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École polytechnique de Louvain

Unequal allocation of Planetary Boundaries using grandfathering sharing principles

Case study: Is transition to renewable energy possible for Belgium's electricity and heat demand covered by fossil fuels ?

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Abstract

This study evaluates the uneven sharing of Planetary Boundaries to assess whether traditional downscaling methods, especially the acquired rights sharing principle based on historical CO_2 emissions, accurately allocate the safe operating space. The feasibility of transitioning Belgium's electricity and heat demand covered by fossil fuels to renewable technologies serves as a case study.

Four sharing principles—egalitarian, grandfathering or acquired rights, prioritarian, and utilitarian—are developed for downscaling the planetary boundaries from the global level to Belgium and then further to the sector level using the acquired rights sharing principle. The share of the safe operating space for electricity and heat demand, differentiated by exergy factors for low, medium, and high-temperature heat, is estimated.

Technological impacts are evaluated using activities from the EcoInvent 3.9 database, and aligned with the Planetary Boundaries framework. Technologies include photovoltaics, onshore and offshore wind, heat pumps for low-temperature heat, and green H_2 for medium and high-temperature heat. Impacts are projected for 2030, 2040, and 2050 using SSP1 and SSP2 scenarios.

The study finds that freshwater use is more constraining than CO_2 for photovoltaics in case of the electricity sector and always for the heat sectors, while nitrogen fixation can be more constraining for heat sectors, highlighting the need for unevenly sharing planetary boundaries. The results indicate that a transition is feasible only with the utilitarian & acquired rights sharing principles, but the installable photovoltaics capacity remains very low because of its high impacts on the planetary boundaries. Therefore, significant impact reductions for photovoltaics are necessary for a realistic transition within the safe operating space.

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I would like to mention that I used ChatGPT for initial inspiration, text editing, coding, and plotting. However, all the research work is entirely my own and has been thoroughly sourced.

Contents

Abbreviations

AA	Acquired Rights & Acquired Rights sharing principle
AF	Allocation Factor
ASR	Absolute Sustainability Ratio
CF	Characterisation Factor
CO2	Carbon Dioxide Planetary Boundary
E	Electricity demand covered by fossil fuels sector
EA	Egalitarian & Acquired Rights sharing principle
FWU	Freshwater Use Planetary Boundary
H	Heat demand covered by fossil fuels sector
HT	High Temperature
LCI	Life Cycle Inventory
LFC	Land-Forest Change Planetary Boundary
LT	Low Temperature
LV	Level
MT	Medium Temperature
N	Nitrogen Planetary Boundary
NG	Natural Gas
OA	Ocean Acidification Planetary Boundary
PA	Prioritarian & Acquired Rights sharing principle
PB	Planetary Boundary
PB-LCIA	Planetary Boundaries Life Cycle Impact Assessment
PV	Photovoltaics
RF	Radiative Forcing Planetary Boundary
SP	Sharing Principle
SOS	Safe Operating Space
SoSOS	Share of the Safe Operating Space
UA	Utilitarian & Acquired Rights sharing principle

1 Introduction

For approximately the past 10,000 years, Earth has remained in a remarkably stable interglacial state, as compared to the previous dynamic fluctuations. This period is known as the Holocene epoch, and it has provided favourable weather conditions, allowing humans to establish settlements. As modern civilisation has evolved, mounting pressures on the Earth's system have pushed it beyond the variability observed during the Holocene. This has ushered in a new era known as the Anthropocene [1], characterised by the introduction of an additional component interacting with the Earth's system—the anthroposphere (all human activities). This novel layer complements the existing components that have interacted for over 3 billion years, namely the geosphere (comprising Earth's inanimate elements and the flow of energy within its environment) and the biosphere (encompassing all ecosystems and living entities). In an endeavor to establish measurable boundaries for maintaining the Earth's Holocene state, scientists have formulated the Planetary Boundaries (PB) framework [2, 3]. Its objective is to delineate thresholds or tipping points that should not be breached, thereby ensuring the preservation of this state and preventing significant alterations in environmental conditions. This framework defines a safe operating space (SOS) for the nine boundaries representing the state of the Earth's system: Climate change, Change in biosphere integrity, Stratospheric ozone depletion, Ocean acidification, Biogeochemical flows: P and N cycles, Land system change, Freshwater change, Atmospheric aerosol loading and Novel entities [4]. At present, it is estimated that six out of the nine tipping points have been crossed [4], with the boundaries related to stratospheric ozone depletion, ocean acidification, and atmospheric aerosol loading remaining unbreached as of the latest estimations .

The PB framework offers a strong contrast to the traditional Life Cycle Assessment (LCA) methods due to the nature of how impacts are assessed. The first evaluates nine absolute ecological thresholds that should not be breached for Earth to remain in its steady state, while the latter measures the impacts of a system by comparing it with a reference system [5], doing this by attributing an impact score to the various impact categories [6]. It can therefore be questioned whether the relative intrinsic nature of LCAs is adequate for assessing the sustainability of a system, as Earth (and thus the reference system on which the LCA method is based) is already beyond the SOS for humanity [4]. Absolute environmental sustainability assessments (AESAs) should as a consequence be preferred over proportional reductions based on transition scenarios [7, 8]. Absolute sustainability is defined as "staying within the allocated share of the safe operating space within one or more environmental impact categories" [9]. Moreover, most LCAs currently emphasise the climate change impact category, which fails to give a comprehensive overview of all the ecological impacts that must not be underestimated, as underscored in the PB framework.

Consequently to the shift of nature of sustainability assessments, two methodologies were proposed to adapt the framework to e.g., strategic decision-making in companies [10], corporate sustainability [11] and policy-making for Earth governance [12]. The first method applies carrying capacities to limit traditional LCA indicators to represent absolute sustainability [13]. This approach utilises the impact categories from a conventional LCA, which, however, do not correspond directly with the PBs that signify absolute sustainability markers. Alternatively, the second method, on which this study will be focused, integrates PB control variables directly as impact indicators, thereby offering a more refined and directly applicable evaluation tool for assessing absolute sustainability [14]. This method requires the definition of characterisation factors (CFs) which assess the impacts of each elementary flow on the control variables of the PB framework [14].

A key challenge in conducting an Environmental Sustainability Assessment (AESA) lies in the fact that the full Safe Operating Space (SOS) cannot directly assess the sustainability of an actor or activity (referred to as system) due to scale differences (scale of an activity in contrast with planetary scale) [13, 15]. To make the concept of SOS operational, a portion of it must be allocated to the system under study. Thus, determining whether the impacts of a system exceed its allocated share of the SOS (SoSOS) allows for an assessment of absolute sustainability [16]. The allocation process, or downscaling, depends on various theories of distributive justice, including egalitarianism, utilitarianism, prioritarianism, and the principle of grandfathering (acquired rights) [17]. Employing one or a combination of these theories helps in establishing sharing principles (SPs), which facilitate the SOS allocation. Presently, the common method for downscaling involves applying the same sharing principle across all PBs (mostly the egalitarian SP, and the acquired rights SP based on historical CO_2 emissions [17]), thus applying the same allocation factor to all PBs. This contrasts with the approach that will form the core of this study, which recommends tailor-allocating the shares of the SOS by historical impact (not only CO_2 emissions), to avoid over-allocation for systems with minimal impact on a given PB, or under-allocation for those critically reliant on it. As the choice of SP for downscaling is inherently subjective and relies on normative judgements [17], this study does not aim to prioritise any particular SP. Instead, it aims to develop various SPs, each yielding different results. The comprehensiveness of these results will provide a nuanced overview from which effective conclusions can be taken.

This study proposes to illustrate the concept of unequally sharing the Planetary Boundaries (PBs) by assessing the feasibility of transitioning Belgium's electricity and heat demand, currently covered by fossil fuels, to renewable energy sources. This assessment explicitly excludes the existing contributions from renewables and nuclear energy, as well as heat generation capacity powered by electricity, all of which are presumed to remain unchanged. Hence, only 22241GWh$_{\text{elec}}$ of electricity production from natural gas (the primary source of electricity from fossil fuels) is considered in this study, representing the electricity that needs replacement, out of the total 95193GWh$_{\text{elec}}$ corresponding to Belgium's electricity production [18]. Similarly, an assumption is applied to assess the amount of fossil fuels effectively used for heat production. The process involves two main steps: first, developing a new model to allocate shares of the SOS to the considered sectors—sectors characterised by the proportion of electricity and heat demand covered by fossil fuels, with heat demand further differentiated by capacity and temperature into low (LT), medium (MT), and high temperature (HT) categories. Secondly, an alternative renewable technology mix is proposed for each sector (electricity, LT heat, MT heat, and HT heat). The impacts (per GW) per PB are compared to the allocated shares of the SOS to determine the capacity that can be installed, effectively conducting a Planetary Boundaries Life Cycle Impact Assessment (PB-LCIA). It is then assessed which SPs and PBs can satisfy the sectoral demand.

Concretely, the technologies considered are: photovoltaics (PV), onshore wind, and offshore wind for electricity; heat pumps (HPs) supplied by the previously mentioned technologies for LT heat; and green hydrogen combustion for MT and HT heat, also supplied by the same technologies. To observe the temporal evolution of the proposed mixes, a prospective LCA (pLCA) approach is suggested. In this approach, the EcoInvent 3.9 Life Cycle Inventory (LCI) [19] in ActivityBrowser [20] is projected for the years 2030, 2040, and 2050. This projection is conducted using the Python *premise* package [21], an extension of Brightway2 [22], which is a Python open-source software for conducting LCAs. The SSP1 (sustainability) and SSP2 (middle of the road) scenarios [23] are followed for this projection, as they align with the transition and are therefore pertinent to this study.

The decision to exclude the transport sector (passenger and freight mobility), which relies on fossil fuels or electricity produced with fossil fuel technologies, was based on this segmentation approach and one additional important consideration: large-scale electrification, along with widespread infrastructure development for new fuels such as hydrogen, will be necessary for the transport sector's transition. This transition is anticipated to bring about a greater coupling between the transport and power generation sectors, which in turn will necessitate an increase in the installed power generation capacity [24]. In contrast, despite a small electricity demand (2.2% [18]) from the transport sector in Belgium in 2021—approximately half of which could be attributed to fossil fuels—the transport sector remains largely decoupled from the power and heat generation sectors. Consequently, this approach focuses on sectors where transitioning to existing alternative technologies is immediately actionable.

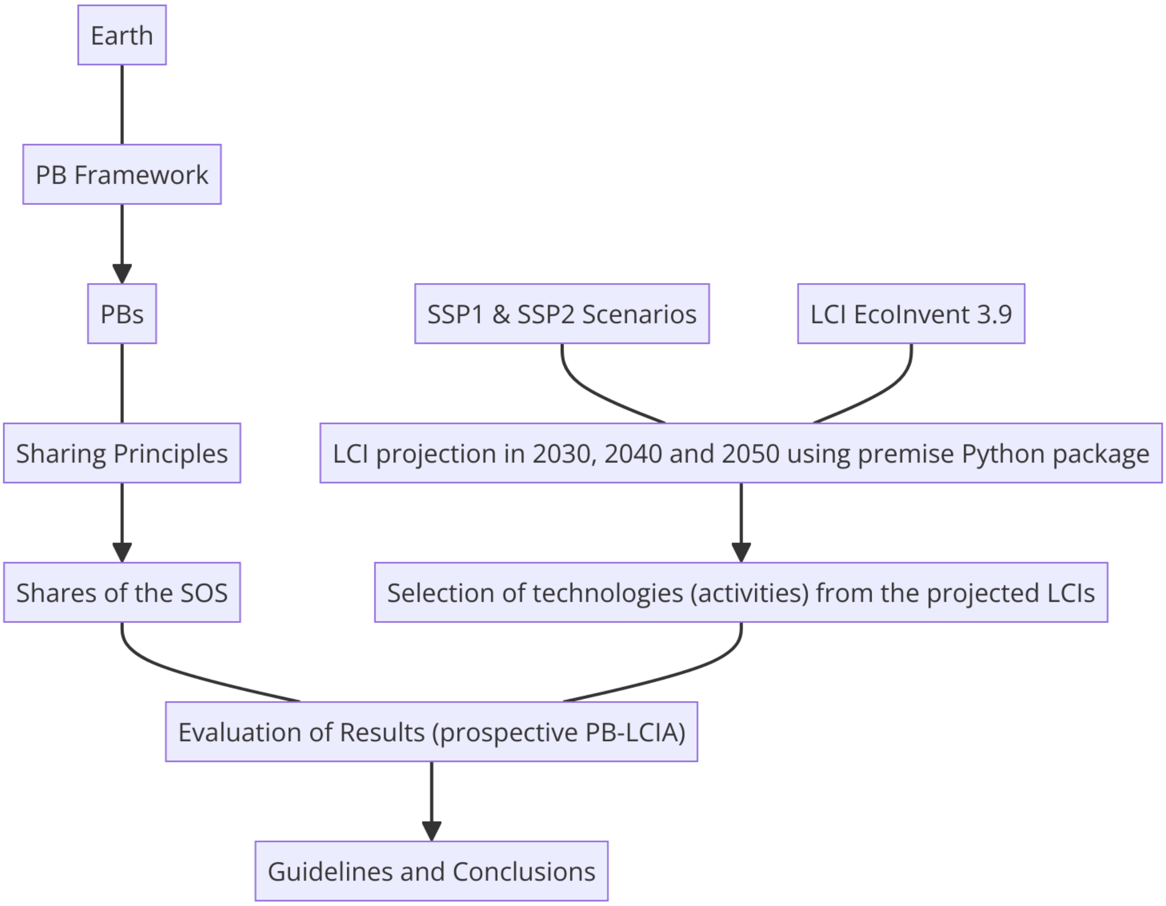

Figure 1: The flowchart summarises the process followed in this study to obtain the results.

2 Methodology - Allocating the Safe Operating Space

2.1 Model structure

This research aims to devise a model that evaluates an SoSOS for the different PBs for both the electricity (E) and heat (H) demand sectors covered by fossil fuels in Belgium. The objective was to create a simple downscaling model limited to a maximum of three steps to reduce uncertainty—a concern noted in the literature (more steps, more uncertainty [15]). The model is intended to assess the impacts of these sectors to evaluate the allocated shares of the SOS and compare them with the impacts of renewable energy mixes. This comparison aims to determine the feasibility of replacing fossil fuels with more sustainable solutions.

Furthermore, the AFs are fixed and not time-dependent. While the technology impacts can evolve over the years, the fixed AFs provide a consistent allocation of the SOS, enabling the assessment of the feasibility and timing of the transition.

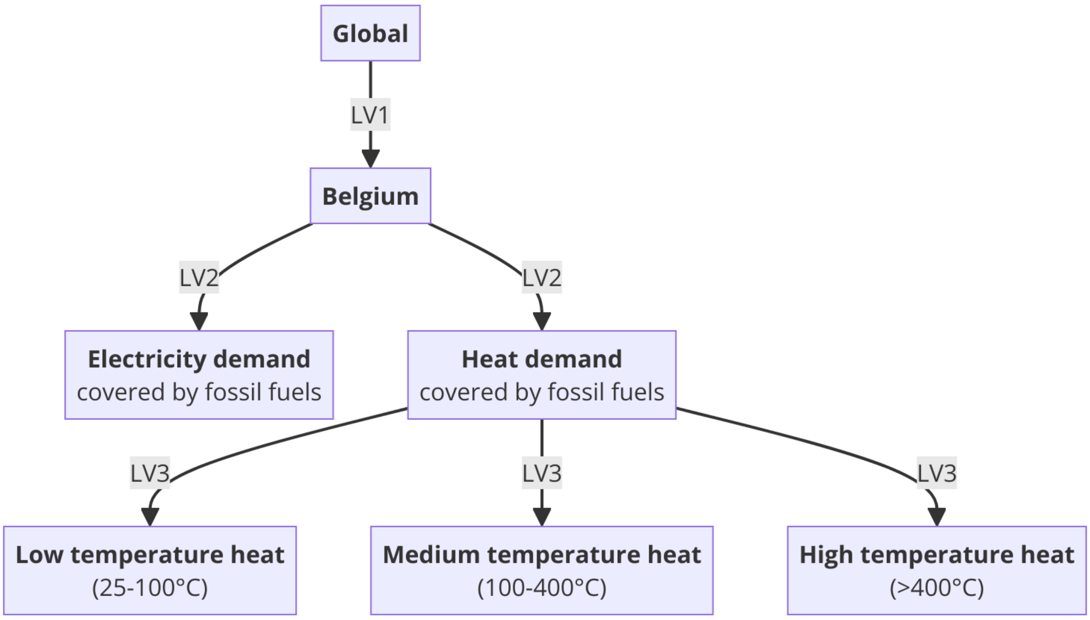

Figure 2: The flowchart illustrates that the electricity generation sector is addressed in two downscaling steps, whereas the capacity-temperature differentiation within the heat generation sector constitutes a third downscaling step.

The first downscaling step transitions from the global scale to the country scale, utilising four sharing principles: egalitarian, acquired rights, prioritarian, and utilitarian (by frequency of use [17]). As mentioned in the Introduction, since SPs are inherently normative, all SPs are included to offer a comprehensive overview of the implications of each one. The sufficientarian principle was excluded due to the challenge of defining what 'enough' means and the concern that ensuring 'enough' for everyone would result in exceeding the planetary boundaries for climate change and biogeochemical flows [25]. Belgium was selected for this study due to its relevance to the author and supervisors, as this study is conducted within the École Polytechnique de Louvain (EPL), which is located in Belgium. Further downscaling precisely targets the E and H sectors within Belgium, applying the acquired rights principle based on the historical impacts on each PB. To minimise increased uncertainty associated with additional downscaling steps, this study directly focuses on the E and H sectors within Belgium, rather than initially narrowing down to the broader energy sector. This approach aligns with recommendations from previous studies on value-based choices in downscaling processes [15].

The sharing principles in this study will be referred to as egalitarian & acquired rights (EA), acquired rights & acquired rights (AA), prioritarian & acquired rights (PA), and utilitarian & acquired rights (UA), corresponding to the principles used for the two main downscaling steps.

Another issue was defining the energy sector and, thus, its subsectors, which can be approached in various ways. For this research, the most relevant definition centers on the energy production needed to meet demand, focusing exclusively on the power and heat generation subsectors and their respective technologies. The transport demand subsector, which includes passenger and freight transport, was excluded to ensure the study remains within its predefined scope as outlined in the Introduction section. Ultimately, to account for the quality of the produced heat, which is reflected by its temperature level, and not merely the installed capacity that understates the challenge of generating heat at higher temperatures (or the resources required), exergy will be used as tool for differentiation. This approach enables the allocation of a larger share to the high-temperature heat generation sector, which is necessary since the technologies involved are more difficult to replace. In the following subsections, all these downscaling steps are going to be discussed in detail.

2.2 Downscaling from world to country scale - Level 1 (LV1)

The decision to focus on Belgium for the initial downscaling step is influenced by several factors. Primarily, this approach facilitates the incorporation of various sharing principles initially, accommodating different ethical perspectives. Secondly, the country scale is commonly used in the literature [17]. The sharing principles selected for this stage are egalitarian, acquired rights, prioritarian, and utilitarian. The AF, $\alpha_{principle,country,PB}$, is defined as follows to downscale to the country level:

$$aSOS_{principle,country,PB} = \alpha_{principle,country,PB} \cdot SOS_{PB} \tag{1}$$

Where SOS_{PB} represents the full safe operating space for the considered PB (or SOS available to humanity) and $aSOS_{principle,country,PB}$ the share of the SOS allocated to the country of interest for the considered sharing principle. The PBs considered in this study are: both CO_2 emissions (CO2) and energy imbalance in the atmosphere or radiative forcing (RF) within the climate change PB, ocean acidification (OA), industrial and intentional N fixation (N), land system change (referred to as land forest change in this study) at global (G) and biome (B) level, and freshwater change (blue) referred to as freshwater use (FWU). The PB related to phosphorus (P) is not calculated because initial attempts to compute its impact revealed negligible effects from the E and H sectors on the P cycle. This finding is supported by explanations from the University of California, Berkeley, which highlight the minimal involvement of these sectors in disrupting the phosphorus cycle [26]. In contrast, N impacts are significant due to NO_x emissions, as discussed in the corresponding Berkeley source [27].

2.2.1 Egalitarian principle

Several options can be considered for per capita allocation: Immediate Equal Per Capita Allocation (IEPC) or Equal Cumulative Per Capita Allocation (ECPC) [28]. IEPC takes the current population figure of Belgium (pop_{Bel})[29] and the global population (pop_{world})[30] to estimate the share to be allocated. In contrast, the ECPC principle accumulates these populations over a certain period to account for the rights of future generations, which can be estimated using various SSP scenarios [28]. The calculation remains the same. Given the focus of this paper on fixing the AFs based on historical rights, IEPC is chosen.

$$\alpha_{egal,country} = \frac{pop_{country}}{pop_{world}} \tag{2}$$

2.2.2 Acquired rights principle

The specificity of the acquired rights SP arises from the fact that its metric can be tailored to the PB of interest, unlike other sharing principles that apply a single metric regardless of the PB in question. Even though the state of the climate change PB is currently often used to downscale all PBs, this study aims specifically to assess the feasibility of replacing fossil fuel power and heat generation in Belgium with better, fuel-free alternatives. Therefore, the goal is to precisely evaluate each PB to determine which are currently most impacted. Consequently, the acquired rights principle will allow for the uneven sharing of the PBs, representing a relatively innovative approach.

$$\alpha_{acq,country,PB} = \frac{impact_{country,PB}}{impact_{world,PB}} \tag{3}$$

The $impact_{World,PB}$ values of the control variables are taken from the Richardson et al. [4] paper and represent the current state of the control variables.

Calculation of impacts at Belgium's scale - CO2, RF and OA boundaries

The CO2, RF, and OA PBs are closely linked, as expressed in Rockström et al. [2] and Richardson et al. [4]. RF reflects changes in the energy entering and leaving Earth, which depend on the concentration of GHGs in the atmosphere. OA directly results from the ocean's absorption of CO2, which forms the main part of the GHG emissions [31]. Therefore, these PBs are assigned the same SoSOS based on the amount of GHGs emitted in Belgium and the world. For this, the $MtCO_{2\text{-eq}}$ metric is used instead of the control variables defined in [4] to compute the AF. This AF, which is assigned to CO2, RF, and OA PBs, represents a proportion that remains representative for each PB. For example, the allocated proportion based on ppm values is similar to those based on $MtCO_{2\text{-eq}}$ values. Since the $impact_{world,PB}$ value of the chosen metric cannot be found in [4], it has been independently determined [32].

Variable	**Value**	**Description**
GHG_{world}	53.79 $GtCO_{2-eq}$ [32]	Annual global GHG emissions
$GHG_{Belgium}$	106.5 $MtCO_{2-eq}$ [33]	Annual GHG emissions in Belgium

Table 1: Data for computation of CO2, RF and OA impacts at Belgium's scale

Calculation of impacts at Belgium's scale - N boundary

Variable	Value	Description
A_{Bel}	3068900 ha [34]	Total area of Belgium.
$N_{\text{surplus,Bel}}$[1]	$80\,\frac{\text{kg}}{\text{ha}\cdot\text{year}}$	Nitrogen surplus per hectare per year in Belgium.

Table 2: Data for computation of N impact at Belgium's scale

The $N_{surplus,Bel}$ value, which represents the difference in nitrogen fixation compared to the Holocene, is based on a model that accounts for all the different mechanisms of nitrogen fixation and removal (see Figure 1 of Batool et al. [35]). Therefore, the total amount of nitrogen fixated in Belgium can be quickly calculated by multiplying this value by the area of the country. Water bodies are not excluded from the calculation, as they also contribute to nitrogen fixation.

$$N_{\text{fix,Bel}} = impact_{Belgium,N} = A_{\text{Bel}} \cdot N_{\text{surplus,Bel}} = 0.25\,\frac{\text{TgN}}{\text{year}}$$

Calculation of impacts at Belgium's scale - LFC boundary

The control variable defined by Richardson et al. [4] for this PB is the remaining forest cover compared to the early Holocene, which is given both at biome (LFC-B) and global (LFC-G) level. The total budget (or SOS available to humanity) to be allocated is the amount of forest that can be deforested. By analogy, following calculations aim to estimate the total amount of forest that has already been deforested.

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[1] Derived from Figure 2 p.14 of [35], which represents the N surplus in Europe in 2015.

Variable	Value	Description
A_{Bel}	30689 km^2 [34]	Total area of Belgium
$\%_{\text{land,Bel}}$	93.5 % [36]	Percentage of land area in Belgium
$\%_{\text{T-forest}^1\text{,Hol,Bel}}$	± 80%[2] [37]	Estimated total forest cover in Belgium during the Holocene
$\%_{\text{T-forest,2021,Bel}}$	22.76% [38]	Current forest cover in Belgium (2021)
A_{Euro}	10.18 million km^2 [39]	Total area of Europe
$\%_{\text{forest,2021,Euro}}$	± 33%[3] [40]	Current forest cover in Europe (2021)
$\%_{\text{T-forest,Euro}}$	50%[4]	Percentage of temperate forest in Europe
$\%_{\text{r-forest}^5\text{,Euro}}$	34.2% [4]	Remaining forest cover in Europe
$\%_{\text{r-forest,Asia}}$	37.9% [4]	Remaining forest cover in Asia
$\%_{\text{r-forest,Amer}}$	51.2% [4]	Remaining forest cover in the Americas

Table 3: Data for computation of LFC impact at Belgium's scale

First, the impact in Belgium must be calculated ($impact_{Belgium,LFC-B\&G}$) corresponding to the total deforested area in Belgium ($A_{d-forest,Bel}$) is calculated by considering the difference in forest cover percentage between the Holocene and 2021 applied to the land area of Belgium:

$$A_{\text{d}^6\text{-forest,Bel}} = A_{\text{Bel}} \cdot \%_{land,Bel} \cdot (\%_{\text{T-forest,Hol,Bel}} - \%_{\text{T-forest,2021,Bel}}) = 16424.6 \text{ km}^2$$

The first step in determining $impact_{world,PB}$ or equally $A_{T-deforest,world}$, is to calculate the current temperate forest cover in Europe:

$$A_{\text{T-forest,2021,Euro}} = A_{\text{Euro}} \cdot \%_{\text{forest,2021,Euro}} \cdot \%_{\text{T-forest,Euro}} = 1.68 \text{ million km}^2$$

The historical temperate cover in Europe is calculated by taking the remaining forest cover in Europe into account:

$$A_{\text{T-forest,Hol,Euro}} = \frac{A_{\text{T-forest,Euro}}}{\%_{\text{r-forest,Euro}}} = 4.91 \text{ million km}^2$$

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[1] "T-forest" stands for "temperate forest", which is assumed to be the only forest biome in Belgium [41].

