

Article

Deep Decarbonisation from a Biophysical Perspective: GHG Emissions of a Renewable Electricity Transformation in the EU

Louisa Jane Di Felice ^{1,*}, Maddalena Ripa ¹ and Mario Giampietro ^{1,2} 

¹ Institute of Environmental Science and Technology, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain; maddalena.ripa@uab.cat (M.R.); mario.giampietro@uab.cat (M.G.)

² Catalan Institution for Research and Advanced Studies (ICREA), Passeig Lluís Companys 23, 08010 Barcelona, Spain

* Correspondence: louisajane.difelice@uab.cat

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Abstract: In light of climate change and security concerns, decarbonisation has become a priority for industrialised countries. In the European Union (EU), decarbonisation scenarios used to support decision-making predict a steady decrease in greenhouse gas (GHG) emissions, mostly driven by changes in production mixes and improvements in efficiency. In the EU's decarbonisation pathways, the power sector plays a large role, reaching zero emissions by 2050. From a biophysical perspective, decarbonisation becomes not just a matter of replacing carbon-intensive with carbon-neutral electricity flows, but also a matter of building and maintaining new infrastructure (funds) which, in turn, is associated with GHG emissions. By not accounting for the emissions associated with funds, particularly those required to increase grid flexibility, scenarios used to inform decarbonisation narratives in the EU are missing a key part of the picture. We show that a rapid and deep decarbonisation of the EU's power sector through a production-side transition between the years 2020 and 2050 leads to cumulative emissions of the order of 21–25 Gt of CO₂ equivalent, within a range of approximately 35–45%. The results are obtained by modelling two decarbonisation pathways where grid flexibility increases either through storage or through curtailment. The analysis suggests that scenarios informing decarbonisation policies in the EU are optimistic and may lead to a narrow focus on sustainable production transformations. This minimises the perceived urgency of reducing overall energy consumption to stay within safe carbon budgets.

Keywords: modelling; science-policy interface; grid flexibility; bio-economics; energy transition; storage; curtailment

1. Introduction

The type of primary energy sources (PES) used by societies to generate a given mix of energy carriers (ECs) is central in shaping their organisation, pace and activities [1,2]. Industrial societies have developed through a heavy reliance on fossil fuels, characterised by their high density. In addition, fossil fuels can be stored and transported across borders, bypassing local natural resource limitations. The exploitation of fossil fuels, while shaping industrial societies' activities and allowing for a high living standard and rapid rates of urbanisation [3], has also led to unbearable environmental effects, locally and globally. As a consequence, moving away from fossil-based energy systems has become a priority for industrialised economies. In addition to environmental concerns, in the EU, a renewable transformation of the energy system is also desirable from a security of supply perspective, given the lack of indigenous fossil fuels on local territory [4–6].

Thus, it has become progressively pressing in the EU to shift to alternative (local) energy sources resulting in lower greenhouse gas (GHG) emissions throughout their lifetime [6]. However, the shift itself has not been easy to initiate, model or govern. The *Energiewende* is an example of this, having led overall to higher electricity prices and higher emissions, despite strong efforts to shift production patterns of energy carriers [7].

Depending on the chosen problem framing, barriers to a renewable energy transition may be conceived as being of a political, economic, social, institutional or biophysical nature. We borrow the term biophysical from the field of bio-economics, where the economic process is viewed not only through the lens of monetary flows, but most importantly through the lens of flows of biological and physical resources that are produced, distributed, consumed and exchanged [8]. In this sense, the amount of water, emissions and labour associated with a certain energy system, for example, may be categorised as biophysical variables, in opposition to economic ones such as energy prices. Within the field of bio-economics, the term energy metabolism is used to describe the way in which societies extract, process and distribute flows of energy in order to carry out tasks that are crucial to the survival of their identity [9].

Taking a biophysical perspective of the energy system, in this paper we focus on the decarbonisation of the EU's power sector. Our aim is to provide an alternative narrative to those underpinning EU decarbonisation pathways, where barriers to energy transformations are mostly relegated to the domain of finance and investments [6]. To do this, we model alternative decarbonisation pathways that include the GHG emissions associated with the lifetime of funds. We borrow the distinction between funds and flows from Georgescu-Roegen [8]. Within Georgescu-Roegen's flow-fund model, given a chosen spatial and temporal scale of analysis, funds are those elements whose identity remains intact, while flows are elements either entering the system without exiting it or exiting it without entering it. From a metabolic perspective, funds are the elements metabolising flows—land, for example, is a fund to be maintained, while the food it grows is a flow. Considering an energy system over a yearly timescale, the electricity and fuels produced and consumed are flows. The infrastructure and human time invested in the production and consumption of flows are the funds of the system.

This distinction is important to study the implications of infrastructural changes in the energy system. The magnitude of infrastructural changes required on the production and consumption side for a decarbonisation of the energy system are not unknown to policymakers [10]. However, there is a tendency within scenarios at the EU's science-policy interface to use biophysical variables to describes changes in flows (e.g., the amount of electricity consumed over a year) and to adopt a monetary perspective to account for changes in infrastructure (e.g., the investments required to build new transmission and distribution lines). When considering changes associated with funds, a biophysical perspective (e.g., the amount of labour, emissions, water and waste associated with infrastructural changes) is often neglected. This is the case, for example, in the EU 2016 Reference Scenario, where capital investments linked to infrastructure are estimated [11].

Building on data available through existing studies, we developed a scenario singling out the EU power sector up to 2050 and hypothesized two different pathways for its decarbonisation. Increasing grid flexibility is central to ensuring that high levels of variable renewable energy (VRE) can be managed by the grid [12]. In the first pathway, grid flexibility was increased through high rates of curtailment of renewable generation and low storage; in the second, lower levels of curtailment were paired with storage technologies. In each pathway, the emissions associated with the cultivation, construction and fabrication (CFC) of funds were calculated at yearly intervals up to the year 2050, in addition to the operational emissions associated with electricity generation (flows). The approach is meta-analytical and adjusts data available in literature, rather than modelling the behaviour of the grid.

The rest of the paper is organised as follows: Section 2 provides an overview of the decarbonisation pathways currently modelled to support EU decision-making and places them within the wider academic discourses of energy and GHG payback time; Section 3 introduces alternative pathways,

with an overview of the underpinning assumptions (Section 3.1) and modelling equations (Section 3.2). The results and discussion are presented in Section 4, split into yearly and cumulative GHG emissions (Section 4.1), variational ranges in results (Section 4.2) and discussion of results (Section 4.3).

