Systemic Properties of Key Production and Consumption Areas

Case studies from the core systems: Food, Energy, Mobility and Housing

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Summary

The European Union has unveiled the European Green Deal (EGD) and the 8th Environment Action Programme (8EAP), initiatives that represent the most comprehensive and forward-looking policy frameworks to date. Central to these programmes is the 'Systemic Change' concept, which has garnered significant political support as a fundamental approach to achieving environmental sustainability goals. It is imperative to acknowledge that the intricacies of environmental challenges demand a nuanced understanding of their systemic nature.

Oversight of systemic phenomena such as non-linear dynamics, rebound effects, lock-ins, burden-shifting, and trade-offs during the policy formulation stage can result in unintended deleterious outcomes and the redistribution of burdens. Consequently, analysing systemic attributes is increasingly vital for informed policy guidance. Such systems-based perspectives will serve for the anticipated State of the Environment Report 2025, designed to facilitate robust policymaking.

This report aims to identify and communicate some essential systemic properties pertinent to 'systemic change' and the journey towards sustainability. It examines various potential systemic properties across production-consumption systems, including energy, food, mobility, and housing, aligning with EEA thematic domains and corresponding policies. For each thematic domain, selected cases are analysed, utilising causal loop diagrams (CLDs) to visualise and assess systemic properties.

The report does not aim for an exhaustive literature review but instead seeks to present illustrative and, at times, provocative scenarios to probe the effectiveness of CLDs in exploring and articulating systemic properties.

The systemic properties analysed in the cases include:

- **Direct and Indirect Rebound Effects** highlight the paradox where efficiency improvements lead to increased consumption.
- **'Fixes that Fail'** illustrates the pitfalls of short-term solutions that neglect underlying issues, resulting in recurring, more complex problems.
- **'Shifting the Burden'** is where short-term remedies prevent the resolution of root causes by fostering dependency.
- **'Limits to Growth'**, underscoring the unsustainable nature of indefinite growth when natural limits are reached.
- ‘**Growth and underinvestment**’ is a systems archetype that describes the scenario when growth potential is hindered by insufficient investment in capacity, leading to performance shortfalls and curtailed growth.

The report ventures partly into more speculative thought experiments, such as the complete **shift from meat to vegan diets**, to explore the implications of drastic changes within complex systems. Despite the speculative nature of these experiments, they underscore the slow pace of systemic change and the potential for rebound effects, highlighting the necessity for comprehensive political measures across the food value chain.

In addressing the **energy transition**, the report emphasises the imperative of moving towards a carbon-neutral, renewable energy system, spotlighting the role of **hydrogen technology**. It critiques current mobility policies' narrow focus on technological upgrades at the expense of broader systemic reforms, advocating for a more integrated approach to sustainability.

Furthermore, the report examines the EU's ambition to **double the annual energy renovation rate by 2030**, considering systemic factors such as cost reduction, material usage, and the promotion of circular economy principles to overcome barriers to building renovation.

1 Systemic properties of key systems of production and consumption

1.1 Approach and justification for the study

The European Union has developed the most ambitious and transformative package of policies by establishing the European Green Deal (EGD) and the 8th Environment Action Programme (8EAP). The concept of 'Systemic Change', as outlined in the 8EAP, has gained political traction and is seen as crucial for achieving environmental and sustainability goals. However, it is essential to recognise that addressing complex challenges requires a comprehensive understanding of the systemic nature of these issues.

If systemic aspects like non-linear dynamics, rebound effects, lock-ins, burden-shifting, and trade-offs are overlooked in the policy design phase, policy interventions may lead to unintended negative consequences and shifts in burdens. Knowledge of systemic characteristics is, therefore, increasingly important for policy advice.

Furthermore, such knowledge is necessary when developing systems-based integrated assessments such as the forthcoming State of the Environment Report 2025 that aim to support sound policymaking (EEA, 2019b). Research on the systemic nature of sustainability transitions has expanded during the recent decade, and potential conceptual frameworks already exist in abundance (EEA, 2017b). Selecting appropriate frameworks that can capture the key systemic aspects of sustainability challenges and meet the requirements of specific decision-making processes and target audiences is, therefore, necessary (EEA, 2016, 2019a).

This report aims to identify, characterise, illustrate, and communicate key systemic properties and their relevance for 'systemic change' and transitions/transformations to sustainability. The intention is to do so in an accessible and understandable way for broad audiences, such as experts from multiple fields and policymakers across different policy sectors. Therefore, discipline-specific concepts and expressions are avoided whenever possible.

The report is based on screening several potential systemic properties within and across production-consumption systems, such as energy, food, mobility, housing, or across EEA thematic domains and related policies. Selected cases serve as illustrative examples to be further developed, given their potential inclusion in SOER 2025. The cases are assessed from a system's thinking perspective and underpinned with concrete causal loop diagrams (CLDs) used as visualisation and analytical tools.

This report overviews the respective definitions used in this study and delineates these from other systems approaches. After this general introduction, four case studies from the core systems of energy, food, mobility, and housing are illustrated. This study does not aim to provide a complete literature review or analysis of the mentioned issues. Instead, the aim is to provide illustrative, partly provocative and extreme cases and pilot if and how small causal loop diagrams can be used to explore and effectively communicate systemic properties.

1.2 The systemic perspective taken in this report.

The term 'system' stems from the Latin word systēma, in turn from Greek σύστημα systēma: 'whole concept made of several parts or members (literally: 'composition')[1]. While the term 'Systems Thinking' (ST) goes back even to ancient civilisations, in this study, the Systems Dynamics (SD) approach is followed using Causa Loop Diagrams that are used for sketching the conceptual model to be quantified later. Jay Forrester originally developed the Systems Dynamics approach in the 1950s and then applied it to the work of the Club of Rome in 1972 and, consequently, to the work by Donella and

[1] https://www.merriam-webster.com/dictionary/system (accessed 28 May 2024)

Dennis Meadows. The publications ’Limits to Growth’ (Meadows et al., 1972) and ‘Thinking in Systems: a Primer’ (Wright and Meadows, 2012) build the basis for the ‘thought construct’ in this analysis.

A system is any group of interacting, interrelated or interdependent parts that form a complex, unified whole with a specific purpose. Without such interdependencies, there is only a collection of parts. The purpose of a system can be obvious, like in technical systems (a telephone is for talking), and it can sometimes be obscure or hidden, like in social groups. All system parts must be present to carry out their intended purpose optimally. The structure and the order of the parts of a system affect the performance and its ‘behaviour’.

The term ‘Systems Thinking’ can mean different things to different people. The discipline of Systems Thinking is more than just a collection of tools and methods – it also encompasses an underlying mindset. While ‘Systems Thinking’ reflects the researchers' attitude, ‘Systems Analysis’ is the approach to understanding the interactions between system components (Kim, 1999; Haraldsson and Sverdrup, 2021).

In societal change, however, the term ‘complex adaptive systems’ is often used (Holling, 2001). The characteristics of self-organisation, adaptability, and emergence go beyond the ‘classic’ system dynamics. In such cases, different modelling approaches, like agent-based models, are often used to explain behavioural emergence, although often in combination with system dynamics (e.g. Balbi and Giupponi, 2009; Shafiei et al., 2013). It is worth mentioning that from this ‘complex adaptive systems perspective’, the state and change of a system are looked at more closely, especially in the context of transition research (Loorbach et al., 2017; EEA, 2019a). The discipline of transition research and system change is not the subject of this report. Consequently, this introduction is not the place to develop an ontology of systems approaches further.

In the following sections, an overview of the systemic properties examined in the different case studies is presented and illustrated in more detail. In chapters 2, 3, 4 and 5, the concrete cases are presented and discussed in the light of the systemic properties.

1.3 Systemic properties considered in this report

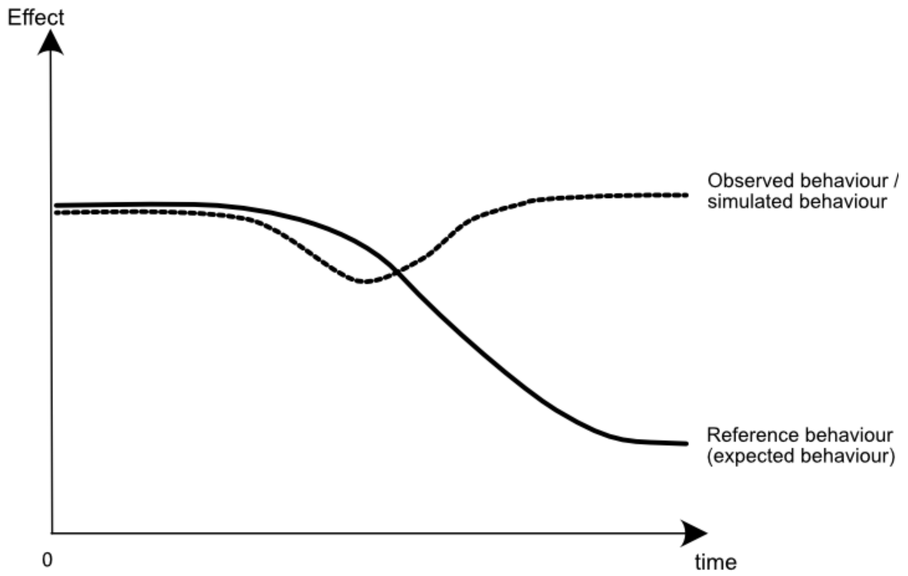
1.3.1 Overview

Systems and system properties can be defined in various ways. For this report, the following definition is taken as a starting point: “(...) a system is a set of elements (principles, rules, forces) dependent on each other and forming an organised whole, (...) Any system works to achieve functionality and a purpose; these are achieved through a process in which the elements that determine both the content and the process specific to the system are involved.” (Cioruța et al., 2020, p. 19 ff). In the context of this study, specific system behavioural patterns are applied. In particular, the focus is on selected ‘archetypes’ briefly introduced in this chapter and explored through case studies focusing on four thematic key areas throughout the following chapters.

Causal Loop Diagrams (CLD) depict different archetypes related to each system. The CLD is a systemic way of thinking where cause and effect are variables that either change in the same direction (indicated with a ‘+’) or change in the opposite direction (indicated with a ‘-’). Processes with a loop (feedback) in the same direction are called reinforced processes (indicated with R) since they amplify the condition. Similarly, the processes that create a loop in the opposite direction (indicated with B) balance (dampen) out a condition. (Haraldsson and Sverdrup, 202*0*).

Besides CLDs, system behaviour can be illustrated with a pattern or curve of a specific variable or indicator over time. In system dynamics, such ‘behaviour over time graphs’ are used to sketch and analyse behavioural curves. They are differentiated into ‘reference behaviour/expected behaviour’ and ‘observed behaviour /simulated behaviour’. Figure 1 shows how such a ‘behaviour over time graph’ might look in system dynamics. In this case, a decrease in the effect (e.g., resource consumption) is expected. In reality, after an initial decrease of the effect, it flips back and overcompensates. Such a ‘flip back’ or even ‘overcompensation’ is also a rebound effect (see section 1.3.2).