[2] Derived from the multiplication of the total forest area (±90%, Figure 4 p.8) and the denseness (87.5%, as contrary of the openness, Figure 6 p.10) in [37].

[3] It is assumed that the forest cover (as a percentage) found for the European Union (EU) is also valid for Europe (Euro).

[4] From Figure 1 of [41], a rough approximation for Europe's proportion of temperate forest is 50%.

[5] "r-forest" stands for "remaining forest cover" and is defined as the proportion of the forest cover during the early Holocene.

[6] "d-forest" stands for "deforested forest".

The assumption is made that the temperate forest cover during the Holocene in Asia and the Americas was approximately half of Europe's based on Figure 1 of [41]:

$$A_{\text{T-forest,Hol,Asia}} = A_{\text{T-forest,Hol,Amer}} = 2.455 \text{ million km}^2$$

These values allow us to calculate the area of temperate forests that have been lost in each region due to deforestation. In Europe:

$$A_{\text{d-T-forest,Euro}} = A_{\text{T-forest,Hol,Euro}} - A_{\text{T-forest,Hol,2021}} = 3.23 \text{ million km}^2$$

In Asia:

$$A_{\text{d-T-forest,Asia}} = A_{\text{T-forest,Hol,Asia}} \cdot (1 - \%_{\text{r-forest,Asia}}) = 1.52 \text{ million km}^2$$

And in the Americas:

$$A_{\text{d-T-forest,Amer}} = A_{\text{T-forest,Hol,Amer}} \cdot (1 - \%_{\text{r-forest,Amer}}) = 1.2 \text{ million km}^2$$

Finally, the total deforested temperate forest ($impact_{world,LFC-B}$) corresponding to $A_{\text{d-T-forest,Hol,world}}$ can be computed:

$$A_{\text{d-T-forest,world}} = A_{\text{d-T-forest,Euro}} + A_{\text{d-T-forest,Asia}} + A_{\text{d-T-forest,Amer}} = 5.95 \text{ million km}^2$$

For comparison, the total deforested forest ($impact_{world,LFC-G}$), which includes the boreal and tropical biomes, is 20 million km^2 [42].

Calculation of impacts at Belgium's scale - FWU boundary

The metric chosen to assess the impact on the FWU boundary is km³, by analogy with the Ryberg et al. [8] paper, as it is more straightforward than using the "upper limit (95th percentile) of global land area with deviations greater than during preindustrial, blue water". Consequently, the $impact_{world,FWU}$ value must also be determined. The water consumption for Belgium was found in [43], although this value is labeled as "water use: water withdrawals". It is supposed to fit the definition of water consumption, which is water consumed that is not directly returned to surrounding river basins or lakes. This definition contrasts with "water withdrawal", which includes water that is returned directly to the surrounding environments, such as in industrial cooling processes.

Variable	**Value**	**Description**
$V_{\text{cons,world}}$	$4600\frac{\text{km}^3}{\text{year}}$ [44]	Annual water consumption of the world
$V_{\text{cons,Belgium}}$	$9.03\frac{\text{km}^3}{\text{year}}$ [43]	Annual water consumption in Belgium

Table 4: Data for computation of FWU impact at Belgium's scale.

2.2.3 k-prioritarian principle

For the prioritarian principle, which aims to prioritise those who are worse off, an "ability to pay" approach is chosen [45], wherein the SoSOS allocated is larger for countries with smaller GDP per capita. This incentivises countries with larger GDP per capita to make greater efforts to reduce their environmental footprints, which often correlates with GDP per capita. For this, the equation from Hjalsted et al. [25], which assigns an SoSOS to an individual, was adapted and scaled to the country level by multiplying by $pop_{country}$. The α factor is calculated[1] such that the sum of all distributed shares equals one, ensuring that the full SOS is not exceeded; it is thus computed as the inverse of the sum of all non-adapted shares (shares not yet multiplied by α).

$$\alpha_{prio,country} = \frac{(GDP/cap)_{\text{world}}}{(GDP/cap)_{\text{country}}} \cdot \frac{\text{pop}_{\text{country}}}{\text{pop}_{\text{world}}} \cdot \alpha \tag{4}$$

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[1] Excel files for population and GDP by country for the year 2022 were retrieved from the "GDP" and "Population, total" pages of [46]. All countries without available data were not considered.

$$\begin{cases} \text{if } \frac{(GDP/cap)_{world}}{(GDP/cap)_{country}} > 1 & \rightarrow \text{prioritised country (below average GDP per capita)} \\ \text{if } \frac{(GDP/cap)_{world}}{(GDP/cap)_{country}} < 1 & \rightarrow \text{not prioritised country (above average GDP per capita)} \\ \alpha = \frac{pop^2_{World}}{GDP_{world} \cdot \sum_{country} [\frac{pop^2_{country}}{GDP_{country}}]} & \rightarrow = 0.243 \text{ (2017, [25]) and } 0.252 \text{ (2022, personal calculation)} \end{cases}$$

The calculations revealed a significant difference in the shares allocated to Belgium and Burundi, despite their similar size and population. Belgium's share per capita was $8.06 \cdot 10^{-12}$, while Burundi's was $1.55 \cdot 10^{-9}$—over 190 times larger. This discrepancy highlighted the need for flexibility in the prioritarian SP to account for such differences and ensure a more equitable distribution that supports the ecological transition for all countries. To address this, the formula was adapted to make the prioritarian SP more suited to ecological transitions, providing a more substantial SoSOS to developed countries while still prioritising developing countries. The core mechanics of the principle remain unchanged; only the scale of deviation from the world average GDP per capita is reduced by dividing by a factor k.

$$\alpha_{k-prio,country}(k) = \left[\frac{(GDP/cap)_{\text{world}}}{(GDP/cap)_{\text{country}}} + \left(1 - \frac{(GDP/cap)_{\text{world}}}{(GDP/cap)_{\text{country}}}\right) / k \right] \cdot \frac{\text{pop}_{\text{country}}}{\text{pop}_{\text{world}}} \cdot \alpha(k) \tag{5}$$

$$\text{with} \quad \alpha(k) = \frac{1}{\sum_{country} \left[\left(\frac{(GDP/cap)_{\text{world}}}{(GDP/cap)_{\text{country}}} + \left(1 - \frac{(GDP/cap)_{\text{world}}}{(GDP/cap)_{\text{country}}}\right) / k \right) \cdot \frac{\text{pop}_{\text{country}}}{\text{pop}_{\text{world}}} \right]} \tag{6}$$

Two interesting properties of the proposed principle are:

$$\begin{cases} \lim_{k \to 1}(\alpha_{k-prio,country}(k)) = \alpha_{egal,country} \\ \lim_{k \to \infty}(\alpha_{k-prio,country}(k)) = \alpha_{prio,country} \end{cases}$$

Now, the remaining step is to determine the k factor in a 'just' way, which is going to be done graphically by considering a sample of countries that cover the whole 'spectrum of development', including Belgium as it is the focus of this study. The following countries are thus chosen: Belgium, Burundi, China, Russia, USA, and Zimbabwe. To keep the graph clear, the values computed for a country are sometimes uniformly divided by a scaling factor (SF), indicated in the legend if applied. The metrics chosen to make the choice are the fractions between the k-prioritarian principle and the prioritarian and egalitarian principles, respectively. This allows us to see the order of magnitude of the change brought by the factor k.

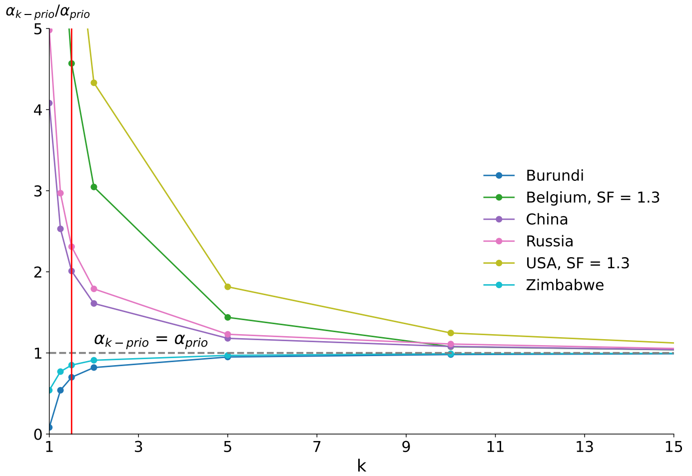

Figure 3: By choosing $k = 1.5$, Belgium's share increases significantly while still providing a substantial SoSOS to developing countries. This adjustment results in a more realistic SoSOS for the transition of developed countries, without over-penalising the developing countries. For large k values, the value of the division reaches 1, as predicted by the calculation of the limit, reaching the initial prioritarian principle. The k-prioritarian formula is highly sensitive to values of k between 1 and 2.

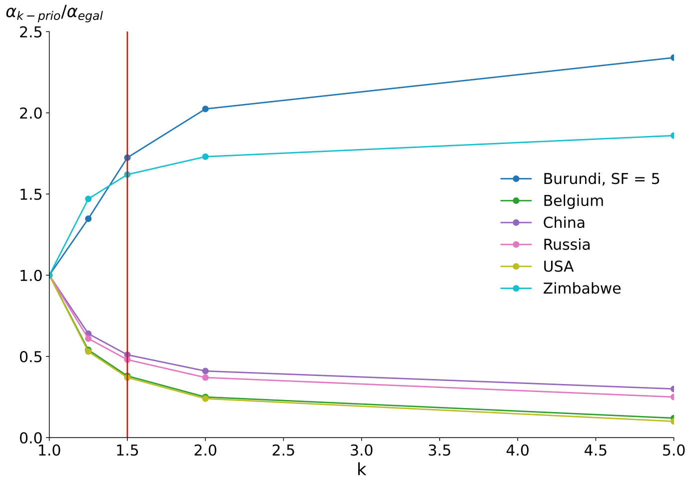

Figure 4: This graph compares the k-prioritarian principle with the egalitarian principle. By fixing $k = 1.5$, the shares allocated to the developed countries in the sample are more balanced, while still providing a substantial share to developing countries. When k reaches 1, the egalitarian principle is obtained.

From analysing the graphs, it is concluded that fixing $k = 1.5$ gives a share per capita of $4.79 \cdot 10^{-11}$ to Belgium, while Burundi gets $1.09 \cdot 10^{-9}$, which is only 22 times larger. Burundi is the country for which the proportion of the SoSOS allocated using the prioritarian SP versus the k-prioritarian SP is the worst, indicating that all other developing countries are less affected, while all developed countries benefit from the k-prioritarian SP drastically.

To provide a clear comparison, the following table presents the prioritarian and k-prioritarian values for the five considered countries:

Country	Development Status	prioritarian SoSOS	k-prioritarian SoSOS
Belgium	Developed	$8.06 \cdot 10^{-12}$	$4.79 \cdot 10^{-11}$
Burundi	Developing	$1.55 \cdot 10^{-9}$	$1.09 \cdot 10^{-9}$
China	Developed	$3.19 \cdot 10^{-11}$	$6.37 \cdot 10^{-11}$
Russia	Developed	$2.59 \cdot 10^{-11}$	$5.99 \cdot 10^{-11}$
USA	Developed	$5.28 \cdot 10^{-12}$	$4.50 \cdot 10^{-11}$
Zimbabwe	Developing	$2.40 \cdot 10^{-10}$	$2.03 \cdot 10^{-10}$

Table 5: Comparison of prioritarian and k-prioritarian SoSOS for selected countries

Given the sensitivity of the k-prioritarian formula and the potential for subjectivity in choosing k, this principle will be included as an additional sharing principle for comparison. However, the core analysis will focus on the other sharing principles. The results of the SoSOS computed using the k-prioritarian principle will be presented for reference but not analysed as extensively as the others.

2.2.4 Utilitarian principle

To evaluate Belgium's share, the metric chosen is the GDP in order for the downscaling factor to reflect its total economic wealth. This choice is also made because GDP data is readily available and facilitates comparison.

$$\alpha_{util,country} = \frac{GDP_{country}}{GDP_{World}} \tag{7}$$

2.2.5 Computed AFs for LV1 downscaling (from World to Belgium)

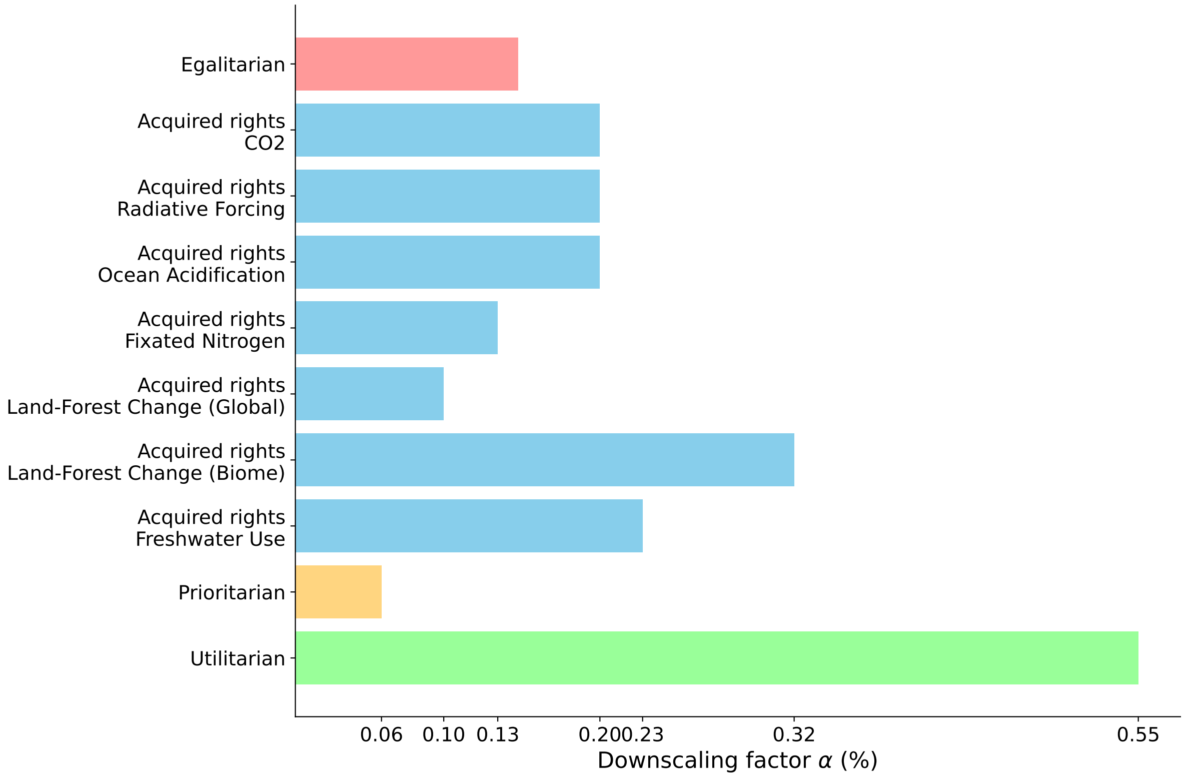

Figure 5: The downscaling factors are presented according to the frequency of use of the corresponding SP [17]. For the acquired rights principle, which is based on historical impacts, a downscaling factor was calculated for each PB, illustrating the concept of uneven sharing of the PBs. Overall, when comparing the allocated shares of the SOS, the prioritarian principle results in the smallest share, while the utilitarian principle yields the largest share, followed by the acquired rights and egalitarian principles. This distribution aligns more or less with the expected trend in Hjalsted et al. [25], where the prioritarian SP, labelled "ability to pay" in the paper, allocated the smallest SoSOS to Denmark (thus smaller AF), which is a developed country. By contrast to the Hjalsted et al. paper, where the egalitarian and acquired rights SP allocate more or less the same SoSOS, the shares allocated in this study with the acquired rights SP oscillate around the egalitarian SP, with a tendency to be slightly larger. The utilitarian principle is not computed in Hjalsted et al., but the large AF in this study can be explained by the large GDP of Belgium, relative to its size or population, when compared with other countries in the world. The available SOS at the world level and the computed SoSOS for Belgium are provided in Appendices A.1 and A.2, respectively.

2.3 Downscaling from country scale to electricity and heat demand in Belgium covered by fossil fuels - Level 2 (LV2)

Selecting the acquired rights principle facilitates an accurate assessment of the impacts of the electricity (E) and heat (H) demand sectors covered by fossil fuels on the PBs. Indeed, trying to determine the population or GDP attributable to the E and H sectors would prove complicated. However, an approach combining downscaling and upscaling is proposed in Hjalsted et al. [25] to address this issue, though it cannot be applied to each PB separately. Therefore, the selection of the acquired rights principle is best adapted to tackling the PBs individually. By analogy with LV1 downscaling, the AF is defined as follows:

$$aSOS_{\text{principle-acq,sector,PB}} = \beta_{\text{acq,sector,PB}} \cdot aSOS_{\text{principle,country,PB}} \tag{8}$$

Where "principle" refers to the downscaling principle chosen to downscale to the country level, "sector" refers to the electricity or heat sector, and "acq" represents the acquired rights principle. $aSOS_{\text{principle-acq,sector,PB}}$ represents the aSOS to the electricity or heat sector by applying one of the four principles defined for LV1 and then the acquired rights principle.

With the AF $\beta_{\text{acq,sector,PB}}$:

$$\beta_{acq,sector,PB} = \frac{impact_{sector,PB}}{impact_{country,PB}} \tag{9}$$

For the electricity sector, this step represents the final stage of downscaling. An example of the entire downscaling process is as follows: To determine the allocated share of the SOS for the E sector in Belgium, specifically for the CO2 planetary boundary (PB), the egalitarian principle is applied first at Level 1 (LV1) and then the acquired rights principle at Level 2 (LV2). This complete sequence of steps in the downscaling chain yields the following results:

$$aSOS_{\text{egal-acq,elec,CO2}} = \alpha_{egal,Bel,CO2} \cdot \beta_{\text{acq,elec,CO2}} \cdot SOS_{CO2} \tag{10}$$

2.3.1 Calculation of impacts of electricity and heat sectors - CO2, RF and OA boundaries

For these PBs specifically, the AF $\beta_{\text{acq,sector,PB}}$ is not determined using eq.9, but rather based on the GHG emission shares presented in Figure 6. The calculation is conducted simultaneously for the electricity and heat sectors by determining the proportion of emissions per sector attributable to electricity or heat demand. The bar chart in Figure 6, derived from the pie chart in [47], represents the global share of GHG emissions for each sector. It is assumed this distribution also applies to Belgium. As described in the caption of Figure 6, the GHG emission sectors unrelated to the E and H sectors are eliminated before proceeding with the calculations.

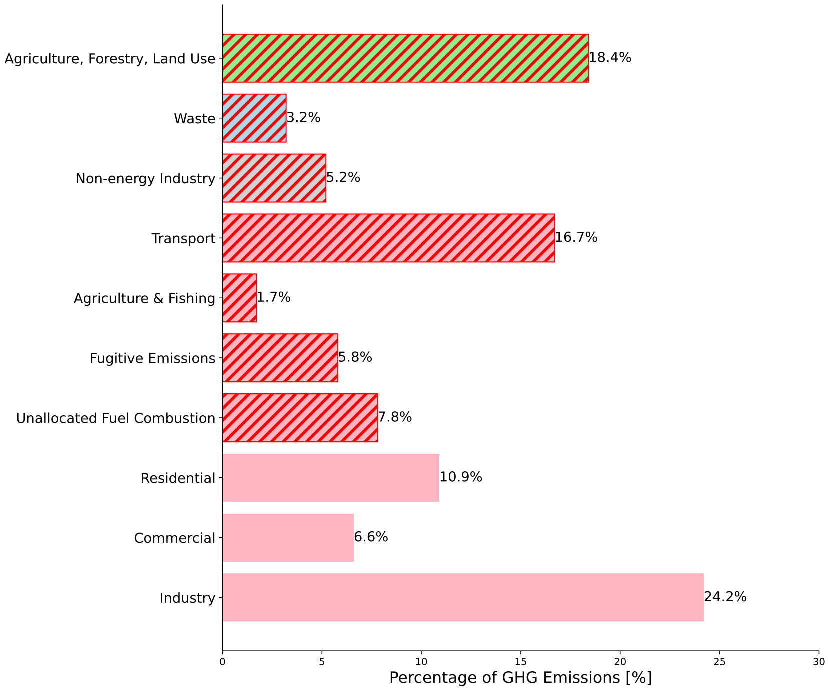

Figure 6: To determine which shares can be downscaled to the electricity and heat sectors, the following sectors are eliminated: non-energy-related sectors such as agriculture, forestry, and land use (18.4%), waste (3.2%), and industry (5.2%), since the emissions are not related to energy; transport (16.7%), as it is not considered in this study; energy use in agriculture and fishing (1.7%), as it involves direct fuel use; fugitive emissions from energy production (5.8%), which arise from the production of fossil fuels themselves; and unallocated fuel combustion (7.8%), which includes sources such as nuclear plants and combined heat and power (CHP) facilities, e.g., that are not related to the considered electricity and heat sectors as previously defined (in this case, the use of fossil fuels is indirectly related to the production of electricity or heat). The share left that can be attributed to the sectors relevant to this study (energy use in buildings and industry) is 41.7% ($\%_{GHG-relevant}$): residential ($\%_{GHG-housing}$: 10.9%), commercial ($\%_{GHG-commercial}$: 6.6%), and industry ($\%_{GHG-industry}$: 24.2%).

Variable	**Value**[1]	**Description**
$E_{\text{Bel,ff,CCGT}}$[2]	$40438 \frac{\text{GWh}_{\text{ff}}}{\text{year}}$	Total fossil fuel energy for electricity production
$\%_{\text{elec-housing}}$	23.7%	Percentage of electricity used for the housing sector
$E_{\text{NG-housing}}$	$35429\text{GWh}_{\text{NG}}$	Energy from NG in the housing sector
$E_{\text{oil-housing}}$	$28147\text{GWh}_{\text{oil}}$	Energy from oil in the housing sector
$\%_{\text{elec-commercial}}$	25%	Percentage of electricity used for the commercial sector
$E_{\text{NG-commercial}}$	$19858\text{GWh}_{\text{NG}}$	Energy from NG in the commercial sector
$E_{\text{oil-commercial}}$	$7124\text{GWh}_{\text{oil}}$	Energy from oil in the commercial sector
$\%_{\text{elec-industry}}$	47%	Percentage of electricity used for the industry sector
$E_{\text{NG-industry}}$	$52656\text{GWh}_{\text{NG}}$	Energy from NG in the industry sector
$E_{\text{oil-industry}}$	$16743\text{GWh}_{\text{oil}}$	Energy from oil in the industry sector
$E_{\text{coal-industry}}$	$9715\text{GWh}_{\text{coal}}$	Energy from coal in the industry sector
EF_{NG}[3]	$180542 \frac{\text{kgCO}_2}{\text{GWh}_{NG}}$	Emission factor of NG
EF_{oil}[3]	$252975 \frac{\text{kgCO}_2}{\text{GWh}_{oil}}$	Emission factor of oil
EF_{coal}[4]	$345327 \frac{\text{kgCO}_2}{\text{GWh}_{coal}}$	Emission factor of coal

Table 6: Data for computation of CO2, RF and OA AFs for dowsncaling to both electricity and heat demand sectors covered by fossil fuels. To compute the $E_{\text{Bel,ff,CCGT}}$, it is assumed that all electricity production from fossil fuels comes from natural gas (NG), in reality it is slightly more than 90%. Another assumption is that the natural gas, oil, and coal demands in each sector are exclusively for producing electricity and heat, with none allocated to cooking.

With this information, it is now possible to determine the amount of CO_2 emissions per sector that are induced by electricity production. Since the electron does not choose its path, the $\%_{\text{elec, sector}}$ values from Table 6 can be directly multiplied by $E_{\text{Bel,ff}}$ in the numerator, as it can thus be considered that $\%_{\text{elec, sector}}$ of natural gas is effectively used to fulfil the electricity demand of the considered sector (e.g., the housing sector). The denominator represents the total amount of energy from fossil fuels required for the considered sector (thus for the electricity and the heat demand). Additionally, each fossil fuel value is multiplied by an emission factor (EF) to account for differences in emissions from various fossil fuels. By dividing the numerator (amount of electricity produced with fossil fuels fulfilling the electricity demand

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[1] All values come from the "electricity", "natural gas", "oil" or "coal" sections of [18].

[2] The calculation was performed using the total electricity produced from natural gas, 22241 GWh_{elec} [18] (in the "electricity" section), divided by a 55% efficiency for a CCGT [48], as the energy content of fossil fuels is used for the computations.

[3] The NG value corresponds to "natural gas" and the oil value to "Diesel and Home Heating Fuel (Distillate Fuel Oil)" from [49]. These values are found in the "For homes and businesses" section. The unit chosen does not matter as the emission factors multiply numerator and denominator.

[4] The coal value corresponds to the mean of all coal types found in the "Coals by type" section of [49].

of a sector) and the denominator (all energy demand of a sector, electricity and heat), the proportion of electricity versus heat can be computed for each sector.

With this information, it is now possible to determine the amount of CO_2 emissions per sector induced by electricity production. Since electrons do not choose their path, the $\%_{\text{elec, sector}}$ values from Table 6 can be directly multiplied by $E_{\text{Bel,ff}}$. This assumes that $\%_{\text{elec, sector}}$ of natural gas is used to fulfill the electricity demand of the respective sector (e.g., the housing sector). The denominator represents the total energy from fossil fuels required for the sector (both electricity and heat demand). Additionally, each fossil fuel value is multiplied by its emission factor (EF) to account for differences in emissions. By dividing the numerator (electricity demand fulfilled by fossil fuels) by the denominator (total energy demand of the sector, electricity and heat), the proportion of electricity versus heat emissions can be computed for each sector.

