# Modelling Endogenized Human Behavior:

*A System Dynamics Based Integration of Pro-Environmental Intention in Integrated Assessment Modelling*

**Benedikt Tusch**

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Joint European Master's in System Dynamics
System Dynamics Group, Department of Geography
University of Bergen, Norway

Supervisor:
Jefferson K. Rajah, *PhD Research Fellow, University of Bergen*

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Studentnumbers: 315936 (UiB) | Candidate No. 102 | 1123037 (Radboud)

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# Executive Summary

There is an ongoing effort to answer the need for a dynamic representation of human behavior that can extend and endogenize existing human behavioral components in integrated assessment models (IAMs). This is not only a plea for representativeness, but also for accuracy: Because behavior and intention develop over time and in relation to feedback from the environment, other actors, or systems. A dynamic integration further allows for investigating simulation-based long-term developments – a critical step to identify high-leverage intervention in these systems. To better understand the representation of dynamical change of intention towards and of pro-environmental behavior in models, this thesis grounds its generic model in insights from behavioral concepts and theories and couples it with IAMs and the Shared-Socioeconomic Pathways.

First, I draw on the Theory of Planned Behavior, the Value Belief Norm Theory and the Protection Motivation Theory to ground the conceptualization. I identify (1) social norms through peers and society, (2) personal worldviews and value sets, corresponding perceptions of threat, risk and awareness of consequences and 3) personal norms, attitude or moral obligation as important for change in intention 4) perceptions about behavioral control and self-efficacy as the critical concepts to be integrated in a more holistic representation.

Second, I construct a generic system dynamics model, anchored in the change of pro-environmental concern observed in the OECD, coupled with IAMs and input the Shared Socio-economic Pathways (SSP). I identify two main routes for human behavior representation: Feedback from within and feedback from with-out. Social injunctive norm and Peer-Group pressure/inspiration drives intention internally. The environment induces feedback through *severeness* and *seriousness* based on our perceptions on the current states.

Lastly, model-based implications are discussed. I identify *energy efficiency* on the technological side, *media efficiency* and instructive *reference conditions* on the social side as promising leverage points for intervention. Additionally, *education*, *thought leaders* or *campaigns* can be used to re-evaluate or activate a broad spectrum of values for awareness and societal sparked inspiration. Furthermore, implications for IAMs and SSPs identify endogenized behavior as a focal point for uncovering, discussing and testing assumptions and raising issue of representational dimensionality, continuity of values in models and narratives.

This thesis builds upon work by WorldTrans Team and contributes to their ongoing effort by further elaborating, refining operationalizing the current conceptualization of human behavior integration through a high-level conceptual model.

# Table of Content

# List of Figures and Tables

## List of Abbreviations

| | | | |
|---|---|---|---|
| IPCC | Intergovernmental Panel on Climate Change | FRIDA | Feedback-based knowledge Repository for IntegrateD Assessments |
| OECD | Organisation for Economic Co-operation and Development | FeliX | Full of Economic-Environment Linkages and Integration dX/dt |
| SES | Social Ecological System | SSP | Social Ecological Pathways |
| STI | Social Tipping Intervention | CFP | Carbon Footprint |
| IAM | Integrated Assessment Model | STA | Surface Temperature Anomaly |
| CSS | Climate-Social-System | GS | Global Sensitivity |
| PEB | Pro-environmental behavior | IEA | International Energy Agency |
| PEBI | Pro-environmental behavior intention | BAU | Business as Usual |
| ESB | Ecologically significant behavior | CEES | Closing Eyes to Environment scenario |
| GEB | General ecological behavioral scale | TERS | Turning to environmental reaction scenario |
| UBS | Umweltbewusstseinsskala (transl.: environmental consciousness scale) | $CO_2$ | Carbon Dioxide |
| NEP | New Ecological Paradigm | $CH_4$ | Methane |
| VO | Value orientation | $SO_2$ | Sulfure Dioxide |
| TPB | Theory of Planned Behavior | $N_2O$ | Nitrous Oxide |
| PBC | Perceived Behavioral Control | | |
| PMT | Protection Motivation Theory | | |
| VBN | Value Belief Norm Theory | | |
| SD | System Dynamics | | |

# 1. Problem Description and Contextualization

> "Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 1.1°C above 1850–1900 in 2011–2020. Global greenhouse gas emissions have continued to increase, with unequal historical and ongoing contributions arising from unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production across regions, between and within countries, and among individuals (high confidence)."
> (IPCC et al. 2023)

This message, sober and clear, is the first statement for policy makers and everyone else that will open the latest IPCC synthesis report. Yet, the IPCC has long warned us of the burdens we put on the earth system – measured for example by the concept of climate tipping points (IPCC 2001). Tipping points define "(…)critical threshold beyond which a system can reorganise in an abrupt or irreversible manner" (OECD 2022a, 19). In their report on climate tipping points and insights for effective policy making, also the OECD, in reference to McKay et al. (2022) and Lee et al. (2021), warns that with the given temperature change we are already in the lower range of triggering 5 of these points (OECD 2022a). Figure 1-1 illustrates that in terms of contribution, the OECD[1] plays a significant part – e.g. emitting continuously on average almost double the amount of $CO_2$ per capita than the world (OECD 2023).

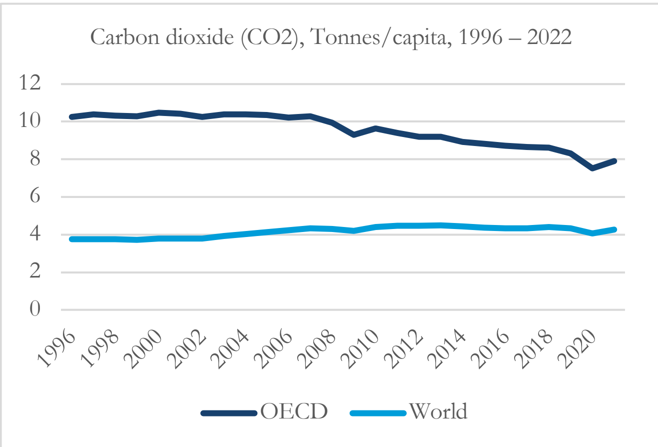


*Figure 1-1 - Comparison of average CO2 Emissions/capita OECD and World*

Figure 1-2 shows the historic reference behavior of per capita $CO_2$ emission of OECD countries throughout the years 1995 to 2018 (OECD 2022b; Yamano and Guilhoto 2020) in blue. The yellow line represents the threshold to within the planetary $CO_2$ boundary and limit to 2ºC warming (O'Neill et al. 2018). The green and red lines depict hypothesized hoped and feared trajectories of emission behavior that either achieves the threshold or not. Both figures clearly support the

[1] Throughout this thesis I use "OECD" also referring to the collective of countries that make up the OECD.

message from the beginning: There is much left to do to stay within the planetary boundaries and to take effort to avoid triggering prognosed (climate) tipping points.

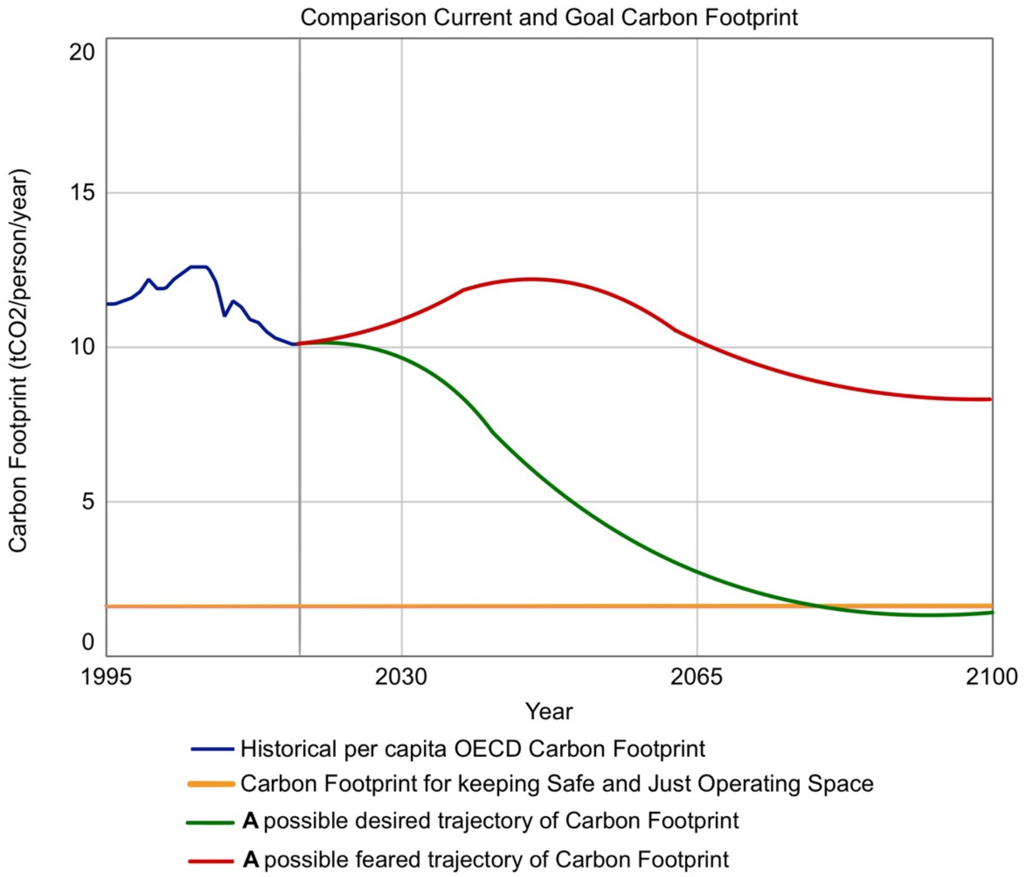


*Figure 1-2 - Reference Behavior for OECD countries per capita CO2 emissions (consumption based), 1995 - 2018 (blue, 11.3 -10.1 tCO2/cap/year), Carbon Footprint for upholding planetary boundary (yellow, 1.61 tCO2/cap/year), possible hoped (green) and feared (red) trajectories*

In the field of Social-Ecological-Systems (SES), the term Social Tipping Point describes a more hopeful concept: Technically similar, they refer to moments of non-linear change of behaviors (Juhola et al. 2022; Milkoreit 2023) within systems that depict the interaction between the environmental (physical) and social systems (Milkoreit et al. 2018). More positively, research on social tipping processes tries to understand the dynamics that hinder or enable transformations towards a more sustainable world, and explore ways of triggering these thresholds to tip the system into a positive direction. Otto et al. (2020) refer to Social Tipping Interventions (STI) as interventions in social systems that utilize mechanisms and feedbacks to trigger these non-linear effects. These interventions can be taken up by governments, intergovernmental institutions, organizations, communities, or individuals – depending on which intervention is to be enacted. Possible interventions refer to the norms and value systems (Otto et al. 2020), while others are concerned with the educational system, financial system, human settlements (urban infrastructure), information feedbacks, and the energy production (Eker and Wilson 2022; Otto et al. 2020). Which forms these interventions take is not as clear. The interventions in the mentioned literature remain vague (e.g., “[...] social and public opinion leader recognize the ethical implications of fossil fuel” (Otto et al. 2020,

2360) because they reside (and purposefully so) on an abstract and aggregated level and describe the interconnection of the subsystems in general terms. There is therefore a call for a better understanding of mechanisms that govern these systems, to be able to utilize interventions. Regardless, these work on Social Tipping dynamics are fundamentally premised on human behavior in relation (and feedback) to the environment and other social systems and actors.

## 1.1 Existing Work for Including Human Behavior

Approaches like Integrated Assessment Models (IAMs) or Climate-Social Systems (CSS) aim at representing the interactions of multiple systems (Beck and Krueger 2016; Moore et al. 2022a) and are used for producing, and analyzing scenarios, possible emission pathways and mitigation efforts (van Beek et al. 2020; Moore et al. 2022a). Yet, detailed, systematic, feedback-orientated coupled interactions between social systems have been researched only rarely (Moore et al. 2022) and IAMs are criticized for their supply-side focus (van Beek et al. 2020) and the mainly economically driven representation human behavior or reduction to economic and statistical exogenous inputs (Beckage et al. 2020; Moore et al. 2022b; Beckage, Moore, and Lacasse 2022). Therefore, there is also a need for more investigation into depicting human behavior that can be coupled with IAMs or CSSs.

To investigate behavior change, especially in reference to pro-environmental behavior (PEB), several theories have come to stand out in the field, e.g., the Theory of Planned Behavior, the Value-Belief -Norm Theory and the Protection Motivation Theory (Conner and Norman 2015; Klöckner 2013; Kurisu 2015). Concerning its representation in complex social systems, especially in relation to norms and values around PEB, several authors apply these successfully (e.g. Beckage et al. 2018; Eker, Reese, and Obersteiner 2019; Ulli-Beer et al. 2010; Karimi and Mohammadimehr 2022; Doherty and Webler 2016; L. Zhang et al. 2020). Yet, only few authors have advanced to use (social) psychological and behavioral theories in a dynamic way, integrated in modelling and coupled with IAMs or CSS (Beckage et al. 2018; Eker, Reese, and Obersteiner 2019; Pettifor et al. 2024; Moore et al. 2022b). The need for dynamic representation is not only for the sake of the integration into IAMs and CSSs, but also demanded by a plea for accuracy: Because behavior and intention develop over time and in relation to feedback from the environment, other actors, or systems. Importantly, a dynamic investigation further allows for investigating long term developments based on simulations, rendering this step critical to identify leverage points for STIs, SES and assess demand side mitigation into CSS.

There is an ongoing effort by WorldTrans Working Group (World Trans and Stark, n.d.) to improve and leverage the inclusion of human behavior into IAMs, address weaknesses and shortcomings of current IAMs and improve transparency about integrated assessments. My work builds upon the current state of the project and conceptualization as described in the deliverable reports by Rajah, Kopainsky, Eker, et al. (2024) and Swamy et al. (2023) by further elaborating and refining the current conceptualization and operationalizing it through a high-level conceptual model (Rajah, Kopainsky, Tusch, et al. 2024a; 2024b).

## 1.2 Research Purpose

The purpose of this thesis is, therefore, to better understand the representation of dynamical change of intention towards and of PEB in models based on insights from behavioral concepts and theories. For application, quantification and testing of this understanding, the research will be anchored in the change of pro-environmental intention observed in the OECD and general input from emission pathway scenarios. The OECD is a reasonable application region, since it contributes significantly to global emissions, data is available, accessible and can be coupled with the SSPs, and it is a region that already aims at streamlined policy cohesion, which is more in line with narrative and policy assumptions and idea-historic background than when applying to the world. To work towards this goal, I formulate my research objectives as three main research questions:

**RQ 1** How do we understand human behavior change and use it endogenously in IAMs to depict behavior change?

- *RQ 1.1* What are the main concepts of PEB as theorized in social-psychology?
- *RQ 1.2* Can these concepts be integrated to conceptualize a holistic picture of PEB change?

**RQ 2** How can we operationalize and integrate the theoretical concepts and insights into IAMs to endogenize human behavior in terms of carbon emissions?

- *RQ2.1* What are general dynamic feedback structures that govern emission behavior, in the exemplary case of the OECD region?
- *RQ2.2* What are the leverage points, within the norms and value system, that can be used to facilitate a shift to a less carbon-intense behavior?

**RQ 3** What are the general model-based implications for endogenizing human behavior in IAMs and emission pathway narratives?

- *RQ3.1* What insights can be drawn from the model analysis about the realism of the used emissions pathways?
- *RQ 3.2* What general challenges do we face while integrating human behavior into IAMs?

In the following, Chapter 2 establishes the theoretical framework. Chapter 3 is dedicated to the methodology and dynamic hypothesis, while Chapter 4 describes validation and testing. Chapter 5 looks at scenarios and analysis and Chapter 6 spells out implications, limitations and further research.

# 2. Theoretical Framework

To begin, I synthesize the theoretical grounding from the various strands of research to build up a conceptual, pluralistic framework, which informs the modelling process. Throughout this chapter, I look at what PEB and pro-environmental behavioral intention (PEBI) is, how it is usually measured and how it might be approached here for the specific purpose of investigating into dynamic change, followed by more details about the used theories.

## 2.1 Pro-Environmental Behavior and Intention

When talking about PEB, we face the difficulty of defining it either through its operational content or its output-oriented classification. Looking at the first one, several studies and articles classify PEB as "(…) deliberate action that can reduce the adverse impact upon the environment" (Mikuła, Raczkowska, and Utzig 2021, 3). It covers recycling and waste behavior, energy and transport choices as well as eco-orientated consumerism (Mikuła, Raczkowska, and Utzig 2021). Here, we run into negative-definitions of PEB: Through *avoiding* a certain other type of behavior (e.g. refrain from taking flights). That is why sometimes PEB might be substituted with another term: "environmentally significant behavior" (ESB, comment by the author) (Mikuła, Raczkowska, and Utzig 2021, 3). Defining ESB by output-orientation, Stern (2000, 408) notes that ESB "changes the availability of materials or energy from the environment or alters the structure and dynamics of ecosystems or the biosphere (…)". This can happen directly (through behavior as defined before), or also indirectly, through e.g. environmental activism or participation in the public sphere (Mikuła, Raczkowska, and Utzig 2021; Stern 2000). In sum, PEB or ESB can be summarized as intentional behavior aimed at avoiding or minimizing negative environmental impact (Balundė, Perlaviciute, and Steg 2019; Steg and Vlek 2009; Donmez-Turan and Kiliclar 2021). Additionally, since this thesis remains generic (not looking at one very specific behavior), I will look at and conceptualize PEB as private-sphere and impact-related (excluding indirect behavior such as environmental activism), aggregated and non-specific (i.e., I will not distinguish one specific behavior, but aggregate PEB as defined above by its impact). Therefore, PEB is defined rather narrow in scope (Kurisu 2015), while still covering a lot of possible behaviors.

To later be able to handle approximative values of PEB and PEBI, we need to ask how PEB can be measured. It is important to distinguish between measuring a factual behavior or an intention to take part in PEB. While several scales measure the extent people take part in PEB

(Markle 2013), others scales (e.g., scales to measure environmental concern) measure a certain attitude (Kurisu 2015).

To advance in the first project, measuring PEB, a scale successfully used is the General Ecological Behavior Scale (GEB) (Gatersleben 2018; Kaiser and Wilson 2004). This scale investigates several different behaviors; yet, based on its underlying framework and model, they collapse them into one unidimensional measure. This measurement employs that "(…) all behaviors regarding a specific goal or attitude object (e.g. environmental conservation) form a transitively ordered set of behaviors (from easy to difficult). The level of engagement in these behaviors reflects the strength of a person's environmental attitude" (Gatersleben 2018, 138). One advantage of this measurement is that it implicitly depicts the attitude towards the behavior (Gatersleben 2018). Note that, here, the behavior measured is goal-directed, i.e. it is necessarily brought by motivational factors. Nevertheless its assumptions, that behavior is retraceable to one certain attitude, are in conflict with concepts that propose multidimensional reasons for PEB as well as theories that encompasses PEB also as non-goal directed behavior (Gatersleben 2018). This theoretical dispute lies beyond the scope of this thesis. It will suffice for the conceptual nature of this work that GEB is a valid unidimensional measurement that may be used as indication of people's behavior and corresponding engagement including an implicit ranking of the relative ease of the behavior in question.

The second type of scale, e.g. scales of environmental concern, is used to investigate into pro-environmental attitudes per se, which can later be used as a base of explaining PEB in general. One example for such a scale is the "New Ecological Paradigm" (Dunlap et al. 2000), which surveys a certain set of beliefs towards the environment. "It measures the extent to which people have an anthropocentric versus an ecocentric worldview" (Gatersleben, Murtagh, and Abrahamse 2014, 377) and was later used for complementing Schwartz "Norm Activation Model" towards Stern's "Value Belief Norm Theory" (Kurisu 2015; Stern 2000; Schwartz 1977). Yet, environmental concern/attitude is distinct from pro-environmental intention, although both are interrelated. Both are connecting concepts between several theories, that explain the drivers of behavior[2] (Kurisu 2015; Gatersleben, Murtagh, and Abrahamse 2014; Ajzen 2016).

UBS (Umweltbewusstseinsskala) (environmental consciousness scale) by Bauske and Kaiser (2019) may bridge between those concepts: The UBS combines 75 opinion statements and behavioral self-reports to assess people's problem awareness and willingness to act, to produces a scale of environmental consciousness. This scale has similarities to the GEB, i.e. both use a Rasch-type calculation method, that allows additional assessment of relative difficulty of items. Bauske and Kaiser (2019, 17) note: "[a] measure of environmental consciousness that has been constructed

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[2] Note, that I do not claim that they are the sole factors driving PEB, see Kurisu (2015) for a thorough discussion.

taking into account the difficulty of the included items and encompassing both self-reports on behaviour and expressions of opinion shows strong correlations with actual environmental behaviour." In that sense the UBS considers attitude, performance difficulty (through the Rasch-type approach) and measurement of behavior and may therefore be reasonably used as a proxy for measuring PEBI. The next section looks at the theories used to approach PEB.

## 2.2 Behavioral Theories for Explaining Pro-Environmental Behavior

Bamberg and Möser (2007) note that PEB can be brought about by different motivations: self-interest (reducing one's own risks experiencing impact from a changing environment) or concern for others or the environment. To accommodate these different motivations, this thesis rests upon multiple theoretical concepts, some maintaining assumptions of self-interest as point of departure, some relying on altruistic, pro-social assumptions. By that it builds upon the conceptualization by Rajah, Kopainsky, Eker, et al. (2024). Due to the scope of this thesis, every elaboration on those theories must fall short. Therefore, I try to extract the most fundamental concepts used in informing the construction of the proposed model, accepting that a thorough discussion is not possible here further improvements might be needed to depict the theoretical concepts exhaustively.

**Theory of Planned Behavior**

Theory of Planned Behavior (TPB)[3] is one of the most popular theories for investigating drivers of behavior (Ajzen 2016) that has proven its applicability in many empirical studies (Ajzen 2020; Bosnjak, Ajzen, and Schmidt 2020). The theory reckons that the performance of behavior rests upon the intention to perform it (Klöckner 2013; Kaiser, Hubner, and Bogner 2005; Ajzen 2020). Intention is in turn "determined by three factors: attitude toward the behavior, subjective norm concerning the behavior, and perceived behavioral control" (Ajzen 2020).

Attitude towards the behavior (positive or negative) are formed by beliefs about the value produced (Ajzen 2020). This attitude formation rests upon concepts from the expected value theory (rational choice) concerning the subjective benefit of the behavior and the probability of its consequences (Ajzen 2020; Kaiser, Hubner, and Bogner 2005).

The subjective norm consists of descriptive and injunctive norms (Ajzen 2020) – concepts usually depicted in social norms formation (Legros and Cislaghi 2020). Within the TPB, a person forms normative beliefs about the expectations, demands or aspirations from its significant reference group (e.g. peer group or family)(Ajzen 2020). These are either descriptive (referring to what others are actually doing) or injunctive (referring to what someone thinks their peer group approves

[3] For an extensive discussion TPB see Conner and Norman (2015); Ajzen (2020; 2001; 2016); Kurisu (2015)

of or wants them to do)(Ajzen 2020; 2016). Since these normative beliefs are subjective, they are termed subjective norm, but they are in line with the insights from social norm formation, that employ the same distinction (Legros and Cislaghi 2020; Gavrilets, Tverskoi, and Sánchez 2024). Yet, a hidden implicit assumption is the weight people give to each of these norm-routes.

Perceived behavior control (PBC) is concerned with subjective estimate about the personal ability to perform the behavior in questions, i.e. control beliefs. Ajzen (2020, 315): "These beliefs are concerned with the presence of factors that can facilitate or impede performance of the behavior. Control factors include required skills and abilities; availability or lack of time, money, and other resources; cooperation by other people; and so forth." In comparing multiple theoretical constructs there is a comparability between the perceived behavioral control and the measure of self-efficacy as proposed by Bandura (1977) (Ajzen 2020). According to Ajzen (2020), the difference between PBC and self-efficacy is not of conceptual nature (what it tries to represent) but more a different approach of measurement. I will therefore treat them as substitute concepts while being aware, that there might be more subtle nuances between these concepts that I put aside. In reference to PBC, Kaiser, Hubner, and Bogner (2005) argue that especially in studies, where there is wide range of behavior under investigation, PBC might be neglected in explaining behavior, while still being relevant to the formation of intention.

Ajzen (2020; 2016) postulates that there are feedback mechanisms that relate the behavior back to its antecedents, although out of simplicity traditional visualizations of TPB do not represent these. This supports the effort to integrate the theory in a more dynamic framework.

**Protection Motivation Theory**

The Protection Motivation Theory (PMT), falls in a similar category as the TPB in that it rests upon expectancy value theory (Floyd, Prentice-Dunn, and Rogers 2000) and rational, self-interested assumptions (Eker, Reese, and Obersteiner 2019). In general terms, PMT employs two routes for building up Protection Motivation: (1) *threat appraisal* refers to the perceived severeness of the situation and the perceived vulnerability to the threat while (2) *coping appraisal* refers to the available behavior that is deemed effective to reduce the threat (*response effective*) as well as one's perceived ability to perform the behavior (*self-efficacy*) (Conner and Norman 2015). As a meta-analysis show, PMT variables are successfully used in numerous studies for behavior change, especially in the health sector (Conner and Norman 2015; Floyd, Prentice-Dunn, and Rogers 2000).

While the PMT does have a stronger focus on threat assessment, researchers have employed a connection between concepts used in PMT and TPB: Conner and Norman (2015), note that *Protection Motivation* can be seen as the *intention* to act in a certain way, while self-efficacy can be related back to PBC. Eker, Reese, and Obersteiner (2019) combined TPB and PMT for conceptualizing people's reaction to environmental feedback when considering dietary shifts.

Both PMT and TPB consider personality characteristics and value orientations only indirectly in acknowledging that these effect variables of their model, e.g. as sources of information informing the processes of appraisal building in the PMT (Floyd, Prentice-Dunn, and Rogers 2000) and as "background factors (…) [that] influence intentions and behavior indirectly by affecting behavioral, normative, and/or control beliefs" (Ajzen 2020, 318). Hence, especially TPB, is under critique for "neglecting moral considerations" (Kaiser, Hubner, and Bogner 2005, 2152). The next section looks at a more value-based theory of explaining PEB.

**Value Belief Norm Theory**

Value Belief Norm theory (VBN) (Stern 2000; Stern et al. 1999) is a popular model to explain especially altruistic or environmentally orientated behavior (Kaiser, Hubner, and Bogner 2005). It integrates concept from Schwartz's *Norm Activation Theory* (Schwartz 1977) and establishes connections between general values, environmental values and behavior (Klöckner 2013; Stern et al. 1999). Comparing TPB and VBN seem to be on par in terms of explanatory power, both achieve to explain between 20% to 30% of the variance in behavior (Klöckner 2013).

Within VBN, behavior is predicted by the *personal norm* (also sometimes called moral norm) which needs to be "activated". This activation is initiated by a worldview (values), which triggers a certain awareness of consequences (AC) (the realization of the consequences of a behavior for objects that one values) and an ascription of responsibility (AR) (a measure of ascribing oneself or others the responsibility to act) (Stern 2000; Klöckner 2013; Kaiser, Hubner, and Bogner 2005).

The worldview within the VBN is measured by the previously discussed New Ecological Paradigm (NEP) scale that categorizes certain sets of values (valued objects) to provide an indication of how strong one's ecological worldview is – it links value orientations through their influence to the personal norm (Klöckner 2013). The theoretical underpinning of values here traces back to the work by Schwartz (1992; 1994) (in De Groot and Steg 2008). There, Schwartz proposed 10 universal values that underly motivation and holds that values transcend actions, function as standards and are essentially ordered by importance. It is the relative ordering that guides behavior action (Schwartz 2012). A person who, for example, values achievement and power higher than universalism and benevolence will depicts a specific set of ordered values that might sacrifice the fulfillment of the later for the fulfillment of the former.

An ordered set of values can be categorized as value orientation (VO) and the VBN refers to three different orientations specifically: egoistic, altruistic and biospheric (altruism towards the environment) (De Groot and Steg 2008). While an egoistic VO focuses on self-enhancement (and personal costs and benefits), altruistic and biospheric VOs focus on self-transcendence (and benefits and costs for all (species))(De Groot and Steg 2008). These VOs are related to the acceptance of the NEP scale (Stern 2000). Recall that the NEP measures a specific form of environmental concern. So, people employing an altruistic or biospheric value orientation are more likely to accept or "score high" on the NEP (De Groot and Steg 2008), which indicates that a personal norm (intention) for PEB is more likely to be triggered via the workings through AC and AR (Kaiser, Hubner, and Bogner 2005). Note, that this means that AC and AR is therefore related to and anchored in a certain set of beliefs, i.e. manifestation of a certain VO.

**Combined Approaches**

To reap the benefits of more than one explanatory model, researchers have started to combine multiple different theories of human behavior into integrated theories. This has not only been done by collapsing concepts between theories like described under PMT (Conner and Norman 2015) but also by combining them whole - e.g., TPB and PMT (Eker, Reese, and Obersteiner 2019). Others show that an integration between VBN and TPB is possible and empirically supported by increasing their explanatory variance (Esfandiar et al. 2020; Gkargkavouzi, Halkos, and Matsiori 2019; Bamberg and Möser 2007; Klöckner 2013; Karimi and Mohammadimehr 2022; Park and Ha 2014; X. Zhang, Geng, and Sun 2017). Therefore, bringing both sides (self-interest and altruistic) of PEB together in one integration of the proposed theories seems not only possible but reasonable. In that, my work builds upon the conceptualization by Rajah, Kopainsky, Eker, et al. (2024) and develops it further.

**Comments on (Social) Norms**

Several theories address the involvement of social, personal or moral norms. Hence, a brief delineation of the concepts used is presented here[4].

Following Conner and Norman (2015) and in reference to Cialdini, Kallgren, and Reno (1991), we can distinguish between descriptive, injunctive and moral norm. While the first two relate to the construct of social norms (Legros and Cislaghi 2020; Conner and Norman 2015) – here also referred to as subjective norm in the TPB – moral norm is the corresponding concept for personal norm (Kaiser, Hubner, and Bogner 2005). Following Schwartz (1977), Bamberg and Möser (2007) term moral norms in reference to strong personal obligations, while Gavrilets, Tverskoi, and Sánchez (2024, 2) explain they are "(…)shaped by an individual's moral values, often stemming from considerations about the welfare of others". A deviation from every norm can be

[4] Note, that this excurse cannot even scratch the surface on norms, but only tries to contextualize the concepts used.

perceived in terms of personal feelings: Feelings of cognitive dissonance (going against one's personal norm), feelings of peer pressure (going against the descriptive norm), feelings of shame or inconformity through disapproval by others (against social norm), or feelings related to non-compliance with official norms from authoritative figures (Gavrilets, Tverskoi, and Sánchez 2024). These constraints, negative feelings, may be conceptualized as costs, burdens or impediments, while these mechanisms may also represent payoffs, e.g., moral satisfaction through conforming to certain norms (Gavrilets, Tverskoi, and Sánchez 2024).

According to Legros and Cislaghi (2020), social norms can exert influence through and fulfill the function of (1) informing individuals about efficient or reasonable courses of action (2) create an external obligation, relating social or actual punishment as consequences to norm deviation and (3) act as internal obligations, in which the consequences of deviation result in guilt or cognitive dissonance. Unlike in TPB (Ajzen 2020), social norms do not only inform the subjective norm. Dannals and Miller (2017) and Legros and Cislaghi (2020) both argue that social norms also bear insights about the ease of the task in question, its efficiency. Doherty and Webler (2016) even argue that especially descriptive social norms can be used to explain variance in the self- and collective efficacy. If others do it, I might be able to do it as well. This argument fits with the theory of TPB in multiple ways: (1) Depicting the mechanisms about forming subjective norms based on social norms and (2) integrating information about the perceived efficacy as a proxy for PBC. Similarly Bamberg and Möser (2007) argue, that social norms fulfill certain functions, e.g. as source of information of appropriate actions, their moral value and ease of performance - or becoming internalized personal norms directing behavior (Gavrilets, Tverskoi, and Sánchez 2024).

In sum, this chapter started out by delineating the concept of PEB used here, while pointing at inherent difficulties in making use of the classification per se. I looked at different ways of measuring and approaching PEB, PEBI and Concern, followed by a presentation of how popular theories conceptualize intention and behavior change. I looked at the TPB, PMT and VBN, closing by pointing towards the successful integration of those concepts. Lastly, I commented on the concept of social norm to lay grounds for the next part – hypothesizing a dynamical model.

# 3. Methodology

This chapter first describes the employed method, approach, data collection and research ethics in more details and closes with describing the dynamic hypothesis in relation to the theories used.

## 3.1 System Dynamics Approach

To be able to tackle the proposed research questions, I developed a quantitative System Dynamics (SD) model. SD modelling is especially apt to depict non-linear change, complex dynamics and explore leverage points through simulation (Sterman 2000). Using SD (as part) of the research approach in the area of environmental attitude, lifestyle or intention change has become more and more popular (e.g. Eker, Reese, and Obersteiner 2019; Eker and Wilson 2022; Beckage et al. 2018; Ulli-Beer et al. 2010; Levine 2003). Contrasting, analyzing and combining the theoretical concepts of the used environmental psychological theories is an established approach as well (e.g. Bamberg and Möser 2007; Kaiser, Hubner, and Bogner 2005; Park and Ha 2014). SD is a very useful tool, to derive policy insights from the interdependent workings of a system (Richardson 2015). Here, I have used SD in a more conceptual fashion and as a method to operationalize the proposed conceptualization on a generic high-level and to depict their possible inclusion in IAMs and SSPs.

Therefore, the research is oriented at a conceptual virtual laboratory research strategy as outlined by De Gooyert (2019), where existing theories are analyzed and combined to generate new or more elaborate insights. Hence, the model builds structure from the outlined theory above. During the model construction phase, I followed the recommended modelling stages from Sterman (2000) with inspiration from "agile SD" approach Warren (2014), resting on iterative improvement of the model produced. I followed best practices of model formulation as proposed by Martinez-Moyano and Richardson (2013) – high level guidelines for advancing in the modelling process, e.g. moving from simple to complex, balance realism and strived for simplicity – and Sterman (2000) for concrete guidelines on model formulation. For adequate transparency and reproducibility, documentation guidelines of Rahmandad and Sterman (2012) are followed. To build confidence in the produced structure, I performed model validation and sensitivity analysis following established guidelines (Sterman 2000; Barlas 1996; Barlas and Carpenter 1990).

## 3.2 Integrated Assessment Modelling Approach

**IAM Modelling**

My work contributes to the efforts of representing human behavior endogenously for integration into larger IAMs: models that integrate representations of higher-level systems such as environment, economy and society on different scales (regional, global, national etc.) (Beck and Krueger 2016; Skea et al. 2021; Trutnevyte et al. 2019), and which are used to investigate and test "(…)different strategies for climate mitigation and inform decision makers" (Van Den Berg et al. 2019, 1). This means that model components are focused on the mechanisms and workings within the respective subsystem and then coupled with each other (e.g., the economic module has impact on the environmental module, which in turn gives input to the societal module and so forth). To contribute to an endogenized representation of human behavior in IAMs, this thesis will use modules of two existing IAMs. This serves two purposes: (1) use their power to produce simulations and projections about the climate developments. To endogenize human behavior, a "reaction" of the environment in different forms is needed. The IAM modules provide established, tested and validated results for that (i.e. temperature variation and extreme events). Here, this project profits from the opportunity to stand upon the shoulders of those works. (2) Directly test the connectivity of the proposed model. Exploring dynamic interactions should also include the possibility of using the generated insights for a possible adaptation back into the IAMs – a connectivity that is conveniently maintained by using them from the start.

**IAM Input**

The FRIDA IAM (Feedback-based knowledge Repository for IntegrateD Assessments), developed by WorldTrans is SD-based model, that aims at better representing the interconnectedness between human behaviour, global economic representation and climate while assuring model transparency for integrated assessments (Schoenberg et al. 2023). Here I use the temperature module, within the climate subsystem, from FRIDA version 1.0 (Schoenberg et al. 2024), which employs a reduced version of the FaiR simplified Climate Model (Leach et al. 2021). The second IAM is called FeliX (Full of Economic-Environment Linkages and Integration dX/dt) Model (Eker et al. 2023; Rydzak et al. 2013). Also SD-based, it encompasses 10 different subsystems and sets out to depict the "[c]ritical interdependencies among these systems (…)to recreate the complex dynamic behaviour which characterizes the Anthropocene" (Eker and Obersteiner 2023). Here I use only the Extreme Climate Event component. The technical coupling between my work and the respective modules is described in Chapter 3 and Appendix A – Model Documentation.

## 3.3 Additional Data Input

**Shared-Socioeconomic Pathways**

This thesis also rests upon the work on the Shared Socioeconomic Pathway (SSP)s – scenarios that hypothesize possible developments of uncertain societal conditions, apt to be implemented and coupled with climate assessment methods for pathway and policy analysis to " (…) explore mitigation, adaptation and residual climate impacts in a consistent framework (O'Neill et al. 2015, 170). In that way, they are for example used in the latest IPCC report to inform about possible pathways, societal projections and emission behavior (IPCC et al. 2023). Coupled with several different IAMs and other modeling packages, they are not only narratives (qualitative) but also quantitative projections each in respect to the corresponding scenario (Riahi et al. 2017; Calvin et al. 2017; Fujimori et al. 2017; Kriegler et al. 2017; Fricko et al. 2017; Van Vuuren et al. 2017). Here, the qualitative

SSP scenarios and quantitative SSP scenario-data will be used as input for projected developments especially of sectors, regions and data that is not addressed through this thesis.

In addition to the structure and data input from the IAMs and SSP, I did not collect primary data. This is partly due to the scope of the project and partly due to the topic choice. Yet, it shall be mentioned especially here, that further development of this topic may rest upon surveys, interviews or otherwise collected primary data in respect to specific PEB(s), their measurements and behavior-related emission data. This research includes data from secondary sources, such as data from the OECD and International Environmental Agency (IEA) and aggregated data about environmental behavior and emissions (see Table 1 for references). Furthermore, peer reviewed literature and articles lie at the base of the model's conceptualization and structure choices. Table 1 summarizes the used data and academic contributions.

*Table 1 - Overview over data collection - selective references only*

| Source | Description | Use |
|---|---|---|
| (Ritchie, Rosado, and Roser 2023a; Community Emissions Data System (CEDS) 2024; Global Carbon Projct 2023; Jones et al. 2024) | Datasets, visualizations and estimations about yearly average GHG emissions by source in per capita unit. | Parameterization and connecting exogenous SSP data to real world data for existing time horizon |
| (Riahi et al. 2017; Fricko et al. 2017; Kriegler et al. 2017; Van Vuuren et al. 2017) | Data and estimations for exogenous input in the respective Shared-Socioeconomic pathways | Parameterization of the exogenous input.<br>Inspiration for Conceptualization |
| (OECD 2022b; Yamano and Guilhoto 2020; IEA 2023) | Dataset for per capita consumption-based $CO_2$ emissions in the OECD countries | Parameterization<br>Validation |
| (Ajzen 2016; 2001; Beckage et al. 2018; Eker, Reese, and Obersteiner 2019; Kaiser, Hubner, and Bogner 2005; Bamberg and Möser 2007; De Groot and Steg 2008; 2009) | Literature and articles used to inform and guide the construction of the modelling choices | Conceptualization<br>Parameterization |

## 3.3 Research Ethics

This research is guided by and committed to the principles proposed by the Economic and Social Research Council code of research ethics (UKRI 2021), Denscombe (2020) and the Guideline for Research Ethics as proposed by The Norwegian National Research Ethics Comittee (2022). Since there was no participatory element to the research, the focus lies on the research being conducted with scientific integrity, honesty, and responsibility, ensured through adhering to scientific standards, guidelines and best practices for SD as quoted above. Just because there is no direct involvement of participants, every SD model and study inevitably deals with connection between the model and the real world. Here, the modeler is accountable for moving back and forth ethically between quantified models and its possible implications, between choices for quantification and drawbacks following its interpretability.

Furthermore, the research topic deals with qualitative concepts (e.g. intention, worldviews), different methods of assessment (self-reporting, aggregated data) and is focused on system representation from diverse cultural contexts (OECD countries) despite their similar political and economic contexts (i.e., OECD as forum with members committing to democracy and market economy). This implies representing a global north, western-centric perspective, excluding important perspectives from the global south – a drawback in global modelling also pointed out by (Eker et al. (2024). This also plays out inevitably in the choices of the model's elements and structure. As Palmer (2017) describes, the modeler is responsible for transparency about assumptions, introduced biases, choices of boundary and clarity about the uncertainties in parameters or concepts. To the best of my ability, I will shed light on the difficulties, assumptions, uncertainties and limitations, especially when trying to assess qualitative concepts through a quantified model and be clear about inferences that can be drawn from that and the model in general.

Referring to the distinction proposed by Sterman (2000), this work is to the best of my ability in line with reflective modelling, instead of protective modelling. This means, that research shall be used to promote reflective discussion about assumptions and the investigation itself, not reassure pre-existing biases and prejudice by using data and tests selectively and covering up uncertainties (Sterman 2000).

## 3.4 Model Description

### 3.4.1 Model Boundary

As in every model, this research has conceptional, theoretical and practical limitations in scope. Since SD is essentially not a project to capture the whole of a system in question, but one to depict the development of behavior of the system in the light of a specific problem/purpose, every (SD) model necessarily suffers incompleteness and has a boundary of included concepts (Sterman 2000). Given this limitation of models, it is important to define the boundaries I have drawn in this model, which also impose limitations. These are mentioned here already to make sure, that the reader may keep them in mind for interpreting the model and its results. In general, as stated above, I chose the OECD context for application, due to emission contribution, data availability, compatibility with SSPs and as region of collective policy trajectories.

### Time Horizon

The time horizon of the model and its simulations is set from 1995 to 2100. This has three distinctive reasons. First, the aim of the time horizon is to be set to see properly also long-term developments of the system's behavior (Sterman 2000). Here, a century was deemed as adequate. That the behavior of the system is levelling off towards the end of the period is a good indication about this assumption. Second, data availability made the starting point of 1995 salient to provide a decent amount of data for the comparable time horizon. Third and ultimately, the SSP data, which has provided the necessary exogenous input for simulating responses in climate and temperature, also covers the time horizon of 100 years.

### Data availability and restriction to $CO_2$

As described above, data availability, especially, consumption-based calculations of the generalized level this model is aiming at, set the scope of the model to include $CO_2$ emissions only. This is to be considered a relevant drawback since several other greenhouse gases are emitted through ESB by human consumption choices. One could suppose that the mere calculation of "per capita" as a unit be a reasonable choice of measurement, yet it distorts the picture, since it does not capture the consumption-based emissions that relate back to human behavior. That is why the focus of this conceptual work lies on $CO_2$ emissions alone, while the inclusion of other greenhouse gases emission is strongly encouraged for further development. Having a more concrete and specific behavior under research will help to find the proper metrics to keep track of individual contribution.

Furthermore, at the core of the model lies the exploration of environmental psychological theories that explain human behavior. If one asks the question of what explains human behavior, especially in environmental respects, one will find a multitude of relevant disciplines, areas and factors (Kurisu 2015; Heeren et al. 2016; Bamberg and Möser 2007; Gavrilets and Richerson 2022). Due to the scope of this thesis, the model boundary excludes the endogenous treatment of media coverage, education and knowledge, authoritative instruction (e.g. state induced media campaigns or instructional, paternalistic policy options) and emission behavior of other regions. Some of the above (e.g., media coverage, data for emissions from other countries than the OECD) are included exogenously. Others (e.g., knowledge and education) might be possible to include in further explorations. Herein lies the great advantage of a conceptual model: to be expendable, adaptable and by that apt to connect to other sub systems of society relevant for research in social tipping and modelling PEB changes.

Due to their prevalence, two boundaries are still to mention more explicitly. First is the conceptual constraint to the theories of change in PEB. As mentioned TPB, VNB and PMT are not the only concepts. Self-Identity orientated explanations, for example, are well established and suggested as an inclusion in TPB (Conner and Norman 2015). Yet due to scope, this model is ignorant of them. This is not to judge or even comment on their validity, but rather a practical limitation to focus eclectically on some of the main theories of the field.

Secondly, the exclusion of GDP and financially related factors pose a surface for critique. Yet, these measures rely heavily on regional availability (e.g. is there an affordable price for renewable energy available in my region), as well as preference choices (e.g. do I want to buy meat-substitute or will plant-based proteins and substitutes suffice. Do I intend to travel the same distance now with trains or do I change destination). To consider these factors with necessary accuracy was not adequate for the scope of the behavior in question and beyond the scope for this project. This imposes a drawback, one that also impedes on PBC. While one part of PBC, i.e. perceptions of ease, feasibility or normality, are incorporated in the social norm and PEBI, the other part relating to resources, e.g. income is not depicted here. Yet, on an aggregated level, especially with anticipated $CO_2$ and renewable energy prices and pro-environmental regulation underway in some countries already, it seems reasonable to work under the assumption that a shift to a more environmentally friendly consumption, does not necessarily come with a rise in costs of living. Especially in using this conceptual model for further specification towards distinctive behaviors, the inclusion of financial factors is strongly advised, easier to calculate, estimate and specify and easy to implement. Table 2 summarizes the endogenous, exogenous and excluded elements.

*Table 2 - Model Boundary Chart*

| Endogenous | Exogenous | Excluded |
|---|---|---|
| Temperature change | Media efficiency | Financial indicators |
| Extreme climate events | Energy efficiency | Knowledge and education |
| OECD $CO_{2\,e}$missions | Rest-of-World greenhouse gas emissions | Demographical factors |
| PEBI | OECD CH4 and N2O Emission | Psychological concepts not mentioned in TPB, VBN and PMT |
| Social norms | SSP narrative ata | |
| | Authoritative norm | |
| | Population | |

### 3.4.2 Dynamic Hypothesis

This section describes the model's dynamic feedback process, focusing on its major loops, and its relation to the established theoretical underpinnings, excluding descriptions from the mechanisms within the IAM (i.e. FRIDA and FeliX) modules. For detailed documentation, formal and in prose, about modelling choices see Appendix A – Model Documentation. Crucial effects or details on certain parameterization choices are taken up in the next Chapter on model validation and sensitivity. Figure 3-1 depicts the simplified high-level feedback structure of the model.

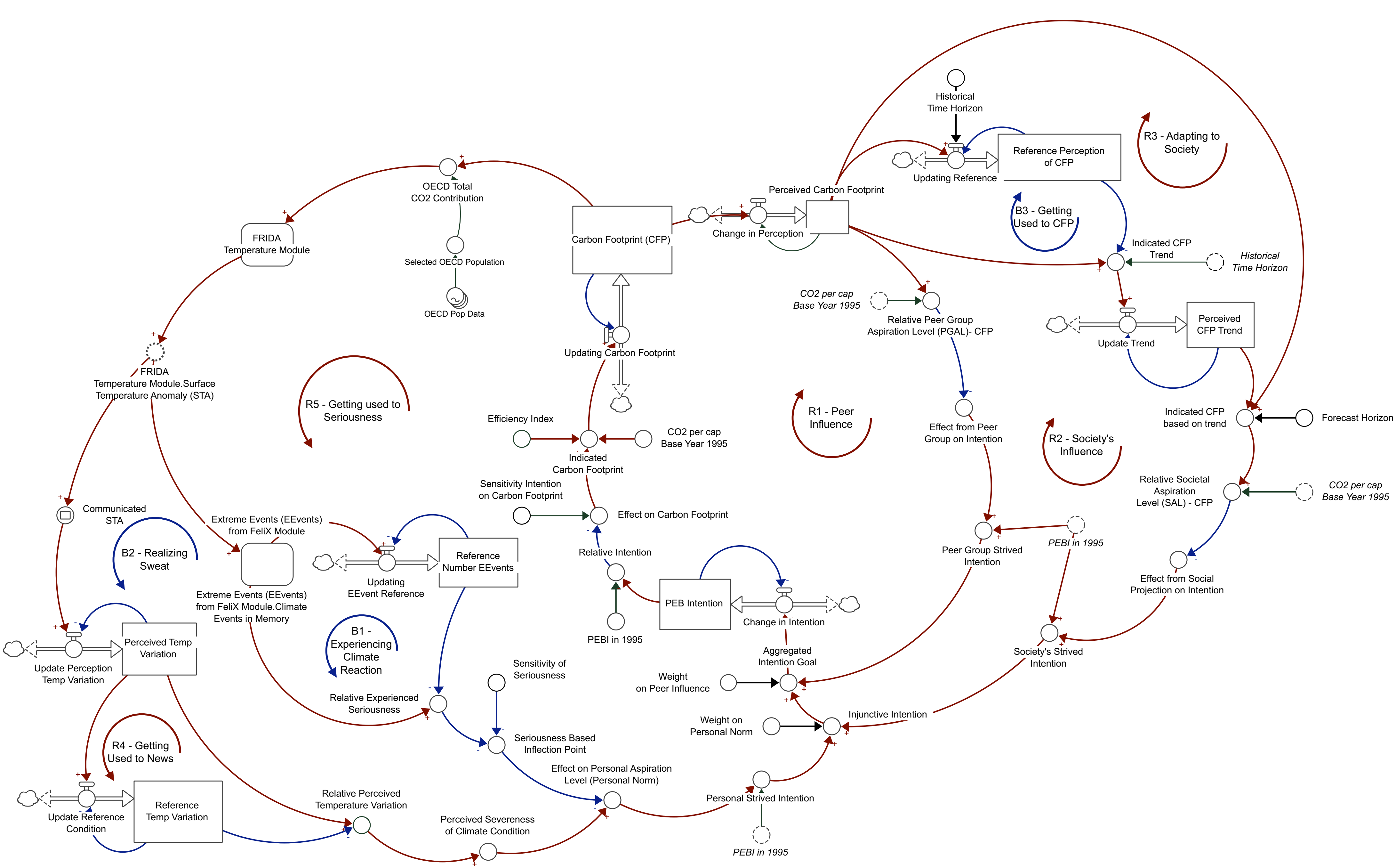


*Figure 3-1 - Simplified model structure, where certain parameters are excluded - see Appendix A for detailed representation*

The following section describes the feedback story that governs the produced model. Reinforcing loops (R- Loops) here indicate that starting out with an increase in variable X leads, through the mechanisms of the loop, to a further increase in variable X. Balancing Loops (B-loops) on the other hand indicate, that an increase in variable X leads, through the mechanism of the loop, to a later decrease of variable X. I conceptualized PEBI ranging between 1 and 0, reflecting a continuous measure, where 1 PEBI refers to 100% Intention, displaying utmost effort in PEB. As discussed above, there are limitations in terms of measurement of PEBI and its comparability (see Appendix A for details). Following the definitions established above, PEB/ESB is conceptualized in relation to its impact through the proxy of Consumption-based Carbon Footprint (CFP).

**Social Norm Influence**

Starting out with an increase in intention, both R1 – Peer Influence and R2 – Society's Influence depict reinforcing loops. The initial increase will manifest in a lower carbon Footprint (CFP), after people adapt their change in intention and translating the new intention it into a new mode of behavior, i.e. lower CFP. Note that this reduction is dragged out through the adjustment processes associated with both concepts and adapted through an energy efficiency (see chapter 4 and Appendix A for a detailed conceptualization). Once people perceive the new lower CFP in their peer group (*Perceived CFP),* they will translate this to a new level of intention – the *Peer Group Strived Intention.* We can think of it in both ways, either as getting inspired or pressured, to adjust to the changed "normal" of the peer group. This new goal is then used as input to further adapt the intention goal – a higher one than before. This narrative follows the concept laid out above, i.e., the adaptation of normative believes through the peer group (TPB), peer pressure and their functions as information about performance ease and acceptance.

Taking the longer route through the injunctive norm, the *Perceived CFP* is watched and projected towards an expectation of society's new normal in five years to come (the time horizon is determined by the *Forecast horizon)*, again functioning as an input to further adapt the intention goal through a *Society Strived Goal.* This is conceptualized through the TREND function structure (see Appendix A for details) and relates to the injunctive norms as discussed above. *R3 – Adapting to Society*, points out a sub-route. People project their current observation into the future – if they observe a high or growing CFP, their projection will reflect that. Hence with higher CFP, the loop gains even more strength, since it is the perception of the peer group that is projected. Vice Versa, *B3 – Getting used to CFP* is a balancing loop that indicates how we adapt to the change we observe. Through updating our reference of what we observe, we don't change our projection about the trend society is experiencing that strong anymore – we got used to a changed level in CFP.

