

Qualculative assemblage in French energy modelling for net zero

Authors: Alain Nadai^a, Christophe Cassen^a, Franck Lecocq^a,

Corresponding author: alain.nadai@cnr.fr

^a Centre International de Recherche sur l'Environnement et le Développement (CIRED), CNRS, EHESS, AgroParisTech, PontsParisTech, CIRAD, Nogent-sur-Marne, France

Author draft, please refer to the published version for quoting

<https://www.sciencedirect.com/science/article/abs/pii/S0016328722001653?dgcid=author>

Length : 8000 to 10 000 words, not incl. references

Abstract: 350 words (233)

The notion of Net-zero 2050 future (NZ 2050) aims at achieving a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century. This paper delves into the relation between numerical modelling, the construction of a NZ future and its performativity, by considering the recent devising of the French national low-carbon strategy (SNBC-2) (2016-2018) and related processes. SNBC-2 was the first attempt to put into calculation a 2050 NZ France, and the path towards it.

We show that, aside from setting up a collective capacity to quantify farther into the future, one major learning brought up by the French attempt at representing 2050 NZ was the limited relevance of available models for doing so - which came as a surprise. The analysis discusses these shortcomings and their meaning as to the performativity of numerical models in making 2050 NZ a doable horizon. Relying on the STS notion of 'qualculation' - which sees calculation as a process that is both qualitative and quantitative, relational and algorithmic - we underline the key and ambiguous role of non-calculative adjustments implemented to offset the calculative limitation of models. While they allow qualculation to proceed ahead in spite of models limitation, populate and organise an image of French NZ 2050, they also tend – if they are not recorded and registered - to disconnect figures from their meaning, and vision from the socio-technical networks that are supposed to make them happen. They are thus potentially a source of both gain and loss in performativity, depending on whether the qualculation process lays them bare, and allows for their critical discussion and memorization.

Key words: France - net zero emissions – modelling - performativity

Introduction

The concept of a net-zero (NZ) future has emerged in the wake of the Paris Agreement to comply with the goal of a global average temperature to no more than 1.5°C above pre-industrial levels. NZ aims at achieving a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century. This goal has penetrated national decarbonization policies under what has been called 'deep decarbonisation strategies' (DDS) (Lecocq et al., 2022).

DDS, flag radical mitigation targets¹ and are a terrain from which to explore the mutual relation between modelling and policy decision. Radical targets such as 2050 NZ can emerge from modelling exercises, as has been the case with bioenergy with CCS (BECCS), and get on to the political agenda (Laren & Markusson, 2020). They also can stem from a political process and impose themselves to the modelling community, as did, for instance, 2050 carbon neutrality on the French mitigation agenda in the wake of the Paris Agreement².

The impact of such a radical shift in political agenda on the way modelling is organised and practiced is an occasion to explore farther the mutual relation between modelling and policy devising. This relation has been a subject of concern for both social scientists interested in the roles that model can play in the construction of low carbon futures and scientists involved in these processes (Edenhofer & Minx, 2014). A significant part of the literature has focused on the critic of IAMs (for an overview see Ellenbeck, 2019) and their role in policy making, notably as black boxes encapsulating built in political bias and influencing political decisions ('political machine') or heuristic devices for exploring and understanding options ('talking points') (Edenhofer & Kowarsch, 2015; Haikola et al, 2019). As far as, techno-economic models are concerned, analyses have pointed out different roles that they can play in the devising of low carbon energy policy, and notably their performative potential, as discursive or material settings, and predictive assemblages that compete for weighing on national climate-energy policies (Aykut, 2019).

This paper delves into the relation between numerical modelling, the construction of a NZ future and its performativity, by considering the recent devising of the French national low-carbon strategy (SNBC-2) (2016-2018) and related processes. SNBC-2 was the first attempt to put into calculation a 2050 NZ France, and the path towards it.

Performativity (Callon, 2007 ; MacKenzie, 2007) refers to a circular and dynamic relation between theory – modelling and economic theory in our case study – and the realm that it pictures (2050 NZ future). It means that the relevance of French 2050 NZ modelling and the advent of this future are regarded as co-dependent. Modelling this future is an algorithmic and relational process, which contributes in assembling all the elements which may compose this future, or in making them emerge, for instance by steering policy processes. Conversely, the progressive emergence of this relational assemblage is what ultimately makes modelling relevant, not because modelling would predict this future but because it takes part in its emergence.

Analysing the performativity of French NZ 2050 modelling thus means analysing both the calculative and the dynamic relational work of modelling, in order to capture the degree of enrolment in and understanding about the future that it brings forth. In order to do so, we rely on the notion of qualculation which sees calculation as a process that is both qualitative and quantitative, relational and algorithmic (Cochoy, 2002 ; Callon and Law, 2005)

We show that, aside from the setting up of a collective capacity to quantify farther into the future, one major learning brought up by the French attempt at qualculating 2050 NZ was the limited relevance of available models for doing so - which came as a surprise. The analysis discusses these shortcomings and their meaning as to the feasibility of a 2050 NZ future. It also underlines the key role of the adjustments implemented to offset the resulting limitation in computation. While often *ad hoc*, not easy to trace back nor amenable to discussion and critic, they nonetheless granted continuity in the

¹ Division by four of greenhouse gases emissions related to a base year or a balancing of remaining emissions by sources and removals by sinks (carbon neutrality)

² 2050 Carbon neutrality was inscribed in the French Plan Climat in 2017.

process and made possible the pursuit of the re-tuning between models and the new political horizon. They should thus be regarded as part and parcel of the modelling assemblage.

We first present the material and method. We then detail the devising of 2050 carbon neutral France and its purported outcomes. Finally, we discuss the performativity of this process.

1. Material and method

Devising 2050 NZ France

The exploration and the devising of a path to a 2050 NZ France has developed at the crossroads of several institutional processes.

The first one is the periodic devising, since the 2015 French Law for the Energy Transition and Green Growth (LTECV), of a long term (2050) national low-carbon strategy including carbon budgets (Stratégie Nationale Bas Carbone [SNBC]) and a short-term (2030) energy policy planning (PPE), which elaborations run in parallel every five years. SNBC and PPE are overseen, respectively, by the environment and the energy branches of the energy and climate department (DGEC) at the French Ministry of the Environment. PPE is submitted to institutionalised public debate. It is closely watched after by stakeholders from the energy sector, because it impacts their current activity. The French SNBC, on the contrary does not have a binding legal status. Yet, its mere existence sets it as a counterpoint to short-term energy policy planning, and forces PPE to explain its coherence with long term Emissions targets. It also is referred to by the French High Council on Climate (HCC) in formulating its recommendation to the government³. Since the summer of 2017, as the objective of long term carbon neutrality (2050 CN) has been embedded into law with the adoption of National Climate Plan, the second SNBC (SNBC-2, 2017 -2019) has been devised according to this new political target.

The second institutional process – known as the ‘Quinet’ commissions (Quinet, 2009, 2019)⁴ - has been the progressive devising of a long term path for the social cost of carbon (SCC), understood as the maximum socially acceptable value for decarbonisation to be accounted for in public policy. Two successive commissions have tailored this cost to the ongoing political target, 2030 Factor 4 in 2009 (F4, dividing by four of carbon emissions in 2030 relative to present) (Quinet, 2009) and 2050 NZ in 2019 (‘net zero’ – i.e., remaining emissions are balanced by removals) (Quinet-2, Q2) (Quinet, 2019).

As a consequence of these agendas, SNBC-2/PPE2 and Q2 have run in parallel in 2018-2019, all with 2050 NZ in view, which was a premiere. They were partly articulated and looped together : the former gathered and articulated a technological path to 2050 NZ and extracted decarbonisation costs, which the latter used as an input in adjusting a SCC path, then passing the SCC cost path back to the former to adjust a new the technological path (cf. Figure 1).

³ https://www.hautconseilclimat.fr/wp-content/uploads/2021/02/hcc_avis_pjl_recommandations.pdf

The High Council on Climate (HCC) is an independent body established by the Decree of 14 May 2019. It is tasked with issuing advice and recommendations to the Government on the implementation of public measures and policies to reduce France's greenhouse gas emissions, in keeping with its international pledges – in particular the Paris Agreement and target to achieve carbon neutrality by 2050. Its purpose is to provide independent, neutral insights on government policy and its socio-economic and environmental impacts. <https://www.hautconseilclimat.fr/en/>

⁴ From the name of the macro-economist Alain Quinet, who has chaired the two successive commissions (2009, 2019) in charge of calculating this cost and its evolution in the future.