Housing sector:

$$\%_{\text{GHG-elec-housing}} = \frac{\%_{\text{elec-housing}} \cdot E_{\text{Bel,ff,CCGT}} \cdot \text{EF}_{\text{NG}}}{E_{\text{NG-housing}} \cdot \text{EF}_{\text{NG}} + E_{\text{oil-housing}} \cdot \text{EF}_{\text{oil}}} = 13\%$$

Commercial sector:

$$\%_{\text{GHG-elec-commercial}} = \frac{\%_{\text{elec-commercial}} \cdot E_{\text{Bel,ff,CCGT}} \cdot \text{EF}_{\text{NG}}}{E_{\text{NG-commercial}} \cdot \text{EF}_{\text{NG}} + E_{\text{oil-commercial}} \cdot \text{EF}_{\text{oil}}} = 33.9\%$$

Industry sector:

$$\%_{\text{GHG-elec-industry}} = \frac{\%_{\text{elec-industry}} \cdot E_{\text{Bel,ff,CCGT}} \cdot \text{EF}_{\text{NG}}}{E_{\text{NG-industry}} \cdot \text{EF}_{\text{NG}} + E_{\text{oil-industry}} \cdot \text{EF}_{\text{oil}} + E_{\text{coal-industry}} \cdot \text{EF}_{\text{coal}}} = 20\%$$

By multiplying the computed values by the emission shares of the considered sectors (housing, commercial, industrial; see caption of Figure 6), the shares attributable to the electricity and heat sectors can be determined.

$$\%_{GHG-elec} = \beta_{acq,elec,CO2,RF,OA} = \sum_{sector} (\%_{GHG-elec-sector} \cdot \%_{GHG-sector}) = 8.5\%$$

$$\%_{GHG-heat} = \beta_{acq,heat,CO2,RF,OA} = \sum_{sector} (\%_{GHG-heat-sector} \cdot \%_{GHG-sector})$$
$$= \%_{GHG-relevant} - \%_{GHG-elec} = 33.2\%$$

2.3.2 Calculation of impacts of electricity sector - N boundary

Variable	**Value**	**Description**
$E_{\mathrm{Bel,ff,CCGT}}$	$40438 \frac{\mathrm{GWh_{ff}}}{\mathrm{year}}$	Total fossil fuel energy for electricity production
$\alpha_{\mathrm{NO_x,CCGT}}$[1]	$918 \frac{\mathrm{kg_{NO_x}}}{\mathrm{GWh_{NG}}}$ [50]	Emission factor for $\mathrm{NO_x}$ from NG combustion
$CF_{\mathrm{NO_x,air}}$	$3.04 \cdot 10^{-10} \frac{\mathrm{TgN/year}}{\mathrm{kg_{NO_x}}/year}$ [8]	Characterisation factor for NO_x fixation from the air

Table 7: Data for computation of N impact at electricity sector level

The impact of Belgium's E sector on the N PB can be estimated by multiplying the total fossil fuel energy consumed by CCGTs to produce electricity ($E_{\mathrm{Bel,ff,CCGT}}$) with the emission factor for $\mathrm{NO_x}$ from NG combustion ($\alpha_{\mathrm{NO_x,CCGT}}$) and the characterisation factor for NO_x fixation from the air ($CF_{\mathrm{NO_x,air}}$). Since approximately 90% of fossil fuel-based electricity production in Belgium comes from natural gas [18], it is assumed that almost all $\mathrm{NO_x}$ emissions from the E sector are due to NG combustion in CCGTs.

$$impact_{elec,N} = E_{\mathrm{Bel,ff,CCGT}} \cdot \alpha_{\mathrm{NO_x,CCGT}} \cdot CF_{\mathrm{NO_x,air}} = 1.13 \cdot 10^{-2} \frac{\mathrm{TgN}}{\mathrm{year}}$$

As a brief explanation of how NO_x in the air can lead to nitrogen fixation in the ground, it occurs through either dry or wet deposition. The former involves the direct contact of nitrogen oxides with the earth's surface, while the latter involves the removal of nitrite and nitrate ions from the atmosphere through precipitation [51]. It is assumed that the CF considered in this study accounts for both processes, as no further precision is available in [8].

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[1] Mean of GT values found at page B111-48.

2.3.3 Calculation of impacts of heat sector - N boundary

Variable	Value	Description
$E_{\text{NG-housing}}$[1]	$25845\frac{\text{GWh}_{\text{NG}}}{\text{year}}$	Annual natural gas for heat use in housing
$E_{\text{oil-housing}}$[1]	$28147\frac{\text{GWh}_{\text{oil}}}{\text{year}}$	Annual oil for heat use in housing
$\alpha_{\text{NO}_x-\text{housing,NG}}$[2][3]	$172.8\frac{\text{kg}_{\text{NO}_x}}{\text{GWh}_{\text{NG}}}$	NO_x emission factor from natural gas in housing
$\alpha_{\text{NO}_x-\text{housing,oil}}$[2][3][4]	$324\frac{\text{kg}_{\text{NO}_x}}{\text{GWh}_{\text{oil}}}$	NO_x emission factor from oil in housing
$E_{\text{NG-commercial}}$[1]	$8848\frac{\text{GWh}_{\text{NG}}}{\text{year}}$	Annual natural gas for heat use in commercial sector
$E_{\text{oil-commercial}}$[1]	$7124\frac{\text{GWh}_{\text{oil}}}{\text{year}}$	Annual oil for heat use in commercial sector
$\alpha_{\text{NO}_x-\text{commercial,NG}}$[2][3]	$172.8\frac{\text{kg}_{\text{NO}_x}}{\text{GWh}_{\text{NG}}}$	NO_x emission factor from natural gas in commercial sector
$\alpha_{\text{NO}_x-\text{commercial,oil}}$[2][3][4]	$324\frac{\text{kg}_{\text{NO}_x}}{\text{GWh}_{\text{oil}}}$	NO_x emission factor from oil in commercial sector
$E_{\text{NG-industry}}$[1]	$33651\frac{\text{GWh}_{\text{NG}}}{\text{year}}$	Annual natural gas for heat use in industry
$E_{\text{oil-industry}}$[1]	$16743\frac{\text{GWh}_{\text{oil}}}{\text{year}}$	Annual oil for heat use in industry
$E_{\text{coal-industry}}$[1]	$9715\frac{\text{GWh}_{\text{coal}}}{\text{year}}$	Annual coal for heat use in industry
$\alpha_{\text{NO}_x-\text{industry,NG}}$[2]	$241.2\frac{\text{kg}_{\text{NO}_x}}{\text{GWh}_{\text{NG}}}$	NO_x emission factor from natural gas in industry
$\alpha_{\text{NO}_x-\text{industry,oil}}$[2][4]	$576\frac{\text{kg}_{\text{NO}_x}}{\text{GWh}_{\text{oil}}}$	NO_x emission factor from oil in industry
$\alpha_{\text{NO}_x-\text{industry,coal}}$[2][5]	$540\frac{\text{kg}_{\text{NO}_x}}{\text{GJ}_{\text{coal}}}$	NO_x emission factor from coal in industry
$CF_{\text{NO}_x,\text{air}}$	$3.04\cdot10^{-10}\frac{\text{TgN/year}}{\text{kg}_{\text{NO}_x/year}}$	Characterization factor for NO_x fixation from the air

Table 8: Data for computation of N impact at heat sector level

Although the EFs were found for boilers, the variation in EF for each sector and fossil fuel is assumed to reflect well the other technologies available.

The N fixation for each sector can be calculated as the sum for each fossil fuel of the fossil fuel energy ($E_{ff,sector}$) multiplied by the emission factor ($\alpha_{NO_x-sector,ff}$). This result must then be multiplied by the CF to obtain the unit aligning with the PB framework.

Housing sector:

$$N_{\text{heat,housing}} = (E_{\text{NG-housing}}\cdot\alpha_{\text{NO}_x-\text{housing,NG}}+E_{\text{oil-housing}}\cdot\alpha_{\text{NO}_x-\text{housing,oil}})\cdot CF_{\text{NO}_x,\text{air}} = 4.13\cdot10^{-3}\frac{\text{TgN}}{\text{year}}$$

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[1] To obtain these values, the annual fossil fuel consumption (for NG, oil, and coal) of each sector is first retrieved from [18] in the sections dedicated to "natural gas," "oil," and "coal." Then, the fossil fuel use attributed to the electricity sector is subtracted from the retrieved values to obtain the amount used for heating.

[2] These values are retrieved from pages B111-47 to B111-49 of [50].

[3] For the housing and commercial sectors, the value for commercial boiler is taken.

[4] From the different oil types in the table, gas-oil is selected in case of the residential and commercial sectors, and the heavier residual oil is selected for the industrial sector [52].

[5] The value for grate-fired (GF) boiler is taken.

Commercial sector:

$$\begin{aligned}N_{\text{heat,commercial}} = & \left(E_{\text{NG-commercial}} \cdot \alpha_{\text{NO}_x-\text{commercial,NG}} + E_{\text{oil-commercial}} \cdot \alpha_{\text{NO}_x-\text{commercial,oil}}\right) \cdot CF_{\text{NO}_x\text{,air}} \\ & = 1.17 \cdot 10^{-3} \frac{\text{TgN}}{\text{year}}\end{aligned}$$

Industrial sector:

$$\begin{aligned}N_{\text{heat,industry}} = & \left(E_{\text{NG-industry}} \cdot \alpha_{\text{NO}_x-\text{industry,NG}} + E_{\text{oil-industry}} \cdot \alpha_{\text{NO}_x-\text{industry,oil}} + E_{\text{coal-industry}} \cdot \alpha_{\text{NO}_x-\text{industry,coal}}\right) \\ & \cdot CF_{\text{NO}_x\text{,air}} = 7 \cdot 10^{-3} \frac{\text{TgN}}{\text{year}}\end{aligned}$$

In total, the sum of all sectors gives an $impact_{heat,N}$ value of $12.3 \cdot 10^{-3} \frac{\text{TgN}}{\text{year}}$.

2.3.4 Calculation of impacts of electricity sector - LFC boundary

Variable	**Value**	**Description**
$E_{\text{Bel,ff}}$	$22241 \frac{\text{GWh}_{\text{elec}}}{\text{year}}$ [18]	Annual fossil fuel electricity production in Belgium
$A_{\text{NG,ref}}$[1]	$0.471 \frac{\text{km}^2}{\text{GW}}$ [53]	Reference area occupied by NG powerplants per GW installed
$C_{p,\text{NG,Bel}}$[2]	0.517	Load factor of NG powerplants in Belgium
$\%_{T\text{-forest,Hol,Bel}}$	±80% [37]	Forest cover in Belgium in the early Holocene
$\%_{T\text{-forest,2021,Bel}}$	22.76% [38]	Current forest cover in Belgium (2021)

Table 9: Data on NG Plant Metrics and Forest Cover in Belgium

In order to determine the impact of the electricity demand covered by fossil fuels, it is first necessary to determine the land-use (LU) factor of NG. For this, data available on the NG sector in the USA was used and scaled to Belgium by using the load factor of NG in Belgium instead of the USA. As assumed previously, the supposition is made that NG is the only fossil fuel used to produce electricity. This gives:

$$LU_{NG,Bel} = \frac{A_{NG,ref}}{8760 \cdot C_{p,NG,Bel}} = 1.04 \cdot 10^{-4} \frac{\text{km}^2}{\text{GWh}_{elec}}$$

Now that the land-use has been determined, it is assumed that the NG sector in Belgium is distributed uniformly. Consequently, only a portion of this sector impacts the LFC boundary, specifically the part situated in areas deforested since the Holocene. These areas are considered

---

[1] Computed by dividing the total area occupied by NG powerplants in the USA with the corresponding installed capacity.

[2] Calculated based on the total installed NG powerplant capacity in Belgium ($Cap_{NG,Bel}$) [54] and the total production of electricity from NG ($E_{Bel,ff}$) [18] as $C_{p,NG,Bel} = \frac{E_{Bel,ff}}{Cap_{NG,Bel} \cdot 8760} = 0.517$.

to contribute to deforestation, even if they were already deforested before the installation of NG power plants. To refine the LFC impact, the original and current forest covers are used:

$$A_{NG,Bel} = impact_{elec,LFC} = LU_{NG,Bel} \cdot E_{Bel,ff} \cdot (\%_{T\text{-forest,Hol,Bel}} - \%_{T\text{-forest,2021,Bel}}) = 1.33\text{km}^2$$

It is assumed that the LFC global and LFC biome AFs are the same as the only forest biome in Belgium is temperate forest. The same assumption is made for the heat sector.

2.3.5 Calculation of impacts of heat sector - LFC boundary

By analogy with the section "Calculation of impacts of heat sector - N boundary", only boilers were considered for calculating this boundary. The area under consideration is that of a boiler room—which includes the boiler itself and the additional space necessary for operation—in relation to the installed capacity. It is assumed that this area is also applicable to other technologies, as after extensive research, no data was found for the rooms containing other heat producing technologies (only information about the sizing of the technologies themselves). Moreover, boilers are a prevalent technology in all considered sectors. In the subsequent graph, the areas for the average boilers used in the residential (31kW$_{th}$ [55][1], justify with average room per person and average persons per home), commercial (2.81MW$_{th}$ [56][2]), and industrial (10.55MW$_{th}$ [56][2]) sectors are determined based on an extended log-log regression that represents the area as a function of installed capacity [57]. For the commercial and industrial sectors it is supposed that the value found for the USA can be generalised to the whole world. It is also assumed that coal boilers require the same area as gas or oil boilers which are supposed to require the same areas as the fuels can often be used interchangeably (industry).

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[1] The mean value of "Recommended Boiler Size" for the property type "Apartment/Flat or House with 2-3 bedrooms and 1 shower" was chosen to represent the typical boiler capacity of a Belgian.

[2] These values are found respectively as 9.6 and 36 MMBtu/h at p. ES-1.

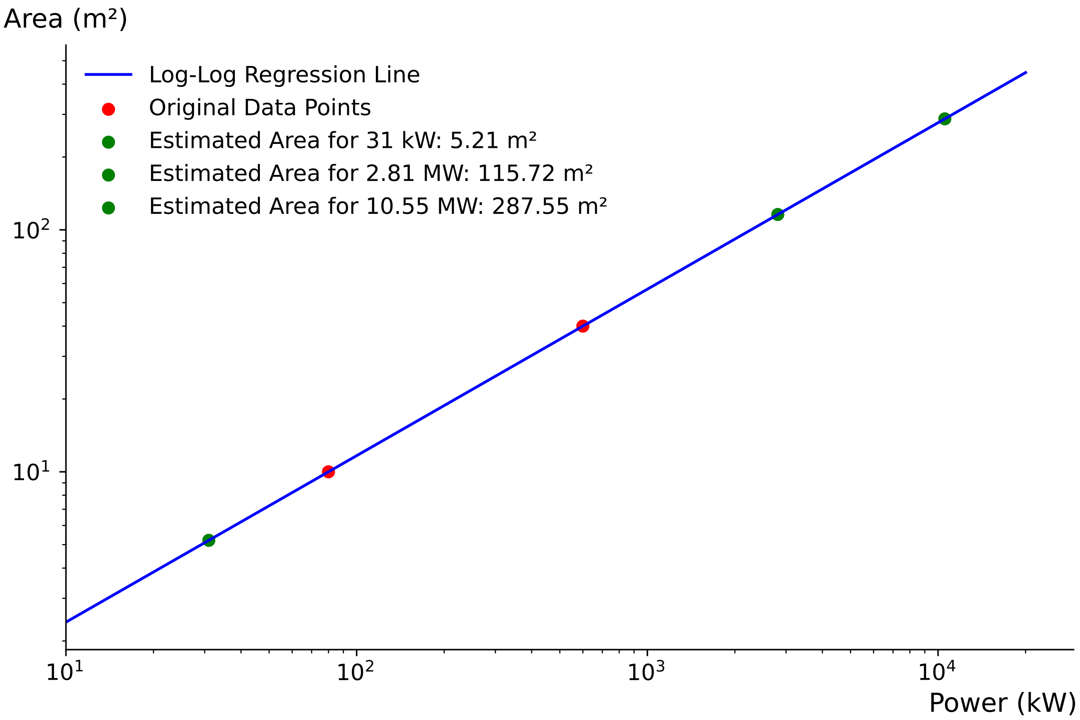

Figure 7: For this relationship to be valid for all boilers, it is considered that NG, oil and coal boilers take approximately the same space for the same installed capacity. While this may be true for NG and oil boilers, coal boilers typically take in more space [57]. However, coal forms approximately only 12% of the fossil fuel supply to the industry sector ([18] considering "natural gas", "oil" and "coal" categories), which is why the assumption is kept. This figure is the same as found at [57], but with an extended range.

Variable	Value	Description
$Q_{\text{ff,Bel,housing}}$[1]	$53992 \frac{\text{GWh}_{\text{ff}}}{\text{year}}$	Annual heat consumption in the housing sector
$Q_{\text{ff,Bel,commercial}}$[1]	$16872 \frac{\text{GWh}_{\text{ff}}}{\text{year}}$	Annual heat consumption of the commercial sector
$Q_{\text{ff,Bel,industry}}$[1]	$60109 \frac{\text{GWh}_{\text{ff}}}{\text{year}}$	Annual heat consumption of the industrial sector
$\eta_{\text{thermal,boiler}}$[2]	90% [58]	Thermal efficiency of boilers
$\overline{\text{Cap}}_{\text{boiler-housing}}$[4]	$0.031\text{MW}_{\text{th}}$ [55]	Average capacity of residential boilers
$A(\overline{\text{Cap}}_{\text{boiler-housing}})$	5.21m^2 [Figure 7]	Area for the average residential boiler
$C_{\text{p,boiler-housing}}$[3]	0.375 [59]	Capacity factor of home boilers
$\overline{\text{Cap}}_{\text{boiler-commercial}}$[4]	$2.81\text{MW}_{\text{th}}$ [56]	Average capacity of commercial boilers
$A(\overline{\text{Cap}}_{\text{boiler-commercial}})$	115.72m^2 [Figure 7]	Area for the average commercial boiler
$C_{\text{p,boiler-commercial}}$	0.16 [56]	Capacity factor of commercial boilers
$\overline{\text{Cap}}_{\text{boiler-industry}}$[4]	$10.55\text{MW}_{\text{th}}$ [56]	Average capacity of industrial boilers
$A(\overline{\text{Cap}}_{\text{boiler-industry}})$	287.55m^2 [Figure 7]	Area for the average industrial boiler
$C_{\text{p,boiler-industry}}$	0.47 [56]	Capacity factor of industrial boilers
$\%_{\text{T-forest,Hol,Bel}}$	± 80% [37]	Estimated total forest cover during the Holocene
$\%_{\text{T-forest,2021,Bel}}$	22.76% [38]	Current forest cover (2021)

Table 10: Data for computation of LFC impact at heat sector level

For each sector (housing, commercial, and industry), the area corresponding to the number of "average units" needed to cover the heat demand is calculated in the following three steps:

Yearly heat production of one "average unit":

$$Q_{\text{sector-unit, year}} = \overline{Cap}_{\text{boiler-sector}} \cdot 8760 \cdot C_{\text{p, boiler-sector}}$$

Amount of "average units" needed to cover the sectoral demand:

$$N_{\text{sector-units}} = \frac{Q_{\text{ff, Bel, sector}} \cdot 10^3 \cdot \eta_{\text{thermal, boiler}}}{Q_{\text{sector-unit, year}}}$$

---

[1] Calculated for each sector as the sum of the heat consumptions covered by each fossil fuel (see Table. 6), from which the share destined for electricity demand was subtracted.

[2] The thermal efficiency for a residential (decentralised) boiler is considered, which is assumed to be similar across commercial and industrial sectors.

[3] The average suggested heating hours per day (8-10 hours) is taken to be 9 hours. This figure is then divided by the total number of hours in a day (24 hours).

[4] The housing sector value is derived from the UK, while the commercial and industrial sector values are sourced from the USA. Belgium's values are expected to be similar.

Area required for the computed amount of "average units":

$$A_{\text{boilers-sector}} = N_{\text{sector-units}} \cdot A\left(\overline{Cap}_{\text{boiler-sector, USA}}\right)$$

A similar assumption as in Section 2.3.4 is used to calculate the final impact, which is that only a part of the heat-producing units impact the LFC PB.

$$impact_{heat,LFC} = (\%_{\text{T-forest,Hol,Bel}} - \%_{\text{T-forest,2021,Bel}}) \cdot \sum_{sectors} A_{\text{boilers-sector}} = 1.88\text{km}^2$$

2.3.6 Calculation of impacts of electricity sector - FWU boundary

Variable	**Value**	**Description**
$V_{w,ff}$	$11.2\frac{\text{km}^3}{\text{year}}$ [60]	Water consumption for fossil fuel electricity production
E_{world}	$29165\frac{\text{TWh}_{\text{elec}}}{\text{year}}$ [61]	Total global electricity generation
$E_{Bel,ff}$	$22241\frac{\text{GWh}_{\text{elec}}}{\text{year}}$ [18]	Annual fossil fuel electricity production in Belgium
$\%_{ff}$[1]	61.4% [62]	Share of global power generation from fossil fuels

Table 11: Data for computation of FWU impact at electricity sector level

The goal is to scale the global water consumption for fossil fuel electricity production to Belgium's electricity sector, using the electricity supply as basis. As a reminder, water consumption is defined as the water consumed that is not directly returned to the surrounding river basins or lakes, thus evaporated [63]. Virtual water use, defined as the water required to produce the fossil fuels [63], is deliberately excluded from consideration, as the scope of this analysis is confined within Belgium's borders. It is assumed that the evaporation rates for fossil fuel technologies have roughly the same order of magnitude (GT: $52\text{m}^3/\text{TJ}_{\text{elec}}$, CCGT: $105\text{m}^3/\text{TJ}_{\text{elec}}$, and Coal ST: $194\text{m}^3/\text{TJ}_{\text{elec}}$) [64]. This assumption is further supported by the fact that the installed capacity and total generation of CCGTs are greater than those of GTs [65][2].

$$V_{cons,elec,Bel} = impact_{elec,FWU} = \frac{E_{Bel,ff} \cdot 10^{-3}}{E_{world} \cdot \%_{ff}} \cdot V_{w,ff} = 0.0135\frac{\text{km}^3}{\text{year}}$$

---

[1] Obtained as the sum of the following shares: NG: 23%, oil: 2.5% and coal: 35.9%.

[2] See Figure 6. from the source. The scope considered in this study was Central Western Europe, but it is assumed that in case of GTs and CCGTs the same trend can be observed at world level.

2.3.7 Calculation of impacts of heat sector - FWU boundary

Variable	**Value**	**Description**
$V_{\text{cons,elec,Neth}}$	$0.038\frac{\text{km}^3}{\text{year}}$ [63][1]	Water consumption ff. electricity production (Netherlands)
$V_{\text{cons,heat,Neth}}$	$0.0043\frac{\text{km}^3}{\text{year}}$ [63][1]	Water consumption for fossil fuel heating (Netherlands)
pop_{Bel}	11.67 million [29]	Population of Belgium
pop_{Neth}	17.59 million [66]	Population of the Netherlands

Table 12: Data for computation of FWU impact at heat sector level

To estimate the water consumption induced by fossil fuels in the Belgian heating sector, the water usage data from the Netherlands will be scaled to Belgium based on population. Additionally, since data is available for the fossil fuel-induced water consumption of the electricity sector, a scaled value will also be calculated. This will allow for a comparison to see if the order of magnitude aligns with the value computed in the previous section.

$$V_{cons,elec,Bel} = V_{cons,elec,Neth} \cdot \frac{pop_{Bel}}{pop_{Neth}} = 0.0253\frac{\text{km}^3}{\text{year}}$$

The computed value for Belgian electricity consumption, $V_{\text{cons,elec,Bel}}$, is $0.0253\frac{\text{km}^3}{\text{year}}$, which is quite close to $0.0135\frac{\text{km}^3}{\text{year}}$. This proximity solidifies the approach taken in the previous section.

$$V_{cons,heat,Bel} = impact_{heat,FWU} = V_{cons,heat,Neth} \cdot \frac{pop_{Bel}}{pop_{Neth}} = 0.00285\frac{\text{km}^3}{\text{year}}$$

It can thus be observed that the FWU impact is lower for the heat sector than for the electricity sector.

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[1] See Figure 6 from the source: "2. Water Consumption" and "(b) Aggregated water use (m^3)".