Figure 1: ‘Behaviour over time’ graph for the rebound effect



Note: The figure is a graph that compares the effect of observed/simulated behaviour and reference/expected behaviour over time. The solid line represents the reference behaviour, which initially remains steady but decreases significantly over time. The dashed line indicates the observed or simulated behaviour, which initially aligns with the reference behaviour but starts diverging and stabilising at a higher level as time progresses. This comparison visually demonstrates the deviation between expected outcomes and actual or projected outcomes over a given period.

Source: Own interpretation, adapted from (Haraldsson, 2004).

(Haraldsson, 2004; Haraldsson and Sverdrup, 2021) provide detailed descriptions of how to define this 'behaviour over time graphs'. Alongside such a behavioural pattern, causal loop diagrams (CLDs) sketch the system's building blocks. In this regard, a system consists of concepts and connections. CLDs and ‘behaviour over time graphs’ are the first steps towards developing a system dynamics model.

The structure of a system (feedback loops, delays) already provides substantial information about its potential behaviour (Kim, 1999). These patterns include exponential growth or decay and oscillations or goal-seeking behaviours. Structural dimensions also help define the boundaries of the system and its relation to the external environment. Certain combinations of loops create a specific behaviour. Such behaviours are often counterintuitive and difficult to explain without considering the systems' structure. In System Dynamics, these typical patterns are called ‘**system archetypes**’ and were first studied in the 1960s and 1970s by Jay Forrester (Lane and Sterman, 2011), Dennis Meadows (Meadows et al., 1972), Donella Meadows (Wright and Meadows, 2012)), and others. In his book, “The Fifth Discipline: The Art and Practice of the Learning Organization”, author Peter Senge explored system archetypes and documented the most common patterns of behaviour in organisations (Senge, 1991).

Identifying a system archetype and finding effective leverage points enables efficient changes in a system. Donella Meadows published a seminal overview of leverage points to intervene in systems (Meadows, 1999). Abson et al. (2017) built on the concept and concluded that *“(...) The notion of leverage points has the potential to act as a boundary object for genuinely transformational sustainability science”*. System analysis and gaining clarity are essential steps towards identifying more systemic policy options.

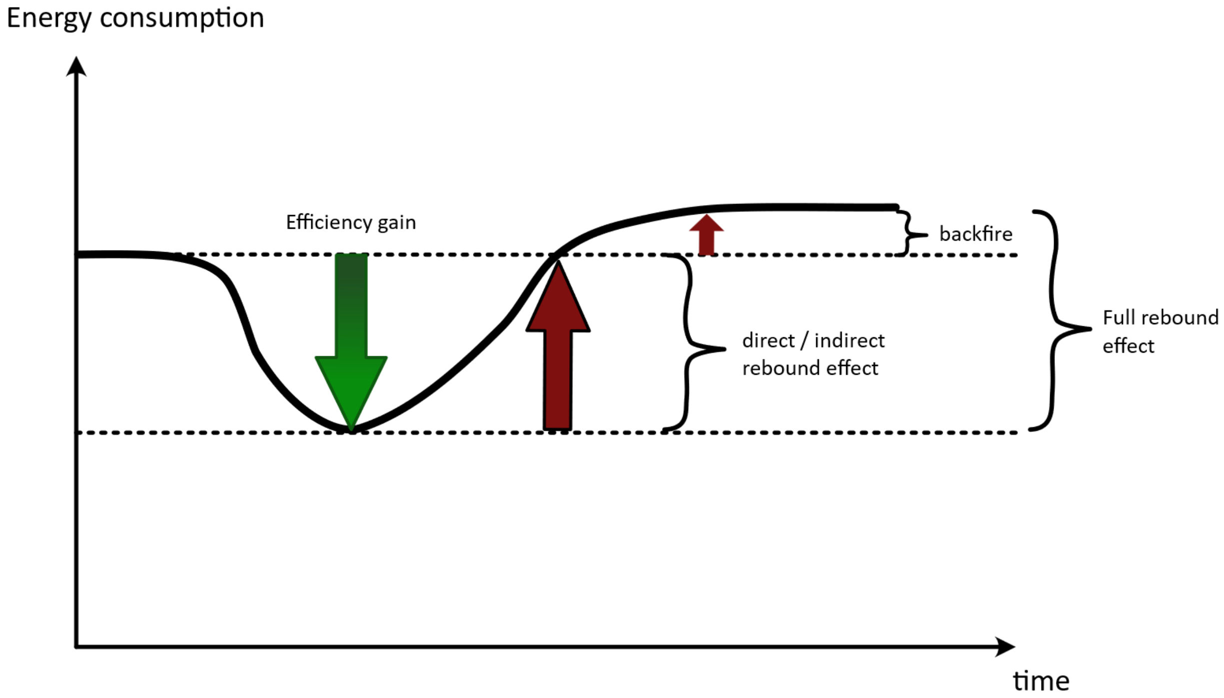
The concept of '**path dependencies**' is another systemic property next to the archetypes. While – similar to rebound effects (see next section) – path dependencies are not typical archetypes (as defined by Meadows et al., 1972; Senge, 1991), they still describe a particular reproducible pattern. Path dependencies emerge when a system's behaviour becomes locked into a particular trajectory due to the cumulative effects of past events and decisions. Each decision or event in a system is influenced by conditions that preceded it, and the outcome of that decision, in turn, affects future choices. Typical examples might be direct vs. alternating currents and the subsequent power infrastructures. The same goes for the use of fossil fuels, where the full motorisation is based on combustion engines and the complete value chain is created to provide this form of energy. Over time, these decisions and events create a path that the system follows, with the current state being heavily influenced by the past (Vergne, 2010).

Delays also play a central role in System Thinking and System Dynamics. Delays can cause oscillations, overshoots, undershoots, or dampening effects in a system's response to a change or disturbance. Delays can also create confusion, frustration, or misperception among the actors in a system, leading to ineffective or counterproductive actions. Donella Meadows (Wright and Meadows, 2012) stated that delays are one of the leverage points, or places to intervene, in a system. She argued that reducing the delays in feedback loops can improve the stability and resilience of a system while increasing the delays can destabilise or destroy a system.

1.3.2 Direct and indirect rebound effects

Rebound effects generally refer to a systemic behaviour where introducing more efficient technologies in production leads to increased consumption and production instead of the expected energy or resource savings. The direct rebound effect refers to the phenomenon where, e.g., energy efficiency improvements result in an overall increase in energy usage. The saved money results in higher energy consumption or extended use of energy-consuming activities, ultimately offsetting a portion of the initial energy savings achieved through efficiency improvements. The indirect rebound effect occurs when energy efficiency gains lead to savings (time, money) that might be used in other domains and create an adverse effect. Initially, direct and indirect rebound effects are concepts of energy economics. They help explain the unintended consequences of energy efficiency improvements. These concepts are closely linked to the so-called 'Jevons Paradox', which posits that increases in energy efficiency can paradoxically lead to higher energy consumption (Sorrell, 2009; Berkhout et al., 2000). The following figure shows an example of how direct and indirect rebound effects might offset or even overcompensate the expected energy saving (adapted from Madlener and Hauertmann, 2011).

Figure 2: Overview of rebound effects



Note: This figure is based on the sketch by Madlener and Hauertmann, although translated to a reference behaviour pattern graph. The energy consumption is reduced over time due to efficiency gains. Direct and indirect rebound effects compensate for these gains and can even increase the energy consumption above levels before the efficiency increases.

Source: inspired by (Madlener and Hauertmann, 2011) .

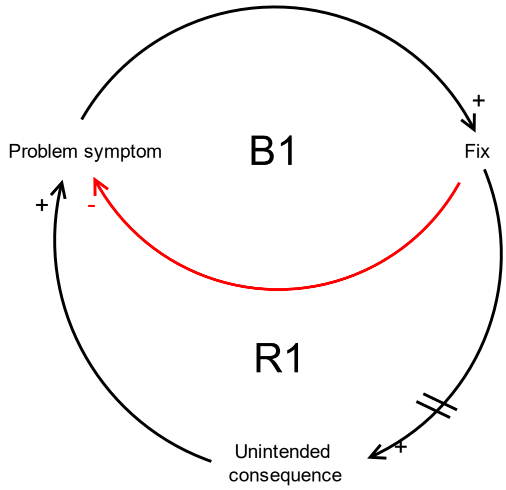
1.3.3 The archetype 'Fixes that Fail'

(Based on the work of Senge, 1991; Braun, 2002; Kim, 1994).

'Fixes that Fail' is a systems archetype that describes a situation where a quick fix is implemented to alleviate a problem's symptom, but the relief is merely temporary, and the symptom returns, often stronger than before. Such a 'flip back-effect' happens because of unintended consequences of the intervention that unfold over a long time or as an accumulated effect of repeatedly applying the solution.

The 'Fixes that Fail' archetype consists of a balancing loop intended to achieve a particular result, yet an insidious reinforcing loop foils the result.

Figure 3: CLD of the archetype 'Fixes that Fail'



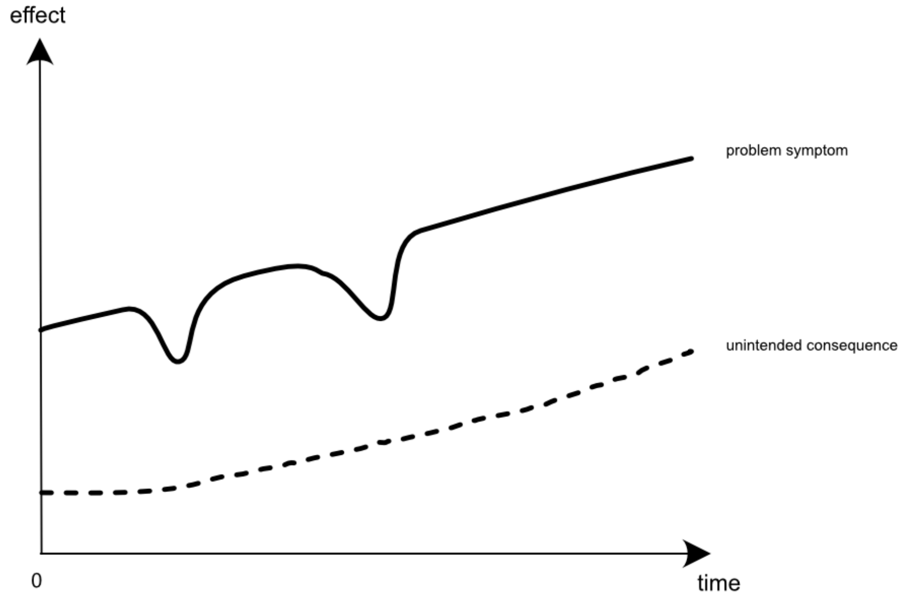
Note: A problem manifests in a problem symptom addressed with a quick 'fix', which reduces the 'problem symptom' (Balancing loop B1). On the other hand, an 'unintended consequence' arises from the 'fix' that increases the 'problem symptoms' (Reinforcing loop R1). Arrows carrying a '+' symbol indicate an increasing relation, while those arrows with a '-'symbol (drawn in red) symbolise a decreasing effect. –

Source: adapted from Braun, 2002.