Again, these new levels (*Peer Group Strived Aspiration Level* and *Society Strived Aspiration Level*) not only work as information about what the current perceived state of CFP is or what to expect, but it also conveys information about the feasibility of adaption. Here, we make use of the concept that social norms also conveys information about the ease of adaption (Legros and Cislaghi 2020). This relates to a dynamic updating of the subjective norm from TPB that also includes a concept of perceived behavioral control (from TPB) and efficacy-concepts (from PMT).

**Realizing Climate Feedback**

Both balancing loops, *B1 – Experiencing Climate Reaction* and *B2 – Realizing Sweat*, depict the balancing feedback mechanisms, that drive a personal norm reaction due to what people experience through events (B1) and perceive through news (B2).

We start with a decrease in intention, which is translated to an increase in CFP at the aggregate individual level and the collective OECD level. Feeding into the climate model, this will stimulate the *Surface-Temperature-Anomaly (STA)*, which drives both, the communicated STA and the climate events (see Appendix A for a detailed explanation). To realize impact through the informational route (*communicated STA, B2 – Realizing Sweat)* takes longer since it is dragged out by mechanisms of investigating (science) and communicating (media) the change as well as adapting to a new level of *severeness* which is additionally moderated by a sensation magnitude exponent, a concept from psychophysics for judging magnitudes of perception (see Appendix A for a detailed description). Although also experiencing the impact through events takes time, this reaction is, due to its palpable characteristic, faster than the other one. Both balancing loops (through seriousness and severeness) lead to an increased *Personal Aspiration Level* which will inform a new goal of intention.

Both loops are also influenced by sub-routes (*R5 – Getting Used to Seriousness, R4 – Getting used to news*) that with some time delay reduce their strengths. This is because information and experiences are not perceived isolated but judged against background information (reference condition). This reference is updated along the way which leads to the fact that any further increase in temperature or extreme events are not compared against the initial values (which would lead to a way stronger reaction) but against the reference which is slowly but steadily getting used to the experience and information. An illustrative example about the mechanism is the shift from the communicated 1.5°C goal to a slow adaption of 2°C as new communicated reference for our society's development, resulting in higher reference and reduced perceived severeness.

Note that these loops account for the shift in activated values through extreme events (the route of VBN) as well as a concept of threat appraisal (PMT) and an update of the personal norm (TPB).

There is a conceptual difference between *seriousness* and *severeness* which lies in the experienced and informational content. While people in less affected regions might be aware, cognitively, of the variation of the condition of the climate, they might not perceive them directly. This awareness refers to the perceived severeness of the condition. On the other hand, imagine someone who is skeptical or unaware of informational input from media/science but experiences more extreme events more in its region. This person might not cognitively think about a relative rise in temperature but becomes aware about the consequences directly through experiences. This awareness refers to the seriousness of the current condition. While this might be a valid theoretical distinction, it must be asked if the concept is not better represented as a single structure. The need to integrate two different concepts becomes more apparent once we think about extreme cases: Imagine the person from before, sheltered and without direct experience of the consequences. This person might very well, due to personal conviction and values, be influenced by the perceived severeness and forms a personal norm to increase PEBI. Vice versa, the person unaware of information based severeness, may not need the cognitive validation. They experience it directly. Consequently, both routes ultimately should result in a variation of personal norm.

In Chapter 2, I laid out that the TPB relies on personal beliefs to form the personal norm which in turn informs intention. To grasp this concept in the model, some combination of the severeness and seriousness needs to be translated into a *Personal Aspiration Level of Intention*, i.e. personal norm. Note, that this route is still employing a cognitive evaluation of the behavior in question, and in contrast to the peer group related goal, is not informed by comparison to others.

The VBN background is more nuanced in this picture. As explained, VBN rests on the assumption, that certain sets of prioritized values influence the amount of support for PEBI. That is to say that a person holding a more altruistic (biospheric) worldview might act with a higher probability than one employing an egoistic worldview. Here again, it is assumed that a combination of seriousness and severeness should capture this concept. Yet, due to its fluidity, a one-shot threshold and categorization of worldviews might be too simplistic. Additionally, as argued above, once people feel personally affected by the current condition, even egoistic worldviews might lead to a higher willingness of action. This relates to the awareness of consequences which indicates that you perceive adverse consequences for your valued objects (Kaiser, Hubner, and Bogner 2005; Stern 2000; De Groot and Steg 2008; 2009). Someone who employs a biospheric worldview is prone to act "earlier" as someone who needs to feel the consequences affecting them personally. A connection can be made here to the PMT, where the severeness is used to form the threat appraisal and people, no matter their worldview, might perceive a threat (Floyd, Prentice-Dunn, and Rogers 2000).

In sum, the experience-based route activates different worldviews by conceptualizing the shift in values affected. In using the combination of both, cognitive severeness and felt seriousness, I have tried to account for all three concepts, i.e. the awareness of consequences (VBN), the severeness concept (PMT) and the personal beliefs (TPB). The strength of the different loops is partially driven by the weights that determine their influence in the newly formed goal. A strong *weight on personal norm* and a mild *weight on peer influence* for example would ensure, that the system reacts stronger to the environmental change and vice versa.

## 4. Model Validation and Sensitivity

To build trust in the model produced, several tests were conducted throughout the modelling process. Testing is an essential part of SD modeling, not only because it improves the confidence of the modeler and, by extension of this document, the readers in the results and analysis of this model (Sterman 2000); but also because it is also a guided process that helps to uncover underlying assumptions, reflect on model purpose, investigate into dynamic behavior closely to generate insights about leverage points and make weaknesses, strengths and required improvements transparent and reportable (Sterman 2000). Following Barlas and Carpenter (1990), validation does not decide between true or false, but refers to "a continuum of usefulness" (Barlas and Carpenter 1990, 157). Also Sterman (2000) refers to the validity of a model in terms of the usefulness considering the model's purpose. In pursuit of confidence in the usefulness of the model, this Chapter documents the validation and sensitivity tests performed. The tests are oriented at the guidelines for model testing and validation provided by Barlas (1996) and Sterman (2000). Direct structure tests refer to parameter and structure assessment, dimensional consistency, integration error and direct extreme conditions. Second, structure-orientated behavior tests refer to indirect extreme conditions, boundary adequacy and behavior sensitivity (Barlas 1996). Note, that these tests are only described and done for the produced model, and not for the modules included from other sources. While the tests include the interaction with these models, the reader is referred to the IAMs documentation for defense of the respective structures (Schoenberg et al. 2024; Eker et al. 2023).

## 4.1 Direct Structure Tests

Generally, "[d]irect structure tests assess the validity of the model structure, by direct comparison with knowledge about real system structure" (Barlas 1996, 189). They compare the models structure and parameter against the current state of both descriptive and numeric knowledge (Sterman 2000).

**Structure and Parameter assessment**

Both tests address the question whether the model refers to the "descriptive knowledge" (Sterman 2000, 859) about the system, whether the used parameters are numerically correct or related to real world counterparts and whether they capture the mechanisms that govern actors (Sterman 2000). Throughout Chapter 3, I related the model's structure back to the insights from the theoretical framework, suggesting a translation of the theoretical concepts into stocks, flows and compounded mechanisms, and by that grounding the modelling choices as described above in Chapter 2 (see also Appendix A for more details). Part of the structure built upon existing work of Rajah, Kopainsky, Eker, et al. (2024), or was inspired and taken from different contexts (e.g., the TREND function), which also represents grounding in literature. Yet naturally, this model has uncertainties in its structure. By that, I refer also to gaps in the literature, be that the precise translation from intention into behavior or the interplay between severeness and seriousness. Considering this uncertainty and as explained above, I argued for a reasonable representation – one that is under testing by this very thesis and following tests.

Since the behavior in question sums a vast multitude of behaviors, several time delays or parameters (e.g. sensitivities of effects) were hypothesized to a reasonable range and then used in calibration of the model against the data provided for the historical OECD consumption-based carbon footprint (Yamano and Guilhoto 2020; OECD 2022b). This also means that especially for development of a case-specific application, the parameters need to be adapted to the respective context, social group and behavior in question.

**Exogenous Emission Data and population**

Initially, the historic population until 2005 was considered as data input. Yet, the uncertainties about the inclusion of member states (several members were added in the period from 1996 to 2021), as well as the underlying assumptions about population dynamics (GDP, fertility rates etc.) inherent in the SSP-2 projection (Riahi et al. 2017; Fricko et al. 2017; Kc and Lutz 2017) made it difficult to harmonize projected with historical data. Therefore, the population from 1995 until

2005 was estimated through extrapolation of the SSP-2 data via the modelling software. Although this implies a data inaccuracy, this way anchored the model on data source, i.e. SSP-2 data.

The SSP-data (SSP Marker Scenario-Baseline) was used as exogenous GHG emission data (Riahi et al. 2017; Fricko et al. 2017; Van Vuuren et al. 2017; Fujimori et al. 2017; Kriegler et al. 2017; Calvin et al. 2017). Since the SSPs provide only data from 2005 onward, for the years from 1995 to 2019 the respective SSP-2 data (up to 2019) was exchanged by the actual GHG data from the respective years (Community Emissions Data System (CEDS) 2024; Global Carbon Projct 2023; Jones et al. 2024; Ritchie, Rosado, and Roser 2023a). This ensured a smooth transition between actual data and projected SSP-input and a way to bring the exogenous input closer to real-life data. To introduce the model's OECD emission behavior, I decomposed the SSP's $CO_2$ input in "OECD" and "the rest", subtracting the exogenous OECD contribution and replacing it with the endogenous model input.

**On Effects and their Sensitivity**

One clear source of uncertainty are the hypothesized nonlinear relationships in the form of effects. While their sensitivity is discussed further below, their precise rationale and analytical formulation is argued exhaustively in Appendix – A. Here, I will just briefly touch up the used effects in more general and their relation to the theories.

*Power Functions.*

The *effect from Intention on CFP* and the *Sensitivity-Based Inflection point* are both conceptualized as power function with respective sensitivities that vary the strength of the power function. Comparing data for UBS (Bauske and Kaiser 2019) and CFP in Germany (Ritchie, Rosado, and Roser 2023b), reveals that a power function fits best to describe the correlation, yet the amount of data did not allow for a robust effect construction from them. It includes a 1:1 anchor relating the normal input (1) to the normal (1) condition. This function is related to a specific inert behavior

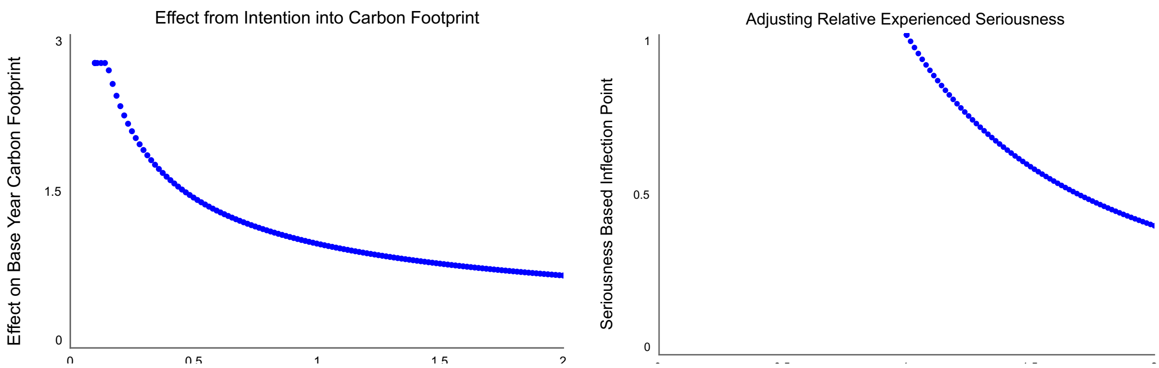


*Figure 4-1 - Structure Graph of "Effect from Intention on CFP" (left) and "Adjusting the Relative Experienced Seriousness " (right)* around the anchor with varying sensitivity further away from it. In relation to the *Effect from Intention on CFP*: It moderates the change below and above the 1:1 point, indicating the people might react to a decrease in intention with some inertia but increase their CFP more significantly, once intention falls significantly low. Vice versa, increasing intention will always yield an inert decrease in the effect to reflect the technical, economic and social difficulties decreasing CFP. Both effects are depicted in Figure 4-1.

Note the upper limit on the *Effect from Intention on CFP*. This *maximum effect* (2.73) and was calculated to depict the maximum amount of reduction, because, even if people are careless, they cannot reasonably increase their CFP endlessly. For a details  on the upper limit see Appendix A.

*S-Shaped Effects.*

Translating the *Relative Peer Group aspired CFP* and the *Relative societal aspired CFP* is hypothesized as a S-shape function (see Appendix A for analytical description). Figure 4-2 depicts the structure graphs. The shape represents that below and above the inflection point (1:1) people react with some inertia and increase their sensitivity to a change in relative CFP towards the upper and lower limit of the spectrum.

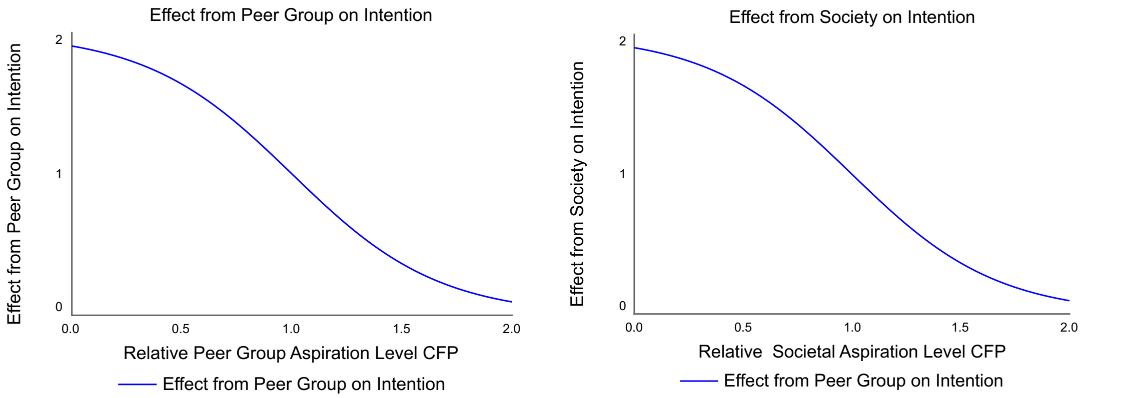


*Figure 4-2 - Structure Graphs of S-Shape Effects in the Social Norm sector. Relative Peer Group CFP to Relative Peer Group Intention (left) and Relative Societal CFP into Relative Societal Intention (right)*

Following a similar reasoning the translation from severeness and seriousness also follows a S-shaped function yet has some alternations. While perceived severeness is kept as the input to determine the effect, seriousness is determining the inflection point. Figure 4-3 shows the structure graph of the effect given certain variations of severeness and seriousness. The seriousness-based inflection point varies based on a certain judgement about the relative experienced seriousness. The mechanism ensures that, the more serious someone judges the current condition, the earlier (i.e. at lower levels of severeness) they show the originally normal intention level – the 1:1-point is shifted towards the left. To make this less abstract: Experiencing higher amount of extreme climate events will result in a high perceived seriousness. Assume, you experience that there are 40% more events than used to, i.e. assume a reference of 40 events per year but now you experience 56. This translates to an inflection point of 0.644. Consult the new effect in Figure 4-3.

Although your cognitive route (severeness) has not changed, you perceive it as a more serious issue. The effect on your personal norm is as high as 1.71 in this scenario. As argued above, conceptualization tries to depict the three concepts, i.e. the awareness of consequences (VBN), the severeness concept (PMT) and the personal beliefs (TPB).

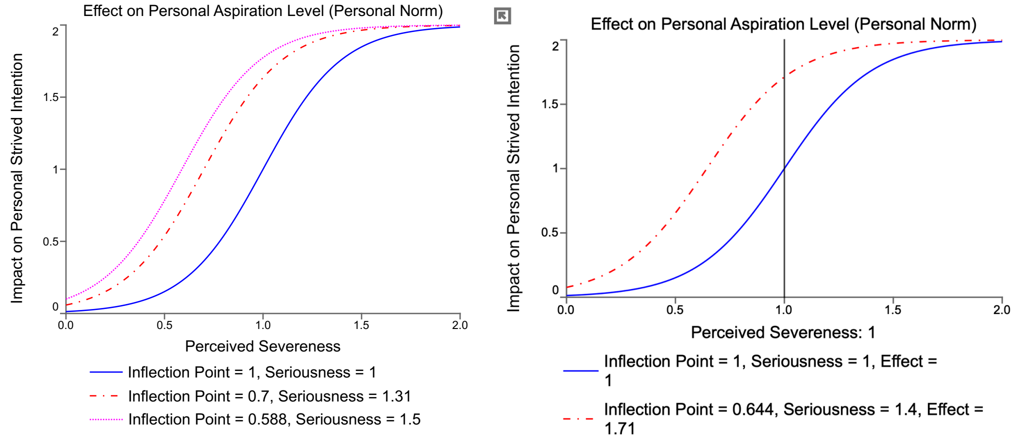


*Figure 4-3 - General Effect on Personal Norm with Variations on Seriousness and Severness (left) and exemplary effect variation (right)*

### Dimensional and Numeric Integration Consistency

The dimensional consistency test aims at ensuring consistency in the models equations without the aid of artificial unit changes with no real-life counterpart (Sterman 2000). For that, direct equation inspections and Stella Software built in functions were used, reporting no dimensional inconsistencies.[5] Also, the model was tested for numeric errors due to the time step and integration method – integration error test (Sterman 2000). Changes in the method of integration might result in differences of numeric output. The interval between calculation steps (DT) and integration method should ensure accuracy in the model outputs in respect to the usefulness of the model, while accounting for a feasible burden for computational power (Sterman 2000). The integration method was tested by trial and error of diminishing DTs and changing methods until consistency in the numeric data output for PEBI until two decimals, i.e. DT = 1/256 (to avoid rounding error), Euler Method. It is to notice that in general there was but only tiny numeric changes.

### Direct extreme condition tests

For direct extreme conditions, the equations and its input are tested against extreme high or low values to investigate if they still uphold under these assumed circumstances (Barlas 1996). This test

[5] Note, that my "Unit Change" parameter is a metric change and bears no concern for dimensional consistency.

is used to ensure – in isolation so to speak – if the equations and behavior or each structural element behaves expectedly, given an extreme input or output. This test revealed computational difficulties when PEBI is extremely low (e.g. PEBI = 0.01), resulting in a very large effect that approaches infinity. Yet, as argued, a reasonable cap of the effect to 2.73 as its maximum value shows that the model passes the test. Some initial stock values (e.g. Initial climate events in memory = 0.001) were modified to similarly small values (e.g. from 0 to 0.001) to avoid computational errors by dividing through 0, while other minor modifications are argued for in Appendix A.

In sum, the model proves to be reasonably robust under the direct structure tests. Although, as shown, some of the parameters and structure are subject to assumptions and inaccuracy, the tests promote the confidence in the model developed.

## 4.2 Structure-Orientated Behavior Tests

*Structure-orientated behavior tests* test the confidence in the model indirectly through analyzing model behavior patterns by simulation under different parameter set ups or conditions (Barlas 1996).

**Indirect Extreme Conditions Test**

With indirect extreme condition tests, model parameters or inputs are varied to test if, even under those extremes, the model behaves expectedly by comparing against the assumed or reasoned behavior the model is supposed to show (Barlas 1996; Sterman 2000). Tests were performed by manipulating initial conditions, zeroing out parameters or deactivating partial structures. One particular test and result should be mentioned here in more detail.

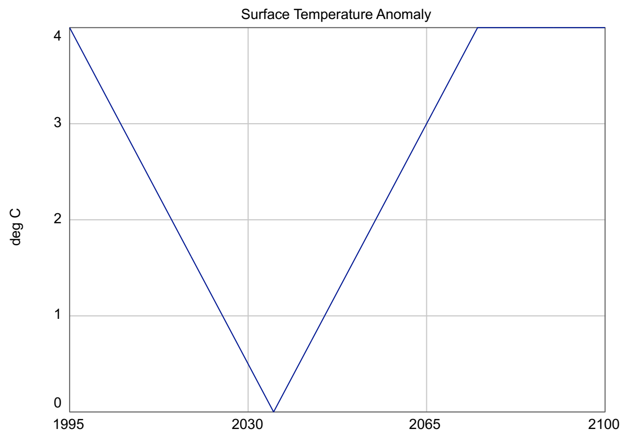


*Figure 4-4 - Variation of the STA under extreme condition test*

Since given the actual developments of the environment, as well as the exogenous emissions input constantly provided by the SSP, the temperature never declines during the simulation. Therefore, this extreme condition tests simulates the model's response when the temperature is artificially manipulated to decrease linearly from 4°C to 0°C (1995-2035) and rises again afterwards until 4ºC. Figure 4-4 shows the decline of the STA during the simulation. To emphasize the reaction, energy efficiency (which would decrease CFP artificially) is turned off for this test.

Thinking about the expected behavior first leads us to expect something like an inverse shape of the STA graph: After realizing the declining trend and the perception of the temperature to be falling, we expect an increase in CFP and vice versa. Figure 4-5 depicts the key variables during the test simulation. As can be seen, in the beginning, due the very low reference temperature, people perceive the risk leading to a rise in intention and an indicated decrease of carbon footprint. At around 2009, the perceived temperature variation falls below the reference - a phase begins where people increasingly reduce their perceived severeness of the condition: They receive the message that temperature variation decreases, hence decreasing their intention. CFP peaks at around 2044 coinciding with the low extrema of the PEBI, shifting the model into a decline in CFP and a steep rise in intention. Later, once the temperature stops varying after 2075, the reference temperature variation starts catching up to the perceived temperature variation, empowering the R4-*Getting Used to News* loop which slowly decreases, leading to the reduction in PEBI towards the end. As such, even under drastically varying STA conditions, the model behaves as expected and hypothesized above, depicting an "inverse" shape from the STA.

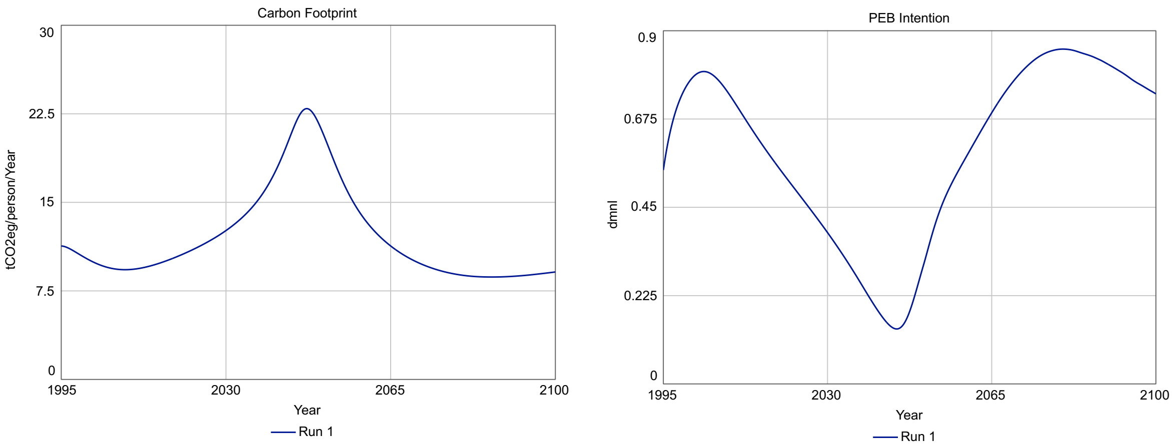


*Figure 4-5 - Carbon Footrprint and Intention under extreme condition test by varying the temperature from 4°C to 0°C to 4°C*

### Boundary Adequacy Test

The boundary adequacy test inspects if the model boundary is well formulated and fit to produce the historic behavior endogenously, as well as whether the model behavior is changed by relaxing the model boundary. The reader is referred to Chapter 2 for justification and clarification of the (theoretical) employed boundaries to the model building in general, as well as the beginning of Chapter 3 where I discussed the model boundary in more detail. As argued previously, the economic dimension remains to be a relevant part of a more rigor investigation into specific behaviors in clearly defined problem-contexts. As such, this yields a conditional "pass" of the boundary adequacy test. As Sterman (2000) mentions, solely omitting a structural component, that one is unsure about, is like claiming it has no impact. This thesis does not assume such thing. While a detailed economic side is clearly relevant for specific behavior, due to the purpose and scope of the project to investigate into specific psychological concepts in relation to general intention, the representation of them in a dynamical fashion and their possible integration in IAMs, this side is excluded from the model boundary. Nevertheless, this may infringe upon, but not invalidate the possible inferences.

**Behavior Sensitivity Tests**

In reference to sensitivity analyses of a model, Sterman notes:

> "Since all models are wrong, you must test the robustness of your conclusions to uncertainty in your assumptions. Sensitivity analysis asks whether your conclusions change in ways important to your purpose when assumptions are varied over the plausible range of uncertainty." (Sterman 2000)

In general, we differentiate between *numeric* – a numeric variation in the model's outputs -, *behavioral* – a variation in the mode of behavior displayed by the model -, and *policy* sensitivity – a change in the models depicted behavior under a specific policy. The rest of the chapter describes and discusses only a sample of sensitivity results. A full description can be found in Appendix C – Sensitivity Analysis.

**Global Sensitivity Comparison**

Before turning towards single parametric sensitivities, the following section compares results from different global sensitivity (GS) runs. In GS run, all assumptive parameters are varied simultaneously. Through that, the tests depict the range of behavior the model can show, given a simultaneous variation in more than only one parameter. Note, that these do not suggest suspension of parametric sensitivity testing but should be seen as an additional effort, since GS only tells us to which extent the model might be sensitive, not which parameters are responsible for it. The runs were conducted using the built-in sensitivity analysis tool from the Stella Software. I varied each parameter between ~±50 % of the base value, with a uniform distribution among them across 10,000 runs (Sobol sampling).

Figure 4-6 shows the 95% confidence intervals of the output variable Carbon Footprint for the Base Run. Given that STA rises in every simulation run (due to the exogenous input) the model is still able to depict several types of ranges and behavior which supports the confidence in model structure. Two phases are especially mentionable: First, in the beginning we can see that numerous runs produce a more drastic increase in CFP – runs in which seriousness and severeness is probably low in the beginning, leading to a low effect on the personal norm. Yet, there are also runs, in which CFP is declining from year one. Here, the model deviates from the usual overshoot and collapse archetype and depicts solely a decline. Further parametric analysis will hypothesize about the influential parameters for that. Secondly, the model always shows a decline of CFP at the end of the simulation with varying degree. This is due to the fact, that *energy efficiency* is responsible for a major reduction in CFP throughout every run. The global sensitivity shows, in line with the feedback story in Chapter 3, that after a certain time, severeness, seriousness, intention and the social norm sector tend toward an equilibrium (note, that this does not have to be the same equilibrium in each run). This level is then continuously and smoothly reduced by the energy efficiency until the end of the simulation.

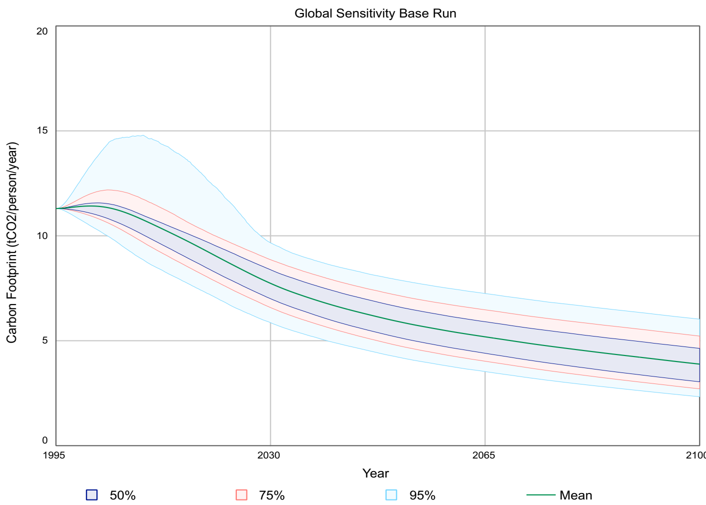


*Figure 4-6 - 95% Confidence intervals for Global sensitivity analysis (Base Run)*

However, during the parametric sensitivity tests, the model was significantly sensitive to the *Energy Efficiency* and *Effect from PEBI on CFP*. Therefore, two additional global sensitivity analyses were conducted to ensure that the above range of behavior is not solely or overly determined by the variations in these parameters. To that end, I compare the model's range of output (1) without varying the sensitivity for the Effect from PEBI on CFP and (2) additionally without the influence of *Energy Efficiency* at all. Figure 4-7 shows the 95% confidence intervals for the respective GS.

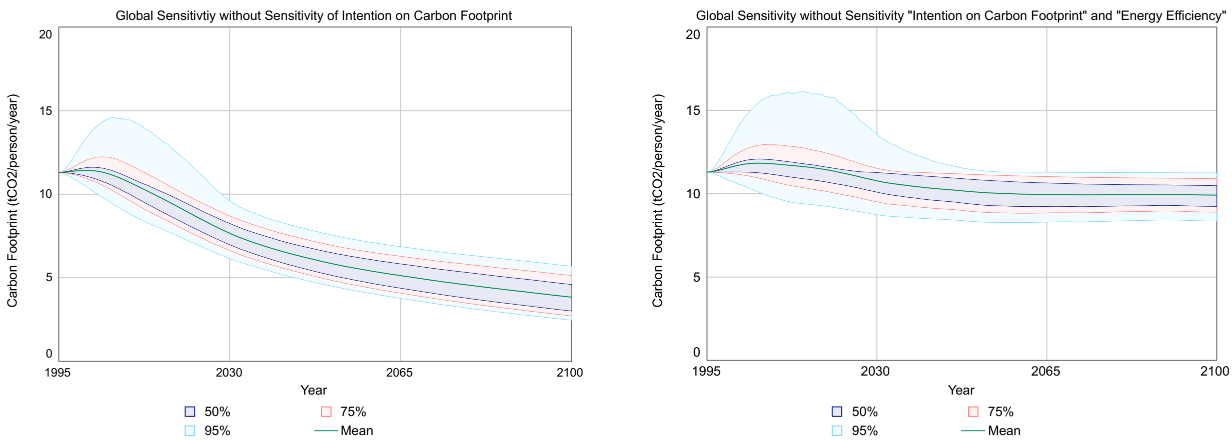


*Figure 4-7 - GS Runs without Sensitivtity on Intention on CFP (left) and without Sensitivity of Intention on CFP and Energy Efficiency (right)*

This comparison shows that, (1) even without varying the sensitivity of the effect that translates Intention to CFP, the model shows the expected behavior with differences being only numerical and in the range it covers. (2) By additionally eliminating the *energy efficiency* we can still see that the model depicts the expected archetypical behavior, yet CFP is of course not decreased as significantly. This further supports the confidence in the model structure, yet it stresses the part energy efficiency plays in the numerical output of the runs.

In sum, the global sensitivity tested the possible model range with the given exogenous inputs under variation of the parameters. The fact that it is still able to depict the expected behavior in all three cases and a broad range of reduction or increase in CFP further supports the confidence in the model structure.

**Parametric Sensitivity Tests**

The following section summarizes the sensitivity tests performed on each parameter and points out salient observations, see Appendix C – Sensitivity Analysis for the full report. Again, a range of ± 50% of the initial parameter value was chosen, the test performed with the Stella built-in sensitivity analysis tool, Sobol sampling, 10 runs each. Overall, parameters were only significant numerically, with minor behavior changes in some cases, which

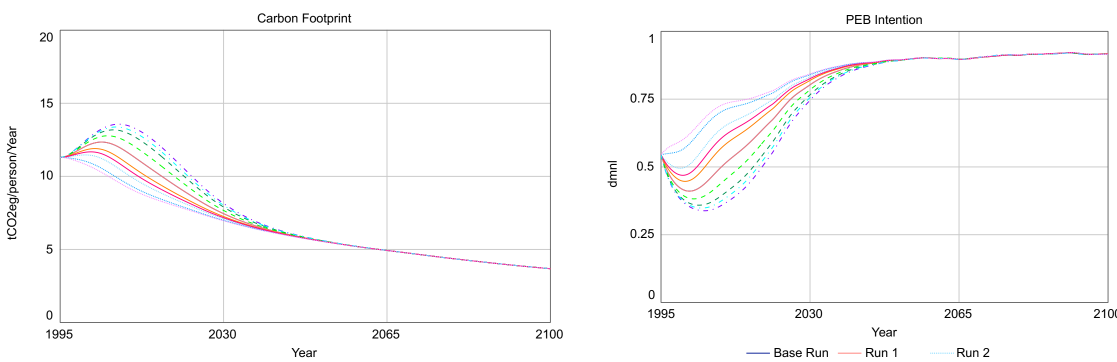


*Figure 4-8 - Sensitivity Runs with Variation in Initial Reference Temperature Variation between 0.22°C and 0.66°C* indicates robustness in the model structure. An exception is the *Initial Reference Temperature Variation,* which leads to an avoidance of the rise of CFP in the beginning. Figure 4-8 depicts the sensitivity runs of varying the *Initial Reference Temperature Variation.*

As soon as the initial reference temperature variation is lower than the perceived, the structure ensures that intention is high and rising leading to a decrease in CFP from the start. Given the relatively higher perceived temperature, *R4 - Getting Used to News loop* needs more time to take over leading to a longer period of lower intention and increased CFP. The sensitivity clearly reflects the uncertainty of the parameter. This is quantitatively due to the sheer number of reference variation, yet it reflects a deeper conceptual uncertainty. The mechanisms through which people evaluate and perceived severeness comes to its limits here. Do people compare the provided news and insights from media and science (as is indicated in this model)? Do people orientate themselves at communicated climate goals and progress (1.5°C – Goal that continuously is being pushed higher to 2°C and probably will ascend to 2.5°C)? If so, against which information would people compare before there was a goal communicated? Considering these uncertainties and due to the behavioral consistency of the model, this assumed conceptualization is kept, yet further investigation is clearly necessary.

Expectedly so, the *Energy intensity improvement rate* changes the model's numeric output (CFP) significantly. Figure 4-9 shows the sensitivity runs respectively.

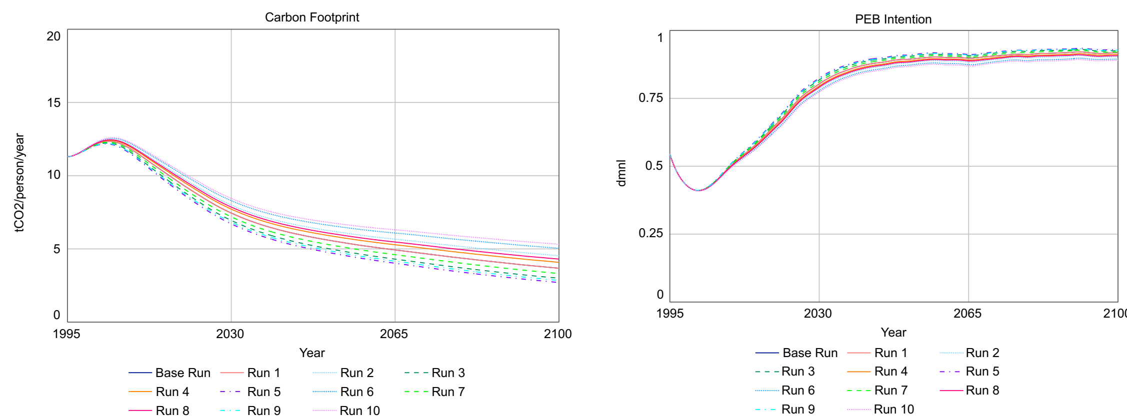


*Figure 4-9 - Sensitivity of Variation in the Energy Efficiency Improvement rate from 0.4% to 1.2%*

Energy efficiency proves to be a tricky concept. On the one hand, the parameter is grounded in IEA data, yet the IEA projects even growing rates in the years to come (IEA 2023). It is not surprising then, that even a small rate of 0.4% (the lowest value tested in the sensitivity) still creates a significant decrease in CFP. It also reflects, the hope on energy efficiency for managing the reduction of CFP, while at the same time, it seems logical to assume that the rate might be decreasing decreasingly, indicating that an increase in efficiency is not without lower limit. A more complex representation of the energy efficiency rate and possible endogenization should be considered for further development.

The *Sensitivity from Intention on CFP*, that determines the power function effect, remains a clear uncertainty. A variation of the sensitivity proves to be only numerically sensitive. It speaks in favor for the robustness of this effect, that the model behavior is not changed, and numerical sensitivity is rather low. Yet the persisting uncertainty can be seen more clearly once the effect is changed entirely. Figure 4-10 depicts three runs comparing the "base run" – power function, against a linear effect and a "classical S-Shaped effect".

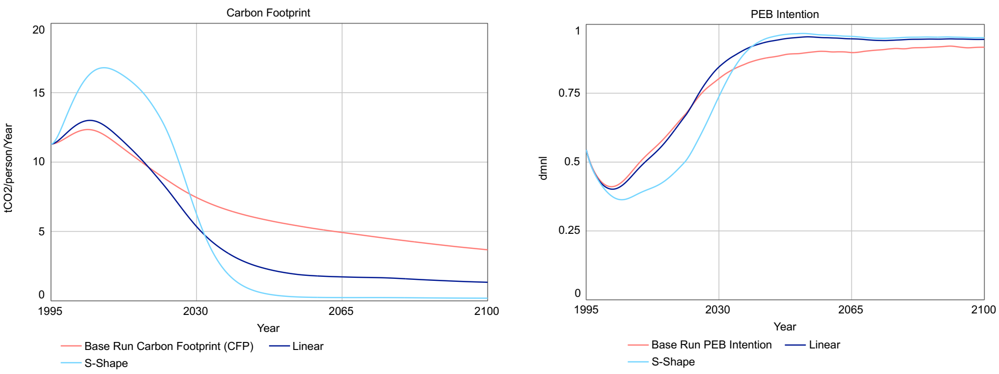


*Figure 4-10 - Sensitivity Runs with alternative effect shapes*

Figure 4-11 presents the graphical representation of the tested effects. Although the model is surely sensitive, the initial behavior pattern is observed throughout all the other runs as well. This is mainly because all effects follow the same logic initially yet hypothesize a different behavioral response. While with the linear effect, change around the normal intention has rather mild effects on the indicated CFP, the S-Shape symbolizes that people react very harshly to even a small change in intention, way stronger than with the power function. The comparison shows very clear, that the translation from Intention to CFP remains an uncertainty and further investigation is required. Yet, the power function yields conservative results, which is favorable given the uncertainty in the parameter and under the premises argued in the model description suggest confidence in the structure chosen.

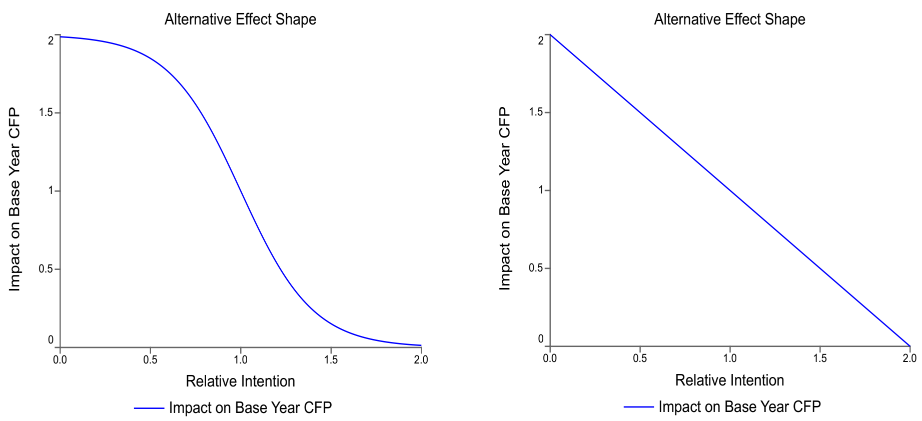


*Figure 4-11 - Structure Graph for alternative tested effect shapes*

The other effects, i.e. effect from Peer Group and Society on Intention also prove to be only numerically sensitive, both to varying the steepness of the effect as well as to a change in effect shape. See Appendix – C for a detailed discussion.

Lastly, media coverage efficiency provides more significant numeric changes as well. Figure 4-12 shows its sensitivity runs. Although sensitive, the response is not unsurprising. Media Coverage Efficiency plays a significant part in conveying the development in the "outside" world to something functional for the cognitive response. The sensitivity represents the uncertainty of the parameter, both numerically but also conceptually.

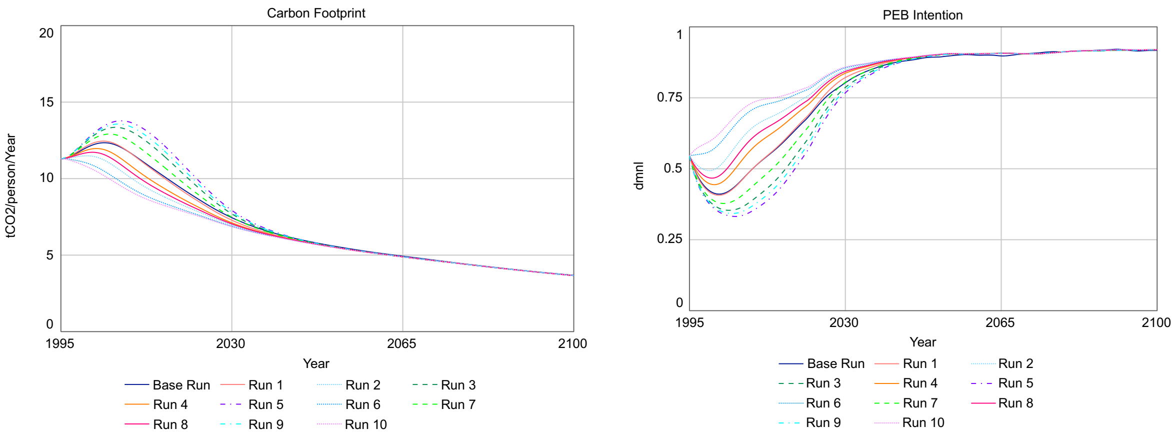


*Figure 4-12 - Sensitivity Runs for variation of Media Coverage Efficiency rate from 0.5 to 1*

Table 3 summarizes the sensitivity analysis for every parameter. It points to the robustness of the model, that for all adjustment times the model shows only mild numeric sensitivity. Additionally, the fact that the sensation exponent and the sensitivity of seriousness also indicate only numeric sensitivity, supports the confidence in the model structures.

*Table 3 - Summary of the sensitivity analysis results - see Appendix C for a detailed discussion.*

| Parameter name | Variation Range | Sensitivity Type | Uncertainty |
|---|---|---|---|
| AT CFP (years) | 2.5 – 7.5 | Numeric (mild) | Moderate. Assumed, Calibrated |
| AT Intention | 1 – 5 | Numeric (mild) | Moderate. Assumed, Calibrated |
| Energy Efficiency (dmnl) | 0.004 – 0.012 | Numeric (moderate) | High. Leverage Point discussed in Chapter 5, based on data. |
| Forecast Horizon (years) | 1 – 10 | Numeric (mild) | Low due to weak sensitivity. Assumed, Calibrated |
| Historical Time Horizon (years) | 12.5 – 37.5 | Numeric (mild) | Low due to weak sensitivity. Assumed, Calibrated. |
| Initial perceived temperature variation (°C) | 0.22 – 0.66 | Behavioral (mild), Numeric (moderate) | High. Leverage Point discussed in Chapter 5, Assumed, Calibrated. |

| | | | |
|---|---|---|---|
| Media Cover Efficiency (dmnl) | 0.4 – 1.2 | Behavioral (mild), Numeric (moderate) | High. Leverage Point discussed in Chapter 5, Assumed, Calibrated. |
| Sensation Magnitude Exponent (dmnl) | 0.5 – 1 | Numeric (mild) | Moderate, Assumed, Calibrated. |
| Sensitvity Intention on CFP (dmnl) | -0.9 – (-0.3) + Linear Effect + S-Shape | Behavioral (mild) Numerical (Strong) | High. Leverage Point discussed in Chapter 5, Assumed, Calibrated. |
| Sensivity of Seriousness | -2.1 – (-0.7) | Numeric (mild) | Moderate, assumption, following sensitivity: low impact. |
| Steepness Personal Norm Effect (dmnl) | 2.5 – 7.5 | Numeric (mild) | Moderate, assumption, calibrated, following sensitivity: low impact. |
| Steepness PGAL (dmnl) | 1.5 – 4.5 | Numeric (weak) | Moderate, assumption, calibrated, following sensitivity: low impact. |
| Steepnees SAL (dmnl) | 1.5 – 4.5 | Numeric (weak) | Moderate, assumption, calibrated, following sensitivity: low impact. |
| Weight on Peer Influence (dmnl) | 0 – 1 | Numeric (moderate) | Moderate. Assumed, Calibrated. |
| Weight on Personal Norm (dmnl) | 0 – 1 | Numeric (moderate) | Moderate. Assumed, Calibrated. |
| TPPC (years) | 1.5 – 4.5 | Numeric (weak) | Low due to weak sensitivity. Assumed, Calibrated. |
| TPPC_1 (years) | 1.5 – 4.5 | Numeric (weak) | Low due to weak sensitivity. Assumed, Calibrated. |
| TPPC_2 (years) | 0.8 – 2.4 | Numeric (weak) | Low due to weak sensitivity. Assumed, Calibrated. |
| TPT (years) | 2.5 – 7.5 | Numeric (weak) | Low due to weak sensitivity. Assumed, Calibrated. |
| THRC_1 (years) | 5 – 15 | Numeric (weak) | Low due to weak sensitivity. Assumed, Calibrated. |
| Time Horizon Extreme Events (years) | 8 – 24 | Numeric (weak) | Low due to weak sensitivity. Assumed, Calibrated. |

Additionally, I investigated the GS outputs to check whether the highest or lowest variation in a parameter contributes significantly (under simultaneous variation of all parameters) to extreme outputs (outputs in the range between the 95% and 100% confidence interval). I used Z-Score statistics to check sample means against the mean of the global data set – a more detailed mathematical description of the procedure can be found in Appendix C. Note that classical statistical sensitivity testing cannot be meaningfully applied to infer actual sensitivity in single parameters (Barlas 1996, 196). I investigate the Z score, nevertheless, to identify potential parameters that might prove relevant in combination with variation of other parameters. All this was based under the assumption, that a normal approximation for the actual output numbers can be assumed, which is supported by the fact of a big sample (n =10 000 runs). The numeric results of the "Base Run Global sensitivity analysis" were exported (see supplementary data). Then, every parametric constellation that led to an output that lies within the extreme interval (95% -100%) of the possible output range was indexed with "1", the rest (i.e., up to 95%) with "0".

Hypothesis: If the variation of the parameter would have no over-proportionally high contribution to an extreme output, the number of "ones" would follow the same distribution as the total sample.

To calculate the Z Score for parameter X, the runs were sorted in a descending order. Then, the runs that contain the, e.g. highest, 30% values for parameter X were considered "a sample" (according to the output value of the respective run, each run is still labeled 1 if it lies in the 95% to 100% interval, 0 else). Now, the mean of this sample was compared to the mean of the data set via its Z-Score, an indication of how many standard deviations (SD) the sample lies apart from the population mean.

A Z score between 0 and ± 1 means the distribution of "1" and "0" is close to the population data set. Z Score between ±1 and ±2 indicates that the mean of the sample lies 1 – 2 SD apart from the data mean – a more moderate and tolerable deviation. Z Scores beyond ±2 or even ±3 SD indicate that the mean is extremely off from the dataset-mean, an indication, that our hypothesis is rather improbable. A Z-Score of more than ±2 therefore suggests that the number of extreme values ("ones") in the sample is very high, so high even, that the parameter seems to have a traceable effect.

Still, this does not tell us if the parameter is in itself (statistically) significant and sensitive, yet the results can be interpreted as follows: If the Z score is very high, it suggests that the variation in the parameter in the considered range (highest or lowest 30%) correlates with extreme output values, which might indicate a collective involvement in bringing about the extreme output values. Figure 4-13 presents the Z-Scores of the most significant ($|Z| > 2$) deviating parameter configurations of the test conducted.

While it is not surprising that configurations with the rate of efficiency and the sensitivity from intention on CFP show very high deviations ($|Z| > 5$), it is noticeable that both *weights* show higher Z-Scores than 2. This indicates that although both *Weights* are only numerically mildly sensitive in the parametric test, they do play a significant role when other parameters are varied simultaneously. Although this might not indicate clear sensitivity of the parameters per se and no direct inference for the robustness of the structure can be made, it does show collective sensitivity and the high uncertainty of the weights ascribed. Hence, these parameters should also be subject to further elaboration, investigating if they might play out as potential leverage points in combination with variations of other parameters.

| Z Score for Parameter | Weight on Peer Influence | 30% Highest Values |
|---|---|---|
| Including the 100 % Confidence Intervall | | |
| | | |
| Expected Mean of Dataset | 0.05 | |
| Deviation from Mean for Runs with Value "0" | 23.75 | |
| Deviation from Mean for Runs with Value "1" | 451.25 | |
| Variance of Data Set | 0.0475 | |
| SD of Data Set | 0.217944947 | |
| | | |
| Average of Sample | 0.059353118 | |
| Standard Error of the Mean | 0.003979112 | |
| | | |
| Z Score Statistic | 2.350553943 | |

| Z Score for Parameter | Weight on Personal Norm | 30% Highest Values |
|---|---|---|
| Including the 100 % Confidence Intervall | | |
| | | |
| Expected Mean of Dataset | 0.05 | |
| Deviation from Mean for Runs with Value "0" | 23.75 | |
| Deviation from Mean for Runs with Value "1" | 451.25 | |
| Variance of Data Set | 0.0475 | |
| SD of Data Set | 0.217944947 | |
| | | |
| Average of Sample | 0.04168056 | |
| Standard Error of the Mean | 0.003979112 | |
| | | |
| Z Score Statistic | -2.090777928 | |

| Z Score for Parameter | Sensitivity Intention on Carbon Footprin | 30% Highest Values |
|---|---|---|
| Including the 100 % Confidence Intervall | | |
| | | |
| Expected Mean of Dataset | 0.05 | |
| Deviation from Mean for Runs with Value "0" | 23.75 | |
| Deviation from Mean for Runs with Value "1" | 451.25 | |
| Variance of Data Set | 0.0475 | |
| SD of Data Set | 0.217944947 | |
| | | |
| Average of Sample | 0.072024008 | |
| Standard Error of the Mean | 0.003979112 | |
| | | |
| Z Score Statistic | 5.534905097 | |

| Z Score for Parameter | Rate of change in Efficiency | 30% Highest Values |
|---|---|---|
| Including the 100 % Confidence Intervall | | |
| | | |
| Expected Mean of Dataset | 0.05 | |
| Deviation from Mean for Runs with Value "0" | 23.75 | |
| Deviation from Mean for Runs with Value "1" | 451.25 | |
| Variance of Data Set | 0.0475 | |
| SD of Data Set | 0.217944947 | |
| | | |
| Average of Sample | 0.084028009 | |
| Standard Error of the Mean | 0.003979112 | |
| | | |
| Z Score Statistic | 8.551658821 | |

| Z Score for Parameter | Sensitivity Intention on Carbon Footprin | 30% Lowest Values |
|---|---|---|
| Including the 100 % Confidence Intervall | | |
| | | |
| Expected Mean of Dataset | 0.05 | |
| Deviation from Mean for Runs with Value "0" | 23.75 | |
| Deviation from Mean for Runs with Value "1" | 451.25 | |
| Variance of Data Set | 0.0475 | |
| SD of Data Set | 0.217944947 | |
| | | |
| Average of Sample | 0.076257076 | |
| Standard Error of the Mean | 0.003979112 | |
| | | |
| Z Score Statistic | 6.598727406 | |

| Z Score for Parameter | Rate of change in Efficiency | 30% Lowest Values |
|---|---|---|
| Including the 100 % Confidence Intervall | | |
| | | |
| Expected Mean of Dataset | 0.05 | |
| Deviation from Mean for Runs with Value "0" | 23.75 | |
| Deviation from Mean for Runs with Value "1" | 451.25 | |
| Variance of Data Set | 0.0475 | |
| SD of Data Set | 0.217944947 | |
| | | |
| Average of Sample | 0.082917083 | |
| Standard Error of the Mean | 0.003979112 | |
| | | |
| Z Score Statistic | 8.272469298 | |

*Figure 4-13 - Summaries of Z Scores for parameters with Z Score |Z|>2*

**Behavior Pattern Test**

Since this is a theory-orientated conceptual model, the behavior reproduction may not have the same focus as with models trying to predict precise real-world developments (Barlas 1996). Here, we compare the models output to the reference behavior of the system, yet this is not to establish correctness of the model (Sterman 2000). Validity and truthfulness are a matter of showing the right behavior for the right reasons – which rests on insights of structural validity tested before. Figure 4-14 shows the Historical Carbon Footprint of the OECD, consumption-based, in comparison against the model's output in the base run.