2. Background

2.1. Decarbonisation in EU Policy

In the EU, the energy sector accounted for approximately 30% of total emissions in 2016. It was the sector with the highest share of emissions, followed by transport and by manufacturing (accounting for approximately 20% each) [13]. EU decarbonisation policies fall under the 2050 low-carbon economy package [14], as part of the EU's wider climate strategy. The low-carbon economy roadmap calls for GHG emissions to be cut by 80% below the 1990 levels by 2050, with two intermediate milestones of 40% by 2030 and 60% by 2040. The strategy is currently being renewed in order to reflect the Paris Agreement and is expected to be updated by early 2019 [15].

The EU Energy Roadmap 2050, published in 2011, highlights four strategic directions for decarbonisation: energy efficiency, renewable energy sources (RES), nuclear and carbon capture and storage (CCS). The four directions are explored through six scenarios: current policies, high efficiency, high RES, delayed CCS, low nuclear and diversified supply technologies. Since the publication of the Energy Roadmap 2050, significant events such as the Paris Agreement and the release of the Clean Energy for all Europeans package have impacted EU energy discourses. In light of this, new scenarios have been developed to inform the EU's mid-century strategy, to be released by fall this year (2018). The scenarios included in the Clean Energy for all Europeans package model pathways to decarbonisation based on efficiency, integration of renewable energy sources and the functioning of the internal energy market [16]. The main trends, which are an increased share of RES, a linear decrease of GHG and an increased electrification, have persisted across the two generations of scenarios.

In the six decarbonisation scenarios of the Energy Roadmap 2050, RES rise significantly, to a minimum of 55% of gross consumption of energy carriers in 2050 and 60–80% of gross electricity production by the same year. Absolute electricity production increases steadily between 20 and 40% by 2050 across the six scenarios, despite an overall reduction in total energy consumption. This reflects trends in mitigation scenarios, where a gradual electrification of the energy system is seen as a key element for its decarbonisation [17]. Emissions across all sectors decrease steadily and monotonically—that is, there is no increase in emissions associated with infrastructural change and there are no relative peaks of GHG emissions throughout the years. Figure 1 shows an example of projected sectoral emission reduction in the high RES pathway.

The power sector, in particular, is seen to reach zero or almost zero emissions by 2050 for all pathways, as further indicated by the low-carbon strategy: “The power sector has the biggest potential for cutting emissions. It can almost totally eliminate CO₂ emissions by 2050” [14]. Similarly, the Intergovernmental Panel on Climate Change (IPCC) highlights the decarbonisation of the power sector as one of the three main components of mitigation scenario studies, together with a gradual electrification of the energy sector and a reduction in energy demand through technology and other substitutions [17].

The scenarios developed to support the Energy Roadmap 2050 build on the PRIMES (Price-Induced Market Equilibrium System) energy model, “a partial equilibrium modelling system that simulates an energy market equilibrium in the European Union and each of its Member States” [18].

For the accounting of GHG emissions, the model simulates the operational emissions associated with electricity production (a flow) but neglects the emissions associated with the construction of infrastructure (a fund). This omission is linked to the fact that grid flexibility requirements are not modelled. A small but growing body of literature in academia, as highlighted in the next sub-section, points towards the emissions associated with renewable infrastructure and to storage, and to how they may impact future decarbonisation pathways. Additionally, the need to increase grid flexibility at high

renewable energy penetrations has been stressed and modelled for specific case studies, including Europe [19], Japan [20], Texas [21] and California [22].

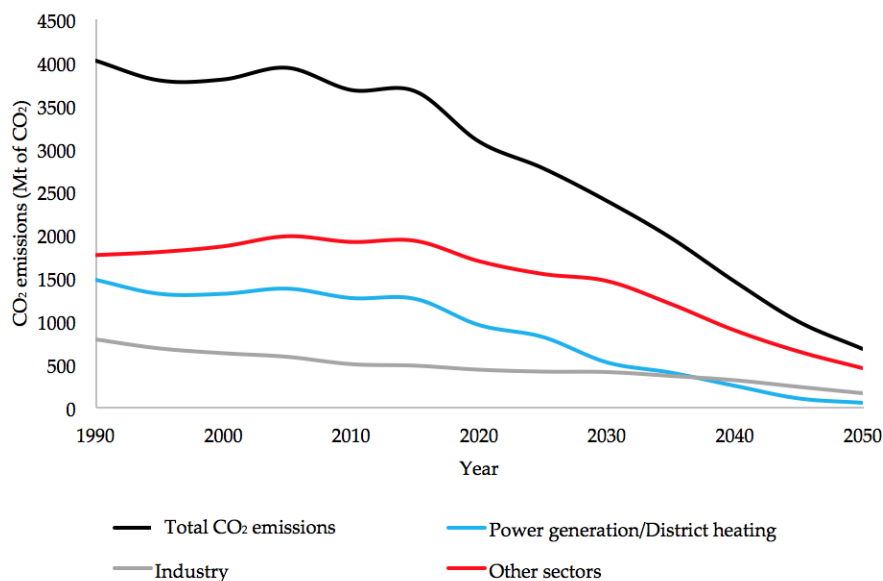


Figure 1. CO₂ emission projections, in megatons (Mt) of CO₂, under the EU high RES decarbonisation pathway. Source: Own elaboration from the EU Energy Roadmap 2050 [10].

However, EU energy policy discourses uphold the narrative that the main barrier to a high integration of RES into the energy system is financial rather than biophysical. The renewable energy package [6], for example, highlights a number of barriers envisioned on the path to a fully renewable energy system, including administrative hurdles, cost-effectiveness, loss of citizen buy-in and uncertainty for investors. Grid stability is also mentioned as an issue, with the electricity system needing to “adapt to an increasingly decentralized and variable production” [6]. Despite this mention, the issue is not framed as being central and no concrete targets for adaptation have been set, nor have the (biophysical) implications of increasing grid flexibility been included in the EU decarbonisation pathways.