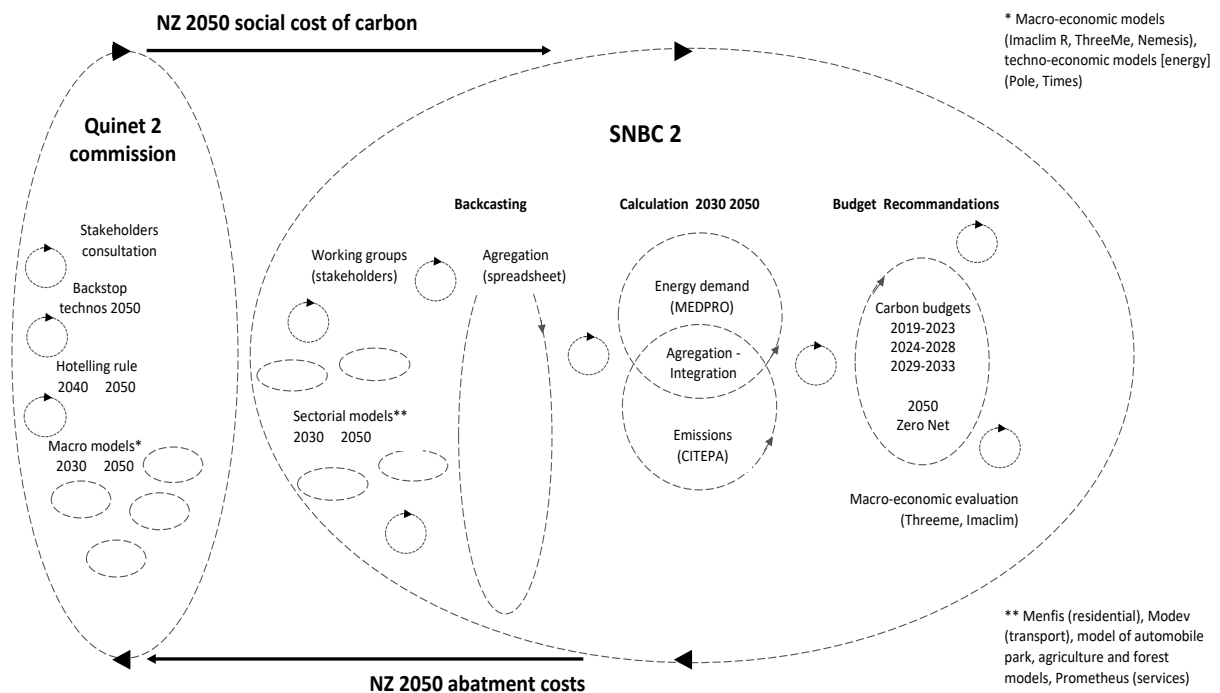


Figure 1 : SNBC-2 / Quinet-2 modelling assemblage⁵

The process thus brought together a large array of models – both techno-economic and macro – articulated through various aggregating devices (e.g. manual spreadsheet, quantitative computational model ...), economic theory and working groups, and involving different branches of the French administration, including Energy (PPE) and Climate (SNBC) services of the Ministry of the Environment, as well as the Ministry of Economy and Treasury (Quinet).

Qualculative assemblage

The literature about techno-economic modelling practices has mostly addressed single-model exercises (for a discussion of this, see Lecocq et al., 2022). The notion of assemblage (Callon, 1986; Walker and Day, 2013) is interesting in order to capture this type of SNBC-2 / Quinet-2 setting because it allows putting the emphasis on the relational dimension of such multi-model settings. The way in which relations are organised is key for the way in which models and protagonists perform in modelling assemblages. Anthropology and STS have pointed out the multiple roles that models can play, for instance as mediators that not only translate theories but have a certain autonomy in representing the economy (Morgan and Morrisson, 1999), or as black boxes enforcing technocratic values and ways of knowing (Wynne, 1984; Jasanoff, 2010).

Our interest here is in specifying the role that model play when modelling an uncharted political horizon (NZ 2050), partly in articulation with (rather abstract) economic thinking (Hotelling rule, calculation of SCC), and the type of performativity that this brings forth. Because NZ 2050 was a much more ambitious target than the F4 horizon, the macro models involved in the Quinet-2 process were forced out of their domain of relevance. Techno-economic models involved in SNBC-2 had thus to offset for the lack of macro-image of 2050 NZ France coming from macro models involved in the Quinet-2 Commission and to produce this image themselves, before charting the path to it.

⁵ CITEPA is a French interprofessional technical center working in the field of air pollution, commissioned to calculate the SNBC-2 aggregated GHG emissions. MEDPRO is developed by a private company, commissioned to aggregate sectorial demand for the SNBC-2.

In such an unsettled situation, a puzzling dimension of the process and assemblage has been its capacity to pursue with calculation. Some factors seem to have contributed in maintaining this capacity to proceed ahead. For instance, the dual status – both singular/qualitative and objective/quantitative - conferred to models and their outcomes (costs, scenarios), allowed stabilising and circulating outcomes (as quantities) while detaching them from the uncertainties underlying their production. The dispatching of modelling capacities also allowed for *ad hoc* adjustments to be implemented in certain parts of the assemblage, in order to offset models limitations, while proceeding ahead with the overall imperative of producing and quantifying a future.

We propose to capture this mix of algorithmic and relational operations through the notion of *qualculation*. The notion was first coined by Cochoy to critic the economic (rational) model of consumer choice and acknowledge the emotional role of packaging in this choice (Cochoy, 2002). It was then extended to a more general approach of calculation (Callon and Law, 2005 ; Callon and Muniesa, 2003). This broadened vision of calculation draws attention to the importance of the "qualitative" work (selection and detachment of entities, classification and linking, etc.) that prepares and frames the manipulation of quantities, as well as to the role of material devices (spreadsheets, accounts, models) in the constitution of common "qualculation spaces" in which quantities can be circulated and compared. Qualculation also allows acknowledging the fact that, alike models, figures such as costs have a dual existence. They are qualitative figures referring to a singular set of assumptions and relations between entities – the calculations of technological costs rely on assumptions about the perimeter and the environment of the concerned technology – as well as quantitative figures allowing for mathematical manipulations. They can thus be constructed in relation to qualitative sets of relations, extracted as quantities, circulated and processed anew as inputs in other qualculative spaces.

Performativity

Central to economic sociology and the sociology of models is the idea that models and economics perform the economy. The notion has triggered a lot of debates (Callon, 2005 ; Mackenzie, D. 2007). We rely on a basic definition (Çalışkan and Callon, 2009) referring to a circular and dynamic relation between theory – modelling and economic theory in our case study – and the realm that it pictures (2050 NZ future). Modelling a future thus contributes in gathering and assembling the know-how, actors and artefacts that are supposed to compose this future, or in making them emerge, if only by steering policy processes. Conversely, the progressive emergence of this relational assemblage is what ultimately makes modelling relevant, not because modelling would predict this future but because it takes part in its emergence. As Callon puts it : ‘Emphasizing the role of materialities - or of what I call sociotechnical agencements⁶ - leads to the notion of performation. Statements and their world are caught in a process of coevolution’ (Callon, 2007: 329). Performativity is about this capacity to imagine and actually entice such sociotechnical assemblages to emerge, while producing the image of this future. It is about keeping an articulation between the production of knowledge about this future (a scenario) and the production of this future (e.g. the actors, the technologies, the social relations which will underlay this future ...).

Keeping such an articulation relies on the possibility for actors who may contribute to the emergence of this future, to share an understanding of the way in which knowledge is being produced. It also relies on enabling models to coherently produce, individually or collectively, an image of the future. The issue is all the more critical in our case study that macro models involved in the Quinet-2 Commission

⁶ Callon uses the term of agencement to emphasize the material dimension and the collective agency brought forth by sociotechnical assemblages (Callon, 2008).

have been brought out of their domain of relevance by the NZ target. Analysing the performativity of French NZ 2050 modelling thus means analysing both the calculative and the dynamic, relational work of modelling, in order to capture the degree of enrolment in and understanding about the future that it brings forth.

