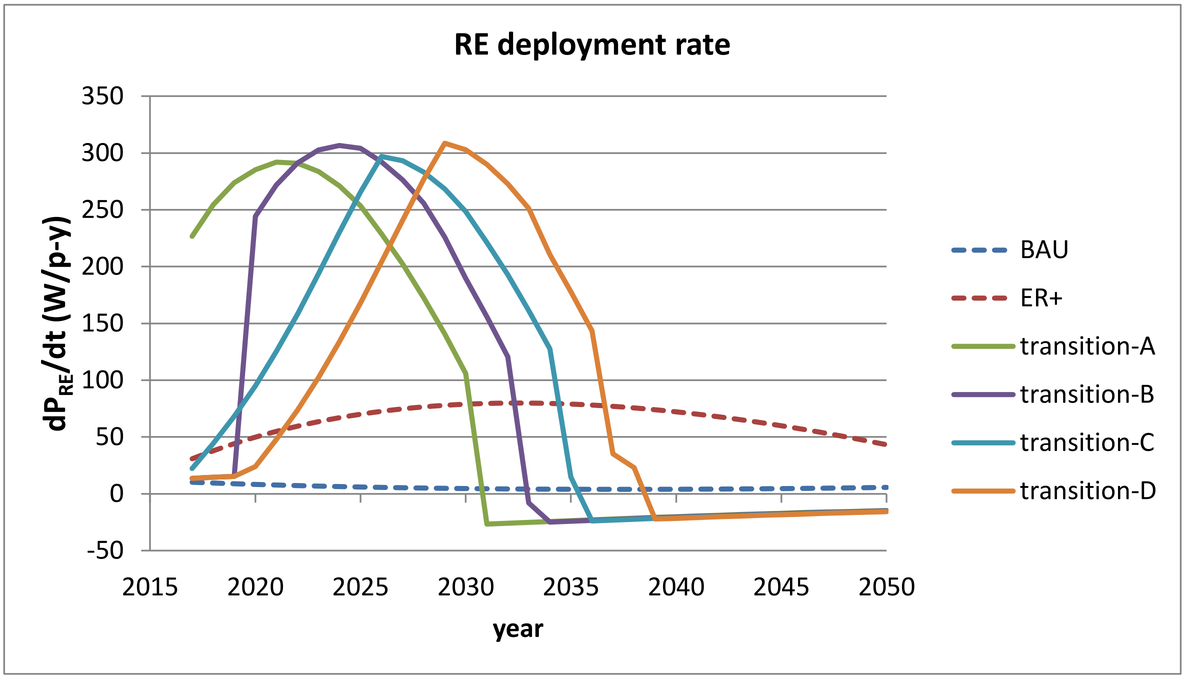

Figure 5: Per capita RES deployment rates for the case without additional requirements to cap internal nuclear and fossil fuel contribution. Results are presented for the four transition paths (A, B, C and D), the BAU and the advanced energy [r]evolution scenario (ER+) from [25].