2.2. Energy and GHG Payback Time

The biophysical investments (such as energy and land) associated with the construction of energy systems have been the subject of a prolific field of energy analysis. The widely used concept of Energy Returned on Energy Invested (EROI) accounts for the amount of net energy generated by an energy system, when the fixed capital and variable operational energy investments required for its construction and maintenance are discounted [23,24]. EROI is particularly relevant for the assessment of alternative energy carriers, such as biofuels, requiring a high energetic investment throughout their production chain [25]. A parallel concept to EROI is the Energy Payback Time (EPBT), accounting for the amount of time it takes for an energy system to break even in terms of the production of energy carriers (in relation to those consumed in its construction). So far, EPBT has been mostly applied to the analysis of solar panels [26,27]. Similar to EPBT, the emissions associated with the construction and operation of energy systems can be accounted for in what is known as the GHG, carbon or environmental payback time (GHGPBT). The GHGPBT indicates the time it takes for a system to become carbon neutral following an initial emission investment due to material extraction, transport and construction [28,29]. Figure 2 shows a schematic view of the concepts of energy and GHG payback time, central to the biophysical accounting of energy systems.

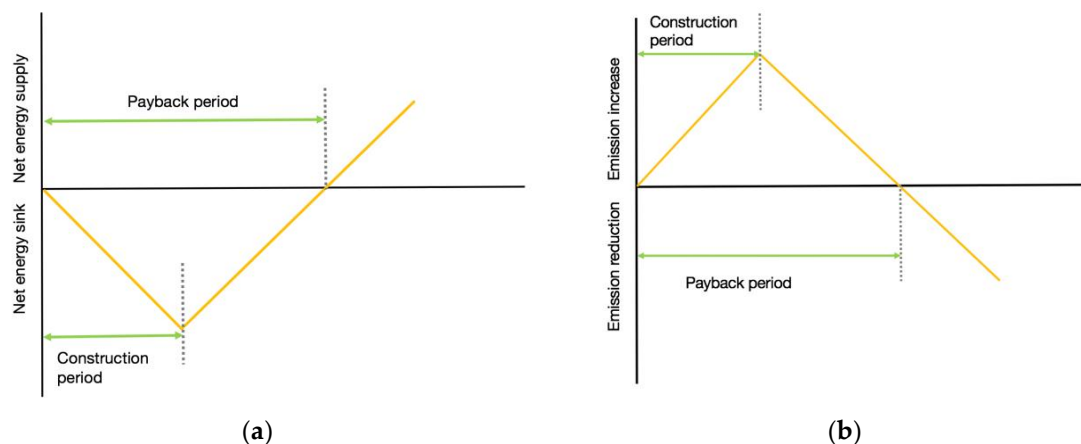


Figure 2. Schematic representation of EPBT (a) and GHGPBT (b).

The concepts of energy and GHG payback time can be applied to storage systems. A high penetration of intermittent energy sources into the electricity grid is likely to require a combination of demand-side management, storage infrastructure and improvement of transmission and distribution lines to ensure that intermittent electricity is dispatchable at all times [12]. Studies on storage estimations for a 100% renewable electricity system present high doses of uncertainty, however, the most thorough reviews point towards storage needs greatly beyond what is currently operational at the global scale [20–22]. Thus, the importance of being able to assess and compare the performance of storage systems has become evident. Building on the idea of EROI, Barnhart and Benson [30] introduced the concept of Energy Stored on Energy Invested (ESOI), accounting for the amount of net energy output provided by storage technologies compared to the energy invested in their construction and operation. Battery technologies show a performance approximately 20 times lower (in terms of ESOI) than compressed air energy storage (CAES) and pumped hydroelectric storage (PHS). However, due to the invasive nature of CAES and PHS and due to the strong limitations to their expansion brought by geographic configurations, batteries have become a popular option in the discussion of storage futures [31].

In a biophysical framing, the GHG emissions of storage technologies throughout their lifetime are a key element in the assessment of future energy scenarios. A thorough review by Denholm [31] showed how PHS is associated with the lowest amount of emissions over its lifetime, while batteries are associated with non-negligible lifetime emissions. In its present form, CAES relies on the use of natural gas and therefore also presents non-negligible lifetime emissions.

Similar to the emissions of storage infrastructure, the GHG emissions associated with the lifecycle of renewable infrastructure have been studied—see Nugent and Sovacool [32] for a thorough review of the topic. The emissions associated with renewable electricity generation over its lifetime are considerably lower than those associated with fossil electricity. As a consequence, not much attention has been placed in exploring the nuances of different pathways and storage options in terms of their associated emissions. Crucial questions regarding the best pathways to decarbonisation in relation to emission curves, thus, remain underexplored [32].

3. Alternative Decarbonisation Pathways

When dealing with complex systems, such as the social-ecological one, modelling may have two purposes: To predict and control future states of the system or to better understand the current one [33]. As the high doses of uncertainty attached to the prediction of future states of the complex social-ecological system become apparent, scenarios used to support decision-making are framed more and more as tools for deliberation, rather than prediction. The EU webpage on energy modelling, for example, states that the EU Reference Scenario, “one of the European Commission’s key analysis tools in the areas of energy, transport and climate action”, (...), “is not designed as a forecast of what

is likely to happen in the future but it provides a benchmark against which new policy proposals can be assessed" [34]. In a similar spirit, the aim of the alternative decarbonisation pathways is not to predict the behaviour of future decarbonisation pathways in the EU. Rather, the aim is to flag the need to include emissions associated with the construction of infrastructure in decarbonisation discourses. This is particularly relevant for intermittent sources of energy and their grid flexibility requirements.

We explored two decarbonisation pathways of the EU's power sector for the years 2020–2050, each dealing differently with grid flexibility requirements. Focus was given to the integration of renewable energy into the grid as a means to decrease GHG emissions, in line with the high RES scenario of the EU's Energy Roadmap 2050, on which the two pathways were based. The values of gross electricity consumption up to 2050, in fact, were taken from the high RES scenario, as well as the share of nuclear electricity at each year. Hydropower was assumed to remain unchanged over the years, while solar power and wind power were assumed to increase until producing 90% of electricity, entirely phasing out fossil power plants. Adjusting data from existing studies, we calculated the emissions associated with the construction and operation of funds (renewable and storage infrastructure) with respect to the reduction in emissions due to the substitution of fossil with alternative energy systems (associated with the electricity generated by the systems—flows).

3.1. Modelling Assumptions

Any model informing the future behaviour of energy systems necessarily relies on heavy sets of assumptions regarding technology, consumption and production patterns. Modelling assumptions of the alternative decarbonisation pathways are split into two sections: grid flexibility and GHG emissions.