In a 'Fixes that Fail' scenario, a problem is countered by a corrective action or a 'quick' fix that seems to solve the issue. However, this action leads to a set of unforeseen consequences. These then form a feedback loop that either worsens the original problem or creates a related one. One of the most important points to address about this archetype is the relationship between the delay in the occurrence of unintended consequences and the timing of organisational performance. Organisations tend to focus on short-term fixes and ignore the long-term consequences of their actions. This leads to a vicious cycle of implementing quick Fixes that Fail, reinforcing the need to continually implement more quick fixes.

To avoid 'Fixes that Fail', it is essential to recognise when the fix only addresses the symptom. It often takes time and effort to understand the full impact of our actions and to find solutions that address the source of the problem, i.e. not only the symptoms. That would require analysing the underlying problem structure and identifying the feedback loops that create the problem. By addressing the root cause of the problem, the vicious cycle of 'Fixes that Fail' can be avoided, and sustainable long-term solutions can be created.

Figure 4: A reference behaviour pattern of the archetype 'Fixes that Fail'



Note: A reference behaviour pattern of the archetype 'Fixes that Fail'. The figure represents a graph showing the relationship between the effect of problem symptoms and unintended consequences over time. The solid line demonstrates the fluctuating nature of problem symptoms, which initially improve but worsen over time. Meanwhile, the dashed line indicates the gradual increase of unintended consequences as time progresses, suggesting that short-term solutions may lead to long-term negative impacts.

Source: adapted from Braun, 2002.

Despite their apparent simplicity, 'Fixes that Fail' can be hard to unravel. It requires a deep commitment to setting aside mental models that may cause managers to not see, or even consider, that there may be a connection between a problem's visible symptoms and the fix(es) they are applying to alleviate them.

1.3.4 The archetype 'Shifting the Burden'

The ''Shifting the Burden' archetype occurs when a quick fix is implemented to alleviate symptoms of a problem rather than addressing the underlying root causes. This creates a situation where the symptoms are temporarily relieved, but the underlying problem persists and may even worsen over time. The archetype gets its name because the system's dependency shifts from the fundamental solution to the quick fix. This often results in a reinforcing feedback loop where more and more effort is put into the symptomatic solution while the underlying problem deteriorates.

'Fixes that Fail' and 'Shifting the Burden' are closely related in that the managerial response is primarily aimed at the problem's symptom rather than focussing on the more complex and time-consuming task of identifying the underlying, systemic problem (or as is more often the case, the system of problems).

- Both archetypes fail to address the underlying problem effectively, leading to a continuation or recurrence of negative impacts.
- In both cases, there is often a reliance on short-term fixes or solutions that do not consider the long-term consequences or systemic dynamics involved.
- Both archetypes highlight the need to understand the systemic nature of environmental issues and the importance of addressing root causes rather than focusing solely on immediate symptoms.

However, the differences are:

- Shifting the Burden typically involves an initial fix that addresses the immediate symptoms or consequences of a problem but does not address the underlying root causes, whereas Fixes that Fail attempt to address the root causes but often do not effectively address the problem in the long run.
- Shifting the Burden archetype tends to involve transferring the responsibility or consequences of the problem to others, while Fixes that Fail focus more on the failure of proposed solutions to achieve the desired outcomes.

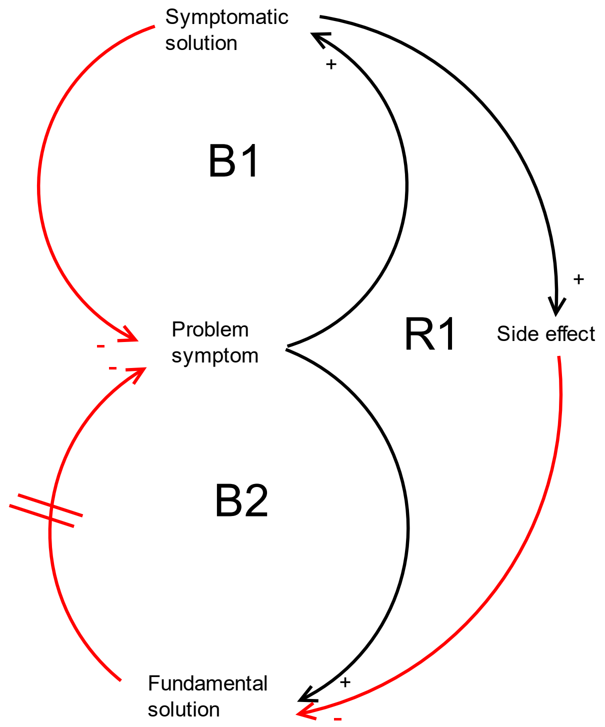
An example of the archetype Shifting the Burden can be found in the case of pesticide use in agriculture. Farmers often rely heavily on chemical pesticides to protect their crops from pests. While pesticides provide an immediate and effective pest control solution, they also negatively affect the environment and human health. The use of pesticides may lead to the development of pesticide-resistant pests, ecological imbalance, and contamination of water sources.

An example of the archetype Fixes that Fail can be seen in fisheries management. When fish populations decline due to overfishing, policymakers often implement short-term fixes such as catch limits or closing certain fishing areas. While these measures may provide temporary relief and allow fish populations to recover, they often fail to address the underlying dynamics that led to overfishing in the first place. Inadequate monitoring and enforcement, lack of alternative livelihoods for fishermen, and market pressures can undermine the effectiveness of these fixes, leading to recurring patterns of overfishing and fish population declines.

Figure 5 shows a CLD of this archetype where a symptomatic solution diminishes a problem. This is depicted as the balancing loop B1. However, the fundamental solution requires more time and would only reduce the symptoms later. As the symptomatic solution already reduces the problem, the fundamental solution is hindered by the symptomatic solution (R1).

Figure 6 shows the behaviour over time pattern of the archetype Shifting the Burden. The real problem does not get solved. The effort to fix the problems gets higher and higher. Contrary to Fixes that Fail, there is an impact on the effective solution or the capacity to find this effective solution.

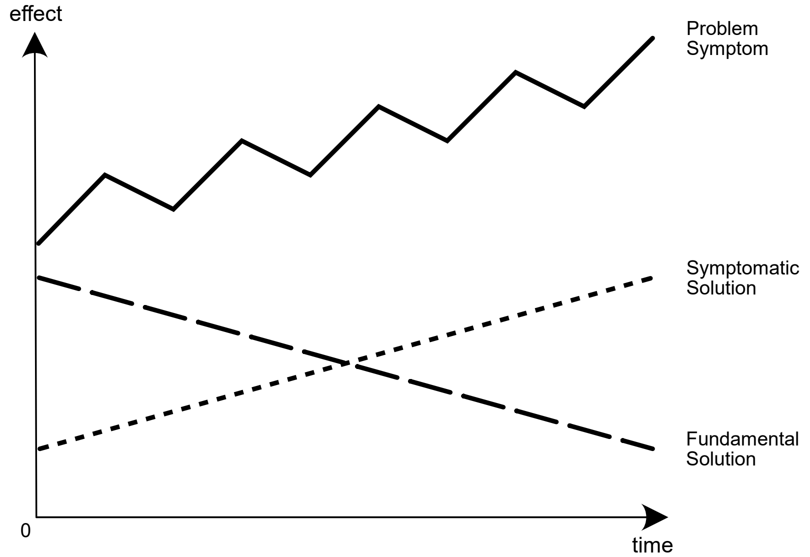
Figure 5: Basic CLD of the archetype 'Shifting the burden'



Note: Causal loop diagram of the archetype 'Shifting the burden'. Arrows with a '+' indicate an increasing effect, while red arrows with a '-'symbolise a decreasing effect. The balancing loop B1 shows that a symptomatic solution reduces a problem symptom. The balancing loop B2 demonstrates that, with the two lines crossing the arrow, a fundamental solution only reduces the problem with a delay. The symptomatic solution, though, creates a side effect that negatively influences the fundamental solution. This creates a reinforcing loop, marked as R1.

Source: adapted from Braun, 2002.

Figure 6: Behaviour pattern of the archetype 'Shifting the burden'



Note: The graph represents the "Shifting the Burden" systems archetype, which illustrates the impact of addressing a problem with two different types of solutions: symptomatic and fundamental. Problem Symptom The solid line shows that despite efforts to manage the issue, the problem symptom continues to fluctuate and overall worsens over time. Symptomatic Solution: The dashed line indicates the symptomatic solution, which initially provides quick relief and improvement. However, as time progresses, its effectiveness diminishes, leading to a resurgence of the problem symptom. Fundamental Solution: The other dashed line represents the fundamental solution, which initially may seem less effective and slower to implement. However, over time it becomes more effective in addressing the root cause of the problem, resulting in sustained improvement. This archetype emphasises the tendency to prioritise quick fixes (symptomatic solutions) over more comprehensive, long-term solutions (fundamental solutions), often leading to a cyclical pattern of temporary relief followed by recurring problems.

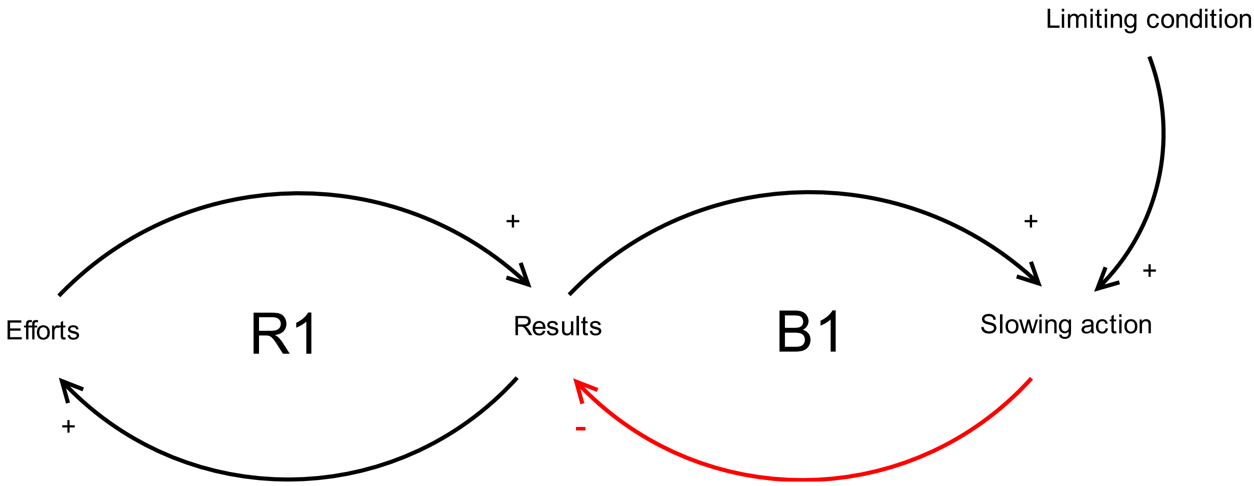
Source: adapted from Braun, 2002.

1.3.5 The archetype 'Limits to Growth'

A system grows until it reaches a certain point at which it can no longer sustain itself and begins to decline. It has reached its limits.