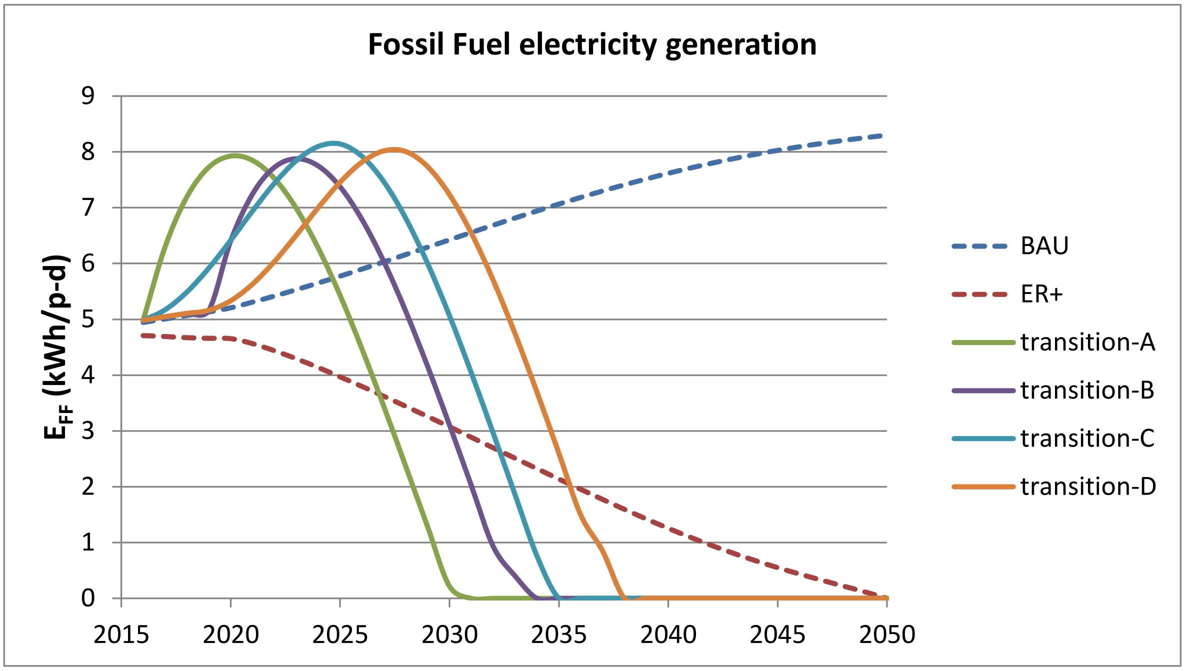

Figure 6: Per capita fossil fuel electricity generation from the original transition analysis with fossil fuel phase-out defined by a decreasing rate in electricity generation share. Results are presented for the four transition paths (A, B, C and D), the BAU and the advanced energy [r]evolution scenario (ER+) from [25].

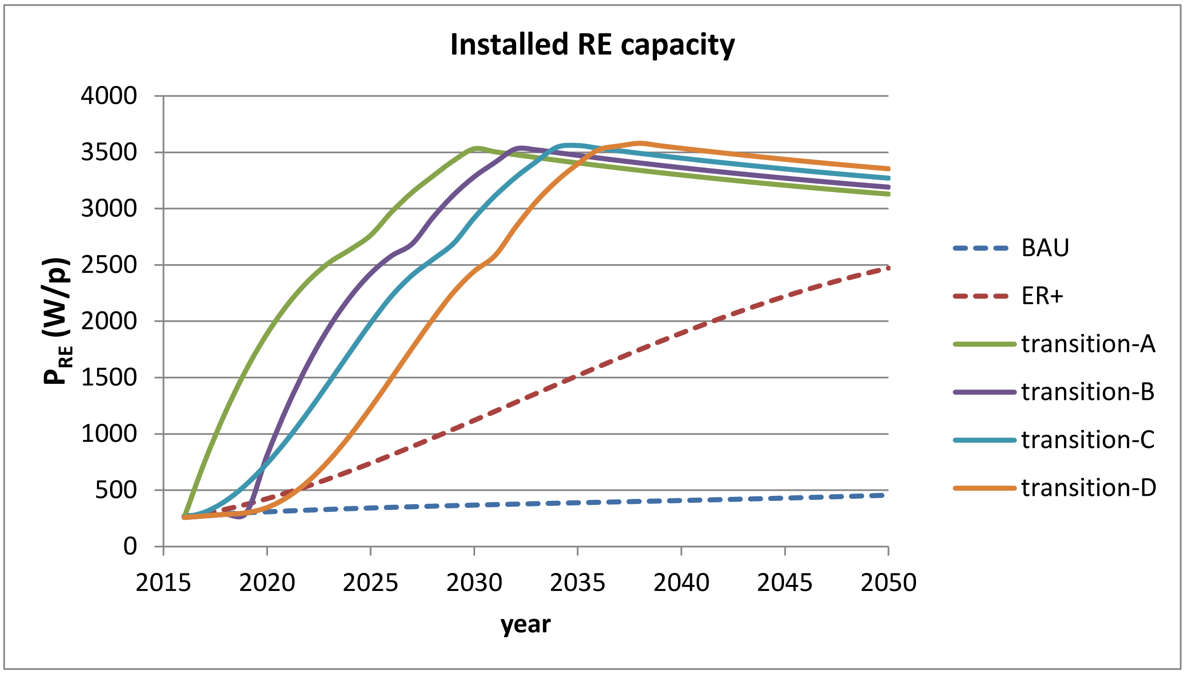

Figure 7: Evolution of the RES installed capacity when introducing additional requirements to eliminate the internal peaks in fossil fuel and nuclear electricity generation. Results are presented for the four transition paths (A, B, C and D), the BAU and the advanced energy [r]evolution scenario (ER+) from [25].

10 Overall transition analysis results

The alignment of a transition pathway with the climate boundary condition cannot be analyzed until the overall GHG impact of the transition has been evaluated, which goes beyond the mitigation of CO_2 emissions in the energy sector, to include the impact of non-energy industrial CO_2 process emissions, industrial non-CO_2 GHG emissions (F-gases), forestry and agriculture GHG emissions, as well as the capability to sequestrate CO_2 from the atmosphere. In our transition analysis, the carbon sequestration potential that has been included is that from the NNE in forestry and agriculture. The impact from the non-CO_2 GHG emissions and their associated mitigation along the transition has been captured through the concept of the carbon budget wedges (CBW).

Figure 8 and Figure 9 present the consolidated transition analysis results for the two extreme analyzed transition paths (A&D), which represent the limits of all the possible transition paths articulated from the input maximum sectoral component's transition rates.