As can be seen, the model stays behind the historical data at some points, yet it does depict the same behavior over the comparative time horizon. This indicates a good fit to the data, which is also due to the fact, that the data was used for the calibration of the uncertain parameters. This is also the reason why the comparison might suggest validity in the model, yet it cannot be taken as any kind of proof for it.

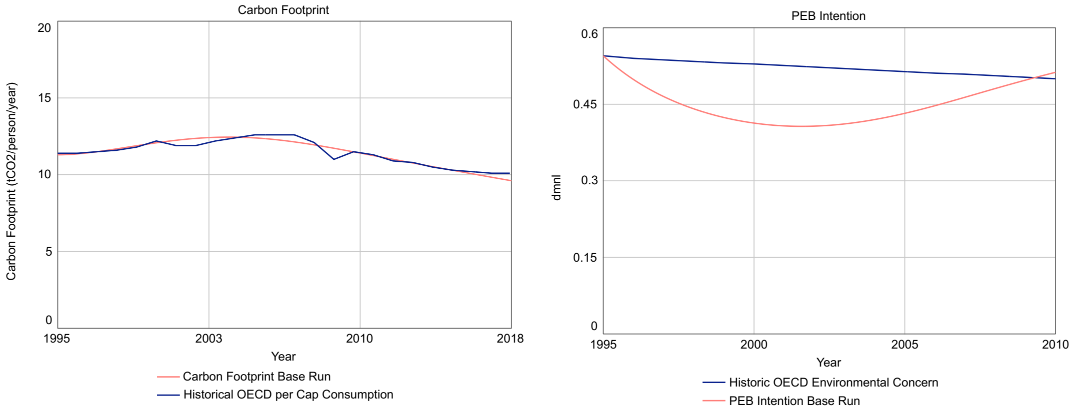


*Figure 4-14 - Comparison of model output with historic data (left) and model output with historic data on environmental concern (right)*

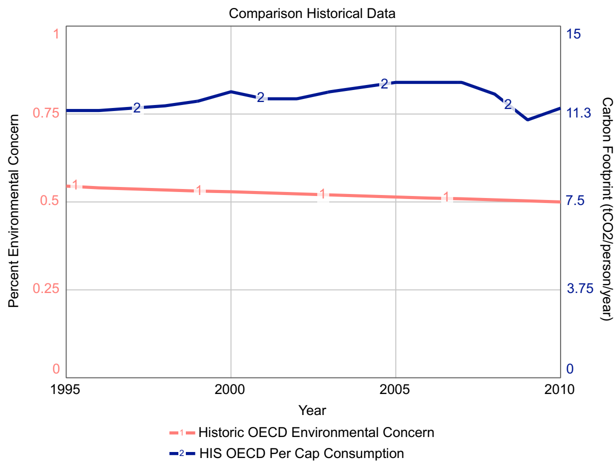


*Figure 4-15 - Comparison of the historical data against each other*

This is more clear, when we compare the PEBI against the data from the OECDs environmental concern, estimated from a study by Franzen and Vogl (2013) (data ranges from 1995 to 2010). Figure 4-14 shows the comparison. Two points need to be mentioned here. (1) The bad fit between model and data does hint that there are some things missing in the current representation. Although this points to the fact that more investigation into the real systems mechanisms is necessary, in the light of the model's purpose, it does not appear to be endangering any conclusions drawn. The model is by choice restricted to only some theories of intention building and does not claim exhaustiveness here. Furthermore, as argued in the previous chapters, measurement of PEBI rest upon uncertainties in measurement tools and several conceptual assumptions and interpretations as to what exactly is measured (i.e. environmental concern vs. general ecological behavioral scale, see chapter 2 for more details). Therefore, the data should not be taken as a rigorous normative standard the model is supposed to reproduce. (2) This last point is also illustrated through the observation of the historical data against each other - see Figure 4-15. Given the very small variations of environmental concern (which is, as argued, different from intention) in the data, it seems implausible to solely account for the stronger fluctuations in the behavioral data.

In sum, the behavior pattern test builds confidence in the model. Yet, given the bias of calibration outcomes to reproduce the reference behavior and the uncertainty in the data, not too much weight should rest on this test. From all previous tests, we can infer sufficient confidence in the model structure and behavior produced, although there are clearly high uncertainties around the sensitivity of the Intention on CFP effect, the initial reference temperature variation, media coverage and energy efficiency improvement rate, that need further back-up through research to come. Table 4 shows a summary of the validation tests.

*Table 4 - Summary of sensitivity tests and results*

| **Test** | **Result** | **Implication / Comment** |
|---|---|---|
| Structure Assessment | Sufficiently to strongly valid | Thoroughly grounded in theory and literature, while recognizing opportunity to put even more details in some concepts |
| Parameter Assessment | Sufficiently valid | Grounded in data where possible, calibrated where necessary. Room for improvement with a more specific behavior as research target. Therefore sufficient for the model's purpose |
| Integration Error Test | Strongly Valid | Choice appropriate for model purpose |
| Dimensional Consistency | Strongly Valid | Dimensionally consistent, yet more "hard" variables are recommended for application to specific behavior |
| Extreme Conditions (direct + indirect) | Strongly Valid | Robust under extreme conditions |
| Boundary Adequacy | Sufficiently valid | Appropriate for the model purpose. Exclusions were commented and improvements pointed out for further development |
| Sensitivity (Parametric + Global) | Sufficiently Valid | Consistent behavior with expectations and assumptions uncertainty. Sensitivity discussed for possible implications and reasons, leverage points pointed out |
| Behavior Pattern Test | Sufficiently Valid | Sufficiently given the bounded available data comparison and the models purpose |

# 5. Model Results and Analysis

This chapter describes and analyzes the experimental setup, results and implications from various scenarios. After giving an overview of the Business as Usual Scenario (BAU) in Section 5.1, I look at scenarios within the SSP-2 data. This is because every scenario inevitably rests on some exogenous input for the "rest of the world" obtained from SSP data. Since the BAU takes data from SSP-2, the scenarios under Section 5.2 also take SSP-2 data. In Section 5.3, I look at scenarios under the SSP narratives SSP-1 and SSP-5.

## 5.1 Business as Usual Scenario

**Experimental Setup**

The BAU is simulated in the conditions described under the dynamic hypothesis and Appendix A. The *SSP-Scenario-Switch* is switched to "2", the BAU is simulated with the SSP-2 projection but with endogenized input from the OECD through the produced model. In the initial setting, due to the fit to the historic data, *Weight on Personal Norm* = 0.7 and the influence of the Peer Group is rather low with *Weight on Peer Influence* = 0.3. See Appendix A for all further settings.

**Results**

Figure 5-1 shows the development of CFP and PEBI. Initially, there is a reduction in PEBI, down to ~41%, which leads to a gradual increase in the CFP until 12.5 $tCO_2$/person/year in year 2004. From then, the continuous trend of increasing PEBI is seen in CFP that is monotonously reducing until the end of the simulation. From ~2023 onward, the growth in PEBI is declining, i.e. PEBI is increasing decreasingly, while CFP is decreasing decreasingly. From around year 2030 and onwards, the reduction in CFP is rather driven by enhancing energy efficiency than because of increasing intention – a behavior discussed in more detail below. CFP reaches 3.66 $tCO_2$/person/year at the end of the century while PEBI levels off at around 92%.

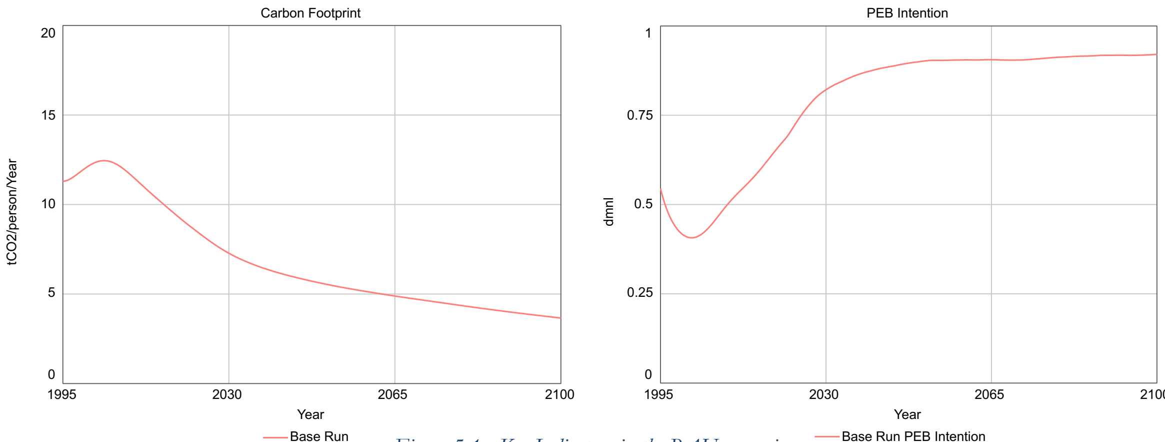


*Figure 5-1 - Key Indicators in the BAU scenario*

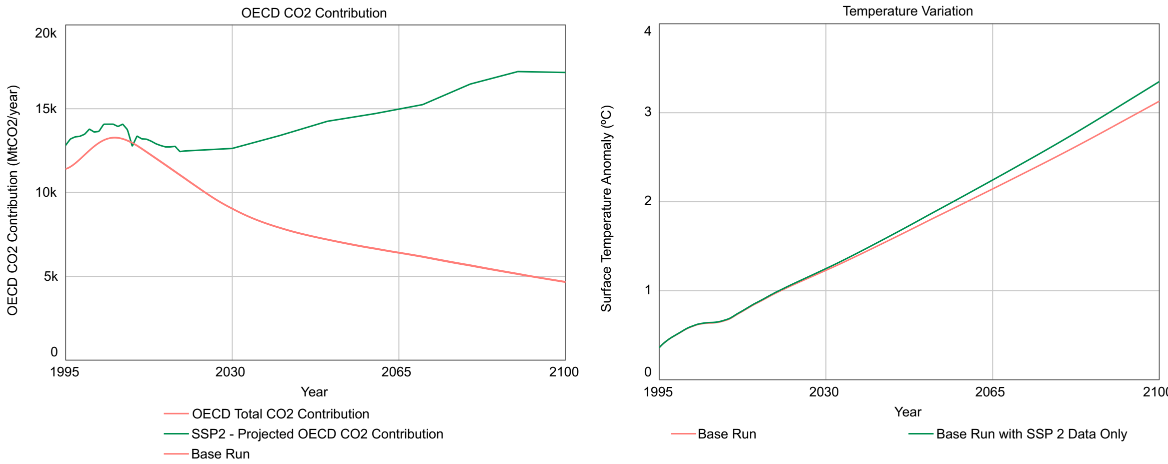


*Figure 5-2 - Key Indicators OECD Contribution and Surface Temperature Anomaly in the BAU scenario*

Figure 5-2 compares the outcome of the model run against the "raw" SSP-2 data. More specifically, it depicts the OECD contribution endogenously produced from the model (orange line, ending in 4.65k $MtCO_2$/year) in comparison with the projection of OECD contribution from the SSP-2 data (green line, ending in 17.2k $MtCO_2$/year). Additionally, the red line in the right graph depicts the temperature variation (ending in 3.35°C) if the climate module runs only on SSP-2 input, the blue line depicts the temperature variation in BAU with endogenized behavior (ending in 3.13°C).

**Behavioral Explanation**

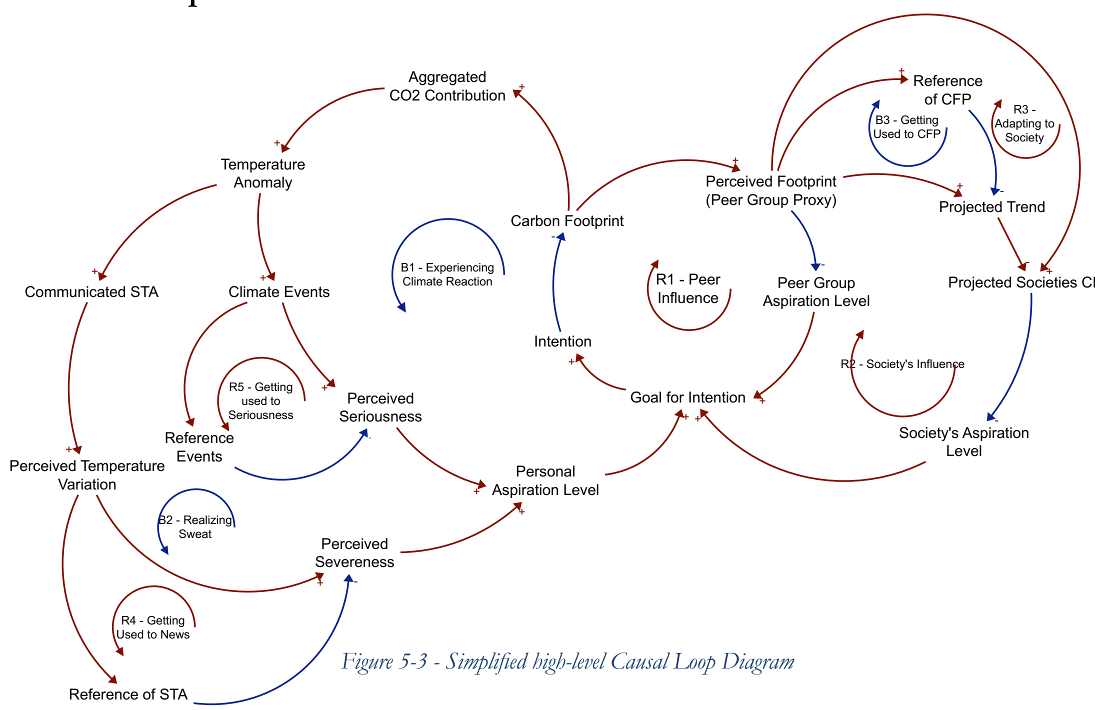


*Figure 5-3 - Simplified high-level Causal Loop Diagram*

Figure 5-3 depicts the same loops from the dynamic hypothesis (Chapter 3) in a simplified version.

At the start of the simulation the behavior is driven mostly by *B2 -Realizing Sweat*, although at that point of the simulation, it is better described as Realizing No-Sweat. Recall, that *B2- Realizing Sweat* provides information from the environment that leads to an increase (or decrease) of the perceived temperature variation, ultimately effecting the personal norm. The comparison of the current temperature variation leads to a low personal norm in the beginning. This is driving the aggregated goal to decline which sets of the corresponding *R1 – Peer Influence* (providing a peer group strived intention goal through observing the behavior "around") and *R2 – Society's Influence* (providing a society strived intention goal through projecting the current observed CFP trend into the future) to adapt to that change. In the first quarter of the simulation, extreme events mostly keep behind the reference number of extreme events, cutting off *B1 – Getting used to Climate Reaction* (the loop providing a judgment of experienced seriousness of the situation to stimulate the effect severeness has on the personal norm) and *R5 – Getting used to Seriousness* (the loop, that ensure that people get used to a rising condition, thereby weakening the impact of a high number of extreme events).

Once the perceived temperature variation crosses the reference point, the model shifts (people realize more and more the aggravating situation). Now influenced by the slowly increasing perceived severeness, the personal norm starts to climb – i.e., people realizing "the sweat". Although dampened by the delayed *R4 – Getting Used to News* (the loop that ensures that people get used to a rising temperature variation), *B2 – Realizing Sweat* drives the personal norm. Both social norm influences, *R1 – Peer Influence* and *R2 – Societies Influence*, further support this development. Intention is levelling at around 2050, now *R4 - Getting Used to News* and *R2 – Getting Used to Seriousness* are keeping the *B1 – Experiencing Climate Reaction* and *B2 – Realizing Sweat* in check since the reference temperature variation and climate events are continuously updating and ensuring only a mild seriousness and severeness. Additionally, *R3 – Adapting to Society* and *B3 – Getting Used to CFP*, as well as *R1 – Peer Group influence* and *R2 – Societies influence* maintain that the level of PEBI and CFP does not vary dramatically anymore. Part of the later variation of CFP is due to the still increasing energy efficiency that drives part of the model behavior.

**Implications**

Since the beginning, innovation is continuously decreasing the carbon footprint. I discussed the drawbacks and assumptions of this parameter both in the model description and the global sensitivity analysis. It is evident, that improvement in energy efficiency rate is part of the real – world, although the precise variation is uncertain. When calculating the impact from energy efficiency on CFP, we can see that even an energy efficiency rate of 0.8%/year –intentionally underrepresenting the target improvement rate (4%/year) needed to reach the Net-Zero Scenario by the IEA (IEA 2023) – would reduce the carbon footprint by 55% over a time horizon of 100 years. This represents the big hope people put in improvements of energy efficiency.

When looking at the comparison between the OECD contributions throughout different runs, we see a noticeable impact, even if energy efficiency is turned off. Figure 5-4 represents the comparison between the BAU, BAU without energy efficiency and the projection only driven from SSP2 -input.

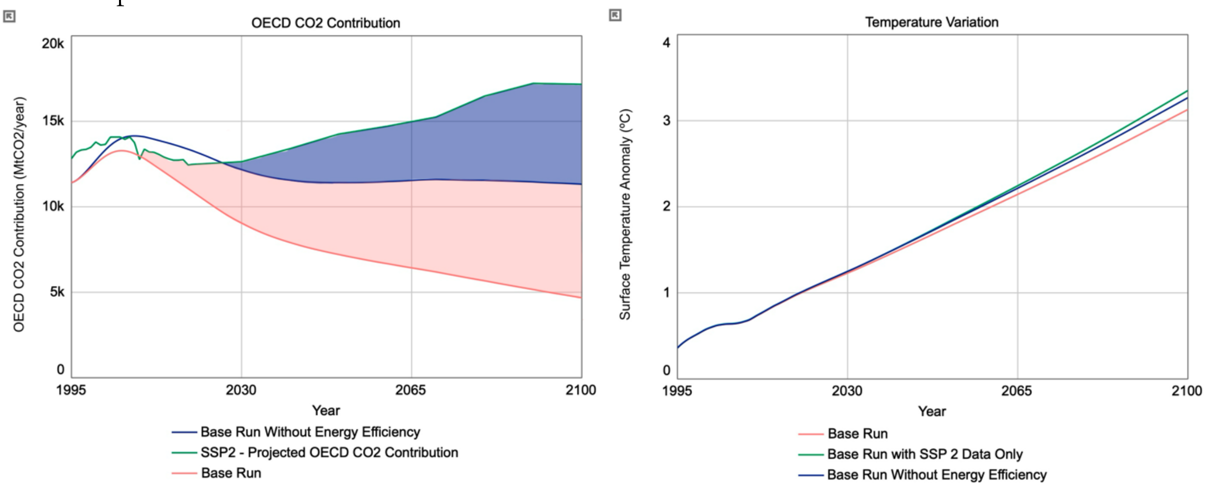


*Figure 5-4 - Comparison of Model Output (with and without energy efficiency) with the project OECD Contribution from the SSP-2 Scenario*

Looking at the graphs we see the clear impact of endogenizing behavior into the model. Sure, given the uncertainty in data and assumptions, these inferences should not be drawn on a numerical level per se, yet even looking at a higher level about the systems behavior we detect a clear impact. As can be seen, even without energy efficiency, there is a noticeable difference between the exogenously projected and endogenously produced OECD contribution and the change in temperature. Both marked surfaces illustrate the part that is due to the endogenized contribution.

## 5.2 Scenarios Under the SSP-2 Input

**Experimental Setup - Closing our Eyes to the Environment Scenario (CEES)**

Closing our Eyes to the Environment represents the situation in which we place more emphasis on the social norm and manipulate weights in the model so that we close our eyes, i.e. the endogenous feedback, to what is happening in the environment. The scenario is run by the SSP-2 input, yet from the start of year 2024, certain parameters are manipulated:

- Weight on Personal Norm is changed from 0.7 to 0.2, indicating that people focus on social norms more heavily.
- Weight on Peer -Influence is increased from 0.3 to 0.5, indicating that people take both influences at the same strength.

- The sensitivity from Intention to CFP is weakened by 50% from -0.621 to -0.311, indicating that people are now even more inert, i.e. it takes a bigger change in intention to achieve the same change in CFP as before.

**Results**

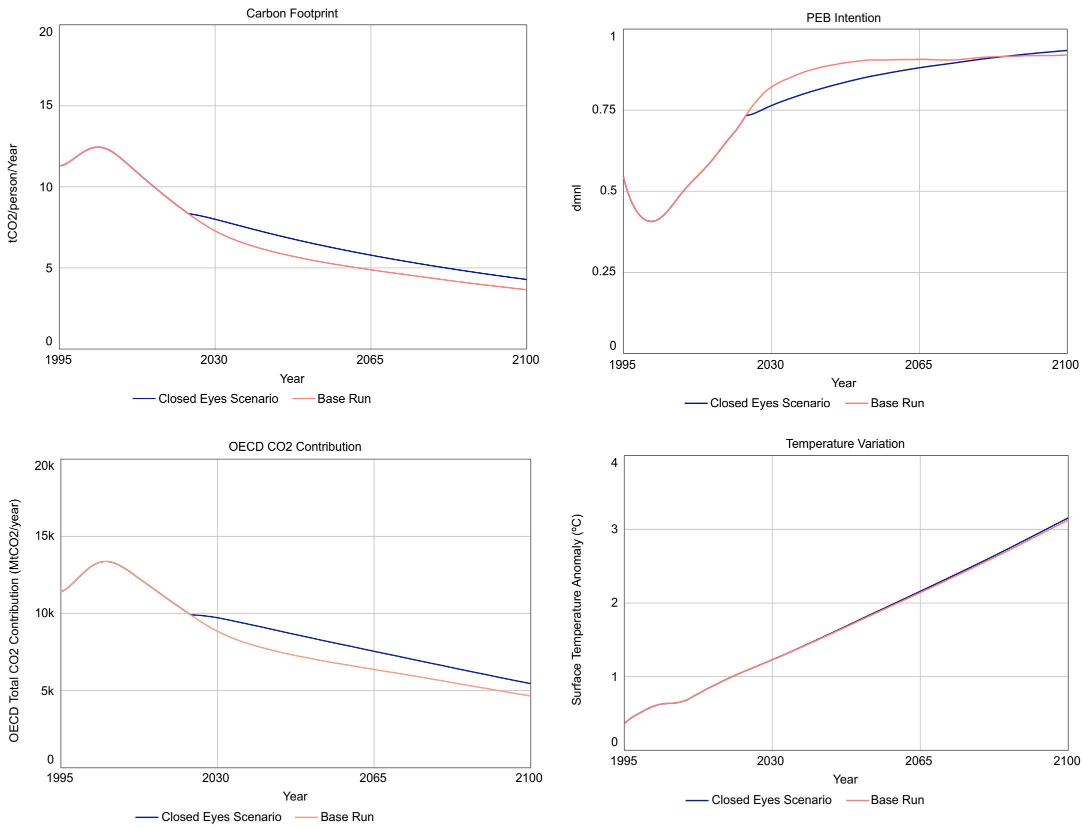


*Figure 5-5 - Key Indicators for the CEE Scenario*

Figure 5-5 depicts the graphs for the key variables under the scenario. As expected, CFP ends higher than in the BAU (~0.6 $tCO_2$/person/year) while PEBI rose around 1% at the end. The OECD contribution has risen by almost 1k Mt $CO_2$, while the temperature variation changed only marginally. The model shows the same mode of behavior.

**Behavioral Explanation**

While in the beginning the behavior is obviously in line with the BAU, after the change in the parameters, the exogenous environmental feedback into Intention formation is cut off. *B1 – Experiencing Climate Reaction*, *B2 – Realizing Sweat, R4 – Getting Used to News* and *R5- Getting used to Seriousness* are reduced in their contribution magnitude so much, that they barely have any influence. We can see this at the small dull in PEBI around 2024 – the personal norm contribution has stopped. Yet, the increase in intention continues and even surpasses the intention in BAU. This is due to two factors.

First, because during the first 30 years of the simulation intention has reached such a level that the reinforcing influence loops *R1 – Peer Influence* and *R2 – Society's Influence* are still empowered and continue to drive the development.

Secondly, energy efficiency gives a continuous boost to *R1 – Peer Influence* and *R2 – Society's Influence* implying that people reduce their CFP by intention, while, in fact, an increase in energy efficiency is the reason. In the BAU, the strong weight given to the personal norm route also implies that *R4 – Getting Used to News* and *R5 – Getting Used to Seriousness*, dampen the enthusiasm for change, having a moderating effect on the aggregated goal. By taking away their influence, these loops do not function as moderators on the aggregated goal – supporting that this CEE Scenario's PEBI surpasses the BAU's PEBI.

Both factors result in an ultimately higher intention and higher CFP. To see how important the right timing and energy efficiency are, compare the runs in Figure 5-6. Here, the scenario alternations were pushed forward to 2002, Sensitivity of Intention on CFP was kept to the BAU-Level and energy efficiency was turned off (so also the comparison Base run is without energy efficiency). We can see that the model has not built enough drive and without the support of energy efficiency induced CFP change, it will not recover fully from cutting off personal norm and after a long period of slow increase in CFP, a new, lower value of Intention is approached towards the end.

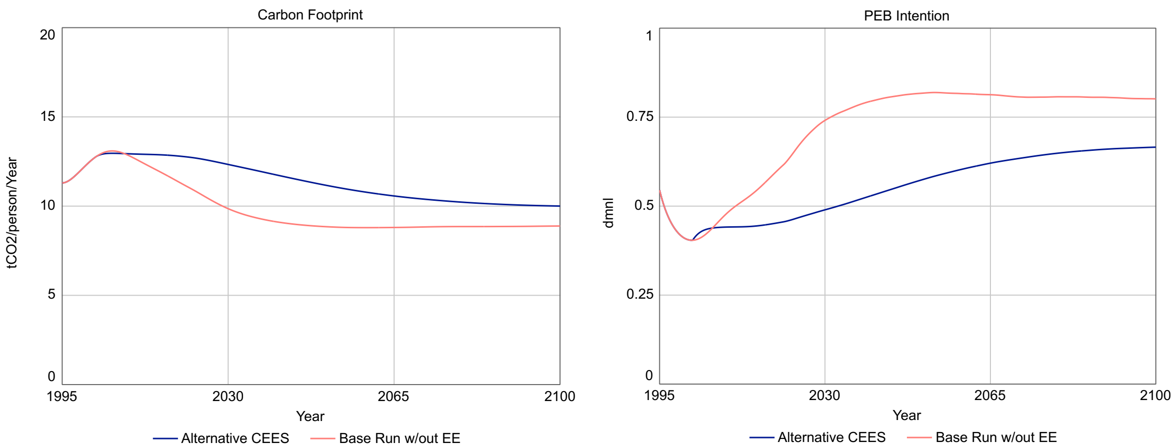


*Figure 5-6 - Key Indicators of CFP and Intention for earlier start of the CEE Scenario*

**Implications**

The scenario illustrates the importance of energy efficiency and personal norms for a development of the system that is aiming at significantly reducing CFP in the long run. Additionally, this scenario supports the inferences from the Z-Score analysis showing that the weights contribute to significant changes in the model behavior once combined with other variations.

Note that "closing eyes to the environment" does not employ an agnostic or contra-environmental attitude, but only limits the considerations about what drives PEBI towards the social norm mechanism. It would be invalid to infer from the scenario depicted, that closing our eyes is a scenario comparable to the BAU, only because it also reaches a comparable level of intention and $CO_2$ contribution, and temperature does not changes significantly. It rests heavily upon the hope on energy efficiency and hitting "the right time" to avoid a significant lower level of Intention and higher level of CFP. The minor temperature reduction is reasonable, since the SSP-2 data for the rest of the world is still driving the temperature predominantly while at the same time, the change plays only a marginal role in grand scheme of things.

**Experimental Setup – Turning towards Environmental Reactions Scenario (TERS)**

Turning towards Environmental Reactions represents the situation where we place more emphasis on the personal norm as input from the environment. Additionally, I assume a more efficient media and science sphere, increasing the efficiency of communicated STA. Specifically, the following parameters were varied again from the year 2024 onwards:

- Increasing Weight on Personal Norm from 0.7 to 0.8
- Reducing Weight on Peer Influence from 0.3 to 0.2
- Increasing Media Coverage Efficiency from 0.78 to 0.9
- Decreasing Sensitivity of Seriousness from -1.37 to -2 (leading to people being more sensitive)
- Reducing the adjustment times AT CFP with 2 and AT Intention with 1 year respectively
- Increasing sensitivity of the Effect from Intention on CFP from -0.621 to -0.921 (making people react more strongly on changes in intention)

**Results**

The result in Figure 5-7 depict only small changes in both domains, OECD related and even smaller globally. While there is some noticeable change in intention in the end (~+3%) the overall contribution (-0.86k $MtCO_2$), individual CFP (-0.68 $tCO_2$/person/year) change mildly and global temperature (0.04ºC) does not change significantly.

**Behavioral Explanation**

After the change in 2024, the balancing loops *B1 – Realizing Climate Reaction* and *B2 – Realizing Sweat* both get boosted by a faster and more intense communication of the change in temperature, as well as higher sensitivity to extreme events. This increased strength translates to the stark increase of intention, and facilitated by the higher sensitivity leads to stronger decline in CFP. As soon as the reference conditions stabilized the severeness and seriousness to a mostly constant ratio (the workings of *R4 – Getting Used to News* and *R5 – Getting Used to Seriousness*) at around 2032, the personal norm goal does not change significantly.

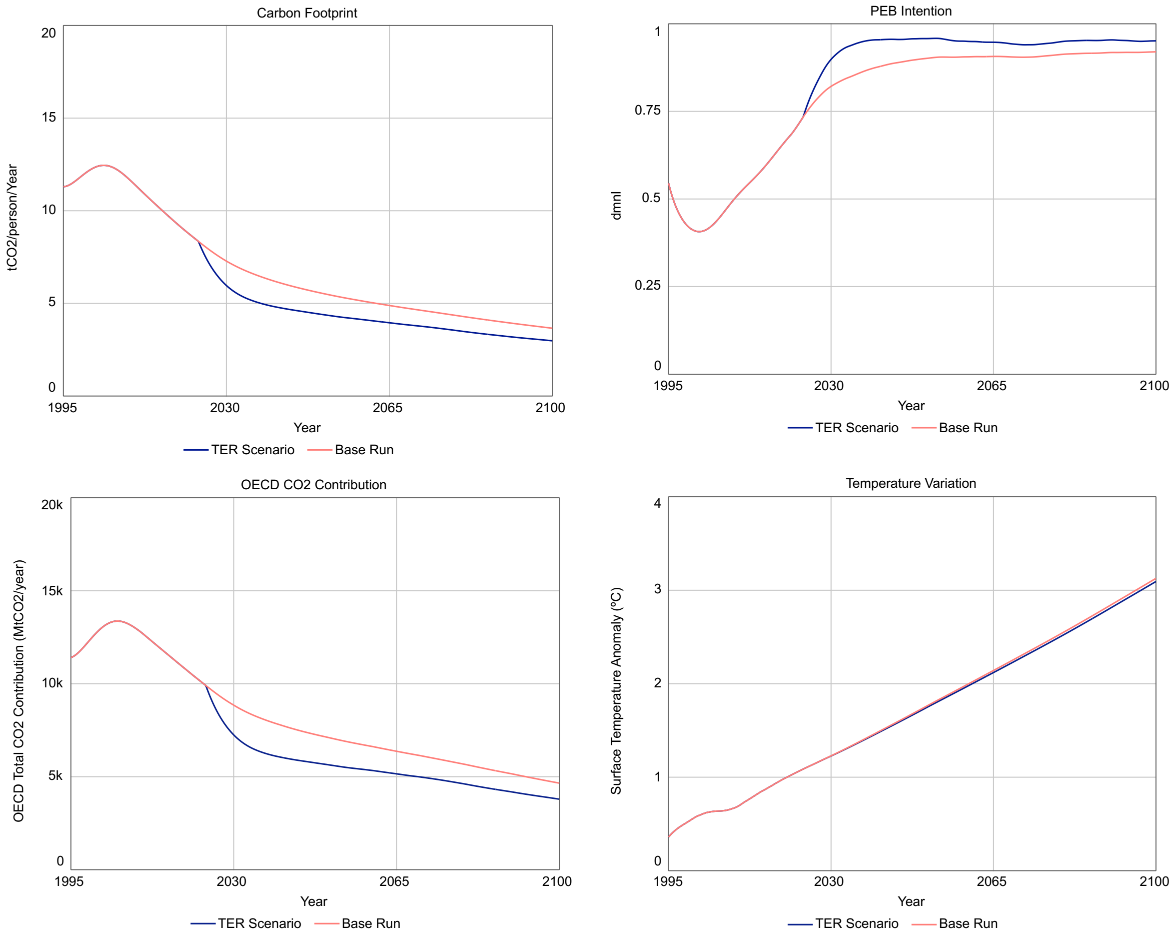


*Figure 5-7 - Key Indicators for the TER Scenario*

**Implications**

This scenario depicts the combined effort of climate communication and focus on considering the endogenous impact from the environment through the personal norm. Yet, as can be seen in the comparison of the global temperatures, it does not result in significant impact, which is again reasonable considering the exogenous input that drives the climate module.

## 5.3 SSP Narratives Scenario

As discussed in Chapter 2, the SSP narratives build the storyline and backbone of climate scenarios. They are generally divided into 5 different Base-scenarios (and several versions of them), where each general scenario comes with a different calculating model and assumptions in the background (Riahi et al. 2017, see also for more details on SSP in general). For testing and analyzing the implementation of the model into the IAMs and scenario narratives, the following scenarios depict the application of the first and fifth SSP scenario. For this, I used the respective quantitative SSP data as a new exogenous input while I translated the qualitative content of the SSP-narratives into parametric changes in the model.[6]

### 5.3.1 SSP 1 – Under the Green Growth Paradigm

**Experimental Setup**

The SSP 1 data (population and emission data) used is based on Van Vuuren et al. (2017). Figure 5-8 presents the summary of the SSP 1 narrative following Riahi et al. (2017). Additionally, I used the qualitative assumptions from O'Neill et al. (2017) for inspiration for entry points. Note that Table 5 does not present all assumptions but only the those that were used for the scenario. All changes are enacted from year 2024 onwards.

> "The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity."

*Figure 5-8 - SSP-1 narrative summary by Riahi et al. (2017)*

*Table 5 - Overview of incorparated assumptions from SSP 1 scenario*

| **Assumptions**<br>from SSP-1 based on O'Neill et al (2017) | **Entry Points in the model**<br>deduced by the modeler |
|---|---|
| • Consumption and Diet: Low growth in material consumption, low-meat diets, first in HICs [High Income Countries] | • Produced endogenously by the model |
| • Carbon and Energy Intensity: Low<br>• Energy Tech Change: Directed away from fossil fuels, toward efficiency and renewables<br>• Technology Development: Rapid | • Increasing energy efficiency rate from 0.8% to 1.3% (number corresponds to the IEAs primary energy intensity improvement indicator in 2023 (IEA 2023) |
| • Policy orientation: Toward sustainable development | • Include a PEB-Intention Boost of 15% (i.e. a step of 0.15) to the social norm sector, acting on the society's strived intention goal, representing a politically/thought leader driven influence on the social norm. |

[6] Note, that at the introduction of the scenarios (2024), the data input changes (emission data as well as population). This leads to a noticeable "jump" in the data around that point. This jump is found in both model and SSP projection and depicts a reasonable switch in assumptions and will therefore be excluded from discussion below.

| | |
|---|---|
| • Environmental Policy: Improved management of local and global issues; tighter regulation of pollutants<br>• Institutions: Effective at national and international levels<br>• "[…]and this SSP assumes that policy changes are driven by changing attitudes. | • Increasing TRHC_1, time to update the reference temperature from 10 to 15 years indicating that people maintain a longer time horizon for the reference leading to comparatively higher severeness for the years after the change.<br>• Increase Media Coverage Efficiency from 0.78 to 1, indicating strong media, science and institutions communicating the current situation |
| • Education: High | • Altering *Sensitivity of Seriousness of 30%* from -1.37 to -1.78. A higher sensitivity means a shift in the inflection point for the effect on the personal norm. This indicates that as education empowers the awareness of consequences perceived, more "valued objects" are triggered and the "normal" severeness triggers a higher reaction of personal norm. |

## Results

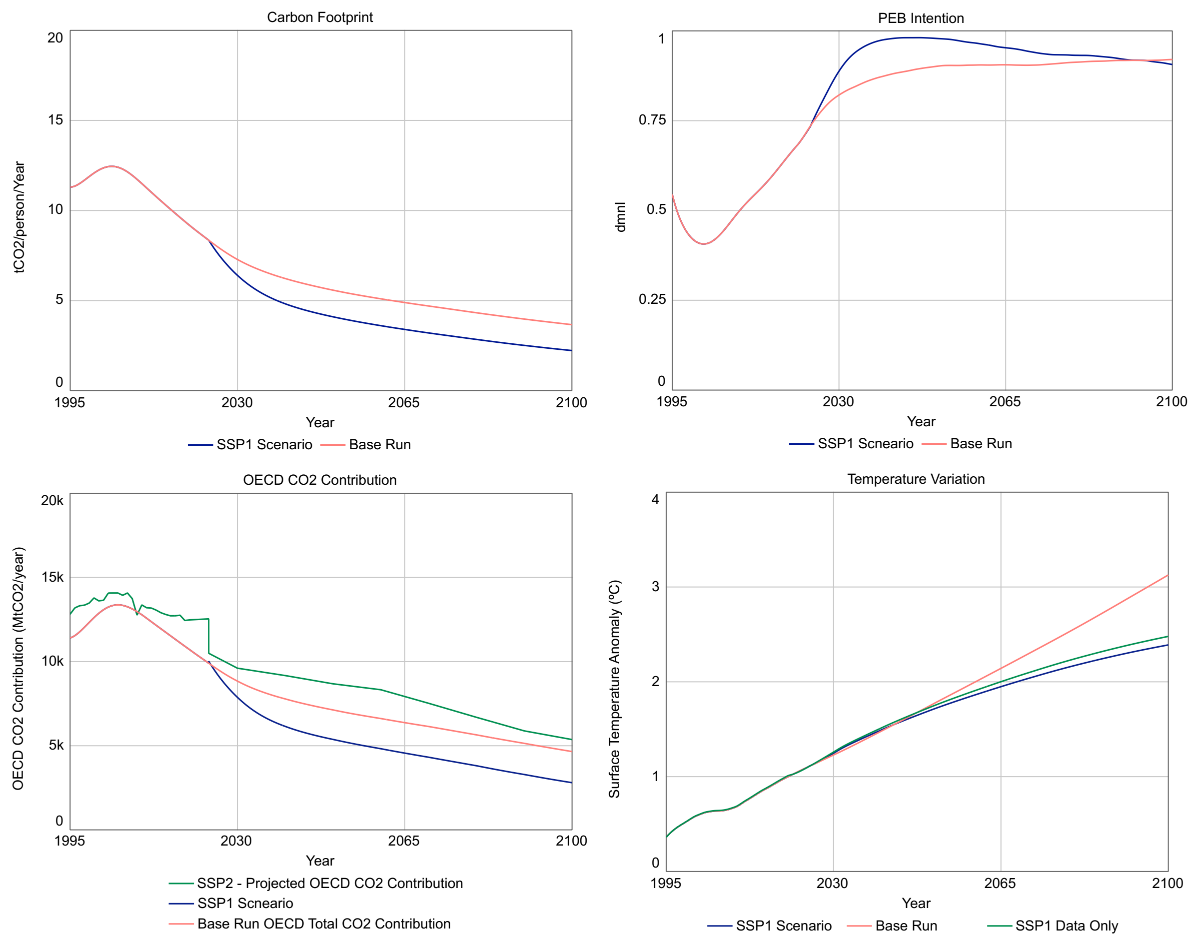


*Figure 5-9 - Key indicators for the SSP-1 scenario*

Figure 5-9 depicts the SSP-1 Scenario and compares against the BAU and the Projected Contributions from SSP-1 data. The CFP is reduced significantly at the end of the simulation – going from 3.66 to 2.22 $tCO_2$/person/year. Simultaneously, we do not see a corresponding increase in PEBI until the end. This indicates the insight that with increasing energy efficiency, people rely heavily on the technological development – so much even, that PEBI is declining. People do not change their intention, yet trust that technological development leads to a lower CFP. Comparing the aggregated OECD contribution, we see that there is (1) a significant decline in $CO_2$ contribution from the BAU and (2) the model follows the same trajectory as the projected SSP data, both in the BAU and in the SPP1-Scenario run. Especially comparing to the BAU, this supports the claim that the model is incorporating the SSP1-assumed carbon reduced consumption and dietary life-style. In terms of global temperature, we see a decrease of 0.74ºC to the end of the simulation in comparison to the BAU and 0.18ºC in comparison to only exogenous data.

**Behavioral Explanation**

After the start of the parameter change, the feedback loops *B1 – Experiencing Climate Reaction* and *B2 – Realizing Sweat* gain more strength due to an empowerment of both routes, the cognitive and the experienced. Media Coverage Efficiency allows for a faster realization of the deteriorating situation while a longer time horizon leads to people not adapting so fast to the change in temperature variations (i.e. *R4 – Getting Used To News* is slowed down). Additionally, both *Weights* on the goal formation imply a strong focus on feedback from the environment, while the *Intention Boost* pushes the social norm to enact a higher societal goal. All this leads to an increase in PEBI in the years after 2024 and a corresponding significant decrease in CFP. The increased energy efficiency rate helps to continuously drive down the CFP. This is even more explicit when comparing the last phase of the runs. Towards the middle of the simulation, while the temperature growth slows down, the reference temperature starts catching up faster: *R4 - Getting Used To the News* gets stronger in relative terms since *B2 – Realizing Sweat* slows down. As severeness starts decreasing at around 2040, the personal norm starts to decrease and consequently people adapt their intention downward. This indicates a policy-resistance: even though the policy was implemented to increase PEBI, people lower their intention again as the situation improves. Yet even while PEBI decreases slowly, CFP is reducing, due to the increased energy efficiency rate.

**Implications**

In general, we see that the model responds well to the altered input and can produce the expected behavior under a scenario focused on environmental awareness, policy and measurements to decrease CFP and the offers leverage entry points to depict the narrative, especially *energy efficiency, Sensitivity from Intention on CFP, Media Coverage Efficiency* and *initial perceived temperature variation (*here *reference of temperature variation).* As in BAU, the gap between the projected SSP contribution and the model's *Total OECD $CO_2$ Contribution* shows the impact of the endogenized behavior. Additionally, the *Intention Boost* can be interpreted as the fourth component of social norms as described by Gavrilets, Tverskoi, and Sánchez (2024), i.e. as the additional exogenous component of complying with an authority. As mentioned above, the policy resistance that the system depicts, counteracts a bit the good intentions of the policy – this counter effect (a type of rebound effect) is neglected by the narrative. The model shows: When the situation improves, people react accordingly. It seems that SSP1 maintains the hypothesis that the improvements we achieve only result in a motivating ambition to further improve. As the model shows, this assumption should be questioned since improvements may also result in further decreased ambition given the "achievements".

### 5.3.2 SSP2 – The Fossil Fuel Highway

**Experimental Setup**

The SSP 5 data (population and emission data) used is based on Kriegler et al. (2017). Figure 5-10 presents the summary of the SSP narrative following Riahi et al. (2017), Table 6 depicts the qualitative assumptions from O'Neill et al. (2017). Changes are enacted from year 2024 onwards.

> This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

*Figure 5-10 - SSP5 narrative summary by Riahi et al. (2017)*

*Table 6 - Overview of incorporated assumptions from SSP-5 scenario*

| **Assumptions**<br>Selected from the SSP-5 based on O'Neill et al (2017) | **Entry Points in the model**<br>deduced by the modeler |
|---|---|
| • Consumption and Diet: Materialism, status consumption, tourism, mobility, meat-rich diets<br>• | • Endogenously produced by the model |
| • "[…]the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. | • Include a PEB-Intention "Bummer" of 15% (i.e. a step of -0.15) to the social norm sector acting on the society's strived intention goal. This represents a politically and societally driven influence on the social norm, e.g. thought leader or policy directive |
| • Carbon and Energy Intensity: High | • Decreasing energy efficiency rate from 0.8% to 0.5%, indicating that development directed towards fossil fuel does |

| | |
|---|---|
| • Energy Tech Change: Directed toward fossil fuels; alternative sources not actively pursued<br>• Technology Development: Rapid | not result that much in energy efficiency improvement or savings of $CO_2$, corresponds to data from SSP5 (Riahi et al. 2017) |
| • Policy orientation: Toward development, free markets, human capital<br>• Environmental Policy: Focus on local environment with obvious benefits to well-being, little concern with global problems<br>• Institutions: Increasingly effective, oriented toward fostering competitive markets | • Decrease Weight from personal norm from 0.7 to 0.5, indicating that the environmental feedback is considered less important.<br>• Stimulating the Reference Temperature Variation through an increase of the inflow *updating the reference temperature variation* with 1.4°C indicating a relaxing in the temperature ambitions, i.e. providing and keeping a higher reference, namely at least 2.0 °C climate goal, which leads to less severeness in the years that follow |
| • Education: High | • Altering *Sensitivity of Seriousness* from -1.37 to -0.96 (indicating that more egoistic sensitive worldviews are triggered and built, leading to people being less sensitive towards experiencing extreme events)<br>• Reducing the Sensation Magnitude Exponent from 0.75 to 0.5 indicating that a change in severeness is not perceived as strongly as before.<br>Both adaptations illustrate that (this type of) education reduces the awareness of adverse consequences against the environment |

**Results**

Figure 5-11 shows the comparative graphs of the key indicators across the BAU, SSP-5 input with endogenized behavior and with a run calculated with the exogenous SSP-5 data only. While we see that from 2024 onwards the model reacts with an increase in CFP and decrease in intention, it is not able to depict the trajectory of the SSP5-Only data (see OECD contributions). Although at the end of the simulation, intention is indeed lower than the BAU (-10%) and individual (+1.6 $tCO_2$/person/year) and OECD contribution (+5.6k $MtCO_2$/year) increased, the model does not manage to depict a comparable rise in key variables.

**Behavioral Explanation**

After activation of the scenario, severeness declines due to the increased reference condition of temperature variation (empowering *R4 – Getting Used to News*) despite the higher temperature. Consequently, personal norm declines since *R4 – Getting Used to News* is counteracting against the weakened *B4 – Realizing Sweat loop*. The focus on the social norm (through manipulating the *weights)* puts even less power to the feedback from the environment (the loops *R4 -Getting Used to News* and *R5*

– *Getting Used to Seriousness* as well as *B1 – Experiencing Climate Reaction and B2 – Realizing Sweat*). This leads to a lowered intention goal and a rise in CFP. After a short period of time though, the increasing *perceived temperature variation* (being the reference condition for judging severeness) does lead to a higher severeness after all, which brings intention to rise again, and CFP starts to decline. This is, again, supported by the energy efficiency rate, that although reduced, leads to significant decline in the overall CFP contribution. Towards the end of this scenario the environmental feedback, although weakened by the reduced awareness produced through the change in sensitivity of seriousness and the lower sensation magnitude exponent, brings intention back up.

## Implications

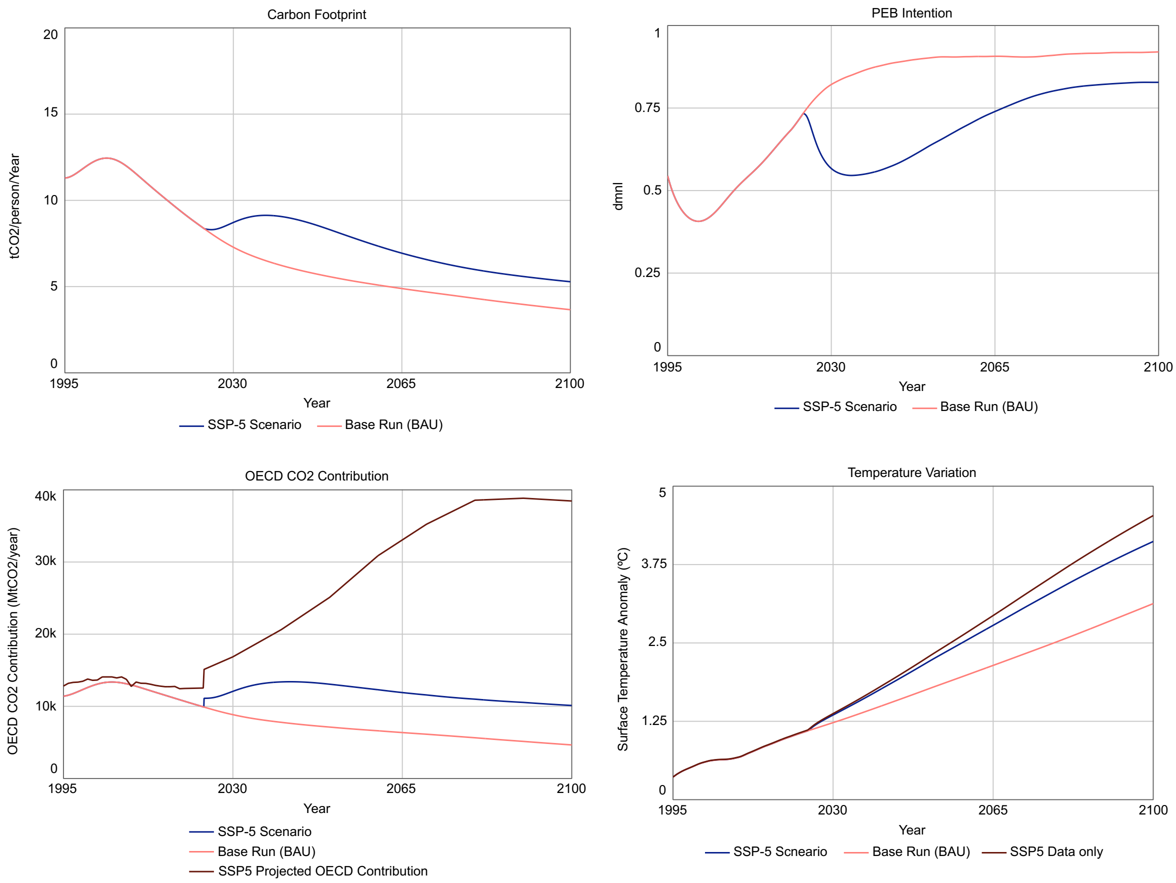


*Figure 5-11 - Key Indicators for the SSP-5 scenario*

While the model does allow for alternations that fit the narrative, the reaction caused cannot reproduce the behavior suggested by the SSP 5 narrative data. Comparing the *OECD Total $CO_2$ Contribution* with the projected $CO_2$ contribution from the SSP5, we see that the difference and general trajectory is vast. When thinking about the projected trajectory, it stands out, that according to the narrative, until the year 2080 there is a continuous and significant increase in CFP. A trajectory that is not reasonably reproduceable by the model's structure. As is expected (and validated through the tests) to create such an intense rise in CFP, PEBI needs to diminish drastically. This might be achieved by (1) an extremely low severeness or (2) a strong stimulation of the social norm (peer group and societal).

Route (1) would use *R4 – Getting Used to Seriousness* to counteract *B1 – Experiencing Climate Reaction*. Essentially, people need to not-experience climate events to establish a judgement of non-seriousness. Equally, *R5 – Getting Used to News* needs to counteract *B2 - Realizing Sweat*: People need to be fed wrong information about the temperature's variations (or given extreme high comparative goals) to lead to judge the condition non-severe. Additionally, it is said that the environmental feedback is less in focus (see narrative above). In sum, it seems that this route is not realistic or in line with the narrative's assumptions.