2.3.8 Computed AFs for LV2 downscaling (From Belgium to E and H sectors)

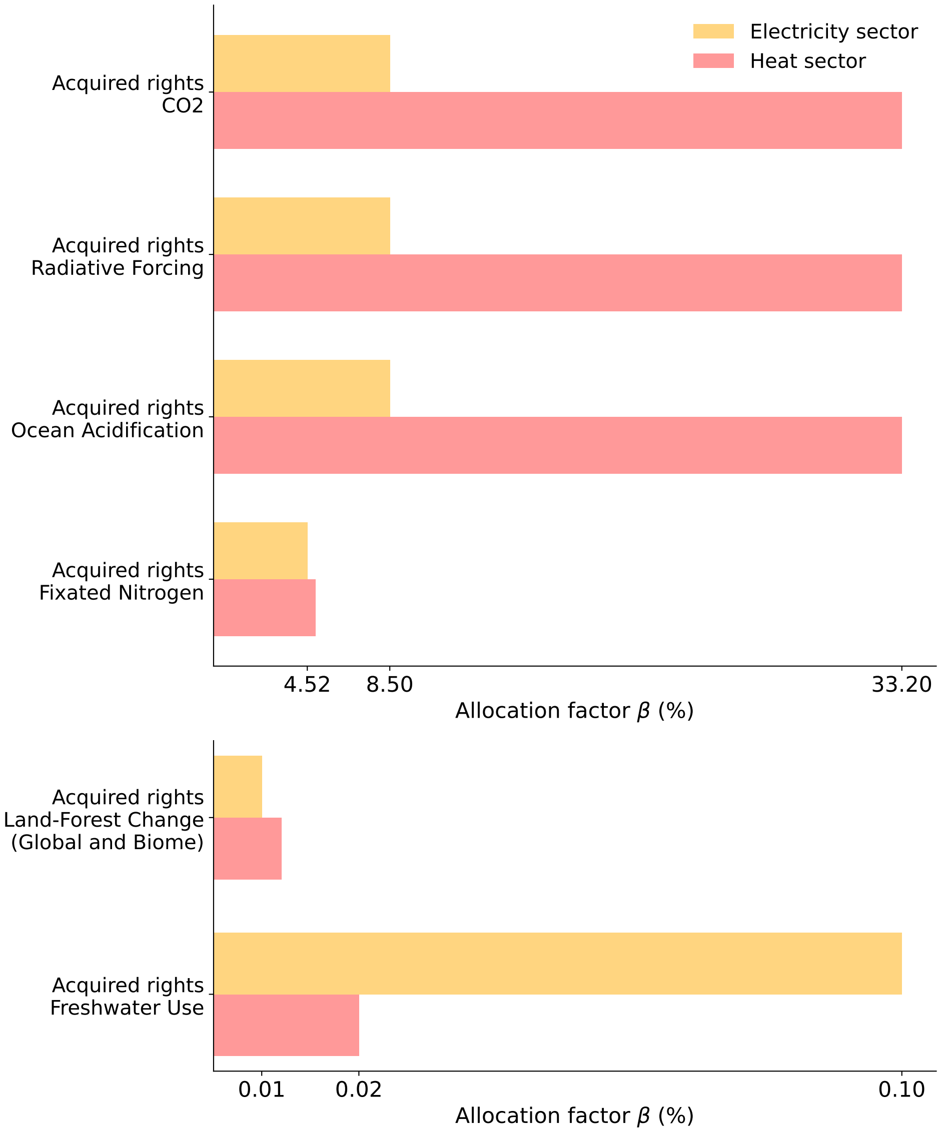

Figure 8: The scale difference between some of the AFs, which are expressed as percentage, is a consequence of the impacts of the assessed system (E and H sectors) on the PBs. Using the current method of applying the acquired rights SP based on historical emissions of CO_2, as expressed in Ryberg et al. [17], to allocate shares to the LFC or FWU PBs, would critically overestimate the LFC or FWU share, which could lead to wrong decision-making. The H sector shares are downscaled further at LV3. The allocated SoSOS are provided in Appendix A.3.

2.4 Exergy to account for heat quality - Level 3 (LV3)

Different fossil-fuelled technologies are used in the heat sector. For low temperature (LT) heat, the predominant technology is boilers, which can be readily replaced with heat pumps (HPs). However, for medium temperature (MT) and high temperature (HT) heat, replacing fossil-fuelled technologies with renewable technologies that meet the same requirements becomes more challenging. To address this variation, three temperature ranges are defined to account for the quality of heat. By applying the exergy factor to each temperature range, better adapted shares for each heat sector can then be determined.

Variable	Value	Description
$Q_{\text{ff,Bel,housing}}$	$53992\frac{\text{GWh}_{\text{ff}}}{\text{year}}$[1]	Annual fossil fuel heat consumption in the residential sector
$Q_{\text{ff,Bel,commercial}}$	$16872\frac{\text{GWh}_{\text{ff}}}{\text{year}}$[1]	Annual fossil fuel heat consumption in the commercial sector
$Q_{\text{ff,Bel,industry}}$	$60109\frac{\text{GWh}_{\text{ff}}}{\text{year}}$[1]	Annual fossil fuel heat consumption in the industrial sector
η_{th}	90% [58](1)	Thermal efficiency for LT-H, MT-H and HT-H sectors
$Q_{\text{LT,industry}}$	$25.7\text{EJ}_{\text{th}}$ (2)	Low-temperature (LT) heat demand in the industry (25-100°C)
$Q_{\text{MT,industry}}$	$28.5\text{EJ}_{\text{th}}$ (2)	Medium-temperature (MT) heat demand in the industry (100-400°C)
$Q_{\text{HT,industry}}$	$53.7\text{EJ}_{\text{th}}$ (2,3)	High-temperature heat (HT) demand in the industry (400-2200°C)
T_{LT}	62.5°C (4)	Average LT heat temperature
T_{MT}	250°C (4)	Average MT heat temperature
T_{HT}	525°C (4)	Average HT heat temperature
T_0	25°C	Ambient temperature

Table 13: (1) Data for computation of exergy differentiation. $\eta_{th} = 90\%$ is assumed to equal $\eta_{thermal,boiler}$ for the LT-H sector, for the MT-H and HT-H sectors, it is assumed that modern burners in furnaces are highly efficient (60-90%, [67]). Although furnaces are not as efficient as boilers, due to their different applications, $\eta_{th} = 90\%$ is maintained to not underestimate the share to be allocated to the MT-H and HT-H sectors[2]. (2) These values are found in [68] according to the defined temperature ranges. The values are global but can be used for the differentiation. The temperature ranges are defined according to the repartition made in [68], but three ranges were defined instead of five: LT, MT and HT. (3) The average temperature for HT heat was determined based on an upper bound of 2200°C, which is the highest temperature for an industrial process found in [69]. (4) Are the average temperatures of the defined temperature ranges.

Definition of the exergy factor (EXF)[73]:

$$EXF(T) = 1 - \frac{T_0}{T}$$

---

[1] As defined in section: "Calculation of impacts of heat sector - LFC boundary".

[2] Indeed for the MT-H and HT-H sectors, transitioning from fossil fuel is harder. While green hydrogen might be a solution, its lower energy density than NG for a given volume [70], its high explosivity [71], and low current economic viability [72], make it challenging to implement.

The values for the various heat demands at world level can be used to determine which part of $Q_{ff,Bel,industry}$ that can be attributed to the defined temperature ranges:

$$Q_{\text{ff,Bel,LT,industry}} = \left(\frac{Q_{\text{LT,industry}}}{Q_{\text{LT,industry}} + Q_{\text{MT,industry}} + Q_{\text{HT,industry}}} \right) \cdot Q_{\text{ff,Bel,industry}} = 14306\text{GWh}_{\text{ff}}$$

$$Q_{\text{ff,Bel,MT,industry}} = \left(\frac{Q_{\text{MT,industry}}}{Q_{\text{LT,industry}} + Q_{\text{MT,industry}} + Q_{\text{HT,industry}}} \right) \cdot Q_{\text{ff,Bel,industry}} = 15868.8\text{GWh}_{\text{ff}}$$

$$Q_{\text{ff,Bel,HT,industry}} = \left(\frac{Q_{\text{HT,industry}}}{Q_{\text{LT,industry}} + Q_{\text{MT,industry}} + Q_{\text{HT,industry}}} \right) \cdot Q_{\text{ff,Bel,industry}} = 29934.3\text{GWh}_{\text{ff}}$$

Now, it is possible to determine the total LT heat demand, considering that $Q_{ff,Bel,housing}$ and $Q_{ff,Bel,commercial}$ are LT heat demands (space heating):

$$Q_{LT} = Q_{\text{ff,Bel,housing}} + Q_{\text{ff,Bel,commercial}} + Q_{\text{ff,Bel,LT,industry}} = 85170\text{GWh}_{\text{ff}}$$

For MT and HT heat, it is considered that $Q_{MT} = Q_{ff,Bel,MT,industry} = 15868.8\text{GWh}_{\text{ff}}$ and $Q_{HT} = Q_{ff,Bel,HT,industry} = 29934.3\text{GWh}_{\text{ff}}$, as there is no MT and HT heat demand in the housing and commercial sectors. Having defined these heat demands per temperature range, it is now possible to determine the useful energy associated to these demands:

$$Q_{\text{useful}}(T_{LT}) = Q_{LT} \cdot \eta_{th} \cdot EF(T_{LT}) = 8564\text{GWh}_{\text{useful}}$$

$$Q_{\text{useful}}(T_{MT}) = Q_{MT} \cdot \eta_{th} \cdot EF(T_{MT}) = 6142.5\text{GWh}_{\text{useful}}$$

$$Q_{\text{useful}}E(T_{HT}) = Q_{HT} \cdot \eta_{th} \cdot EF(T_{HT}) = 21484.1\text{GWh}_{\text{useful}}$$

Shares assigned by temperature range in function of the quality of the heat:

$$\delta_{heat,LT} = \frac{Q_{\text{useful}}(T_{LT})}{Q_{\text{useful}}(T_{LT}) + Q_{\text{useful}}(T_{MT}) + Q_{\text{useful}}(T_{HT})} = 23.7\% \tag{11}$$

$$\delta_{heat,MT} = \frac{Q_{\text{useful}}(T_{MT})}{Q_{\text{useful}}(T_{LT}) + Q_{\text{useful}}(T_{MT}) + Q_{\text{useful}}(T_{HT})} = 17\% \tag{12}$$

$$\delta_{heat,HT} = \frac{Q_{\text{useful}}(T_{HT})}{Q_{\text{useful}}(T_{LT}) + Q_{\text{useful}}(T_{MT}) + Q_{\text{useful}}(T_{HT})} = 59.3\% \tag{13}$$

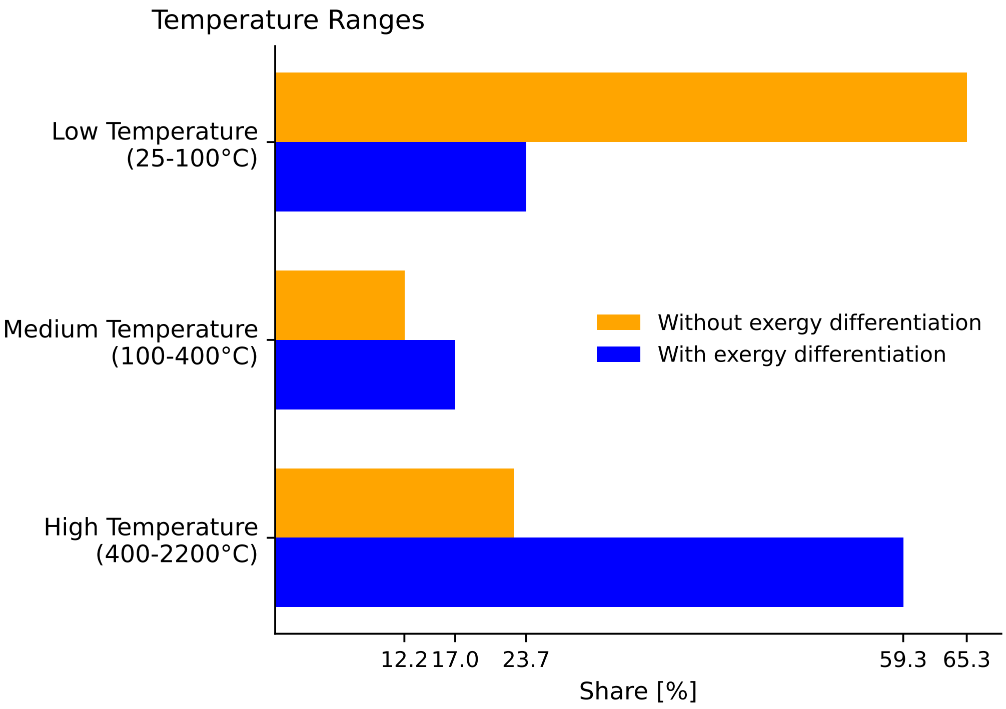

Figure 9: By differentiating the various temperature ranges using the exergy factor, high temperature heat receives a significantly larger share for the transition. This share acts as a safeguard against the impacts of the technologies in the HT heat sector, which cannot be replaced as easily as those for the low temperature or medium temperature heat sectors.

In the heat sector, where an additional downscaling step is involved (LV3), the following is an example of the complete downscaling chain:

$$aSOS_{\text{egal-acq,heat-LT,CO2}} = \alpha_{egal,Bel,CO2} \cdot \beta_{\text{acq,heat,CO2}} \cdot \delta_{heat,LT} \cdot SOS_{CO2} \tag{14}$$

2.5 PB exceedance at sectoral level

The heatmap is designed to show how much the real sectoral impacts exceed or not the allocated share of the SOS for each PB and SP at the sectoral level. A property of the downscaling methodology used, is that this heatmap is uniform across all sectors. This can be explained by the fact that to downscale from Belgium to sector level, both the allocated shares of the SOS and the real impacts must be multiplied by the same LV2 acquired rights AFs, which thus cancel out in the Absolute Sustainability Ratio (ASR). In essence, the heatmap of the ASRs obtained at Belgian level is the same as for each sector, hence the uniformity.

The heatmap ratio represents the ASR [16, 25]:

$$\text{ASR} = \frac{\text{real impact}}{\text{allocated SoSOS}} \leq 1 \rightarrow \text{Absolutely sustainable} \tag{15}$$

$$\text{ASR} = \frac{\text{real impact}}{\text{allocated SoSOS}} \geq 1 \rightarrow \text{Not absolutely sustainable} \tag{16}$$

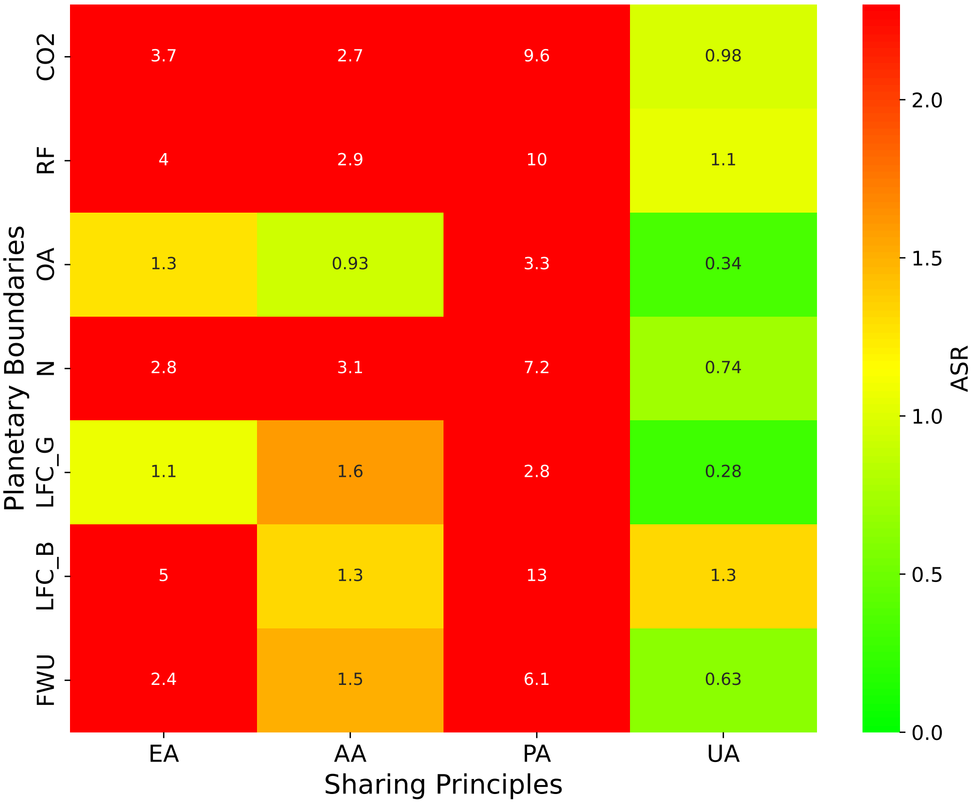

Figure 10: In this figure, we see that the EA and AA SPs slightly exceed the ASR, similar to the results found in Hjalsted et al. [25]. In contrast, the PA SP surpasses the ASR completely, which aligns with Hjalsted et al. [25]. Only the UA SP ensures a sufficient SoSOS for the PBs to remain within limits.

3 Methodology - Prospective Planetary Boundaries Life Cycle Impact Assessment (pPBLCIA)

3.1 Technology Selection

The main goal of this study is to evaluate the sustainable transition to renewable energy for the electricity (E) and heat (H) demand sectors covered by fossil fuels. The chosen technologies must be chosen to meet this objective. The Ecoinvent 3.9 database [19], that reflects the energy situation in 2019, represents a comprehensive Life Cycle Inventory (LCI) where the technologies needed are directly available. In Table 14, the technologies are referred to as activities, as it is the activity of constructing these technologies that is characterised in the Ecoinvent 3.9 database.

For the H sectors, electricity is used to produce heat. Therefore, the impacts of PV, onshore wind, and offshore wind technologies are used for each sector. Specifically, for the E sector, only these technologies' impacts are considered. For the LT-H sector, it is assumed that water and space heating are provided exclusively by HPs using 'green' electricity (see section 3.3). For the MT-H and HT-H sectors, since EcoInvent 3.9 lacks an activity for green hydrogen combustion for heat, only the impacts of renewable electricity production are considered, specifically PV, onshore wind, and offshore wind.

The impacts of these technologies are aligned with the PB framework by multiplying the elementary flows (ELF) with specific characterisation factors (CFs) [14]:

$$impact_{tech,PB} = \sum_{i} CF_{PB,i} \cdot ELF_i \qquad \forall PB \tag{17}$$

These impacts are then annualised over their lifetimes and scaled to impact per GW (electrical or thermal useful) of capacity installed.

For PV, an installation on a slanted roof was chosen to best represent the typical setting of residential households, as there is limited space available for field PV. Moreover, multi-Si was chosen over single-Si due to its affordability [77] and lower climate impact for the same installed capacity. Although single-Si could have been preferred for its higher efficiency, the impacts for different PV panel types are similar and yield comparable results. For offshore wind, the construction of fixed and moving parts was characterised separately in Ecoinvent 3.9; both were included to calculate the impact of constructing an offshore wind turbine. For

Activity	**Lifetime (years)**
Photovoltaic slanted-roof installation, 3kWp, multi-Si, panel, mounted on roof	25 [74]
Wind turbine construction, 2MW, onshore	20 [75]
Wind power plant construction, 2MW, offshore, fixed parts	20 [75]
Wind power plant construction, 2MW, offshore, moving parts	20 [75]
Heat pump production, 30kW	18 [76]

Table 14: Activities and their lifetimes. The technology impacts are provided in Appendix A.4.

HPs, given the high demand for heating from the residential sector, the lifetime for a domestic air source HP was selected.

3.2 Prospective LCA (pLCA)

To understand how the impacts of the selected technologies evolve over time and to assess when the implementation of these renewable mixes becomes feasible, the Python *premise* package [21], an extension of Brightway2 [22], was used to project the Ecoinvent 3.9 database to the years 2030, 2040, and 2050. This package updates the underlying processes of the Life Cycle Inventory (LCI) based on the REMIND Integrated Assessment Model (IAM) [78], which projects the evolution of the energy sector and global economy for various SSP-RCP scenarios.

For this study, only SSP1: Sustainability and SSP2: Middle of the Road were considered, as SSP3: A Rocky Road and SSP4: Inequality do not align with positive social and economic outcomes, and SSP5: Taking the Highway is contradictory to the goal of reducing fossil fuel use [23]. Currently, only the Base scenarios of REMIND, which do not limit atmospheric CO_2 concentrations, have been considered. Future work could include RCP-1.9 and RCP-2.6 scenarios, limiting radiative forcing to $1.9W/m^2$ and $2.6W/m^2$, respectively [79]. The sharing principles, fixed based on historical impacts, remain unchanged in future scenarios. Using these updated LCIs, the same technologies can be selected, and their impacts determined as described previously.

3.3 Calculation of LT-H Impacts

As the HPs are considered to consume 'green' electricity, it is necessary to estimate how much installed capacity of PV, onshore wind, or offshore wind is required to supply one HP. For this, the yearly production of an HP must be characterised.

Parameter	Value	Description
$C_{p,HP}$	0.263 [80]	HP load factor for space and water heating below 800 meters
COP_{HP}	4 [81]	Average COP for a domestic HP
$C_{p,PV}$	0.113 [58][1]	PV load factor in Belgium
$C_{p,onsh}$	0.23 [58][1]	Onshore wind load factor in Belgium
$C_{p,offsh}$	0.38 [82]	Offshore wind load factor in the Belgian North Sea

Table 15: Parameters for LT-H impacts calculation

To determine the amount of each technology needed to supply an HP, the ratio between the yearly production of an HP, converted to electricity, and the yearly production of each technology can be computed. Although the daily profiles of PV, onshore wind, and offshore wind supply may not match the LT-H demand curve, this study focuses on a yearly scope. The installed capacity of $30 \cdot 10^{-6}$ GW for the HP is selected based on the chosen activity from AB. For all other technologies, the yearly production for 1 GW installed will be computed.

$$Cap_{tech,HP-30kW} = \frac{(30 \cdot 10^{-6} \cdot 8760 \cdot C_{p,HP})/COP_{HP}}{1 \cdot 8760 \cdot C_{p,tech}} \tag{18}$$

This yields 17.5 kW of PV, 8.58 kW of onshore wind, and 5.19 kW of offshore wind to supply a 30 kW HP. For 1 GW of HPs installed, it is thus required to install:

$$Cap_{tech,HP-1MW} = 1\text{GW} \cdot \frac{Cap_{tech,HP-30kW}}{30} \tag{19}$$

This gives 0.583 GW for PV, 0.286 GW for onshore wind, and 0.173 GW for offshore wind. These values can be used to estimate the installed capacities of the different renewable technologies once the installed HP capacity has been computed by comparing the impacts.

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[1] Values are characterized for Switzerland, but conditions are assumed to be similar in Belgium for PV and onshore wind.

The impacts, which are provided in Appendix A.5, can thus be calculated as:

$$impact_{tech-HP,PB} = impact_{HP,PB} + Cap_{tech,HP-1MW} \cdot impact_{tech,PB} \qquad \forall PB \tag{20}$$

3.4 Planetary Boundaries Life Cycle Impact Assessment (PB-LCIA)

Now that the allocated shares and the technology impacts have been determined, the maximum installed capacity of PV, onshore wind, and offshore wind for each sharing principle, sector, and PB can be computed as follows:

$$Cap_{tech,principle,sector,PB} = \frac{aSOS_{principle,sector,PB}}{impact_{tech,PB}} \qquad \forall PB \tag{21}$$

These capacities can be calculated for the years 2024, 2030, 2040, and 2050 for the SSP1 and SSP2 scenarios. By combining all the previously defined concepts, the outcome of this study is a comprehensive pPB-LCIA. As a reminder for clarity, the impacts of technologies are independent of the sharing principle considered, but not of the scenario considered (SSP1 or SSP2).

4 Results

4.1 Assessing fulfilment of electricity and heat demands covered by fossil fuels for the proposed technologies

This section evaluates whether the allocated shares from various SPs for each PB can meet Belgium's electricity (E) and heat (H) demands currently covered by fossil fuels. Although the demand and allocated shares are fixed to provide a reference point for the transition of the sectors, the impacts of the technologies change over time (see Section 2.1). For each sector (electricity, LT heat, MT heat, and HT heat), the maximum installed capacity of each individual technology producing electricity—PV, onshore wind, and offshore wind—is therefore evaluated for each PB and SP up to 2050. This enables an assessment of when each PB meets the demand under the given SP. For LT heat, this electricity powers heat pumps, and for MT and HT heat, it produces green hydrogen. The LFC PBs are omitted due to their higher permissible capacities compared to the N and OA PBs. If the N and OA PBs are satisfied, the LFC PBs will be satisfied as well.

In the figures, the green zone indicates that sectoral demand is met, while the red zone shows unmet demand. The dotted gray line represents the minimum installed capacity required to meet demand with the given technology. Both SSP1 and SSP2 transition scenarios were considered in the pPBLCA. Since SSP2 allocations were only slightly higher than SSP1 and SSP1 aligns better with the transition to net zero, only SSP1 results are shown. Any notable SSP2 results are mentioned in the figure captions.

4.1.1 Electricity sector

For the E sector, $22241\text{GWh}_{\text{elec}}$ are required to meet the yearly demand. Which corresponds to $22.47\text{GW}_{\text{elec,PV}}$, $11.04\text{GW}_{\text{elec,onsh}}$ and $6.68\text{GW}_{\text{elec,offsh}}$.

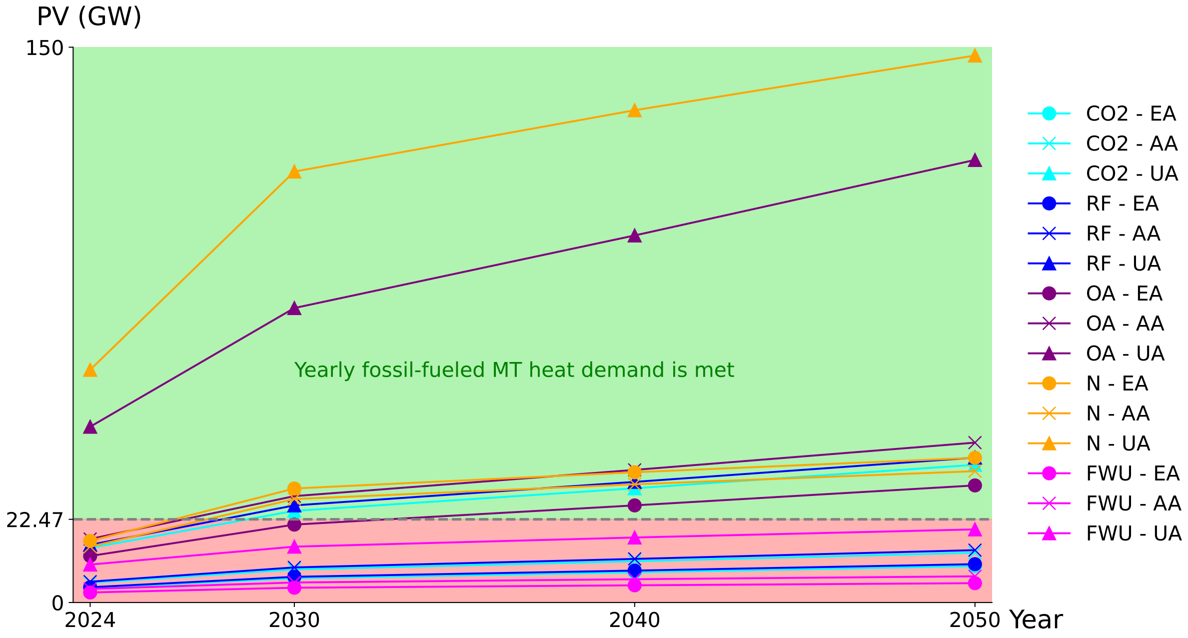

Figure 11: In 2024, only the N and OA PBs, which are the less constraining, allow to meet the E demand, considering the UA SP, which allocates the largest share of the SOS (SoSOS). By 2030, CO2 and RF PBs meet the E demand with the UA SP. By 2040, N and OA PBs prove sufficient for whichever SP. The FWU PB never allows to satisfy the E demand.