Some comments to interpret the results presented in Figure 8 and Figure 9:

- The transition's cumulative CO_2 emissions are presented in the leftmost bar from the graphs ('positive emissions'), with their breakdown between energy, industry non-energy (process), agriculture and forests. We may appreciate how in both transition-A and transition-D the cumulative CO_2 emissions are strongly dominated by the energy sector, tough the industry process emissions represent a significant share of overall cumulative emissions. This cumulative CO_2 emissions are the result of the transition process after deploying the CO_2 mitigation potential, and in absence of the articulation of other transition capacities, are the ones that should be compared with the carbon budgets (red portion of the three rightmost bars) to evaluate the alignment of the transition with the climate boundary condition. Figure 8 shows that in transition-A the cumulative emissions are just below the carbon budget for 1.5C global warming with 50% likelihood (1.5C@50%), which is the one that is being interpreted as the Paris Agreement goal. Therefore, the transition analysis shows that it is still possible to align the cumulative CO_2 emissions with the available carbon budget for 1.5C@50%, but for doing so the maximum transition rates should be deployed immediately and instantaneously (transition-A). Indeed, if we look at the results from transition-D in Figure 9, the cumulative CO_2 emissions significantly overshoot the 1.5C@50% carbon budget. Transitions B&C also overshoot the 1.5C@50% carbon budget. Moreover, even in transition-A the cumulative emissions are very close to the available carbon budget for 1.5C@50% and significantly overshoot the budget for having a 66% likelihood for keeping the global warming at 1.5C (1.5C@66%). Therefore we can conclude that even with the most aggressive transition, and because of the accumulated delay in undertaking effective climate action up till now, CO_2 mitigation alone leaves us with a limited likelihood of keeping global warming below 1.5C. In fact we should note that for materializing transition-A, we should have started applying the maximum transition rates globally from the 1st January 2017, which we clearly still didn't do, and therefore even if starting at some point in time a transition-A pathway, the additional delay that we are already accumulating in 2017 would lead to higher cumulative emissions than the ones presented in Figure 8. Therefore, if the only transition options we would have available would be CO_2 mitigation, even going beyond the energy sector, as of today we would be screwed to align our transition with the 1.5C climate boundary condition.

- Natural negative emissions (NNE) are the only carbon sequestration elements that we have considered in this transition analysis for sustainability and resilience reasons. NNE transition results are represented in Figure 8 and Figure 9 by the second bar from the left, with the breakdown between forest and agriculture contributions, for transitions A & D. When subtracting from the cumulative positive CO_2 emissions the transition's NNE we obtain the transition's net CO_2 emissions (represented by the third bar from the left), which are the ones that should be compared with the carbon budgets (red portion of the three rightmost bars) to evaluate the alignment of the transition with the climate boundary conditions when only CO_2 mitigation and CO_2 sequestration are considered for the transition. Figure 8 shows that transition-A has negative net emissions, and therefore is fully aligned with the climate boundary condition, providing a very high likelihood (well above 66%) of stabilizing global warming below 1.5C. However, delays and a gradual deployment of the maximum transition rates (transition-D) leads to net CO_2 emissions that are just below the 1.5C@50% carbon budget and well above the 1.5C@66% carbon budget (Figure 9). Therefore, although when including NNE transition-D is also aligned with the Paris Agreement's climate boundary condition (1.5C@50%), it doesn't provide much room for having high likelihoods of staying within the 1.5C global warming (just around 50%), to which when we add the fact that there are significant uncertainties in the NNE estimate, we could conclude that it is more unlikely than likely that a transition-D pathway would be aligned with the 1.5C global warming climate boundary condition when counting only with CO_2 mitigation and NNE. In transition-B net emissions are almost null, and in transition-C they are just below the 1.5C@66% carbon budget.
- The last transition element that we have included into the transition analysis is the effect of non-CO_2 GHG mitigation, which we articulate through the concept of the carbon budget wedge (CBW), which is an estimate of the original carbon budget's modification because of the non-CO_2 GHG mitigation. Therefore, in Figure 8 and Figure 9 the CBW are presented in the three rightmost columns above the original carbon budgets, in such a way that the total column represents the modified carbon budget (original carbon budget plus the CBWs). Figure 8 and Figure 9 present the CBW breakdown between agriculture (CH_4 and N_2O mitigation) and F-gases mitigation. In order to evaluate the climate alignment of a given transition pathway that articulates all CO_2 mitigation, NNE and CBW, the net emissions bar (third bar by the left) has to be compared with the modified carbon budgets (carbon budget plus CBWs) presented in the three rightmost bars. As we can see, in this case, both transition-A and transition-D (and therefore all the possible transition pathways implementing the maximum transition rates considered in this transition analysis) provide a high likelihood (well above 66%) of staying within the 1.5C global warming climate

boundary condition, and therefore, in spite of the uncertainties associated to the NNE and CBW estimates, we can conclude that it is still feasible to articulate a transition that aligns our socio-economic system with the climate boundary condition adopted in the Paris Agreement (1.5C global warming), but for doing so we need to articulate a comprehensive and integral transition, simultaneously deploying the potentials for CO_2 mitigation, NNE and CBW, and due to the uncertainties in NNE and CBW we should be as aggressive as we manage to be with the CO_2 mitigation component.