Limits to Growth was introduced by Donella Meadows, Dennis Meadows, Jørgen Randers, and William Behrens in 1972 in their identically named book (Meadows et al., 1972). The book has spawned a generation of "World" models that critically examine policies that deplete natural resources over long periods, arguing that we are sowing the seeds of our destruction in the future. A 50-year follow-up report was published in 2022 (Dixson-Declève et al., 2022). This archetype states that a reinforcing process of accelerating growth (or expansion) will encounter a balancing process as the limit of that system is approached. It hypothesises that continuing efforts will produce diminishing returns as the limits are being approached.

Figure 7: Basic CLD of the archetype 'Limits to Growth'



Note: Causal Loop Diagram of the archetype 'Limits to Growth'. Arrows with a "+" indicate an increasing effect, while red arrows with a "-"symbolise a decreasing effect. A reinforcing loop R1 symbolises that efforts are creating a result. The more a result is achieved, the more effort goes into further increasing it. This R1--loop would result in exponential growth. On the other hand, the closer one gets to the desired result, the more of a slowing action is feeding back and dumping the results (Balancing loop B1). A limiting condition determines the slowing action. As a result, a logistic growth curve is created.

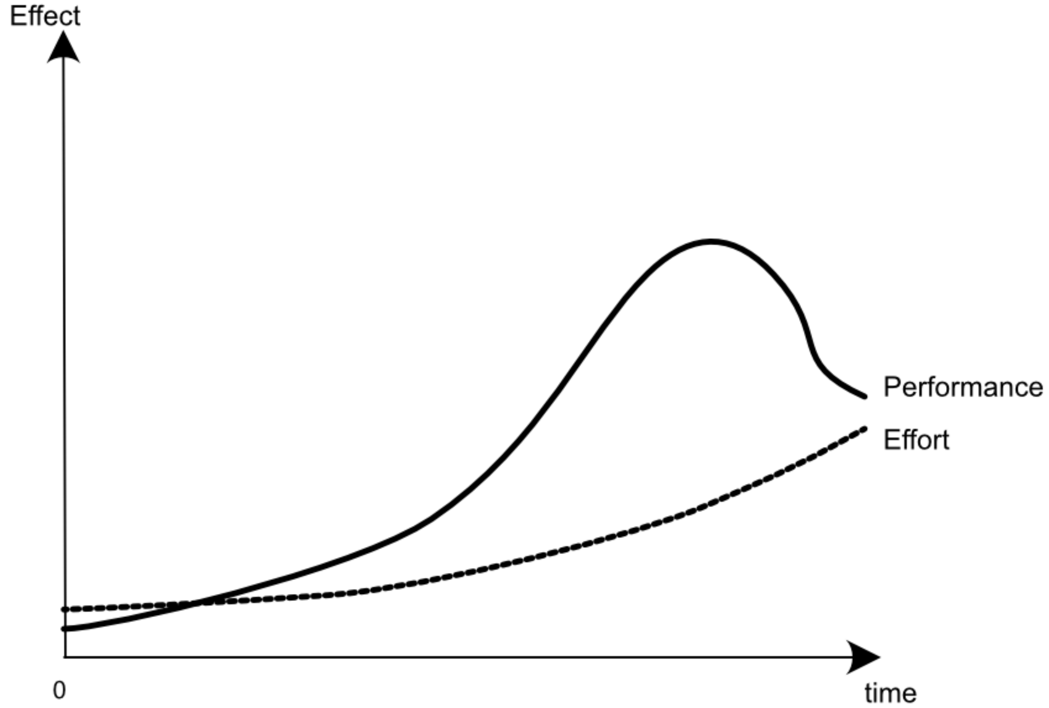
Source: adapted from (Braun, 2002).

Efforts to grow an effect are successful in the initial stages, perhaps even exponentially. However, as the limits to growth are approached, the growth engine begins to lose effectiveness, and the growth rate begins to flatten. In the end, despite continued pressure from the growth engine, the growth rate stops and reverses.

This archetype has various consequences. While it seems clear that there might not be endless growth, there is always some balancing trend slowing down the increase. In addition, it is worth noting that counterintuitively, at a particular stage, more effort leads to a decreasing result (see Figure 8).

For policy or management, two aspects are important here: (1) identifying the limiting condition and (2) the specific action that is slowing down the growth.

Figure 8: 'Behaviour over time graph' of the archetype 'Limits to Growth'



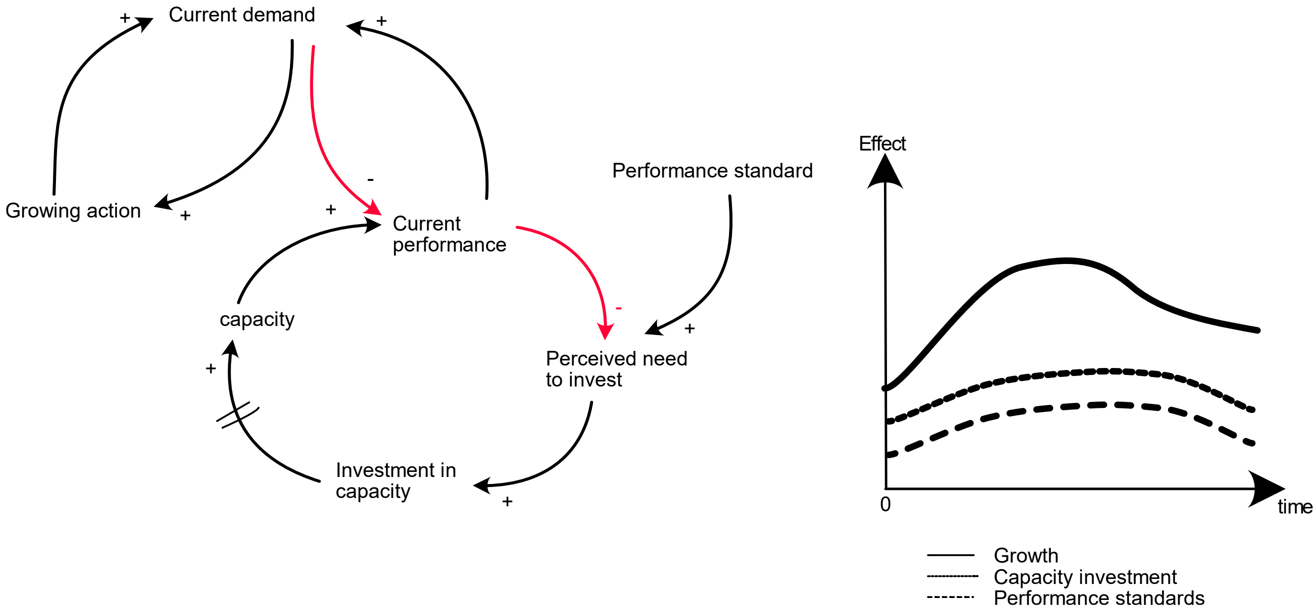
Note: The graph represents the "Limits to Growth" systems archetype, illustrating the relationship between performance and effort over time. As effort increases, performance rises significantly, indicating a positive and productive growth phase. However, after a certain point, the growth in performance starts to level off despite continued increases in effort. Eventually, performance peaks and begins to decline, suggesting the presence of limiting factors or constraints that counteract the added effort. This archetype highlights the natural progression of growth followed by a stabilisation and eventual decline when limits are encountered.

Source: adapted from Braun, 2002.

1.3.6 The archetype 'Growth and Underinvestment'

The systems archetype 'growth and underinvestment' describes a situation where a system's growth potential is limited by a lack of investment in its capacity. The system may initially proliferate but faces increasing pressure to meet the demand as it approaches its capacity limit. However, the decision-makers may be reluctant or unable to invest in expanding the capacity because they do not perceive the need, have the resources, or have other competing priorities. This leads to a vicious cycle of declining performance, customer dissatisfaction, reduced revenues, and further underinvestment. The system may eventually collapse or lose its competitive advantage unless the feedback loops are broken and the capacity is increased.

Figure 9: CLD of the Archetype growth and underinvestment



Note: The Growth and Underinvestment archetype builds upon Limits to Growth by explicitly addressing a firm's need to invest in its resources, capabilities and core competencies. A growing action seeks to stimulate and reinforce demand while the firm's current performance level may behave as the limit to its growth. Similar to Limits to Growth, if current performance adversely affects demand, no growing action will overcome customers' reluctance to reward the organisation with sales.

Source: Adapted from Braun, 2002.

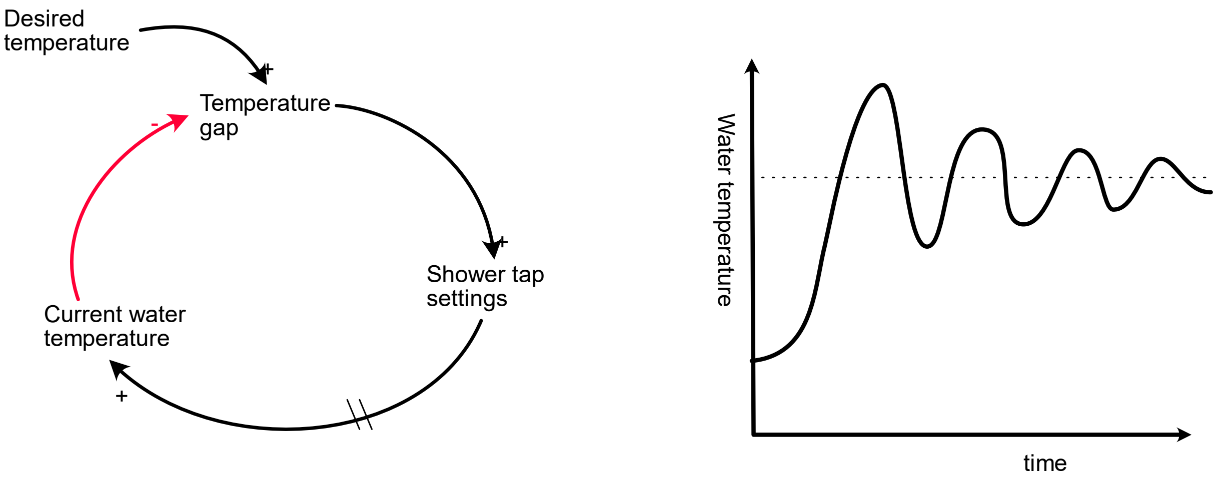
1.3.7 The role of delays in a system

Delays are indispensable to comprehending and analysing system dynamics in system thinking. Delays in a system refer to the temporal discrepancy between a cause and its subsequent effect. They possess the potential to significantly influence the behaviour of a system, frequently resulting in unforeseen consequences. For instance, within a feedback loop, delays can induce oscillations or instability. Consequently, comprehending and incorporating delays becomes imperative within system thinking as it facilitates precise modelling and prediction of system behaviour. Additionally, this understanding aids in crafting more efficacious interventions while mitigating the likelihood of unintended repercussions.

The predictability of delays remains challenging. Frequently, the duration of a delay is uncertain, leading to adopting a trial-and-error approach for assessing delay times, as exemplified by the shower case. Generally, longer delays engender larger oscillations and impact the system more. Lengthy delays pose difficulties in problem analysis, as feedback loops can easily be overlooked, particularly if their cycle surpasses the observation period.