Route (2), using the social norm sector, might only work if there is a constant and significant exogenous drive of the social norm. The social norm sector with its loops *R1 – Peer group influence* and *R2 – Societies Influence* establishes an equilibrium around the initial CFP, unless there is additional deviating input (e.g. the input from environment). Hence, to focus on this sector and to induce such a steep increase in CFP as depicted in the SSP 5 data, is only possible if it is initiated and maintained through something else than the personal norm – i.e. a permanent and strongly exogenously induced decrease of societies strived intention.

Both routes additionally face the problem, that, even reduced, the energy efficiency rate is still constantly pushing CFP further down. All in all, it seems that the narrative depicts assumptions (and by that data) that cannot be realistically brought in line with the endogenized behavior. Route (1) implies that at least until year 2080, people do not perceive the developing situation as severe enough at all to react in any way but on the contrary reducing their intention ever so forth and while stop advancing in exploring more energy efficient procedures and technology. Route (2) would imply a heavily manipulated societal norm, steered through outside instructions.

Nevertheless, under completely arbitrary variations the model can come close to the narratives data. Figure 5-12 shows a trial using parametric variation to come close to the projected behavior. The following unrealistic (or contra the narratives assumptions) alternations were used from 2024 onwards (only changes in comparison to the scenario settings are reported here):

- A stable *reference temperature variation* goal of 5.1°C, ensuring the decline in severeness
- Increase *Weight on Personal Norm* from 0.7 to 0.9 (i.e. focus on environment to reduce severeness)
- Eradicate the artificial social norm "Bummer"
- Altered *sensitivity of seriousness* from -1.37 to 0.01 (meaning cutting of the experienced route)
- Increasing *the time to perceive* the temperature variation from 1.65 to 4.56 years and *AT CFP* from 4.5 to 8, indicating that people resist new information and behavior change

- Reduce media efficiency from 0.78 to 0.5, indicating significantly inefficient and misguided provision of information

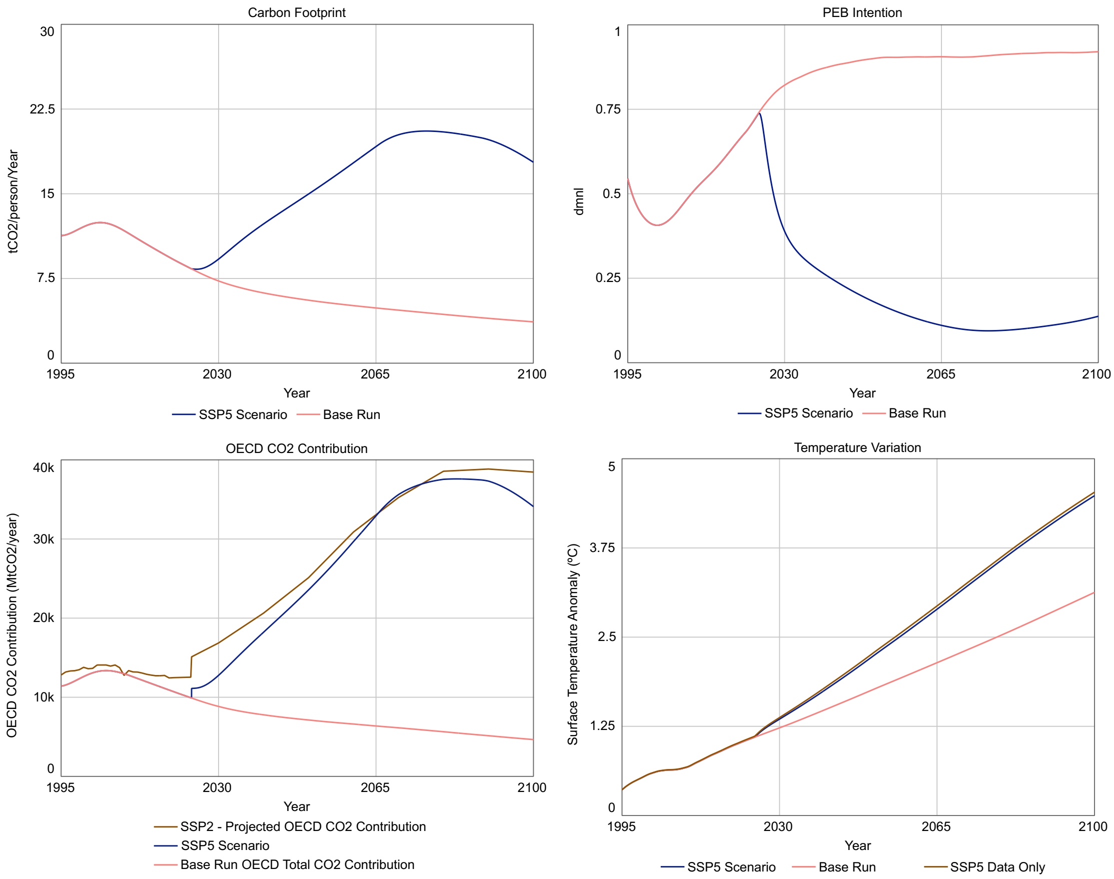


*Figure 5-12 - Key Indicators for arbitrary alternation of SSP-5 scenario to come closer to the projected data*

In sum, although there are ways to force the model to show comparable behavior, this is not possible while maintaining realistic assumptions. This might either mean that the narrative depicts a non-realistic assumptions to begin with, or that more work needs to put in to investigate into other leverage points that allow for such a behavior change while maintaining realistic assumption, or both.

# 6. Discussion, Limitations and Further Research

After analyzing the model's sensitivity, BAU and scenarios, this Chapter discusses its broader implications – first, in general terms for the project of this thesis and the use of both the SSP and environmental psychology theories and second, in more concrete terms for policy insights on shifting towards a more pro-environmental intention. Thereafter, I discuss the limitations of this work and possible future research directions.

## 6.1 General Implications

**Integration of human behavior**

As shown through this conceptual work, implementing human behavior about intention change proves to be not only possible, but promising. Human behavior plays a significant part both, in producing the current state of environmental impact and in changing it. Hence, in striving for a more holistic representation, we should consider advancing in representing human behavior in our models (Beckage et al. 2020). This is further supported by the work of Otto et al. (2020) and Eker and Wilson (2022), which analyzes the potential for social tipping elements and interventions.
As shown, the implementation of endogenized human behavior makes a considerable difference on the smaller output level (OECD and individual contribution falls drastically) and a smaller one on higher level (global temperature decreases a little). Additionally, we can use this integration to better explore and discuss underlying assumption and mechanisms of IAMs. This thesis therefore supports the plea to endogenize behavioral components and takes further steps in spelling out how they might look. Vice versa, we saw, that the theories are not only open to be coupled with, but under a dynamic inspection are of course influenced by the feedback provided through the environment. This is in line with the theories itself, as for example Ajzen (2020) pointed out, that the TPB might be a dynamic process.

**SSP**

Going beyond that, the proposed implementation also supports the ability to depict not only *a* representation about human behavior, but *multiple* ones under different narratives about future development. As the SSP scenarios depict themself: Projecting future development is always based on uncertainty. Therefore, these scenarios rest not necessarily on a fixed quantitative projection but on a more qualitative narrative about the development that leaves room for uncertainties, variations and confidence-driven ranges. As the coupling with the SSP data and the two SSP-Scenarios in this thesis show, the endogenized human behavior component can depict these varying stories – although of course further research on a more precise representation of nuances in the narratives needs to be done. It can also raise issues with the scenarios. Through endogenizing human behavior, the model raised awareness that (1) there might be an intention-associated rebound effect (SSP-1 scenario showed the decline in PEBI after the environmental feedback relaxed) (2) the SSP-5 narrative, even considering that (current) unrealistic assumptions might be part of the narrative process, might rest on some assumptions that are questionable to hold under endogenized behavior.

**Support of the underlying theories**

This project also revealed that in their rudimentary setup, the used (environmental) psychology conceptualizations about change in intention are not enough to represent human behavior exhaustively. As was shown in the SSP5 scenario, policy directions, technology-based alternation of the characteristics of the behavior in question, and a more nuanced perspective on the social norm formation cannot be fully represented. Here, the insights from the social norm formation provided by Gavrilets, Tverskoi, and Sánchez (2024) were needed to support that area. This might unfold its potential even more in future work with clear contexts, specific behavior and a representative "society" to conceptualize social norm dynamics.

From a different point of view, it highlighted the difficulties for explanatory psychological concepts to be used in dynamic theories since the evaluation of the concepts in question change over time: While at one point one behavior, e.g. taking public transport, may be seen in line with personal values/norm, a change in social norm or technology might change that evaluation or concept 20 years from now. Clearly, the use of those environmental concepts has proven its applicability with fixed time periods, reference groups and in a stable context (Conner and Norman 2015; Kurisu 2015; Bosnjak, Ajzen, and Schmidt 2020; Klöckner 2013). Yet, in a dynamic complex world, its explanatory power over long time periods needs to be further investigated. Note, that this is not to render those theories unfit for dynamic contexts but should be seen as an invitation to refine the explanation of their workings under a longer time horizon.

## 6.2 Model-Based Policy Insights

Several model-based policy insights can be derived from the analysis provided in the chapters above. Note that these insights are based on the goal to support a transition towards a more sustainable future. Note, that this indicates a switch towards a subjective frame of reference from which I provide these insights.

**Reference of Temperature Variation and Extreme Events**

All of the proposed theories, especially VBN and the PMT, rest upon some conception about perceived risk (De Groot and Steg 2009; Stern 2000), threat appraisal (Floyd, Prentice-Dunn, and Rogers 2000) or evaluation of a personal attitude towards a certain behavior (Ajzen 2020). A crucial point for those evaluations is the reference conditions used to form these beliefs. Intervening on those reference conditions poses a leverage point in that it immediately varies the perceived risk which indicates an urgency, that is translated into a new personal norm (the workings, *B1 – Realizing Climate Reaction* and *B2 – Realizing Sweat*). On some level, this is already underway by science, politics and media communicating and agreeing on certain climate goals and ambitions in reductions of CO, which was also officially initiated by the Kyoto Protocol, Paris agreement and the Sustainable Development Goals. Yet, looking at insights from the model, it is not enough to communicate these goals in isolation. They need to be conveyed at best as a relative perceive temperature variation to spark action. As we see from the model, when we rely on an updating reference condition that is based on our current perception only, there is a tendency to never realize the actual urgency since we adapt to a new normal without information on "how badly we are on track". Therefore, a clear concept of reference might help to activate the routes of awareness and should be communicated if we are to spark a sense of urgency.

**Strong Institutions and Climate Communication**

Insights from the model show that a fast and accurate communication of climate developments is a crucial part of enabling the personal norm and the feedback from the environment. Only by high *media coverage efficiency*, can there be a clear sense for the development of the environment around us, that empowers the mechanisms that lead to a higher personal norm. Possible policy insights might therefore suggest strengthening the ability of this communication by investing into research, ensuring the coverage of the topic in the public sphere but also individual confrontation with it. Here, the responsibility lies not only at a governmental or business level. As we seen in the CEE scenario - closing our eyes is not a successful strategy.

Yet, as Levine (2003) shows, a critical point here is the trust in the source of communication itself – a concept not depicted in this model (or considered by the underlying psychological theories) and further theoretical underpinning is needed.

**Changing Worldviews and investing in Education**

Environmental education has been considered since long as one of the main contributors to pro-environmental intention and attitude (Heeren et al. 2016). That this might be a misconception rests on a form of naïve realism – the conviction that "(…) if individuals "only knew better" they would engage in more sustainable behaviours" (Heeren et al. 2016). The study by Heeren et al (2016) shows, using the TPB, that sustainability knowledge has little effect when other measurements (i.e. TPBs personal and social norms and behavioral controls) are considered. Nevertheless, as argued by Liobikienė and Poškus (2019) knowledge and education do play a vital role in building up certain worldviews and to increase people's environmental awareness. This model already accounted for this indirect inclusion of impact of education. As a policy lever, however, more and stronger educational effort in schools, universities or even changes in organizational culture may not have a direct influence on behavior. Rather, we should acknowledge its indirect mechanisms of transforming value-related worldviews and the sensitivity of reactions to change in the environmental feedback (i.e. forming awareness). This in line with insights from Mikuła, Raczkowska, and Utzig (2021), investigating educational variables correlating with PEB, and it supports the findings by Otto et al. (2020) and Eker and Wilson (2022) laying out a clearer linkage between the educational and the norms and value sector.

**Social Norms – Authority and Thought Leadership**

Although TPB and VBN refer to social and personal norms, taken at the conceptual level, they prove to be difficult to operate with. Here, that adaptation of Gavrilets, Tverskoi, and Sánchez (2024) proposition of modelling norm formation helped to identify routes for formalization of them. Model analysis demonstrated the responsiveness of the personal norms to environmental feedback. This feedback is an important input to the social norm sector, since it essentially stimulates the variation of it – if there are no "new" impulses, then people will adapt to each other. Authority or Thought-Leadership, as can be seen in the SSP 1 and SSP5 Scenarios, can be a crucial additional input to the social norm sector to foster change in intention not only through the environment but from within. As such, this represents an entry point for the Social Tipping Intervention by Otto et al. (2020) of thought leaders that stimulate the norms and value sectors. Note, that this is not to suggest any specific type of ideologically driven norm formation, but only points out, where concepts, that rests on politically or publicly driven norm influence, might enter the picture.

**Relying on Energy Efficiency**

Throughout the discussion of the model, I made apparent that the concept and application of energy efficiency improvement plays a major role when looking at the systems behavior. On the positive side, it indeed presents a huge opportunity, one on which many rest their hope, as can be seen by the reports from the IEA (IEA 2023)(aiming for 4% improvement rate to maintain their net-zero scenario), IPCC (IPCC et al. 2023) and the current SSP pathways (Riahi et al. 2017). On the other side, it contributes to a dynamic of rebound or convenience, conveying the idea, that we do not have to change but can be rest assured through the dream of ever-increasing development – a dynamic that is contributing to a regression of PEBI.

Another indicator here is the continuously growing energy consumption (around +2.4% per year over the last 250 years), usually a measure correlated with GDP growth, unless both are absolutely decoupled from another (Brockway et al. 2021). This indicates that while there is an increase in economic growth (as the SSPs assume) there needs to be a complementary increase in energy efficiency combined with or resting on a global decoupling of economic growth and rise in energy consumption per se – an absolute decoupling that is currently questionable (Brockway et al. 2021; Parrique et al. 2019). In any case, research on energy efficiency and energy intensity has been and will continue to be an important entry point for the development of policies that can significantly contribute to systemic behaviors. As the model shows, if we close our eyes to the environment (cutting off, its feedback–input), then energy efficiency and exogenous input to societal norms (e.g. thought leaders and such) might be the remaining hopes for shifting PEBI.

## 6.3 Limitations

In this section I look at limitations posed to the model and its inferences. Note that two drawbacks from the model's boundary, i.e. focus on $CO_2$ as sole endogenized emitted gas and excluding the financial sector, have been discuss already in the respective section in Chapter 3. Here I address only limitations beyond them.[7]

One limitation lies in the attempt alone to integrate several dimensional levels within one model: Worldviews – and their respective changes – and estimates of one's own behavioral control, are usually formed on an individual level. Social Norms on the other hand are processes related to one's peer group, community or cultural group. Environmental consequences are observed and investigated on a global level, yet the experience of extreme events to give just one example might be a very national, regional or even local issue. While economic and climate related sectors can be aggregate on a higher level, human behavior (and socio-cultural norms) is a complex issue where aggregation might be possible to some extent, yet also brings some crude generalizations. Respectively, the model does not consider the socio-cultural differences between OECD member states but generalizes across them – which of course needs to be taken into perspective and should be seen as a limitation. Targeting a smaller research group as a focus will help to get a hold of that limitation, yet it inevitably leads to a bigger amount of exogenous input, when considered in dependence to the rest of the world. There is a balance to find that mediates between a higher accuracy of the socio-cultural sphere while simultaneously restricting the boundary so that the contribution is still large enough to affect the feedback from the environment. In sum, the integration of the three spheres (individual, societal and globally) will remain a challenge due to the increasing

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[7] Note, limitations here are not addressing the bigger IAM models directly. For limitations on IAMs in general see for example Gambhir et al. (2019); Beck and Krueger (2016)

complexity of the phenomena we are investigating. For that, deciding on a narrower defined behavior (e.g. only dietary choice) will help to draw a more reasonable scope.

Furthermore, a limitation lies in the socio-cultural contexts per se that govern human behavior – recall that different priorities of valued objects comprise ascribed worldviews, as depicted in Chapter 2. Constructing a model that runs for 100 years should justifiably face the question, whether it can reasonably tell us anything about the mechanisms and worldviews 50 or 80 years from now, especially because worldviews not only change from one group to another, but likely change within themselves. This objection does not go against the model structure of this thesis per se. Since this is a conceptual work, this limitation voices a reasonable concern, but does not invalidate the pattern–related inferences drawn. Beyond that, this issue questions the aptness of constructing models, narratives and assumptions about worldviews that range much further than a reasonably foreseeable future. This is not to say at all that a narrative based projection is not useful, yet it is inevitably bound to the assumptions and projections we, at the current state, are able to think of – and so will necessarily be every model constructed on such narratives and every policy enlightened by them. In that, also this research and model faces the limitation that it assumes that worldviews and social norms can be maintained without ever changing themselves over a vast time horizon.

Additionally, this conceptualization faces the underlying assumption, that focus is drawn only to the issue at hand. As Scheffer, Westley, and Brock (2003) argue, analyzing slow responses from society, multiple parallel problems increase not only social costs but can impair the available dedication for problem recognition and finding solutions, individually and society wide. This might have impact through the concept of adverse consequences, where consequence from behavior to different problems/crisis might counteract each other. This "polycrisis awareness split" might impair people's responsiveness in terms of forming a clear personal norm or impeding their perceived behavioral control.

As we can see with this model, narrative-driven projections are needed to start investigating quantitatively future developments. The SSP data poses a good example for this in both ways: First they make aligned academic work for future development possible, providing several "guardrails" for certain narratives within which uncertainty is allowed. Yet, it would be misguided to take them at face-value, not questioning or updating their assumptions frequently. This is the constant reminder that the assumptions we put in our models, especially for future development are essentially assumption-driven, and therefore need to be reflected accordingly.

Looking at suggestions for modelling social norms by Gavrilets, Tverskoi, and Sánchez (2024); Gavrilets (2021) one limitation to this research is in some part the SD method itself. Norm formation especially as detailed as suggested by the authors are based on individual estimates and network dynamics. Both might be aggregated and implemented in an SD model, as was proposed in this thesis. Still, to depict this part of endogenizing human behavior with more accuracy, an actor-oriented modelling approach might be chosen.

## 6.4 Further Research

Based on this last point of the limitations, one field of further development would be a hybrid approach to endogenized human behavior into IAMs or models in general. Several examples successfully document the fruitful combination of System Dynamics and Agent-Based-Modelling (ABM)[8]. A combined integrated model would be able to take care of the individual-oriented social and personal norm formation (ABM-based), while at the same time account for higher level macro dynamics within the different systems of society, economics and environment (SD-based).

Furthermore, focusing on one specific behavior explicitly, will eventually eradicate some of the proposed drawbacks: Socio-Cultural evaluations are easier to investigate, economic factors might be easier to implement, a more precise decomposition of individual contribution feasible. This thesis and model advanced to endogenize human behavior more exhaustively in a larger modelling environment. Further research might draw from this more abstract perspective and collect experience with applying it to more tangible behavior directly.

Additionally, this project laid the ground for building an endogenized framework for human behavior that is responsive and able to include already some of the propositions from the research related to Social Tipping Interventions. As such it can be seen as an example for a step towards a more quantified "norms and value" system that is responsive to input (or coupling) towards the educational system or information system, connections proposed by Otto et al. (2020) and Eker and Wilson (2022). Further research in establishing these connections that can traceably connect these different sub-systems are needed to advance in the endeavor to leverage Social Tipping Interventions for shifting towards a more sustainable society.

[8] Agent Based Modelling focuses on representing interactions between individual actors (agents) and its environment with a specific focus on emergent behavior (Kelly et al. 2013).

# 7. Conclusion

To conclude this thesis, I summarize the work presented and conclusions drawn in the form of answers to the research questions posed.

**RQ 1** How do we understand human behavior change and use it endogenously in IAMs to depict behavior and value change?

- *RQ 1.1* What are the main concepts of pro-environmental behavior as theorized in social psychology?

"PEB" is easier used than defined. When looking for integrating PEB into models, we need to focus on goal-orientated behavior to capture the intention-induced change. We saw that social-psychology theories understand PEB complementary in terms of both self-interest (TPB and PMT) and altruistic motivation (VBN). In particular, we identified (1) social norms through peers and society, (2) personal worldviews and value sets, corresponding perceptions of threat, risk and awareness of consequences and 3) personal norms, attitude or moral obligation as important for change in intention 4) perceptions about behavioral control and self-efficacy.

- *RQ 1.2* Can these concepts be integrated to conceptualize a holistic picture of pro-environmental behavior change?

Both existing literature and this thesis suggest that an integration is not only possible but desirable. PEB incorporates a tremendous range of complexity in motivational behavior, touching upon factual restrictions (efficacy of oneself and behavior in general), worldviews and beliefs, as well as social norm components and political dimensions. Yet, the yes is a modest one: through integrating the proposed theories into each other we do take a step into a more holistic picture, including self- and social-interest. Still, we need to keep in mind the context of the theories: Does their explanatory power focus on specific behavior or aggregated one? At individual perceptions or aggregated social norms? Factual and goal-directed behavior or indirect, activism-related ones? To attest to the theoretical limits that are inherent in each of the theories, more remains to be done in proving the compatibility theoretically and practically. Here, as argued, research of aggregated behavior may come to its limits. A focus on specific behavior in a specific cultural context may help to reduce the demand of complexities that needs to be embedded to make the representation more holistic and realistic.

**RQ 2** How can we operationalize and integrate the theoretical concepts and insights into IAMs to endogenize human behavior in terms of carbon emissions?

- *RQ2.1* What are general dynamic feedback structures that govern emission behavior, in the exemplary case of the OECD region?

Departing form the theoretical grounding, I identified two main routes for driving PEBI and ultimately PEB: One orientated on feedback within society, one focused on feedback from environment. Social injunctive norm and Peer-Group pressure/inspiration is driving PEBI internally (loops *R1 – Peer Influence, R2 – Societies Influence, R3 – Adapting to Society*). The environment induces feedback through severeness and seriousness, leading to adopt intentions based on our perceptions on the current states (*B1 – Experiencing Climate Reaction, B2 – Realizing Sweat*). Additionally, a continuous factor is the tendency to get used to current developments thereby blocking upcoming drive for change (*B3 – Getting Used to CFP, R1 – Getting Used to Seriousness* and *R3 – Getting Used to News*). Through the coupling with FRIDA, we were able to see, that the integration of human behavior into IAMs resulted in more nuanced outcomes responsive to changes in the environment. The loops are also able to operationalize trajectories and assumptions from the SSP pathways.

- *RQ2.2* What are the leverage points, within the norms and value system, that can be used to facilitate a shift to a less carbon-intense behavior?

The model analysis shows that especially energy efficiency on the technological side, and media coverage and clear and instructive reference conditions on the social side are promising ways to intervene. Additionally, education, thought-leaders or campaigns to trigger a re-evaluation or activation of a broad spectrum of values and worldviews (or effect sensitivities) is another step to foster norm shift towards more awareness and societal sparked inspiration. This supports, concretizes and formalizes some of the Social Tipping Elements, put forward by Otto et al (2020), i.e. thought leaders, climate education. Note, that these are to be treated as insights, not recommendations, since this model is conceptual and generic and cannot be used to predict policy outcomes or evaluate their broader effects of implications

**RQ 3** What are the general model-based implications for endogenizing human behavior in IAMs and emission pathway narratives?

- *RQ3.1* What insights can be drawn from the model analysis about the realism of the used emissions pathways?

The integration of endogenous human behavior and responses in the model proves to be able to simulate and test assumptions and narrative based future scenarios. More specifically, the analysis showed the model to be apt to investigate – and expose – the translatability and realism of certain assumption. We saw that the SSP-1 scenario was reproduceable by integrating human behavior, while the SSP-5 assumptions and projections raised serious questions about its realism and translatability. This does not prove them wrong but raises awareness that further backing is necessary.

- *RQ 3.2* What general challenges do we face while integrating human behavior into IAMs? Integrating human behavior into IAMs is a challenge of dimensionality – balancing individual, societal and global dimensions. With a too intense focus on mechanisms of norm change (individual level), we might get lost in its complexity, which is not functional for the broad scope. If we remain too aggregated in terms of behavior researched, we run into challenges of explanatory power of the behavioral theories and face the challenge of aggregating world views (changes) throughout different cultural contexts and frames of reference. Further, there is a challenge of impact when zeroing in on specific behavior: All used theories have a concept of considering how effective a behavior is, in terms of coping (PMT), avoiding adverse consequences (VBN) or as concept of "the right thing to do" (TPB). Single specific behavior will reasonably have small impact on global scale developments, and feedback might not be expectable. To create noticeable responses through the environment, either the feedback reference needs to be smaller (e.g. observations about a nations progress in mitigation instead of global progress), or behavior needs to have at least a scale that creates big enough impact – note, that we come back to the first challenge through this. Therefore, further work needs to make reasonable (and transparent) boundary decisions to improve system representation balancing the three dimensions (individual, societal, global) and to advance into representing influences among the environmental, economic and society systems.

In building upon and refining the pre-existing work by the WorldTrans Working Group, my work contributes to the efforts of integrating human behavior into IAM environments. It operationalizes psychological theories and concepts for dynamics environments apt for an endogenous representation of behavior change. The model also builds upon the emission pathway narratives and proves to be a useful tool for cross-checking and simulating assumptions to identify policy insights, not only into coupling several sub-systems but to challenge the assumptive narratives themselves. In that, it took steps to answer the call for integrating human behavior into our integrated climate models (Otto et al. 2020; P. I. Palmer and Smith 2014).

## Cited Work


Ajzen, Icek. 2001. "Nature and Operation of Attitudes." *Annual Review of Psychology* 52 (1): 27–58. https://doi.org/10.1146/annurev.psych.52.1.27.

———. 2016. "Consumer Attitudes and Behavior: The Theory of Planned Behavior Applied to Food Consumption Decisions." *Italian Review of Agricultural Economics*, February, 121–38. https://doi.org/10.13128/REA-18003.

———. 2020. "The Theory of Planned Behavior: Frequently Asked Questions." *Human Behavior and Emerging Technologies* 2 (4): 314–24. https://doi.org/10.1002/hbe2.195.

Balundė, Audra, Goda Perlaviciute, and Linda Steg. 2019. "The Relationship Between People's Environmental Considerations and Pro-Environmental Behavior in Lithuania." *Frontiers in Psychology* 10 (October):2319. https://doi.org/10.3389/fpsyg.2019.02319.

Bamberg, Sebastian, and Guido Möser. 2007. "Twenty Years after Hines, Hungerford, and Tomera: A New Meta-Analysis of Psycho-Social Determinants of pro-Environmental Behaviour." *Journal of Environmental Psychology* 27 (1): 14–25. https://doi.org/10.1016/j.jenvp.2006.12.002.

Bandura, Albert. 1977. "Self-Efficacy: Toward a Unifying Theory of Behavioral Change." *Psychological Review* 84 (2): 191–215. https://doi.org/10.1037/0033-295X.84.2.191.

Barlas, Yaman. 1996. "Formal Aspects of Model Validity and Validation in System Dynamics." *System Dynamics Review* 12 (3): 183–210. https://doi.org/10.1002/(SICI)1099-1727(199623)12:3<183::AID-SDR103>3.0.CO;2-4.

Barlas, Yaman, and Stanley Carpenter. 1990. "Philosophical Roots of Model Validation: Two Paradigms." *System Dynamics Review* 6 (2): 148–66. https://doi.org/10.1002/sdr.4260060203.

Bauske, Emily, and Florian Kaiser. 2019. "Umwelteinstellung in Deutschland von 1996 bis 2016: Eine Sekundäranalyse der Umweltbewusstseinsstudien." 128 / 2019. Umweltbundesamt. https://www.umweltbundesamt.de/publikationen/umwelteinstellung-in-deutschland-von-1996-bis-2016.

Beck, Marisa, and Tobias Krueger. 2016. "The Epistemic, Ethical, and Political Dimensions of Uncertainty in Integrated Assessment Modeling." *WIREs Climate Change* 7 (5): 627–45. https://doi.org/10.1002/wcc.415.

Beckage, Brian, Louis J. Gross, Katherine Lacasse, Eric Carr, Sara S. Metcalf, Jonathan M. Winter, Peter D. Howe, et al. 2018. "Linking Models of Human Behaviour and Climate Alters Projected Climate Change." *Nature Climate Change* 8 (1): 79–84. https://doi.org/10.1038/s41558-017-0031-7.

Beckage, Brian, Katherine Lacasse, Jonathan M. Winter, Louis J. Gross, Nina Fefferman, Forrest M. Hoffman, Sara S. Metcalf, et al. 2020. "The Earth Has Humans, so Why Don't Our Climate Models?" *Climatic Change* 163 (1): 181–88. https://doi.org/10.1007/s10584-020-02897-x.

Beckage, Brian, Frances C. Moore, and Katherine Lacasse. 2022. "Incorporating Human

Behaviour into Earth System Modelling." *Nature Human Behaviour* 6 (11): 1493–1502. https://doi.org/10.1038/s41562-022-01478-5.

Beek, Lisette van, Maarten Hajer, Peter Pelzer, Detlef van Vuuren, and Christophe Cassen. 2020. "Anticipating Futures through Models: The Rise of Integrated Assessment Modelling in the Climate Science-Policy Interface since 1970." *Global Environmental Change* 65 (November):102191. https://doi.org/10.1016/j.gloenvcha.2020.102191.

Bosnjak, Michael, Icek Ajzen, and Peter Schmidt. 2020. "The Theory of Planned Behavior: Selected Recent Advances and Applications." *Europe's Journal of Psychology* 16 (3): 352–56. https://doi.org/10.5964/ejop.v16i3.3107.

Brockway, Paul E., Steve Sorrell, Gregor Semieniuk, Matthew Kuperus Heun, and Victor Court. 2021. "Energy Efficiency and Economy-Wide Rebound Effects: A Review of the Evidence and Its Implications." *Renewable and Sustainable Energy Reviews* 141 (May):110781. https://doi.org/10.1016/j.rser.2021.110781.

Calvin, Katherine, Ben Bond-Lamberty, Leon Clarke, James Edmonds, Jiyong Eom, Corinne Hartin, Sonny Kim, et al. 2017. "The SSP4: A World of Deepening Inequality." *Global Environmental Change* 42 (January):284–96. https://doi.org/10.1016/j.gloenvcha.2016.06.010.

Chen, Jianshe, Shiyi Tian, Xinmiao Wang, Yuezhong Mao, and Lei Zhao. 2021. "The Stevens Law and the Derivation of Sensory Perception." *Journal of Future Foods* 1 (1): 82–87. https://doi.org/10.1016/j.jfutfo.2021.09.004.

Cialdini, Robert B., Carl A. Kallgren, and Raymond R. Reno. 1991. "A Focus Theory of Normative Conduct: A Theoretical Refinement and Reevaluation of the Role of Norms in Human Behavior." In *Advances in Experimental Social Psychology*, 24:201–34. Elsevier. https://doi.org/10.1016/S0065-2601(08)60330-5.

Community Emissions Data System (CEDS). 2024. "Sulphur Dioxide ($SO_2$) [Dataset] – Processed by Our World in Data." https://ourworldindata.org/explorers/air-pollution?Sector=From+all+sectors+%28Total%29&Pollutant=Sulphur+dioxide+%28SO₂%29&Per+capita=false.

Conner, Mark, and Paul Norman, eds. 2015. *Predicting and Changing Health Behaviour: Research and Practice with Social Cognition Models*. Third edition. Maidenhead, Berkshire: Open University Press.

Dannals, Jennifer E., and Dale T. Miller. 2017. "Social Norms in Organizations." In *Oxford Research Encyclopedia of Business and Management*, by Jennifer E. Dannals and Dale T. Miller. Oxford University Press. https://doi.org/10.1093/acrefore/9780190224851.013.139.

Dannenberg, Astrid, Gunnar Gutsche, Marlene C. L. Batzke, Sven Christens, Daniel Engler, Fabian Mankat, Sophia Möller, et al. 2024. "The Effects of Norms on Environmental Behavior." *Review of Environmental Economics and Policy* 18 (1): 165–87. https://doi.org/10.1086/727588.

De Gooyert, Vincent. 2019. "Developing Dynamic Organizational Theories; Three System Dynamics Based Research Strategies." *Quality & Quantity* 53 (2): 653–66. https://doi.org/10.1007/s11135-018-0781-y.

De Groot, Judith I. M., and Linda Steg. 2008. "Value Orientations to Explain Beliefs Related to Environmental Significant Behavior: How to Measure Egoistic, Altruistic, and Biospheric Value Orientations." *Environment and Behavior* 40 (3): 330–54. https://doi.org/10.1177/0013916506297831.

———. 2009. "Morality and Prosocial Behavior: The Role of Awareness, Responsibility, and Norms in the Norm Activation Model." *The Journal of Social Psychology* 149 (4): 425–49. https://doi.org/10.3200/SOCP.149.4.425-449.

Denscombe, Martyn. 2020. *Research Proposals: A Practical Guide*. Second edition. Open UP Study Skills. London: Open University Press.

Dimant, Eugen, Fabio Galeotti, and Marie Claire Villeval. 2023. "Motivated Information Acquisition and Social Norm Formation." *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4525398.

Doherty, Kathryn L., and Thomas N. Webler. 2016. "Social Norms and Efficacy Beliefs Drive the Alarmed Segment's Public-Sphere Climate Actions." *Nature Climate Change* 6 (9): 879–84. https://doi.org/10.1038/nclimate3025.

Donmez-Turan, Aygul, and Ibrahim Erdem Kiliclar. 2021. "The Analysis of Pro-Environmental Behaviour Based on Ecological Worldviews, Environmental Training/ Knowledge and Goal Frames." *Journal of Cleaner Production* 279 (January):123518. https://doi.org/10.1016/j.jclepro.2020.123518.

Dunlap, Riley E., Kent D. Van Liere, Angela G. Mertig, and Robert Emmet Jones. 2000. "New Trends in Measuring Environmental Attitudes: Measuring Endorsement of the New Ecological Paradigm: A Revised NEP Scale." *Journal of Social Issues* 56 (3): 425–42. https://doi.org/10.1111/0022-4537.00176.

Eker, Sibel, Qi Liu, Claudia Reiter, and Michael Kuhn. 2023. "Full of Economic-Environment Linkages and Integration dX/Dt (FeliX)." https://github.com/iiasa/Felix-Model/blob/master/Documentation/FeliX_model_documentation_2023_v9.pdf.

Eker, Sibel, and Michael Obersteiner. 2023. "Full of Economic-Environment Linkages and Integration dX/Dt (FeliX)." International Institute for Applied System Analysis. February 2023. https://iiasa.ac.at/models-tools-data/felix.

Eker, Sibel, Gerhard Reese, and Michael Obersteiner. 2019. "Modelling the Drivers of a Widespread Shift to Sustainable Diets." *Nature Sustainability* 2 (8): 725–35. https://doi.org/10.1038/s41893-019-0331-1.

Eker, Sibel, and Charlie Wilson. 2022. "System Dynamics of Social Tipping Processes," March. https://pure.iiasa.ac.at/id/eprint/17955/1/IIASA_SocialTipping-Points_WorkshopReport.pdf.

Eker, Sibel, Charlie Wilson, Niklas Höhne, Mark S. McCaffrey, Irene Monasterolo, Leila Niamir, and Caroline Zimm. 2024. "Harnessing Social Tipping Dynamics: A Systems Approach for Accelerating Decarbonization." *One Earth* 7 (6): 976–88. https://doi.org/10.1016/j.oneear.2024.05.012.

Esfandiar, Kourosh, Ross Dowling, Joanna Pearce, and Edmund Goh. 2020. "Personal Norms and the Adoption of Pro-Environmental Binning Behaviour in National Parks: An Integrated Structural Model Approach." *Journal of Sustainable Tourism* 28 (1): 10–32. https://doi.org/10.1080/09669582.2019.1663203.

Floyd, Donna L., Steven Prentice-Dunn, and Ronald W. Rogers. 2000. "A Meta-Analysis of Research on Protection Motivation Theory." *Journal of Applied Social Psychology* 30 (2): 407–29. https://doi.org/10.1111/j.1559-1816.2000.tb02323.x.

Franzen, Axel, and Dominikus Vogl. 2013. “Two Decades of Measuring Environmental Attitudes: A Comparative Analysis of 33 Countries.” *Global Environmental Change* 23 (5): 1001–8. https://doi.org/10.1016/j.gloenvcha.2013.03.009.

Fricko, Oliver, Petr Havlik, Joeri Rogelj, Zbigniew Klimont, Mykola Gusti, Nils Johnson, Peter Kolp, et al. 2017. “The Marker Quantification of the Shared Socioeconomic Pathway 2: A Middle-of-the-Road Scenario for the 21st Century.” *Global Environmental Change* 42 (January):251–67. https://doi.org/10.1016/j.gloenvcha.2016.06.004.

Fujimori, Shinichiro, Tomoko Hasegawa, Toshihiko Masui, Kiyoshi Takahashi, Diego Silva Herran, Hancheng Dai, Yasuaki Hijioka, and Mikiko Kainuma. 2017. “SSP3: AIM Implementation of Shared Socioeconomic Pathways.” *Global Environmental Change* 42 (January):268–83. https://doi.org/10.1016/j.gloenvcha.2016.06.009.

Gambhir, Ajay, Isabela Butnar, Pei-Hao Li, Pete Smith, and Neil Strachan. 2019. “A Review of Criticisms of Integrated Assessment Models and Proposed Approaches to Address These, through the Lens of BECCS.” *Energies* 12 (9): 1747. https://doi.org/10.3390/en12091747.

Gatersleben, Birgitta. 2018. “Measuring Environmental Behaviour.” In *Environmental Psychology*, edited by Linda Steg and Judith I. M. Groot, 1st ed., 155–66. Wiley. https://doi.org/10.1002/9781119241072.ch16.

Gatersleben, Birgitta, Niamh Murtagh, and Wokje Abrahamse. 2014. “Values, Identity and pro-Environmental Behaviour.” *Contemporary Social Science* 9 (4): 374–92. https://doi.org/10.1080/21582041.2012.682086.

Gavrilets, Sergey. 2021. “Coevolution of Actions, Personal Norms and Beliefs about Others in Social Dilemmas.” *Evolutionary Human Sciences* 3:e44. https://doi.org/10.1017/ehs.2021.40.

Gavrilets, Sergey, and Peter J. Richerson. 2022. “Authority Matters: Propaganda and the Coevolution of Behaviour and Attitudes.” *Evolutionary Human Sciences* 4:e51. https://doi.org/10.1017/ehs.2022.48.

Gavrilets, Sergey, Denis Tverskoi, and Angel Sánchez. 2024. “Modelling Social Norms: An Integration of the Norm-Utility Approach with Beliefs Dynamics.” *Philosophical Transactions of the Royal Society B: Biological Sciences* 379 (1897): 20230027. https://doi.org/10.1098/rstb.2023.0027.

Gkargkavouzi, Anastasia, George Halkos, and Steriani Matsiori. 2019. “Environmental Behavior in a Private-Sphere Context: Integrating Theories of Planned Behavior and Value Belief Norm, Self-Identity and Habit.” *Resources, Conservation and Recycling* 148 (September):145–56. https://doi.org/10.1016/j.resconrec.2019.01.039.

Global Carbon Projct. 2023. “Annual $CO_2$ Emissions from Land-Use Change – GCB. With Major Processing by Our World in Data.” https://ourworldindata.org/explorers/co2?Count=Per+country&Accounting=Territorial&Gas+or+Warming=$CO_2$&Fuel+or+Land+Use+Change=Land+use+change&Relative+to+world+total=false.

Heeren, Alexander John, Ajay S. Singh, Adam Zwickle, Tomas M. Koontz, Kristina M. Slagle, and Anna C. McCreery. 2016. “Is Sustainability Knowledge Half the Battle?: An Examination of Sustainability Knowledge, Attitudes, Norms, and Efficacy to Understand Sustainable Behaviours.” *International Journal of Sustainability in*

*Higher Education* 17 (5): 613–32. https://doi.org/10.1108/IJSHE-02-2015-0014.

IEA, I Ea. 2023. “Energy Efficiency 2023.” Paris: IEA. https://www.iea.org/reports/energy-efficiency-2023.

IPCC. 2001. *Climate Change 2001: Synthesis Report*. Edited by R. T. Watson, Daniel L. Albritton, Intergovernmental Panel on Climate Change, and Intergovernmental Panel on Climate Change. Cambridge ; New York: Cambridge University Press.

IPCC, [Core Writing Team], Katherine Calvin, Dipak Dasgupta, Gerhard Krinner, Aditi Mukherji, Peter W. Thorne, Christopher Trisos, et al. 2023. “Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (Eds.)]. IPCC, .” First. Geneva, Switzerland: Intergovernmental Panel on Climate Change (IPCC). https://doi.org/10.59327/IPCC/AR6-9789291691647.

Jones et al. 2024. “Per-Capita Greenhouse Gas Emissions. – with Major Processing by Our World in Data.” https://ourworldindata.org/co2-and-greenhouse-gas-emissions.

Juhola, Sirkku, Tatiana Filatova, Stefan Hochrainer-Stigler, Reinhard Mechler, Jürgen Scheffran, and Pia-Johanna Schweizer. 2022. “Social Tipping Points and Adaptation Limits in the Context of Systemic Risk: Concepts, Models and Governance.” *Frontiers in Climate* 4 (September):1009234. https://doi.org/10.3389/fclim.2022.1009234.

Kaiser, Florian G., Gundula Hubner, and Franz X. Bogner. 2005. “Contrasting the Theory of Planned Behavior With the Value-Belief-Norm Model in Explaining Conservation Behavior1.” *Journal of Applied Social Psychology* 35 (10): 2150–70. https://doi.org/10.1111/j.1559-1816.2005.tb02213.x.

Kaiser, Florian G., and Mark Wilson. 2004. “Goal-Directed Conservation Behavior: The Specific Composition of a General Performance.” *Personality and Individual Differences* 36 (7): 1531–44. https://doi.org/10.1016/j.paid.2003.06.003.

Karimi, Saeid, and Sahra Mohammadimehr. 2022. “Socio-Psychological Antecedents of pro-Environmental Intentions and Behaviors among Iranian Rural Women: An Integrative Framework.” *Frontiers in Environmental Science* 10 (September):979728. https://doi.org/10.3389/fenvs.2022.979728.

Kc, Samir, and Wolfgang Lutz. 2017. “The Human Core of the Shared Socioeconomic Pathways: Population Scenarios by Age, Sex and Level of Education for All Countries to 2100.” *Global Environmental Change* 42 (January):181–92. https://doi.org/10.1016/j.gloenvcha.2014.06.004.

Kelly, Rebecca A., Anthony J. Jakeman, Olivier Barreteau, Mark E. Borsuk, Sondoss ElSawah, Serena H. Hamilton, Hans Jørgen Henriksen, et al. 2013. “Selecting among Five Common Modelling Approaches for Integrated Environmental Assessment and Management.” *Environmental Modelling & Software* 47 (September):159–81. https://doi.org/10.1016/j.envsoft.2013.05.005.

Klöckner, Christian A. 2013. “A Comprehensive Model of the Psychology of Environmental Behaviour—A Meta-Analysis.” *Global Environmental Change* 23 (5): 1028–38. https://doi.org/10.1016/j.gloenvcha.2013.05.014.

Kriegler, Elmar, Nico Bauer, Alexander Popp, Florian Humpenöder, Marian Leimbach, Jessica Strefler, Lavinia Baumstark, et al. 2017. “Fossil-Fueled Development

(SSP5): An Energy and Resource Intensive Scenario for the 21st Century." *Global Environmental Change* 42 (January):297–315. https://doi.org/10.1016/j.gloenvcha.2016.05.015.

Kurisu, Kiyo. 2015. *Pro-Environmental Behaviors*. Tokyo: Springer Japan. https://doi.org/10.1007/978-4-431-55834-7.

Leach, Nicholas J., Stuart Jenkins, Zebedee Nicholls, Christopher J. Smith, John Lynch, Michelle Cain, Tristram Walsh, Bill Wu, Junichi Tsutsui, and Myles R. Allen. 2021. "FaIRv2.0.0: A Generalized Impulse Response Model for Climate Uncertainty and Future Scenario Exploration." *Geoscientific Model Development* 14 (5): 3007–36. https://doi.org/10.5194/gmd-14-3007-2021.

Lee, June-Yi, Jochem Marotzke, Govindasamy Bala, Long Cao, Susanna Corti, John P. Dunne, Francois Engelbrecht, Erich Fischer, John C. Fyfe, and Christopher Jones. 2021. "Future Global Climate: Scenario-Based Projections and near-Term Information." In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 553–672. Cambridge University Press.

Legros, Sophie, and Beniamino Cislaghi. 2020. "Mapping the Social-Norms Literature: An Overview of Reviews." *Perspectives on Psychological Science* 15 (1): 62–80. https://doi.org/10.1177/1745691619866455.

Levine, Ralph. 2003. "Models of Attitude and Belief Change from the Perspective of System Dynamics," January.

Liobikienė, Genovaitė, and Mykolas Simas Poškus. 2019. "The Importance of Environmental Knowledge for Private and Public Sphere Pro-Environmental Behavior: Modifying the Value-Belief-Norm Theory." *Sustainability* 11 (12): 3324. https://doi.org/10.3390/su11123324.

Markle, Gail L. 2013. "Pro-Environmental Behavior: Does It Matter How It's Measured? Development and Validation of the Pro-Environmental Behavior Scale (PEBS)." *Human Ecology* 41 (6): 905–14. https://doi.org/10.1007/s10745-013-9614-8.

Martinez-Moyano, Ignacio J., and George P. Richardson. 2013. "Best Practices in System Dynamics Modeling: I. J. Martinez-Moyano and G. P. Richardson: Best Practices in SD Modeling." *System Dynamics Review* 29 (2): 102–23. https://doi.org/10.1002/sdr.1495.

McKay, A., Arie Staal, Jesse F. Abrams, Ricarda Winkelmann, Boris Sakschewski, Sina Loriani, Ingo Fetzer, Sarah E. Cornell, Johan Rockström, and Timothy M. Lenton. 2022. "Exceeding 1.5°C Global Warming Could Trigger Multiple Climate Tipping Points." *Science* 377 (6611): eabn7950. https://doi.org/10.1126/science.abn7950.

Miczka, Switbert. 2006. "To TREND or Not to: Comments on the Representation of Expectation Formation Processes in System Dynamics," June.

Mikuła, Aneta, Małgorzata Raczkowska, and Monika Utzig. 2021. "Pro-Environmental Behaviour in the European Union Countries." *Energies* 14 (18): 5689. https://doi.org/10.3390/en14185689.

Milkoreit, Manjana. 2023. "Social Tipping Points Everywhere?—Patterns and Risks of Overuse." *WIREs Climate Change* 14 (2): e813. https://doi.org/10.1002/wcc.813.

Milkoreit, Manjana, Jennifer Hodbod, Jacopo Baggio, Karina Benessaiah, Rafael

Calderón-Contreras, Jonathan F Donges, Jean-Denis Mathias, Juan Carlos Rocha, Michael Schoon, and Saskia E Werners. 2018. "Defining Tipping Points for Social-Ecological Systems Scholarship—an Interdisciplinary Literature Review." *Environmental Research Letters* 13 (3): 033005. https://doi.org/10.1088/1748-9326/aaaa75.

Moore, Frances C., Katherine Lacasse, Katharine J. Mach, Yoon Ah Shin, Louis J. Gross, and Brian Beckage. 2022a. "Determinants of Emissions Pathways in the Coupled Climate–Social System." *Nature* 603 (7899): 103–11. https://doi.org/10.1038/s41586-022-04423-8.

———. 2022b. "Determinants of Emissions Pathways in the Coupled Climate–Social System." *Nature* 603 (7899): 103–11. https://doi.org/10.1038/s41586-022-04423-8.

Noyes, Willard. 2021. "COVID's Dynamic Impact on Consumer Behavior in the US." Bergen: University of Bergen. https://hdl.handle.net/11250/2761420.

OECD. 2022a. *Climate Tipping Points: Insights for Effective Policy Action*. OECD. https://doi.org/10.1787/abc5a69e-en.

———. 2022b. "Trade in Embodied CO2 Database (TECO2)." January 2022. https://stats.oecd.org/OECDStat_Metadata/ShowMetadata.ashx?Dataset=IO_GHG_2021&ShowOnWeb=true&Lang=en.

———. 2023. *Environment at a Glance Indicators*. Organisation for Economic Co-operation and Development. https://doi.org/10.1787/ac4b8b89-en.

O'Neill, Brian C., Elmar Kriegler, Kristie L. Ebi, Eric Kemp-Benedict, Keywan Riahi, Dale S. Rothman, Bas J. Van Ruijven, et al. 2015. "The Roads Ahead: Narratives for Shared Socioeconomic Pathways Describing World Futures in the 21st Century." *Global Environmental Change* 42:169–80. https://doi.org/10.1016/j.gloenvcha.2015.01.004.

O'Neill, Fanning, Lamb, and Steinberger. 2018. "A Good Life for All within Planetary Boundaries." *Nature Sustainability* 1 (2): 88–95. https://doi.org/10.1038/s41893-018-0021-4.

Otto, Ilona M., Jonathan F. Donges, Roger Cremades, Avit Bhowmik, Richard J. Hewitt, Wolfgang Lucht, Johan Rockström, et al. 2020. "Social Tipping Dynamics for Stabilizing Earth's Climate by 2050." *Proceedings of the National Academy of Sciences* 117 (5): 2354–65. https://doi.org/10.1073/pnas.1900577117.

Palmer, Erika. 2017. "Beyond Proximity: Consequentialist Ethics and System Dynamics." *Etikk i Praksis - Nordic Journal of Applied Ethics*, no. 1 (May), 89–105. https://doi.org/10.5324/eip.v11i1.1978.

Palmer, Paul I., and Matthew J. Smith. 2014. "Earth Systems: Model Human Adaptation to Climate Change." *Nature* 512 (7515): 365–66. https://doi.org/10.1038/512365a.

Park, Joohyung, and Sejin Ha. 2014. "Understanding Consumer Recycling Behavior: Combining the Theory of Planned Behavior and the Norm Activation Model." *Family and Consumer Sciences Research Journal* 42 (3): 278–91. https://doi.org/10.1111/fcsr.12061.

Parrique, T., J. Barth, F. Briens, C. Kerschner, A. Kraus-Polk, A. Kuokkanen, and J.H Spangenberg. 2019. "Decoupling Debunked: Evidence and Arguments against Green Growth as a Sole Strategy for Sustainability." European Environmental

Bureau. eeb.org/decoupling-debunked.

Pettifor, Hazel, Alessio Mastrucci, Charlie Wilson, Bas Van Ruijven, Maureen Agnew, and Thomas Le Gallic. 2024. "Endogenous Simulation of Low-Carbon Lifestyle Change in Global Climate Mitigation Pathways." *Environmental Research Letters* 19 (1): 014016. https://doi.org/10.1088/1748-9326/acf6d6.

Prochaska, James O., and Wayne F. Velicer. 1997. "The Transtheoretical Model of Health Behavior Change." *American Journal of Health Promotion* 12 (1): 38–48. https://doi.org/10.4278/0890-1171-12.1.38.

Rahmandad, Hazhir, and John D. Sterman. 2012. "Reporting Guidelines for Simulation-Based Research in Social Sciences: Reporting Guidelines for Simulation-Based Research." *System Dynamics Review* 28 (4): 396–411. https://doi.org/10.1002/sdr.1481.

Raihan, N, and M Cogburn. 2023. "Stages of Change Theory." StatPearls. Stages of Change Theory. March 6, 2023. https://www.ncbi.nlm.nih.gov/books/NBK556005/.