Material

Our analysis relies on a qualitative study combining document analysis and interviews undertaken in 2019 and 2020 with modellers, policy officers, energy consultants and experts who had been involved in at least one of the two related processes under consideration (See Appendix 1)⁷. As shown in figure 1, these processes are interrelated through exchanging and reciprocally proceeding their outcomes (SCC, technology portfolios) so that they jointly take part into the process of modelling French 2050 NZ. Each of these processes also stages a version of a difficulty to represent and reach French 2050 NZ. We analyse each of them and its challenge, and the articulation of these challenges.

2. Assembling a 2050 NZ France

Emergence and institutionalisation of 2050 NZ

The preparation of the SNBC-2 was launched in 2017, but the work process, which began in the spring, only unfolded when thematic groups were set up in the autumn. The Government's Climate Plan was presented by Nicolas Hulot, Minister for Ecological and Solidarity Transition, on 6 July 2017. It aims to mobilise all ministries to accelerate the energy and climate transition and the implementation of the Paris Agreement. The latter sets an ambition of carbon neutrality by 2050.

Only two months after the presidential election, the legal inscription of NZ 2050 in the Climate Plan was a genuine shock in the corridor of the DGEC [4,12]. In spite of its inclusion in the Paris agreement since 2015, nobody had prepared to it. It was thought that international carbon compensation to bridge the gap between F4 and NZ [4]. Only its sudden inclusion in the Climate Plan made it into a tangible national target to account for.

As a matter of fact, from autumn 2017, NZ 2050 is relayed by the Bureau for Climate Change Mitigation (DLES, within DGEC) for the preparation of the SNBC-2.

The SNBC-2 process, collecting relevant technologies

In the construction of SNBC-1 in 2015, the DGEC at the Ministry for the Environment outsourced the development of the underlying numerical scenario to a private consultancy. The revision of SNBC and PPE was based on an assessment of their first version (SNBC-1 and PPE1). Two bodies were involved in this review: an expert committee (CETE), endorsing a methodological role, and a consultative body (CNTE) represented by a committee (CIO) endorsing a steering role⁸.

For SNBC-2, by contrast to SNBC-1, DGEC brought together a wide array of models, controlled by several public agencies and loosely coupled together. Working in a condensed timeframe (Spring 2016 – Autumn 2018), they produced a unique scenario, which served as the backbone of SNBC-2.

⁷ Sources of assertions are indicated in the text into bracket [] by the interview number.

⁸ The Committee of Experts for the Energy Transition (CETE) is an expert committee set up by the LTECV, and is in charge of producing advices about the content and implementation of carbon budgets, SNBC and PPE. The National Council for Ecological Transition (CNTE) is consulted on draft laws concerning the environment or energy (CNTE, <https://www.ecologique-solidaire.gouv.fr/cnte>). It is composed of representatives of different segments of civil society. The CIO is composed of a large part of CNTE members as well as of relevant organisations and individuals (e.g. Entreprises pour l'Environnement).

DGEC changed methodology because of limited funding. Outsourcing was also regarded as hampering capitalisation of expertise within the administration, and as lacking agility when it came to interacting, internally, with the ministerial cabinet [1]. SNBC-2 was also marked by reinforced mitigation ambition, from 2050 F4 to 'net zero'. Though the initial political demand did not specify the allowable amount of remaining emissions in 2050, it was widely understood that it would be lower than the target of SNBC-1. Additionally, one ambition at DGEC was to extend the horizon of quantification, which had only been developed until 2035 in SNBC-1 : the 2035-2050 projection had remained qualitative.

The initial plan (Figure 1) was to simulate the 2050 "net zero" horizon with macroeconomic models to frame runs of sectorial techno-economic models, the outcomes of which (in 2030 and 2050) would be aggregated using the multi-sectorial MEDPRO model and translated into a set of intermediary emissions targets consistent with the net zero objective in 2050. Last, a macroeconomic evaluation of the SNBC would be performed to inform policy recommendations. The 2030 outcomes would be based on the full implementation of existing (but not yet necessarily implemented) policy measures (EPM); while 2050 would include supplementary policy measures (SPM), not yet adopted but deemed necessary to meet neutrality.

Things did not unfold according to plan, however, as the macro-models produced extreme pictures of a net zero France in 2050 (sky-rocketing energy prices, de-structured industries, etc (September 2017) These could not be interpreted easily as the models, mostly designed for the F4 type of mitigation, appeared to be beyond their domain of validity with the net zero objective. DGEC thus decided to shift to a three-step 'backcasting' exercise as follows [1]. The first step was to construct a technical image of a "carbon neutral" France in 2050 and the associated sectorial targets. This image was elaborated by calculating a 2030 target based on EPM, and then a 2050 target based on SPM. Both of them were elaborated based on available scenarios and expert judgement (September 2017 - December 2017). This preliminary image of 2050 NZ was discussed within DGEC, between the technical and political branch (Minister Cabinet), adjusted internally and with other ministries (December 2017 - April 2018), before being discussed with stakeholders, within the CIO (April 2018). The second step was to work with modellers and sectorial groups (including stakeholders), in order to adjust the 2020-2050 mitigation pathway to reach the 2050 goal defined in the first step (May 2018). The third step included calculating and aggregating the physical and emissions scenarios, and the emissions budgets corresponding to this trajectory (Summer-Autumn 2018). The SNBC-2 scenarios were released in December 2019, after what a macro-economic assessment of them was commissioned (December 2018 - December 2019).

The exercise proved challenging in several ways. As of the fall 2017, when macro models did not deliver their expected outcomes, DGEC was clearly short of time to implement the new 'backcasting' methodology [QD]. Albeit a stakeholders consultation had been run in order to gather suggestions of long term policy measures, the resulting list did not help to think of a long term horizon in one go. This seemed only possible by asking some actors - especially those having developed scenarios such as ADEME, CGDD, negaWatt⁹ - about their 2030 and 2050 visions for the future, and then reasoning quantitatively about global sectorial targets (50% reduction in agriculture, zero emission in the energy sector ..) [1,5].

⁹ Ademe : French Energy Agency, has developed the ThreeMe Keynesian macro model.

CGDD : General Commission for Sustainable Development, within the French Ministry of the Environment, developing the Titan multi-sectorial model.

Negawatt : NGO specialised on energy issues, has developed the negawatt model, a technical-physical model incorporating assumptions about low-carbon ways of living.

The reduced timeframe also forced DGEC to become more involved in the management of the sectorial stakeholders working groups. Regular working group meetings (about 35 in total) contributed to building relationships among stakeholders, but also with the other ministries and the ministerial services at DGEC. This was necessary to gather views and reaction about what seemed doable, and to adjust accordingly and produce sectorial sheets that could be discussed within the April 2018 CIO [1]. While this involved one or two model(s) per sector (starting March 2018), modellers were not really part of the working groups [2, 5]. They were often, but not always, invited to present their results to the working groups, DGEC *de facto* becoming the nodal point for the relationships between modellers and experts [1, 2,5]. Within this organisation, modellers could not always grasp the meaning of their contribution to the whole process nor make sense of the trial-and-error iterations at work between DGEC and other stakeholders [2].

The limited sub-contracting budget also led DGEC to wait until late in the process before directing MEDPRO (run by a private consultancy) to aggregate the results of the sectorial models. Intermediary aggregations proved necessary, notably to answer political demands and exchange with the political branch within DGEC. These ended being run by DGEC officers using an ad hoc spreadsheet-based dashboard they had developed. This became highly challenging when it came to aggregating not just 2050 end points, but also entire trajectories manually and under significant time pressure [1].

At the end of the process, it appeared that the 2030 emissions derived from the PPE were higher than the 2030 emissions in the SNBC. Negotiations between the parties involved eventually led to an upward revision of the SNBC emissions trajectory to fit with PPE data. The revision was forced into some of the sectorial models by playing with economic variables (adjusting discount rate) [2].