3.1.1. Grid Flexibility

Integrating high levels of variable renewable energy (VRE), such as the electricity produced by wind turbines or solar photovoltaic (PV) panels, into the grid requires an increase in the flexibility of the grid. Grid flexibility can be achieved in various ways. Kondziella and Bruckner [12] identified seven possible measures on the production and on the consumption side: highly flexible power plants, large-scale energy storage, curtailment of renewable surplus, demand-side management, grid extension, virtual power plants and linkage of energy markets. These measures, either individually or in unison, can ensure that electricity demand is met at all times. Here, focus was given to the production-side measures of large-scale energy storage and of the curtailment of renewable surplus.

Existing studies [12,19–22,35,36] show that increasing grid flexibility becomes essential when the share of VRE fed into the grid reaches levels of 40 to 50%. Grid flexibility can be increased through large-scale energy storage. In this case, surplus electricity generated by VRE when production is higher than demand can be converted into gravitational, thermal or electrochemical energy and fed back into the system when production is lower than demand. Curtailment of renewable surplus, on the other hand, relies on the installation of more renewable infrastructure than what is needed to cover average yearly demand (also known as backup power plants). When the combined electrical output of the renewable infrastructure is higher than the demand at a given point in time, the output of VRE plants is curtailed. As a result, curtailment of renewable surplus as a means to improve grid flexibility has an impact on the utilisation factor (UF) of renewable plants. The review paper by Kondziella and Bruckner [12] provided a thorough overview of existing studies assessing grid flexibility requirements for high renewable integration.

Steinke [19] examined the interplay between storage, curtailment and grid extensions for a 100% renewable electricity system in Europe. Denholm and Hand [21] and Denholm and Margolis [22] modelled, respectively, the electricity grids of Texas and California to provide an assessment of how grid flexibility can be achieved in low and high storage scenarios. The models of US case studies, produced for the National Renewable Energy Laboratory (NREL), have not been replicated in the EU to this level of detail and are the most comprehensive reference points for assessments of grid flexibility.

Building on these studies [21,22], we hypothesised two pathways for decarbonisation: a low storage high curtailment (LSHC) pathway and a high storage low curtailment (HSLC) one. In the former, we assumed that no extra storage technologies were added to the EU's electricity system, therefore the only storage services available up to 2050 were those produced by current PHS facilities (at a storage capacity of approximately 600 GWh [37]). To ensure grid flexibility, renewable back up power was added and renewable generation was assumed to be curtailed. In the latter, curtailment was greatly decreased by the addition of storage services. Both scenarios adapted the curtailment and flexibility rates from the comprehensive model of the Texas grid [21]. The relations between curtailment and flexibility in the EU depend on specific geographies and grid configurations. However, for the purpose of these pathways—i.e., to point towards a problem in GHG accounting rather than to provide accurate predictions—this approximation was considered satisfying.

The total amount of storage required by 2050 was calculated following Steinke [19] and Renner and Giampietro [35]. Assuming that grid expansions were limited to the national scale and that no backup generation was provided, Steinke estimated that the EU would require between 7 and 30 days of storage to accommodate shares of 90% or more of VRE. Analysing data for Germany and Spain over an 84 months and 132 months, with a resolution of 60 minutes and 10 minutes respectively, Renner and Giampietro estimated that the two countries would require approximately one week of storage capacity in a 100% intermittent penetration scenario. The study used the comprehensive datasets available for the two countries to check “the extent of the predicted worst annual hypothetical ‘failure event’ (where the guaranteed level of intermittently sourced electricity is not met)”. The results by Renner and Giampietro for Germany are in line with the analysis by Kuhn [36], predicting a requirement of installed storage charging power in Germany of the order of 53 GW by 2050. Similar values apply to the case of Japan [20], where, despite a different energy mix and configuration, it was also found that storage requirements are on the order of a week of average electricity supply.

Thus, storage capacity requirements for 2050, where gross electricity production is assumed to grow to approximately 5140 TWh, were assumed to be on the order of a week of average daily demand. It was then assumed that PHS, the most implemented and mature storage technology in the EU and worldwide, increased up to its viable potential in the EU, following the analysis by Gimeno-Gutiérrez and Lacal-Arántegui [38]. Then, battery energy storage (BES) was introduced to cover the gap between the maximum PHS potential and the total storage capacity needed. The relevant assumptions shared across pathways and those differing for each pathway are collected in Tables 1 and 2 respectively, at ten-year snapshots between 2020 and 2050.

Table 1. Assumptions on the evolution of the energy system shared for the two decarbonisation pathways (low storage high curtailment—LSCH, and high storage low curtailment—HSLC).

Variable	2020	2030	2040	2050
Gross electricity consumption (GWh)	3,665,400	3,666,000	4,357,600	5,140,600
Daily electricity consumption (GWh)	10,042	10,043	11,939	14,084
Hydropower (%)	10	10	9	7
Nuclear (%)	24	16	8	3
Fossil plants (%)	40	27	14	0
Wind power (%)	14	29	46	62
Solar power (%)	6	12	20	27
Other renewables (%)	5	5	5	0

Following the EU high RES pathway, gross electricity consumption increased in both pathways, despite an overall reduction in energy consumption—mirroring the trend of electrification. Hydropower (excluding PHS) was assumed to remain unchanged throughout the years, therefore as electricity generation increased its share in the electricity mix decreased. Nuclear power was assumed to gradually decrease in absolute and relative terms. All other non-renewable power plants were grouped under the umbrella term fossil plants and eliminated by 2050. The share of wind and solar

power rose gradually until reaching 90% of the total generation share in 2050. The relative contribution of wind and solar power remained fixed at 70 and 30% respectively, mirroring their 2016 relative contribution in the EU. This was also in line with what was identified by Denholm and Hand [21] as the optimal balance between the two types of generation technologies to ensure minimum curtailment.

Table 2. Relevant characteristics of two decarbonisation pathways: low storage high curtailment (LSHC) and high storage low curtailment (HSLC).