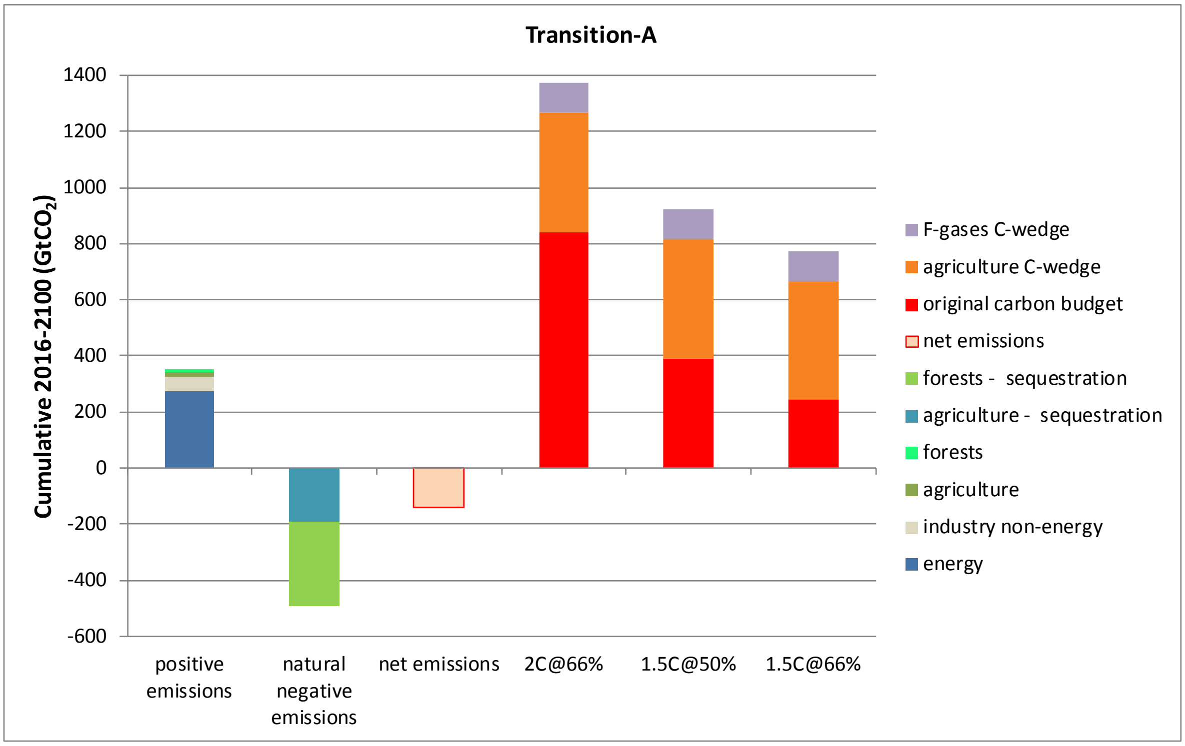

Figure 8: Consolidated overall transition analysis results: Transition-A. Positive emissions are the cumulative CO_2 emissions after the mitigation applied during the transition. Net emissions are the result of subtracting the natural negative emissions (NNE) from the positive CO_2 emissions. The carbon budget wedges (CBW) are added up on top of the original carbon budgets to get the modified carbon budgets. Three carbon budgets are presented: carbon budget for 2C global warming with 66% likelihood (2C@66%), carbon budget for 1.5C global warming with 50% likelihood (1.5C@50% - the Paris Agreement goal), and carbon budget for 1.5C global warming with 66% likelihood.