Importantly, as the modelling assemblage developed, the communication between the technical and political branches of the French Ministry of Environment also became difficult, raising a transparency issue. As political measures had to be translated into proxies in some models, it became increasingly hard to convey, in simple terms, the complex web of proxies and technicalities that had been incorporated into the models to reach the decarbonisation targets [1]. In the end, technical adjustments that the modellers deemed worthy of noting were not necessarily explained nor recorded.

The SNBC-2 process marked an unprecedented progress in assembling models and calculating the future. It included a significant amount of *ad hoc* computational (excel template, discount rates, CO2 sinks) and relational (initial guesstimate) adjustments to offset limits in calculation and answer tensions. While these were not necessarily recorded, which limited the possibility of shared understanding, they allowed pursuing with the devising of 2050 NZ. They thus seemed key, notably in order to face the difficulties incurred by macro-models at the outset of the process, in the Quinet-2 commission.

The Quinet-2 commission, extracting a social cost of carbon

The social cost of carbon (SCC) is the value that society associates with decarbonization. It measures, in monetary terms, the value attached by society to getting rid of one additional ton of carbon dioxide. This value can be assessed at any point in the future. It can be produced by a model, but it can also be agreed upon, through stakeholders consultation, based on a range of information, including calculation(s) by model(s).

Not all countries use SCC as a steering value. US and France do. EU does not and favours a sectorial approach to decarbonisation by fear of a downward harmonization effect (agreement on the lowest CSC) [7], which as such betrays the steering power conferred to its use. As a matter of fact, once adopted, SCC is a circulating norm that should be accounted for in any policy decision.

In the case of the Quinet commission, SCC is neither a carbon tax nor a value to be imposed for the carbon tax. The value is aimed at being used as a shadow price to steer decarbonisation policy – i.e. as a cap on decarbonisation cost. Policies relying on SCC should only support projects that have a decarbonisation cost inferior to it. Accordingly, NZ scenarios may only include technologies with decarbonisation cost slower than SCC, which was the reason why SNBC-2 also had to account for it.

In France, SCC has been evaluated on several occasions, starting in 2001 in relation to transport infrastructure investments¹⁰. This value was then updated in 2009 by the Quinet-1 commission¹¹, when the F4 referential had been embedded into law (2005)¹² and the Grenelle Forum for the Environment (2007-2009) had reaffirmed France's commitment to fighting against climate change. In 2017, Treasury officers had mentioned their difficulty to picture NZ 2050 in their model, based on the then ongoing value of SCC. They asked DGEC for a SCC update to NZ 2050 [7]. In 2019, the Quinet-2 commission was set up to do so and assess the SCC to be accounted for in SNBC-2.

Thus, SNBC-2 and Quinet-2 were supposed to work jointly (Cf. Figure 1). Quinet-2 was meant to provide SNBC-2 with a SCC value curve (from now until 2050), which would allow SNBC-2 modellers to determine relevant decarbonisation technology roadmaps, that they would feed back into Quinet-2 to allow for the finetuning of SCC assessment. And so on. In spite of many exchanges between SNBC-2 and Quinet-2 about technology roadmaps – especially as carbon sinks were repeatedly adjusted in the SNBC-2 – SNBC-2 ended before Quinet-2 and adjusted only one time to the Quinet-2 outcome [7].

The Quinet-2 commission gathered three macro-economic models and two technico-economic models, each with a singular architecture and purpose (Cf. Appendix 2). SNBC-2 technological roadmaps were used to harmonize assumptions and allow comparing models outcomes. Translating roadmaps seemed easy for technoeconomic models (including technological costs) but less for macro-economic models, which required interpreting things in term of elasticities. The meaning, if not the feasibility, of comparing outcomes from such different models seemed debatable [8, 9]. Each model had its own architecture and generated outcomes that, albeit commensurable, had singular meanings – for instance, prices came out of macroeconomic models whereas techno-economic models generated marginal costs (i.e the economic value of additional decarbonization efforts) [9]. In spite of this, the commission brought outcomes on a single chart, which displayed convergence until a F4-2030 point, and divergence beyond (Quinet, 2019: 98) (Cf. Figure 2). Pre-2035 convergence was interpreted as a confirmation of the SCC value. Divergence was of two types [12]: first, for each individual model, attempts at reaching NZ 2050 led to bursting energy prices and the downfall of industry ; second, models outcomes were not converging altogether towards the same value, especially after 2040. Attempts were made at tinkering with carbon sinks in SNBC-2 in order to soften the decarbonisation constraint and overcome divergence, before admitting that divergence related to a structural problem in the models : they were made for F4 and not beyond [9].

¹⁰ In 2001, the Commission "Transport: choice of investments and cost of nuisances" chaired by Marcel Boiteux recommended a reference value for CO₂ of 27 €/ t CO₂ (corresponding to a carbon value of 100 euros per ton).

¹¹

¹² POPE Law, 2007, <https://www.legifrance.gouv.fr/loda/id/JORFTEXT000000813253/>

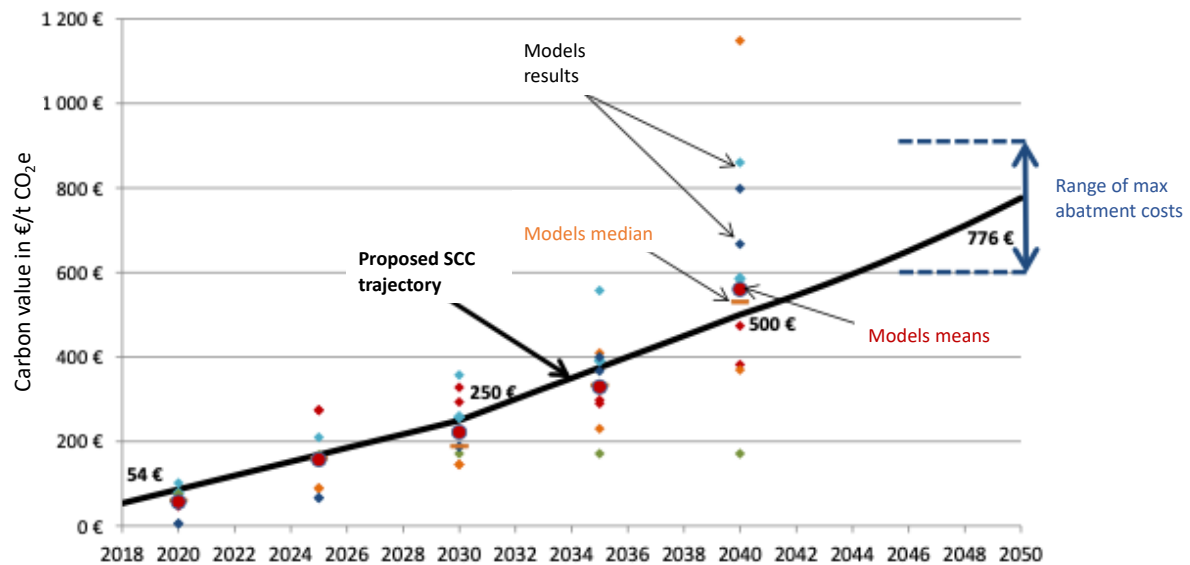


Figure 2 : CSS trajectory (source : Quinet A. 2019 : 122).

The discussion then turned to address ways to offset the lack of relevant model outcomes. Using the Hotelling rule seemed an usual candidate, albeit debated (Gaspard & Missemmer, 2022). This rule prescribes equating the rate of evolution of SCC with the discount rate until 2050, so that there is no incentive to postpone CO₂ emissions : from today's perspective, emitting a ton of CO₂ in the future is worth exactly the same as emitting a ton of CO₂ today.