Variable	Alternative Pathway	2020	2030	2040	2050
Gross electricity consumption (GWh)	LSHC	3,665,400	3,666,000	4,357,600	5,140,600
	HSLC	3,665,400	3,666,000	4,357,600	5,140,600
Gross production from wind power (GWh)	LSHC	505,270	1,057,690	2,228,440	5,110,500
	HSLC	505,270	1,057,690	2,049,370	3,194,070
Gross production from solar PV (GWh)	LSHC	216,540	453,300	955,040	2,190,220
	HSLC	216,540	453,300	878,300	1,587,910
Curtailment rate (%)	LSHC	0	0	10	60
	HSLC	0	0	0	20
Storage capacity (GWh)	LSHC	600	600	600	600
	HSLC	600	14,570	51,100	87,630
Wind power UF (%)	LSHC	24	24	21	15
	HSLC	24	24	23	21
Solar PV UF (%)	LSHC	13	13	12	8
	HSLC	13	13	13	11
Wind power capacity (GW)	LSHC	240	500	1060	2430
	HSLC	240	500	980	1760
Solar PV capacity (GW)	LSHC	190	400	840	1920
	HSLC	190	400	770	1390

Given the higher curtailment rate in the LSHC scenario, although the gross electricity consumption was the same as in the HSLC scenario, a higher amount of wind and solar power were assumed to be generated (see the second and third row of Table 2). The surplus generation was not assumed to enter the grid but was curtailed. The curtailment rates, also included in Table 2, were taken from Denholm and Hand [21], by assuming that curtailment rates as a function of VRE penetration can be generalised. Contrary to storage requirements, which tend to increase linearly as VRE integration increases, curtailment increases exponentially, meaning that it becomes less and less favourable to rely on curtailment at higher rates. The amount of storage capacity, in GWh of installed capacity, did not increase throughout the years for the LSHC scenario. Eurostat does not provide statistics on storage capacity, and the value of 600 GWh of PHS in the EU was taken from Kougiyas and Szabó [37]. In the HSLC scenario, the storage capacity increased up to a week of average demand. The curtailment rates in both scenarios led to a gradual decrease in the utilisation factors (UF) of wind and solar power, calculated as the amount of time throughout the year when electricity generated by wind and solar (GWh_{used}) was fed into the grid:

$$UF (\%) = \frac{GWh_{used}}{GW_{installed}} \times \frac{100}{8760} \quad (1)$$

where $GW_{installed}$ is the installed power capacity, and 8760 is the number of hours in a year.

3.1.2. GHG Emissions of Renewable Infrastructure, Storage and Fossil Plants

The values of lifetime GHG emissions of renewable infrastructure, and their associated ranges, were adjusted from the comprehensive meta-review by Nugent and Sovacool [32]. For GHG emissions of storage technologies, values were taken from Denholm and Kulcinski [39]. Table 3 summarises the main technological assumptions of both studies. For renewable infrastructure, Nugent and Sovacool provide intensive data derived from a number of studies, each with different technical specifications.

Therefore, the values do not refer to specific technological characteristics. This enlarges the range of the estimated values, but also their robustness. Storage infrastructure values, similarly, refer to a review of various existing plants, with the range of technological characteristics included in Table 3. As the GHG emissions associated with battery energy storage (BES) were an important variable for the results, the values of Denholm and Kulcinski, dating to 2004, were cross-checked against a recent study referring specifically to lithium-ion batteries [40]. and were found to be consistent. Since the scenarios were modelled at the EU level, they did not take into account differences across member states. The values taken from literature, associated with a range of technological characteristics, reflect the heterogeneity of infrastructure required across the EU.

Table 3. Ranges of technological assumptions of infrastructure: (a) Renewable infrastructure, adjusted from Nugent and Sovacool [32]; (b) storage infrastructure, adjusted from Denholm and Kulcinski [39].

(a)		
Variable	Wind Power	Solar PV
Number of studies	41	23
Hub height (m)	10–108	N/A
Rotor diameter (m)	2–116	N/A
Technology	N/A	Ribbon-Si, Multi-Si, Mono-Si, CdTe
Irradiance (kWh/m ²)	N/A	1600–1800
Mounting	N/A	roof, ground, single axis
Lifetime (years)	20–30	15–30
GHG cultivation and fabrication (mean) (g CO ₂ eq./kWh)	42.98	33.67
GHG construction (mean) (g CO ₂ eq./kWh)	14.43	8.98
GHG operation (mean) (g CO ₂ eq./kWh)	14.36	6.15
(b)		
Variable	PHS	BES
Number of facilities	9	N/A
Completion date	1978–1995	N/A
Power (MW)	31–2100	15
Storage capacity (MWh)	279–184,000	120
Energy/power ratio (hours)	13	8

The GHG emissions from the review studies were adjusted as the renewable share of the electricity mix in the pathways increased, since the electricity mix strongly affects GHG emissions. As we were singling out the power sector, emissions associated with the use of fuels and other forms of thermal energy remained invariant. To adjust the values throughout the years, the carbon intensity of the EU's electricity mix was estimated each year, starting from 320 g/kWh in 2016 [41] and reaching almost zero in 2050. The contribution of the electricity mix to the overall GHG emissions of wind power infrastructure was estimated by comparing existing studies which made a direct link between the carbon intensity of the electricity production system and the GHG emissions associated with infrastructure (see Reference [42] for a comparison of Germany and China, Reference [43] for Brazil and Reference [44] for different values of carbon intensities). The effect of different electricity mixes on the construction on the lifetime of solar panels was assessed directly by Reich [45] in relation to the CO₂ emission factor of electricity supply. Varying GHG emissions for CFC and Operation are included in Table 4.

Table 4. Varying GHG emissions for the cultivation, fabrication and construction (CFC) and operation of renewable and storage infrastructure.

Variable	2020	2030	2040	2050
CFC, wind infrastructure (t CO ₂ eq./GW)	906,700	766,020	617,000	470,000
CFC, solar infrastructure (t CO ₂ eq./GW)	1,418,000	1,199,000	965,000	735,000
CFC, PHS (t CO ₂ eq./GWh.inst *)	33,800	28,500	23,000	17,500
CFC, BES (t CO ₂ eq./GWh.inst *)	123,500	104,400	84,000	64,000
Operation, wind turbines (t CO ₂ eq./GWh)	5	5	5	5
Operation, solar PV (t CO ₂ eq./GWh)	6	6	6	6
Operation, fossil plants (t CO ₂ eq./GWh)	450	450	450	450
Operation, PHS (t CO ₂ eq./GWh)	1.8	1.8	1.8	1.8
Operation, BES (t CO ₂ eq./GWh)	3.5	3.5	3.5	3.5

* GWh.inst: amount of storage capacity installed.