Hence, it becomes essential to identify the variables contributing to prolonged feedback loops. Often, decisions can instigate instability and oscillations in a system that are not immediately noticeable. Consequently, we may exert significant force on certain variables without promptly observing the desired results. However, it is crucial to remember that the more forcefully we influence the system, the more vigorously it pushes back. This recognition assumes vital importance when contemplating long-term circumstances.

Figure 10: The effect a delay creates in a balancing loop



Note: The small CLD on the left shows a balancing loop when adjusting the water temperature in a shower. The resulting Reference Behaviour Pattern is shown on the right. There is a delay between setting the tap and setting the current water temperature to match the desired temperature. The delay often leads to over-adjusting (too hot – too cold), resulting in an oscillation that gets smaller.

Source: (Haraldsson and Sverdrup, 2021).

1.4 Overview of the selected cases

The cases analysed in this report are selected from four larger production-consumption systems commonly addressed in the sustainability literature as key sectors or areas of transformation (EEA, 2019b; GSDR, 2023). Recent publications, both scientific literature and reports from EU institutions, OECD and alike, have been scanned to determine whether systemic properties are implicitly or explicitly mentioned. Based on this initial screening, more specific cases representing the four systems were selected for closer analysis.

First, **food** is essential to human survival, and various needs for food production and consumption changes have been recognised, ranging from fair and transparent global trade chains to improved local farming practices. There is an obvious need to meet the minimum nutritional targets and end hunger. At the same time, controlling the obesity epidemic in many parts of the world, minimising harmful environmental effects of food production, and promoting healthy, affordable, and enjoyable food cultures are the central topics. Many aspects of sustainable food policy have been extensively studied, and various policies aiming to support a shift towards a more sustainable food system have been proposed. On the European Union level, the 'farm to fork' strategy, along with many related action plans and programmes, is one of the main strategic documents in the realm of the European Green Deal. Along the food value chain from production, processing and distribution to consumption and waste management, various subsystems directly and indirectly impact the environment and human health. Agriculture, transport, energy, packaging, the food industry, retail, and waste management are subsystems. They are addressed by various studies, often from the perspective of food production and supply. This report focuses on food consumption, specifically the role of highly processed vegan and vegetarian food.

Second, the **energy system** represents a widely studied societal sector essential to human well-being. It comprises multiple intertwined technologies (e.g. lighting, heating and cooling) used for several purposes (e.g. mobility, housing, and nutrition) in various other sectors. Energy production causes various environmental effects, including resource extraction and use, direct emissions from burning fuels, and the taking up of space by energy utilities and infrastructure. During the past decade, the energy system has often been addressed from the perspective of climate change mitigation and greenhouse gas emissions. In particular, the possibility of phasing out carbon-intensive energy production with fossil fuels has been highlighted. The European Green Deal and associated policy initiatives, including the 'Fit for 55' legislative packages and RePowerEU, aim to facilitate Europe's climate neutrality by 2050. With measures aiming for energy savings and improved energy efficiency, measures advancing renewable energy such as wind, solar, or bioenergy will ensure a steady supply of clean and affordable energy. However, novel energy carriers and energy storage technologies are also needed. Here, the specific case of hydrogen will be explored.

Third, **mobility** represents another essential societal system. In a fast-paced world, where the need to get around and reach a destination is a daily affair, the significance of mobility and accessibility is thereof obvious. However, the mobility system has been under pressure due to societal, environmental and technological developments (Hoerler et al., 2021). Mobility serves as a bridge between individuals and locations. It involves the convenience of moving from one place to another using various modes of transportation. Accessibility concerns how easily we can reach vital destinations such as schools, hospitals, and shops. These intertwined concepts, mobility and accessibility, collectively shape how we interact with our environment and daily activities. However, a complex issue arises when focusing on improving mobility, potentially affecting access to local areas. The mobility system is not a stand-alone entity. It is part of a complex network of socio-technical systems. These networks have many connected actions and responses that do not always happen linearly. This case study aims to provide more insights into the dynamics at play. A systemic approach is taken to shed more light on how different factors in the mobility system interact and influence people's ability to get to different locations. The power of embracing a systems approach in policymaking also becomes apparent when recognising that individual decisions do not solely shape people's behaviours. Instead, their choices are influenced by the structures of the larger system they act within. This approach acknowledges that the context and environment in which individuals operate significantly impact the choices available to them. Therefore, redesigning systems is crucial in making choices available (Buckle et al., 2020).

Fourth, **housing** is a system that covers basic human needs. Decent living conditions are considered a basic human right. At the same time, housing is responsible for considerable resource use and energy consumption (EEA, 2021). Here, the focus is on the role of renovations, which is sometimes overlooked in housing policies. Focus on new buildings alone is inadequate because of the high amount of existing building stock and relatively high potential for resource-wise renovations, improving energy efficiency and living conditions (EEA, 2022a). In 2020, energy use in buildings accounted for 42% of the EU's total energy consumption, 35% of energy-related greenhouse gas emissions, and a significant share of air pollutant emissions (EEA, 2021). To achieve the EU's energy, climate, and air quality targets, it is critical to reduce the energy consumption of buildings, paralleled by decarbonising the heating, cooling, and electricity sectors. This creates an imperative for new buildings to be carbon neutral and existing buildings to be renovated to improve their energy performance (EEA, 2023c). To achieve this, the EU's renovation wave aims to at least double the annual energy renovation rate of residential and non-residential buildings by 2030 and to initiate deep energy renovations that can reduce the energy consumption of buildings by at least 60%. However, despite progress being made and demonstrated potential, current investments in improving the energy performance of EU buildings are too low to meet the EU's climate objectives (EEA, 2023c). Therefore, renovation serves as an interesting case that will be explored here.

Table 1 below gives an overview of the four cases that have been analysed. It shows which of the presented archetypes is illustrated in which case.

Table 1: Key systemic archetypic behaviours identified and explored from the selected case studies

Case	Systemic property			
	Rebound	Fixes that Fail	Shifting the burden	Limits to growth
Vegan food	💡		💡	💡
Hydrogen energy		💡		💡
Mobility		💡	💡	
Renovation	💡	💡	💡	

2 Food – the case of vegan and vegetarian highly processed food

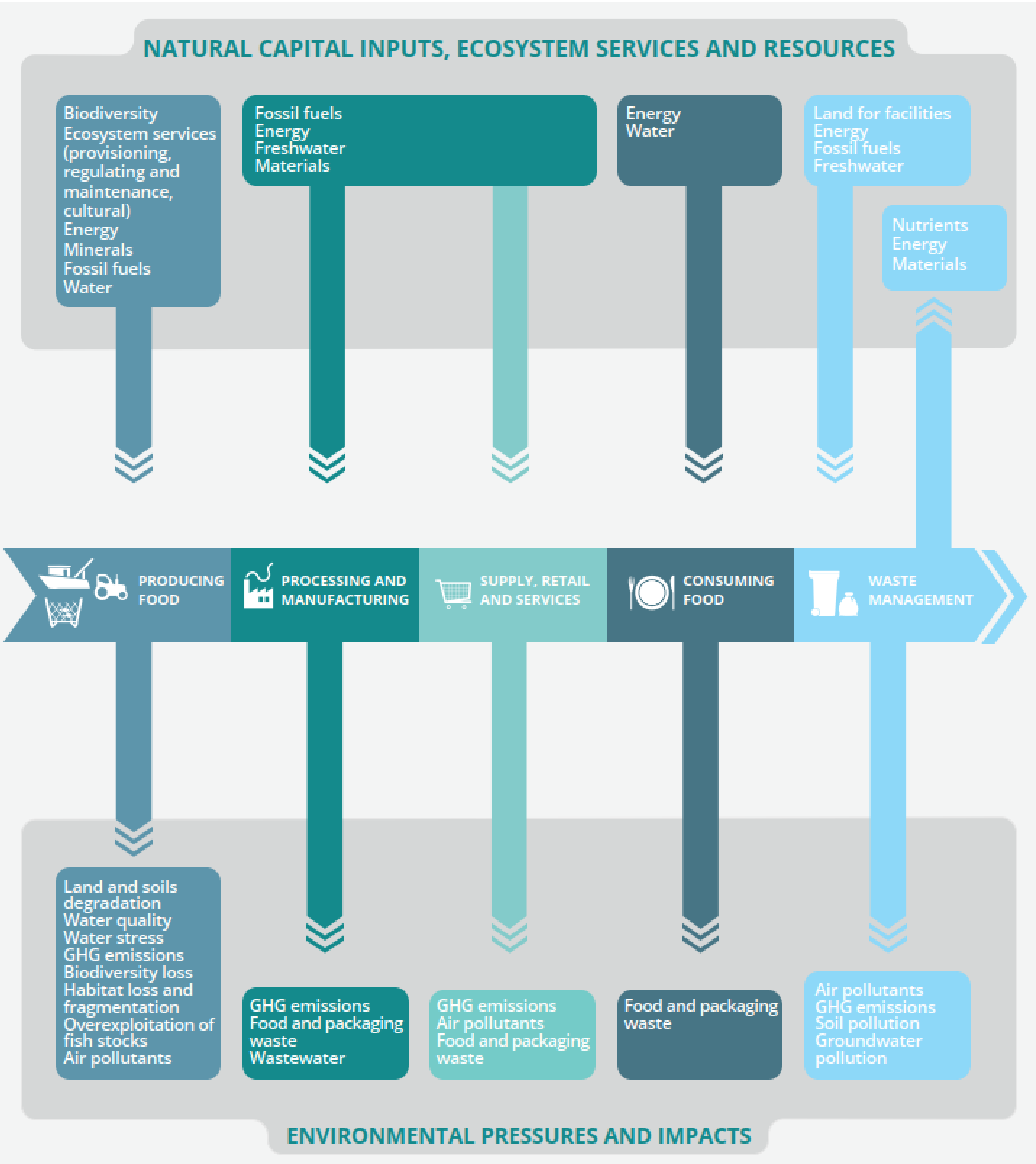
by Ullrich Lorenz

2.1 Introduction

The European Green Deal is seen as a key response to the threats created by climate change and environmental degradation (EC, 2019); according to the fact sheet about the Farm to Fork strategy (EC, 2020b), the EU's primary policy strategy to deliver this objective. The Farm to Fork Strategy (F2F) has three main objectives: (1) to ensure European food systems have a neutral or positive environmental impact; (2) to make sure that everyone has access to sufficient, nutritious, sustainable food; and (3) to preserve the affordability of food while generating fairer economic returns in across the food value chain (EC, 2020b).