The question however emerged about how to adjust the curve, so to bridge the gap between the 2030 F4 point and possible backstop technologies in 2050. Hearings and technology reviews about technologies for 2050 was undertaken – or, as one interviewee puts it, ‘a bit more of a guesstimate approach, one that relies on the expertise of engineers [...]’- and allowed ‘setting a point on the horizon’ [9] . It did not point to genuine ‘backstop’ technologies (allowing to do without fossil energies for a stabilized cost) but to a portfolio of technologies including a more extensive use of decarbonized electricity and hydrogen produced in a decarbonized manner by water electrolysis (Quinet, 2009: 23), and suggested orders of magnitude around 600 to 900€/ton CO₂. Last, a negotiation with stakeholders, mostly worried about CSS being distinct from a carbon tax as the Gilets Jaunes were demonstrating [7], decided on the final value of CCS - 250€₂₀₁₈ /ton CO₂ for 2030 - which allowed bridging the 600 to 900€/ton CO₂ target in 2050 with a hotelling rule calculation at 4,5% discount. Eventually, the commission endorsed a storytelling that was rationalising the final trajectory as a result of both modelling until 2030 and technological prospective [7], accounting for “stronger international cooperation, accelerating the production and dissemination of innovations, and making disruptive technologies possible.” (Quinet 2019 : 11).

Alike SNBC-2, the Quinet-2 process suffered from limitations in calculation, since these originated in the macro-models it gathered. It also reacted to models divergence through adjustments (exploring carbon sinks, recursing to Hotelling rule and backstop proxies), but these ended up being more clearly scripted in a story telling which acknowledged model divergence and explained the choice made.

The looping between SNBC-2 and commission Quinet-2 was however important in allowing qualculation to proceed ahead. Macro models invoked the unification of their technological assumptions (drawn from SNBC-2 work of assembling technological scenarios) as a pledge of scientific quality in the collective production of SCC. SNBC-2 protagonists invoked, on their side, their alignment with the SCC value stemming from Quinet-2 macro-models, as a factor of coherence in devising their

2050 scenario. This coupling resulted in each of the calculating spaces being legitimised by the quantitative output of the other, in a joint work of extracting a 2050 NZ future.

Purported outcomes

Interviewees have flagged a certain number of outcomes from these processes.

In the case of the SNBC-2, according to its coordinators, one main quality of the process has been to set up a modelling assemblage which allowed pushing farther the frontier of calculation, from 2030 and F4 to 2050 NZ [1, 4]. Such a calculation is seen as a premiere, even if officers are aware of its incompleteness and approximation [1] : co-benefits had not been taken into account, the methodology for cost calculation had not been harmonised [6, 7]¹³, the challenging context (time frame, failure of macro-models, limited budget) did not allow DGEC to adjust a proper methodology. Additionally, and different from SNBC-1, no variants of scenarios had been explored in order to assess the robustness of SNBC-2 outcomes¹⁴. Setting up its own modelling assemblage was nonetheless a way for the administration to ‘capitalise’ [1, 4] on both the existing modelling capacities (by articulating them together) and the learning that can be derived from them through time. This has, indeed, contributed to latter explorations in harmonising cost calculations (France Stratégie, 2021) or in collecting information about abatement technologies in the different sectors (underway at the moment of writing, within SNBC-3). It also is perceived as a way for the technical branch within the Ministry of Environment to become more agile in communicating with the political branch (Minister cabinet).

The second outcome underlined is that such a calculation allowed the parties in both processes to gauge the extent of the challenge associated with NZ 2050. According to one coordinator of the SNBC-2 process, it showed that NZ 2050 was ‘doable on a French scale, provided relevant policy packages are set in place’ [1]. According to others, it allowed seizing the issue for the different sectors : necessity to fully decarbonise the energy sector and halve the emissions from the agricultural sector, need to recalibrate the carbon sinks (forest, agriculture) which initially were unrealistically oversized [10, 4]. The conflict with energy stakeholders about the 2030 PPE target also witnessed of the current impossibility to follow in the short term the NZ 2050 path that was proposed : it resulted in postponing the effort to the post-2030 period. While the path to 2050 NZ that was explored may only be one among potential others (no variants had been explored in this SNBC exercise), these tensions nonetheless shed light on the remaining gap to heading towards it, and challenge the capacity of SNBC to sustain a genuine commitment to NZ 2050 in the very short term [4].

3. Discussion

Overall, the outcomes flagged by actors relate to what we have called performativity. They concern the capacity of the process to dynamically articulate together the production of knowledge about a 2050 NZ future with the assemblage of a socio-technical network (knowledge, knowledge producing tools, experts and stakeholders) without which this future will never happen. Several aspects, however, deserve further discussion, when it comes to assess the performativity of the calculation that took place.

As suggested in the above, these joint-processes display both a promise – 2050 NZ, intractable beforehand, is now seen as conditionally ‘doable’ by part of the protagonists – and a difficulty,

¹³ Different from co-benefits approach, cost-efficiency does not account for the systemic impact of sectorial technological changes it only assess abatement cost in each sector.

¹⁴ Except, to a certain extent, in the ex-post macro-economic assessment of the scenario, the model Imaclim included two versions of anticipations (intertemporal and adaptative [reactive to outcomes]). [7]

In SNBC-1 two variants were shortly explored for gas and electricity in the confrontation with PPE-1 [10].

expressed by the limits of modelling and the many adjustments required to offset it. The question then comes about how to interpret these results.

The circular and dynamic nature of performativity prevents us from inferring clear cut conclusions about the doability of 2050 NZ. The point of the process is neither to freeze these dimensions nor to predict 2050 NZ : it is to explore and contribute in assembling farther the conditions for its emergence.

A key question in assembling these conditions is nonetheless the capacity of the process to advance a shared understanding of the challenge at stake. Making the ways in which models have been used and worked intelligible to as many as possible is key in this regard, as it keeps the production of the future articulated to those knowledgeable and supposed to make it happen. In what follows, we discuss three dimensions about this articulation: the intelligibility of the process, the intelligibility of the models and the meaning that actors ascribe to models divergence/convergence¹⁵.

Process intelligibility

Process intelligibility is the extent to which the process lays bare the respective role that computational and relational operations have played in the calculation.

The Quinet-2 commission was a rather simple setting : models were working in parallel and the process managed sessions where modellers could expose and discuss their models. This provided an occasion for modelers and experts to exchange about the structure, purpose and outcomes of the different models. While such an occasion was recognised as quite unusual by modelers, it was also perceived as limited by time constraints and the lack of training of non-academic participants to such exchanges [3]. Eventually, while academic participants seemed to value this exchange as a moment of objectivation, non-academic understanding proved limited when it came to discuss and interpret, later in the process, the meaning of the costs values stemming out of the different models [3]. Furthermore, the technicalities incurred in interpreting models divergence (see below) and mobilising economic theory (Hotelling rule) for the post 2030 period were not understood by all the participants, even academic [6, 7, 8].

Different from Quinet-2, the SNBC-2 process was based on a much complex assemblage. First, sectorial models were interrelated through their outcomes. Second, these were aggregated together on the go and manually in a template, which did not leave way to much discussion and transparency as to the method used. Third, there was no arena where modelers could exchange with their pairs, and discuss methods and outcomes [3]. While modellers were invited in working groups, this was to present their results to stakeholders and not to discuss methodological issues with their pairs. Only modelers or close DGEC coordinators seemed to gauge the necessary and ad hoc adjustments that had been implied in the process [4].

Overall, the technicalities of both the Quinet-2 and the SNBC-2 exercises remained understood by a limited number of participants [6, 8], be it about the ways in which to calculate decarbonisation costs [6], the way to interpret marginal costs of decarbonisation [8], the meaning of the proxies used in order to represent certain policies in sectorial models [4], or the ways in which to implement economic theory for the post 2030 period [6, 8]. As mentioned in the above, the looping between the two processes was also a source of detachment of the outcomes from their uncertainties: the overall structuration of this looping was clear and meaningful to only some of our interviewees.

¹⁵ Our vocabulary in this part is inspired by Jebeile et al. (2021), but we do not give the same meaning to notion. Jebeile et al. address the case of climate models, which are supposed to relate to and represent existing bio-physical entities and processes.

Thus, while the Quinet-2 process allowed for critical exchanges about the models and a clearer inscription of methodology and adjustments in a written report, and definitely seemed simpler and clearer than SNBC-2 in its structuration, the technicalities of both processes, the extent of adjustments and their influence on the resulting image of future remained shared by a limited circle of experts or modellers.

Models intelligibility

Models are more or less complex and have their own potential to make intelligible the way in which they relate to the processes they aim at exploring. They can, internally, script techno-economic entities and processes – including policy measures - in more or less explicit, if not accurate, ways. They can also organise their outcomes so that these can be confronted against available techno-economic knowledge and data concerning the state of economy and society. While the former is more typical of techno-economic models and the second of macro-economic ones, most models involved in the Quinet-2 process were hybrid and borrowed to both modes of intelligibility.