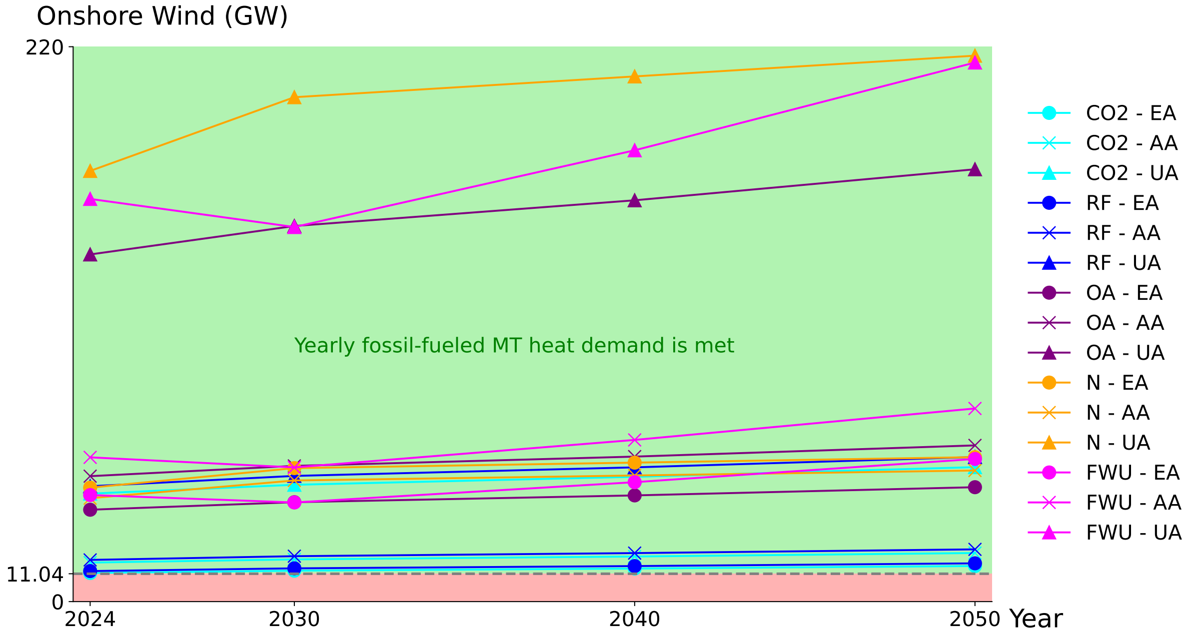

Figure 12: For all SPs, all PBs are satisfied in 2024, CO2 is the most constraining PB. The decrease in allocated share for FWU between 2024 and 2030 is a consequence of assumptions of the Premise Python package.

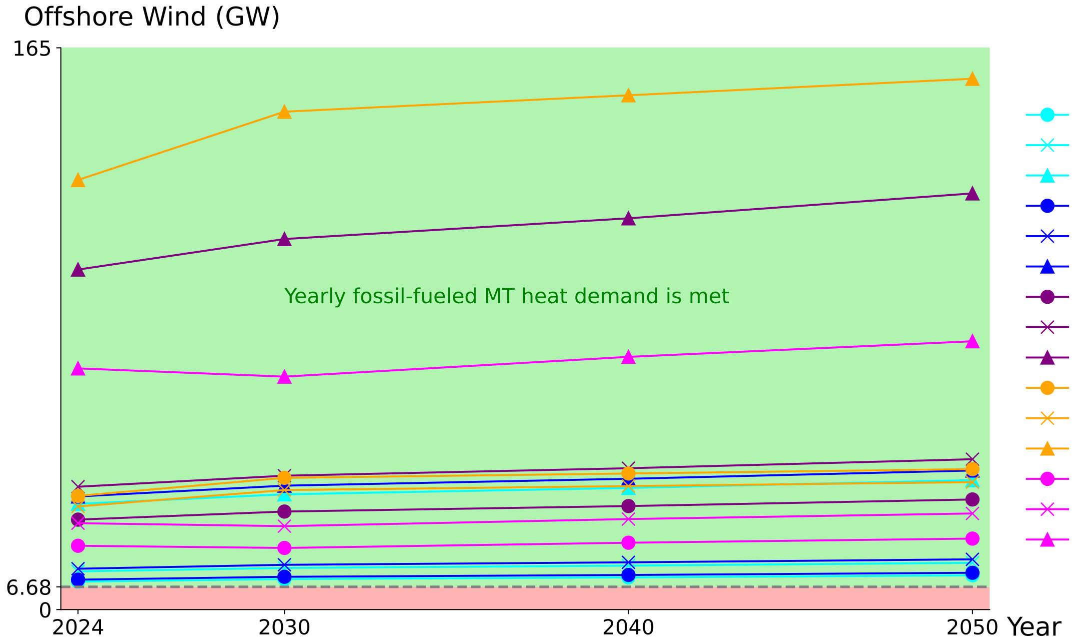

Figure 13: For all SPs, all PBs always satisfy the E demand, CO2 is the most constraining PB. The decrease in allocated share for FWU between 2024 and 2030 is a consequence of assumptions of the Premise Python package.

The main conclusion for the electricity sector is that PV has a significantly larger impact on the PBs, especially FWU, compared to onshore and offshore wind, both of which could feasibly replace the electricity demand currently met by fossil fuels (considering the yearly scope). This larger impact results from both the increased capacity needed due to the lower C_p and the larger PV impacts compared to onshore and offshore wind (see Appendix A.4, Tables 22, 23 and 24). The primary issue, common to all technologies, is the need for large installed capacities.

4.1.2 Low temperature heat sector

For the LT-H sector, 76653GWh$_{\text{th}}$ ($Q_{\text{LT}} \cdot \eta_{th}$, see Section 2.4) have to be met, which corresponds to an installed capacity of 33.27GW$_{\text{th,HP}}$. By multiplying this value with the factors calculated with eq. 19, the corresponding renewable capacities are determined: 19.4GW$_{\text{elec,PV}}$, 9.52GW$_{\text{elec,onsh}}$ and 5.76 GW$_{\text{elec,offsh}}$.

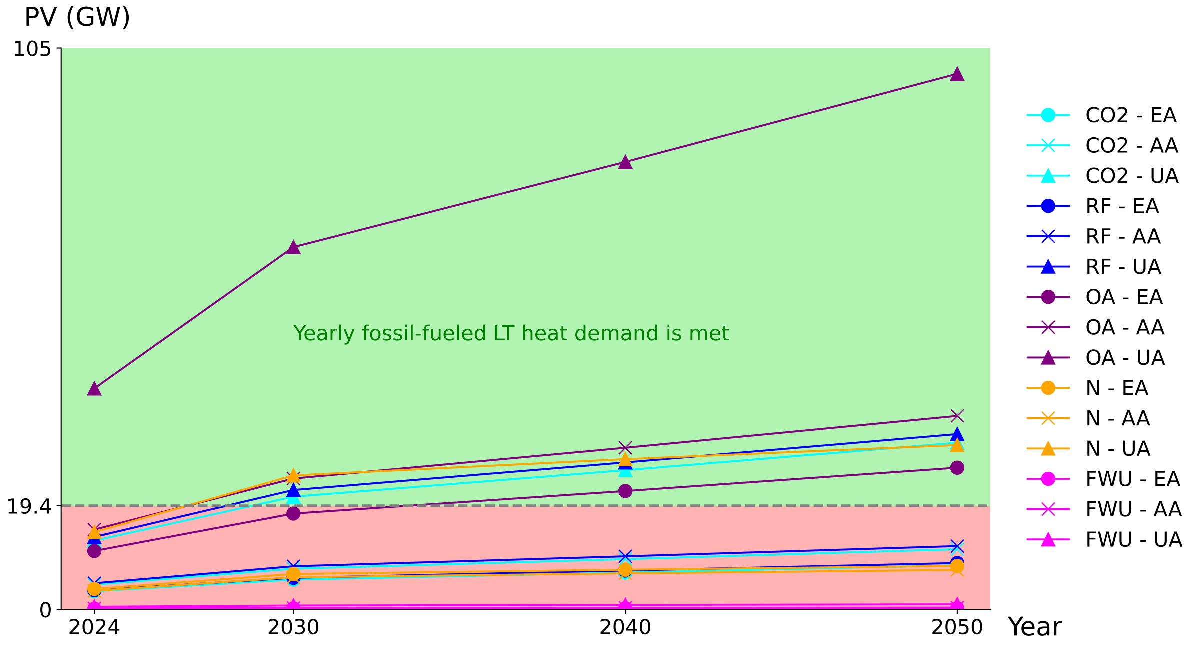

Figure 14: In 2024, only the OA PB under the UA SP allocates a sufficient SoSOS. By 2030, except for FWU, all PBs under the UA SP meet the LT heat demand, and the OA PB meets the demand across all SPs.

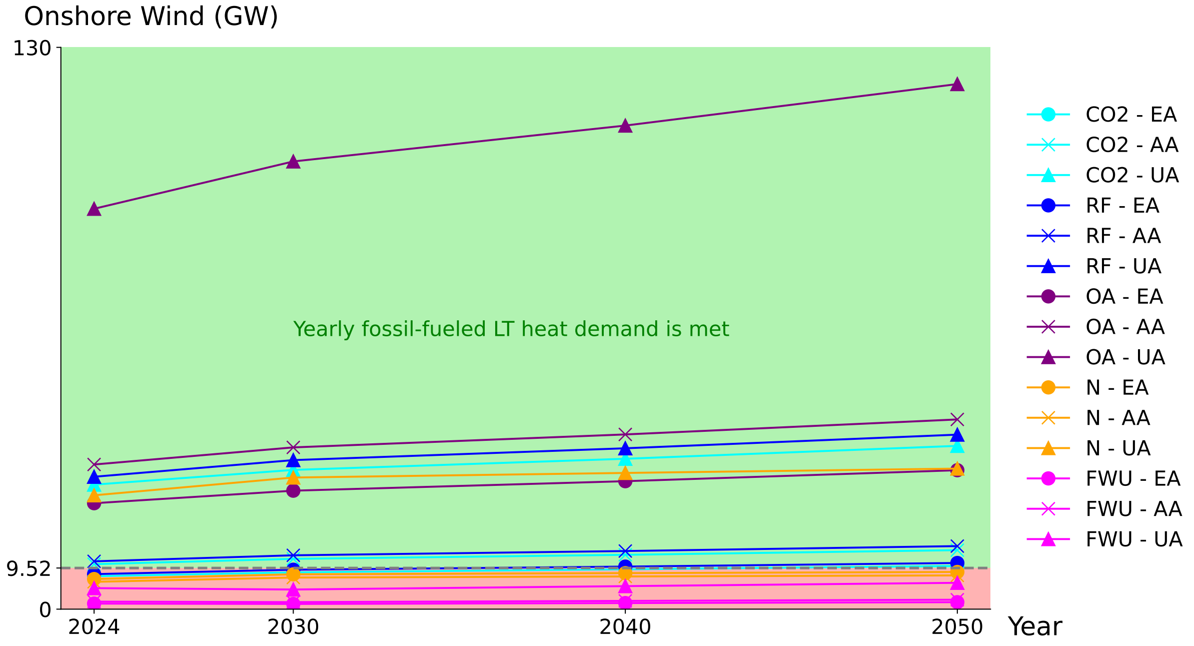

Figure 15: For EA, the OA, RF and CO2 PBs give a sufficient share respectively in 2024, 2040 and 2050. For AA, CO2 gives a sufficient share directly in 2024. For both SPs, the N PB, being the most constraining PB after FWU, does not yield a sufficient installed capacity. For UA, all PBs, except FWU, are sufficient from 2024 onwards.

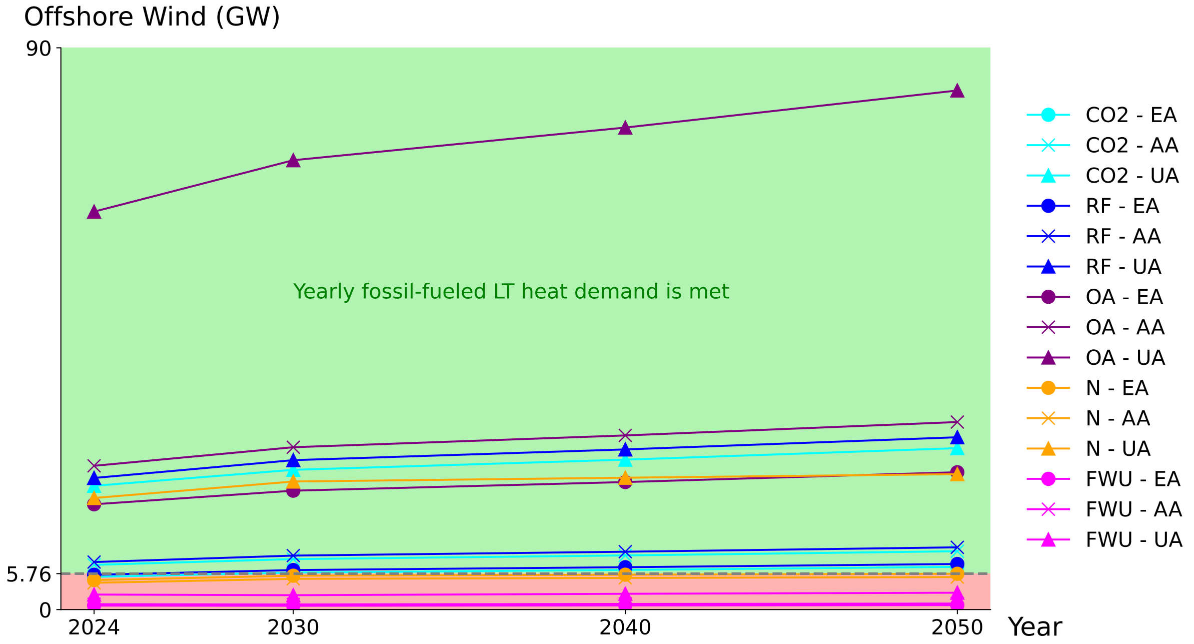

Figure 16: For EA, the OA, CO2 and N PBs give a sufficient share respectively in 2024, 2030 and 2050, but N only for scenario SSP2. For AA, CO2 gives a sufficient share directly in 2024. For UA, all PBs, except FWU, are sufficient from 2024 onwards.

Compared to the E sector, notable differences include a greater impact of renewables on the N PB, which arises from their combination with HPs. Additionally, the FWU PB has become disproportionately constraining for all technologies.

4.1.3 Medium temperature heat sector

For the MT-H sector, 14282GWh$_{\text{th}}$ ($Q_{\text{MT}} \cdot \eta_{th}$, see Section 2.4) have to be met to fulfil the demand. To translate this into an electricity demand, following formula is used:

$$\mathrm{P}_{\text{renewables}} = \left(\frac{14282}{\eta_{\text{th,H}_2}} \cdot \frac{\text{prop}_{\text{elec-H}_2}}{\text{LHV}_{\text{H}_2}} \right) \Big/ (8760 \cdot C_p) \tag{22}$$

With $\eta_{\text{th,H2}} = 90\%$—noting that "combusting hydrogen achieves relatively similar efficiencies to fossil fuels" [83], η_{th} from Section 2.4 is used—this efficiency could be lower, which would reduce the SoSOS for MT-H (see eq. 12). Under this assumption, more electricity would be required to meet demand, making the calculated values for MT-H and HT-H potential lower bounds for necessary capacity installations. The lower heating value (LHV$_{\text{H2}}$) is $33.3{\cdot}10^{-6}$GWh$_{\text{th}}$/kg$_{\text{H}_2}$ [84], and the electricity required for H2 production (prop$_{\text{elec-H}_2}$) averages $52.5 \cdot 10^{-6}$GWh$_{\text{elec}}$/kg$_{\text{H2}}$ [85]. Considering the load factors C_p (refer to Table 15), the resulting necessary installed capacities are 25.27GW$_{\text{elec,PV}}$, 12.42GW$_{\text{elec,onsh}}$, and 7.52GW$_{\text{elec,offsh}}$.

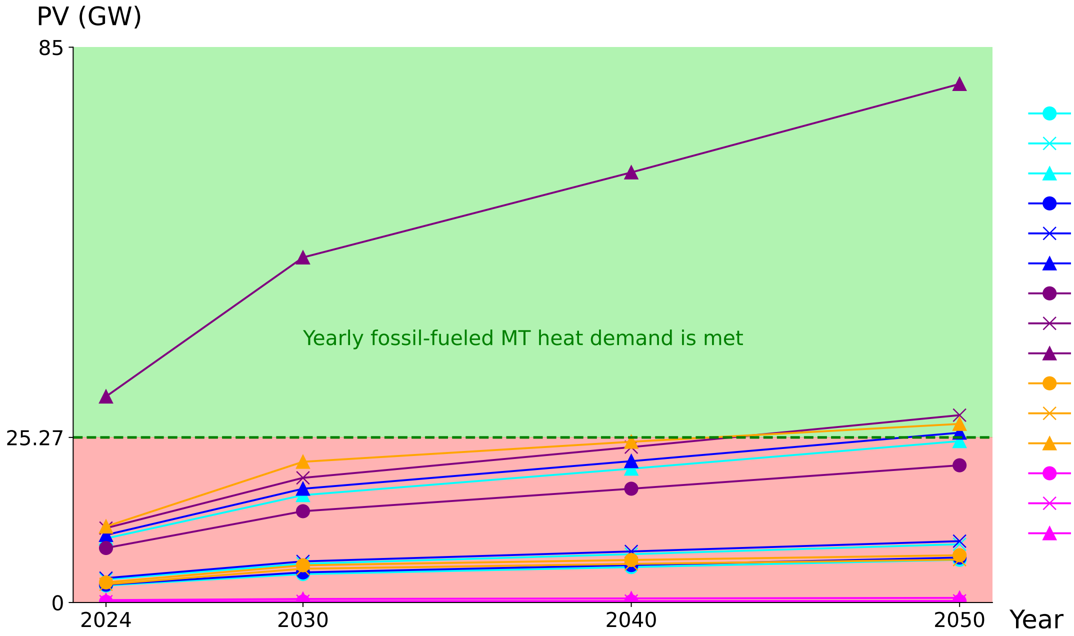

Figure 17: For EA, no allocated share ever meets the MT demand. For AA, only OA is sufficient in 2050. For UA, all PBs except FWU meet the MT demand in 2050, with CO2 only achieving this under the SSP2 scenario.

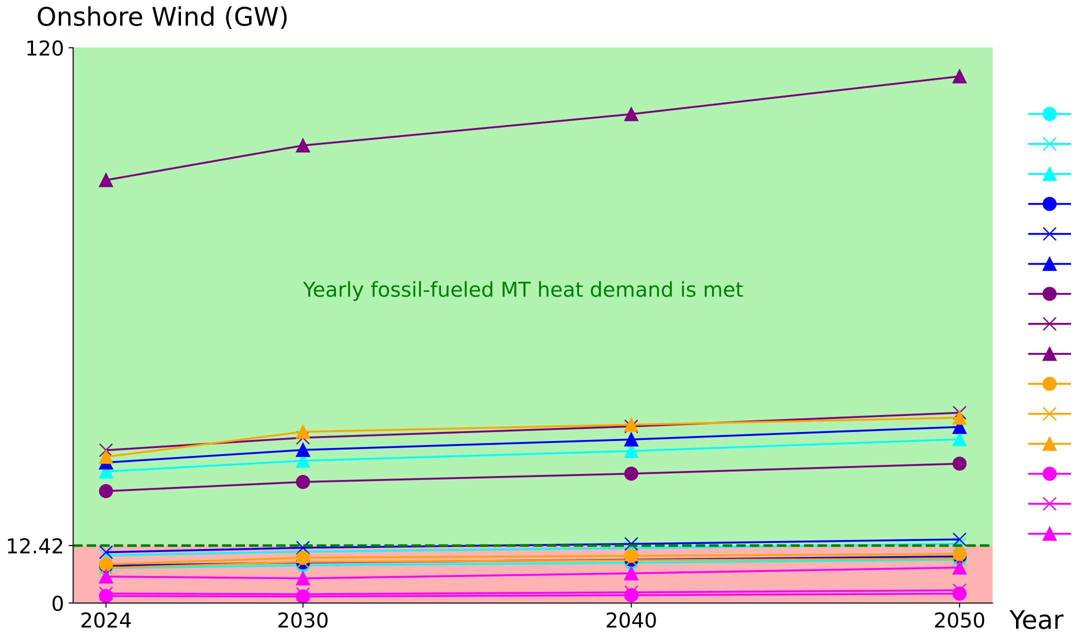

Figure 18: For EA, only the OA PB yields a sufficient share in 2024. For AA, OA provides a sufficient share in 2024, while RF and CO2 PBs meet the requirements in 2030 and 2040 respectively, but only under the SSP2 scenario. For UA, all PBs except FWU are satisfied in 2024.

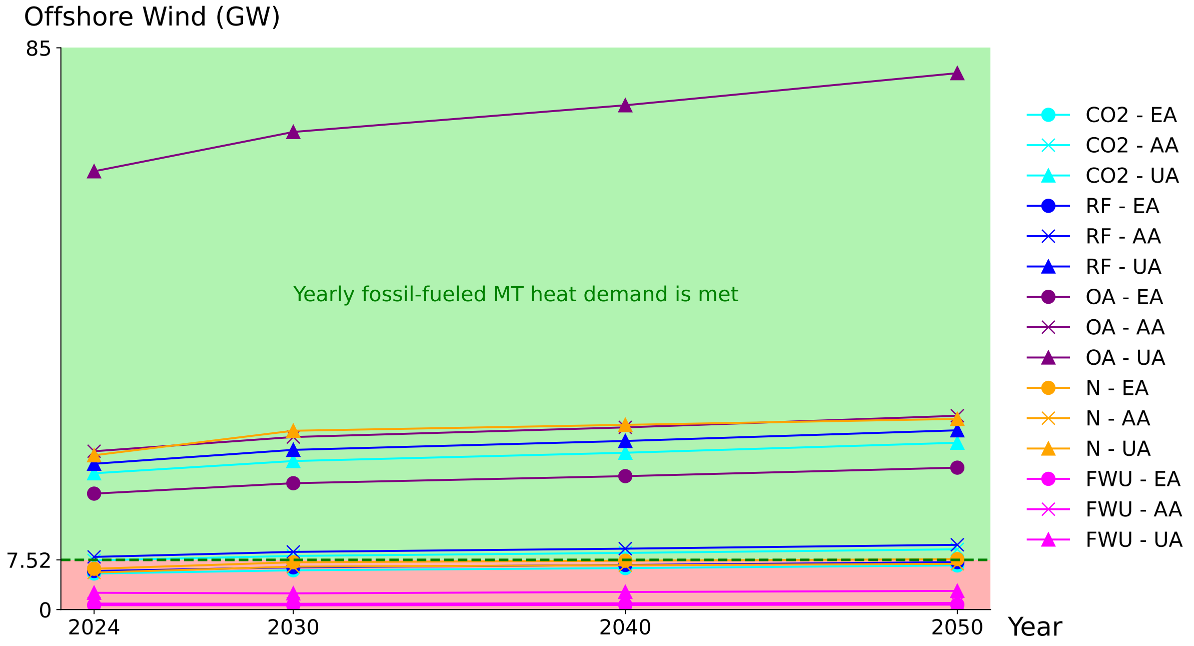

Figure 19: For EA, only OA provides a sufficient share in 2024. For AA, OA offers a sufficient share in 2024, while RF and CO2 reach sufficiency in 2030 and 2040, respectively, but only under the SSP2 scenario. For UA, all PBs except FWU meet the requirements in 2024.

Overall, transitioning the MT-H sector requires very large installed capacities of renewables, and even then, the shares allocated by the EA and AA SPs are almost entirely unmet. Since only the impacts of renewables were considered to estimate the capacities for each PB and SP (see Section 3.1), and not the impacts of H2 infrastructure, the actual capacities allocated per PB should be lower. However, a lower $\eta_{\text{th},\text{H}_2}$ would require even more installed capacity. These conflicting considerations make it difficult and unrealistic to transition the MT-H sector with H_2 alone. Other 'green' fuels like biofuel or ammonia could be better alternatives.

4.1.4 High temperature heat sector

For the HT-H sector, $26941\text{GWh}_{\text{th}}$ ($Q_{\text{HT}} \cdot \eta_{th}$, see Section 2.4) have to be met to fulfil the demand. By analogy with the MT-H sector, using eq. 22, the required capacities are $47.68\text{GW}_{\text{elec,PV}}$, $23.42\text{GW}_{\text{elec,onsh}}$, and $14.18\text{GW}_{\text{elec,offsh}}$.