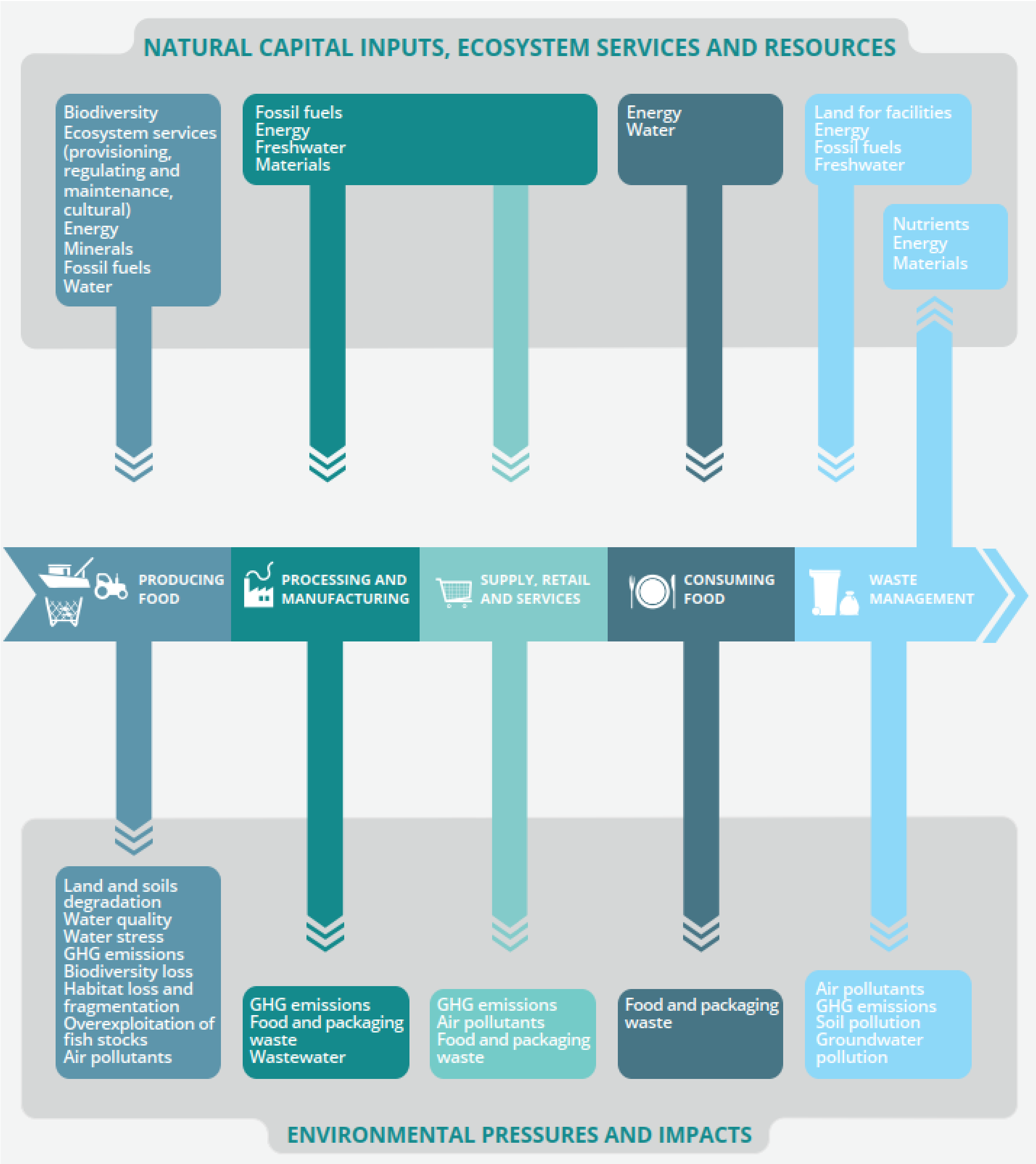
The environmental effects/impact of the food value chain are well known, as elaborated in the flagship report "Food in a green light" (EEA, 2017a):

Figure 11: Natural capital inputs and environmental pressures/impacts of the food value chain.



Source: (EEA, 2017a).

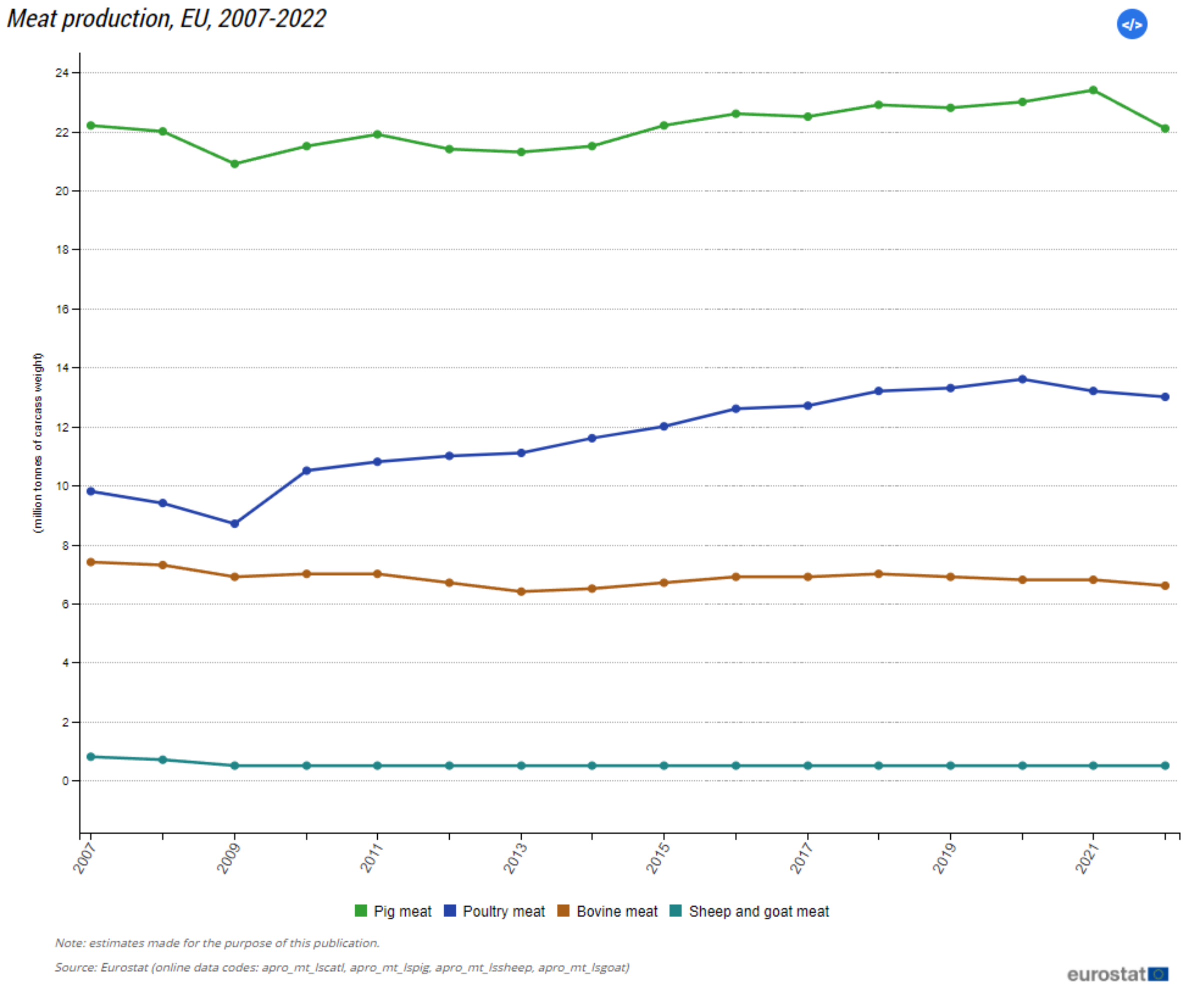
Moving towards sustainable food value chains remains challenging (Kusch-Brandt, 2020). Environmental impact is created at all value chain stages, and political measures could potentially positively reduce these impacts. While, as stated in Figure 11: Natural capital inputs and environmental pressures/impacts of the food value chain.



, food consumption directly influences environmental impacts concerning food and packaging waste, the indirect effect due to food choice is also significant. However, dietary patterns are influenced by numerous external factors such as ‘cultural taste’ and customs, nutritional and economic aspects, lifestyle, and consumer preferences. In general, a diet shift towards less meat is considered more sustainable. For instance, EAT-Lancet calls for “(...) a greater than 50% reduction in global consumption of unhealthy foods, such as red meat and sugar, and a greater than 100% increase in consumption of healthy foods, such as nuts, fruits, vegetables, and legumes” (Willett et al., 2019). Meat production has enormous environmental impacts, like the emission of greenhouse gases, eutrophication of freshwater and land use. Nearly 60% of all greenhouse gases from food production come from meat, with beef production alone accounting for a quarter of global greenhouse gas emissions in the food industry (Poore and Nemecek, 2018; Ritchie, 2019). Agriculture sources 11% of all greenhouse gases (including methane and nitrous oxide) emitted. Additionally, the current agricultural practice contributes to nutrient discharges and the emissions of NOx, and especially ammonia, which are the two central substances for eutrophication and contribute to ground-level ozone formation (EEA, 2023b). The intensive livestock industry is also connected to risks of antimicrobial resistance and the emergence of new diseases.

Hence, reducing meat production and consumption is seen as one of key measures to reduce the climate effects and positively affect the environment. Next to the environmental effects, a more balanced diet, consisting of less meat consumption and more plant-based diets, is seen as a healthy and environmentally friendly lifestyle, also responding to animal welfare concerns. Various papers refer to case studies showing an increasing demand for vegan and vegetarian foods and changing food consumption practises, for example (EEA, 2023d, 2023b; Canto, 2021; SkyQuest Technology Consulting Pvt. Ltd., 2023). Recent (autumn 2023) statistical analysis by the EU commission highlights a slight drop in per capita meat consumption of 1,5% (-6,6 % in pig production, +3,3 % poultry production and +15% in sheep imports in 2023), (DG Agriculture and Rural Development, 2023).

Figure 12: Screenshot from EUROSTAT showing the meat production statistics (EU, 2007 – 2022).



Note: The line graph titled "Meat production, EU, 2007-2022" shows the production trends of four types of meat—pig meat, poultry meat, bovine meat, and sheep and goat meat—within the European Union over a 16-year period. Pig meat (green line): started around 22.5 million tonnes/year in 2007, experienced some fluctuations, and generally remained stable, ending at just over 22 million tonnes/year by 2022. Poultry meat (blue line): began at about 10.5 million tonnes/year in 2007 and showed a steady increase, peaking at nearly 14 million tonnes/year in 2020 before slightly declining by 2022. Bovine meat (orange line): hovered around 7.8 million tonnes/year consistently throughout the period, with minor fluctuations. Sheep and goat meat (turquoise line) remained relatively low and stable, fluctuating slightly around 0.7 million tonnes/year. Overall, the graph illustrates that poultry meat production saw the most significant growth, while pig meat production remained stable but dominant, and both bovine and sheep/goat meat production maintained relatively constant levels.

Source: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agricultural_production_-_livestock_and_meat#Meat_production, accessed 30.01.2024

However, two major food consumption patterns raise **environmental concerns**: first, the already mentioned consumption of mass meat, and second, the consumption of ultra-processed food, which is also considered an unsustainable diet as it is related to both lower dietary quality and intensive food production, creating environmental pressure (Ohlau et al., 2022).

Next to environmental concerns, **health-related concerns** also play a crucial role when examining Western diets. The Western dietary pattern is related to obesity, type 2 diabetes, cardiovascular diseases, and cancer (Clemente-Suárez et al., 2023).