A series of issues have been flagged by the interviewees as regards to the capacity of models to address 20250 NZ in a way they felt intelligible. The first issue relates to the fact that none of the models involved in either SBNC-2 or Quinet-2 represented changes in ways of life or energy sufficiency, otherwise than by introducing exogenous constraints on the outcome [9]. The second issue relates to the way in which costs should be calculated and, above all the absence, at the time of SNBC-2, of shared methodology for this calculation. A commission has since then be set up to advance this point¹⁶. The third issue was that policy measures could not always be represented in techno-economic models : proxies were used to mimic them [1, 4]]. They consisted in playing on variables (e.g. technological costs, discount rates) or in forcing technological development to match desired policy objectives (e.g. for energy refurbishing) and storytelling [3]. This ended up raising transparency issues when DGEC officers had to explain to the DGEC political branch the exact content of policy packages which underlaid the scenarios [4]. Last but not least, the limitation of macro-models in representing medium and long term targets beyond F4 was an issue that limited their understanding, as the reason for such a limitation could not be clearly attributed to a cause. One interviewee invoked the reliance of these models on short term elasticities as a reason for their divergence and irrelevance in representing long term radical decarbonisation targets [9]. However, most of the models involved in the Quinet-2 process (except Nemesis) were hybrid (e.g. Imaclim), or even Keynesians (e.g. ThreeMe) : they include representations of both technologies and elasticities, or include feedback-loop between technology deployment, employment and consumption, which all together made the understanding of outcomes challenging. Models were thus not calibrated to reach NZ 2050, without the reasons for such a divergence to be clearly explicated and shared in any of the two processes.

Eventually, both processes ended up working on more abstract grounds in order to picture the post-2035 period. In SNBC-2, policy measures could hardly be envisioned as most of them had been implemented for the pre-2040 period. So for technologies, except for a few technologies – mostly hydrogen – which played the role of (fuzzy) 2050 benchmark for decarbonisation costs (abt 750€/t carbon). In both processes - SNBC-2 because of the near-exhaustion of empirical references, Quinet 2 because of the limits of macro-models – the discussion on the post-2040 period became more global, either reasoning along macro-economic optimisation (hotelling rule, 2030 stair-step effect, 2050 back-stop reference, for Quinet-2) or a rough inter-sectorial allocation of the effort (for SNBC-2). The latter was deliberately based on expert judgment, which was part of the early reversal in method, when macro-models failed to deliver long term guidance.

¹⁶ Commission Criqui, <https://www.strategie.gouv.fr/publications/couts-dabattement>, consulted April 11th, 2022.

Models relation to the future they were supposed to represent was thus mediated differently depending on the period under consideration. It was scripted in the models for the pre-2040 period but relied on a mix of expert judgement – if not guesstimate ('doigt mouillé') [1, 10] - and abstract macro-economic reasoning for the post-2040 period. The confrontation with PPE, and the adjustment of the 2030 point, proved the decisive role of talking points in triggering stakeholders concern and critic. They also showed how malleable such outcomes can be when confronted with direct political pressure.

Interviewees witnessed of a clear consciousness of the limits of the calculation undertaken, be it because of guesstimate [4] and abstract reasoning [8], or because the way in which costs were calculated had not yet been harmonised [6, 7]. They could not however always understand the reasons why calculation, at some point, became irrelevant, as well as the meaning to associate to it when it stood relevant.

Making sense of divergence, and convergence

The failure of macro-models to represent 2050 NZ made 'divergence' into a central issue. It marked a limit in the modelling of 2050 NZ which may highlight a difficulty in charting, and thus in reaching, this objective. Yet, concluding so may be hastily, as the reasons for models divergence are anything but clear. While the existence of a limit of the 'macro' models seemed logical to most interviewees [3, 7, 9, 10], the evidence that available models were all *made for* F4 2035 but not beyond, came as a surprise [10].

The term 'divergence' has a dual meaning in the interviews. For one model, depending on the interview, divergence meant the impossibility to generate realistic energy prices, or the impossibility to generate any energy price at all, for the required political objective. For a set of models, divergence meant that models produced very different energy prices. Convergence was supposed to be the symmetric of divergence.

In the Quinet-2 process, as shown by figure 2, all models seem to have produced trajectories of SCC, but not always realistic, and with very different values after 2040. Techno-economic models were said to diverge because they did not incorporate the appropriate range of technologies to reach NZ or because backstop technologies and their cost in 2050 were difficult to anticipate (endogenous technological progress was not represented in the models) [9]. While the harmonisation of technological assumptions, based on the information delivered by the SNBC-2 process, was indeed perceived as approximative [8], structural equations may also have differed between models and make them diverge. Macro-economic models were said, by one interviewee [9], to diverge because the elasticities they incorporated were benchmarked on recent, business as usual, small variations in prices and quantities, and did not allow to reach radical targets such as NZ, unless with skyrocketing energy prices. As developed in the above, several models that were not exclusively based on elasticities also produced unrealistic energy prices. Thus in both cases, the reasons for divergence do not seem to have been made sense of, at least not collectively.

The individual divergence of the models after 2035 demonstrated that they all had incorporated a F4 2040 political objective and were somewhat (out) dated. Importantly, this had an epistemological value as it witnessed of a reciprocal relation between these models and the yet prevailing political norm. Whether this meant an actual difficulty in reaching 2050 NZ is a question that at least requires tuning the models to this new norm to be answered and raises the question of the relevant process(es) to do so (make models converge again). The answers which arose in the interviews are of two types. The first possibility is academic progress as all of these models are maintained and developed by academic departments [7]. There is, indeed, a genuine international pressure on academic

departments involved in such modelling to update their models to the 2050 NZ norm, if they ambition to remain relevant in their field. The second possibility is the periodic repetition of institutional exercises and modelling arenas such as SNBC. For instance, a per-sector detailed inquiry about decarbonisation technologies and potentials is currently under way within SNBC-3, so to feed the next NZ 2050 modelling exercise. The NZ 2050 norm is thus making its way in the corridors of the high administration and the stakeholders groups, and re-aligning actors anticipations about the future.

The collective convergence of models until 2040 in the Quinet-2 exercise raised another challenge as to the intelligibility of the process. The issue touches upon the meaning of convergence. Models are paradigmatic calculative spaces. Modellers set categories, they encode the realm into a system of logical and computable relations, and derive descriptive figures.

For part of the modelers interviewed [8, 9], figures should [only] be interpreted in the light of an understanding of the categories and relations that are scripted in the model that produced them. In this respect, extracting figures and bringing them in one and the same chart, for the sake of comparison, as has been done in the Quinet-2 commission (cf. Figure 2), is problematic as it frames convergence as a quantitative issue. For some, '[this] makes the figure [...] meaningless and erases all the underlying information' [8]. Said differently, quantitative convergence is nothing but fortuitous if the reasons the models have to converge is not laid bare [8]: comparable quantitative outcomes may mean very different things depending on the model they derive from. As much as for divergence, the qualitative meaning of convergence is the only thing that can make sense of it.

For others, quantitative convergence is re-assuring when the models are very different, because differing models have few reason to converge, except for the phenomenon that they are all supposed to describe [9]. Those however warn about quantitative convergence becoming a token of consistency in modelling or co-publishing projects. Thus, according to them too, framing convergence as a quantitative issue gives way to making quantitative convergence into a proof of success or objectivity. Forcing quantitative convergence is not suitable as it carries the risks of 'autorealisation' – i.e. that models are reduced to producers of meaningless figures and lose their epistemic potential, as they guide us towards a future of figures. To a certain extent this is what Mc McLaren & Markusson (2020) emphasize in their analysis of the role of 'prevarication' technologies in the climate process, when they flag that BECCS technologies, because they were promises, and not realistic commitment to investment and action, made us postpone action once they were incorporated in the modelling of futures in order to answer the 1.5°C moto. Said differently, these promises were just figures in models and not plans about the future.