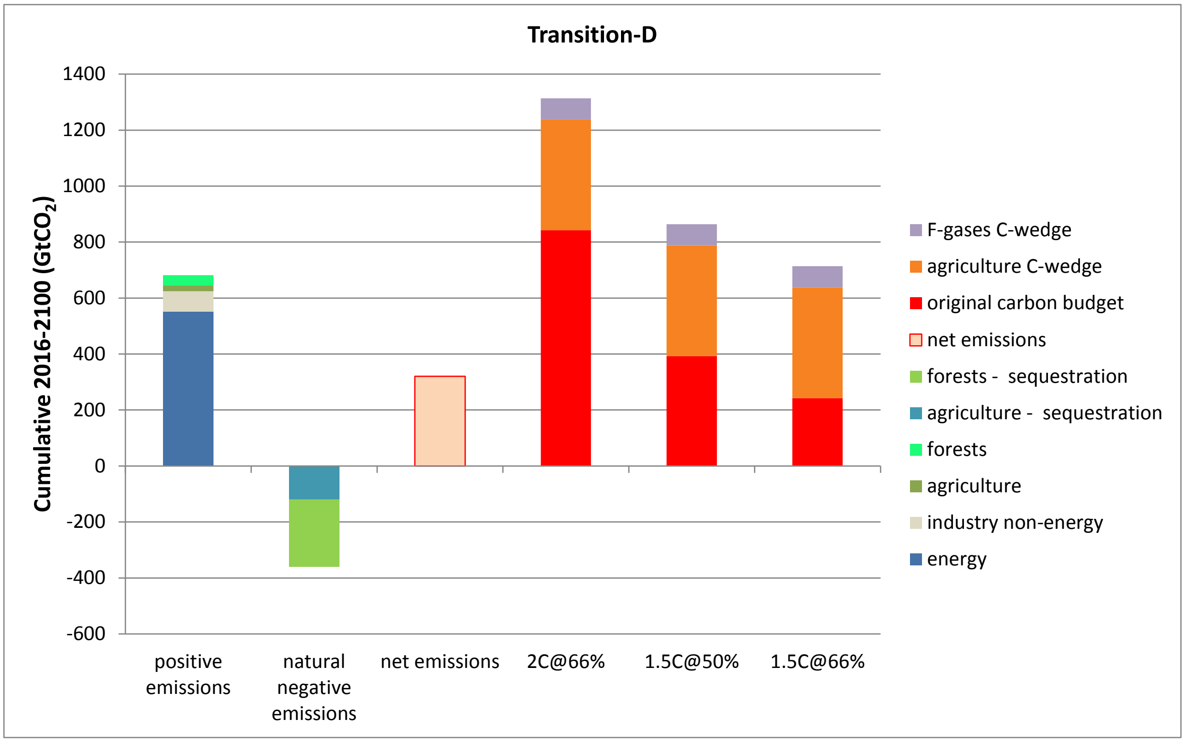

Figure 9: Consolidated overall transition analysis results: Transition-D. Positive emissions are the cumulative CO_2 emissions after the mitigation applied during the transition. Net emissions are the result of subtracting the natural negative emissions (NNE) from the positive CO_2 emissions. The carbon budget wedges (CBW) are added up on top of the original carbon budgets to get the modified carbon budgets. Three carbon budgets are presented: carbon budget for 2C global warming with 66% likelihood (2C@66%), carbon budget for 1.5C global warming with 50% likelihood (1.5C@50% - the Paris Agreement goal), and carbon budget for 1.5C global warming with 66% likelihood.

11 Equity and fair shares

The transition analysis herewith presented is a global analysis and it does not include regional resolution. Splitting the global transition requirements regionally (or nationally) in such a way that the regional aggregation leads to a feasible global transition aligned with the climate boundary condition, needs a thorough consideration and incorporation of equity and fairness issues.

Indeed, although as we have shown in our transition analysis there is still room to articulate a global transition aligned with the climate requirements, its articulation requires the materialization of rather high transition rates simultaneously applied over the different dimensions from our systems, which can only be reached within the limited available time window by structural changes underpinned by a direct social participation and involvement. And we cannot expect any global and focused social involvement unless the pursued transition path is globally felt as fair and equitable.

The Paris Agreement states that: “This Agreement will be implemented to reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances”

However, the Paris Agreement lacks objective frames of reference for interrogating the equity and adequacy of individual country commitments on emissions of GHG, objective frames of reference for determining rights and obligations in terms of financial support for mitigation efforts, and principles for apportioning responsibility for climate change loss and damage (including the costs of adaptation) **[29]**, although reference to these were included in the Draft Agreement and Draft Decision developed by the UNFCCC Ad Hoc Working Group on the Durban Platform for Enhanced Action (ADP) and submitted at the beginning of the COP21 that culminated in the Paris Agreement. This lack of concretion into the Paris Agreement leads to the emissions gap **[3]** and finance gap to materialize the required transition.

In this context, another element to keep in mind is the lack of convergence from virtually all transition scenarios currently available, which means that they perpetuate the inequality at the end of the scenarios, with some countries or regions consuming huge amounts of per capita resources, and others having a much lower per capita share of the available resources, which clearly is also not a fair transition end point, and therefore all these transition scenarios are essentially incomplete, with the transition proceeding beyond its pretended end-point until convergence is achieved, which if not properly accounted for may have significant implications in terms of the real transition’s final alignment with the climate boundary condition.

In our transition analysis we included a basic approach to fairness and equity, with the idea to provide a preliminary estimate of the associated regional implications. When developing a fairness and equity framework, many different considerations can be included. However, the more complex the framework results, the more difficult it can become to reach a global agreement to articulate the framework in the very narrow available time window. That’s what led Crosland T. et al. (**[6]**, **[29]**) to propose a very straight forward framework, which basically is aligned with the one we included in our transition analysis to quantify the fairness and equity transition implications.