Rajah, Jefferson, Birgit Kopainsky, Sibel Eker, Hannah Prawitz, Jannes Breier, and Jonathan Donges. 2024. "Report on Conceptualization of Pro-Environmental Value Shifts for Modeling Human Behavioral Changes." D2.3.

Rajah, Jefferson, Birgit Kopainsky, Benedikt Tusch, and Gard Hammerseng. 2024a. "Conceptualising an Endogenous Representation of Human Behaviour Change in a Feedback-Based, Global-Scale Integrated Assessment Model [Submitted for Conference]." In . [unpublished, submitted to conference].

———. 2024b. "Towards Modelling (Pro-)Environmental Human Behaviour in Integrated Assessment Models from a Systems Approach [Submitted for Conference]." In . [unpublished, submitted for conference].

Riahi, Keywan, Detlef P. Van Vuuren, Elmar Kriegler, Jae Edmonds, Brian C. O'Neill, Shinichiro Fujimori, Nico Bauer, et al. 2017. "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview." *Global Environmental Change* 42 (January):153–68. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Richardson, George P. 2015. "System Dynamics, The Basic Elements Of." In *Encyclopedia of Complexity and Systems Science*, edited by Robert A. Meyers, 1–10. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-27737-5_536-3.

Ritchie, Hannah, Pablo Rosado, and Max Roser. 2023a. "$CO_2$ and Greenhouse Gas Emissions." Our World in Data. 2023. https://ourworldindata.org/co2-and-greenhouse-gas-emissions.

———. 2023b. "Per Capita Consumption-Based $CO_2$ Emissions." $CO_2$ and Greenhouse Gas Emissions. 2023. https://ourworldindata.org/grapher/consumption-co2-per-capita.

Rydzak, F., M. Obersteiner, F. Kraxner, S. Fritz, and I. McCallum. 2013. "FeliX3 – Impact Assessment Model - Systemic View across Societal Benefit Areas beyond Global Earth Observation." Laxenburg: IIASA. https://github.com/iiasa/Felix-Model/blob/master/Felix3_ModelReport.pdf.

Scheffer, Marten, Frances Westley, and William Brock. 2003. "Slow Response of Societies to New Problems: Causes and Costs." *Ecosystems* 6 (5): 493–502. https://doi.org/10.1007/s10021-002-0146-0.

Schoenberg, W., S. Mashhadi, C. Mauritzen, C. Smith, B. Callegari, D. Collste, and A. Gjermundsen. 2023. "Towards a Fully Coupled Integrated Climate Assessment Model: FRIDA Version 0.1 (Feedback-Based Knowledge Repository for IntegrateD Assessments)."

Schoenberg, W., A. Mauritzen, M. Adakudlu, B. Blanz, J. Breier, M. Grimeland, S. Mashhadi, J. Rajah, L. Ramme, and C. Wells. 2024. "Towards a 'Fit for Purpose', Fully Coupled, Integrated, and Interdisciplinary World-Earth Model – FRIDA Version 1.0. [Unpublished at the Time of Writing]." In . Norway.

Schwartz, Shalom H. 1977. "Normative Influences on Altruism." In *Advances in Experimental Social Psychology*, 10:221–79. Elsevier. https://doi.org/10.1016/S0065-2601(08)60358-5.

———. 1992. "Universals in the Content and Structure of Values: Theoretical Advances and Empirical Tests in 20 Countries." In *Advances in Experimental Social Psychology*, 25:1–65. Elsevier. https://doi.org/10.1016/S0065-2601(08)60281-6.

———. 1994. "Are There Universal Aspects in the Structure and Contents of Human Values?" *Journal of Social Issues* 50 (4): 19–45. https://doi.org/10.1111/j.1540-4560.1994.tb01196.x.

———. 2012. "An Overview of the Schwartz Theory of Basic Values." *Online Readings in Psychology and Culture* 2 (1). https://doi.org/10.9707/2307-0919.1116.

Skea, Jim, Priyadarshi Shukla, Alaa Al Khourdajie, and David McCollum. 2021. "Intergovernmental Panel on Climate Change: Transparency and Integrated Assessment Modeling." *WIREs Climate Change* 12 (5). https://doi.org/10.1002/wcc.727.

Slovic, Paul. 2007. "Psychic Numbing and Genocide: (718332007-003)." https://doi.org/10.1037/e718332007-003.

Steg, Linda, and Charles Vlek. 2009. "Encouraging Pro-Environmental Behaviour: An Integrative Review and Research Agenda." *Journal of Environmental Psychology* 29 (3): 309–17. https://doi.org/10.1016/j.jenvp.2008.10.004.

Sterman, John. 1987. "Systems Simulation. Expectation Formation in Behavioral Simulation Models." *Behavioral Science* 32 (3): 190–211. https://doi.org/10.1002/bs.3830320304.

———. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World.* Boston: Irwin McGraw-Hill.

Stern, Paul C. 2000. "New Environmental Theories: Toward a Coherent Theory of Environmentally Significant Behavior." *Journal of Social Issues* 56 (3): 407–24. https://doi.org/10.1111/0022-4537.00175.

Stern, Paul C, Thomas Dietz, Troy Abel, Gregory A Guagnano, and Linda Kalof. 1999. "A Value-Belief-Norm Theory of Support for Social Movements: The Case of Environmentalism." *Human Ecology Review* 6 (2).

Stevens, Stanley Smith, Geraldine Stevens, and Lawrence Edward Marks. 1986. *Psychophysics: Introduction to Its Perceptual, Neural, and Social Prospects*. Facsim ed. New Brunswick Oxford: Transaction books.

Swamy, Sibel Eker, Jefferson Rajah, Birgit Kopainsky, Kristina BenCallegari, Jonathan Donges, and Jannes Breier. 2023. “Report on Human Behavior in IAMs with Regard to Value, Norm and Behavior Changes.” D2.1.

The Norwegian National Research Ethics Comittee. 2022. “Guidelines for Research Ethics in the Social Sciences and the Humanities.” 5th edition. Oslo. https://www.forskningsetikk.no/en/about-us/our-committees-and-commission/nesh/guidelines-nesh/guidelines-for-research-ethics-in-the-social-sciences-humanities-law-and-theology2/.

Trutnevyte, Evelina, Léon F. Hirt, Nico Bauer, Aleh Cherp, Adam Hawkes, Oreane Y. Edelenbosch, Simona Pedde, and Detlef P. van Vuuren. 2019. “Societal Transformations in Models for Energy and Climate Policy: The Ambitious Next Step.” *One Earth* 1 (4): 423–33. https://doi.org/10.1016/j.oneear.2019.12.002.

UKRI. 2021. “Framework for Research Ethics.” United Kingdom Research and Innvoation - Economic and Social Research Council. August 17, 2021. https://www.ukri.org/councils/esrc/guidance-for-applicants/research-ethics-guidance/framework-for-research-ethics/our-core-principles/#contents-list.

Ulli-Beer, Silvia, Fritz Gassmann, Mathias Bosshardt, and Alexander Wokaun. 2010. “Generic Structure to Simulate Acceptance Dynamics.” *System Dynamics Review* 26 (2): 89–116. https://doi.org/10.1002/sdr.440.

Van Den Berg, Nicole J., Andries F. Hof, Lewis Akenji, Oreane Y. Edelenbosch, Mariësse A.E. Van Sluisveld, Vanessa J. Timmer, and Detlef P. Van Vuuren. 2019. “Improved Modelling of Lifestyle Changes in Integrated Assessment Models: Cross-Disciplinary Insights from Methodologies and Theories.” *Energy Strategy Reviews* 26 (November):100420. https://doi.org/10.1016/j.esr.2019.100420.

Van Vuuren, Detlef P., Elke Stehfest, David E.H.J. Gernaat, Jonathan C. Doelman, Maarten Van Den Berg, Mathijs Harmsen, Harmen Sytze De Boer, et al. 2017. “Energy, Land-Use and Greenhouse Gas Emissions Trajectories under a Green Growth Paradigm.” *Global Environmental Change* 42 (January):237–50. https://doi.org/10.1016/j.gloenvcha.2016.05.008.

Warren, Kim. 2014. “Agile SD: Fast, Effective, Reliable.” In *Proceedings of the 32nd International Conference of the System Dynamics Society. Presented at the Conference of the System Dynamics Society, Systems Dynamics Society*.

World Trans, and Charlotte Stark. n.d. “World Trans - The EU Call That World Trans Responded To.” World Trans - Transparent Assessment for Real People. Accessed June 18, 2024. https://worldtrans-horizon.eu/about-the-worldtrans-project/.

Yamano, N., and J. Guilhoto. 2020. “CO2 Emissions Embodied in International Trade and Domestic Final Demand: Methodology and Results Using the OECD Inter-Country Input-Output Database.” OECD Science, Technology and Industry Working Papers 2020/11. Vol. 2020/11. OECD Science, Technology and Industry Working Papers. https://doi.org/10.1787/8f2963b8-en.

Zhang, Lu, Jorge Ruiz-Menjivar, Biliang Luo, Zhihui Liang, and Mickie E. Swisher. 2020. “Predicting Climate Change Mitigation and Adaptation Behaviors in Agricultural Production: A Comparison of the Theory of Planned Behavior and the Value-Belief-Norm Theory.” *Journal of Environmental Psychology* 68 (April):101408. https://doi.org/10.1016/j.jenvp.2020.101408.

Zhang, Xiaojie, Guojie Geng, and Ping Sun. 2017. “Determinants and Implications of Citizens’ Environmental Complaint in China: Integrating Theory of Planned Behavior and Norm Activation Model.” *Journal of Cleaner Production* 166 (November):148–56. https://doi.org/10.1016/j.jclepro.2017.08.020.

Zwislocki, Jozef J. 2009. *Sensory Neuroscience: Four Laws of Psychophysics*. Boston, MA: Springer US. https://doi.org/10.1007/978-0-387-84849-5.

# A. Appendix A – Model Documentation

This section contains two parts. First a detailed description, in prose, that explains the modelling choices and conceptualizations. The second part depicts the formal model documentation following the recommendations by Rahmandad and Sterman (2012).

**Detailed Model Description**

This section introduces the precise modelling choices, its stocks, flows, modules, variables and exogenous estimates and parameters. Throughout this description, where necessary, I first introduce the structure on a more general level, while then bringing it together with the insights from the literature screening and relating them to the problem at hand.
A broad separation of the involved modules and sectors can be seen in Figure A-1- the big picture overview. In the following, I will look at each of part of the model in more detail.

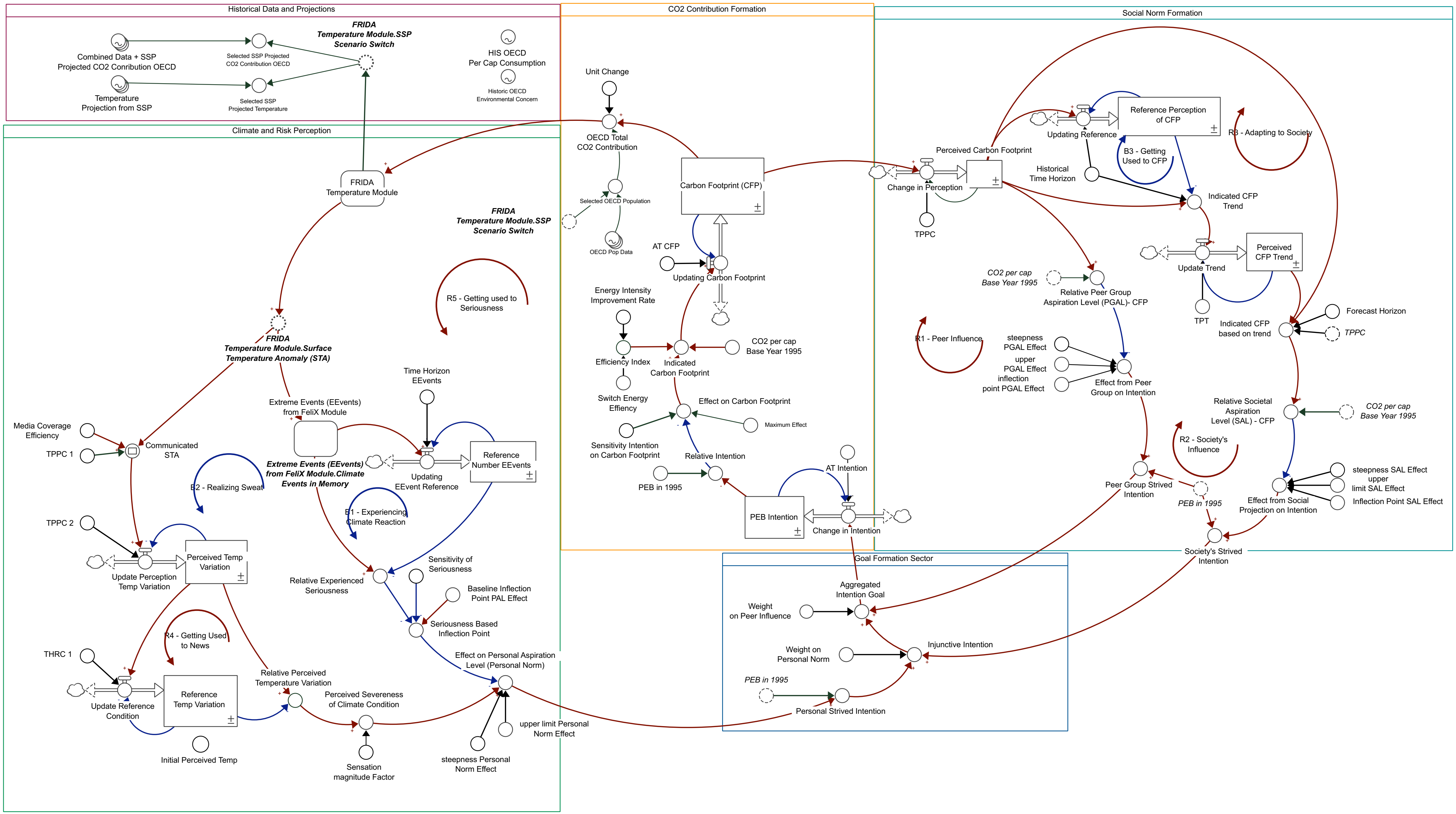


*Figure A-1 - Complete Model Overview*

**$CO_2$ Contribution Formation**

This sector represents the translation of Pro-Environmental-Behavioral Intention (PEBI) into Carbon Footprint (CFP). To operationalize the concept of PEB that was laid down in Chapter 2, I will conceptualize PEB within the model through CFP as a proxy. This is since it (1) indicates a clear direction: Higher intention leads to behavior that causes a smaller CFP (2) it allows for a broad number of behaviors to be subsumed under one resulting impact: Carbon Footprint. There is clearly more impactful (changing to clean energy) and less impactful (reducing the time and temperature when showering) behavior. Both might be born from an intention towards more PEB, and both result ultimately in a (bigger or smaller) change in one's Carbon Footprint.

The $CO_2$ Contribution Formation shows the adaptation of PEBI to a generated goal and how it reflects on CFP. The two central stocks in this sector are *Carbon Footprint (CFP)* and *PEB Intention*. PEBI is conceptualized ranging between 1 and 0 and reflects a continuous measure, where 1 PEBI refers to 100% Intention. This conceptualization should be understood in the concept of UBS (Umweltbewusstseinsskala) by Bauske and Kaiser (2019). The UBS combines 75 opinion statements and behavioral self-reports to assess people's problem awareness and willingness to act, to produces a scale of environmental consciousness. This scale has similarities to the more behavior orientated GEB scale (Kaiser and Wilson 2004), and also uses a Rasch-type method that allows additional assessment of relative difficulty of expression of the tested items. As Bauske and Kaiser (2019, 17) note: "A measure of environmental consciousness that has been constructed taking into account the difficulty of the included items and encompassing both self-reports on behaviour and expressions of opinion shows strong correlations with actual environmental behaviour ". On that scale "1" translates to as answering all survey questions assessing a with yes, displaying utmost effort in pro environmental behavior, while the Rasch-Type approach indicates additionally the "ease" of the actions in questions. In that it captures parts of the concept of "perceived behavioral control", which includes factors that facilitate or prohibit the behavior coupled with the subjective evaluation of one's control (Ajzen 2020). Note, that this is not a representation of the very own individual subjective control beliefs, but the social norm in its function as information conveyor, gives an indication about average ease of performing the behavior. Since this model is only conceptual and aggregates about many behaviors, the individual PBC is not factored in, yet might by amended at a different point in time.

Here, PEBI for OECD is anchored in the Base Year at 1995 with 54.5% (Franzen and Vogl 2013). Note, that this no UBS-measurement, but refers to environmental concern, since there are no UBS measurements for the OECD. Bauske and Kaiser (2019) indicate german UBS at 51% in the year of 1996. While being aware that both measurements are not substitues, due to the proximity of both and assumed representativeness, 54,5% was used as Base Year Intention for the OECD to stick to OECD data while maintaining the UBS concept in mind.

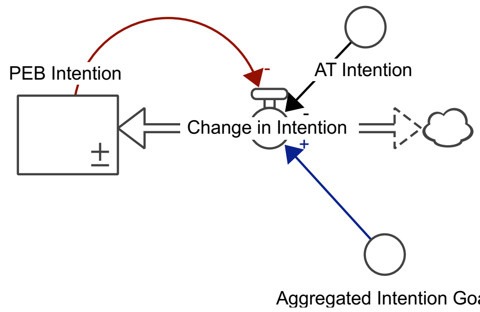


*Figure A-2 - Stock and Flow structure of adjusting the PEB intention*

Figure A-2 depicts the structure of the adjustment process. The adjustment of PEBI follows a simple first order information delay (Sterman 2000, 428–32), depicting a goal-gap formulation (Sterman 2000, 523–24). The different routes of influence on the intention-goal are summarized in the *aggregated goal of intention* (see end of this chapter for detailed description) which functions as an input to drive the adjustment of the *PEB Intention* towards the goal, with *AT Intention* as the adjustment time. Raihan and Cogburn (2023) argue in relation to the transtheoretical model, a popular approach to explain and predict intentional behavior change, that there is a necessary period of time to change behavior in the long term. They report on a study investigating intentional behavior change, where it took participants up to 5 years to establish a very robust new behavior (Raihan and Cogburn 2023; Prochaska and Velicer 1997).[9] Here, 5 years was used as the starting point for the adjustment time, which was then calibrated to 3 (2.78).

The change in PEBI is then translated into an indicated amount of CFP, measured in tonnes $CO_2$ per person per year. Considering the UBS data from Germany in the years between 1996 and 2016 (Bauske and Kaiser 2019), and correlating estimates from this study to data of consumption-based $CO_2$ emissions in the same period (Ritchie, Rosado, and Roser, 2023), shows that a nonlinear relationship describes the data most fitting. Yet, due the scope of the data available, the range of data points remains too small to construct a reliable estimate

[9] In its original form, the TTM refers to intentional change in behavior that is decisively adverse (e.g. smoking, alcohol abuse, etc.). This is not to say that changing ones PEBI is comparable to tackle addictive behavior. The time horizon mentioned in the TTM only functions as a initial inspiration for the needed time to establish long-term intentional behavioral change.

for the complete effect that translates PEBI to CFP. As mentioned above, this translation is a considerable uncertainty in the model, yet it needs to be hypothesized. For example, Beckage et al. (2018) use three different forms of effects and test out linear, logistic and cubical relations between risk perception and action. While the previous chapters of the thesis argued that there is considerable certainty about the existence of an effect from intention on behavior, the precise relation is unclear so far.

On that ground, the effect relating PEBI and CFP is hypothesized and assumed as a non-linear relationship in the form of a power function, the effect is depicted in Figure A-3. The power function includes the 1-1 point translating a "normal intention" to the "normal CFP". The effect is anchored around the corresponding values of the base year 1995, being *PEB Base Year 1995* = 0.545 (dmnl) (Franzen and Vogl 2013) and $CO_2$ *per cap Base Year 1995* = 11.3 (tonnes$CO_2$/person/year ) (OECD 2022b; Yamano and Guilhoto 2020). Nevertheless, it moderates the change below and above the anchors, indicating the people might react to decrease in intention with some inertia but increase their CFP more significantly, once intention falls very low. On the other side, increasing intention will always yield an inert decrease in the effect to reflect the technical, economic and social difficulties decreasing CFP. The corresponding structure of the effect is also depicted in Figure A-3.

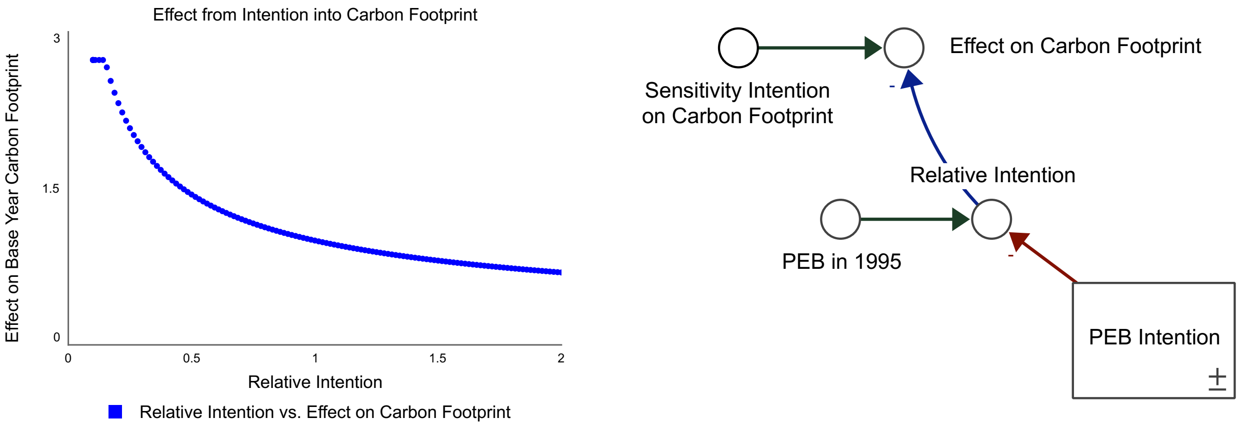


*Figure A-3 - Structure graph of the effect relating normal intention to CFP (left) and Stock and Flow Structure of the effect on CFP (right)*

The analytical version of the effect corresponds to the equation of:

$$Effect\ Intention\ on\ Carbon\ Footprint =$$
$$MIN\ (Maximum\ effect, Relative\ Intention^{Sensitivity\ Intention\ on\ CFP})$$

Where MIN(Maximum Effect,…) ensures a limit on the effect. This is because, even if people are careless, they cannot reasonably increase their CFP endlessly. To reason about a justifiable upper limit, I used the average carbon footprint of all OECD members in the most recent year (2018) (OECD 2022b) and compared it to the average of the OECD in the respective year to calculate the standard deviation around the mean. I then used 5 standard deviations to calculate the "maximum" CFP that the effect will be able to represent, leading to a maximum effect of 2.73. This means that 2.73*Intitial Base Year CFP results in an CFP that is 5 standard deviations away from the mean CFP of the OECD in the year 2018.

The indicated CFP is next manipulated by an efficiency index, comprised of

$$Efficiency\ Index = Energy\ Intensity\ Improvement\ Rate * Switch\ Energy\ Efficiency$$

, which is (de-)activated by the *Switch Energy Efficiency*. Energy Efficiency is an important parameter, since (1) it will drive the indicated CFP continuously down and (2) they are a common way to represent technological development or even policy choices (Riahi et al. 2017). The indicators used in the SSPs, energy intensity improvement rate (varying across the marker scenarios between ~ 0.5%/year in SSP5 and 2%/year in SSP1) and carbon intensity improvement rate (varying across the marker scenarios between ~0.1%/year SSP5 and 0.6%/year SSP1) (Riahi et al. 2017), are collapsed into a single energy intensity improvement rate. It is assumed and generalized, that both energy efficiency and carbon efficiency result in lower CFP. The value of the rate of improvement is kept constant to 0.8%/year throughout the time period and rests on data from the IEA energy intensity improvement rate for the years between 2001 and 2010 (IEA 2023).

Ultimately, *indicated Carbon Footprint* and *Carbon Footprint (CFP)* follow the structure of a goal gap formulation, that updates the displayed behavior. The *indicated CFB* is thereby calculated by relating the baseline $CO_2$ emission per cap to the relative intention, translated by the *effect of intention on CFP* and manipulated by the *efficiency index*.

$$Indicated\ Carbon\ Footprint = Effect\ from\ Intention\ on\ CFP * CO2\ per\ Cap\ Base\ 1996 * Effiency\ Index$$

and

$$Carbon\ Footprint_{t+1} = \frac{(Indicated\ Carbon\ Footprint - Carbon\ Footprint_t)}{AT\ CFP}$$

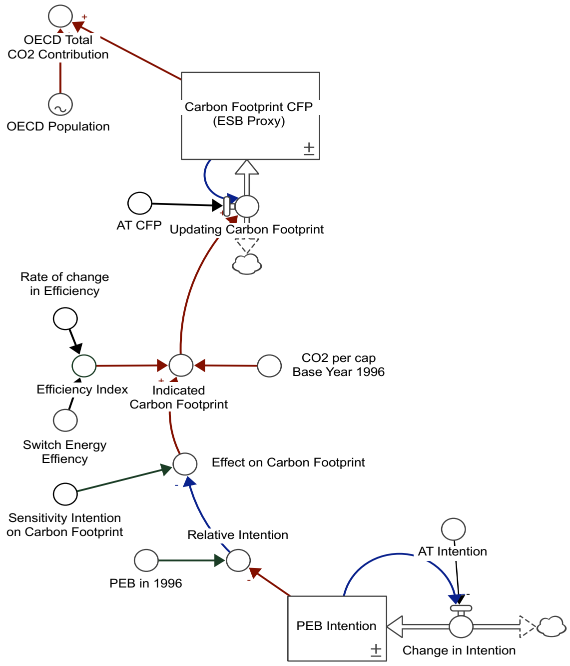


*Figure A-4 - Stock and Flow Structure of the CO2 Contribution Formation*

With *AT CFP*= 4.5 (calibrated) years to adjust and display fully the adapted emission behavior. The structure for the process of translating the PEBI into CFP is depicted in Figure A-4. Departing from the current individual carbon footprint, the model calculates a $CO_2$ contribution of the OECD region. For that, the individual CFP is simply multiplied by the population of the OECD region (SSP 2 population data is based on (Kc and Lutz 2017; Fricko et al. 2017). Initially, the actual historic population until 2005 was considered as a data input. Yet, the unclear inclusion of member states (several members were added in the period from 1996 to 2021), as well as the underlying assumptions about population dynamics (GDP, fertility rates etc.) inherent in the SSP-2 projection (Riahi et al. 2017; Fricko et al. 2017) made it difficult to harmonize the historical data with the projected data. Therefore, the population from 1996 until 2005 was estimated through extrapolation of the SSP-2 data. Although this implies a data inaccuracy, this way the model was anchored in the development of on data source, namely the SSP-2 scenario. The OECD total $CO_2$ contribution is calculated by

$$OECD\ Total\ CO2\ Contribution = CFP_t * \ OECD\ Population_t$$

Where $CFP_t$ = the current Carbon Footprint at time (t) and OECD Population = the projected OECD population at time (t).

In sum, this sector receives an aggregated intention goal as its input, translates that to an indicated carbon footprint and calculates the total $CO_2$ contribution of the OECD that is then used in the climate and risk perception sector. Before turning towards the climate sector, the next section will look at the social norm formation.

## Social Norm Sector

As argued above, social norms - disjunctive and injunctive ones - play an important role in forming intention (Ajzen 2016; 2001; Kaiser, Hubner, and Bogner 2005; Kurisu 2015; Dannenberg et al. 2024). The conceptualization follows the theoretical concepts laid out in the previous chapter and focuses on constructing (1) the disjunctive norm as perception of the behavior of the "peer group", collective behavior in this case, and (2) the injunctive norm as expectation and projection about the course of behavior within the society that informs the trajectory of the norm development. The structure, depicted in Figure A-5, is adapted from formulations on the TREND function, generally and successfully used to model complex expectations (Sterman 2000; 1987; Miczka 2006).

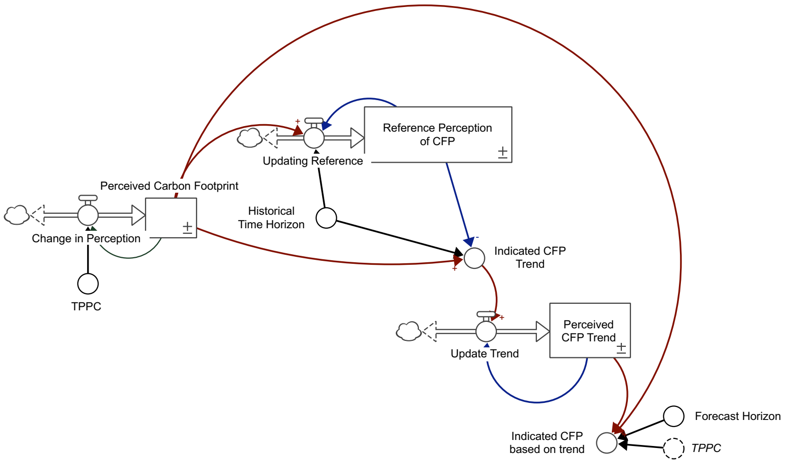


*Figure A-5 - Stock and Flow Structure of Descriptive and Injunctive CFP*

The TREND function assumes a univariate, historical driven, autoregressive mechanism behind forming expectations, which means that the expectation is based on one input information, bound to historical time series and projects a regressive trend into the future (Miczka 2006). Despite the critique, that the TREND formulation represents not the most adequate mechanisms at hand (Miczka 2006), the TREND function has been used successfully in numerous models (Sterman 1987). If applied to a specific behavior, additional relevant and instructive information or variables that are used by agents to form expectations can be used for improving the TREND function (Miczka 2006). Due to lack of data about the precise formation of expectations about societal trends, it is deemed appropriate to use the TREND function in this case.

The TREND function "(…)represents a behavioral theory of how people form expectations and takes into account the time required for people to collect and analyze data, the historic time horizon they use, and the time required to react to changes in the growth rate" (Sterman 2000, 634). In particular, first, the smoothed input forms the perceived present condition. The argument for the smooth is rested on assumptions about measurement delays and to eliminate and make sense of noise from the data. This perceived condition then informs the reference condition, the memory of the measured perceived input to compare growth or decline. Third, an indicated trend (in relation to the time horizon of the reference condition) is calculated relative to the reference (this indicates the perceived fractional growth of the smoothed input in relation to the reference). Lastly, this trend undergoes a final smoothed adjustment process, in which a previous expected fractional growth rate is updated with the new indicated information (Sterman 1987; 2000).

Here, this concept is used as follows: Carbon Footprint, the input, is smoothed by a TPPC (time to perceive present condition) to calculate the *Perceived Carbon Footprint.* The value of TPPC = 3, is assumed to be longer than a year, as suggested by (Sterman 2000, 636), and was calibrated. The *Perceived CFP* informs the reference condition *Reference Perception of CFP*, constructed over time window that is assumed and calibrated to 25 years, indicating, that trends in the population are monitored that long. Both inputs are then related to each other, normalized by the *Reference Perception of CFP* and related to the time horizon. Lastly, this *indicated CFP Trend* is then smoothed by the *Time to Perceive Trend (TPT)* towards the *Perceived CFP Trend.* sums up the equations for the stocks and flows involved.

*Table 7 - Equations involved in the TREND function*

| Variable | Equation |
|---|---|
| Change in Perception | $\frac{Carbon\ Footprint_t - Perceived\ Carbon\ Footprint_t}{TPPC}$ |
| Perceived Carbon Footprint$_{t+1}$ | $Perceived\ Carbon\ Footprint_t + Change\ in\ Perception$ |
| Update Reference | $\frac{Perceived\ Carbon\ Footprint_t - Reference\ Perception\ of\ CFP_t}{Historical\ Time\ Horizon}$ |
| Reference Perception of CFP$_{t+1}$ | $Reference\ Perception\ of\ CFP_t + Update\ Reference$ |
| Indicated CFP Trend | $\frac{Perceived\ Carbon\ Footprint - Reference\ Perception\ of\ CFP}{Reference\ Perception\ of\ CFP} / Historical\ Time\ Horizon$ |
| Update Trend | $\frac{Indicated\ CFP\ Trend - Perceived\ CFP\ Trend_t}{TPT}$ |
| Perceived CFP Trend | $Perceived\ CFP\ Trend_t + Update\ Trend$ |

Ultimately, this expectation about the fractional growth of CFP is then used to calculate the anticipated CFP at the end of the Forecast Horizon of 5 years (assumed and calibrated value). The equation for this projected CFP is adapted from (Sterman 2000, 644):

$$Indicated\ CFP\ based\ on\ trend = Perceived\ Carbon\ Footprint * (1 + TPPC * Perceived\ CFP\ Trend) * e^{Perceived\ CFP\ Trend * Forecast\ Horizon}$$

First, the *Perceived Carbon Footprint* is adjusted to the expected actual value (multiplying with TPPC) and then altered according to the cumulated growth of the forecast horizon (the exponential part). The following paragraphs place these calculations in the theory discussed above.

**Descriptive Norm**

As discussed in Chapter 2, the descriptive norm can be seen as the "[…] empirical component that indicates what other people do (…)"(Dimant, Galeotti, and Villeval 2023). Following Dannenberg et al. (2024), disjunctive norm can be conceptualized, as in several empirical experiments, as either objective or perceived social disjunctive norm. Objective refers to settings, in which information about behavior of others was given to individuals, while in settings with perceived social descriptive norm, individuals had to guess or estimate information about others (Dannenberg et al. 2024).

Here, the *Perceived Carbon Footprint* is used as a proxy for a perceived social descriptive norm. Assuming that the CFP of the average individual is somewhat representative of the average behavior of some societal group, the perceived CFP stock represents the perception of the emission behavior of others. Note that this is a limiting assumption, since peer groups probably form around specific behaviors. The precise dynamic of this average peer group behavior is a limitation and needs further research and justification. Yet, for the scope of this thesis, it may suffice to assume that, while the actual average behavior of a specific peer group remains unclear, an average peer group behavior in society can be assumed through the process described above.

**Injunctive Norm**

As second component, injunctive norms "(…)[are] used to reference the modal or average attitude towards a behavior" (Dannals and Miller 2017). Dannenberg et al. (2024) argue – analog to the specification of objective and perceived as above – that objective injunctive norms are the aggregation of an attitude toward behavior from individuals across the population. Here, this is depicted through the observed TREND of change in the CFP and the projected anticipated average CFP in 5 years, given the current observed development. Hence, it is in the indication of the trend, individuals expect to perceive in society further years down the road and its respective behavior.

In the model, both social norms are normalized towards the initial $CO_2$ emission from the base year, resulting in a relative aspiration level, the level of CFP that either the peer group (*Peer Group Aspiration Level CFP (PGAL)*) or the societal projection (*Societal Aspiration Level CFP (SAL)* is striving to. Consequently, both aspiration levels are translated "back" to an indicated intention. This is assumed as a non-linear relationship in the form of an S-shape. This represents that below and above the inflection point (1/1) people react with some inertia and increase their sensitivity to a change in relative CFP (either from the group or from societal projection) towards the upper and lower limit. The corresponding structure of the entire sector plus the strived intentions is depicted in Figure A-6. The effects are graphically depicted in Figure A-7.

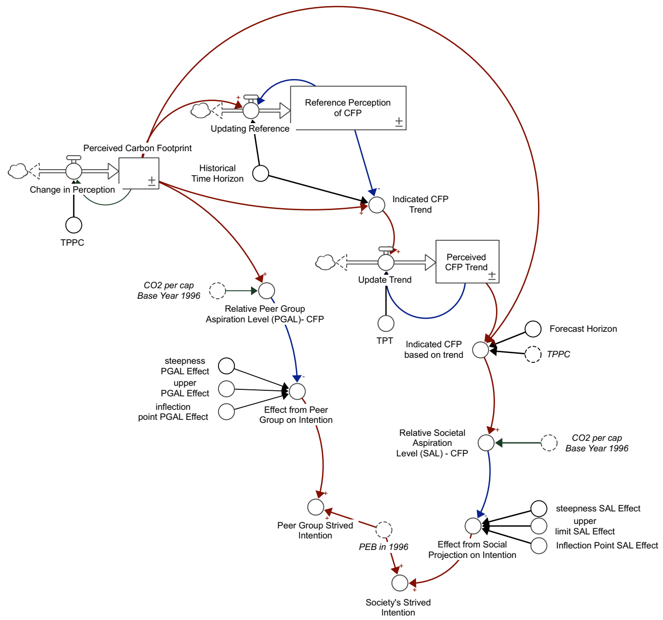


*Figure A-6 - Stock and Flow Structure of Entire Social Norm Formation*

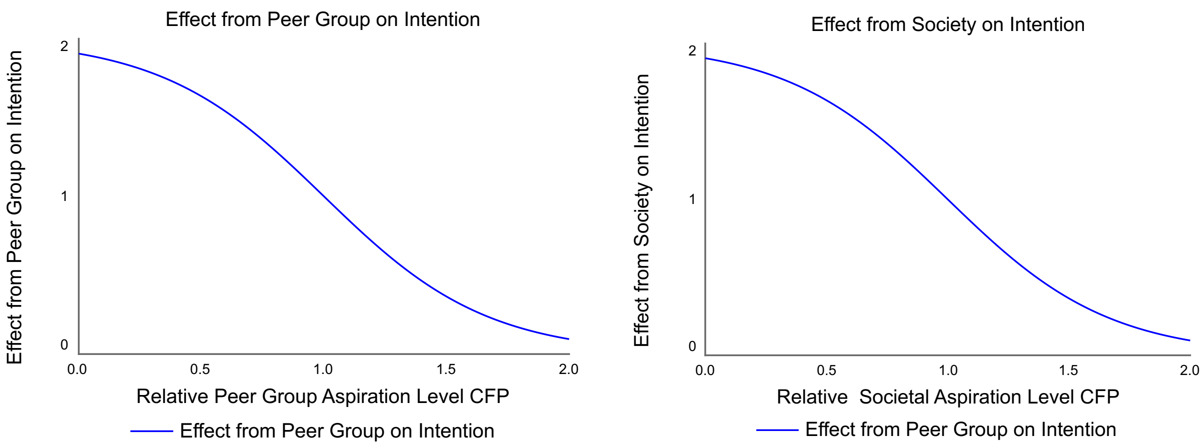


*Figure A-7 - Structure Graph of Effects from Peer Group and Society on Intention*

The analytical version of the effect corresponds to the equation of:

$$Effect\ Intention\ from\ Social\ Projection\ on\ Intention = \frac{upper\ limit\ SAL\ effect}{1 + e^{steepness\ SAL\ effect * (Relative\ Social\ Aspiration\ Level\ ESB\ (SAL) - Inflection\ Point\ SAL\ Effect)}}$$

Where the (1) *upper limit intention effect* = 2 restricts, that CFP cannot be extended infinitely and 0 intention corresponds to double the amount of CFP as normal, (2) the *steepness intention effect = 3* (calibrated) corresponds to the sensitivity around the inflection point, (3) *Relative Social Aspiration Level* is the normalized input of CFP (against the base year) and (4) the *inflection point intention effect* = 1 ensures, that the S-Shape changes the mode of growth in the point (1/1), by that translating a "normal CFP" to the "normal Intention". Ultimately by multiplying with the *Base year PEB Intention,* this effect calculates the *Peer Group's Strived Intention* and *Society's Strived Intention.*

According to Legros and Cislaghi (2020), social norms can exert influence through and fulfill the function of (1) informing individuals about efficient or reasonable courses of action (2) create an external obligation, relating social or actual punishment as consequences to norm deviation and (3) act as internal obligations, in which the consequences of deviation result in guilt or cognitive dissonance. Unlike in TPB (Ajzen 2020), social norms do not only inform the subjective norm. Dannals and Miller (2017) and Legros and Cislaghi (2020) both argue that social norms also bear insights about the ease of the task in question, its efficiency. Doherty and Webler (2016) even argue that especially descriptive social norms can be used to explain variance in the self- and collective efficacy. If others do it, I might be able to do it as well. This argument fits with the theory of TPB in multiple ways: (1) Depicting the mechanisms about forming subjective norms based on social norms and (2) integrating information about the perceived efficacy as a proxy for perceived behavioral control.

### Climate Sector, Seriousness, Severeness and Personal Norm

This sector includes both modules from the IAMs. The FRIDA 1.0 Climate Module is used for temperature calculation with given emission data input - see Schoenberg et al. (2024) for documentation. The FeliX Extreme Events Module is used in its entirety to produce a number of extreme events given a temperature input – see Eker et al. (2023) for the model documentation. Note, that the following part only covers documentation for additional model parts.

Departing from the individual carbon footprint, the OECD Total $CO_2$ Contribution is connected to the temperature module of FRIDA. The SSPs provide exogenous input for the relevant greenhouse gases ($CH_4$, $CO_2$, $SO_2$ and $N_2O$) used in the FRIDA model. To couple the model input of OECD emission behavior, the $CO_2$ input from the SSP database (Riahi et al. 2017; Fricko et al. 2017; Van Vuuren et al. 2017; Fujimori et al. 2017; Kriegler et al. 2017; Calvin et al. 2017) was decomposed in OECD and "the rest", subtracting the exogenous projected OECD contribution and replacing it by the input endogenously generated by the model. The new *Total $CO_2$ emissions* is calculated by

$$Total\ CO2\ emissions$$
$$= \text{Selected SSP World Minus OECD Total CO2 Emission} + \text{OECD\_Total\_CO2\_Contribution}$$

SSPs provide only data from 2005 onward. For the years from 1995 to 2019, the respective SSP-2 data was exchanged by the actual GHG emission data from respective years (Community Emissions Data System (CEDS) 2024; Global Carbon Projct 2023; Jones et al. 2024; Ritchie, Rosado, and Roser 2023a). This was to ensure, both a smooth transition between actual data and projected input based on the SSP-2 scenario and to bring the exogenous input closer to reality.

As mentioned, the FRIDA Temperature module provides, given the endogenous OECD contribution and projected greenhouse gas contribution from the SSP-2 scenario, a *Surface Temperature Anomaly (STA)*, an indicator of the global temperature rise compared against the pre-industrial age.

This feeds back into the main model structure through two routes, (1) and informational route and (2) and experienced route.

**Cognitive Information Route through Severeness**

The informational route depicts the communicated development on the current climate conditions. These communicated consequence are dependent on the media coverage efficiency (the amount on information correctly analyzed and processed by scientific research and media coverage) and its respective time delay. The *Communicated STA* translates to an information about the current STA, smoothed by an assumed third order information delay to depict the process of data collection, analysis, publication and communication:

$$Communicated\ STA =$$
$$SMTH3(Surface\ Temperature\ Anomaly * Media\ Coverage\ Efficiency, TPPC_1)$$

where *SMTH3* is a STELLA software built-in to calculate the third order information delay, *TPPC_1 = 3 years* corresponds to the time delay (calibrated) and *Media Coverage Efficiency* is a control parameter to depict potential media efficiency loss (to inefficiencies in research, media and communication) and was assumed and calibrated to *Media Coverage Efficiency = 0.78*, indicating that only 78% of the original STA is transmitted.

Similar to the previously described formalization on expectation development, the *Communicated STA* is used as an input to form a *Perceived Temp Variation*, i.e. a perception about the variation of the Surface Temperature, that is adjusted by an information-delay (time delay *TPPC2 = 1.65 years (calibrated)* anchoring and adjustment process, and a *Reference Temp Variation*, i.e. an indicator of what people perceive as reference. This formalization represents the process by which people adapt to the variation in temperature – they get used to a change in temperature and keep in mind a representation of the variation considered over the time horizon THRC_1 = 10 years (the value was assumed and calibrated). The following equations depict the use of the *Communicated STA*, figure Table 1 depicts the corresponding structure.

$$Update\ Perception\ Temp\ Variation = \frac{Communicated\ STA - Perceived\ Temp\ Variation_t}{TPPC_2}$$

$$Perceived\ Temp\ Variation_{t+1} = Perceived\ Temp\ Variation_t + Update\ Perception\ Variation$$

$$Update\ Reference\ Condition = \frac{Perceived\ Temp\ Variation_t - Reference\ Temp\ Variation_t}{THRC\_1}$$

$$Reference\ Temp\ Variation_{t+1} = Reference\ Temp\ Variation_t + Update\ Reference\ Condition$$

The previous calculation provides insights in the relative perceived temperature variation, dependent on a changing impression about the environment, the reference condition. Yet, insights from psychophysics suggest, that this information is not necessarily what people might have in mind when making sense of these sensations. It has to be noted, that the field of psychophysics was initially used to think about relations between physical, observable stimuli and their translation into psychological representation of those stimuli (the sensation of them) (Zwislocki 2009). A classic example, and the initial exploration field, is the study of volume or brightness representation. Research shows, that the physical stimulus (for example a brightness) is transformed against the background condition (e.g. brightness of the room) into a modified sensation representation by a power law (Zwislocki 2009; Stevens, Stevens, and Marks 1986). In its general form, this power law takes the form of $\psi = k\phi^{\theta}$ with ψ symbolizing the sensation magnitude (our perceived severeness), ϕ the magnitude of the physical stimulus (our) relative temperature variation), θ the power exponent (our sensation magnitude exponent, and k, a dimensional constant (note, that this constant is omitted here, since it is cancelled out mathematically through the ratio formation of the temperature variation).

Stevens, Stevens, and Marks (1986) notes, that the exponent is fixed given the continuum of scale and the varying circumstances yet remains the same throughout the relation it is supposed to describe. A list of varying exponents in relation to its perceptual continua can be found in Stevens, Stevens, and Marks (1986), and Chen et al. (2021). For the applications in question, it can be seen, that the exponent varies dependent on the experiment between 0.42 and 3.5 with values below 1 indicating a concave curve, the concept of marginal diminishing growth, and above 1 indicating an exponential growth between stimulus and perception.

Investigating its generalizability from physical stimuli to social concepts, Stevens, Stevens, and Marks (1986) discusses several experimental applications of the power law in social settings, among them judging the magnitude of an attitude, the perception of prestigious occupations or the seriousness of offenses. The precise translatability of the concept remains in its essence contested, since the experiments tried to use translations of the concepts into physical stimuli and refer to specific mechanisms of scaling and continuum construction. Nevertheless, Stevens concludes, that given the experimental evidence there is reason to infer a power-law like relationship in respect to human judgement (Stevens, Stevens, and Marks 1986). In more recent times, the power law was applied to psychological numbing of genocides (Slovic 2007) and as part of a representation of human behavior during the COVID 19 pandemic (Noyes 2021). In its application in this model, the concept remains an uncertainty and assumption. Yet it is a step in capturing the mechanism that the judgment of the severeness of a condition is dependent on the reference scale of stimuli and diminishing in its deviation from the relative value. Figure A-8 shows the effect on calculating the severeness of the current condition given the relative perceived temperature rise.

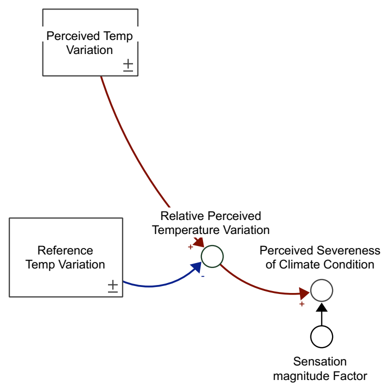


*Figure A-8 - Structure of Perceived Severeness Formation*

The value of the exponent *Sensation Magnitude Exponent* = 0.75 was calibrated in the range from 0 to 1. In consequence, the *Perceived Severness of the Temp Variation* is given by the equation

$$Perceived\ Severness\ of\ Temp\ Variation$$
$$= Relative\ Perceived\ Temp\ Variation^{Sensation\ Magnitude\ Exponent}$$

A more detailed demarcation of the concept of severeness follows the explanation of the second, experience route, in its contrast to the concept of Seriousness.

**Experienced Route through Seriousness**

The experienced route starts again with the surface temperature anomaly. The FRIDA output is hooked up to the module for extreme event calculation of the FeliX IAM (for documentation of the FeliX model see Eker et al. (2023). In its essence, this module takes as an input the Surface Temperature Anomaly and calculates a number of extreme climate events for each year. The formulation is based on work from Beckage et al. (2018). In their article, the authors used a different set of input parameters (Beckage et al., Supplementary Material, 2018), which was adapted by for the FeliX model (Eker, Reese, and Obersteiner, Supplementary Material, 2019). In its essence, the formalization considers a reference mean temperature and provides a Poisson-distributed output number of extreme climate events. It serves as a relation between the change in temperature and a projected consequence in terms of climate events induced by such a change like droughts, floods, cyclones etc. By that, it represents the narrative, that not only is earth "warming" up, but in its consequence, climate events become more frequent and extreme.

The output of the FeliX module is a specific number of climate events in memory, which is filled with the incoming events and depleted by a forget-factor, to keep a stable comparative time horizon sensitive to periodical developments. Figure A-9 depicts the structure of the integration into the model. The events in memory are related to a *Reference Number of Extreme Events*, to form the *Relative Experienced Seriousness*. The reference of extreme events is initialized in $Reference\ Number\ EEvents_{t=0} = 20$ events indicating an amount of events that are considered to be "normal", as is used by (Beckage et al. 2018), and is smoothed throughout a time horizon of *Time Horizon EEvents* = 16.2 years (calibrated).

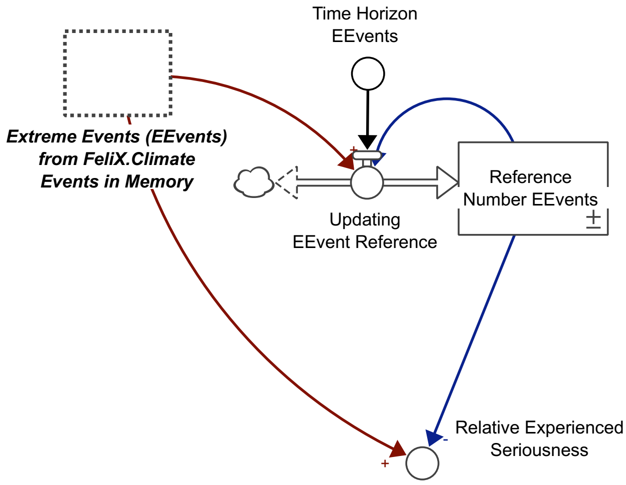


*Figure A-9 - Stock and Flow of FeliX Integration and Extreme Events Structure*

The conceptual difference between the seriousness and the severeness lies in the experienced and informational content. While people in more sheltered and less affected regions might be aware, cognitively, of the variation of the condition of the climate, they might not perceive them directly. This awareness refers to the perceived severeness of the condition. On the other hand, imagine someone who is skeptical or unaware of informational input from media and science but experiences more droughts and floods more frequently in its region. This person might not cognitively think about a relative rise in temperature cognitively but becomes aware about the consequences directly through experiences. This awareness refers to the seriousness of the current condition.

The need to integrate two different concepts becomes more apparent once we think about some extreme cases: Imagine the person from before, sheltered and without direct experience of the consequences. This person might very well, due to personal conviction and values, be influenced by the perceived severeness and forms an intention to behave more pro-environmentally. Vice versa, the person unaware of information based severeness, may not need the cognitive validation, that the situation is severe. They experience it directly. Consequently, both routes ultimately should result in a variation of personal conviction to form a pro-environmental intention.

In chapter 2 I laid out, that the TPB relies on personal beliefs to form the personal norm which in turn informs intention. To grasp this concept in the model, some combination of the severeness and seriousness needs to be translated into a *Personal Aspiration Level of Intention*, i.e. personal norm. Note, that this route is still employing cognitive evaluation of the behavior in question, and in contrast to the peer group related goal, is not informed by comparison to others.

The VBN is more nuance in this picture. As explained above, the VBN rests on the assumption, that certain sets of prioritized values influence the amount of support for pro-environmental intention. That is to say that a person holding a more altruistic or biospheric worldview might perform PEB with a higher probability than one employing a more egoistic worldview. Here again, it is assumed, that a combination of seriousness and severeness should capture this concept. Yet, due to its fluidity, a one-shot threshold and categorization of worldviews might be too simplistic. Additionally, as argued above, once people feel personally affected by the current condition, even egoistic worldviews might lead to a higher willingness of action. This relates to the awareness of consequences which indicates that you perceive adverse consequences for your valued objects (Kaiser, Hubner, and Bogner 2005; Stern 2000; De Groot and Steg 2008; 2009). Someone who employs a biospheric worldview is prone to act "earlier" as someone who needs to feel the consequences affecting them personally. A connection can be made here to PMT, where the severeness is used to form a threat appraisal (Floyd, Prentice-Dunn, and Rogers 2000). In sum, the experience-based route activates different worldviews by conceptualizing the shift in values affected.