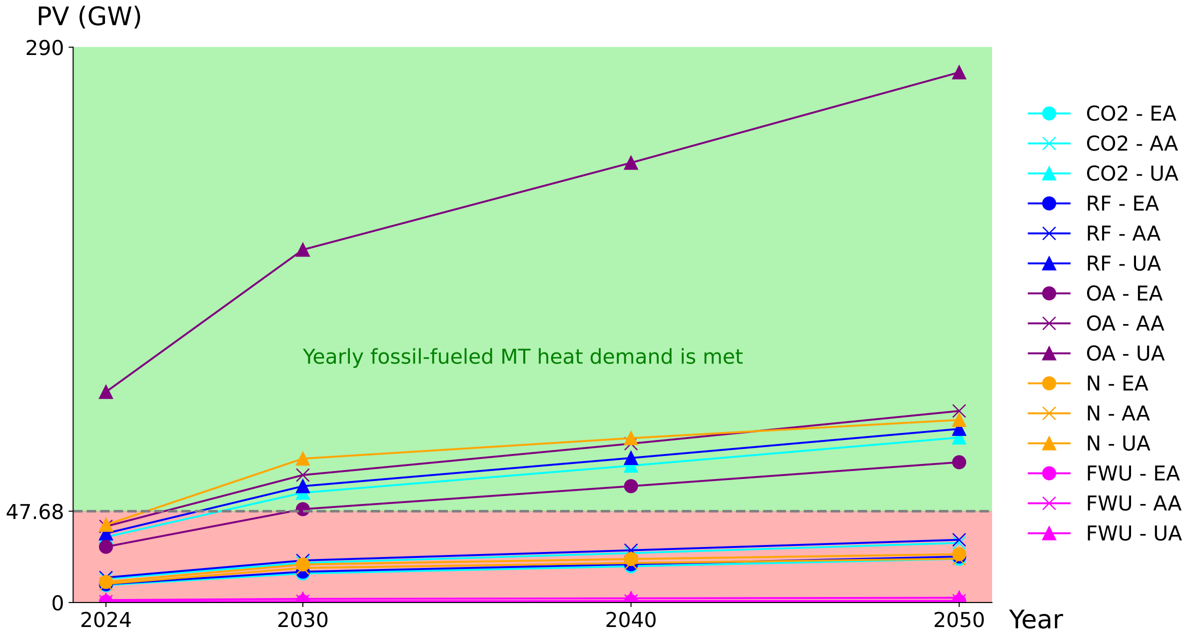

Figure 20: For EA and AA, only OA is sufficient from 2030 onwards. For UA, OA is satisfied in 2024, while the rest of the PBs, except FWU, are satisfied from 2030 onwards.

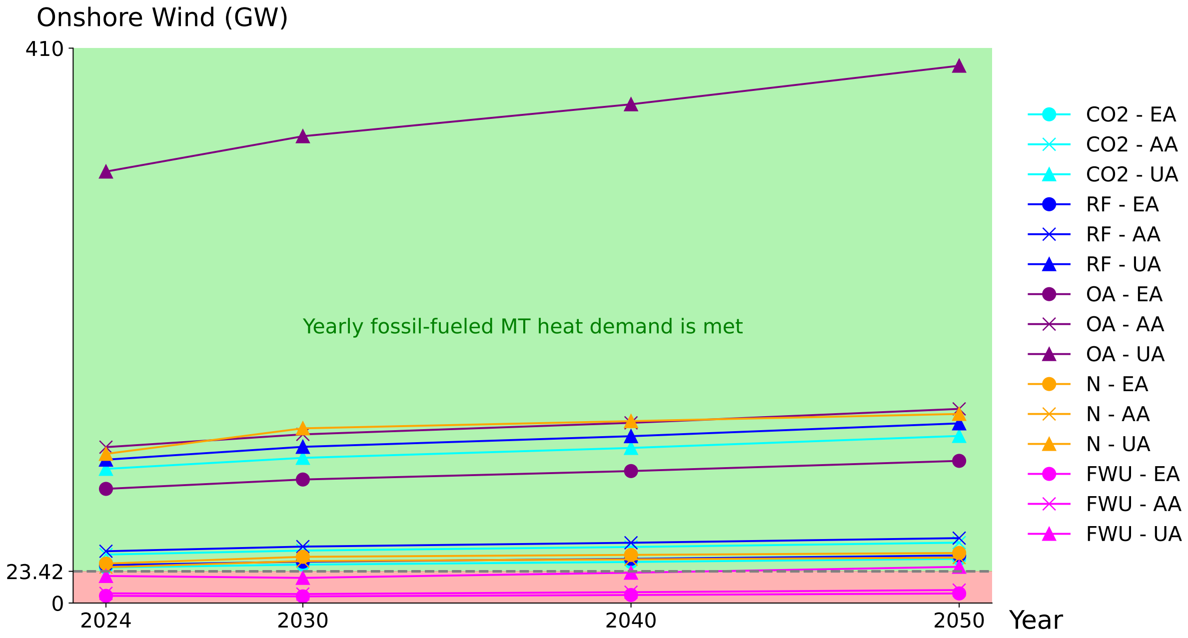

Figure 21: All PBs, except FWU, are always respected from 2024 onwards. FWU is only satisfied for the UA SP in 2050.

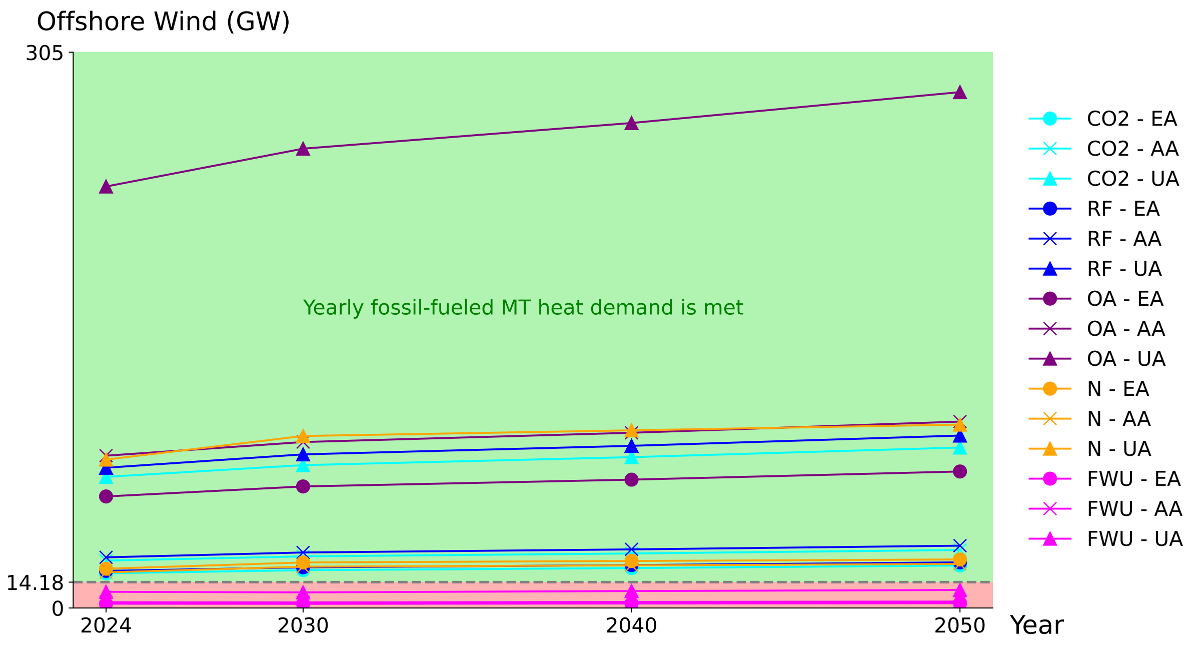

Figure 22: All PBs, except FWU, are always respected from 2024 onwards.

In contrast with the MT-H sector, the transition is feasible for each SP and PB, especially for onshore and offshore wind, except for the FWU PB. This feasibility is largely due to the larger share allocated at LV3 downscaling to the HT-H sector. There is a noticeable margin between the allocated and required capacities, which would be reduced when considering the infrastructure impacts of building H_2. This margin could potentially be allocated to the LT-H and MT-H sectors, which have a greater need for additional SOS to facilitate the transition.

Overall, transitioning the energy sectors in Belgium involves substantial challenges, particularly in terms of the required installed renewable energy capacities. In the electricity sector, although the transition appears most feasible, it necessitates a significant expansion of renewable resources. This necessity escalates further if the transport sector shifts to relying on electricity or hydrogen, demanding even greater renewable capacity to meet energy needs sustainably. The heat sector faces the most significant hurdles; transitioning to hydrogen, for instance, is impractical without massive renewable installations and careful consideration of the impacts from unaccounted hydrogen infrastructure. Instead, alternative green fuels such as ammonia or biofuels might offer more viable solutions. Overall, while the UA SP provides the broadest shares and suggests theoretical feasibility across sectors, the immense installed capacities and the complexity of integrating various energy needs make the transition technically challenging. Direct electricity use remains a more straightforward and feasible option for the transport sector.

4.2 Assessing absolute sustainability and demand fulfilment for technology mixes

This section illustrates when technology mixes achieve absolute sustainability while meeting sectoral demands, achievable exclusively under the UA SP. For other SPs, where a fully sustainable mix falls short of the demand, advancing into the "zone of increasing risk" for the most constraining PBs is considered. The decision to use this approach is the responsibility of decision-makers. In the energy production sector, which typically employs a variety of technologies, this section proposes technology mixes that can achieve absolute sustainability, based on successful cases from individual evaluations (see Section 4.1). It also discusses the regions of uncertainty associated with each PB and assesses how reasonable it might be to venture into these zones to meet the demand. In the PB framework, the SOS is established using the precautionary principle, as the exact tipping points within the zone of uncertainty are unknown. The risk of breaching these tipping points increases as one moves further from the SOS. These zones of increasing risk guide limitations on allowances within the region of uncertainty, as detailed by Richardson et al. [4].

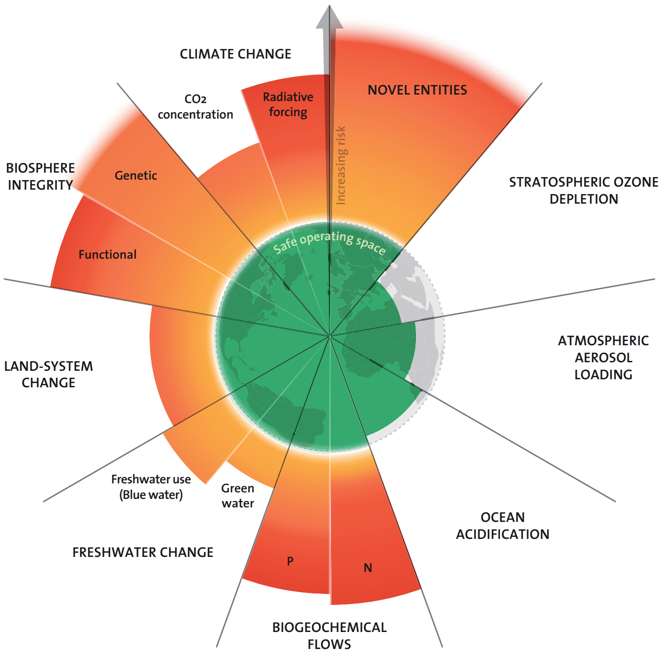

Figure 23: Credit: Azote for Stockholm Resilience Centre, Stockholm University. Based on analysis in Richardson et al. 2023. [4]. In green: the SOS, in red: the zone of increasing risk.

To evaluate if a technology mix is absolutely sustainable for a given PB, assuming each technology is absolutely sustainable on its own, the property of convexity [86] can be applied, stating:

$$aSOS = w_{PV} \cdot P_{PV} \cdot \text{impact}_{PV} + w_{onsh} \cdot P_{onsh} \cdot \text{impact}_{onsh} + w_{offsh} \cdot P_{offsh} \cdot \text{impact}_{offsh} \quad (23)$$

$$\text{where} \quad w_{PV} + w_{onsh} + w_{offsh} = 1 \quad \text{and} \quad w_i \geq 0$$

Here, $P_{PV}, P_{onsh}, P_{offsh}$ represent the impacts of the technologies, and $w_{PV}, w_{onsh}, w_{offsh}$ are the proportions. Similarly, this applies to meeting the sectoral demand:

$$\text{Demand} = w_{PV} \cdot P_{PV} \cdot 8760 \cdot C_{p,PV} + w_{onsh} \cdot P_{onsh} \cdot 8760 \cdot C_{p,onsh} + w_{offsh} \cdot P_{offsh} \cdot 8760 \cdot C_{p,offsh} \quad (24)$$

The property of convexity for absolute sustainability thus ensures that the triangles in upcoming sections, representing the technology mixes, are all absolutely sustainable for the considered PBs. If these properties are satisfied for all PBs, it can be concluded that the technology mix is absolutely sustainable for all PBs. If each technology meets the sectoral demand on its own, convexity for the demand is satisfied. However, not all of the triangles meet the required sectoral demand, as exposed in Section 4.1. An ideal energy mix should thus satisfy both properties. If the triangles intersect to form a polygon, the property of convexity for the demand can no longer be assured, but absolute sustainability is still guaranteed.

Each figure represents a 2D projection of a 3D plot with axes for PV, onshore wind, and offshore wind. Colours denote the share of the SOS for each PB, forming triangles originating at (0,0) and plotted in descending order of area. The green overlap indicates the 'absolutely sustainable mix for all PBs,' meaning absolute sustainability is respected for all PBs. The same colour code as in Section 4.1 is used for all PBs. The FWU PB, which makes the transition impossible (see Sections 4.1.2, 4.1.3, and 4.1.4), is excluded from the heat sector analyses. However, it is important to note that the FWU PB is currently near the upper limit of the "zone of increasing risk" (see Figure 23), indicating that the SOS for FWU is breached for the heat sectors. This exclusion can be attributed to the heat sector's impact on the FWU PB being $\mathcal{O}(10^1)$ lower compared to the electricity sector. The UA SP is prioritised for analysis as it is the only SP that makes the transition feasible. Each figure will assess whether the demand is met or if entering the "zone of increasing risk" is necessary and reasonable.

4.2.1 Electricity sector

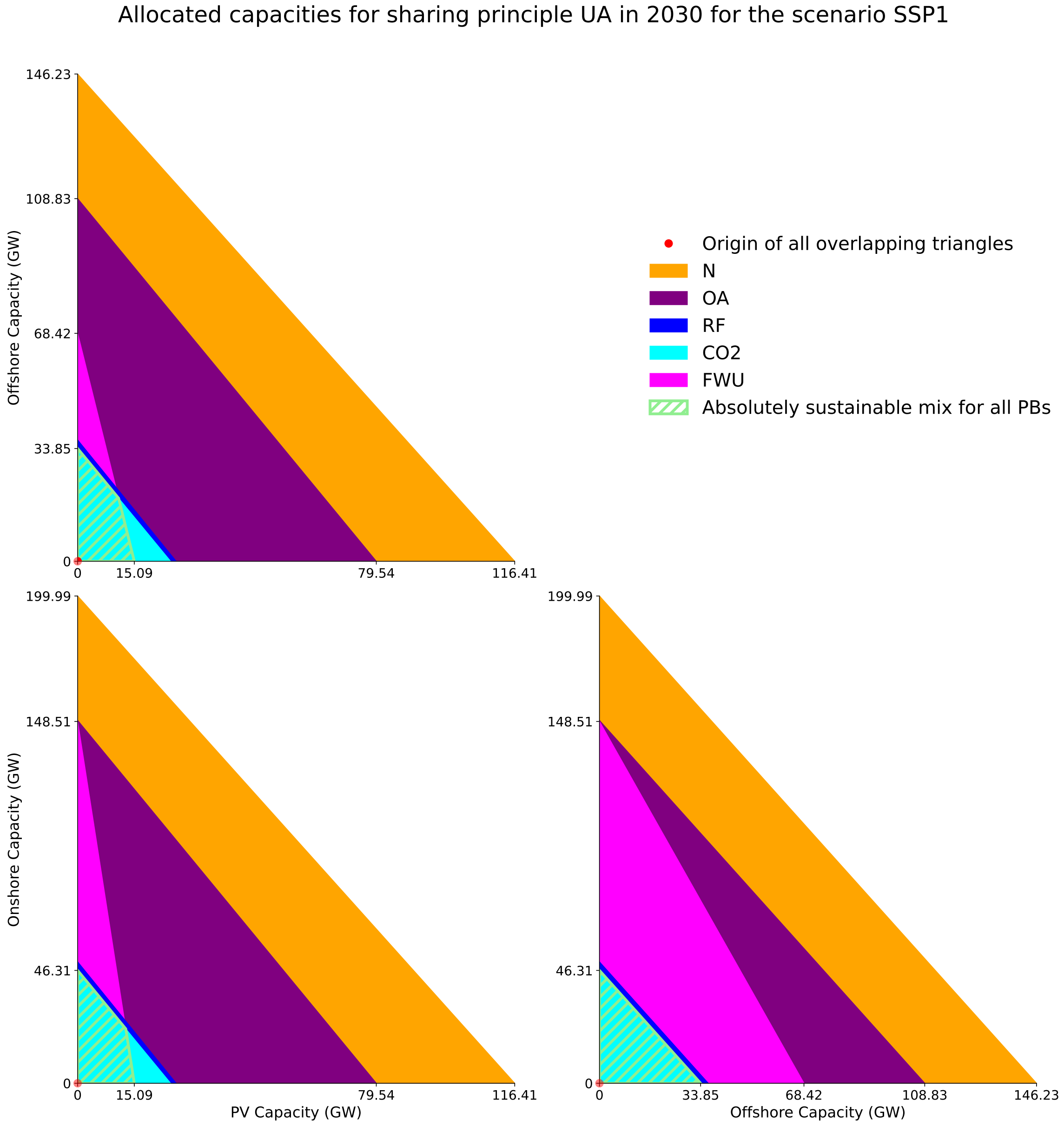

Figure 24: UA SP (2030): From this year onwards, all technologies can meet the demand while remaining absolutely sustainable (see Figures 11, 12 and 13), except for FWU in the case of PV. However, the intersection of CO2 and FWU (figures on the left) complicates satisfying the demand if PV is included, as convexity is not satisfied. Conversely, if only onshore and offshore wind are considered (figure on the right), the demand is met for all PBs as the 'absolutely sustainable mix' corresponds to the allocated capacity for CO2, validating the property of convexity. To meet the demand, the FWU allocated share of the SOS for PV could be slightly exceeded since FWU is not in the "high risk zone".

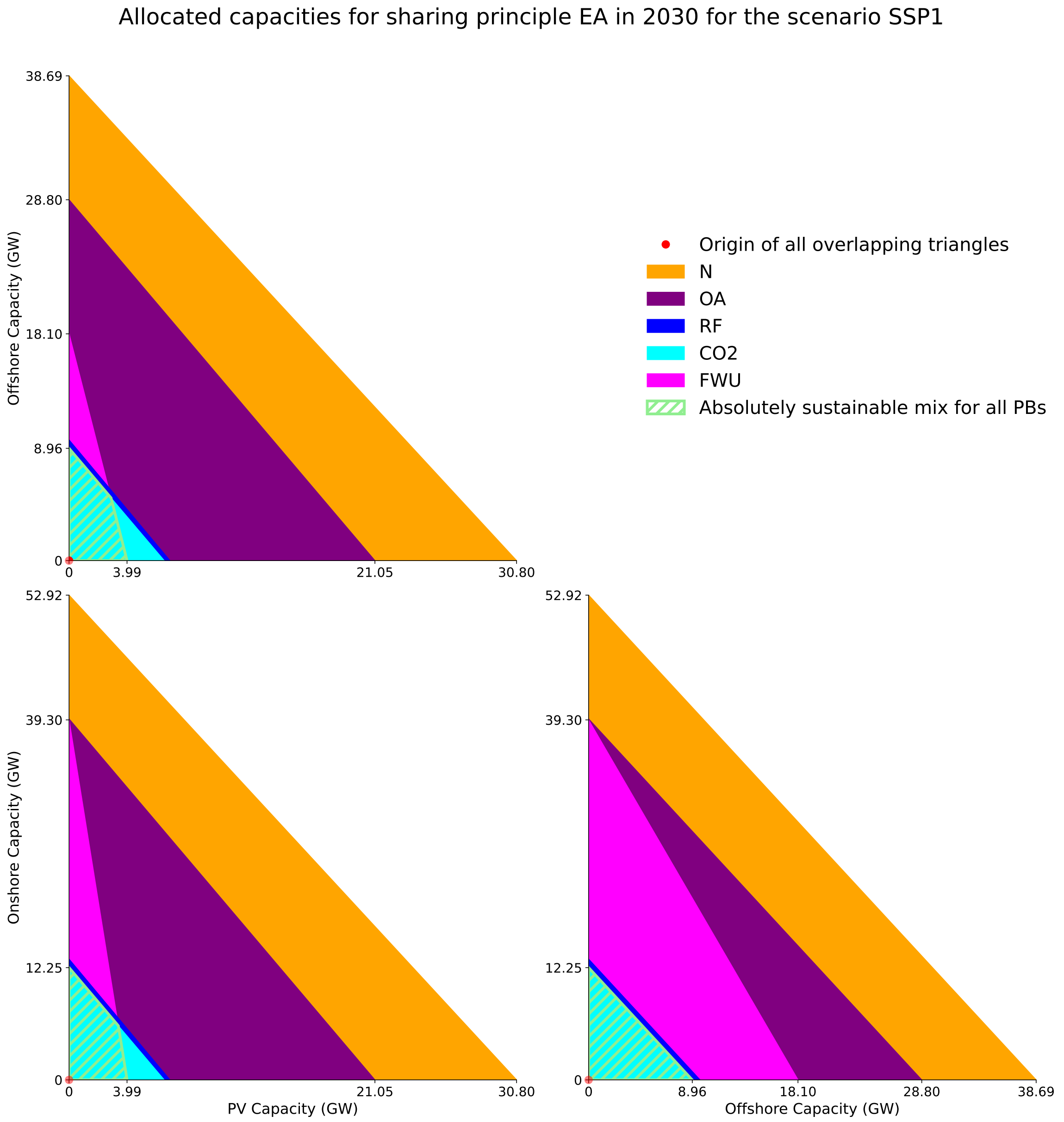

Figure 25: EA SP (2030): In contrast to the UA SP for 2030 (and onwards), only N meets the demand for PV, with OA nearly meeting it, while other PBs fall short (see Figure 11). For onshore and offshore wind, the demand is always met. To meet the demand, CO2, RF, and FWU must be pushed to the "high risk zone," RF potentially breaching its tipping point.

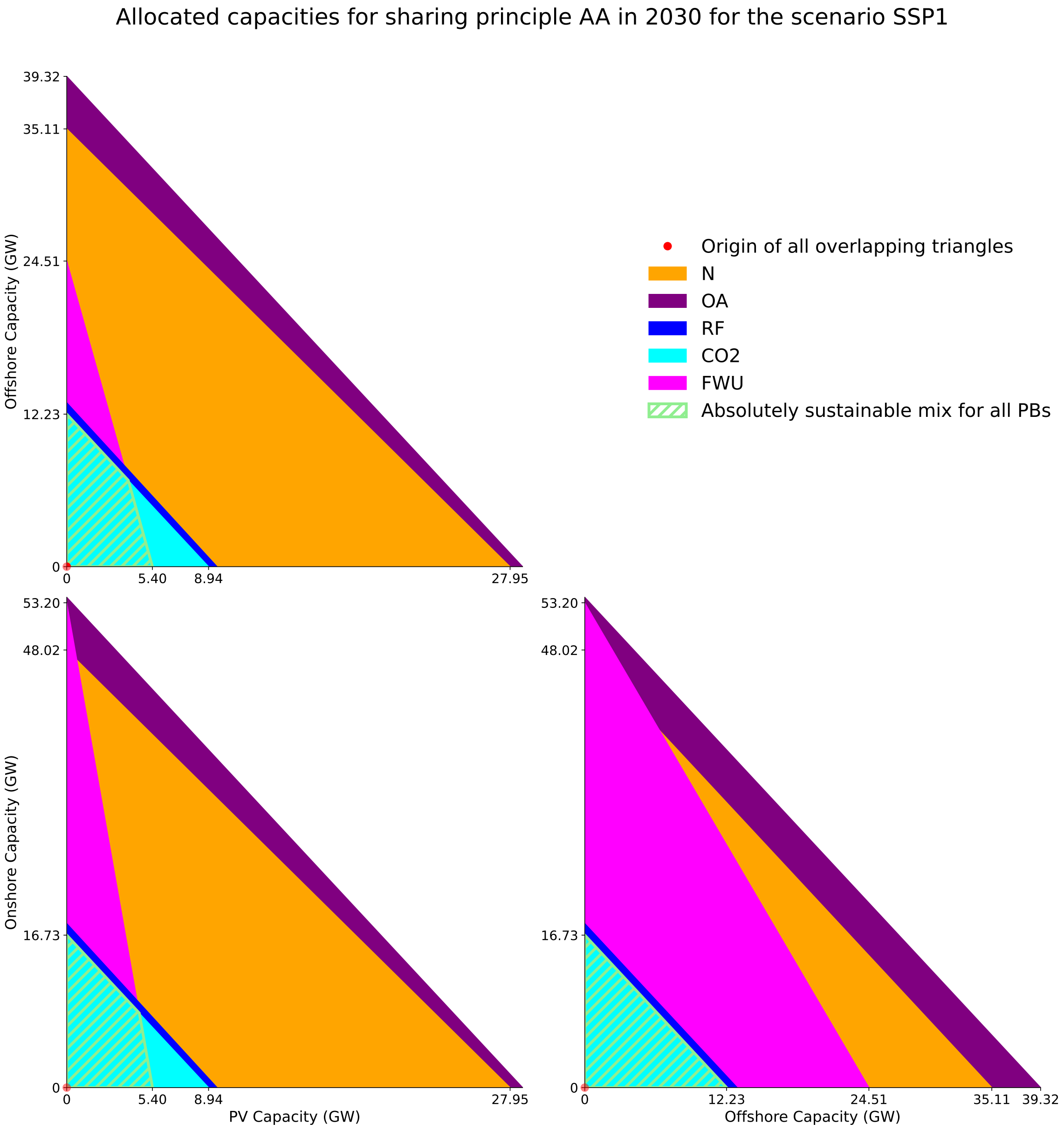

Figure 26: AA SP (2030): The conclusions for the AA SP in 2030 (and onwards) are similar to those for the EA SP in 2030. The only difference is the higher SoSOS allocated to OA (even higher than N), which meets the demand (see Figure 11). Compared to Figure 25, this results in the purple triangle being larger than the yellow one.