What fairness and equity considerations teach us is that basically there is an utterly need for the global North to think beyond bringing their own emissions to zero, and for global South to effectively articulate the compensatory mitigation and adjust their transition to the available budgets. Sad enough, there seems to be an absolute lack of consciousness about these fundamental transition issues in most of the ongoing discussions both at national and international level. Specifically in the global North, after the Paris Agreement in December 2015 we are assisting to a proliferation of national and municipal pretenses of consistent climate policy that do not include any consideration to transition fairness and equity **[30]** for the Netherlands, **[31]** for Australia, **[32]** for Germany, **[33]** for Paris,… This attempt to quickly produce public self-justifications of being contributing the local shares to the overall transition, by completely missing the overarching transition implications from the equity and fairness considerations, will ultimately lead us to missing the climate transition goal itself.

Figure 10 presents the conceptual basic approach we proposed for the determination of fair shares from the remaining carbon budget as well as the required compensatory mitigation action. An explanation of its meaning follows:

- The leftmost big bar represents the 'overall global carbon budget' consistent with a given climate goal (currently the 1.5C@50%). It is composed by the dominant already emitted CO_2 (light brown part of the bar – historic cumulative emissions), and the remaining budget as of 2016: the maximum additional CO_2 we can emit in order to stay within the adopted climate goal.
- A basic approach to equity and fair shares would allocate an available equal per capita budget to each of the Plant inhabitants. This is obtained by dividing the 'overall global carbon budget' (leftmost big bar) by the World's population and the result would be represented by the small green bar. This is the 'overall per capita carbon budget' and includes both the historic cumulative emissions and the remaining budget. We could find two cases for the implications from this 'overall per capita carbon budget': A low historic emitter country (or region) and a high historic emitter country (or region).
- In a 'low historic emitter' country (or region) the historic per capita cumulative emissions (small light brown bar) is smaller than the 'overall per capita carbon budget' (green bar), and therefore there is a remaining available fair carbon budget from today to the future (small blue bar). The inhabitants of this country (or region) would have, for equity reasons, the right to emit this additional amount of carbon while building their transition to a decarbonized economy. However, since some countries already have a carbon debt (high historic emitters), the remaining available fair per capita carbon budgets, if emitted, would cause that we would collectively exceed the 'overall global carbon budget' to stay within the adopted climate goal. Therefore there is need for additional compensatory mitigation actions (red bar) to adjust overall global emissions to the 'overall global carbon budget'.
- In a 'high historic emitter' country (or region) the historic per capita cumulative emissions (small light brown bar) is bigger than the 'overall per capita carbon budget' (green bar), and since none of these countries (regions) has yet completed the transition (but in fact are far from it), they will still emit an additional amount of per capita carbon before completing the transition (dark brown bar). This countries (regions) are already now in per capita carbon debt (they emitted more than their available per capita fair share), and their carbon debt will increase further until they complete the transition. The overall per capita carbon debt from each of these countries (regions) is represented by the red bar. In view of this situation it is grotesque seeing nowadays the publication of reports materializing the pretenses of many global North countries of aligning their transition with the Paris Agreement requirements, without any reference to equity and fair shares, and proposing to keep on emitting carbon until 2040, 2050 or beyond, when they should really have completed the transition a few decades ago.

High historic emitter countries (regions) have contracted a per capita compensation mitigation obligation which will still increase until their transition is completed. Part of the structural changes required to materialize a transition aligned with the climate boundary condition is the social internalization of this compensatory mitigation, finding participatory ways to articulate it effectively and efficiently, which involves both global North and global South societies' direct involvement. Indeed, the track record of institutional development cooperation is really too poor to place our trust on it as an effective structure to channel all the compensatory mitigation and adaption. The scale and criticality from these compensatory obligations really require a direct social involvement into its materialization. Characterizing this compensatory obligation in per capita terms facilitates the direct involvement and participation from society.