In using the combination of both, cognitive severeness and felt seriousness, I have tried to account for all three concepts, i.e. the awareness of consequences from the VBN, the concept employed by the PMT and the personal beliefs referred to by the TPB.

The *Effect on Personal Aspiration Level* takes the form of an s-shaped growth where the input is set to the *Perceived Severeness of Climate Condition* and the inflection point of the effect is set to a transformed input of the *Relative Experienced Seriousness.* The equation of the effect is depicted below, while the reader is referred to the *Effect Intention from Society on Intention* above for the general explanation of the analytically constructed s-shape.

$$Effect\ on\ Personal\ Aspiration\ Level = \frac{Upper\ Limit\ Personal\ Norm\ Effect}{1 + e^{\text{Steepnes Personal Norm Effects} * (\text{Seriousness Based Inflection Point}(-\text{Perceived Severeness of Climate Condition})}}$$

Figure A-10 shows the effect in the normal condition for the full range varying the input *Perceived Severeness of Climate Condition* from 0 to 2, with 1 indicating a "normal" severeness. The inflection point is set to 1, indicating that with a "normal" severeness (1) and a "normal" seriousness (1) , effect will provide 1 which translates to a *Personal Aspiration Level Intention* that meets the *Base year PEB Intention* = 0.54 (a "normal" intention).

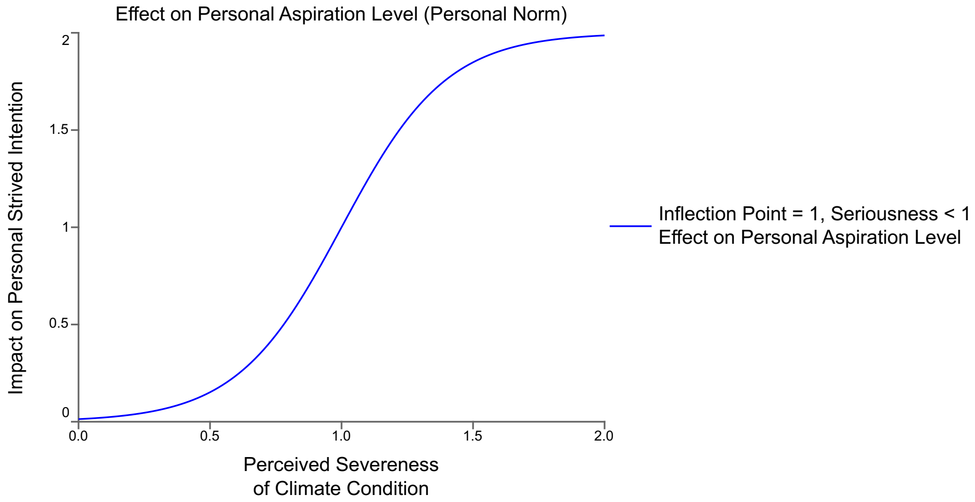


*Figure A-10 - Effect from Severness and Seriousness on Personal Norm*

The s-shape secures that an increase in the *Perceived Severeness of Climate Condition* beyond 1 results in an decreasingly increasing rise in the effect on the Base Year Intention, i.e. it lets the effect grow, goal seeking, towards the maximum of the effect which is set to *upper limit Personal Norm Effect* = 2. Vice versa, once *Perceived Severeness of Climate Condition* falls below 1, the effect decreases decreasingly, i.e. with goal-seeking behavior, until it reaches the minimum of the effect of 0, since this model is not accounting for negative intentions. In sum, given that extreme events are equal or lower than the reference condition, severeness will drive the effect on personal norm.

The concept of Seriousness is used to vary the inflection point based on a certain judgement about the relative experienced seriousness. In its essence the mechanism ensures that, the more serious someone judges the current condition, the earlier (i.e. at lower levels of severeness) they show the originally normal intention level – the point 1,1 is therefore shifted towards the left. As can be seen in the red and pink lines, Figure A-12 shows the *effect on personal norm* throughout the whole continuum of severeness given a different state of experienced seriousness (Red-dashdotted-line: Relative experienced seriousness =1.37-; Pink dotted line: Relative experience seriousness = 1.7).

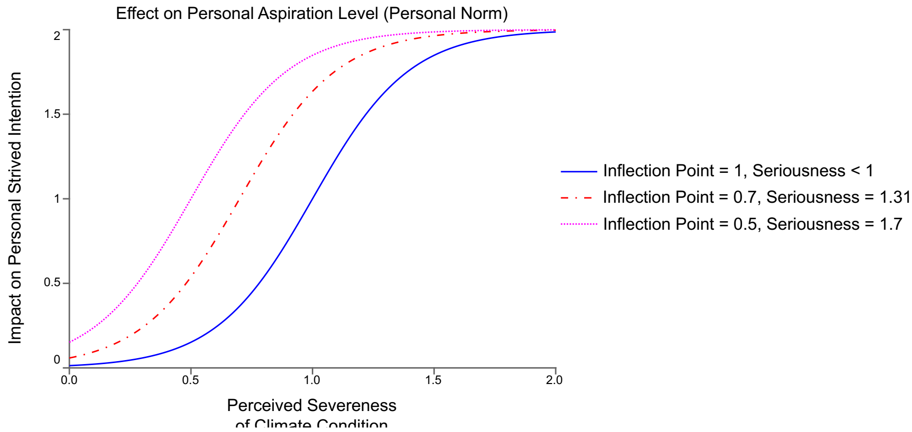


*Figure A-12 - Effect on Personal Norm under Variation of the Seriousness Based Inflection Point*

Conceptually, this depicts that although the same cognitive severeness is present, a higher relative experience seriousness results in judging adverse consequences for more valued objects. For that, the relative experienced seriousness is transformed by a sensitivity of seriousness to calculate a new inflection point for the *Effect on personal norm* based on the given judgement of the seriousness of the relative condition.

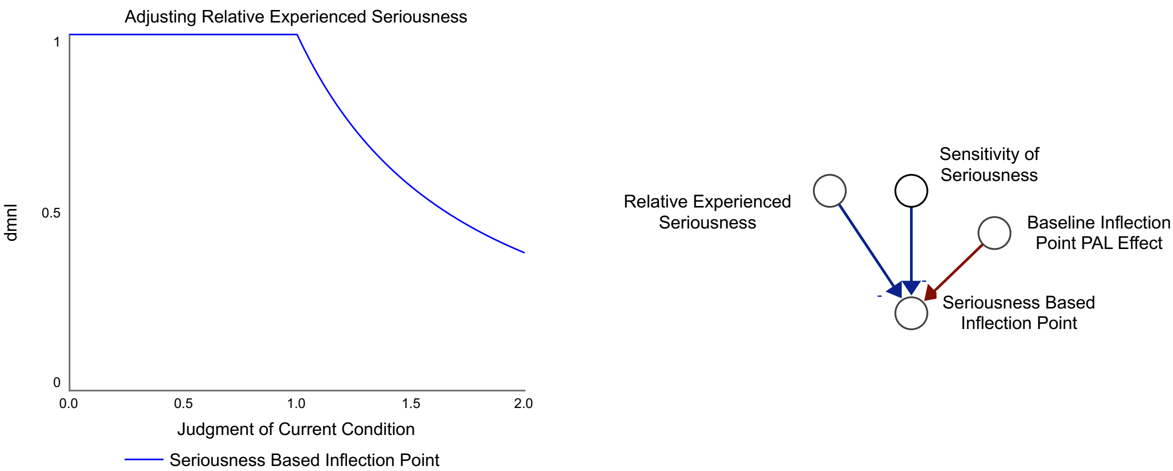


*Figure A-11 - Structure for Translating the Relative Experience Seriousness into an Inflection Point Input for the Effect on Personal Norm*

Figure A-11 displays the translation of the relative seriousness to the inflection point, where the higher the input, the lower will be the new inflection point. The sensitivity of -1.37 was calibrated. It is assumed here, that there is no further shift to the right, meaning that if the experienced seriousness falls below 1 (given the reference people don't experience anything unusual) the effect will use the *Baseline Inflection Point PAL Effect* = 1, as the normal inflection point to ensure the relatability to the base year.

To make this less abstract: Experiencing higher amount of extreme climate events will result in a high perceived severeness. Let's assume, you experience that there are 40% more events than you are used to, i.e. assume you are used to 40 events per year but now experience 56 events. This would translate to an inflection point of 0.664. The representation of the new effect can be seen in Figure A-13. Now, even though the cognitive route has not provided new, you perceive it as a more serious issue. Here, personal norm is as high as 1.71.

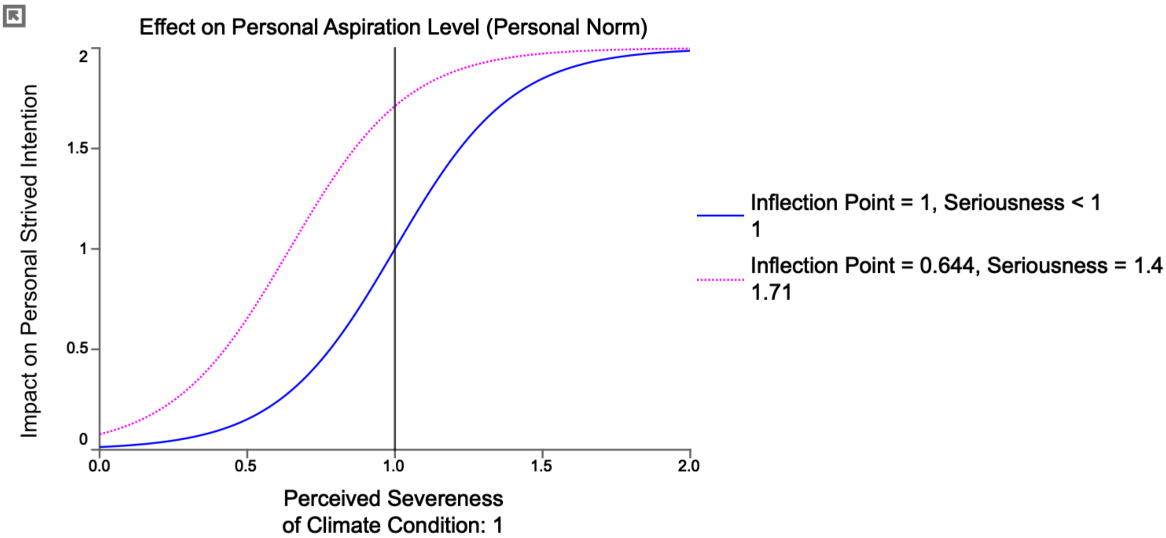


*Figure A-13 - Exemplary Change in Effect on Personal Norm under Variation of the Serioussness and Severeness*

In sum, this sector translates the input of OECD environmental significant behavior into a variation in temperature as deviation from the normal temperature. This information is used on two routes: (1) Cognitively to form beliefs about the severeness of the situation through a mechanism to represent peoples judgement process of current conditions, (2) through the experienced route to trigger different levels of affected values – awareness of consequences – that affects the "normal" reaction given a certain experience. The combined effect translates the *Base Year PEB Intention* into a new *Personal Strived Intention*, i.e. the level of intention the individual is striving for, given the two routes of judging "how bad (serious and severe)" the situation is.

Finally, we will look at how the three calculated Aspiration Levels of Intentions are combined into an aggregated goal of intention, that is used to inform the intention setting with which we started out.

**Goal Formation Sector**

At this point we have three aspiration levels that functions as goal for a new intention: (1) Personal, (2) Societal and (3) Peer Group Aspiration Level. Aspiration levels (1) and (2) are categorized into an injunctive intention - aspirations that are formed by adhering to either the expectation of the future intention, i.e. the aspiration level informed about the society's development, or the personal aspirational level, i.e. the aspiration level built by the combination between severeness and seriousness that represents the personal norm, sometimes also called moral norm. (3) Peer Group aspiration level refers to the aspiration level informed by the peer group.

In that, the three aspiration levels refer to the "sources" of intention building from the VBN, the TPB and PMT as outlined in Chapter 2. That is, these concepts are to represent the subjective norm from TPB (Ajzen 2016), the personal norm influenced by personal beliefs, worldviews, values and perception of risk as proposed by the VBN, TPB and PMT (Bamberg and Möser 2007; Ajzen 2020; Floyd, Prentice-Dunn, and Rogers 2000; Stern 2000). Additionally, as argued in the sections before, the social norm already includes an informational component that represents part of the perceived behavior control, the ease of actions in questions.

Each of these aspiration levels is weighted so as to form an *Aggregated Intention Goal* varying between 0 and 1. Each weight is kept exogenous, since their precise value will vary according to the behavior in question, and even on individual assessment (Ajzen 2001). The calibration shows a *weight of personal norm* = 0.75, putting the focus on moral and personal beliefs, while in respect to the categories outlines above, the calibration shows a focus on injunctive, that is informational aspiration levels with a *weight on peer influence* = 0.3. This relates to the literature, where Dannenberg et al. (cite the year & page numbers) note that, "[o]nce formed, the personal injunctive norm exerts a decisive influence on an individual's behavior, because deviations from the personal injunctive norm create feelings of inner conflict, failure, guilt, or shame (Schwartz 1977; Thøgersen 2006)." (Dannenberg et al. 2024)

In more general terms, every aspiration level can create different cognitive hurdles for the person forming them. In their articles about modelling norm formation by utility functions, Gavrilets, Tverskoi, and Sánchez (2024); and Gavrilets (2021) describe that these influences can be termed: (1) cognitive dissonance referring to the gap between the personal belief and the current state (2) social pressure or disapproval by others, referring to the gap between social injunctive norm and current state and (3) (dis)conformity with peers or peer pressure, referring to the gap between the social descriptive norm and the current state. In their paper Gavrilets and Richerson (2022) explicitly describe the influence of a fourth component, an externally given (authoritative) goal, as can be proposed by a government or inspired by a thought leader. Since this might depict a political instructive decision, this concept is not depicted in the base run, but will be used in the scenario.

In their paper, the authors argue for a utility-based representation, that refer to specific utility measures for the material and normative payoff of the behavior and the cost of deviation as stated in the factor 1 to 3 (4) above. Since this model focuses on aggregated unspecific behavior, this payoff cannot be established here, hence the utility function is not used as the goal formulation. Yet as shown, the structure integrated in the model can depict the conceptual factors mentioned in modelling norms as proposed by Gavrilets and Richerson (2022), Gavrilets (2021), and Gavrilets, Tverskoi, and Sánchez (2024). Additionally, it may be noted here, that making use of the utility function play out as a valuable further development of the structure, once a clear behavior with utility payoffs and costs can be constructed more precisely and implemented.

Ultimately, the structure to calculate the new intention goal is depicted in Figure A-14 and serves as the adjusting goal for the intention formation process as described at the beginning of this documentation - closing all feedback loops.

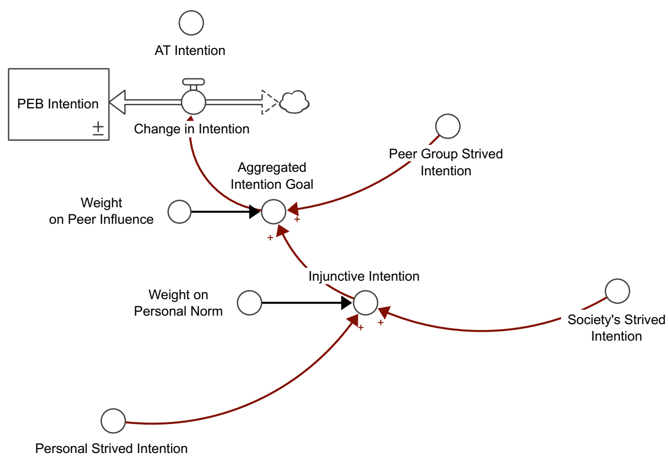


*Figure A-14 - Stock and Flow Structure of the Formation of a new Intention Goal*

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**Formal Model Description**

The following pages provide the formal model documentation for the top-level model as well as several variables that were placed in the IAM modules to establish the coupling. Variables are arranged according to 1) Top-Level-Model 2) FeliX Module 3) FRIDA Module.

| Total | Count | Including Array Elements |
|---|---|---|
| Variables | 308 | 718 |
| Modules | 2 | |
| Sectors | 5 | |
| Stocks | 23 | 23 |
| Flows | 31 | 31 |
| Converters | 254 | 664 |
| Constants | 157 | 547 |
| Equations | 128 | 148 |
| Graphicals | 13 | 31 |
| Macro Variables | 20 | |

| Run Specs | |
|---|---|
| Start Time | 1995 |
| Stop Time | 2100 |
| DT | 1/256 |
| Fractional DT | True |
| Save Interval | 0.00378787878788 |
| Sim Duration | 1.5 |
| Time Units | Year |
| Pause Interval | 0 |
| Integration Method | Euler |
| Keep all variable results | True |
| Run By | Run |
| Calculate loop dominance information | True |
| Exhaustive Search Threshold | 1000 |

| Name | Equation | Documentation + Units + Annotation + Properties |
|---|---|---|
| **Top Level Model** | | |
| "Carbon_Foot-print_(CFP)"(t) | "Carbon_Footprint_(CFP)"(t - dt) + (Updating_Carbon_Footprint) * dt | Average Carbon Footprint emitted per year per person, consumption based value.<br>The intial value is the actual historic data of the start year 1995, i.e. 11.3 $tCO_2$/person/year (OECD, 2022)<br><br>Proxy and measurement for the impact of behavior that is environmentally significant. Increasing your pro-environ-mental behavior results in less carbon emissions.<br>Unit: t $CO_2$/person/Year<br><br>Properties:<br>INIT "Carbon_Footprint_(CFP)" = CO2_per_cap_Base_Year_1995 |

| | | |
|---|---|---|
| PEB_Intention(t) | PEB_Intention(t - dt) + (Change_in_Intention) * dt | PEBI is conceptualized ranging between 1 and 0 and reflects a continuous measure, where 1 PEBI refers to 100% Intention. The initial value reflects the current value of the base year 1995<br><br>Unit: dmnl<br><br>Properties:<br>INIT PEB_Intention = PEB_in_1995 |
| Perceived_Carbon_Footprint(t) | Perceived_Carbon_Footprint(t - dt) + (Change_in_Perception) * dt | Perceived Version of the actual Carbon Footprint. Represents the perception of the average behavior in society<br><br>Unit: $tCO_2$/person/Year<br><br>Properties:<br>INIT Perceived_Carbon_Footprint = INIT("Carbon_Footprint_(CFP)") |
| Perceived_CFP_Trend (t) | Perceived_CFP_Trend(t - dt) + (Update_Trend) * dt | Perceived CFP Trend indicates, that the actual indicated Trends needs first to be communicated and updated, because people do not perceive the trend immediately (Sterman 2000)<br><br>Unit:dmnl/year<br><br>Properties:<br>INIT Perceived_CFP_Trend = Indicated_CFP_Trend |
| Perceived_Temp_Variation(t) | Perceived_Temp_Variation(t - dt) + (Update_Perception_Temp_Variation) * dt | Perception of current actual STA. Updated through information gathering and adapting to the information one perceives.<br>Unit: deg C<br><br>Properties: |

| | | |
|---|---|---|
| | | INIT Perceived_Temp_Variation = Communicated_STA |
| Reference_Number_EEvents(t) | Reference_Number_EEvents(t - dt) + (Updating_EEvent_Reference) * dt | Non-Climate Change related Extreme Events are kept as an initial reference Number, that is considered "Normal". This relates to the concept, that once extreme events are more frequent, people will get used to it. If it is less than the reference number though, then people do not accredit it towards the climate and this information has no effect on the effect of personal Aspiration Level.<br><br>Unit: events<br><br>Properties:<br>INIT Reference_Number_EEvents = 20 |
| Reference_Perception_of_CFP(t) | Reference_Perception_of_CFP(t - dt) + (Updating_Reference) * dt | Represents the Reference Condition for the perceived CFP. From the description of the Trend Forumlation: "Decision makers then compare the perceived present condition to its past values, measured by the Reference Condition RC, to determine whether the input is rising or falling." (Sterman 2000, p. 636)<br><br>Unit: $tCO_2$/person/year<br><br>Properties:<br>INIT Reference_Perception_of_CFP = Perceived_Carbon_Footprint |
| Reference_Temp_Variation(t) | Reference_Temp_Variation(t - dt) + (Update_Reference_Condition) * dt | The Reference Temperature people hold for the last time horizon. It represents the temperature variation that people have in mind when thinking about whether or how the current perception is deviating from what is deemed normal.<br><br>Unit: deg C |

| | | |
|---|---|---|
| | | Properties:<br>INIT Reference_Temp_Variation = Initial_Perceived_Temp |
| Change_in_Intention | (Aggregated_Intention_Goal-PEB_Intention)/AT_Intention | Update of Intention. Follows a simple first order information delay. Depicts a Goal-Adjustment Process where the Intention is smoothed towards the aggregated Intention goal.<br><br>Unit: dmnl/year |
| Change_in_Perception | ("Carbon_Footprint_(CFP)"-Perceived_Carbon_Footprint)/TPPC | Unit: t $CO_2$ /person/Year/Year<br><br>Time to update the perception of carbon footprint. Structure represent a first order information delay. |
| Update_Perception_Temp_Variation | (Communicated_STA-Perceived_Temp_Variation)/TPPC_2 | Unit: deg C/Year<br>Update of Perception of temperature Variation, representing the process of perceiving the Communicated STA. First order information delay. |
| Update_Reference_Condition | IF TIME < 2005 THEN MAX(0, (Perceived_Temp_Variation-Reference_Temp_Variation)/THRC_1) ELSE (Perceived_Temp_Variation-Reference_Temp_Variation)/THRC_1 | Porcess to update the Reference Condition subject to the change of perceived reference condition. Since it is not clear against what temperature variation people actually compare the current perception is assumed, at least for the time being that the Kyoto Protocoll was enacted in 2005 and the "international community" made transparent a certain goal of carbon reduction to achieve, this reference condition is kept stable.<br>This is an assumption and the formulation should be updated once there is a better understanding of how people compare the current against the reference condition and how this condition is updated.<br><br>Unit: deg C/Year |

| | | |
|---|---|---|
| Update_Trend | (Indicated_CFP_Trend-Perceived_CFP_Trend)/TPT | "beliefs do not adjust instantly to new information" (Sterman 2000, p. 636). Therefore this smoothing delay functions as mechanism to perceive the actual trend.<br><br>Unit: dmnl/year/Year |
| Updating_Carbon_Footprint | (Indicated_Carbon_Footprint-"Carbon_Footprint_(CFP)")/AT_CFP | Unit: t $CO_2$ /person/Year/Year<br><br>Updates the Carbon Footprint to the indicated Carbon Footrprint, the result from taken into consideration PEBI, as a goal adjustment. |
| Updating_EEvent_Reference | ("Extreme_Events_(EEvents)_from_FeliX_Module".Climate_Events_in_Memory-Reference_Number_EEvents)/Time_Horizon_EEvents | Flow to update the Reference Number of events. Given the comparison to the current, this can either be an increase or a decrease.<br><br>Unit: Events/Year |
| Updating_Reference | (Perceived_Carbon_Footprint-Reference_Perception_of_CFP)/Historical_Time_Horizon | Update of the Reference Perception of CFP. Depicts a simple first order information delay.<br><br>t $CO_2$ /person/Year/Year |
| Aggregated_Intention_Goal | Peer_Group_Strived_Intention*Weight_on_Peer_Influence + (1-Weight_on_Peer_Influence)*Injunctive_Intention | This represents the agggregated intention, that is influencing PEBI as an adjustment goal. Here these are additive weights that split the focus between input from the PeerGroup (social descriptive norm) and the injunctive norms (social injunctive and personal norm).<br>The equation ensures that the intention goal is varying between 0 and 1.<br>If the weight on Peer Groups influence is 0, then the complete goal is taken from the Injunctive Intention and vice versa with weight 1 on the PeerGroup Influence. |

| | | |
|---|---|---|
| | | Unit: dmnl |
| AT_CFP | 4.5 | Time to adjust the current displayed behavior to the new indicated one. Represents the amount of time to fully change from an old to a new level of behavior, in changing habit, technology, consumption behavior etc. Assumed and calibrated.<br><br>Unit: year |
| AT_Intention | 3 | Time to update Pro-environmental intention.<br>Raihan and Cogburn (2023) argue there is a necessary time to change behavior in the long term. They report on a study investigating intentional behavior change, where it took participants up to 5 years to establish a very robust new behavior (Raihan and Cogburn 2023; Prochaska and Velicer 1997). The value was assumed and calibrated. It should be taken into consideration, that additionally to this time delay, AT CFP presents a second time delay that together account for the time to translate a change in Intention into observable CFP<br><br>Unit: year |
| Baseline_Inflection_Point_PAL_Effect | 1 | Ensures a 1:1 Point in the effect shape, that translates the normal input 1 to a normal output 1.<br>Presents the point where the function "shifts" growth behavior.<br><br>Unit: dmnl |
| Carbon_Footrprint_for_SOS | 1.61 | Unit: t $CO_2$/person/Year<br>Average Carbon Footprint to maintain safe operating space with upholding a maximum global warming of 2ºC (O'Neill et al. 2018) |

| | | |
| --- | --- | --- |
| CO2_per_cap_Base_Year_1995 | 11.3 | Base year value of per capita Carbon Footprint, consumption based, i.e. account for emissions that are imported or exported through trade.<br>Data taken from OECD (2022) and Yamano and Guilhoto (2020).<br><br>Unit: tCO2/person/Year |
| "Combined_Data_+_SSP_Projected_CO2_Contribution_OECD"[SSP_1] | GRAPH(TIME) Points: (1994.0, 12586.366), (1995.0, 12815.984), (1996.0, 13193.226), (1997.0, 13320.542), (1998.0, 13355.842), (1999.0, 13478.472), (2000.0, 13784.303), (2001.0, 13610.699), (2002.0, 13646.551), (2003.0, 14075.948), (2004.0, 14077.375), (2005.0, 14077.674), (2006.0, 13940.986), (2007.0, 14078.852), (2008.0, 13745.423), (2009.0, 12763.356), (2010.0, 13368.698), (2011.0, 13201.698), (2012.0, 13183.369), (2013.0, 13061.625), (2014.0, 12905.829), (2015.0, 12801.482), (2016.0, 12721.988), (2017.0, 12722.748), (2018.0, 12756.717), (2019.0, 12444.488), (2020.0, 11086.694), (2030.0, 9608.727), (2040.0, 9170.819), (2050.0, 8680.832), (2060.0, 8328.524), (2070.0, 7522.618), (2080.0, 6689.971), (2090.0, 5882.984), (2100.0, 5366.855) | Data input.<br>From 1995 to 2019: Data from (Community Emissions Data System (CEDS) 2024; Global Carbon Projct 2023; Jones et al. 2024; Ritchie, Rosado, and Roser 2023a) (equal throughout the array)<br>From 2020 to 2100: Projected data in respect to the SSP narrative (Riahi et al. 2017; Fricko et al. 2017; Van Vuuren et al. 2017; Kriegler et al. 2017)<br><br>Unit: $MtCO_2$ /Year<br><br>Properties:<br><br> |
| "Combined_Data_+_SSP | GRAPH(TIME) Points: (1994.0, 12586.366), (1995.0, 12815.984), | Properties: |

| | | |
|---|---|---|
| _Pro-jected_CO2_Con-ribu-tion_OECD"[SSP_2] | (1996.0, 13193.226), (1997.0, 13320.542), (1998.0, 13355.842), (1999.0, 13478.472), (2000.0, 13784.303), (2001.0, 13610.699), (2002.0, 13646.551), (2003.0, 14075.948), (2004.0, 14077.375), (2005.0, 14077.674), (2006.0, 13940.986), (2007.0, 14078.852), (2008.0, 13745.423), (2009.0, 12763.356), (2010.0, 13368.698), (2011.0, 13201.698), (2012.0, 13183.369), (2013.0, 13061.625), (2014.0, 12905.829), (2015.0, 12801.482), (2016.0, 12721.988), (2017.0, 12722.748), (2018.0, 12756.717), (2019.0, 12444.488), (2020.0, 12479.414), (2030.0, 12631.625), (2040.0, 13400.404), (2050.0, 14251.976), (2060.0, 14709.627), (2070.0, 15245.505), (2080.0, 16471.534), (2090.0, 17216.995), (2100.0, 17163.062) |  |
| "Com-bined_Data_+_SSP_Pro-jected_CO2_Con-ribu-tion_OECD"[SSP_5] | GRAPH(TIME) Points: (1994.0, 12586.366), (1995.0, 12815.984), (1996.0, 13193.226), (1997.0, 13320.542), (1998.0, 13355.842), (1999.0, 13478.472), (2000.0, 13784.303), (2001.0, 13610.699), (2002.0, 13646.551), (2003.0, 14075.948), (2004.0, 14077.375), (2005.0, 14077.674), (2006.0, 13940.986), (2007.0, 14078.852), (2008.0, 13745.423), (2009.0, | Properties:  |

| | | |
|---|---|---|
| | 12763.356), (2010.0, 13368.698), (2011.0, 13201.698), (2012.0, 13183.369), (2013.0, 13061.625), (2014.0, 12905.829), (2015.0, 12801.482), (2016.0, 12721.988), (2017.0, 12722.748), (2018.0, 12756.717), (2019.0, 12444.488), (2020.0, 13936.961), (2030.0, 16862.543), (2040.0, 20633.013), (2050.0, 25110.007), (2060.0, 30886.99), (2070.0, 35239), (2080.0, 38564.039), (2090.0, 38841.037), (2100.0, 38456.003) | |
| Communi-cated_STA | SMTH3(FRIDA_Tempera-ture_Module."Surface_Tempera-ture_Anomaly_(STA)"*Me-dia_Coverage_Efficiency,TPPC_1) | Represents the process of researching, analysing, preparing and communicating the surface temperature anomaly. The input is manipulated by the media coverage efficiency and smoothed by a third order information delay.<br><br>Unit: deg C<br><br>Annotation: Delay Converter |
| Ef-fect_from_Peer_Group_on_Intention | upper_PGAL_Ef-fect/(1+EXP(steep-ness_PGAL_Effect*("Rela-tive_Peer_Group_Aspira-tion_Level_(PGAL)-_CFP"-inflec-tion_point_PGAL_Effect ))) | This effect follows an S-Shaped form and is descriped in more detail in Appendix A - model description.<br><br>The effect translates the normalized input of perceived CFP (peer groups behavior) to an respective Intention an-chored in the base year intention (see Peer Group Strived Intention)<br><br>Unit: dmnl |

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|---|---|---|
| Effect_from_Social_Projection_on_Intention | upper_limit_SAL_Effect/(1+EXP(steepness_SAL_Effect*("Relative_Societal_Aspiration_Level_(SAL)_-_CFP"-Inflection_Point_SAL_Effect ))) | This effect follows an S-Shaped form and is descriped in more detail in Appendix A - model description.<br>The effect translates the normalized input of perceived CFP (peer groups behavior) to an respective Intention anchored in the base year intention (see Peer Group Strived Intention)<br><br>Unit: dmnl |
| Effect_on_Carbon_Footprint | MIN(Maximum_Effect, Relative_Intention^(Sensitivity_Intention_on_Carbon_Footprint)) | Effect that translates the relative intention into a indicated carbon footprint. Assumed power function, see sensitivity Intention on Carbon Footprint for explanation of sensitivity. The effect is bounded through the Min function to not exceed the maximum effect.<br><br>Unit: dmnl |
| "Effect_on_Personal_Aspiration_Level_(Personal_Norm)" | (upper_limit_Personal_Norm_Effect/(1+EXP(steepness_Personal_Norm_Effect*(Seriousness_Based_Inflection_Point-Perceived_Severeness_of_Climate_Condition)))) | This effect follows an S-Shaped form and is descriped in more detail in Appendix A - model description.<br><br>Uses as an input the perceived severeness (cognitive route) and relates it, based on a varying inflection point due to the experiences seriousness, to an effect on the base line intention. This is how a personal aspiration level of intention is formed.<br><br>Unit: dmnl |
| Efficiency_Index | EXP(-(Energy_Intensity_Improvement_Rate)*(TIME-STARTTIME))*Switch_Energy_Effiency + (1 -Switch_Energy_Effiency) | Uses the Energy intensity improvement rate to calculate a compound rate of improvement that is then applied to the carbon footprint calculated through the effect from intention, see indicated Carbon Footprint<br><br>Unit: dmnl |

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|---|---|---|
| Energy_Intensity_Improvement_Rate | 0.008 | SSPs indicators energy intensity improvement rate (varying across the marker scenar-ios between ~ 0.5%/year in SSP5 and 2%/year in SSP1) and carbon intensity improvement rate (varying across the marker scenarios between ~0.1%/year SSP5 and 0.6%/year SSP1) (Riahi et al. 2017), are collapsed into a single energy intensity improvement rate. It's assumed, that both energy efficiency and carbon efficiency result in lower CFP. The value of the rate of improvement is kept constant to 0.8%/year throughout the time period and rests on data from the IEA energy intensity improvement rate for the years between 2001 and 2010 (IEA, 2023).<br><br>Unit: dmnl/year |
| Forecast_Horizon | 5 | Time considered to for projecting CFP into the future. Forecast horizons of long term growth are suspected to be placed with a long term historical view and are not to react to sudden short term movenments Sterman (2000, p. 641). Value Assumed and Calibrated.<br><br>Unit: year |
| HIS_OECD_Per_Cap_Consumption | GRAPH(TIME) Points: (1996.0, 11.40), (1997.0, 11.50), (1998.0, 11.60), (1999.0, 11.80), (2000.0, 12.20), (2001.0, 11.90), (2002.0, 11.90), (2003.0, 12.20), (2004.0, 12.40), (2005.0, 12.60), (2006.0, 12.60), (2007.0, 12.60), (2008.0, 12.10), (2009.0, 11.00), (2010.0, 11.50), (2011.0, 11.30), (2012.0, 10.90), (2013.0, 10.80), (2014.0, 10.50), (2015.0, 10.30), (2016.0, 10.20), (2017.0, 10.10), (2018.0, | Historical OECD Consumption Based per Capita CO2 emissions (i.e. emissions including trade).<br>Data retrieved from OECD (2022) and Yamano and Guilhoto (2020).<br><br>Unit: $tCO_2$ /person/Year |

10.10), (2019.0, NaN), (2020.0,
NaN), (2021.0, NaN), (2022.0,
NaN), (2023.0, NaN), (2024.0,
NaN), (2025.0, NaN), (2026.0,
NaN), (2027.0, NaN), (2028.0,
NaN), (2029.0, NaN), (2030.0,
NaN), (2031.0, NaN), (2032.0,
NaN), (2033.0, NaN), (2034.0,
NaN), (2035.0, NaN), (2036.0,
NaN), (2037.0, NaN), (2038.0,
NaN), (2039.0, NaN), (2040.0,
NaN), (2041.0, NaN), (2042.0,
NaN), (2043.0, NaN), (2044.0,
NaN), (2045.0, NaN), (2046.0,
NaN), (2047.0, NaN), (2048.0,
NaN), (2049.0, NaN), (2050.0,
NaN), (2051.0, NaN), (2052.0,
NaN), (2053.0, NaN), (2054.0,
NaN), (2055.0, NaN), (2056.0,
NaN), (2057.0, NaN), (2058.0,
NaN), (2059.0, NaN), (2060.0,
NaN), (2061.0, NaN), (2062.0,
NaN), (2063.0, NaN), (2064.0,
NaN), (2065.0, NaN), (2066.0,
NaN), (2067.0, NaN), (2068.0,
NaN), (2069.0, NaN), (2070.0,
NaN), (2071.0, NaN), (2072.0,
NaN), (2073.0, NaN), (2074.0,
NaN), (2075.0, NaN), (2076.0,
NaN), (2077.0, NaN), (2078.0,
NaN), (2079.0, NaN), (2080.0,
NaN), (2081.0, NaN), (2082.0,
NaN), (2083.0, NaN), (2084.0,
NaN), (2085.0, NaN), (2086.0,

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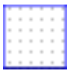
| | NaN), (2087.0, NaN), (2088.0, NaN), (2089.0, NaN), (2090.0, NaN), (2091.0, NaN), (2092.0, NaN), (2093.0, NaN), (2094.0, NaN), (2095.0, NaN), (2096.0, NaN), (2097.0, NaN), (2098.0, NaN), (2099.0, NaN), (2100.0, NaN) | |
| Historic_OECD_Environmental_Concern | GRAPH(TIME) Points: (1995.00, 0.545), (1996.00, 0.54), (1997.00, 0.537), (1998.00, 0.534), (1999.00, 0.531), (2000.00, 0.529), (2001.00, 0.526), (2002.00, 0.523), (2003.00, 0.52), (2004.00, 0.517), (2005.00, 0.514), (2006.00, 0.511), (2007.00, 0.509), (2008.00, 0.506), (2009.00, 0.503), (2010.00, 0.5) | Historic OECD Environmental Concern. Data retrieved by estimate from Franzen and Vogl (2013)<br><br>Unit: dmnl<br><br>Properties:<br><br> |
| Historical_Time_Horizon | 25 | Timeperiod, that people change their long term comparison horizon. Assumed and calibrated, yet it is reasonable that this is a rather long period of time, due to the effort it takes to compare and take hold of the measurement.<br>"The time horizon for establishing the reference condition THRC represents the time frame over which the trend is assessed and will depend on the purpose of the forecast. In general, the longer the time horizon for the forecast, the longer the historical horizon should be." (Sterman 2000, p. 637)<br><br>Unit: year |
| Indicated_Carbon_Footprint | (Effect_on_Carbon_Footprint*CO2_per_cap_Base_Year_1995)*Efficiency_Index | Combines the effect from intention with the base year and indicated the CFP based on the current level of intention. |

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| | | This value is manipulated through the energy efficiency index to depict the technological development<br><br>Unit: $tCO_2$ /person/Year |
| Indicated_CFP_based_on_trend | Perceived_Carbon_Footprint*(1+Perceived_CFP_Trend*TPPC)*EXP(Perceived_CFP_Trend*Forecast_Horizon) | Unit: $tCO_2$ /person/Year<br><br>Fractional growth of CFP (perceived trend) is used to calculate the anticipated CFP at the end of the Forecast Horizon of 5 years. The equation is adapted from (Sterman 2000, 644) |
| Indicated_CFP_Trend | ((Perceived_Carbon_Footprint-Reference_Perception_of_CFP)/Reference_Perception_of_CFP)/Historical_Time_Horizon | "(...) [T]he indicated trend (...) is the difference between the perceived present condition of the input and the reference condition, expressed as a fraction of the reference condition and then divided by the time horizon for the reference condition.<br>The indicated trend provides the most up-to-date information on the current fractional rate of change in the input"(Sterman 2000, p. 636)<br><br>Unit: dmnl/year |
| inflection_point_PGAL_Effect | 1 | Ensures a 1:1 Point in the effect shape, that translates the normal input 1 to a normal output 1.<br>Presents the point where the function "shifts" behavior.<br><br>Unit: dmnl |
| Inflection_Point_SAL_Effect | 1 | Ensures a 1:1 Point in the effect shape, that translates the normal input 1 to a normal output 1.<br>Presents the point where the function "shifts" behavior.<br><br>Unit: dmnl |

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|---|---|---|
| Initial_Perceived_Temp | 0.44 | Initial temperature variation when the model starts. This parameter is assumed, calibrated and highly uncertain. Discussed in sensitivity analysis, see main text for elaboration<br><br>Unit: deg C |
| Injunctive_Intention | Personal_Strived_Intention*Weight_on_Personal_Norm + Society's_Strived_Intention*(1-Weight_on_Personal_Norm) | This represents the injunctive intention, that is combined influencing the aggregated intention goal. Here these are additive weights that split the focus between input from the Personal Strived Intention (personal norm) and societies strived intention (social injunctive norm). Since both values depict an information about what either one self - or society is prescribing, these injunctive norms are treated differently from the descriptive intentional goal.<br>The equation ensures that the combined injunctive intention is varying between 0 and 1. If the weight on personal norm is 0, then society's strived intentions weight is 1, and vice versa.<br><br>Unit: dmnl |
| Maximum_Effect | 2.73 | Maximum effect ensures a upper limit to the effect. This is because, even if people are careless, they cannot increase their CFP endlessly. To limit the effect at a reasonable upper bound, the value reflects that given the Base Year CO2 per cap, the maximum reached value lies 5 standard deviations apart from the mean CO2 carbon footprint of all OECD countries at the most recent data year, i.e. 2018 (OECD, 2022).<br><br>Unit: dmnl |
| Media_Coverage_Efficiency | 0.78 | Represents the efficiency of research, science communication and media communication. A low number indicates that only less of what is actually happening is |

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| | | communicated. This could be either through not acknowledging what is happing, wrong attribution, missinformation and so forth.<br>Assumed and calibrated.<br><br>Unit: dmnl |
| OECD_Pop_Data[SSP_1] | GRAPH(TIME) Points: (2005.00, 1087291000), (2010.00, 1120404000), (2020.00, 1179611000), (2030.00, 1231694000), (2040.00, 1276424000), (2050.00, 1312339000), (2060.00, 1338173000), (2070.00, 1348781000), (2080.00, 1341483000), (2090.00, 1311221000), (2100.00, 1261898000) | Arrayed converter, that depicts the population data for the SSP scenarios 1,2 and 5.<br>From 1995 to 2005: Extrapolated data from the SSP narrative. Extrapolation formed by Stella Software<br>From 2005 to 2100: The respective data is taken from SSP database (Riahi et al. 2017; Fricko et al. 2017; Kc and Lutz 2017; Van Vuuren et al. 2017; Kriegler et al. 2017)<br><br>Unit: person<br><br>Annotation: GF Extrapolated<br><br>Properties:<br> |
| OECD_Pop_Data[SSP_2] | GRAPH(TIME) Points: (2005.00, 1078420000), (2010.00, 1112820000), (2020.00, 1168270000), (2030.00, 1214970000), (2040.00, 1251290000), (2050.00, 1278590000), (2060.00, 1298590000), (2070.00, 1308060000), (2080.00, 1306710000), (2090.00, | Properties:<br><br> |

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|---|---|---|
| | 1294620000), (2100.00, 1271880000) | |
| OECD_Pop_Data[SSP_5] | GRAPH(TIME) Points: (2005.00, 1187300000), (2010.00, 1.22e+09), (2020.00, 1295500000), (2030.00, 1385600000), (2040.00, 1477400000), (2050.00, 1573600000), (2060.00, 1672800000), (2070.00, 1761000000), (2080.00, 1833600000), (2090.00, 1885300000), (2100.00, 1916100000) | Properties:<br><br> |
| OECD_Total_CO2_Contribution | (("Carbon_Footprint_(CFP)"*Selected_OECD_Population)/Unit_Change)*1 | Calculates the total contribution by the OECD given the individual carbon footprint and the current population data, based on the selection of SSP scenario.<br><br>Unit: $MtCO_2$ /Year |
| PEB_in_1995 | 0.545 | Reflects the intention of the society at the year 1995. The value is taken from Franzen and Vogl (2013) and is an estimated of the measured environmental concern of OECD countries.<br><br>Note, that as argued, environmental concern is not the same as intention. A comparison to the GEB of Germany around that time (1996) (Bauske and Kaiser 2019) suggests a very similar value (51%), so here, environmental concern was used as a proxy.<br><br>Unit: dmnl |

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| Peer_Group_Strived_Intention | (PEB_in_1995*Effect_from_Peer_Group_on_Intention) | Calculated intention-goal stemming from the observation of the peer group normalized to the base year.<br><br>Unit: dmnl |
| Perceived_Severeness_of_Climate_Condition | SMTH1(Relative_Perceived_Temperature_Variation^Sensation_magnitude_Factor, 1) | Represents both the moderation of the relative perceived Temperature Variation and a smooth function to represent the time people need to become aware of the new condition themselves. This is arguably a low value due to the already happening cognitive process from before and is therefore foremost used to smooth the change in the relative severeness.<br><br>Unit: dmnl |
| Personal_Strived_Intention | "Effect_on_Personal_Aspiration_Level_(Personal_Norm)"*PEB_in_1995 | Reflects the personal strived intention in reference to the baseline intention based on the perceived severeness and experienced seriousness.<br><br>Unit: dmnl |
| Relative_Experienced_Seriousness | "Extreme_Events_(EEvents)_from_FeliX_Module".Climate_Events_in_Memory/Reference_Number_EEvents | Represents the ratio between Reference Number of events and the current number of events in memory. This represents the Relative Experienced Seriousness.<br><br>Unit: dmnl |
| Relative_Intention | (PEB_Intention/PEB_in_1995) | The current Intention is compared and normalized against the models baseline from 1995.<br><br>Unit: dmnl |
| "Relative_Peer_Group_ | Perceived_Carbon_Footprint/CO2_per_cap_Base_Year_1995 | Building a ratio between the Perceived CFP and the Base Years CFP to normalize the perceived CFP to be used as an input for the Effect from Peer Group On Intention. |

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|---|---|---|
| Aspiration_Level_(PGAL)-_CFP" | | Unit: dmnl |
| Relative_Perceived_Temperature_Variation | Perceived_Temp_Variation/Reference_Temp_Variation | Relative Perceived Temperature Variation is the direct comparison of the current comparison against the reference condition.<br><br>Unit: dmnl |
| "Relative_Societal_Aspiration_Level_(SAL)_-_CFP" | (Indicated_CFP_based_on_trend)/CO2_per_cap_Base_Year_1995 | Building a ratio between the indicated CFP based on the projected Trend and the Base Years CFP to normalize and to be used as an input for the Effect from Peer Group On Intention.<br><br>Unit: dmnl |
| Selected_OECD_Population | (IF FRIDA_Temperature_Module.SSP_Scenario_Switch = 1 THEN OECD_Pop_Data[SSP_1] ELSE IF FRIDA_Temperature_Module.SSP_Scenario_Switch = 2 THEN OECD_Pop_Data[SSP_2] ELSE IF FRIDA_Temperature_Module.SSP_Scenario_Switch = 3 THEN 0 ELSE IF FRIDA_Temperature_Module.SSP_Scenario_Switch = 4 THEN 0 ELSE IF FRIDA_Temperature_Module.SSP_Scenario_Switch=5 THEN OECD_Pop_Data[SSP_5] ELSE 0) | Represents the population data for the OECD corresponding to the SSP scenario selected via the Switch.<br>The equation match the input from the switch to select the respective scenario data from the OECD Population Data Array<br><br>Unit: person |

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|---|---|---|
| Selected_SSP_Projected_CO2_Contribution_OECD | (IF FRIDA_Temperature_Module.SSP_Scenario_Switch = 1 THEN "Combined_Data_+_SSP_Projected_CO2_Conribution_OECD"[SSP_1] ELSE IF FRIDA_Temperature_Module.SSP_Scenario_Switch = 2 THEN "Combined_Data_+_SSP_Projected_CO2_Conribution_OECD"[SSP_2] ELSE IF FRIDA_Temperature_Module.SSP_Scenario_Switch = 3 THEN 0 ELSE IF FRIDA_Temperature_Module.SSP_Scenario_Switch = 4 THEN 0 ELSE IF FRIDA_Temperature_Module.SSP_Scenario_Switch=5 THEN "Combined_Data_+_SSP_Projected_CO2_Conribution_OECD"[SSP_5] ELSE 0) | Depicts the Projected OECD Contribution from the selected SSP Narrative based on the SSP sceario switch<br><br>Unit: $MtCO_2$ /Year |
| Selected_SSP_Projected_Temperature | (IF FRIDA_Temperature_Module.SSP_Scenario_Switch = 1 THEN Temperature_Projection_from_SSP[SSP_1] ELSE IF FRIDA_Temperature_Module.SSP_Scenario_Switch = 2 THEN Temperature_Projection_from_SSP[SSP_2] ELSE IF FRIDA_Temperature_Module.SSP_Scenario_Switch = 3 | Depicts the Projected temperature variation based from the selected SSP Narrative based on the SSP scenario switch.<br><br>Unit: deg C |

| | | |
|---|---|---|
| | THEN 0 ELSE IF FRIDA_Temperature_Module.SSP_Scenario_Switch = 4 THEN 0 ELSE IF FRIDA_Temperature_Module.SSP_Scenario_Switch=5 THEN Temperature_Projection_from_SSP[SSP_5] ELSE 0) | |
| Sensation_magnitude_Factor | 0.75 | This structure and exponent is inspired and adapted from literature on psychophysical stimulus perception. See model description in Appendix A for a detailed elaboration on the concept. This exponent dampens and moderates the perception. Value is arguably between 0 and 1 (Noyes, 2021; Stevens, Stevens, and Marks 1986). Value assued and calibrated<br><br>Unit: dmnl |
| Sensitivity_Intention_on_Carbon_Footprint | -0.621 | Effect is assumed as a non-linear relationship in the form of a power function, this parameter is its sensitivity. 1-1 point translating “normal intention” to “normal CFP”. The effect is anchored around the corresponding values of the base year 1995. Value is assumed and calibrated.<br><br>Unit: dmnl |
| Sensitivity_of_Seriousness | -1.37 | Assumed Value that defines how strong the reaction of an increased Experienced Seriousness is. Manipulates the shape of the power function that sets the new inflection point.<br><br>Unit: dmnl |

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| Serious-ness_Based_Inflec-tion_Point | MIN (Baseline_Inflec-tion_Point_PAL_Ef-fect,SMTH1(Relative_Experi-enced_Seriousness^Sensitiv-ity_of_Seriousness, 2)) | Sets the new Inflection Point for the Effect on Personal Aspiration level. With increasing relative experienced seri-ousness the inflection point is, manipulated through a powerfunction, transformed towards zero, meaning that in an very extreme case people experience such bad events, that all their value motivations are triggered, leading them to adopt 100% intention, no matter how they cognitively judge the current condition.<br><br>Since people take time to both perceive the relative experi-enced seriousness (which is a rather fast route) and adapt to the new inflection point the input is smoothed by a first order information delay.<br><br>It is assumed, that the inflection point is either normal (1) or lower (more values are activated).<br><br>Unit: dmnl |
| Socie-ty's_Strived_Inten-tion | (PEB_in_1995*Effect_from_So-cial_Projection_on_Intention) | Calculated Intention-Goal stemming from the projection of the societies trend, normalized to the base year.<br><br>Unit: dmnl |
| Steepness_Per-sonal_Norm_Ef-fect | 5 | Corresponds to the sensitivity around the inflection point. Represents the characteristic of how much does an mar-ginal (de-) in-crease in severeness around the inflection point result in a change in personal strived intention nor-malized to the base year. The higher the steepness, the stronger the reaction and vice versa. A steepness of 1 would indicate a linear relationship. Value assumed and calibrated.<br><br>Unit: dmnl |

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| Steep-<br>ness_PGAL_Effect | 3 | Corresponds to the sensitivity around the inflection point. Represents the characteristic of how much does an mar-ginal (de-) in-crease in CFP around the inflection point re-sult in a change in intention normalized to the base year. The higher the steepness, the stronger the reaction and vice versa. A steepness of 1 would indicate a linear rela-tionship. Value assumed and calibrated.<br><br>Unit: dmnl |
| steepness_SAL_Ef-<br>fect | 3 | Corresponds to the sensitivity around the inflection point. Represents the characteristic of how much does an mar-ginal (de-) in-crease in CFP around the inflection point re-sult in a change in intention normalized to the base year. The higher the steepness, the stronger the reaction and vice versa. A steepness of 1 would indicate a linear rela-tionship. Value assumed and calibrated.<br><br>Unit: dmnl |
| Switch_En-<br>ergy_Effiency | 1 | Switch to turn on or off the Energy Efficiency<br><br>Unit: dmnl |
| Temperature_Pro-<br>jec-<br>tion_from_SSP[SS<br>P_1] | GRAPH(TIME) Points: (2005.00, 0.913), (2010.00, 0.988), (2020.00, 1.223), (2030.00, 1.506), (2040.00, 1.771), (2050.00, 2.022), (2060.00, 2.246), (2070.00, 2.460), (2080.00, 2.669), (2090.00, 2.856), (2100.00, 3.018) | Data input.<br>From 1995 to 2005: Extrapolated data from the SSP narra-tive. Extrapolation formed by Stella Software<br>From 2005 to 2100: Projected data in respect to the SSP narrative (Riahi et al. 2017; Fricko et al. 2017; Van Vuuren et al. 2017; Kriegler et al. 2017)<br><br>Unit: deg C<br><br>Annotation: GF extrapolated |