As mentioned earlier, it is a clear recommendation from an environmental perspective to reduce meat and dairy consumption (from mass meat production). If people decide to consume less meat, what would be the replacement?

It is well known that alternative protein sources are needed for a balanced diet, and there are even alternative protein sources for vegan lifestyles. However, when considering meat replacements that are similar in texture and taste to real meat or at dairies replacements, we are looking at a relatively new group of ultra-processed food where systematic and comprehensive research is still lacking (Wickramasinghe et al., 2021).

What are vegan/vegetarian Ultra-Processed Foods (UPF)

Vegan UPF are plant-based substitutes with heavy processing and contain additives such as texturizers, dyes, emulsifiers, preservatives, sweeteners, colours, flavours, and processing aides. Some examples of ultra-processed vegan foods include biscuits, cakes, ice cream, carbonated drinks, breakfast cereals, and many ready-to-heat products, including pre-prepared pies, pasta and pizza dishes. Some plant-based meat substitutes, tofu deli meats, vegan desserts, coconut yoghurt, frozen meals, and veggie chips are also highly processed and may contain additives.

In the case of **vegetarian** processed food, ingredients like honey, eggs, milk and potentially insects are also included.

From a health perspective, highly processed vegan foods often contain added ingredients such as sugar, salt, and fat. They are often high in calories, low in nutrients, and can be detrimental to health if consumed in excess (Rauber et al., 2020; Gupta et al., 2019; Blanco-Rojo et al., 2019; Steele et al., 2017).

The environmental impact of ultra-processed vegan and vegetarian food is undoubtedly lower than that of mass meat production and consumption, including dairy. García et al. (2023) conclude in their study that (1) decreasing consumption of ultra-processed foods may improve environmental sustainability, (2) the lower ultra-processed food dietary contents, the lower the environmental footprint of the diet, and (3) decreasing ultra-processed food consumption should be considered for health and environmental protection.

Anna Kustar et al. (2021) reviewed environmental life cycle assessments. They found that vegan diets significantly reduce land use, water use, and greenhouse gas emissions compared to omnivorous diets, even when highly processed plant-based burgers are included. In the time given, more systematic studies about complete life-cycle analysis of vegan or vegetarian ultra-processed food have not been found for this review.

This case study systemically explores the implications and pathways for reduced meat consumption, assuming people are replacing meat with vegan or vegetarian ultra-processed food. It is acknowledged that a) reduced meat consumption does not necessarily imply zero meat consumption (see recommendation by EAT-Lancet commission), b) Reduced or no meat consumption does not automatically mean vegan lifestyles, c) Not all vegan and vegetarian lifestyles automatically imply the consumption of UPF. However, in the following paragraphs, the motivation of people to choose a vegan/vegetarian lifestyle is briefly explored before diving into the systemic thought games. Motivation is key to understanding which fraction of the population might consider the shift and which fraction might end up with UPF. Interestingly, UPF is primarily vegan/vegetarian, looking at the ingredients (Gupta et al., 2019). So, for this case study, one can assume that the studies on UPF are also valid for vegan and vegetarian lifestyles. UPF – no matter whether it is intentionally meant as a replacement for meat or only convenience food - is connected with environmental and health effects (Aliouche, 2022; Clemente-Suárez et al., 2023; Suksatan et al., 2021).

A vegan diet promotes a lifestyle excluding all forms of exploitation of animals for food, clothing or any other purpose. A vegetarian diet does not contain meat, poultry or fish. However, the variety of sub-styles and variations, especially in vegan lifestyles, is wide depending on the primary motivation of the consumer. The following is compiled based on (North et al., 2021; Simons et al., 2021; Fox and Ward, 2008):

- **Ethical consideration:** the primary motivation is to avoid mass meat production and the 'usage' of animals. The concern is for animals and their welfare.
- **Environmental considerations**: These individuals choose (often) a vegan lifestyle due to environmental sustainability concerns. Many vegetarians also are motivated by environmental concerns.
- **Dietary vegans/ Raw vegans**: These individuals choose a vegan lifestyle for health reasons or due to dietary restrictions. The latter consume only raw, unprocessed foods.
- **Religious considerations**: These individuals choose a vegan lifestyle due to religious beliefs, such as Jainism, which believes in respecting all life and avoiding harm to animals.

Some nutritional lifestyles, like the paleo diet, are based on the idea of eating foods that early humans likely ate and are designed to avoid modern diets that grew out of farming. The paleo diet emphasises lean meats, fish, fruits, vegetables, nuts, and seeds and discourages highly processed foods with artificial ingredients and colourings. The diet is based on the assumption that the rise in chronic diseases in modern society stems from the agricultural revolution and suggests that adding grains, legumes, and dairy to meals may lead to a host of chronic diseases and conditions, from obesity to allergies.

However, Cambeses-Franco et al. (2021) conclude in their study that the paleo diet has a worse environmental profile than other dietary patterns. However, vegetables and fruits in the diet are associated with a lower risk of cardiovascular disease, type 2 diabetes mellitus, colorectal cancer, obesity, and stroke, making sustainability assessments a helpful tool to guide citizens towards the most appropriate diet.

Given such a variety of different motivations and lifestyles, this systemic overview cannot cover all such peculiarities. Therefore, this case study focuses on **ultra-processed vegetarian and vegan food (UPF)** that replaces meat. In this sense, this case study consciously narrows down the range of alternative diets and possible replacements of protein sources.

Whenever possible, statements and conclusions in the following sections are backed by scientific and peer-reviewed articles. Nonetheless, the topic in this case study is more of a hypothesis or thought experiment based on logical conclusions. When reports or web articles are available to illustrate the ideas, they will be mentioned. In some cases, only systematic and systemic thoughts cannot be directly backed by literature. These are speculations or, in the best case, follow logical conclusions (mostly abductive ones). Such statements or hypotheses are marked as such.

2.2 Systemic properties in the case of ultra-processed vegan/vegetarian food

2.2.1 Rebound effects in shifts of diets towards vegan food

Introduction

A rebound effect occurs when an increase in efficiency is meant to reduce the absolute effect but is offset directly (more of the same) or indirectly (something else with the same impact).

Applied to the shift to a different diet with less meat, the assumption (to identify a possible rebound effect) is that the motivation/intention is to reduce the environmental impact. The question that will be explored in the following section is if the environmental effect can be reduced or if there are direct rebound effects (the meat replacement creates more of the same negative environmental effect) or indirect rebound effects (economic effects counterbalancing positive environmental effects) occur.

The following sections examine (a) what happens if the dietary shift intends to diminish the negative environmental impact (specifically greenhouse gas emissions) and (b) if the intention of the dietary shift is on health (and the means is vegan UPF). Finally, the indirect rebound effect is looked at more closely. The interplay of health and environment is highlighted in section 2.2.3.

Intention on relieving the environmental impact

To explore a possible rebound effect, one has to specify the intention (-> assumption) and then explore the possible balancing effects. In this context, the motivation is why (and how) people are shifting to a meatless diet.

In section 2.1, it was already argued that meat production creates an environmental burden (climate change, land use, eutrophication, energy demand). Reducing meat consumption **should reduce** the environmental impact. This case will be explored as a systemic thought experiment to determine if reducing meat consumption reduces environmental impact.

What would be the direct effects of a shift towards a vegan diet as a principal measure to reduce mass meat production? What would be the short-term, mid-term and long-term effects? Which counterbalancing effects might occur, setting off potential relief on environmental pressures? Is this already a rebound effect?

Exploring the extreme –reducing meat consumption (the role of delays)

There would be several delays in the system that would prevent an immediate effect: The decision to reduce meat production today would take some minimum time to take effect considering the lifespan of the animals (unless all animals were culled).

The entire economic value chain from farmers, meat producers, transport companies, and supermarkets is a buffering system that will create more delays. The nature of a buffer is that it can produce output even if the input is reduced (at least for a while). Nevertheless, let us assume the domestic demand has dropped, and the number of animals is decreasing with a delay. The environmental pressure of direct emissions would drop (e.g. emptying stables, stopping in meat fabrics). However, emissions from transport, food processing and retailing would remain until the buffers in the system run “low”. In addition, there would not be an immediate relief on land use as the infrastructure (stables, grassland) remains until restructured. Another buffer in the system is the stored manure. The decomposition of manure on the grassland would also take time, and the manure might be applied to the acre later. Fodder production for animals will follow with another delay in the downscale.

Taking all the possible delays in the system together, the immediate environmental effect of no meat consumption would be low; however, with several delays, the impact on the environment will finally decrease. In this regard, no rebound effect can be expected.

What would be the consequences on the consumer side?

It has been assumed that the consumer is replacing the meat in his/her diet and not consuming it anymore. Depending on the vegan/vegetarian food source, let us assume three different alternatives what to consume instead. This comparison intends to illustrate the effect of the consumer decision to choose UPF compared to vegetarian and vegan alternatives (see also):

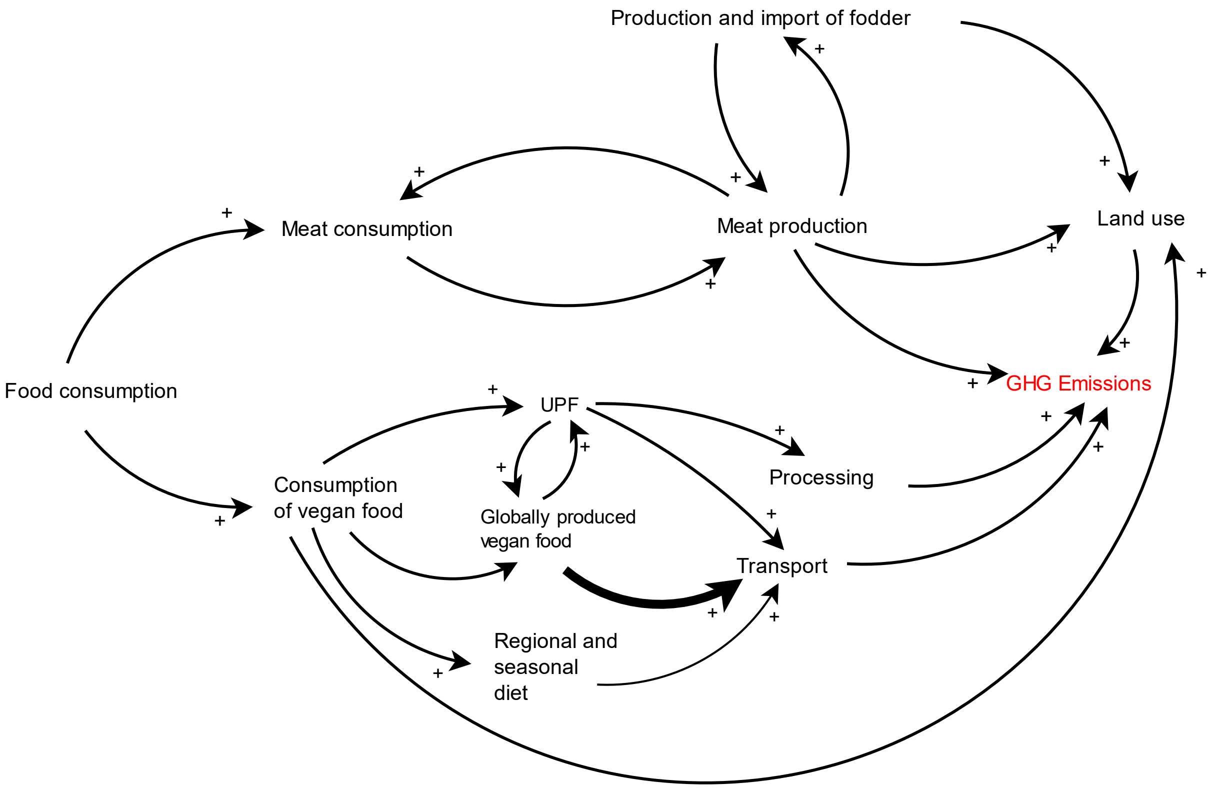
1. If consumers decide to consume raw, unprocessed vegan food locally, and all food rests (uneatable parts, food "waste") are composted regionally. Then, we can assume a maximal positive effect on the environment. There might be evidence that local transport would also increase and that there might be some loss of efficiency (i.e. loss of scale effects).