These considerations suggest that the performativity of modelling is conditioned upon keeping figures related to the meaning out of which they derive *and* keeping this meaning related to the socio-technical networks supposed to make it happen (Cf. Figure 3). Making sense of models convergence and/or divergence takes part into performativity because it is part and parcel of the relational chain that goes from figures to objects, from quantitative visions to socio-technical networks.

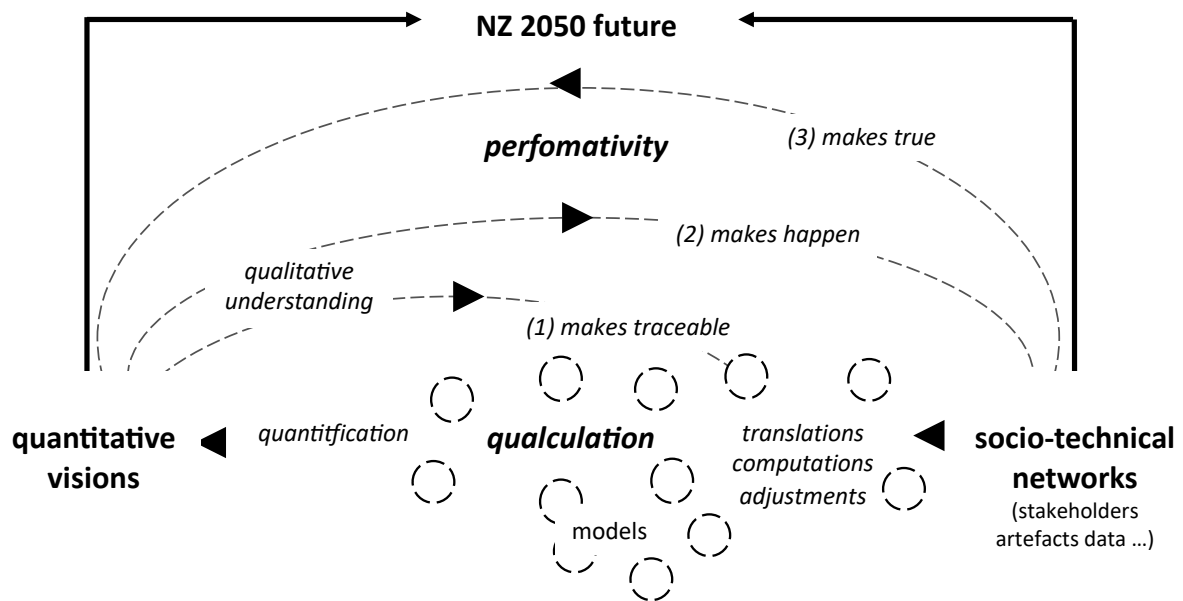


Figure 3 : Performativity and the qualculation of 2050 NZ

Akin to the Latourian pedofil¹⁷ de Boavsita for pedology which maps the fieldwork in order to keep data associated with space and soil as they travel from the Amazonian forest to the scientific laboratory (Latour, 1995), the qualitative understanding of convergence / divergence is the thread that keeps figures related with their qualculation space and object. In our case, however, it has a double function : it makes quantitative visions traceable back to the models, translations, computations and adjustments from which they derive (as does the pedofil) ((1) in fig.3) ; it also keeps these visions related to the socio-technical networks that are supposed to make them happen ((2) in fig.3) (and to ultimately confirm that these visions were true ((3) in fig.3)).

This suggests that the performativity of modelling is brought into tension between two ways of assembling the future : unifying outcomes (around quantities) or multiplying visions (around qualitative and relational understandings). It shows that, while models are aimed at quantifying, qualitative understanding is decisive for them to be performative. Modellers know it. The practice of variants and sensibility analysis, has been a field of intense innovation and sophistication over the past two decades (Lecocq et al, 2019). They consist in exploring the space of possible trajectories for one and the same model [8] by : scanning the possible values for uncertain input parameters, relating divergence to variations in parameters, and exploring the robustness of trajectories. They thus produce qualitative meaning out of quantitative iterations. Interestingly, sensibility analysis has recently reached a genuine computational dimension by which qualitative insight about the robustness of scenarios are derived from highly quantitative explorations (e.g. Guivarch et al., 2022).

If anything, these considerations about convergence and divergence tell us that what ideally missed in both the Quinet-2 and SNBC-2 processes was means and time to deploy variants because variants allow interpreting quantities within their own field of qualitative relations. The issue is whether the complexity of multi-model assemblages such as SNBC-2 allow for the practice of variants. As multiple models are involved in one and the same scenario, it might become difficult to draw inferences from comparing variants. One should also note here that the issue of quantitative convergence and

¹⁷ To put it in a nutshell, the pedofil is a thin thread that pedologist use to map the area of soil they study and locate the sample they take to laboratory.

epistemic performativity arose in the interview as regards to Quinet-2, because this process allowed for the confrontation, exchange and mutual criticism between modelers and models. The SNBC-2 process, however did recourse to quantitative forcing to match targets – for instance, in playing with discount rates - but did not allow for reciprocal confrontation and criticism, because of its complex organisation.

Conclusion

NZ has been introduced in French decarbonisation policy making through two joint-processes: SNBC-2 and the Quinet-2 Commission. Together, these processes display both a promise and a difficulty. Both processes made advances in calculating for the long term and French 2050 NZ, once thought intractable by the high administration, is now regarded as conditionally 'doable' by part of the French policy makers. With regard to the difficulty, both processes demonstrated that models were (out)dated and - at least temporarily - irrelevant to chart this objective, betraying a gap between the current state of representation of our economic / sociotechnical system and the desired future. Interestingly, this difficulty also shows that the relation between models and policy making is somewhat reciprocal : as models do incorporate a form of politics they can be challenged by upcoming political objectives.

The detailed analysis of these processes does not allow deriving clear cut conclusions about the doability of French 2050 NZ. This is not surprising as the purpose of these processes is performative : it is to contribute in assembling the conditions for its emergence, conditions which are not necessarily yet there nor assembled in readable manner. Analysing these processes as exercises in performing this future through calculative and non-calculative operations (qualculation), allows us to derive a few conclusions as regards to the role of models and their performativity in these processes.

First, models and thus 2050 NZ performativity is tightly related to a qualitative understanding of models quantitative outcomes because this understanding is what relates figures with both the models from which they originate and the socio-technical networks that are supposed to make these visions happen.

Second, many non-calculative adjustments have been required in both processes to offset calculative limitation. These adjustments have a decisive but ambiguous function as regards to performativity. On the one hand, they play a key role in sustaining performativity because they offset shortage in calculation and allow qualculation to proceed ahead. The qualculative assemblage can thus pursue its work of populating and organising an image of French NZ 2050, and of confronting academic and institutional actors with this perspective. Non-calculative adjustments thus give models a chance to be re-adjusted in time through further inquiry (on technologies) and methodological improvement (in cost calculation), as SNBC qualculation will periodically repeat. On the other hand, these adjustments are a source of loss in performativity if they are not explained or recorded, because they then limit the qualitative understanding of outcomes, and tend to disconnect figures from their origin, vision from the socio-technical networks that are supposed to make them happen.

Third, unsurprisingly, whatever the model under consideration, 2050 NZ paths are based on more abstract grounds when it comes to the post-2040 period, which becomes a malleable recipient for (pre-2040) unsolved decarbonisation. This somewhat echoes lessons about the role of 'technologies of prevarication' in the evolution of climate mitigation targets. Furthermore, as ways of living and energy sufficiency were not represented in any of the Quinet-2 and SNBC-2 models, the process has a bias towards and limitation to technological solutions. This limits their ability to address the short term

decarbonisation objectives and makes the tensions over the tangible 2030 talking point even more intense, as witnessed by the confrontation with PPE.

Last but not least, all of this depends a lot on how the calculating processes are organized and whether they set conditions for a critical dialog about quantitative outcomes to take place. From this point of view we saw that both processes raised challenges as to the way in which they proceeded outcomes (convergence / divergence), and that the circles having a full-enough understanding of the way in which shortages in calculation were overcome, are not very large. The Quinet-2 process, however, because it was simpler in its organisation and brought models side-to-side in a similar exercise, allowed for a better confrontation, critic and recording of the path taken and of the choices made.