4.2.2 Low temperature heat sector

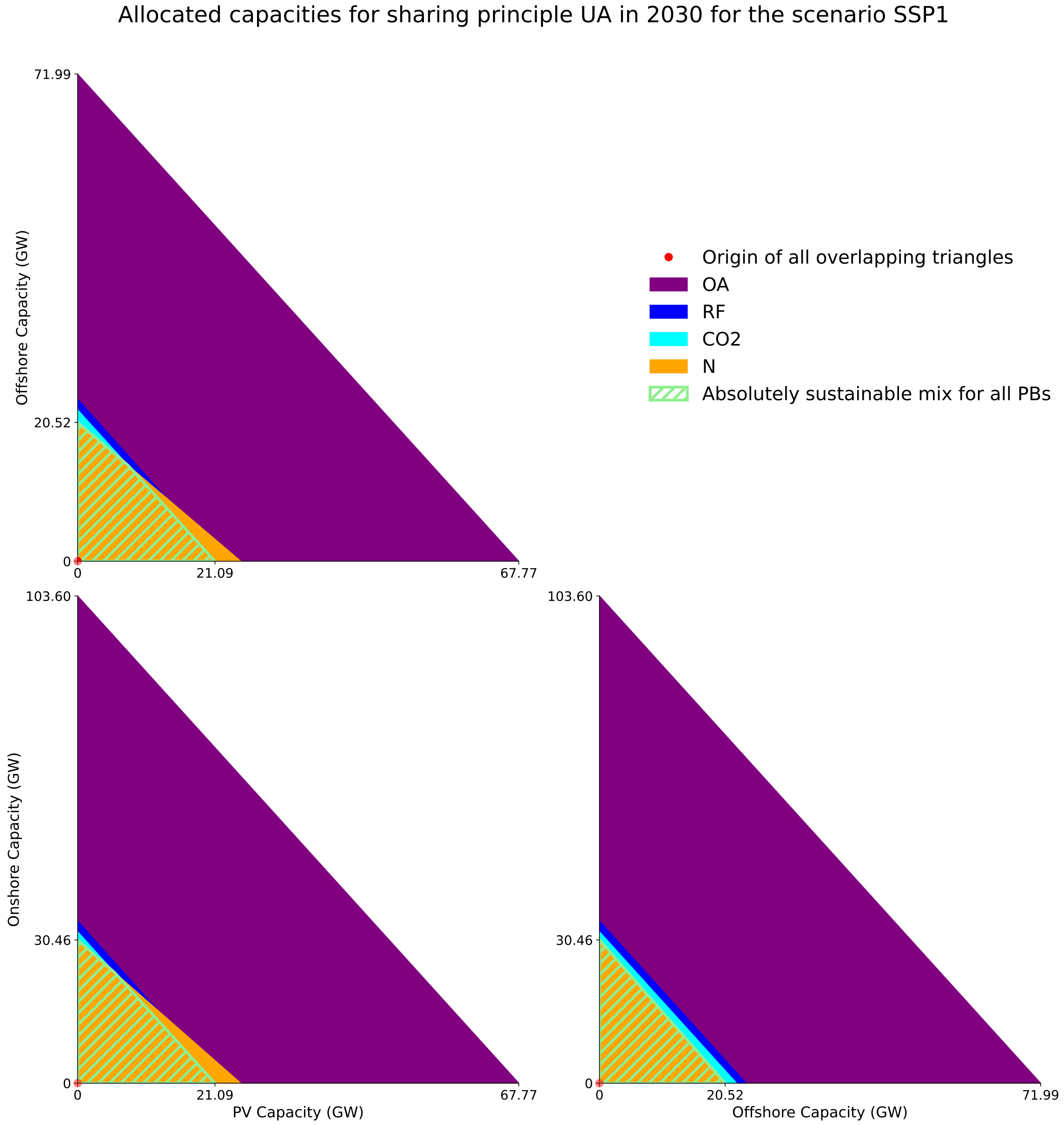

Figure 27: UA SP (2030): The UA SP is chosen as it is the only scenario providing sufficient shares for all technologies to meet the low-temperature heat demand from 2030 onwards (see Figures 14, 15 and 16). As noted earlier, the FWU PB is excluded from this analysis. Omitting FWU likely pushes its impacts into the "high risk zone". The polygon formed by the intersection of CO2 and N PBs (figures on the left) does not theoretically ensure the demand is satisfied; however, it can be approximated by the CO2 triangle for which the property of convexity is valid, almost ensuring the demand is met for any mix.

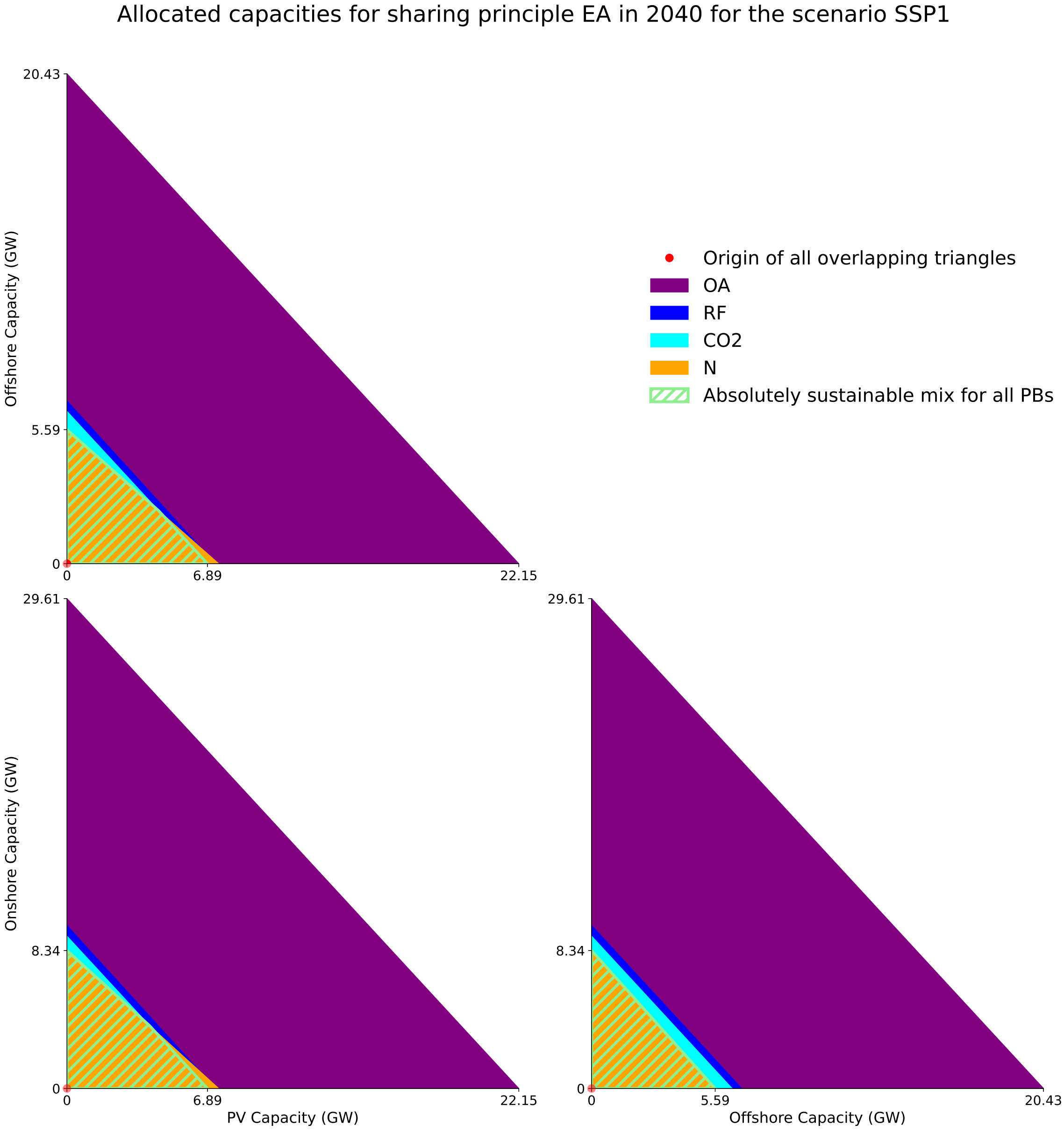

Figure 28: EA SP (2040): In 2040 and onwards, under the EA SP, the OA PB provides a sufficient share to meet the demand for all technologies (see Figures 14, 15 and 16). However, since the RF and N PBs are already in the "high risk zone", pushing them risks breaching their tipping points.

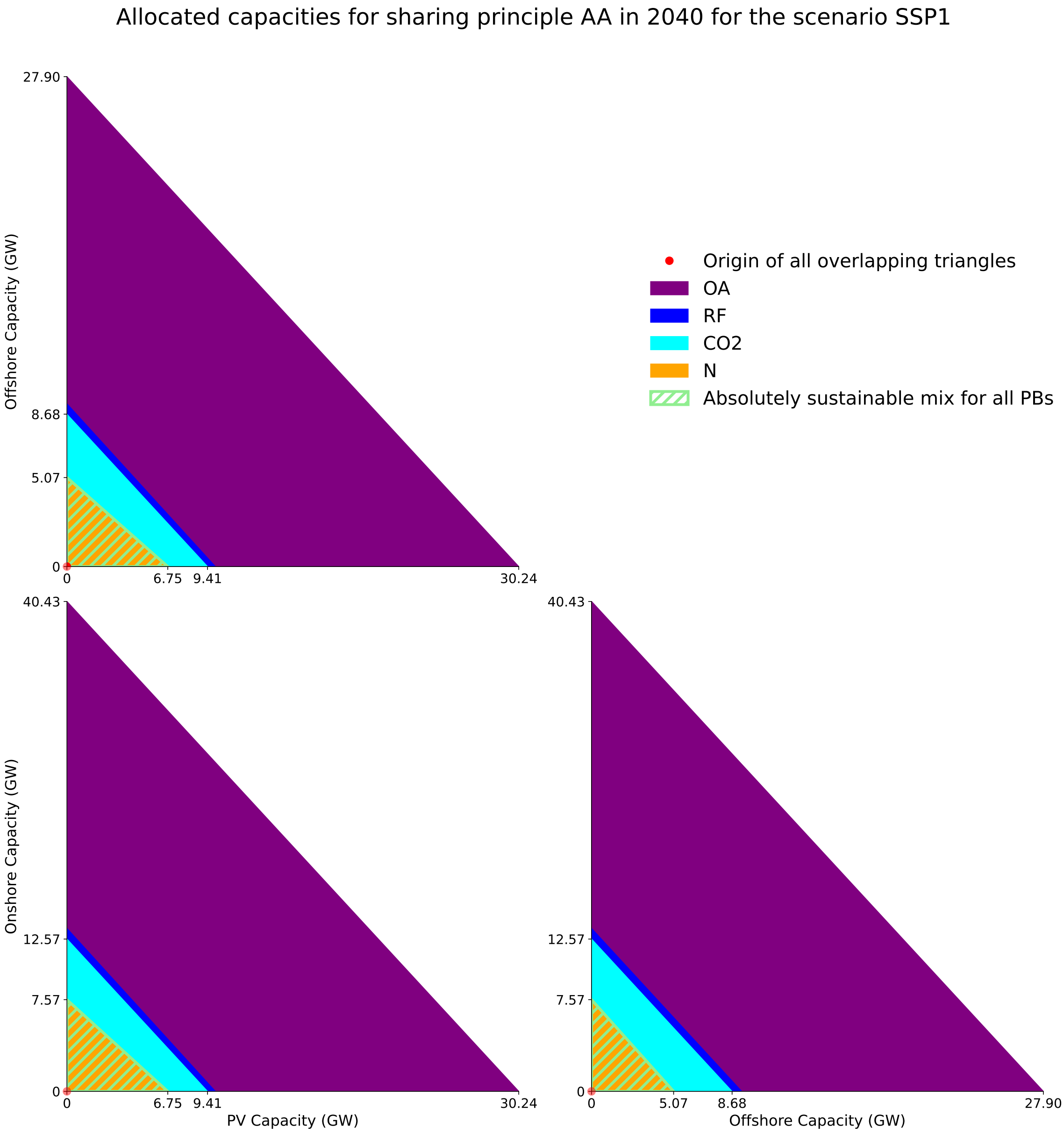

Figure 29: AA SP (2040): The AA SP yields similar results in 2040 and onwards as the EA SP, with the primary difference being the even higher share allocated to OA. The second difference, is the lower SoSOS to the N PB for each technology.

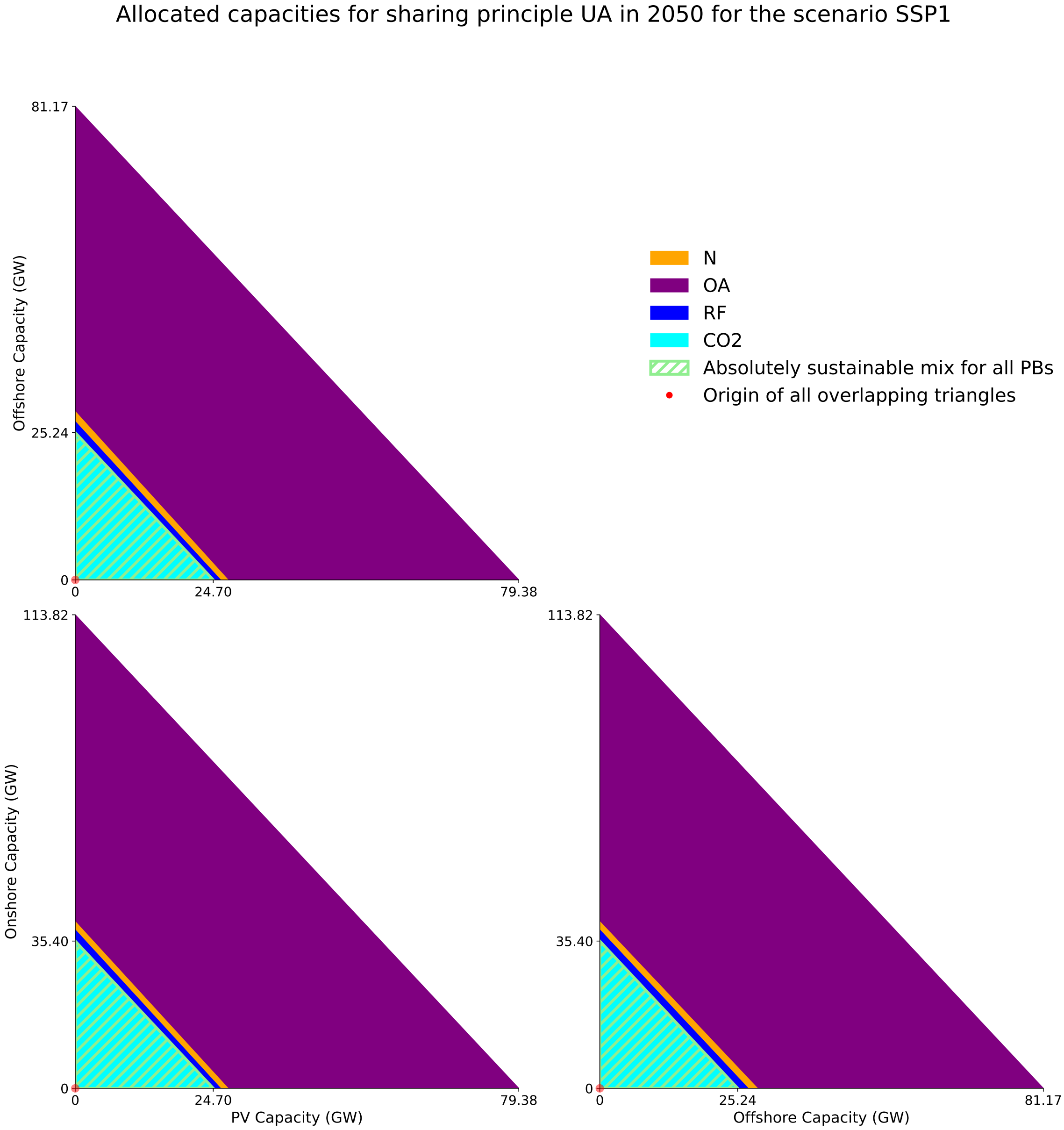

Figure 30: UA SP (2050): In 2050, under the UA SP, the RF PB for PV nearly meets the demand, as indicated in Figure 17. A modest push into RF's risk zone might achieve demand satisfaction; however, given RF's high-risk status, such adjustments must be made with caution to avoid taking significant risks.

4.3 High temperature sector

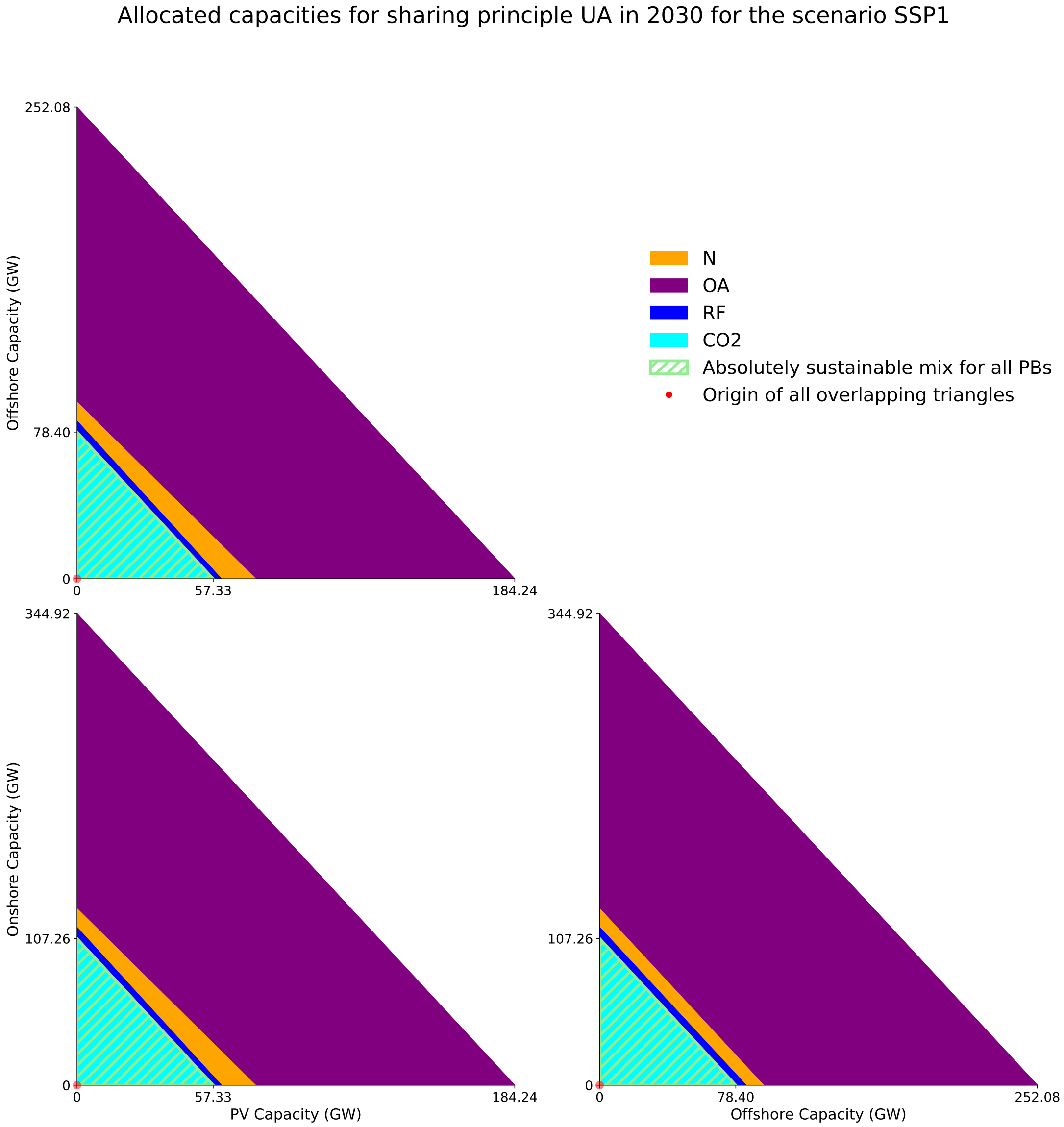

Figure 31: UA SP (2030): From 2030 onwards, the UA SP ensures all allocated shares, except for the FWU PB, meet the demand (see Figures 20, 21 and 22).

The main conclusions are that the transition can be considered absolutely sustainable by 2040-2050 with UA SP, meeting demand in heat sectors consistently, whereas in the electricity sector it depends on the mix used, with limited PV installation possible. FWU is more limiting than CO2 for both electricity and heat sectors, while N constraints the LT heat sector. It's feasible to extend PBs into a "zone of increasing risk" to meet demand if capacity is nearly sufficient. However, it's recommended to maintain absolute sustainability across as many PBs as possible.

5 Limitations and suggested improvements

This section aims to address the various limitations of this work and suggest potential pathways for improvement. The first limitation is the non-consideration of the transport demand sector (including freight), which is currently covered by fossil fuels. Including this sector would provide a more comprehensive overview of the energy sector (when characterised by its demand) and enhance the understanding of the potential transition to renewables. Its implementation can be conducted using the same methodology as proposed in this study, which consists of determining its current impacts on each planetary boundary, fixing the allocation factors, selecting the activities that would replace fossil-fuelled transport in the projected Life Cycle Inventories (e.g., electric or hydrogen-fuelled vehicles), and conducting a prospective Planetary Boundaries Life Cycle Impact Assessment to evaluate the feasibility and timing of the transition to renewable alternatives.

Secondly, for the medium temperature and high temperature heat demand sectors, only the impacts of the renewable technologies providing 'green electricity' (photovoltaics, onshore wind, and offshore wind) were considered. This approach fails to account for the technologies required to produce and burn hydrogen for heat, as these were not available in the Life Cycle Inventories. It would be useful to model these technologies in the ActivityBrowser.

Furthermore, an improvement could be made by combining the medium temperature and high temperature heat sectors into a single high temperature heat sector, as the distinction between medium temperature and high temperature heat is inherently subjective. The boundary between the low temperature and high temperature heat sectors would also be adjusted to the minimum heating temperature required to avoid legionella, which is slightly above 60°C if the water is to be heated to 60°C [87].

Additionally, the assumption was made that only natural gas is used to produce electricity in Belgium. In reality, natural gas accounts for slightly more than 90%, with coal making up the remaining 10%. To improve the results, this part of the generation should also be taken into account. Further assumptions were made in this study regarding the parameters chosen to characterise the allocated shares of the safe operating space (a lot of assumptions were made for the heat sector) or the characterisation of the technology impacts (e.g., location for which the activity is characterised in ActivityBrowser). If more accurate data becomes available, these parameters should be adapted to reflect the local situation as accurately as possible.

Moreover, SSP scenarios are often paired with an RCP scenario that limits the amount of radiative forcing in line with the Paris Agreement. Future work could include these scenarios. The RCP1.9 and RCP2.6 scenarios, which align best with a rapid transition, are particularly relevant given the current state of the planetary boundaries.

Lastly, the technologies chosen in this study may fulfil the yearly demand for energy, aligning with the annual scope of Planetary Boundaries Life Cycle Impact Assessments. However, this approach may overlook the daily or seasonal dynamics of renewable energy sources. A potential solution could be the development of renewable energy mixes that fit the daily or seasonal demand curve and treating them as an entity to assess how much capacity can be installed in comparison with the allocated share of the safe operating space.

6 Conclusion and guidelines

The principal conclusion of this study highlights the need to distribute planetary boundaries unevenly for a more effective allocation of the SOS to the electricity and heat demand sectors covered by fossil fuels. This contrasts sharply with the traditional approach that relies on an acquired rights sharing principle based on historical CO_2 emissions. In practice, the most limiting planetary boundaries vary: freshwater use notably emerges as a significant constraint alongside the CO_2 emissions planetary boundary in the electricity sector and dominates in the heat sector. Meanwhile, nitrogen fixation significantly restricts alongside CO_2 in the heat sectors, particularly under the acquired rights & acquired rights sharing principle where its impact is even more pronounced. Always using historical CO_2 emissions for downscaling therefore underestimates the potential of other planetary boundaries to be more constraining.

Looking forward, projections suggest the transition could be absolutely sustainable by 2040-2050 with the utilitarian & acquired rights sharing principle, reliably meeting demand in the heat sectors. In the electricity sector, meeting the demand depends on the energy mix, with limitations on photovoltaics installations. Overall, when assessing the installation of photovoltaics, the freshwater use planetary boundary should be considered. For the heat sectors, at least the nitrogen fixation planetary boundary should be assessed, as the freshwater use planetary boundary is too constraining. However, its consideration always proves insightful. Expanding planetary boundaries into a "zone of increasing risk" can be considered to meet demand where capacity is nearly sufficient. However, it is crucial to strive for absolute sustainability across as many planetary boundaries as possible to avoid underestimating the broader environmental risks.

In contrast with the capacity restrictions on future photovoltaics installations due to their substantial impacts on planetary boundaries, as detailed in this study, numerous transition scenarios, including the Energyville scenarios [88], forecast considerable photovoltaics deployments. These projections are motivated by the technology's scalability—particularly its suitability for rooftop installations—and its relatively lower cost compared to other renewable technologies [89]. Nonetheless, technologies that are currently more compatible with an absolutely sustainable transition are onshore and offshore wind. Offshore wind, however, faces challenges in expanding capacity due to the need for extensive infrastructure, such as robust foundations and subsea cables to connect the generated electricity to the mainland

[90]. Onshore wind encounters resistance primarily due to the Not In My BackYard (NIMBY) mentality [91], which restricts the feasible installable capacity. To play a more effective role in the transition, the environmental impacts associated with the manufacturing and installation of photovoltaics must be substantially mitigated.

To enhance the precision and comprehensiveness of Planetary Boundaries Life Cycle Impact Assessments that unequally share the planetary boundaries, future studies should aim to align their findings with the control variables proposed in the Planetary Boundaries framework. Given that the method for unequally sharing the planetary boundaries varies significantly depending on the system considered, it is beneficial to categorise different systems (e.g., countries, sectors, companies, technologies, individuals) based on their nature. For each category, a specific downscaling method can be developed using tailored sharing principles and parameters. Consequently, studies within a particular system type should align their results with the control variables of the Planetary Boundaries framework according to the system's nature. It is crucial that the sharing principles developed incorporate various ethical principles to provide a comprehensive overview of the implications of different ethical choices.