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| | | Properties:<br> |
| Temperature_Pro-jec-tion_from_SSP[SSP_2] | GRAPH(TIME) Points: (2005.00, 0.913), (2010.00, 0.989), (2020.00, 1.241), (2030.00, 1.483), (2040.00, 1.762), (2050.00, 2.053), (2060.00, 2.356), (2070.00, 2.681), (2080.00, 3.023), (2090.00, 3.388), (2100.00, 3.763) | Properties:<br> |
| Temperature_Pro-jec-tion_from_SSP[SSP_5] | GRAPH(TIME) Points: (2005.00, 0.913), (2010.00, 0.989), (2020.00, 1.266), (2030.00, 1.603), (2040.00, 2.013), (2050.00, 2.480), (2060.00, 2.976), (2070.00, 3.504), (2080.00, 4.050), (2090.00, 4.576), (2100.00, 5.052) | Properties:<br> |
| THRC_1 | 10 | Defines the historical time horizon over which the temper-ature variation is monitored. Value assumed and calibrated.<br><br>Unit: year |
| Time_Hori-zon_EEvents | 16.2 | Defines the historical time horizon over which events are updated. Value assumed and calibrated.<br><br>Unit: year |
| TPPC | 3 | Time to update the perception of CFP.<br>General expected to be higher than a year in environmental and social contexts (Sterman 2000, p. 636), assumed and calibrated.<br><br>Unit: year |

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|---|---|---|
| TPPC_1 | 3 | Time that is needed to research the current conditions as well as properly communicate them. Value is assumed and calibrated |
| TPPC_2 | 1.65 | Time needed to update the current perception towards the communicated condition. Answers the question of long people take their time to update the current condition<br><br>Unit: year |
| TPT | 5 | Time to perceive the new Trend. Assumed and calibrated value. 5 years may seem a long time, yet as Sterman proposes in respect to trends in the organizational context. "The adjustment lag depends not only on the time required for individual decision makers to recognize the change but also on organizational inertia. A new trend may have to become part of the conventional wisdom before some are willing to act." (Sterman 2000, p.637)<br><br>Unit: year |
| Unit_Change | 1000000 | Calculating a numerical change in the measurement of the units (not a general unit change).<br><br>Unit: $tCO_2$ /MtCO2 |
| Upper_limit_Personal_Norm_Effect | 2 | Upper Limit of the effect. Reasonably assumed to be 2.<br><br>Unit: dmnl |
| Upper_limit_SAL_Effect | 2 | Upper Limit of the effect. Reasonably assumed to be 2.<br><br>Unit: dmnl |
| Upper_PGAL_Effect | 2 | Upper Limit of the effect. Reasonably assumed to be 2.<br><br>Unit: dmnl |

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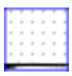
| Weight_on_Peer_Influence | 0.3 | Weight put on the Peer Group Influence instead of the Injunctive Intention. For more detailed description see the main text and Appendix A - Model description. Value is assumed and calibrated.<br><br>Unit: dmnl |
| Weight_on_Personal_Norm | 0.7 | Depicts the weight people allocate to information from the personal norm.<br><br>Unit: dmnl |
| CEE_SW | 0 | Switch to activate Scenario CEE<br>Unit: dmnl |
| TER_SW | 0 | Switch to activate Scenario TER<br>Unit: dmnl |
| SSP_1_Scenario_SW | 0 | Switch to activate Scenario SSP 1<br>Unit: dmnl |
| SSP_5_Scenario_SW | 0 | Switch to activate Scenario SSP 5<br>Unit: dmnl |
| SSP_5_Alternative_SW | 0 | Switch to activate Scenario SSP 5 Alternative<br>Unit: dmnl |
| **FeliX Module Extreme Events** | | |
| Climate_Events_in_Memory(t) | Climate_Events_in_Memory(t - dt) + (Perception_of_Events - Forgetting_of_Events) * dt | Number of Extrem Events that are currently in Memory of people based on the generated extreme Events caused by the current surface temperature anomaly.<br><br>Unit: events<br><br>Properties:<br><br>INIT Climate_Events_in_Memory = 0.01 |

| | FRIDA Module | |
|---|---|---|
| World_To-tal_N2O_SSP2[SSP_1] | GRAPH(TIME) Points: (1994.0, 8258.196337), (1995.0, 8490.454212), (1996.0, 8664.614286), (1997.0, 8589.86337), (1998.0, 8647.449451), (1999.0, 8696.156044), (2000.0, 8638.310256), (2001.0, 8677.031868), (2002.0, 8807.843223), (2003.0, 8862.030769), (2004.0, 9161.205128), (2005.0, 9243.060806), (2006.0, 9389.076923), (2007.0, 9660.549451), (2008.0, 9558.757875), (2009.0, 9450.813919), (2010.0, 9668.814286), (2011.0, 10032.70696), (2012.0, 10135.50037), (2013.0, 10089.71209), (2014.0, 10212.37912), (2015.0, 10235.78755), (2016.0, 10300.02564), (2017.0, 10510.99048), (2018.0, 10496.49707), (2019.0, 10449.08901), (2020.0, 10193.926), (2030.0, 10514.839), (2040.0, 10616.954), (2050.0, 10498.269), (2060.0, 10268.842), (2070.0, 10159.419), (2080.0, 10014.053), | Data input $N_2O$ Emission<br>From 1995 to 2019: Data from (Community Emissions Data System (CEDS) 2024; Global Carbon Projct 2023; Jones et al. 2024; Ritchie, Rosado, and Roser 2023a) (equal throughout the array)<br>From 2020 to 2100: Projected data in respect to the SSP narrative (Riahi et al. 2017; Fricko et al. 2017; Van Vuuren et al. 2017; Kriegler et al. 2017)<br><br>Unit: $KtN_2O$/Year<br><br>Properties:<br><br> |

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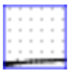
| | (2090.0, 9825.722), (2100.0, 9418.887) | |
| World_Total_NO2_SSP2[SSP_2] | GRAPH(TIME) Points: (1994.0, 8258.196337), (1995.0, 8490.454212), (1996.0, 8664.614286), (1997.0, 8589.86337), (1998.0, 8647.449451), (1999.0, 8696.156044), (2000.0, 8638.310256), (2001.0, 8677.031868), (2002.0, 8807.843223), (2003.0, 8862.030769), (2004.0, 9161.205128), (2005.0, 9243.060806), (2006.0, 9389.076923), (2007.0, 9660.549451), (2008.0, 9558.757875), (2009.0, 9450.813919), (2010.0, 9668.814286), (2011.0, 10032.70696), (2012.0, 10135.50037), (2013.0, 10089.71209), (2014.0, 10212.37912), (2015.0, 10235.78755), (2016.0, 10300.02564), (2017.0, 10510.99048), (2018.0, 10496.49707), (2019.0, 10449.08901), (2020.0, 9742.624), (2030.0, 10959.872), (2040.0, 11930.028), (2050.0, 12689.418), (2060.0, 13157.974), (2070.0, 13459.986), (2080.0, 13872.232), | Properties:  |

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| | (2090.0, 14478.796), (2100.0, 15094.255) | |
| World_Total_NO2_SSP2[SSP_5] | GRAPH(TIME) Points: (1994.0, 8258.196337), (1995.0, 8490.454212), (1996.0, 8664.614286), (1997.0, 8589.86337), (1998.0, 8647.449451), (1999.0, 8696.156044), (2000.0, 8638.310256), (2001.0, 8677.031868), (2002.0, 8807.843223), (2003.0, 8862.030769), (2004.0, 9161.205128), (2005.0, 9243.060806), (2006.0, 9389.076923), (2007.0, 9660.549451), (2008.0, 9558.757875), (2009.0, 9450.813919), (2010.0, 9668.814286), (2011.0, 10032.70696), (2012.0, 10135.50037), (2013.0, 10089.71209), (2014.0, 10212.37912), (2015.0, 10235.78755), (2016.0, 10300.02564), (2017.0, 10510.99048), (2018.0, 10496.49707), (2019.0, 10449.08901), (2020.0, 11994.362), (2030.0, 12889.186), (2040.0, 13578.425), (2050.0, 13317.114), (2060.0, 13529.877), (2070.0, 13484.531), (2080.0, 13483.656), | Properties:  |

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| | (2090.0, 13225.088), (2100.0, 12723.682) | |
| Selected_SSP_World_Minus_OECD_Total_CO2_Emission | (IF SSP_Scenario_Switch=1 THEN World_CO2_Emission_Minus_OECD[SSP_2] ELSE IF SSP_Scenario_Switch=2 THEN World_CO2_Emission_Minus_OECD[SSP_2]ELSE IF SSP_Scenario_Switch=3 THEN 0 ELSE IF SSP_Scenario_Switch=4 THEN 0ELSE IF SSP_Scenario_Switch=5 THEN World_CO2_Emission_Minus_OECD[SSP_5] ELSE 0) | Depicts the Historic and Projected CO2 Emission for World without the OECD from the selected SSP Narrative based on the SSP scneario switch<br><br>Unit: $MtCO_2$ /Year |
| Selected_SSP_World_Total_CO2_Emissions | (IF SSP_Scenario_Switch=1 THEN World_CO2_Emission_Total[SSP_1] ELSE IF SSP_Scenario_Switch=2 THEN World_CO2_Emission_Total[SSP_2] ELSE IF SSP_Scenario_Switch=3 THEN 0 ELSE IF SSP_Scenario_Switch=4 THEN 0 ELSE IF SSP_Scenario_Switch=5 THEN World_CO2_Emission_Total[SSP_5] ELSE 0) | Unit: $MtCO_2$ /Year |
| SSP_Scenario_Switch | 2 | This switch enables going back and forth between the different input for the SSP narratives, with the switches number indicating which SSP-narrative is currently "active"<br><br>Unit: dmnl |

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| "SSP-Selected_CH4_(World_Total)" | (IF SSP_Scenario_Switch = 1 THEN World_Total_CH4_SSP2[SSP_1] ELSE IF SSP_Scenario_Switch = 2 THEN World_Total_CH4_SSP2[SSP_2] ELSE IF SSP_Scenario_Switch = 3 THEN 0 ELSE IF SSP_Scenario_Switch = 4 THEN 0 ELSE IF SSP_Scenario_Switch=5 THEN World_Total_CH4_SSP2[SSP_5] ELSE 0) | Depicts the Historic and Projected CH4 Emission from the selected SSP Narrative based on the SSP scneario switch<br><br>Unit: $MtCH_4$/Year |
| "SSP-Selected_Landuse_SSPs_(World_Total)" | (IF SSP_Scenario_Switch = 1 THEN World_CO2_Emission_Landuse[SSP_1] ELSE IF SSP_Scenario_Switch = 2 THEN World_CO2_Emission_Landuse[SSP_2] ELSE IF SSP_Scenario_Switch = 3 THEN 0 ELSE IF SSP_Scenario_Switch = 4 THEN 0 ELSE IF SSP_Scenario_Switch=5 THEN World_CO2_Emission_Landuse[SSP_5] ELSE 0) | Depicts the Historic and Projected Landuse CO2 Emission from the selected SSP Narrative based on the SSP scneario switch<br><br>Unit: $MtCO_2$ /Year |
| "SSP-Selected_NO2_(World_Total)" | (IF SSP_Scenario_Switch = 1 THEN NEW_World_Total_NO2_SSP2[SSP_1] ELSE IF SSP_Scenario_Switch = 2 THEN NEW_World_Total_NO2_SSP2[SSP_2] ELSE IF SSP_Scenario_Switch = 3 THEN 0 ELSE IF SSP_Scenario_Switch = 4 THEN 0 ELSE IF SSP_Scenario_Switch=5 THEN | Depicts the Historic and Projected $N_2O$ Emission from the selected SSP Narrative based on the SSP scneario switch<br><br>Unit: $KtN_2O$/Year |

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| | NEW_World_Total_NO2_SSP2[SSP_5] ELSE 0) | |
| "SSP-Selected_SO2_(World_Total)" | (IF SSP_Scenario_Switch = 1 THEN World_Total_SO2_SSP2[SSP_1] ELSE IF SSP_Scenario_Switch = 2 THEN World_Total_SO2_SSP2[SSP_2] ELSE IF SSP_Scenario_Switch = 3 THEN 0 ELSE IF SSP_Scenario_Switch = 4 THEN 0 ELSE IF SSP_Scenario_Switch=5 THEN World_Total_SO2_SSP2[SSP_5] ELSE 0) | Depicts the Historic and Projected SO2 Emission from the selected SSP Narrative based on the SSP scneario switch<br><br>Unit: $MtSO_2$/Year |
| "Surface_Temperature_Anomaly_(STA)" | (T1-T1_1850_1900_offset)*UNIT_Celcius_to_Kelvin | Computated Output by Frida Model. Represents the current Surface Temperature Anomaly based on the current and previous emitted GHG.<br><br>Unit: deg C |
| Total_CO2_Emissions[SPPs] | (Selected_SSP_World_Minus_OECD_Total_CO2_Emission+.OECD_Total_CO2_Contribution)*1+ Selected_SSP_World_Total_CO2_Emissions*0 | Depicts the total $CO_2$ Emission through combining the selected SSP World Minus OECD Total $CO_2$ Emission with the endogenized OECD Total $CO_2$ Contribution.<br><br>The second part of the equation allows for producing output only run through the SSP data. The parameter than ignores the input from before and uses the Selected SSP World Total $CO_2$ Emissions only.<br><br>Unit: $MtCO_2$ /Year |
| World_CO2_Emission_Landuse[SSP_1] | GRAPH(TIME) Points: (1994.0, 5776.43), (1995.0, 5639.4824), (1996.0, 5997.3084), (1997.0, 7480.9964), (1998.0, 6165.1323), | Data input Landuse $CO_2$ Emission<br>From 1995 to 2019: Data from (Community Emissions Data System (CEDS) 2024; Global Carbon Projct 2023; Jones et al. 2024; Ritchie, Rosado, and Roser 2023a) (equal |

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| | (1999.0, 6004.002), (2000.0, 5375.662), (2001.0, 5036.168), (2002.0, 5385.1766), (2003.0, 5833.54), (2004.0, 5393.811), (2005.0, 4891.904), (2006.0, 5234.708), (2007.0, 4556.0376), (2008.0, 4740.7887), (2009.0, 5236.149), (2010.0, 5177.513), (2011.0, 5218), (2012.0, 5345.19), (2013.0, 4858.7817), (2014.0, 5214.2874), (2015.0, 5630.261), (2016.0, 4598.992), (2017.0, 4564.99), (2018.0, 4285.1459), (2019.0, 4597.514), (2020.0, 3176.77), (2030.0, 2972.976), (2040.0, 1917.707), (2050.0, -213.854), (2060.0, -1436.361), (2070.0, -1718.86), (2080.0, -1940.187), (2090.0, -2014.942), (2100.0, -2436.092) | throughout the array)<br>From 2020 to 2100: Projected data in respect to the SSP narrative (Riahi et al. 2017; Fricko et al. 2017; Van Vuuren et al. 2017; Kriegler et al. 2017)<br><br>Unit: $MtCO_2$ /Year<br><br>Properties:<br><br> |
| World_CO2_Emission_Landuse[SSP_2] | GRAPH(TIME) Points: (1994.0, 5776.43), (1995.0, 5639.4824), (1996.0, 5997.3084), (1997.0, 7480.9964), (1998.0, 6165.1323), (1999.0, 6004.002), (2000.0, 5375.662), (2001.0, 5036.168), (2002.0, 5385.1766), (2003.0, 5833.54), (2004.0, 5393.811), (2005.0, 4891.904), (2006.0, 5234.708), (2007.0, 4556.0376), (2008.0, 4740.7887), (2009.0, 5236.149), (2010.0, 5177.513), (2011.0, 5218), (2012.0, 5345.19), | Properties:<br><br> |

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| | (2013.0, 4858.7817), (2014.0, 5214.2874), (2015.0, 5630.261), (2016.0, 4598.992), (2017.0, 4564.99), (2018.0, 4285.1459), (2019.0, 4597.514), (2020.0, 5114.4), (2030.0, 4220.249), (2040.0, 3865.736), (2050.0, 3037.158), (2060.0, 1935.181), (2070.0, 907.574), (2080.0, 65.652), (2090.0, -248.572), (2100.0, -481.563) | |
| World_CO2_Emission_Landuse[SSP_5] | GRAPH(TIME) Points: (1994.0, 5776.43), (1995.0, 5639.4824), (1996.0, 5997.3084), (1997.0, 7480.9964), (1998.0, 6165.1323), (1999.0, 6004.002), (2000.0, 5375.662), (2001.0, 5036.168), (2002.0, 5385.1766), (2003.0, 5833.54), (2004.0, 5393.811), (2005.0, 4891.904), (2006.0, 5234.708), (2007.0, 4556.0376), (2008.0, 4740.7887), (2009.0, 5236.149), (2010.0, 5177.513), (2011.0, 5218), (2012.0, 5345.19), (2013.0, 4858.7817), (2014.0, 5214.2874), (2015.0, 5630.261), (2016.0, 4598.992), (2017.0, 4564.99), (2018.0, 4285.1459), (2019.0, 4597.514), (2020.0, 5062.389), (2030.0, 5566.452), (2040.0, 4025.617), (2050.0, 2306.466), (2060.0, 150.416), (2070.0, -238.674), (2080.0, - | Properties:  |

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| | 147.852), (2090.0, -495.368), (2100.0, -1530.31) | |
| World_CO2_Emission_Minus_OECD[SSP_1] | GRAPH(TIME) Points: (1994.0, 15629.944), (1995.0, 15721.71), (1996.0, 16374.778), (1997.0, 17843.768), (1998.0, 16384.567), (1999.0, 16575.746), (2000.0, 16298.265), (2001.0, 16308.39), (2002.0, 17177.848), (2003.0, 18564.208), (2004.0, 19022.155), (2005.0, 19455.811), (2006.0, 20896.744), (2007.0, 20914.652), (2008.0, 21963.911), (2009.0, 22939.534), (2010.0, 24021.952), (2011.0, 25333.952), (2012.0, 25988.151), (2013.0, 25903.135), (2014.0, 26642.116), (2015.0, 27118.438), (2016.0, 26146.357), (2017.0, 26626.467), (2018.0, 27019.403), (2019.0, 27913.597), (2020.0, 28982.31), (2030.0, 33044.507), (2040.0, 34607.677), (2050.0, 33773.926), (2060.0, 33273.404), (2070.0, 31694.914), (2080.0, 26702.323), (2090.0, 22735.43), (2100.0, 19246.059) | Data input on $CO_2$ emission. To calculate the OECD data was substracted from the worlds data.<br><br>From 1995 to 2019: Data from (Community Emissions Data System (CEDS) 2024; Global Carbon Projct 2023; Jones et al. 2024; Ritchie, Rosado, and Roser 2023a) (equal throughout the array)<br>From 2020 to 2100: Projected data in respect to the SSP narrative (Riahi et al. 2017; Fricko et al. 2017; Van Vuuren et al. 2017; Kriegler et al. 2017)<br><br>Unit: $MtCO_2$ /Year<br><br>Properties:<br><br> |
| World_CO2_Emission_Minus_OECD[SSP_2] | GRAPH(TIME) Points: (1994.0, 15629.944), (1995.0, 15721.71), (1996.0, 16374.778), (1997.0, 17843.768), (1998.0, 16384.567), (1999.0, 16575.746), (2000.0, 16298.265), (2001.0, 16308.39), (2002.0, 17177.848), (2003.0, | Properties:<br><br> |

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| | 18564.208), (2004.0, 19022.155), (2005.0, 19455.811), (2006.0, 20896.744), (2007.0, 20914.652), (2008.0, 21963.911), (2009.0, 22939.534), (2010.0, 24021.952), (2011.0, 25333.952), (2012.0, 25988.151), (2013.0, 25903.135), (2014.0, 26642.116), (2015.0, 27118.438), (2016.0, 26146.357), (2017.0, 26626.467), (2018.0, 27019.403), (2019.0, 27913.597), (2020.0, 29783.011), (2030.0, 34095.926), (2040.0, 38206.048), (2050.0, 42399.653), (2060.0, 46692.642), (2070.0, 50751.474), (2080.0, 57662.095), (2090.0, 63811.382), (2100.0, 68521.142) | |
| World_CO2_Emission_Minus_OECD[SSP_5] | GRAPH(TIME) Points: (1994.0, 15629.944), (1995.0, 15721.71), (1996.0, 16374.778), (1997.0, 17843.768), (1998.0, 16384.567), (1999.0, 16575.746), (2000.0, 16298.265), (2001.0, 16308.39), (2002.0, 17177.848), (2003.0, 18564.208), (2004.0, 19022.155), (2005.0, 19455.811), (2006.0, 20896.744), (2007.0, 20914.652), (2008.0, 21963.911), (2009.0, 22939.534), (2010.0, 24021.952), (2011.0, 25333.952), (2012.0, 25988.151), (2013.0, 25903.135), (2014.0, 26642.116), (2015.0, 27118.438), (2016.0, 26146.357), | Properties:  |

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| | (2017.0, 26626.467), (2018.0, 27019.403), (2019.0, 27913.597), (2020.0, 30673.428), (2030.0, 39863.909), (2040.0, 49228.604), (2050.0, 59326.459), (2060.0, 70414.626), (2070.0, 82260.826), (2080.0, 90935.309), (2090.0, 91556.495), (2100.0, 87641.68) | |
| World_CO2_Emission_Total[SSP_1] | GRAPH(TIME) Points: (1994.0, 28216.31), (1995.0, 28537.694), (1996.0, 29568.004), (1997.0, 31164.31), (1998.0, 29740.409), (1999.0, 30054.218), (2000.0, 30082.568), (2001.0, 29919.089), (2002.0, 30824.399), (2003.0, 32640.156), (2004.0, 33099.53), (2005.0, 33533.485), (2006.0, 34837.73), (2007.0, 34993.504), (2008.0, 35709.334), (2009.0, 35702.89), (2010.0, 37390.65), (2011.0, 38535.65), (2012.0, 39171.52), (2013.0, 38964.76), (2014.0, 39547.945), (2015.0, 39919.92), (2016.0, 38868.345), (2017.0, 39349.215), (2018.0, 39776.12), (2019.0, 40358.085), (2020.0, 40069.004), (2030.0, 42653.234), (2040.0, 43778.496), (2050.0, 42454.758), (2060.0, 41601.928), (2070.0, 39217.532), (2080.0, 33392.294), (2090.0, 28618.414), (2100.0, 24612.914) | Data input on $CO_2$ Emission.<br>From 1995 to 2019: Data from (Community Emissions Data System (CEDS) 2024; Global Carbon Projct 2023; Jones et al. 2024; Ritchie, Rosado, and Roser 2023a) (equal throughout the array)<br>From 2020 to 2100: Projected data in respect to the SSP narrative (Riahi et al. 2017; Fricko et al. 2017; Van Vuuren et al. 2017; Kriegler et al. 2017)<br><br>Unit: Mt $CO_2$ /Year<br><br>Properties:<br><br> |

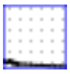
| | | |
|---|---|---|
| World_CO2_Emission_Total[SSP_2] | GRAPH(TIME) Points: (1994.0, 28216.31), (1995.0, 28537.694), (1996.0, 29568.004), (1997.0, 31164.31), (1998.0, 29740.409), (1999.0, 30054.218), (2000.0, 30082.568), (2001.0, 29919.089), (2002.0, 30824.399), (2003.0, 32640.156), (2004.0, 33099.53), (2005.0, 33533.485), (2006.0, 34837.73), (2007.0, 34993.504), (2008.0, 35709.334), (2009.0, 35702.89), (2010.0, 37390.65), (2011.0, 38535.65), (2012.0, 39171.52), (2013.0, 38964.76), (2014.0, 39547.945), (2015.0, 39919.92), (2016.0, 38868.345), (2017.0, 39349.215), (2018.0, 39776.12), (2019.0, 40358.085), (2020.0, 42262.425), (2030.0, 46727.551), (2040.0, 51606.452), (2050.0, 56651.629), (2060.0, 61402.269), (2070.0, 65996.979), (2080.0, 74133.629), (2090.0, 81028.377), (2100.0, 85684.204) | Properties:  |
| World_CO2_Emission_Total[SSP_5] | GRAPH(TIME) Points: (1994.0, 28216.31), (1995.0, 28537.694), (1996.0, 29568.004), (1997.0, 31164.31), (1998.0, 29740.409), (1999.0, 30054.218), (2000.0, 30082.568), (2001.0, 29919.089), (2002.0, 30824.399), (2003.0, 32640.156), (2004.0, 33099.53), (2005.0, 33533.485), (2006.0, | Properties:  |

| | | |
|---|---|---|
| | 34837.73), (2007.0, 34993.504), (2008.0, 35709.334), (2009.0, 35702.89), (2010.0, 37390.65), (2011.0, 38535.65), (2012.0, 39171.52), (2013.0, 38964.76), (2014.0, 39547.945), (2015.0, 39919.92), (2016.0, 38868.345), (2017.0, 39349.215), (2018.0, 39776.12), (2019.0, 40358.085), (2020.0, 44610.389), (2030.0, 56726.452), (2040.0, 69861.617), (2050.0, 84436.466), (2060.0, 101301.616), (2070.0, 117499.826), (2080.0, 129499.348), (2090.0, 130397.532), (2100.0, 126097.683) | |
| World_Total_CH4_SSP2[SSP_1] | GRAPH(TIME) Points: (1994.0, 267.7430537), (1995.0, 271.8055705), (1996.0, 274.753906), (1997.0, 274.8567114), (1998.0, 272.7091711), (1999.0, 274.1760503), (2000.0, 279.4803356), (2001.0, 279.3814597), (2002.0, 279.1143289), (2003.0, 286.8295134), (2004.0, 293.0963087), (2005.0, 298.3625839), (2006.0, 304.2951007), (2007.0, 307.073255), (2008.0, 310.7521812), (2009.0, 309.0324832), (2010.0, 315.2124497), (2011.0, | Data input $CH_4$ Emission<br>From 1995 to 2019: Data from (Community Emissions Data System (CEDS) 2024; Global Carbon Projct 2023; Jones et al. 2024; Ritchie, Rosado, and Roser 2023a) (equal throughout the array)<br>From 2020 to 2100: Projected data in respect to the SSP narrative (Riahi et al. 2017; Fricko et al. 2017; Van Vuuren et al. 2017; Kriegler et al. 2017)<br><br>Unit: $MtCH_4$/Year<br><br>Properties:<br><br> |

| | | |
|---|---|---|
| | 324.3875168), (2012.0, 327.7453356), (2013.0, 326.8757383), (2014.0, 329.7897315), (2015.0, 330.3645973), (2016.0, 331.2122819), (2017.0, 336.6013087), (2018.0, 341.5553356), (2019.0, 343.7707383), (2020.0, 365.639), (2030.0, 381.187), (2040.0, 389.852), (2050.0, 379.503), (2060.0, 362.19), (2070.0, 338.688), (2080.0, 304.959), (2090.0, 273.297), (2100.0, 246.207) | |
| World_Total_CH4_SSP2[SSP_2] | GRAPH(TIME) Points: (1994.0, 267.7430537), (1995.0, 271.8055705), (1996.0, 274.753906), (1997.0, 274.8567114), (1998.0, 272.7091711), (1999.0, 274.1760503), (2000.0, 279.4803356), (2001.0, 279.3814597), (2002.0, 279.1143289), (2003.0, 286.8295134), (2004.0, 293.0963087), (2005.0, 298.3625839), (2006.0, 304.2951007), (2007.0, 307.073255), (2008.0, 310.7521812), (2009.0, 309.0324832), (2010.0, 315.2124497), (2011.0, 324.3875168), (2012.0, | Properties:  |

| | | |
|---|---|---|
| | 327.7453356), (2013.0, 326.8757383), (2014.0, 329.7897315), (2015.0, 330.3645973), (2016.0, 331.2122819), (2017.0, 336.6013087), (2018.0, 341.5553356), (2019.0, 343.7707383), (2020.0, 345.346), (2030.0, 373.12), (2040.0, 393.495), (2050.0, 411.433), (2060.0, 425.59), (2070.0, 433.325), (2080.0, 436.418), (2090.0, 434.125), (2100.0, 422.185) | |
| World_Total_CH4_SSP2[SSP_5] | GRAPH(TIME) Points: (1994.0, 267.7430537), (1995.0, 271.8055705), (1996.0, 274.753906), (1997.0, 274.8567114), (1998.0, 272.7091711), (1999.0, 274.1760503), (2000.0, 279.4803356), (2001.0, 279.3814597), (2002.0, 279.1143289), (2003.0, 286.8295134), (2004.0, 293.0963087), (2005.0, 298.3625839), (2006.0, 304.2951007), (2007.0, 307.073255), (2008.0, 310.7521812), (2009.0, 309.0324832), (2010.0, 315.2124497), (2011.0, 324.3875168), (2012.0, 327.7453356), (2013.0, | Properties:  |

| | | |
|---|---|---|
| | 326.8757383), (2014.0, 329.7897315), (2015.0, 330.3645973), (2016.0, 331.2122819), (2017.0, 336.6013087), (2018.0, 341.5553356), (2019.0, 343.7707383), (2020.0, 407.709), (2030.0, 477.146), (2040.0, 570.473), (2050.0, 630.66), (2060.0, 644.562), (2070.0, 646.021), (2080.0, 620.756), (2090.0, 582.778), (2100.0, 540.025) | |
| World_Total_SO2_SSP2[SSP_1] | GRAPH(TIME) Points: (1994.0, 123.28524), (1995.0, 120.81163), (1996.0, 117.479736), (1997.0, 117.210264), (1998.0, 113.97983), (1999.0, 108.47918), (2000.0, 107.800536), (2001.0, 108.48728), (2002.0, 107.36466), (2003.0, 111.72819), (2004.0, 117.09624), (2005.0, 122.964616), (2006.0, 123.619224), (2007.0, 122.38312), (2008.0, 118.8464), (2009.0, 109.399976), (2010.0, 105.69075), (2011.0, 109.038296), (2012.0, 105.98769), (2013.0, 101.40317), (2014.0, 96.6652), (2015.0, 91.23651), (2016.0, 87.83277), (2017.0, 84.85462), (2018.0, 83.25885), (2019.0, 81.43515), (2020.0, 95.879), (2030.0, 64.427), (2040.0, 60.487), (2050.0, 56.424), (2060.0, 53.727), (2070.0, 48.621), | Data input $SO_2$ Emission<br>From 1995 to 2019: Data from (Community Emissions Data System (CEDS) 2024; Global Carbon Projct 2023; Jones et al. 2024; Ritchie, Rosado, and Roser 2023a) (equal throughout the array)<br>From 2020 to 2100: Projected data in respect to the SSP narrative (Riahi et al. 2017; Fricko et al. 2017; Van Vuuren et al. 2017; Kriegler et al. 2017)<br><br>Unit: $MtSO_2$/year<br><br>Properties:<br><br> |

| | | |
|---|---|---|
| | (2080.0, 38.79), (2090.0, 28.825), (2100.0, 19.804) | |
| World_To-tal_SO2_SSP2[SSP_2] | GRAPH(TIME) Points: (1994.0, 123.28524), (1995.0, 120.81163), (1996.0, 117.479736), (1997.0, 117.210264), (1998.0, 113.97983), (1999.0, 108.47918), (2000.0, 107.800536), (2001.0, 108.48728), (2002.0, 107.36466), (2003.0, 111.72819), (2004.0, 117.09624), (2005.0, 122.964616), (2006.0, 123.619224), (2007.0, 122.38312), (2008.0, 118.8464), (2009.0, 109.399976), (2010.0, 105.69075), (2011.0, 109.038296), (2012.0, 105.98769), (2013.0, 101.40317), (2014.0, 96.6652), (2015.0, 91.23651), (2016.0, 87.83277), (2017.0, 84.85462), (2018.0, 83.25885), (2019.0, 81.43515), (2020.0, 77.969), (2030.0, 79.199), (2040.0, 72.289), (2050.0, 65.157), (2060.0, 61.17), (2070.0, 56.31), (2080.0, 52.965), (2090.0, 48.531), (2100.0, 43.898) | Properties:  |
| World_To-tal_SO2_SSP2[SSP_5] | GRAPH(TIME) Points: (1994.0, 123.28524), (1995.0, 120.81163), (1996.0, 117.479736), (1997.0, 117.210264), (1998.0, 113.97983), (1999.0, 108.47918), (2000.0, 107.800536), (2001.0, 108.48728), (2002.0, 107.36466), (2003.0, 111.72819), (2004.0, 117.09624), | Properties:  |

(2005.0, 122.964616), (2006.0, 123.619224), (2007.0, 122.38312), (2008.0, 118.8464), (2009.0, 109.399976), (2010.0, 105.69075), (2011.0, 109.038296), (2012.0, 105.98769), (2013.0, 101.40317), (2014.0, 96.6652), (2015.0, 91.23651), (2016.0, 87.83277), (2017.0, 84.85462), (2018.0, 83.25885), (2019.0, 81.43515), (2020.0, 77.239), (2030.0, 65.961), (2040.0, 59.928), (2050.0, 48.567), (2060.0, 41.758), (2070.0, 35.219), (2080.0, 29.339), (2090.0, 24.668), (2100.0, 18.953)

| Array Dimension | Indexed by | Elements |
|---|---|---|
| ClimateCase | Number | 11 |
| Education | Label (4) | noEd<br>primary<br>secondary<br>tertiary |
| SPPs | Label (3) | SSP_1<br>SSP_2<br>SSP_5 |

| **Custom Unit** | **Aliases** | **Equation** |
|---|---|---|
| G$ | | Giga*$ |
| Gh | | Giga*h |
| Gph | | Gh*p |
| GtCO2e | | Giga*tCO2e |
| k$ | | kilo*$ |
| kh | | kilo*h |

| | | |
|---|---|---|
| M$ | | Million*$ |
| Mha | | Million*ha |
| Mkh | | Million*kh |
| Mkm2 | | Million*km2 |
| Mm2 | | Million*m2 |
| Mp | | Million*p |
| Mt redmeat | | Million*t redmeat |
| MtCO2 | | Million*tCO2 |
| Mtcrop | | Million*tcrop |
| MtH2 | | Million*tH2 |
| MtN | | Million*tN |
| MtN2O | | Million*tN2O |
| MZJ | | Million*ZJ |
| MtCH4 | | Million*tCH4 |
| MkgH2 | | Million*kgH2 |
| TWh | | Million*MWh |
| kWh | | kilo*w*h |
| Mtoe | | Million*toe |
| GW | | TWh/(kilo*h) |
| kilowatt hours per day | | kWh/day |
| kilowatts | kilowatt | kW |
| Hour | Hours | |
| Unit | Units | |
| Week | Weeks | |
| MtSO2 | | Million*tSO2 |
| KtN2O | | kilo*tN2O |
| MKg | | Million*kg |
| p | | people |
| item | items | |
| order | orders | |
| G | | Giga |

| | | |
|---|---|---|
| GtCO2 | | Giga*tCO2 |
| GtCH4 | | Giga*tCH4 |
| GtN2O | | Giga*tN2O |
| Euros | EUR<br>euro | |
| euros per year per person | | EUR/(person-year) |
| Person | People<br>Persons | |
| dollars per job | | USD/jobs |
| dollars per month per worker | | USD/(worker-mo) |
| jobs per month per worker | | jobs/(worker-mo) |
| months per year | | mo/yr |
| K | C | |
| degreeC | degreesC | |
| event | events | |
| W | Watt | |
| M | | Million |
| meter | meters | |
| Dimensionless | dmnl<br>unitless<br>fraction | 1 |

| User Macro | Output |
|---|---|
| PCTILE5(<in>) | out |

| | Equation | Units |
|---|---|---|
| in | 1 | dmnl |
| out | IF in = 1 THEN 0 ELSE IF in = 2 THEN 25 ELSE IF in = 3 THEN 50 ELSE IF in = 4 THEN 75 ELSE IF in = 5 THEN 100 ELSE 0 | dmnl |

## Simulation Experiment Report

Modelling Softwarte: Stella Architect
Integration Method: Euler
DT= 1/256
Time Units = Year
Start Time = 1995 Stop Time = 2100

**Business As Usual Scenario**
PEBI in Year 1995 = 0.545
Sensitivity Intention on Carbon Footprint = -0.621
Maximum Effect = 2.73
Switch Energy Efficiency = 1
Energy Intensity Improvement Rate = 0.008
CO2 per Cap Base Year 1995 = 11.3
AT CFP = 4.5
TPPC = 3
Historical Time Horizon = 25
Forecast Horizon = 5
Steepness SAL Effect = 3
Upper Limit SAL Effect = 2
Inflection Point SAL Effect = 1
Steepness PGAL Effect = 3
Upper Limit PGAL Effect = 2
Inflection Point PGAL Effect = 1
Weight on Personal Norm = 0.7
Weight on Peer Influence = 0.3
AT Intention = 3
Unit Change = 1000000
SSP Scenario Switch = 2
Media Coverage Efficiency = 0.78
TPPC_1 = 3
TPPC_2 = 1.65
THRC_1 = 10
Initial Perceived Temp = 0.44
Sensation Magnitude Factor = 0.75
Steepness Personal Norm Effect = 5
Time Horizon EEvents = 16.2
Sensitivity of Seriousness = -1.37
Basline Inflection Point PAL Effect = 1
CEES_SW = 0
TERS_SW = 0
SSP_1_Alternativ_SW = 0
SSP_5_Scenario_SW = 0
SSP_5_Alternativ_SW = 0

**CEE Scenario**
As in BAU, except:
CEES_SW = 1
**OR**
As listed in BAU, except:
Weight on Personal Norm = 0.7 – STEP(0.5,2024)
Weight on Peer -Influence = 0.3 + STEP(0.2, 2024)
Sensitivity from Intention to CFP = -0.621 + STEP(0.31, 2024)

**TERS Scenario**
As in BAU, except:
TERS_SW = 1
**OR**
As listed in BAU, except:
Weight on Personal Norm = 0.7 + STEP (0.1, 2024)
Weight on Peer Influence = 0.3 – STEP (0.1,2024)
Sensitivity of Seriousness = -1.37 - STEP (0.63,2024)
AT CFP = 4.5 – STEP (2 ,2024)
AT Intention = 3 – STEP (1, 2024)
Sensitivity from Intention on CFP = -0.621 – STEP (0.3, 2024)

**SSP1 Scenario**
As in BAU, except:
SSP_1_Scenario_SW = 1
**OR**
As listed in BAU, except:
SSP Switch = 2 – STEP (1, 2024)
Energy Efficiency Improvement Rate = 0.008 + STEP (0.005, 2024)

THRC_1 = 10 + STEP(5, 2024)
Media Coverage Efficiency = 0.78 + STEP (0.22, 2024)
Sensitivity of Seriousness = -1.37 - STEP (0.41,2024)
Society's strived intention = MIN (1, (PEBI_in_1995*Effect_from_Social_Projection_on_Intention) + STEP (0.15, 2024))

**SSP 5 Scenario**
As in BAU, except:
SSP_5_Scenario_SW = 1
**OR**
As listed in BAU, except:
SSP Switch = 2 + STEP (3, 2024)
Society's strived intention = (PEBI_in_1995*Effect_from_Social_Projection_on_Intention) - STEP (0.15, 2024)
Energy Efficiency Improvement Rate = 0.008 - STEP (0.003, 2024)
THRC_1 = 10 - STEP(5, 2024)
Updating Reference Temperature Variation = MAX(0, (Perceived_Temp_Variation-Reference_Temp_Variation)/THRC_1) + STEP(1.4, 2024, 1)
Weight on Personal Norm = 0.7 – STEP (0.2, 2024)
Sensation Magnitude Exponent = 0.75 - 0.5
Sensitivity of Seriousness = -1.37 + STEP (0.41,2024)

**Alternative SSP-5 (arbitrary variations)**
As in BAU, except:
SSP_5_Alternativ_SW = 1

**OR**
As in SSP 5 Scenario, except:
Society's strived intention = (PEB_in_1995*Effect_from_Social_Projection_on_Intention)
Updating Reference Temperature Variation = MAX(0, (Perceived_Temp_Variation-Reference_Temp_Variation)/THRC_1) + STEP(4.5, 2024, 1)
Weight on Personal Norm = 0.7 + STEP (0.2, 2024)
Sensitivity of Seriousness = -1.37 + STEP (1.36, 2024)
TPPC_2 = 1.65 + STEP (3, 2024)
Media Coverage Efficiency = 0.78 - STEP (0.28, 2024)
AT CFP 4.5 + STEP (3.5, 2024)

# B. Appendix B – Calibration Documentation

| Payoff: | **Payoff** |
|---|---|
| Action | minimize |
| Kind | Calibration |
| Element | Carbon Footprint (CFP) |
| Weight | auto |
| Comparison Variable | |
| Comparison Run | Calibration Data |
| Comparison Type | Squared Error |
| Comparison Tolerance | |

| Method | stoponerr | tolerance | maxiter | init_step |
|---|---|---|---|---|
| **Powell** | | 0.00001 | 0 | 1 |

The historic average carbon footprint of OECD member countries from the year 1995 to 2018 was used as Calibration Data (OECD 2022b; Yamano and Guilhoto 2020)

| Parameter: | Sensitivity Intention on CFP | Historical Time Horizon | TPT | steepness SAL Effect | steepness PGAL Effect | steepness Personal Norm Effect | Weight on Peer Influence | Weight on Personal Norm | AT Intention | THRC 1 | TPPC 2 | TPPC 1 | Media Coverage Efficiency | Sensation magnitude Factor | Initial Perceived Temp | AT CFP | Sensitivity of Seriousness | Time Horizon EEvents | Forecast Horizon |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| min_value | -4 | 10 | 1 | 3 | 3 | 1 | 0.3 | 0.3 | 1 | 10 | 1 | 1 | 0.7 | 0.25 | 0 | 1 | -2 | 10 | 5 |
| max_value | 0 | 25 | 5 | 5 | 5 | 5 | 0.7 | 0.7 | 5 | 20 | 3 | 3 | 1 | 0.75 | 0.5 | 5 | 0 | 25 | 20 |
| scaling | 100 | 1 | 10 | 100 | 100 | 100 | 10 | 10 | 1 | 1 | 1 | 1 | 10 | 100 | 10 | 1 | 10 | 1 | 1 |

| | Sensitivity Intention on CFP | Historical Time Horizon | TPT | steepness SAL Effect | steepness PGAL Effect | steepness Personal Norm Effect | Weight on Peer Influence | Weight on Personal Norm | AT Intention | THRC 1 |
|---|---|---|---|---|---|---|---|---|---|---|
| Star | -0.445 | 25 | 5 | 3 | 3 | 5 | 0.3 | 0.7 | 2.2 | 10 |
| After 7018 runs | -0.527406 | 25(max) | 5(max) | 3(min) | 3(min) | 5(max) | 0.3(min) | 0.7(max) | 2.78613 | 10(min) |

| | TPPC 2 | TPPC 1 | Media Coverage Effi-ciency | Sensation magnitude Fac-tor | Initial Perceived Temp | AT CFP | Sensitivity of Seriousness | Time Horizon EEvents | Forecast Horizon | **Payoff** |
|---|---|---|---|---|---|---|---|---|---|---|
| Start | 1.33 | 3 | 0.7 | 0.75 | 0.39 | 5 | -1.34 | 18.8 | 5 | |
| After 7018 runs | 1.82281 | 3(max) | 0.700166 | 0.75(max) | 0.407614 | 4.59938 | -1.31104 | 18.024 | 5(min) | 15.5621 |

# C. Appendix C – Sensitivity Analysis

**Z Score – Detailed description**

I investigated the global sensitivity run data to check if the highest or lowest variation in a parameter contributes significantly (under simultaneous variation of all parameters) to extreme outputs (outputs in the range between the 95% and 100% confidence interval). I used Z-Score statistics to check sample means against the mean of the global data set. Note, that classical statistical sensitivity testing cannot be meaningfully applied to infer actual sensitivity in the parameters, see Barlas (1996, 196) for a detailed comment. I investigate the Z score nevertheless, to identify potential parameters that might prove relevant in combination with variation of other parameters. All this was based under the assumption, that a normal approximation for the actual output numbers can be assumed, which is supported by the fact of a big sample (n =10 000 runs) and the included confidence interval calculations. The numeric results of the "Base Run Global sensitivity analysis" were exported. Then, every parametric constellation that led to an output that lies within the interval between 95% and 100% of the possible output range was indexed with "1", the rest (i.e., up to 95%) with "0". Hypothesis: If the variation of the parameter would have no over-proportionally high contribution to an extreme high or extreme low output, the number of "ones" would follow the same distribution as the total sample.

This can be translated to the null-hypothesis H0: The highest (or lowest) 30% of the parameter variation have no significant impact on the magnitude of the output variable. To test this hypothesis, the Z Score for parameter X, the runs were sorted in a descending order. Then, the runs that contain the highest 30% values for parameter X were considered "a sample" (N=3000, due to Uniform distribution in variation of the parameter) (according to the output value of the respective run, each run is still labeled 1 if it lies in the 95% to 100% interval, 0 else).

The mean of the sample (the 3000 runs) was compared to the mean of the total data set and the deviation of the mean calculated. The average of the total set can be calculated rather easily, due to the coding with 1 and 0. The total set contains 500 "ones" and 9500 "zeros". This leads to an average of the set of 0.05. The variance of such a set can be calculated with the formula

$$\sigma^2 = \frac{1}{n} * \sum_{i=1}^{N} (X_i - \mu_{dataset})^2$$

With $\sigma^2$ = variance, N(n)= 10.000 $X_i$= the value of the run (1 or 0) and $\mu_{Dataset}$ = mean of the dataset. With SD (standard deviation) being $\sqrt{\sigma^2}$ and applied to our case we can calculate:

$$SD\ (\sigma) = \sqrt{\frac{1}{10000} * ((0 - 0.05)^2 * 9500 + \ (1 - 0.05)^2 * 500}$$

This will result in the mean μ = 0.05 and SD = 0.218. These calculations were then used to compare it with the distribution of the sample (i.e. the coded output distribution of the 3000 runs of the highest (lowest) end of variation of one specific parameter X), which results in a Z score indicating a first indication of how probable this distribution is, given the hypothesis that the parameter does not contribute over-proportionally to the generation of extreme outputs. For that we need the standard error of the SEM, an indicator for standard deviation of the means between the data set and a sample set.

$SEM = \frac{\sigma}{\sqrt{Nsample}} \rightarrow SEM = \frac{\sigma}{\sqrt{3000}}$ = 0.0039

To calculate the Z-Score, we compare the mean of the sample to the mean of the data set and dived by the SEM.

$$Z\ Score = \frac{\mu_{parameter\ Sample} - \mu_{dataset}}{SEM}$$

With $\mu_{sample}$= the mean of the 3000 runs

A Z score between 0 and ± 1 means the distribution of “1” and “0” is close to the population data set. Z Score between ±1 and ±2 indicates that the mean of the sample lies 1 – 2 SD apart from the data mean – a more moderate and tolerable deviation. Z Scores beyond ±2 or even ±3 SD indicate that the mean is rather off from the dataset-mean, an indication, that our hypothesis is rather improbable. A Z-Score of more than ±2 therefore suggests that the number of extreme values (“ones”) in the sample is very high, so high even, that the parameter seems to have a traceable effect.

The excel file with the corresponding data is provided in the supplementary material.

**Parametric Sensitivity Analysis**

Find below the sensitivity analysis for the parameters and effect functions in the model. The test was performed with a +/- 50% range of the baseline value for each parameter and 10 runs with the "Stella" sensitivity analysis tool. The further settings where Sobol Sampling and uniform distribution. Effect – Shapes were varied manually and the tested graphs are depicted along the analysis. The parameters are sorted by 1. Time Adjustments 2. Effect parameters 3. Other parameters

1. **Time Adjustments**

**AT CFP**

Base value: 4.5 years

Tested range: 2.5 – 7.5 years

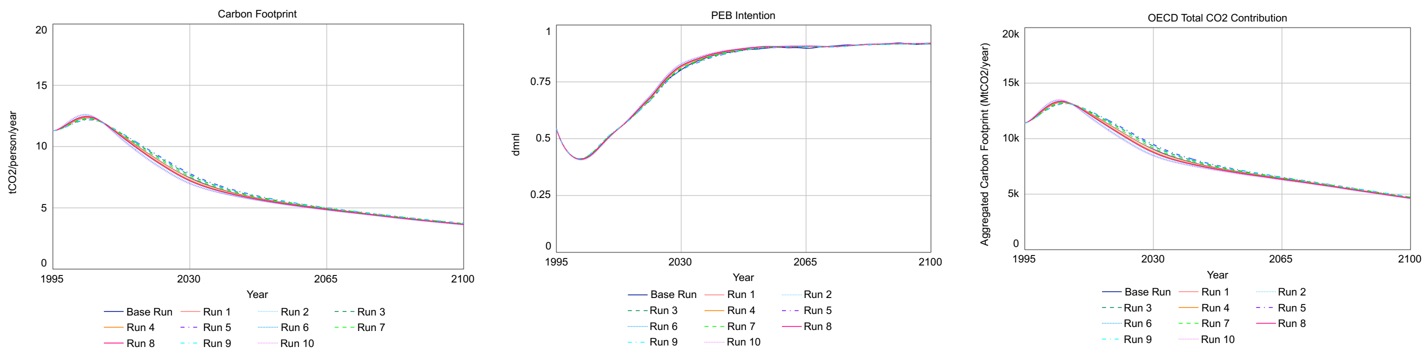



*Figure C-1 - Sensitivity Runs Adjustment Time CFP*

The model is almost not sensitive to this parameter. Given the same behavior pattern, the alternation in this parameter does not affect the models behavior significantly. Yet, a very small change in the numeric values is observable. This is to be expected, as a higher (lower) AT CFP decreases (increases) the reaction time towards changes in intention. People enact the intended new goal faster. The value was inspired by data from the transtheoretical model (see Appendix A model description for details) and was calibrated. For a specific application, this value should reflect more real-life data on how fast people might be able to fully translate their intention into new behavior.