3.2. Modelling Equations

The values of GHG emissions at a given year were calculated from the secondary data, adjusted to the EU's electricity mix for each year, through the following equations:

$$\text{GHG}_{\text{st}_n} = \text{GW}_{\text{PV},n} \times \text{GHG}_{\text{stPV},n} + \text{GW}_{\text{wind},n} \times \text{GHG}_{\text{stwind},n} + \text{GW}_{\text{PHS},n} \times \text{GHG}_{\text{stPHS},n} + \text{GW}_{\text{BES},n} \times \text{GHG}_{\text{stBES}} \quad (2)$$

$$\text{GHG}_{\text{op}_n} = \text{GWh}_{\text{PV},n} \times \text{GHG}_{\text{opPV},n} + \text{GWh}_{\text{wind},n} \times \text{GHG}_{\text{opwind},n} + \text{GWh}_{\text{PHS},n} \times \text{GHG}_{\text{opPHS},n} + \text{GWh}_{\text{BES},n} \times \text{GHG}_{\text{opBES}} + \text{GWh}_{\text{fossil},n} \times \text{GHG}_{\text{opfossil},n} \quad (3)$$

where:

- GHG_{st_n} are the GHG emissions, in tons of CO₂ equivalent, emitted at year n due to the cultivation, fabrication and construction (CFC) of infrastructure;
- GW_{PV} and GW_{wind} are the amounts of extra solar PV and wind power capacity installed each year;
- GWh_{PHS} and GWh_{BES} are the amounts of extra storage capacity, PHS and BES, added each year;
- GHG_{op_n} are the varying infrastructure emissions at each year n , depending, in turn, on the electricity mix and expressed in tons of CO₂ equivalent/GW for renewable infrastructure and tons of CO₂ equivalent/GWh for renewable infrastructure;
- GWh_n is the electricity generation at year n by each technology.

Similarly, the emissions due to the operation of power plants were calculated at each year as the total amount of electricity generated by each type of power plant (including curtailed electricity) times the associated operational emissions. The total GHG emissions at year n , thus ($\text{GHG}_{\text{total},n}$) were a combination of multiple factors varying across the years. What we refer to as cumulative emissions, finally, is the sum of the emissions over the 2020–2050 time period:

$$\text{GHG}_{\text{total}} = \sum_{n=2020}^{2050} \text{GHG}_{\text{total},n} \quad (4)$$

4. Results and Discussion

The results and discussion are structured in three sections. Firstly, the yearly and cumulative emissions of the decarbonisation pathways are presented and linked to EU decarbonisation scenarios, and carbon budgets (Section 4.1); then, variational ranges of the results are discussed (Section 4.2). Section 4.3, finally, discusses the role played by biophysical variables at the science-policy interface.

4.1. GHG Emission Curves and Cumulative Emissions

To discuss the results of the two decarbonisation scenarios, emissions can be viewed from three perspectives:

1. Emission curves at a yearly resolution, useful to comment on the temporal behaviour of emissions and their possible non-linear evolution;
2. Cumulative emissions up to the year 2050, i.e., the sum of the yearly emissions, which can be related to carbon budgets;
3. Yearly emissions at the target year 2050, currently the only view used to inform EU decision-making processes (with different targets set for different years).

Starting with the emission curves provided throughout the years, Figures 3 and 4 show the behaviour of the GHG emissions of the EU power sector (including cultivation, fabrication and construction of infrastructure) under the low storage high curtailment (LSHC) scenario. The total emissions are shown in Figure 3, while Figure 4 breaks the emissions down into those linked to the operation of power plants (associated with electricity flows) and those linked to the cultivation, fabrication and construction of renewable infrastructure (associated with funds).

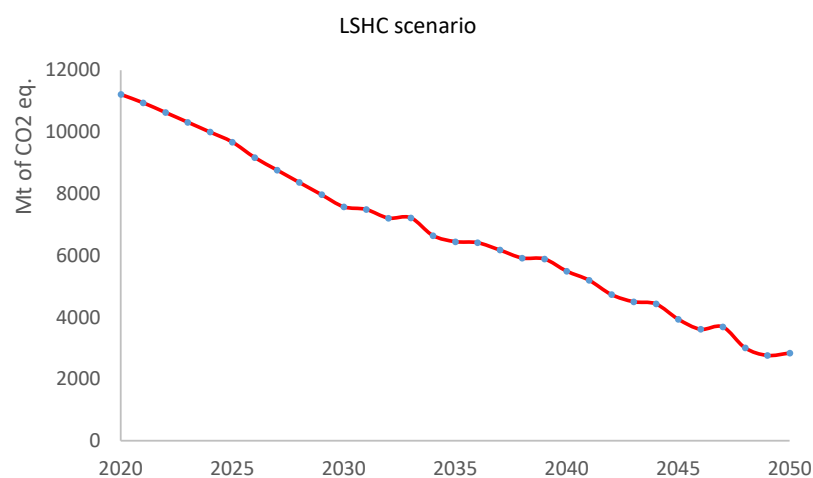


Figure 3. Total GHG emissions in the low storage high curtailment (LSHC) scenario.

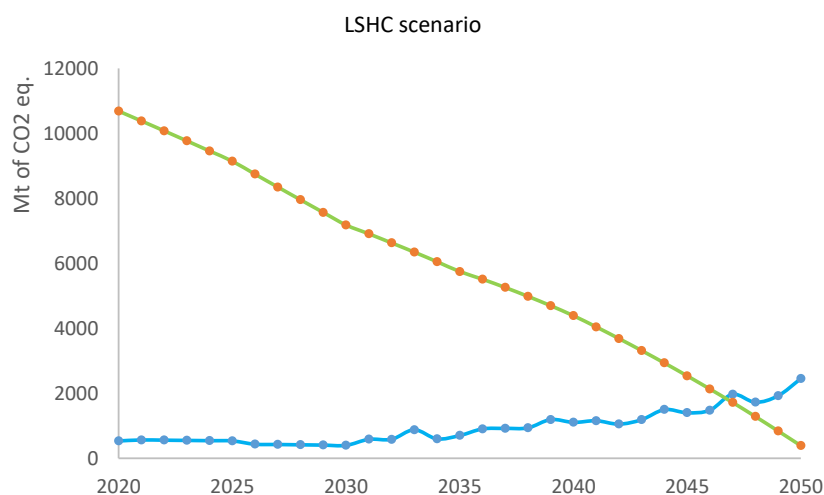


Figure 4. GHG emissions in the LSHC scenario, broken down into operational (flows, green line) and infrastructural (funds, blue line).