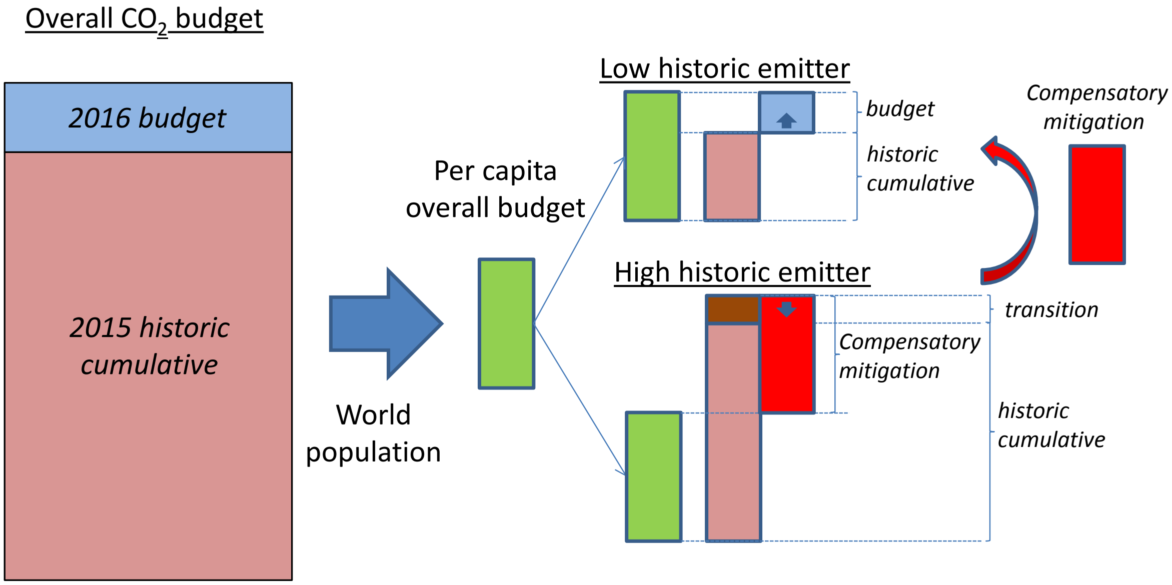

Figure 10: Basic approach for determination of fair shares of the available carbon budget, as well as the required equity compensatory mitigation.

In order to obtain an estimate of the current size of the remaining fair carbon budgets and associated compensatory obligations, we used information compiled by the Global Carbon Project **[12]** to evaluate the historic cumulative emissions from fossil fuels and cement[2] in the 10 World regions considered by IEA.

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[2] All GHG emissions should be included in the fair shares' evaluation, adding to fossil fuels and cement emissions the CO_2 emissions from LUC and using the CBW concept to include all other GHG emissions. However, we did not find comprehensive databases for cumulative historic emissions beyond those form fossil fuels combustion and cement manufacture, and therefore, for the purpose of illustrating the proposed methodology and its implications we applied it to fossil fuel and cement emissions.

Figure 11 shows the results of the historic cumulative emissions aggregated for the 10 considered World regions (the light brown bars from Figure 10), compared with the fair share per capita overall carbon budget[3] (green bar from Figure 10). As we may see there are six World regions (red bars in Figure 11) that still did not use their fair share of the carbon budget, and therefore would have a remaining fair share of carbon budget, while four World regions (yellow bars in Figure 11) already significantly exceeded their fair share of the carbon budget, and therefore have already contracted a per capita carbon debt that is of the same order of magnitude or higher than their fair share of overall carbon budget itself.

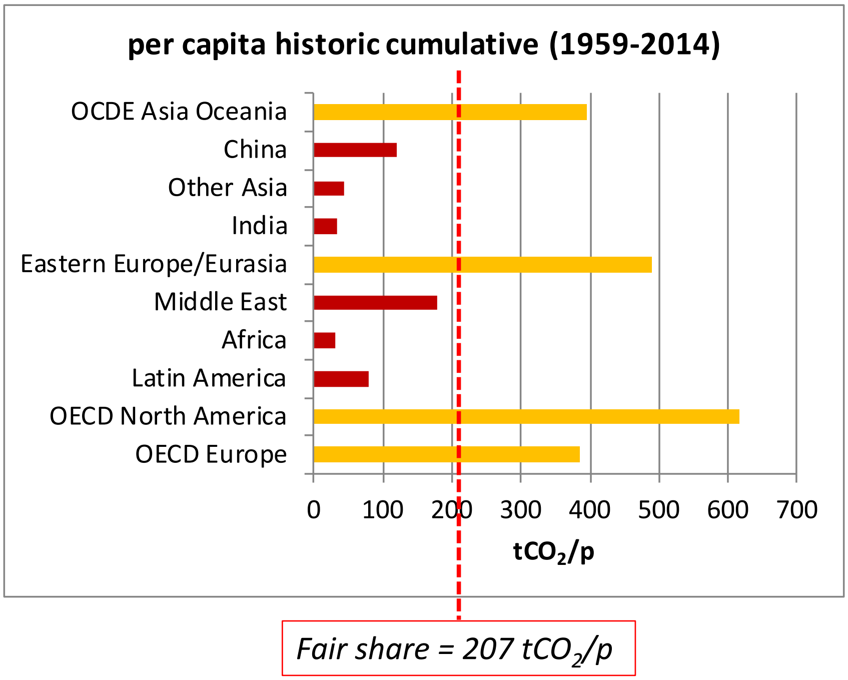

Figure 11: Comparing historic cumulative emissions (fossil fuels & cement) with fair share per capita budget.