---

**AT Intention**

Basevalue in BAU: 5 years

Tested Range: 3.5 – 7.5 years

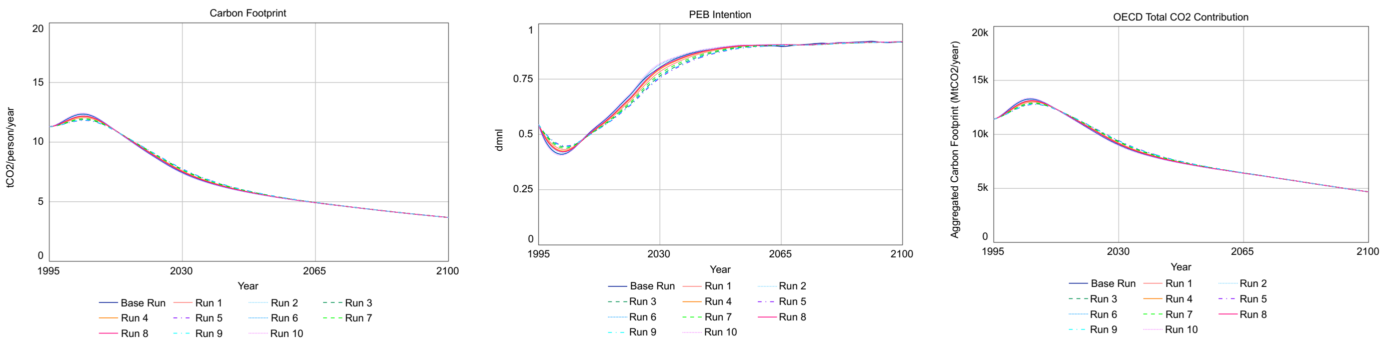



*Figure C-2 - Sensitivity Runs Adjustment Time Intention*

The model is almost not sensitive to this parameter. Given the same behavior pattern, the alternation in this parameter does not affect the models behavior significantly. Yet, a very small change in the numeric values is observable. This is to be expected, as a higher (lower) AT Intention decreases (increases) the reaction time towards changes in the aggregated goal. Information would enacted faster, behavior changed more directly to change in the model. In case of more practical application of the model a more precises value specific to the behavior in question should be sought. Additionally, a specific behavior might imply psychological insights of the value of the parameter (e.g. empirical data how long people take to change their intention of e.g smoking)

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**Historical Time Horizon**

Base Value: 25 years

Tested Range: 12.5 – 37.5 years

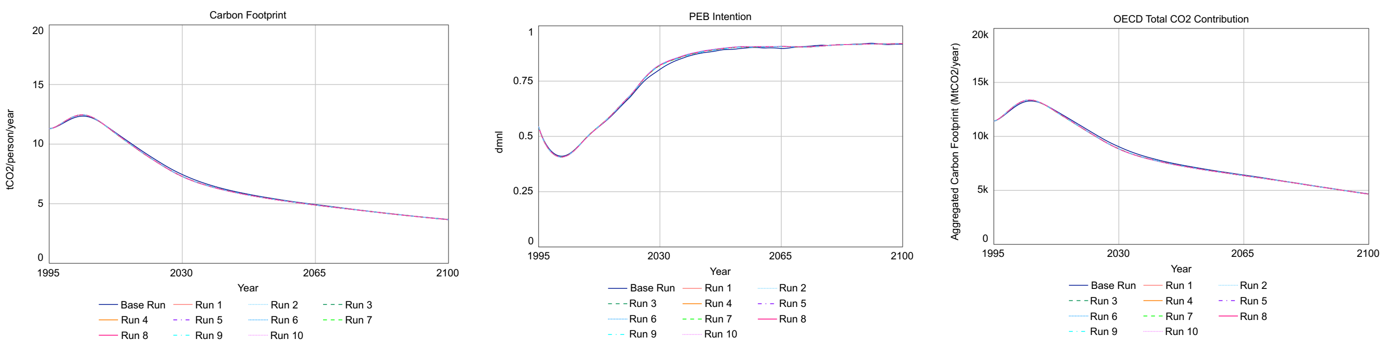


*Figure C-3 - Sensitivity Runs Historical Time Horizon*

The model is almost not sensitive to this parameter at all. This is interesting as it does present a longer / shorter observed time period which might translate into different indicated trend. The reason might be, that the Time Horizon is high enough even with 12.5 years to make the model robust to higher/lower comparisons of perceived CFP. The parameter was assumed and calibrated and its insensitivity supports the robustness of the value. Survey data to specific considerations about behavior change might inform this parameter in further work. Additionally, a specific behavior might imply psychological insights of the value of the parameter.

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**TPPC 1**
Base Value: 3 years

Tested Range: 1.5 – 4.5 years

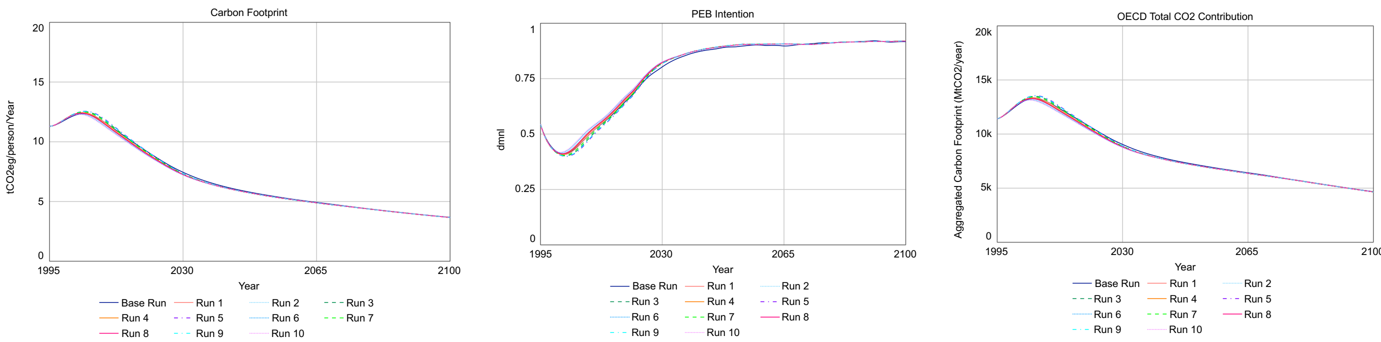


*Figure C-4 - Sensitivity Runs TPPC_1*

The model is almost not sensitive to this parameter, expect a minor marginal numerical sensitivity. This is interesting as it does present a faster / slower time to translate the actual surface temperature anomaly to people. As this represents the time for investigative effort of media and science to report on developments, the very weak sensitivity indicates robustness for the assumed and calibrated value. The reason might be, that the change in surface temperature anomaly is so small, that even a higher / shorter time lag, does not have a noticeable impact on the dynamics of the rest of the model.

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**TPPC 2**
Base Value: 1.65 years
Tested Range: 0.825 – 2.475 years

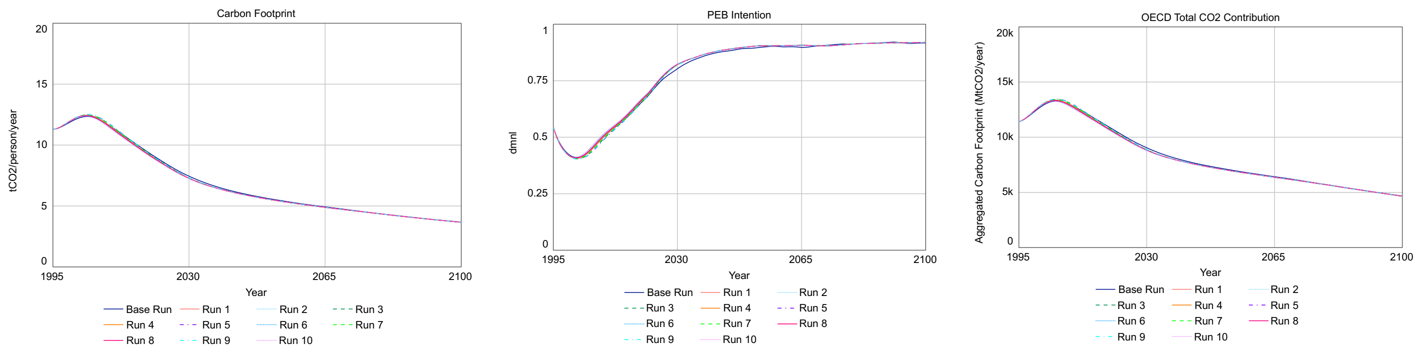


*Figure C-5 - Sensitivity Runs TPPC_2*

The model is almost not sensitive to this parameter at all. This is interesting as it does present a faster / slower time to adapt to the actual surface temperature anomaly. As this represents the time for updating the information people hold, the very weak sensitivity indicates robustness for the assumed and calibrated value. observed time period which might translate into different indicated trend. Further specification of data on how often people consume news about this type of informations and how long it takes to change the conviction about their value is needed to inform a more data-based value for this parameter.

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**THRC_1**
Base value: 10 years
Tested range: 5 – 10 years

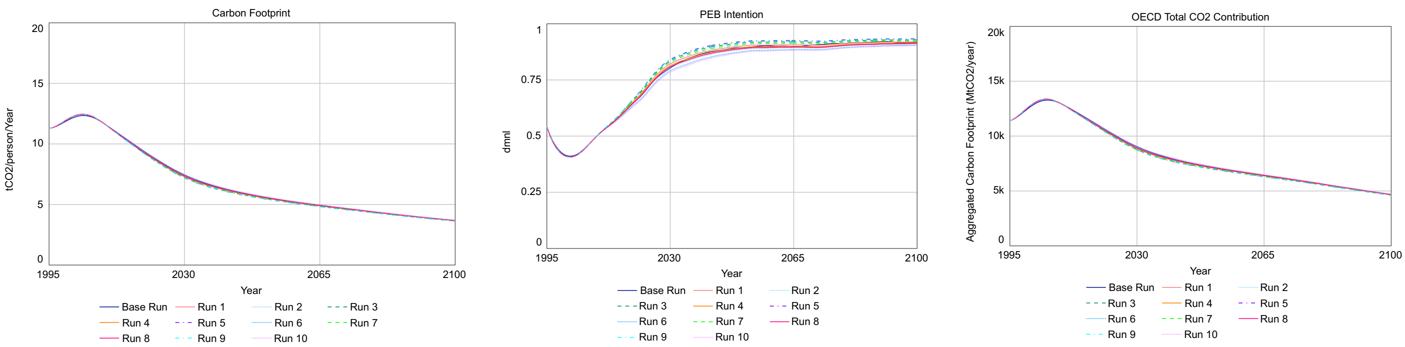


*Figure C-6 - Sensitivity Runs THRC_1*

The model is only very mildly sensitive to this parameter, except numerical changes in PEBI. This is to be expected. THRC_1 depicts the time horizon people consider when comparing the perceived temperature variation with the reference. A smaller (higher) time horizon indicate that people compare the temperature variation over a longer (shorter) period which leads to faster / slower balancing feedback through *R4 - Getting Used to News*. The weak sensitivity supports the confidence in the assumed and calibrated parameter. Further investigation into this comparison is needed to inform a more data-based value for this parameter.

---

**Time Horizon EEvents**

Base value: 16 years
Tested range: 8 -24 years

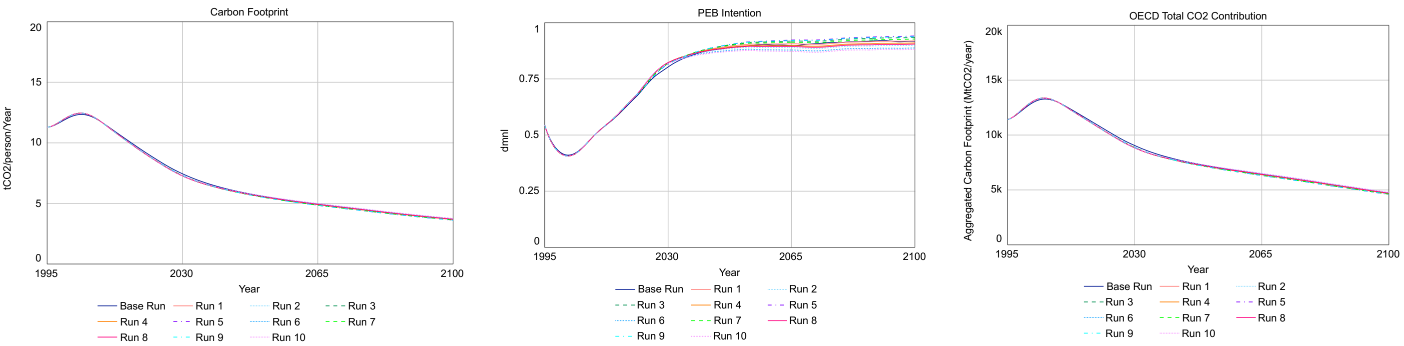


*Figure C-7 - Sensitivity Runs Historical Time Horizon EEvents*

The model is almost not sensitive to this parameter, except numerical changes in PEBI. This is to be expected. Time Horizon EEvents depicts the time horizon people consider when comparing the current number of extreme events with the reference. A smaller (higher) time horizon indicate that people compare number of events over a longer (shorter) period which leads to faster / slower balancing feedback through *R5 - Getting Used to Seriousness*. The weak sensitivity supports the confidence in the assumed and calibrated parameter. Further investigation into this comparison is needed to inform a more data-based value for this parameter.

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### TPPC

Base value: 3 years
Tested range: 1 -5 years

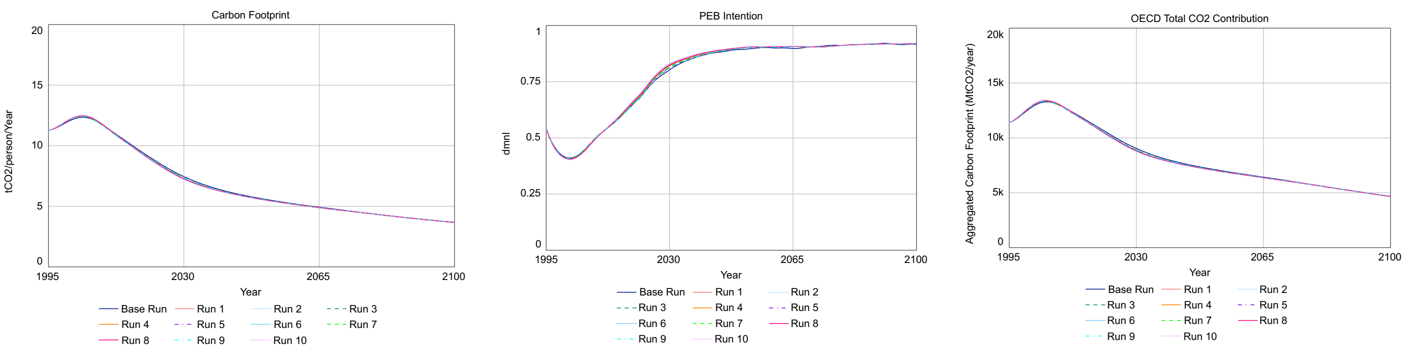


*Figure C-8 - Sensitivity Runs TPPC*

The model is almost not sensitive to this parameter at all (only very numerically weak). This is expected as it presents a faster / slower time to perceive the current CFP and by that drives the speed of the loops connected to the social norm. As the model output (given the weigths in the BAU and the general modification of the model) is not heavily driven by the speed of these loops, the low sensitivity is unsurprising, yet hints the lag of clarity in the workings of updating ones belief. Further specification of data on how people update their perceived representation of the peer groups current behavior is needed to inform a more data-based value for this parameter.

---

### TPT

Base value: 5 years
Testeed range: 2.5 – 7.5 years

The model is basically not sensitive to this parameter at all. This is as expected as it presents a faster / slower time to perceive the current trend of rate of change. This change is extremely small,

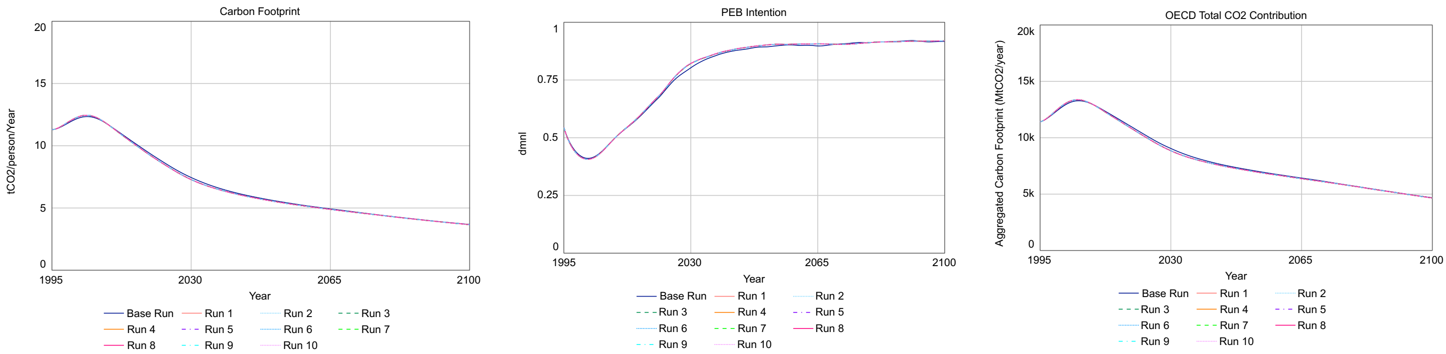


*Figure C-9 - Sensitivity Runs TPT*

therefore a change in the time to update the trend will not result in any significant adaptation of the models behavior. Although this is an assumed and calibrated value, the very weal sensitivity supports the robustness of this parameter.

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### Forecast Horizon

Base value: 5 years
Tested range: 2.5 – 7.5 years

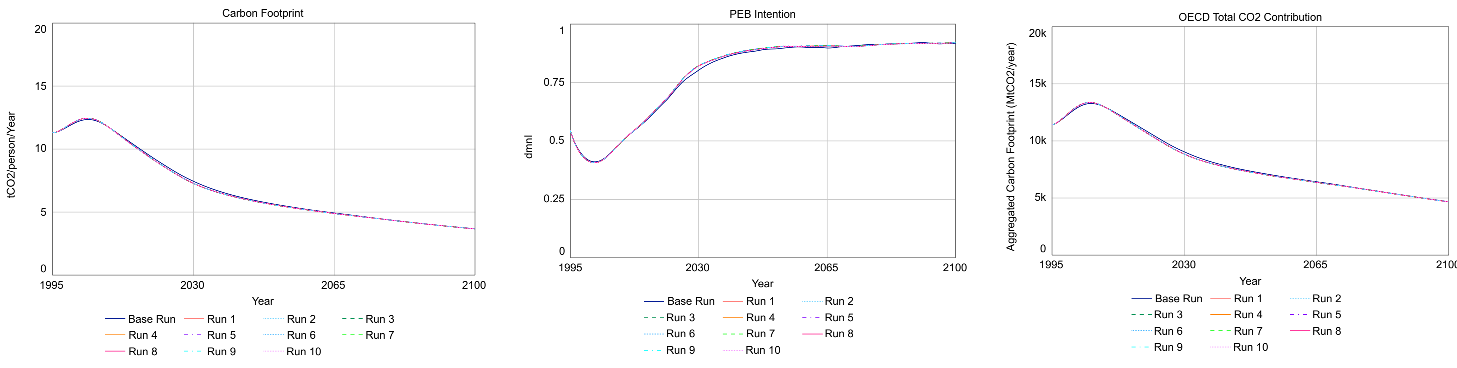


*Figure C-10 - Sensitivity Runs Forecast Horizon*

The model is basically not sensitive to this parameter at all. This is as expected. It presents a longer/ shorter time horizon that is considered when projecting the current trend. to perceive. Yet the change of the trend is extremely small, therefore a change in the timehorizon of the forcast will not significantly vary in its magnitude and therefore will not result in any significant adaptation of the models behavior. Although this is an assumed and calibrated value, the very weal sensitivity supports the robustness of this parameter.

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## 2. Effect Parameters

### Sensation Magnitude Exponent

Base value: 0.75 dmnl

Tested range: 0.5 – 1 dmnl

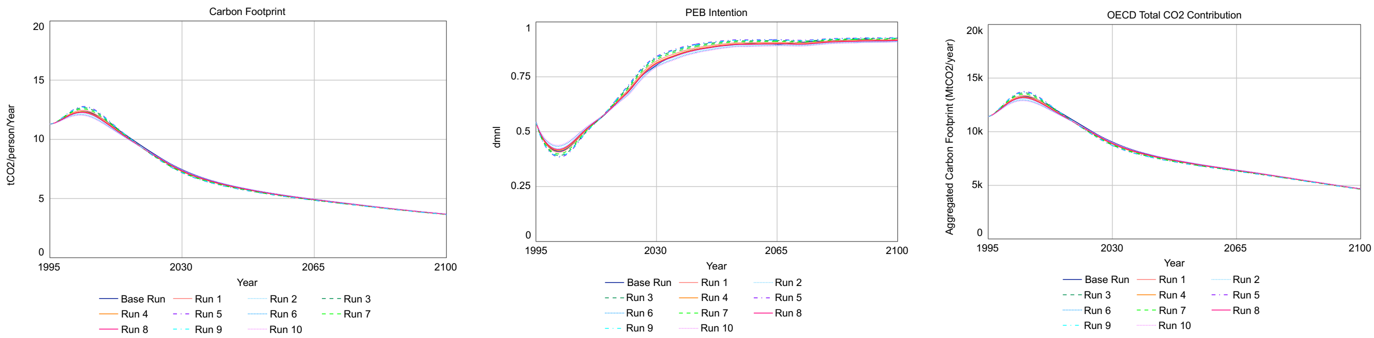


*Figure C-11 - Sensitivity Runs Sensation Magnitude Exponent*

The model is only weakly numerical sensitive to this parameter. This is to be expected. The sensation magnitude Exponent is an additional factor that moderates the perception of the relative severeness of the current climate condition (cognitive route). The parameter is anchored in reasoning about psychophysical effects as argued in the model description, yet assumed and calibrated. In essence, it dampens the capability to perceive the relative severeness directly, therefore it is to be expected, that a lower exponent value (which dampens the perception) will lead to less severeness, translating into a not so strong felt urgency and a lower personal norm, hence the variation in the models numerical output. Vice versa for an increase of the parameter. Since this manipulation is, given the values for the severeness rather low, the variation of the parameter shows only mild effects. As argued, this concept is borrowed from the field of psychophysics and its transferability and applicability to the present context needs to be tested further to gain even more confidence for both the concept and the parameters value.

## Sensitivity Intention on CFP

Base value: - 0.621 dmnl

Tested range: - 1.2 to 0 dmnl

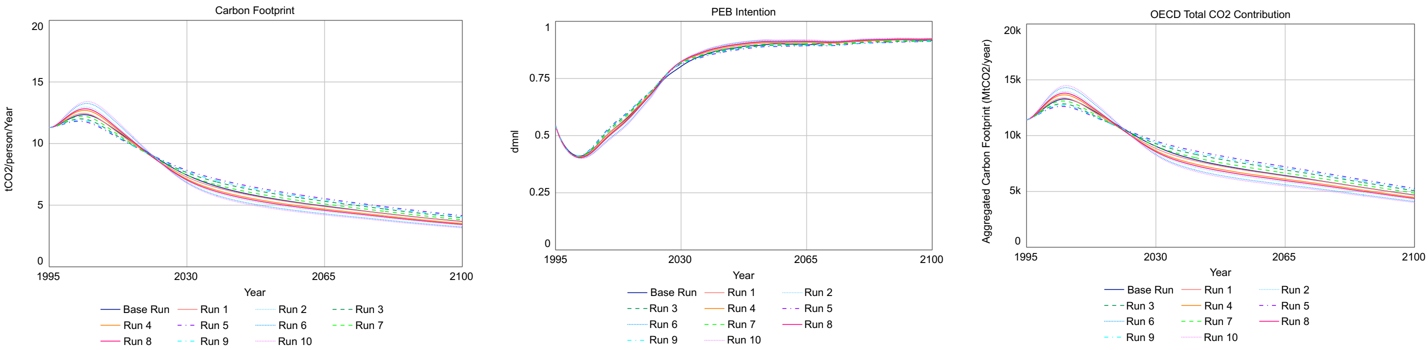


*Figure C-12 - Sensitivity Runs Sensitivity Intention on CFP*

The model is numerical sensitive to this parameter. This is to be expected, since the sensitivity from intention on CFP is the parameter that varies the "aggressiveness" of the adaptation of CFP given a change in intention. If the sensitivity is very low (not that this means a higher negative value) than people react very sensitive on a change in intention which leads to a higher de/increase of the indicate CFP through the effect. If the parameter is high (which means a value closer to 0), than the reaction is mild. That the general sensitivity for this parameter is only numerical supports a conservative representation of the effect and supports stability. Yet if the effect shape is altered, we see that the model is reacting much stronger. See the main sensitivity analysis in chapter 4 for verbal description. Below are again the graphs of the model output and the graphs for the varied shapes.

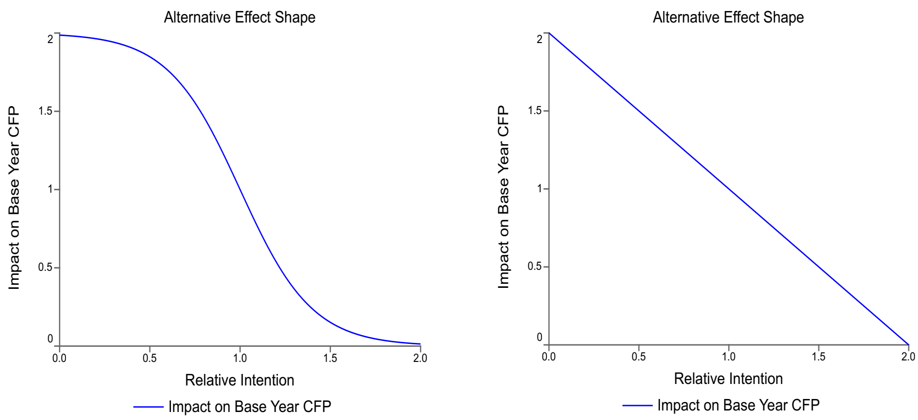


*Figure C-13 - Alternative Effect Shapes Sensitivity Intention on CFP*

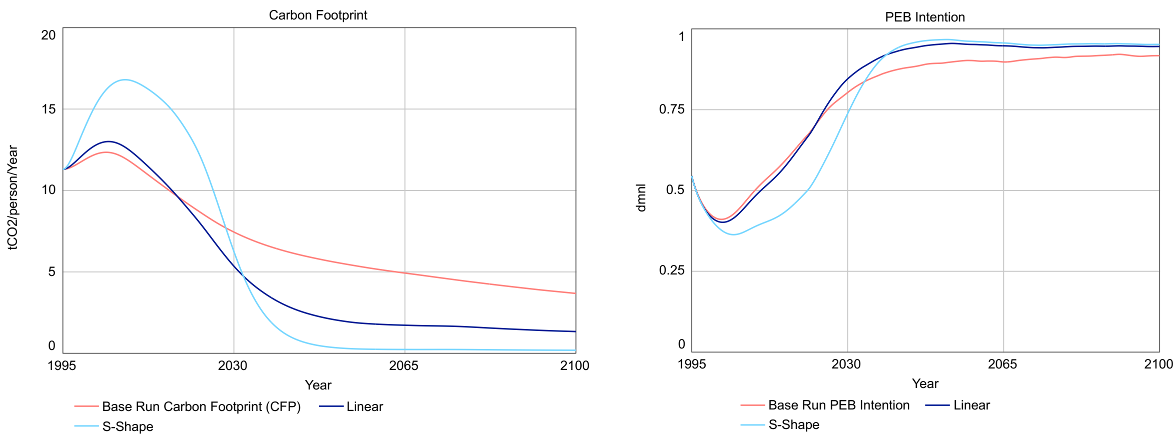


*Figure C-14 - Sensitivity Runs with alternative Effect Shape Sensitivity Intention on CFP*

## Steepness PGAL

Base value: 3 dmnl

Tested range: 1.5 -1.5 dmnl

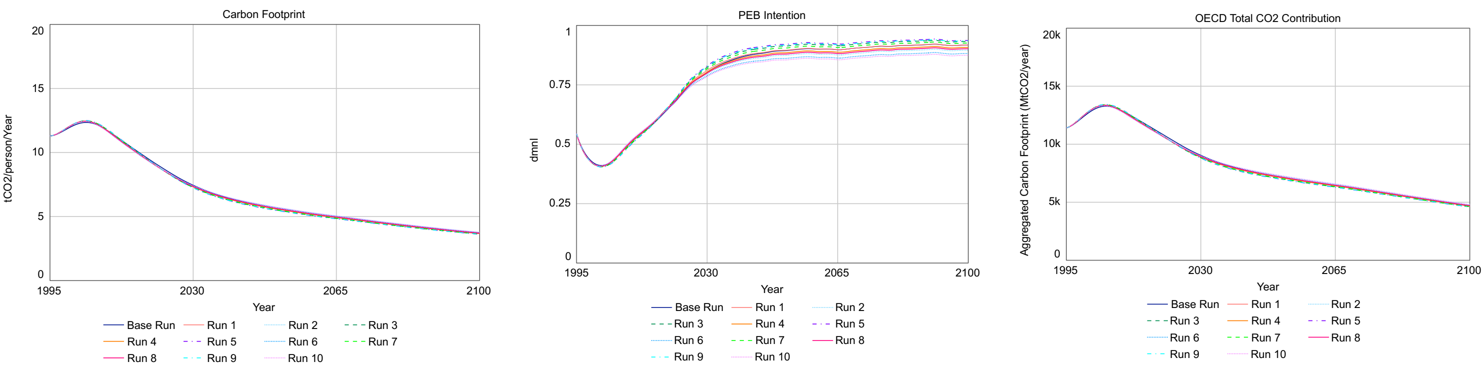


*Figure C-16 - Sensitivity Runs Steepness PGAL*

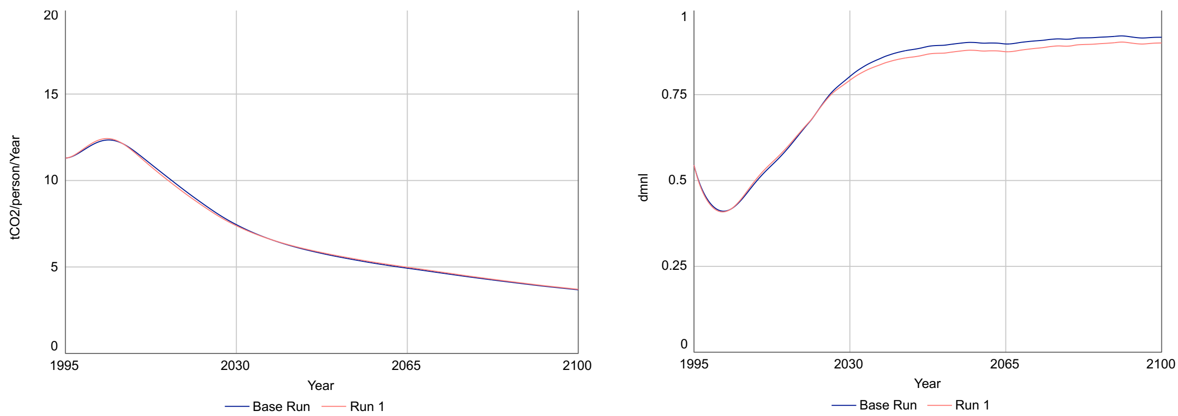


*Figure C-15 - Comparative Run with linear effect Steepness PGAL*

The model is only weakly numerically sensitive to this parameter. This is interesting yet uneventful. Recall that the Effect from Peer Group on Intention is a S-shaped effect. The steepness of the effect is indicating how sensitive people are reacting around the inflection point of the effect. A high steepness means that people change very drastically and vice versa. A steepness of on indicates a linear effect. See Appendix A model description for a more analytical description of the effect and its variation. By testing with a parameter run with a linear effect there is also only a minor numerical variation of the model outputs observable – see the graphs below for the output with a linear effect. This does reflect the uncertainty of the parameter, yet the only numerical sensitivity at least not diminishes the parameter choice.

---

**Steepness SAL**
Base value: 3 dmnl

Tested range: 1.5 – 4.5 dmnl

See the same reasoning as above. Again, below are the graphs that show the runs with a linear effect.

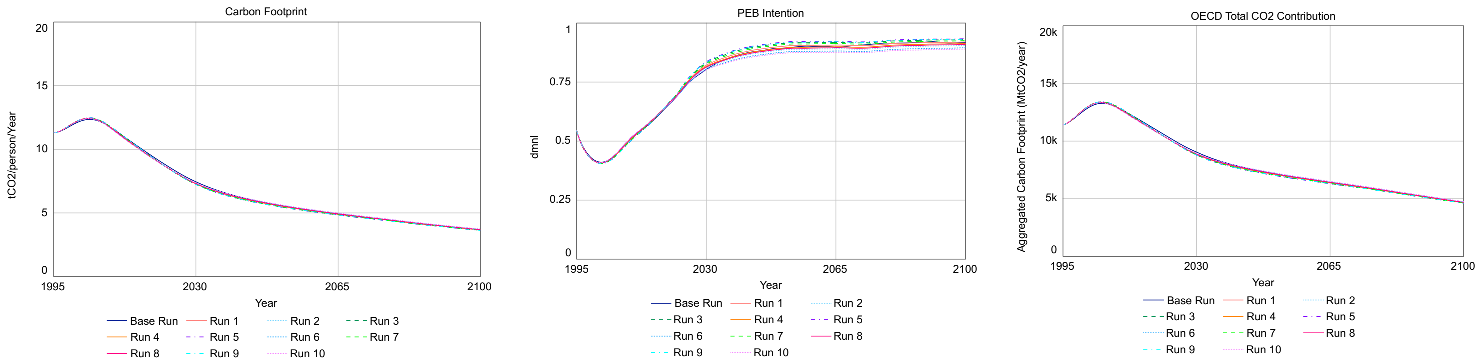


*Figure C-18 - Sensitivity Runs Steepness SAL*

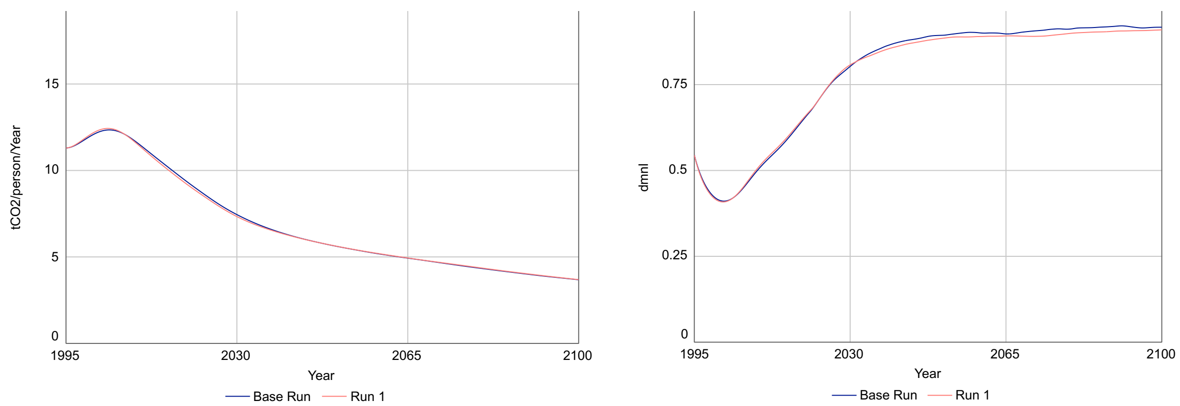


*Figure C-17 - Comparison run with effect shape Steepness SAL*

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### Steepness Personal Norm Effect

Base Value: 5 dmnl
Tested Range: 2.5 -7.5 dmnl

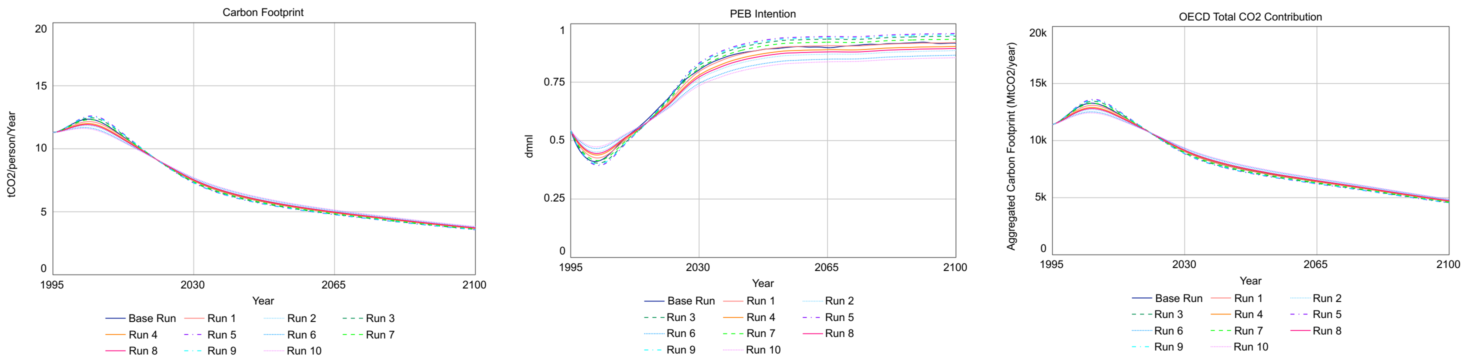

*Figure C-19 - Sensitivity Runs Steepness Personal Norm Effect*

The model is only numerical sensitive to the parameter. See reasoning about S-Shape and Steepness above. A variation in the steepness of the Personal Norm Effect is expectedly more sensitive than the other ones. This is because it gets stronger input variations through severeness than the social norm effects and the baseline steepness is higher. The numerical sensitivity is expectable. See below the runs with a linear shaped function, where seriousness results still in shifting the function to the left, as can be seen exemplary in structure graph below of the implemented linear effect. We can see in the model output that the model is only numerical sensitive. This is to be expected, since a linear effect changes, that people do not react that drastically around the normal point 1,1. This does reflect the uncertainty of the parameter, yet the only numerical sensitivity at least not diminishes the confidence the parameter choice.

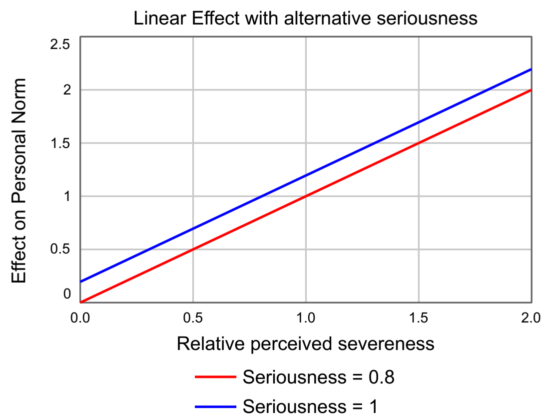

*Figure C-20 - Sensitivity Runs with Linear Effect and varying seriousness on Personal Norm Effect*

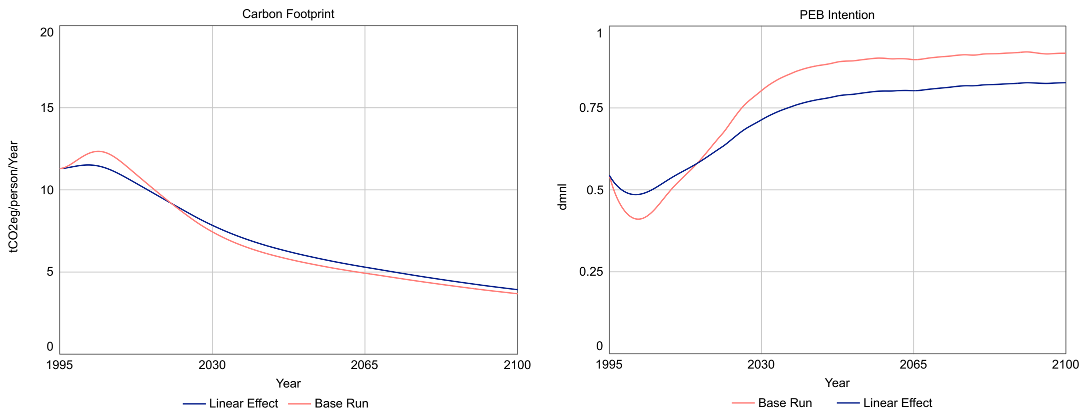


*Figure C-21 - Comparison Run with linear shape Personal Norm Effect*

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**Sensitivtity of Seriousness**

Base value: - 1.37 dmnl

Tested range: -2.1 – (-0.7) dmnl

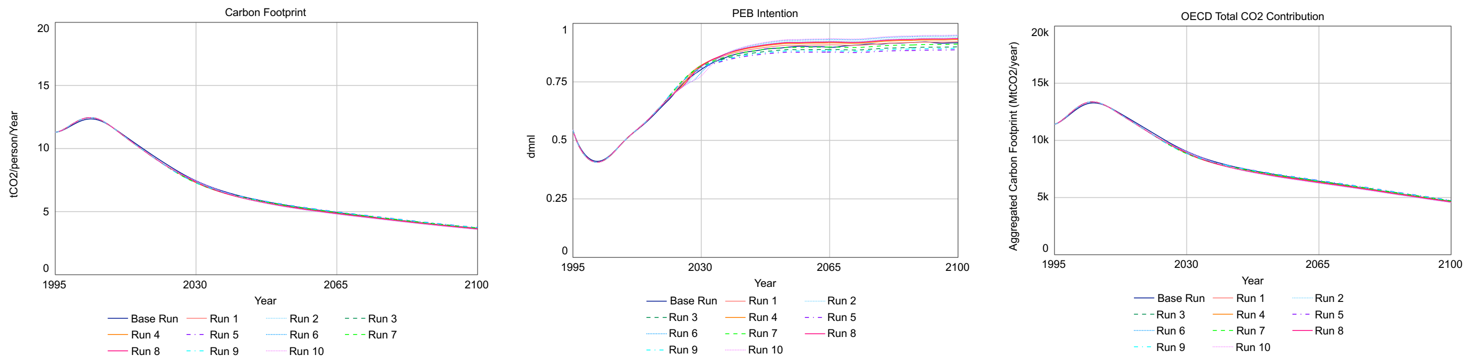


*Figure C-22 - Sensitivity Runs Sensitivity of Seriousness*

The model is only weak numerically sensitive to this parameter. See model description in Appendix A for a detailed discussion on the parameter and its workings as the sensitivity of the power function effect. The structure graph below shows the variation of the effect under variation of the sensitivity. As can be seen, the major variation manifests only on very high relative values, which are usually not present in the model. Therefore, the resulting impact on the models output variation may be rather low, yet noticeable in the intention, because it empowers the feedback from the environment. Although the low sensitivity in the parameter is at least not indicating a high uncertainty, the parameter, and especially the structure around it is necessarily a high uncertainty and needs further back up.

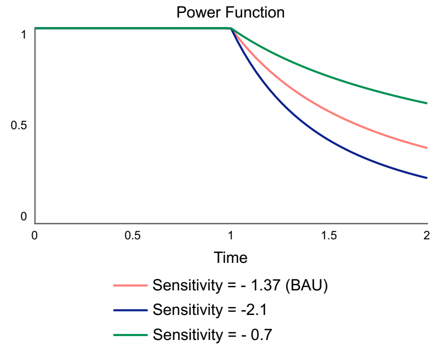


*Figure C-23 - Variation of the power function effect on seriousness based on variation in the sensitivity of seriousness*

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### Energy Efficiency

Base value: 0.008 dmnl

Tested range: 0.004 – 0.012 dmnl

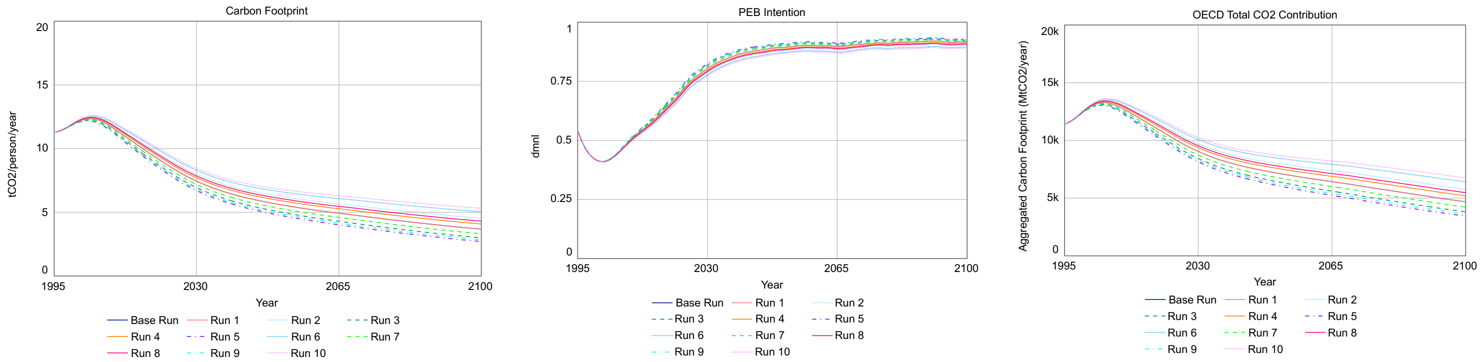


*Figure C-24 - Sensitivity Runs Energy Efficiency*

Numerically sensitive. For thorough discussion see sensitivity analysis in the main text

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### Initial Perceived Temperature Variation

Base value: 0.44°C

Tested range: 0.22°C – 0.66°C

Numerically and behavioral sensitive. For thorough discussion see main text – parametric sensivity analysis.

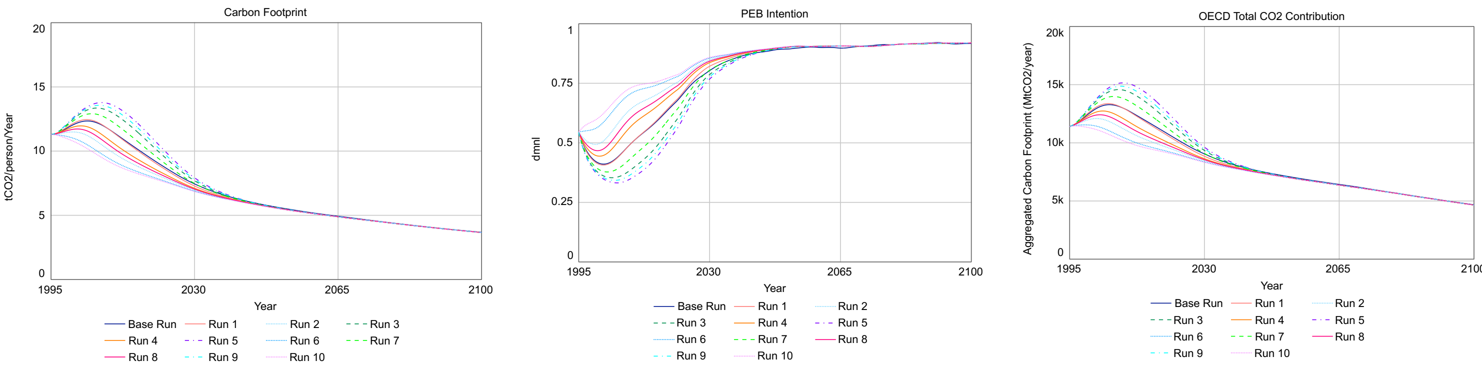


*Figure C-25 - Sensitivity Runs Initial Perceived Temperature Variation*

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**Media Coverage Efficiency**

Base value: 0.78 dmnl

Tested range: 0.5 – 1.1dmnl

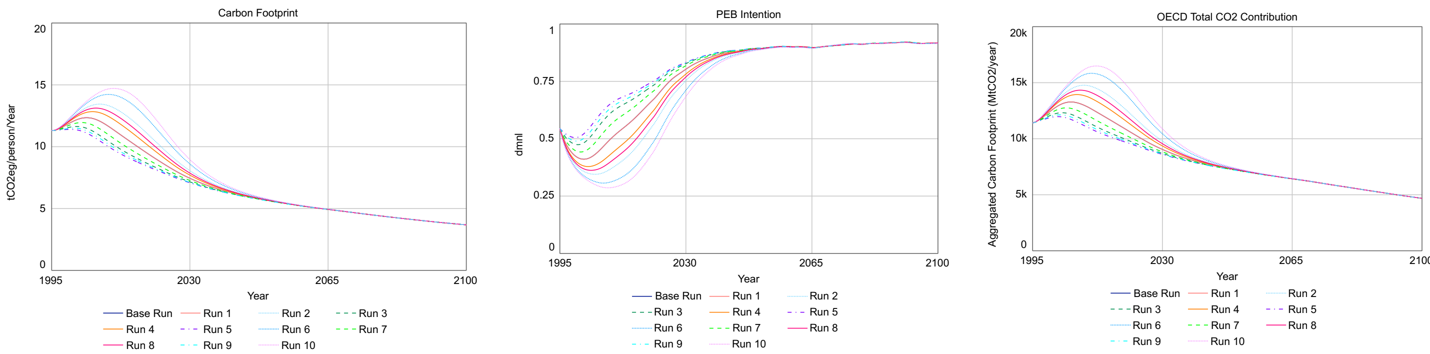


*Figure C-26 - Sensivity Runs Media Coverage Efficiency*

Numerically and weak behavioral sensitive. For thorough discussion see main text – parametric sensivity analysis.

---

**Weight on Personal Norm**

Base Value: 0.7 dmnl

Tested Range: 0 – 1 dmnl

The model is moderate to weakly numerically sensitive to the parameter. This is to be expected, since it manipulates (increases/reduces) the power of the feedback loops that brings in the feedback from the environment. Higher weight on personal norm therefore means more weight to the feedback from the society. Lesser weight on personal norm means more weight to the social norm – injunctive route, i.e. the feedback from society. The parameter is not conceptual uncertain –

there is at least some weight that people put towards the personal norm, yet the value here is calibrated, see model description in Appendix A for more details. When applying to a specific behavior more data is needed to place a value with more confidence. As for further development, it might even make sense to think about endogenizing the weight put on the personal norm to some other variable, like the worldview proxy or a conceptualization about education.

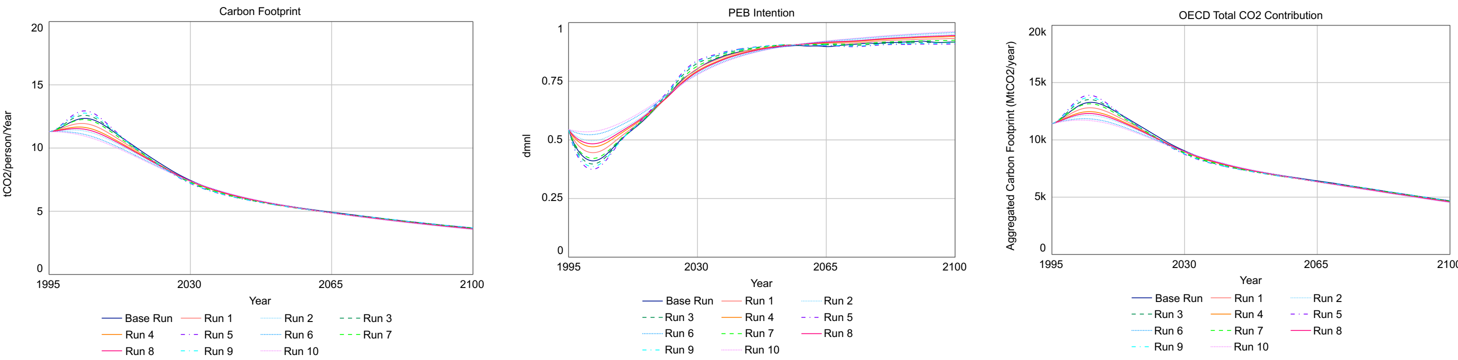


*Figure C-27 - Sensitivity Runs Weight on Personal Norm*

## Weight on Peer Influence

Base value: 0.3 dmnl

Tested range: 0 – 1 dmnl

The model is moderate to weakly numerically sensitive to the parameter. This is to be expected, since it, as the other weight, manipulates the power of the feedback loops both indirectly from environment interdependent on the *Weight on Personal* Norm and directly through tuning in and out the input from the Peer Group. Higher Weight on Peer Influence therefore means more less weight to the feedback from the environment/society. Lesser weight on personal norm means more weight to the societal norm / personal. Similarly, as above the parameter is not conceptual uncertain – there is at least some weight that people put towards the peer group, yet the value is calibrated. There might be estimates in certain behavioral contexts if people put more or less weight on the peer group. When applying to a specific behavior more data is needed for a value with more confidence.

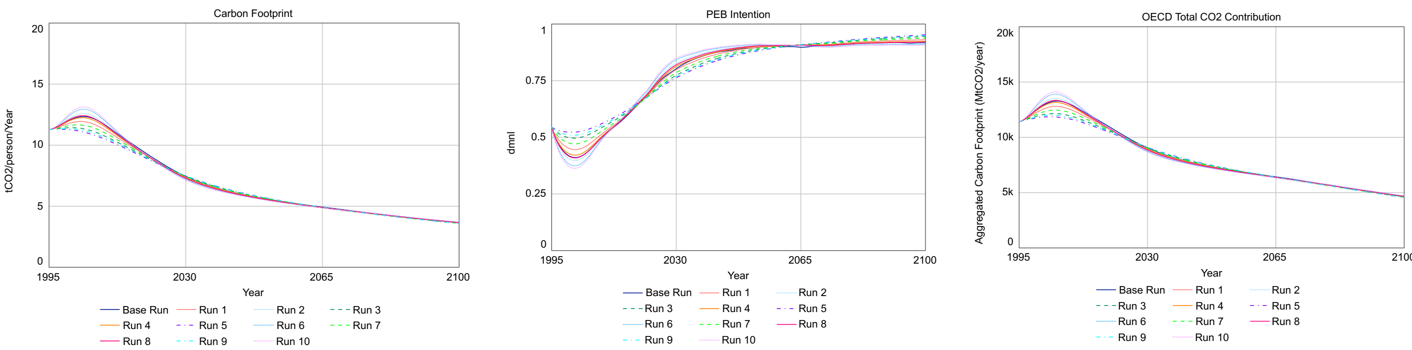


*Figure C-28 - Sensitivity Runs Weight on Peer Influence*