In the LSHC scenario, while the amount of wind and solar infrastructure installed each year increased exponentially (see Table 2), the GHG emissions associated with the cultivation, fabrication and construction phases of the infrastructure were mitigated by the steady reduction in operational emissions, which dropped to almost 0 by 2050. The initial steady decrease in emissions became less linear from the year 2030, i.e., when curtailment of renewable electricity started. As curtailment

increased, emissions due to an infrastructure rise led to relative peaks in emissions between the years 2030 and 2050, with overall emissions associated with infrastructure increasing despite the increased renewable penetration into the system. The behaviour of the curve depended on the rate that renewable infrastructure was installed.

With high levels of emissions associated with the installation of both PHS and BES storage technologies (see Table 3), the yearly emission curve for the low curtailment high storage (LCHS) scenario displays a behaviour which is less linear, as seen in Figures 5 and 6.

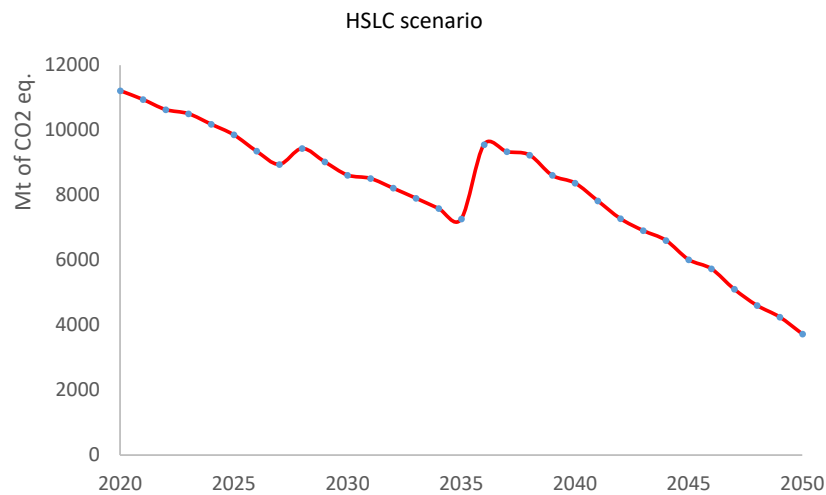


Figure 5. Total GHG emissions in the high storage low curtailment (HSLC) scenario.

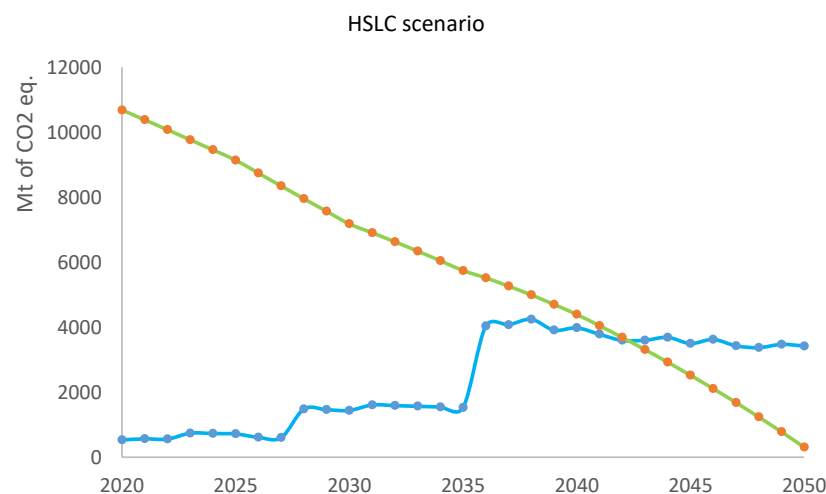


Figure 6. GHG emissions in the HSLC scenario, broken down into operational (flows, green line) and infrastructural (funds, blue line).

Emissions were strongly dependent on the type of storage infrastructure and on when it was integrated into the system. Emissions gradually decreased up to the year 2027, when the amount of installed PHS started to increase considerably. The biggest peak, however, was visible at the year 2035, when BES technologies were introduced, as PHS reached its maximum capacity. The peak can be softened if BES is gradually installed from the start, however, in this case, cumulative emissions would be higher as the manufacturing process would rely more heavily on fossil fuels. Thus, different timing options should be carefully considered from a biophysical perspective.

The behaviour of the curves of Figures 3 and 5, and the presence or absence of relative GHG emission peaks, can be varied by varying assumptions on timings and introduction of technologies. This would also vary cumulative emissions, as the emissions associated with the construction of

infrastructure also depend on the yearly electricity mix. Cumulative emissions are a useful indicator as they can give us an idea of how much is being emitted by the EU's power sector during its transitional phase towards deep decarbonisation. It is expected that, on average, the EU has a carbon budget on the order of 90 Gt in order to remain within a 2° temperature range for the period between 2020 and 2100 [46]. Cumulative emissions associated with the power sector and to the manufacturing of infrastructure were of the order of 20,830 Mt of CO₂ eq. and 25,150 Mt of CO₂ eq. respectively, for the HCLS and LCHS scenarios. Thus, under deep decarbonisation pathways, between the years 2020 and 2050 alone the power sector and its associated manufacturing would emit 23–28% of the total budget available to the whole society up to the year 2100. As we discuss in Section 4.3, this suggests that efforts on the production side of the energy system are not enough to stay within safe carbon budgets.

4.2. Analysis of Variational Ranges in the Results

The scenarios presented in this paper build on secondary data collected and adjusted at different levels of the energy system, from individual technologies to systemic production and consumption patterns, expressed in the form of estimate ranges. Table 5 collects the estimate ranges associated with the main variables in the analysis, for the years 2020 and 2050. Table 6 shows how much each variable contributes to the cumulative emissions at the years 2020 and 2050, reflecting the weight that the variable's estimate range holds in the final interval.

The interval associated with the assessments of yearly operational and infrastructural GHG emissions is determined by a combination of estimate ranges associated with GHG emissions in the base year from which the data is taken and the estimate range associated with the adjustment of emissions as renewable penetration increases, using the squaring method for error propagation. At a higher level, the interval associated with the assessment of consumption patterns can be checked by calculating the lowest and highest values of electricity consumption present in the six EU decarbonisation scenarios. The factors playing the largest impact on the final cumulative GHG emission assessments are the GHG emissions associated with storage infrastructure, curtailment rates and the maximum PHS potential in the EU. Combining the various ranges into the final assessment of cumulative emissions leads to intervals on the order of 35% for the high curtailment scenario and 45% for the high storage scenario. This value is high, especially when it comes to storage GHG emissions and estimations of storage requirements, however, it does not weaken the main message of the analysis.

Table 5. Variational ranges of the variables.