Acknowledgments

The authors gratefully thank the funding of ADEME as part of the 'State of the art of prospective modeling' (contract n° 18MAR000099186715) and the chair Long term modeling for Sustainable Development (ENPC- Mines Paristech) for its support.

References

- Aykut, S.C. 2019. Reassembling Energy Policy. Models, Forecasts and Policy Change in Germany and France. *Science and Technology Studies*. 32(4), 13-35. DOI: 10.23987/sts.65324.
- Çalışkan, Koray, and Michel Callon, M. 2009. "Economization, part 1: shifting attention from the economy towards processes of economization." *Economy and Society* 38, no.3 (2009) : 369–398.
- Callon M. et Muniesa F. 2003. Les marchés économiques comme dispositifs collectifs de calcul, *Réseaux* 2003/6, n°122, p. 189-233.
- Callon, M., Law J. 2005. "On qualculation, agency, and otherness", *Environment and Planning D: Society and Space* 2005, volume 23, pages 717-733, DOI:10.1068/d343t
- Callon, M. 1986. "Some Elements of a Sociology of Translation: Domestication of the Scallops and the Fishermen of St. Brieuc Bay." In *Power, Action, and Belief: A New Sociology of Knowledge?* Edited by John Law, 196–222. London: Routledge.
- Callon, M. 2005. Why Virtualism Paves the Way to Political Impotence: A Reply to Daniel Miller's Critique of The Laws of the Markets. *Economic, Sociology European Electronic Newsletter* 6(2): 3–20.
- Callon, M. 2007 "What Does It Mean to Say That Economics Is Performative?" In *Do economists make markets? On the performativity of economics*. Edited by Donald MacKenzie, Fabian Muniesa and Lucia Siu, 311–357. Princeton, NJ: Princeton University Press.
- Callon, M. 2008. "Economic Markets and the Rise of Interactive Agencements: From Prosthetic Agencies to Habilitated Agencies." In *Living in a Material World. Economic Sociology Meets Science and Technology Studies*, edited by Pinch Trevor, Swedberg Richard, 29-56. Boston: The MIT Press.
- Cochoy F, 2002. Une Sociologie du Packaging ou l'Ane ne de Buridan Face au Marche ' [A sociology of packaging, or Buridan's ass in the face of the market] (Presses Universitaires de France, Paris)
- Day, Rosie, and Gordon Walker. 2013. "Household Energy Vulnerability as 'Assemblage'." In *Energy Justice in a Changing Climate: Social Equity and Low-Carbon Energy*, edited by Karen Bickerstaff, Gordon Walker, and Harriet Bulkeley. New York: Zed Books.
- Edenhofer O and Kowarsch M 2015 Cartography of pathways: a new model for environmental policy assessments *Environ. Sci. Policy* 51 56–64
- Edenhofer O, Minx J. 2014. Climate policy. Mapmakers and navigators, facts and values. *Science*. 2014 Jul 4 ;345(6192) :37-8. Doi : 10.1126/science.1255998.
- Gaspard M., Missemer A. 2022. Optimalité, équité et prix du carbone : à propos de Harold Hotelling et de sa règle en économie du climat. *Revue de l'OFCE*, Presses de Sciences Po, 2022 (176).
- Guivarch, C., Le Gallic, T., Bauer, N. et al. Using large ensembles of climate change mitigation scenarios for robust insights. *Nat. Clim. Chang.* 12, 428–435 (2022). <https://doi.org/10.1038/s41558-022-01349-x>
- Haikola, S., Hansson, A., & Fridahl, M. 2019. Map-makers and navigators of politicised terrain: expert understandings of epistemological uncertainty in integrated assessment modelling of bioenergy with carbon capture and storage. *Futures*, 114, 102472.

- Jasanoff, S. 2010. A New Climate for Society. *Theory, Culture et Society* 27:233–53. DOI 10.1177/0263276409361497
- Jebeile, J., Lam, V. & Rätz, T. 2021. Understanding climate change with statistical downscaling and machine learning. *Synthese* 199, 1877–1897 (2021). <https://doi.org/10.1007/s11229-020-02865-z>
- Latour, Bruno, 1995. « The “Pedofil” of Boa Vista : a Photo-philosophical Montage », *Common Knowledge*, vol. 4, 1995, p. 144-187.
- Lecocq F, Nadaï A. Cassen C. 2019. Etat de l’art de la modélisation prospective. 123 p. Cet ouvrage est disponible en ligne www.ademe.fr/mediatheque
- Lecocq F, Nadaï A. Cassen C. forthcoming2022. « Getting models and modellers to inform deep decarbonisation20decarbonization strategies », *Climate Policy*, .16(1), 1469-3062, doi: 10.1080/14693062.2021.2002250
- Mackenzie, D. 2007 “Is Economics Performative? Option Theory and the Construction of Derivatives Markets” In *Do economists make markets? On the performativity of economics*. Edited by Donald MacKenzie, Fabian Muniesa and Lucia Siu, 54-86. Princeton, NJ: Princeton University Press.
- MacLaren, D., Markusson, N. 2020 The co-evolution of technological promises, modelling, policies and climate change targets. *Nat. Clim. Chang.* 10, 392–397 (2020). <https://doi.org/10.1038/s41558-020-0740-1>
- Morgan, M. S., Morrison, M. (Eds.) 1999. *Models as mediators: Perspectives on natural and social science*. Cambridge University Press, Cambridge.
- Quinet A. 2009. *La valeur tutélaire du carbone*, Rapport de la commission présidée par Alain Quinet, Centre d’Analyse Stratégique, La documentation Française, (16) 2009.
- Quinet A. 2019. *La valeur de l’action pour le climat - Une valeur tutélaire du carbone pour évaluer les investissements et les politiques publiques*, Rapport de la commission présidée par Alain Quinet, France Stratégie, Février 2019.
- Saskia Ellenbeck, Johan Lilliestam. 2019, How modelers construct energy costs: Discursive elements in Energy System and Integrated Assessment Models, *Energy Research & Social Science*, Volume 47, p 69-77, <https://doi.org/10.1016/j.erss.2018.08.021>
- Wynne, B. 1984. The institutional context of science, models, and policy: the IIASA energy study. *Policy Sciences* 17:277–320.

Appendix 1 – List of interviews

1	QD	Public administration, coordination, background in engineering and economics
2	MLN	Public institution, modeler, background in economics
3	NM	Energy consultancy, modeler, background in engineering and economics
4	GC	Public administration, head of department, background in engineering
5	MC	Public administration, economist, background in engineering and economics
6	PC	Academic researcher and energy expert, economist/modeler, background in economics
7	BM	Public institution, head of department, background in engineering and economics
8	NM	Academic researcher, modeler, background in applied mathematics
9	BLH	Public institution, economist, background in engineering and economics
10	BDG	Public administration, head of department, background in engineering and economics

Appendix 2 – The Quinet-2 models

Technico-economic models

TIMES-France is an inter-temporal optimization model of the French energy system driven by demand: based on a representation of the sectors of the entire energy chain, its objective is to determine a choice of technologies that satisfies demand while minimizing the total discounted cost of the French energy system over a certain time horizon, while taking into account the constraint of greenhouse gas emissions on the energy system.

POLES-Enerdata is an energy system simulation model. It is a dynamic recursive model that calculates its variables year after year with adaptive anticipations. POLES has the particularity of endogenously calculating energy demand, supply, energy prices on the various regional markets, as well as sectoral emissions of six greenhouse gases

Macroeconomic models

IMACLIM-R France is a computable general equilibrium model with recursive dynamics that represents the French economy in fifteen economic sectors. It has the particularity of also including endogenous technical-economic modules.

ThreeME is a multi-sector computable general equilibrium macroeconomic model (CGEM) of neo-Keynesian inspiration, designed to evaluate the macroeconomic impacts of public policies, particularly energy and environmental policies. The model has recursive dynamics and adaptive expectations. Energy consumption depends in particular on the evolution of the stock of housing, vehicles, capital goods and their characteristics.

NEMESIS is a system of sectoral econometric models developed for each of the 28 countries of the European Union. It is intended for quantitative forecasting and analysis of economic policies, particularly so-called "structural" policies. The economy is disaggregated into thirty production sectors. Once again, it is a dynamic recursive model (resolution by annual steps) with adaptive expectations