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[3] Note that for a consistent approach, this fair share per capita budget makes reference also only to fossil fuels and cement emissions. In order to obtain this budget from the overall carbon budgets we assumed the LUC share is the same documented in the IPCC AR5 report for year 2010.

12 Conclusions

A transition analysis methodology has been presented which allows for a fast and flexible evaluation of the transition possibilities, requirements and implications, capturing the transition impact of potential structural changes. This transition analysis complements that of the widespread IAM and EEM scenarios by adding information about different transition paths which can inform IAM and EEM runs so that they manage to capture a wider spectrum of transition options.

The transition analysis methodology is based on an estimate of the maximum feasible transition rates to be achieved within different dimensions from our techno-economic-social systems, once potential structural changes have been taken into account. From these maximum component's transition rates, different overall transition paths are put together which embrace the different transition options that could be expected when factoring in elements like the delay in undertaking the transition and the gradualism in deploying the maximum transition rate.

Results from this transition analysis methodology applied to the whole World are presented here. The analysis aims at exploring the feasibility of still aligning our transition with the 1.5C at 50% climate goal without resorting to false solutions like CCS and nuclear energy, as well as the associated transition implications and requirements.

The transition analysis shows that as of today, in order to achieve the 1.5C at 50% climate goal, an integral transition strategy going beyond the energy system needs to be articulated, even if the maximum transition rates within the energy sector are deployed.

Mitigation in the energy system, even accounting for the impact of structural changes and considering smart energy system integration, is by itself not enough anymore for aligning the transition with the climate goal. Indeed, only in the most aggressive transition (starting in January 2017 with a sudden deployment of all the maximum transition rates) would be tightly aligned with the 1.5C at 50% likelihood climate goal. Delaying the transition or considering gradualism in the deployment of the maximum transition rate would have the energy system on its own failing to align the transition with the climate goal. Considering likelihoods of transition success above 50% would also lead to the energy system being unable on its own to facilitate a transition aligned with the climate goal.

After all these decades of extremely limited effective climate action, the transition requirements are significantly tighter and require an integral approach to align our society with the climate boundary condition. With such an integral approach, articulating a simultaneous transition with multisectoral CO_2 mitigation (energy, process-industry, agriculture and forests), adding the NNE potential from forestry and agriculture, and including the impact of non-CO_2 GHG mitigation as CBW, the transition analysis herewith presented shows that there is still room to align our transition with the climate boundary condition while keeping high likelihoods of success.

Structural changes are a must for articulating a transition with the capability to align our systems with the climate boundary condition. Integration and smartness deployment are linked to several of these structural changes. However, what underpins most of the structural changes is an evolution from representative to participative contexts, which includes politics, governance, economics, investment-finance and system's operation and definition, but also reaching out to other social dimensions like environmental organizations. Indeed, the structural limitations associated to the representative contexts, where personal and corporate limitations and interests jeopardize and block social interests, produce unsurmountable transition barriers.

The means for articulating and structuring a direct participation are nowadays available, but the structures that have been governing our systems up to today need to be rethought and reformulated to embrace the participative paradigm. And the social context is also getting ripe for this transformation: many people would like to contribute to the transition but simply are disappointed about the available options in a representative context.

Social accountability is an important element for articulating participative contexts, moving away from the current situation where individual transition contributions dilute and seem to be lost in the middle of the mainstream and dominating representative status quo. At the end of the day materializing a transition of the required dimensions can only be done adding up the contribution from each one of us (corporations and representative institutions are simply too small), assuming all the individual responsibilities in the process, and having a clear and transparent social accountability of these contributions is one of the main facilitating elements.

The transition analysis herewith presented highlights the existence and relevance of potential transition barriers directly linked to the delay in undertaking the transition up till now. A clear example of these is documented for the power sector, where potential peaks for fossil fuel and nuclear electricity generation (and their associated stranded assets) could show up as a consequence of the opposing transition trends of system integration and efficiency deployment. A novel transition analysis has been undertaken to document the dynamics at play between RES deployment and fossil fuels / nuclear phase-out, and how these could eventually evolve in the development of serious transition barriers. All of this, points to the need for smart transition planning and managing: Just undertaking any transition action won't make the trick.

Equity and fair shares are an important transition enabler. Without a clear approach to these, one of the main drivers to articulate a widespread participative transition will be just missing. Structural changes are also required here in order to effectively materialize the kind of participative collaboration that holds the key for a climate consistent global transition. And unfortunately there is no advance at all on this front, even missing effective communication to facilitate the social understanding and internalization of its relevance. Tough the equity and fair shares issue can be hugely elaborated to include many related dimensions and second derivatives, in the transition analysis herewith presented we adopted a plain and direct fundamental approach, based on a fair per capita allocation of the available carbon budget, which has the power to directly communicate and illustrate the basic fairness implications of the transition.

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