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A Appendix

A.1 Global SOS and portion available to humanity

PBs	Global real impacts	SOS (onset high risk)	SOS for humanity (Holocene value)
CO2 [ppm]	417	350 (450)	70 (280)
RF [W/m²]	2.91	1 (1.5)	1 (0)
OA [Ω_{arag}/year]	2.8	2.75 (<2.75)	0.688 (3.44)
N [TgN/year]	190	62 (100)	62 (0)
LFC Global [%]	40	25 (46)	25 (100)
LFC Biome [%]	65.8	50 (70)	50 (100)
FWU [km³/year]	4600	4000 (>4000)	4000 (0)

Table 16: Global real impacts and SOS values at world scale. The SOS for humanity is defined as the portion of the SOS that can actually be used, calculated as the difference between the PB and the preindustrial Holocene base value [4].

A.2 Allocated shares of the SOS to Belgium

PBs	EA	UA	PA	AA
CO2 [ppm/year]	$1.01 \cdot 10^{-1}$	$3.84 \cdot 10^{-1}$	$3.92 \cdot 10^{-2}$	$1.98 \cdot 10^{-1}$
RF [(W/m²)/year]	$1.45 \cdot 10^{-3}$	$5.48 \cdot 10^{-3}$	$5.60 \cdot 10^{-4}$	$2.82 \cdot 10^{-3}$
OA [Ω_{arag}/year]	$5.97 \cdot 10^{-3}$	$2.25 \cdot 10^{-2}$	$2.30 \cdot 10^{-3}$	$1.16 \cdot 10^{-2}$
N [TgN/year]	$8.99 \cdot 10^{-2}$	$3.40 \cdot 10^{-1}$	$3.47 \cdot 10^{-2}$	$8.18 \cdot 10^{-2}$
LFC Global [%/year]	$3.63 \cdot 10^{-2}$	$1.37 \cdot 10^{-1}$	$1.40 \cdot 10^{-2}$	$2.41 \cdot 10^{-2}$
LFC Biome [%/year]	$7.27 \cdot 10^{-2}$	$2.75 \cdot 10^{-1}$	$2.80 \cdot 10^{-2}$	$5.50 \cdot 10^{-2}$
FWU [km³/year]	$5.80 \cdot 10^{0}$	$2.19 \cdot 10^{1}$	$2.23 \cdot 10^{0}$	$1.76 \cdot 10^{0}$

Table 17: Allocated share of the SOS for Belgium under different SPs

A.3 Allocated shares of the SOS per sector

Electricity sector	**EA**	**UA**	**PA**	**AA**
CO2 [ppm/year]	$8.63 \cdot 10^{-3}$	$3.26 \cdot 10^{-2}$	$3.33 \cdot 10^{-3}$	$1.18 \cdot 10^{-2}$
RF [(W/m^2)/year]	$1.23 \cdot 10^{-4}$	$4.66 \cdot 10^{-4}$	$4.76 \cdot 10^{-5}$	$1.68 \cdot 10^{-4}$
OA [Ω_{arag}/year]	$8.48 \cdot 10^{-5}$	$3.20 \cdot 10^{-4}$	$3.27 \cdot 10^{-5}$	$1.16 \cdot 10^{-4}$
N [TgN/year]	$4.06 \cdot 10^{-3}$	$1.54 \cdot 10^{-2}$	$1.57 \cdot 10^{-3}$	$3.69 \cdot 10^{-3}$
LFC global [%/year]	$2.50 \cdot 10^{-6}$	$9.44 \cdot 10^{-6}$	$9.65 \cdot 10^{-7}$	$1.66 \cdot 10^{-6}$
FWU [km^3/year]	$8.67 \cdot 10^{-3}$	$3.28 \cdot 10^{-2}$	$3.35 \cdot 10^{-3}$	$1.17 \cdot 10^{-2}$

Table 18: Allocated shares of the SOS for the Electricity sector for different sharing principles. The LFC biome impacts are not computed, but yield a larger SoSOS than the global impacts.

LT Heat sector	**EA**	**UA**	**PA**	**AA**
CO2 [ppm/year]	$7.99 \cdot 10^{-3}$	$3.02 \cdot 10^{-2}$	$3.08 \cdot 10^{-3}$	$1.09 \cdot 10^{-2}$
RF [(W/m^2)/year]	$1.14 \cdot 10^{-4}$	$4.31 \cdot 10^{-4}$	$4.41 \cdot 10^{-5}$	$1.56 \cdot 10^{-4}$
OA [Ω_{arag}/year]	$7.85 \cdot 10^{-5}$	$2.97 \cdot 10^{-4}$	$3.03 \cdot 10^{-5}$	$1.07 \cdot 10^{-4}$
N [TgN/year]	$1.05 \cdot 10^{-3}$	$3.96 \cdot 10^{-3}$	$4.05 \cdot 10^{-4}$	$9.51 \cdot 10^{-4}$
LFC global [%/year]	$8.37 \cdot 10^{-7}$	$3.16 \cdot 10^{-6}$	$3.23 \cdot 10^{-7}$	$5.57 \cdot 10^{-7}$
FWU [km^3/year]	$4.34 \cdot 10^{-4}$	$1.64 \cdot 10^{-3}$	$1.68 \cdot 10^{-4}$	$5.87 \cdot 10^{-4}$

Table 19: Allocated shares of the SOS for the LT Heat sector for different sharing principles. The LFC biome impacts are not computed, but yield a larger SoSOS than the global impacts.

MT Heat sector	**EA**	**UA**	**PA**	**AA**
CO2 [ppm/year]	$5.73 \cdot 10^{-3}$	$2.17 \cdot 10^{-2}$	$2.21 \cdot 10^{-3}$	$7.82 \cdot 10^{-3}$
RF [(W/m^2)/year]	$8.18 \cdot 10^{-5}$	$3.09 \cdot 10^{-4}$	$3.16 \cdot 10^{-5}$	$1.12 \cdot 10^{-4}$
OA [Ω_{arag}/year]	$5.63 \cdot 10^{-5}$	$2.13 \cdot 10^{-4}$	$2.17 \cdot 10^{-5}$	$7.69 \cdot 10^{-5}$
N [TgN/year]	$7.52 \cdot 10^{-4}$	$2.84 \cdot 10^{-3}$	$2.90 \cdot 10^{-4}$	$6.82 \cdot 10^{-4}$
LFC global [%/year]	$6.00 \cdot 10^{-7}$	$2.27 \cdot 10^{-6}$	$2.32 \cdot 10^{-7}$	$3.99 \cdot 10^{-7}$
FWU [km^3/year]	$3.11 \cdot 10^{-4}$	$1.18 \cdot 10^{-3}$	$1.20 \cdot 10^{-4}$	$4.21 \cdot 10^{-4}$

Table 20: Allocated shares of the SOS for the MT Heat sector for different sharing principles. The LFC biome impacts are not computed, but yield a larger SoSOS than the global impacts.

HT Heat sector	**EA**	**UA**	**PA**	**AA**
CO2 [ppm/year]	$1.99 \cdot 10^{-2}$	$7.55 \cdot 10^{-2}$	$7.72 \cdot 10^{-3}$	$2.73 \cdot 10^{-2}$
RF [(W/m²)/year]	$2.85 \cdot 10^{-4}$	$1.08 \cdot 10^{-3}$	$1.10 \cdot 10^{-4}$	$3.90 \cdot 10^{-4}$
OA [Ω_{arag}/year]	$1.96 \cdot 10^{-4}$	$7.42 \cdot 10^{-4}$	$7.59 \cdot 10^{-5}$	$2.68 \cdot 10^{-4}$
N [TgN/year]	$2.62 \cdot 10^{-3}$	$9.91 \cdot 10^{-3}$	$1.01 \cdot 10^{-3}$	$2.38 \cdot 10^{-3}$
LFC global [%/year]	$2.09 \cdot 10^{-6}$	$7.92 \cdot 10^{-6}$	$8.09 \cdot 10^{-7}$	$1.39 \cdot 10^{-6}$
FWU [km³/year]	$1.09 \cdot 10^{-3}$	$4.10 \cdot 10^{-3}$	$4.19 \cdot 10^{-4}$	$1.47 \cdot 10^{-3}$

Table 21: Allocated shares of the SOS for the HT Heat sector for different sharing principles. The LFC biome impacts are not computed, but yield a larger SoSOS than the global impacts.

A.4 Technology impacts for electricity, MT heat and HT heat sectors

PV (SSP1)	**2024**	**2030**	**2040**	**2050**
CO2 [ppm/(GW·year)]	$2.21 \cdot 10^{-3}$	$1.32 \cdot 10^{-3}$	$1.06 \cdot 10^{-3}$	$8.76 \cdot 10^{-4}$
RF [$\frac{W}{m^2}$/(GW·year)]	$2.99 \cdot 10^{-5}$	$1.78 \cdot 10^{-5}$	$1.43 \cdot 10^{-5}$	$1.19 \cdot 10^{-5}$
OA [Ω_{arag}/(GW·year)]	$6.75 \cdot 10^{-6}$	$4.03 \cdot 10^{-6}$	$3.23 \cdot 10^{-6}$	$2.68 \cdot 10^{-6}$
N [TgN/(GW·year)]	$2.44 \cdot 10^{-4}$	$1.32 \cdot 10^{-4}$	$1.15 \cdot 10^{-4}$	$1.04 \cdot 10^{-4}$
LFC global [%/(GW·year)]	$5.02 \cdot 10^{-8}$	$2.79 \cdot 10^{-8}$	$2.52 \cdot 10^{-8}$	$2.34 \cdot 10^{-8}$
FWU [km^3/(GW·year)]	$3.20 \cdot 10^{-3}$	$2.17 \cdot 10^{-3}$	$1.87 \cdot 10^{-3}$	$1.66 \cdot 10^{-3}$

Table 22: PV impacts for SSP1

Onshore wind (SSP1)	2024	2030	2040	2050
CO2 [ppm/(GW·year)]	$7.62 \cdot 10^{-4}$	$7.04 \cdot 10^{-4}$	$6.59 \cdot 10^{-4}$	$6.12 \cdot 10^{-4}$
RF [$\frac{W}{m^2}$/(GW·year)]	$1.02 \cdot 10^{-5}$	$9.35 \cdot 10^{-6}$	$8.75 \cdot 10^{-6}$	$8.13 \cdot 10^{-6}$
OA [Ω_{arag}/(GW·year)]	$2.33 \cdot 10^{-6}$	$2.15 \cdot 10^{-6}$	$2.01 \cdot 10^{-6}$	$1.87 \cdot 10^{-6}$
N [TgN/(GW·year)]	$8.99 \cdot 10^{-5}$	$7.68 \cdot 10^{-5}$	$7.38 \cdot 10^{-5}$	$7.09 \cdot 10^{-5}$
LFC global [%/(GW·year)]	$1.48 \cdot 10^{-8}$	$4.99 \cdot 10^{-10}$	$4.26 \cdot 10^{-10}$	$4.32 \cdot 10^{-10}$
FWU [km^3/(GW·year)]	$2.05 \cdot 10^{-4}$	$2.21 \cdot 10^{-4}$	$1.83 \cdot 10^{-4}$	$1.53 \cdot 10^{-4}$

Table 23: Onshore wind impacts for SSP1

Offshore wind (SSP1)	**2024**	**2030**	**2040**	**2050**
CO2 [ppm/(GW·year)]	$1.05 \cdot 10^{-3}$	$9.63 \cdot 10^{-4}$	$9.12 \cdot 10^{-4}$	$8.58 \cdot 10^{-4}$
RF [$\frac{W}{m^2}$/(GW·year)]	$1.40 \cdot 10^{-5}$	$1.28 \cdot 10^{-5}$	$1.21 \cdot 10^{-5}$	$1.14 \cdot 10^{-5}$
OA [Ω_{arag}/(GW·year)]	$3.21 \cdot 10^{-6}$	$2.94 \cdot 10^{-6}$	$2.79 \cdot 10^{-6}$	$2.62 \cdot 10^{-6}$
N [TgN/(GW·year)]	$1.22 \cdot 10^{-4}$	$1.05 \cdot 10^{-4}$	$1.02 \cdot 10^{-4}$	$9.85 \cdot 10^{-5}$
LFC global [%/(GW·year)]	$2.40 \cdot 10^{-8}$	$4.32 \cdot 10^{-9}$	$4.18 \cdot 10^{-9}$	$4.12 \cdot 10^{-9}$
FWU [km^3/(GW·year)]	$4.63 \cdot 10^{-4}$	$4.79 \cdot 10^{-4}$	$4.41 \cdot 10^{-4}$	$4.16 \cdot 10^{-4}$

Table 24: Offshore wind impacts for SSP1

PV (SSP2)	**2024**	**2030**	**2040**	**2050**
CO2 [ppm/(GW·year)]	$2.21 \cdot 10^{-3}$	$1.28 \cdot 10^{-3}$	$1.02 \cdot 10^{-3}$	$8.41 \cdot 10^{-4}$
RF [$\frac{W}{m^2}$/(GW·year)]	$2.99 \cdot 10^{-5}$	$1.73 \cdot 10^{-5}$	$1.38 \cdot 10^{-5}$	$1.14 \cdot 10^{-5}$
OA [Ω_{arag}/(GW·year)]	$6.75 \cdot 10^{-6}$	$3.92 \cdot 10^{-6}$	$3.12 \cdot 10^{-6}$	$2.57 \cdot 10^{-6}$
N [TgN/(GW·year)]	$2.44 \cdot 10^{-4}$	$1.30 \cdot 10^{-4}$	$1.14 \cdot 10^{-4}$	$1.02 \cdot 10^{-4}$
LFC global [%/(GW·year)]	$5.02 \cdot 10^{-8}$	$2.78 \cdot 10^{-8}$	$2.53 \cdot 10^{-8}$	$2.33 \cdot 10^{-8}$
FWU [km³/(GW·year)]	$3.20 \cdot 10^{-3}$	$2.16 \cdot 10^{-3}$	$1.86 \cdot 10^{-3}$	$1.64 \cdot 10^{-3}$

Table 25: PV impacts for SSP2, are slightly lower than for SSP1.

Onshore wind (SSP2)	**2024**	**2030**	**2040**	**2050**
CO2 [ppm/(GW·year)]	$7.62 \cdot 10^{-4}$	$6.73 \cdot 10^{-4}$	$6.23 \cdot 10^{-4}$	$5.87 \cdot 10^{-4}$
RF [$\frac{W}{m^2}$/(GW·year)]	$1.02 \cdot 10^{-5}$	$8.95 \cdot 10^{-6}$	$8.28 \cdot 10^{-6}$	$7.81 \cdot 10^{-6}$
OA [Ω_{arag}/(GW·year)]	$2.33 \cdot 10^{-6}$	$2.06 \cdot 10^{-6}$	$1.90 \cdot 10^{-6}$	$1.79 \cdot 10^{-6}$
N [TgN/(GW·year)]	$8.99 \cdot 10^{-5}$	$7.50 \cdot 10^{-5}$	$7.11 \cdot 10^{-5}$	$6.87 \cdot 10^{-5}$
LFC global [%/(GW·year)]	$1.48 \cdot 10^{-8}$	$3.65 \cdot 10^{-10}$	$3.13 \cdot 10^{-10}$	$1.60 \cdot 10^{-10}$
FWU [km³/(GW·year)]	$2.05 \cdot 10^{-4}$	$1.87 \cdot 10^{-4}$	$1.08 \cdot 10^{-4}$	$6.90 \cdot 10^{-5}$

Table 26: Onshore wind impacts for SSP2, are slightly lower than for SSP1.

Offshore wind (SSP2)	**2024**	**2030**	**2040**	**2050**
CO2 [ppm/(GW·year)]	$1.05 \cdot 10^{-3}$	$9.32 \cdot 10^{-4}$	$8.77 \cdot 10^{-4}$	$8.34 \cdot 10^{-4}$
RF [$\frac{W}{m^2}$/(GW·year)]	$1.40 \cdot 10^{-5}$	$1.24 \cdot 10^{-5}$	$1.17 \cdot 10^{-5}$	$1.11 \cdot 10^{-5}$
OA [Ω_{arag}/(GW·year)]	$3.21 \cdot 10^{-6}$	$2.85 \cdot 10^{-6}$	$2.68 \cdot 10^{-6}$	$2.55 \cdot 10^{-6}$
N [TgN/(GW·year)]	$1.22 \cdot 10^{-4}$	$1.03 \cdot 10^{-4}$	$9.93 \cdot 10^{-5}$	$9.66 \cdot 10^{-5}$
LFC global [%/(GW·year)]	$2.40 \cdot 10^{-8}$	$4.05 \cdot 10^{-9}$	$4.02 \cdot 10^{-9}$	$3.87 \cdot 10^{-9}$
FWU [km³/(GW·year)]	$4.63 \cdot 10^{-4}$	$4.55 \cdot 10^{-4}$	$3.91 \cdot 10^{-4}$	$3.57 \cdot 10^{-4}$

Table 27: Offshore wind impacts for SSP2, are slightly lower than for SSP1.

A.5 Technology impacts for LT heat sector

PV + HP (SSP1)	**2024**	**2030**	**2040**	**2050**
CO2 [ppm/(GW·year)]	$1.37 \cdot 10^{-3}$	$8.35 \cdot 10^{-4}$	$6.76 \cdot 10^{-4}$	$5.65 \cdot 10^{-4}$
RF [$\frac{W}{m^2}$/(GW·year)]	$1.86 \cdot 10^{-5}$	$1.13 \cdot 10^{-5}$	$9.15 \cdot 10^{-6}$	$7.67 \cdot 10^{-6}$
OA [Ω_{arag}/(GW·year)]	$4.19 \cdot 10^{-6}$	$2.55 \cdot 10^{-6}$	$2.07 \cdot 10^{-6}$	$1.73 \cdot 10^{-6}$
N [TgN/(GW·year)]	$1.60 \cdot 10^{-4}$	$9.22 \cdot 10^{-5}$	$8.22 \cdot 10^{-5}$	$7.52 \cdot 10^{-5}$
LFC global [%/(GW·year)]	$3.10 \cdot 10^{-8}$	$1.68 \cdot 10^{-8}$	$1.52 \cdot 10^{-8}$	$1.41 \cdot 10^{-8}$
FWU [km³/(GW·year)]	$1.90 \cdot 10^{-3}$	$1.31 \cdot 10^{-3}$	$1.12 \cdot 10^{-3}$	$1.00 \cdot 10^{-3}$

Table 28: PV and HP impacts for SSP1, for $1\mathrm{GW}_{\mathrm{th,HP}}$ of HPs installed.

Onshore + HP (SSP1)	**2024**	**2030**	**2040**	**2050**
CO2 [ppm/(GW·year)]	$3.00 \cdot 10^{-4}$	$2.68 \cdot 10^{-4}$	$2.48 \cdot 10^{-4}$	$2.28 \cdot 10^{-4}$
RF [$\frac{W}{m^2}$/(GW·year)]	$4.03 \cdot 10^{-6}$	$3.58 \cdot 10^{-6}$	$3.31 \cdot 10^{-6}$	$3.05 \cdot 10^{-6}$
OA [Ω_{arag}/(GW·year)]	$9.16 \cdot 10^{-7}$	$8.19 \cdot 10^{-7}$	$7.58 \cdot 10^{-7}$	$6.98 \cdot 10^{-7}$
N [TgN/(GW·year)]	$4.30 \cdot 10^{-5}$	$3.72 \cdot 10^{-5}$	$3.59 \cdot 10^{-5}$	$3.48 \cdot 10^{-5}$
LFC global [%/(GW·year)]	$5.90 \cdot 10^{-9}$	$6.76 \cdot 10^{-10}$	$6.20 \cdot 10^{-10}$	$6.12 \cdot 10^{-10}$
FWU [km³/(GW·year)]	$9.64 \cdot 10^{-5}$	$1.03 \cdot 10^{-4}$	$8.80 \cdot 10^{-5}$	$7.70 \cdot 10^{-5}$

Table 29: Onshore wind and HP impacts for SSP1, for $1\mathrm{GW}_{\mathrm{th,HP}}$ of HPs installed.

Offshore + HP (SSP1)	**2024**	**2030**	**2040**	**2050**
CO2 [ppm/(GW·year)]	$2.63 \cdot 10^{-4}$	$2.33 \cdot 10^{-4}$	$2.17 \cdot 10^{-4}$	$2.02 \cdot 10^{-4}$
RF [$\frac{W}{m^2}$/(GW·year)]	$3.54 \cdot 10^{-6}$	$3.12 \cdot 10^{-6}$	$2.91 \cdot 10^{-6}$	$2.70 \cdot 10^{-6}$
OA [Ω_{arag}/(GW·year)]	$8.05 \cdot 10^{-7}$	$7.13 \cdot 10^{-7}$	$6.65 \cdot 10^{-7}$	$6.17 \cdot 10^{-7}$
N [TgN/(GW·year)]	$3.83 \cdot 10^{-5}$	$3.34 \cdot 10^{-5}$	$3.24 \cdot 10^{-5}$	$3.16 \cdot 10^{-5}$
LFC global [%/(GW·year)]	$5.81 \cdot 10^{-9}$	$1.28 \cdot 10^{-9}$	$1.22 \cdot 10^{-9}$	$1.20 \cdot 10^{-9}$
FWU [km³/(GW·year)]	$1.18 \cdot 10^{-4}$	$1.23 \cdot 10^{-4}$	$1.12 \cdot 10^{-4}$	$1.05 \cdot 10^{-4}$

Table 30: Offshore wind and HP impacts for SSP1, for $1\mathrm{GW}_{\mathrm{th,HP}}$ of HPs installed.

PV + HP (SSP2)	2024	2030	2040	2050
CO2 [ppm/(GW·year)]	$1.37 \cdot 10^{-3}$	$8.11 \cdot 10^{-4}$	$6.51 \cdot 10^{-4}$	$5.42 \cdot 10^{-4}$
RF [$\frac{W}{m^2}$/(GW·year)]	$1.86 \cdot 10^{-5}$	$1.09 \cdot 10^{-5}$	$8.82 \cdot 10^{-6}$	$7.37 \cdot 10^{-6}$
OA [Ω_{arag}/(GW·year)]	$4.19 \cdot 10^{-6}$	$2.48 \cdot 10^{-6}$	$1.99 \cdot 10^{-6}$	$1.66 \cdot 10^{-6}$
N [TgN/(GW·year)]	$1.60 \cdot 10^{-4}$	$9.11 \cdot 10^{-5}$	$8.11 \cdot 10^{-5}$	$7.41 \cdot 10^{-5}$
LFC global [%/(GW·year)]	$3.10 \cdot 10^{-8}$	$1.68 \cdot 10^{-8}$	$1.52 \cdot 10^{-8}$	$1.41 \cdot 10^{-8}$
FWU [km^3/(GW·year)]	$1.90 \cdot 10^{-3}$	$1.30 \cdot 10^{-3}$	$1.12 \cdot 10^{-3}$	$9.85 \cdot 10^{-4}$

Table 31: PV and HPs impacts for SSP2, for 1$GW_{th,HP}$ of HPs installed.

Onshore + HP (SSP2)	2024	2030	2040	2050
CO2 [ppm/(GW·year)]	$3.00 \cdot 10^{-4}$	$2.57 \cdot 10^{-4}$	$2.35 \cdot 10^{-4}$	$2.19 \cdot 10^{-4}$
RF [$\frac{W}{m^2}$/(GW·year)]	$4.03 \cdot 10^{-6}$	$3.43 \cdot 10^{-6}$	$3.14 \cdot 10^{-6}$	$2.93 \cdot 10^{-6}$
OA [Ω_{arag}/(GW·year)]	$9.16 \cdot 10^{-7}$	$7.84 \cdot 10^{-7}$	$7.17 \cdot 10^{-7}$	$6.69 \cdot 10^{-7}$
N [TgN/(GW·year)]	$4.30 \cdot 10^{-5}$	$3.65 \cdot 10^{-5}$	$3.50 \cdot 10^{-5}$	$3.41 \cdot 10^{-5}$
LFC global [%/(GW·year)]	$5.90 \cdot 10^{-9}$	$6.39 \cdot 10^{-10}$	$5.87 \cdot 10^{-10}$	$5.14 \cdot 10^{-10}$
FWU [km^3/(GW·year)]	$9.64 \cdot 10^{-5}$	$9.20 \cdot 10^{-5}$	$6.34 \cdot 10^{-5}$	$4.90 \cdot 10^{-5}$

Table 32: Onshore wind and HPs impacts for SSP2, for 1$GW_{th,HP}$ of HPs installed.

Offshore + HP (SSP2)	2024	2030	2040	2050
CO2 [ppm/(GW·year)]	$2.63 \cdot 10^{-4}$	$2.25 \cdot 10^{-4}$	$2.08 \cdot 10^{-4}$	$1.95 \cdot 10^{-4}$
RF [$\frac{W}{m^2}$/(GW·year)]	$3.54 \cdot 10^{-6}$	$3.01 \cdot 10^{-6}$	$2.79 \cdot 10^{-6}$	$2.62 \cdot 10^{-6}$
OA [Ω_{arag}/(GW·year)]	$8.05 \cdot 10^{-7}$	$6.88 \cdot 10^{-7}$	$6.37 \cdot 10^{-7}$	$5.97 \cdot 10^{-7}$
N [TgN/(GW·year)]	$3.83 \cdot 10^{-5}$	$3.30 \cdot 10^{-5}$	$3.19 \cdot 10^{-5}$	$3.11 \cdot 10^{-5}$
LFC global [%/(GW·year)]	$5.81 \cdot 10^{-9}$	$1.23 \cdot 10^{-9}$	$1.19 \cdot 10^{-9}$	$1.14 \cdot 10^{-9}$
FWU [km^3/(GW·year)]	$1.18 \cdot 10^{-4}$	$1.17 \cdot 10^{-4}$	$1.00 \cdot 10^{-4}$	$9.10 \cdot 10^{-5}$

Table 33: Offshore wind and HPs impacts for SSP2, for 1$GW_{th,HP}$ of HPs installed.

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