Category	Variable	Unit	2020		2050	
			Average	+/-	Average	+/-
Carbon intensity of technologies	CFC wind power	t CO ₂ eq./GW	906,700	165,000	470,000	108,100
	CFC solar PV	t CO ₂ eq./GW	1,418,000	985,000	735,000	514,500
	CFC PHS	t CO ₂ eq./GWh	33,800	4600	17,500	2800
	CFC BES	t CO ₂ eq./GWh	123,500	18,000	64,000	11,500
	Operation wind power	t CO ₂ eq./GWh	5	1	5	1
	Operation solar PV	t CO ₂ eq./GWh	6	1	6	1
	Operation PHS	t CO ₂ eq./GWh	2	1	2	1
	Operation BES	t CO ₂ eq./GWh	4	1	4	1
Storage	Total storage requirement	GWh	0	0	98,600	32,500
	Efficiency of PHS and BES	%	80	20	80	20
	EU PHS potential	TWh	30	15	30	15
Production and consumption patterns	Total electricity consumption	GWh	3,665,380	146,615	5,140,565	668,273
	Curtailment rate (LSHC)	%	0	0	60	15
	Curtailment rate (HSLC)	%	0	0	20	5

Table 6. Relative contribution of each variable (%) to yearly GHG emissions, 2020 and 2050.

Variable	2020				2050			
	LSHC		HSLC		LSHC		HSLC	
	Mt of CO ₂ eq.	%	Mt of CO ₂ eq.	%	Mt of CO ₂ eq.	%	Mt of CO ₂ eq.	%
Solar PV infrastructure	29.5	3	29.5	3	135.6	48	60	16
Wind infrastructure	23.8	2	23.8	2	109.6	39	48.5	13
PHS infrastructure	0	0	0	0	0	0	0	0
BES infrastructure	0	0	0	0	0	0	233.8	63
Fossil operation	1064.7	95	1064.7	95	0	0	0	0
Solar operation	1.3	0	1.3	0	13.1	5	9.5	3
Wind operation	2.5	0	2.5	0	25.6	9	18.5	5
PHS operation	0.1	0	0.1	0	0.1	0	0.7	0
BES operation	0	0	0	0	0	0	2.1	1
Total	1122		1122		284		373	

4.3. Discussion

To inform decision-making, the type of GHG accounting proposed here is incomplete, as it needs to be associated with economic analyses and with the assessment of other biophysical variables such as land and water. While the high curtailment scenario results in overall lower emissions than the high storage one, it would lead to other trade-offs in different domains, including higher electricity prices and large areas of land occupied by renewable infrastructure. On the other hand, the high storage scenario would also be associated with high levels of lithium requirements (to be imported), which may not be desirable from a security perspective. Additionally, increasing PHS to its maximum potential may have important consequences for natural water cycles. Synergies and trade-offs also emerge within and outside EU borders. A part of the emissions derived in the scenarios would necessarily be located outside of EU borders, such as those for the extraction of primary materials. This points towards the need of discussing the impact of EU climate targets at different geographical scales.

When it comes to the integration of renewable energy, differences across countries are also important and should be modelled in relation to grid flexibility and associated GHG emissions. The Netherlands, for example, is mostly flat and does not have any PHS potential, therefore in an increased flexibility scenario, it would either require high rates of curtailment (which may interfere with current land use patterns) or high interconnections to neighbouring countries. Utilisation factors of technologies also vary across countries, depending on weather conditions. In addition to differences across spatial scales, the temporal scale is also important when considering decarbonisation scenarios: different types of storage services, in fact, are useful for fluctuations occurring at different scales [47]. Current statistics do not allow for this type of analysis. Therefore, it would be advisable for supra-national statistical bodies such as Eurostat to include data across shorter timescales.

The results presented are considered to be conservative, as two elements which have not been included in the model may increase GHG emissions substantially: (i) the change in end-use infrastructure required by an increased electrification of the energy sector (such as the manufacturing of electric cars); and (ii) the turnover of funds. There is uncertainty associated with the possible lifetime of grid-scale batteries [47], however, it is likely that within the 30-year timeframe considered in the study some turnover will be necessary, by either producing new batteries or recycling existing ones.

Accounting for the emission flows associated with funds leads to higher emissions than those envisioned by current scenarios. Thus, results suggest that sustainable production narratives cannot alone lead to a decarbonisation of the energy sector. To be effective, sustainable production efforts must be paired with strong efforts for sustainable consumption [48]. These should not only spurred by mechanisms such as efficiency and technology but also, and crucially, by radical changes in consumption patterns. This is line with the metabolic view of society [49], which draws a clear connection between production and consumption patterns: changes in the way in which energy carriers are produced inevitably require changes in the way in which they are consumed. This may

entail a shift not only in how things are done (structural changes, e.g., technology and efficiency) but also in what is done and why (functional changes, e.g., who is consuming what energy, to do what).

5. Conclusions

Fighting climate change, reducing air pollution and increasing security are three entangled priorities of the EU. Decarbonisation has become a central strategy to deal simultaneously with these disparate targets. However, governing a shift to a decarbonised economy has not been simple. We suggest that this difficulty is partly due to the framing of models used to inform deliberative processes. A focus on the monetary aspects of funds, particularly infrastructure, rather than on the biophysical ones, such as GHG emissions, has minimised discourses linked to the magnitude of the material transformations required to restructure the energy system.

Focusing on the EU power sector in the years 2020–2050, we modelled two decarbonisation pathways in relation to GHG emissions. The scenarios consider operational GHG emissions of electricity generation, as well as those associated with the lifetime of renewable and storage infrastructure. Contrary to the decarbonisation pathways used to inform EU decision-making, the alternative decarbonisation pathways take into account grid flexibility requirements from a biophysical perspective. For the chosen pathways, this entails accounting for the GHG emissions associated either with high rates of curtailment or with storage infrastructure. The results show how emission curves behave differently under different flexibility pathways, and relative peaks of GHG emissions across the years, as well as overall higher cumulative emissions, may emerge depending on the set of assumptions.

Many questions arise from a biophysical problem framing of decarbonisation, for example: What is the best timing to implement technologies? What are the trade-offs among different technological pathways and storage solutions? What trade-offs may emerge between local and global environmental effects? By suggesting that a rapid decarbonisation of the EU power sector by 2050 is “feasible and viable” [14], and therefore glossing over biophysical obstacles to renewable transformations, the scientific tools informing EU decision-making do not open up a space to discuss these crucial issues.

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