2. If the consumer decides to consume globally produced and **imported vegan and vegetarian food**, there would still be a negative environmental impact due to the way of production and transportation of the meat alternatives. For example, the consumption of almonds or other nuts strongly impacts water demand in the growing region. A study from the European Commission Joint Research Centre shows that 74% of irrigated nuts are produced under water stress (of which 63% are under severe water stress) throughout many regions of the world, most notably in India, China, Pakistan, the Middle East, the Mediterranean region and the USA (JRC, 2020). The same applies to a certain degree for soybeans (although used as animal feed to a large extent, (Karlsson et al. 2020), palm oil (Meijaard et al., 2020), sugarcane ((Martinelli et al., 2011), and to a certain degree other crops grown in intensive agricultural practice under water stress. In such a case the environmental impact is practically translocated and substituted.

3. If the consumer decides to consume **ultra-processed vegan/vegetarian food**, the energy demand for the processing may be high. Taken together with transport, the environmental impact should be lower than that of meat-based food but higher than regional and seasonal vegan nutrition based on whole fruit, vegetables, grain, and nuts (Anna Kustar et al., 2021). As UPF contain large quantities of carbon hydrates (e.g. sugar), sugar production must also be considered (e.g. Martinelli et al., 2011).

As an intermediate conclusion, the lack of effect on the environment at the beginning of the reduction of meat production does not create **a direct rebound effect**. There are only several delays and buffers in the system, making the effect of any reduction in meat consumption and production only visible later.

Figure 13: Simplified Pathway Diagram, showing part of the rebound effect in the food system



Note: Food consumption can take three ‘pathways’ as highlighted in the preceding text: meat consumption, consumption of ultra-processed food and regional and seasonal diet. The diagram is intentionally kept simple. The only loop in this figure is the production-consumption loop in the ‘meat pathway’. The thickness of an arrow indicates the strength/relevance of the connection compared to the other arrows.

Source: own sketch

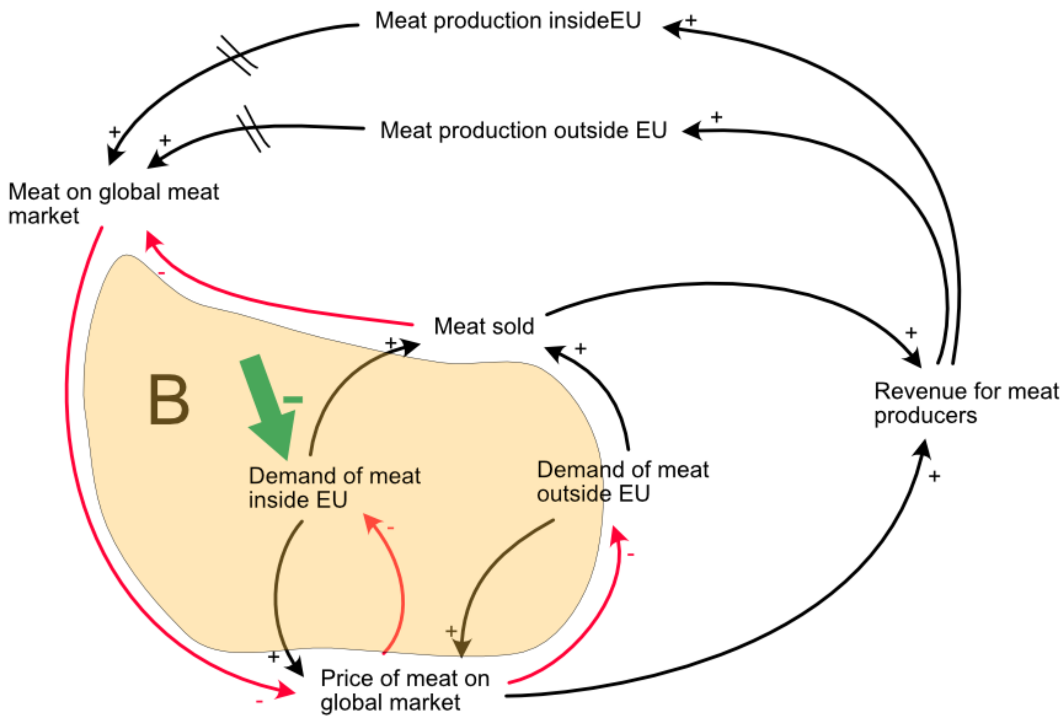
Rebound effects – taking the (global) economy into play.

Reduced meat **consumption** inside the EU does not automatically imply reduced **production** inside the EU, given that there are global imports and exports. However, recent statistics show that the European market is nearly self-sufficient, and only a tiny fraction (approx. 10%) is exported outside the EU2. Nonetheless, meat production, including slaughter and processing, is an established industrial sector, and meat markets are global. If prices drop due to lower demand for meat inside the EU, demand on the global market might prefer EU meat as it is highly subsidised and cheaper than other regions. Once export/import routes are established, there is barely any incentive for the meat industry to stop meat production inside the EU. (Tukker et al., 2011) conclude in their paper ‘Environmental impacts of changes to healthier diets in Europe’: ‘(...)This analysis showed that the European meat production sector will most likely respond by higher exports to compensate for losses on the domestic meat market. (...)’.

The following Figure 14 gives a simplified overview of how demand inside and outside the EU are mutually influencing each other and managed by a price-building effect on a global market (this price-building scheme can also be found in (Olafsdottir and Sverdrup, 2019).

2 https://ec.europa.eu/eurostat/web/agriculture/data/database

Figure 14: CLD illustrates the offer/demand of meat production inside the EU with exports.



Note: The arrows with a '+' symbolise an increasing effect, while the red arrows with a '-' symbolise a decreasing effect. The figure illustrates a causal loop diagram depicting the dynamics of meat production and market demand within and outside the EU. The balancing loop (B) shows how the demand for meat inside the EU affects the global meat market price, and how this price influences overall meat production. Meat production within and outside the EU impacts the global market supply, where increased revenue from meat sales further drives production efforts.

Source: Authors own representation, inspired by (Guðbrandsdóttir et al., 2018)

This direct feedback or shift from a domestic to a global market is an excellent example of a direct rebound effect moderated by the global market. In other words, the same production and export levels offset the intended reduction of environmental pressures due to reduced meat consumption regionally. Long-range transport (cooled and time-critical transport) accounts for significant energy consumption and emissions (GHG, PMx).

However, the cheaper meat gets, the more motivation to flip back to meat consumption is likely.

The role of Health effects

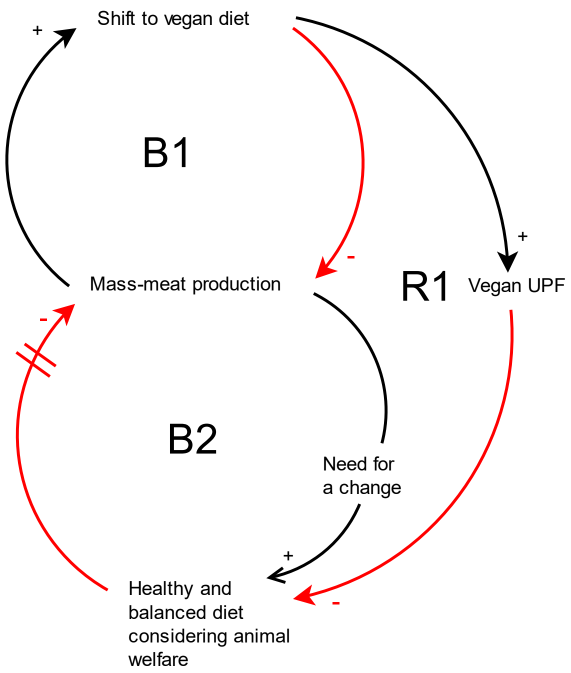
If the motivation or expectation for the rebound effect of the shift to a vegetarian diet is better health, both the direct and indirect rebound effects are not fully applicable as the causalities are not straightforward. Some studies suggest positive health effects of vegan and vegetarian lifestyles, e.g. (Le and Sabaté, 2014). Others point to deficits of specific nutrients, e.g. (Eveleigh et al., 2020; Suksatan et al., 2021; Blanco-Rojo et al., 2019; Rauber et al., 2020).

2.2.2 Shifting the burden

The role of feedback loops and replacing one problem with another is the central characteristic for the shifting the burden archetype.

Figure 15 shows a 'pure' form of the shifting the burden archetype concerning vegan UPF.

Figure 15 A simple CLD showing the archetype shifting the burden concerning a dietary shift



Note: The arrows with a '+'-symbol indicate an increasing effect, while the red arrows with a '-'must be read as a decreasing relation. The quick fix in this example is to switch to vegan UPF, while the fundamental solution would be a healthy and balanced diet, considering animal welfare. The more mass-meat production, the higher the need for a fundamental solution. In this archetype, the fundamental solution is bypassed with a quick fix, which also hinders the fundamental solution. B1 symbolises the balancing loop, reducing mass meat production with a shift to a vegan diet, while B2-loop limits mass meat production with a shift to a healthy and balanced diet. The solution with vegan UPF creates a reinforcing loop R1 (with a delay), increasing mass-meat production.

Source: Author's sketch

In the case presented here, the problem is mass meat production (be it for environmental, animal well-being or health impact). The quick solution in this thought experiment is a shift to a vegan diet. However, this might lead to the consumption of vegan UPF because, in a fast-paced society, consumers often opt for readily available, processed meals due to their convenience. However, as mentioned earlier, these foods offer immediate satisfaction, but they often lack nutritional value and contribute to health issues such as obesity (Sandoval-Insausti et al., 2020) and chronic diseases (Lane et al., 2020). A more effective and sustainable solution (the 'fundamental solution' in the sense of the archetype, see section 1.3.4) to mass-meat production, however, would be a healthy and balanced diet, considering animal welfare.[3]

3 https://www.eufic.org/en/healthy-living/article/food-based-dietary-guidelines-in-europe, accessed NovemberNovember 2023

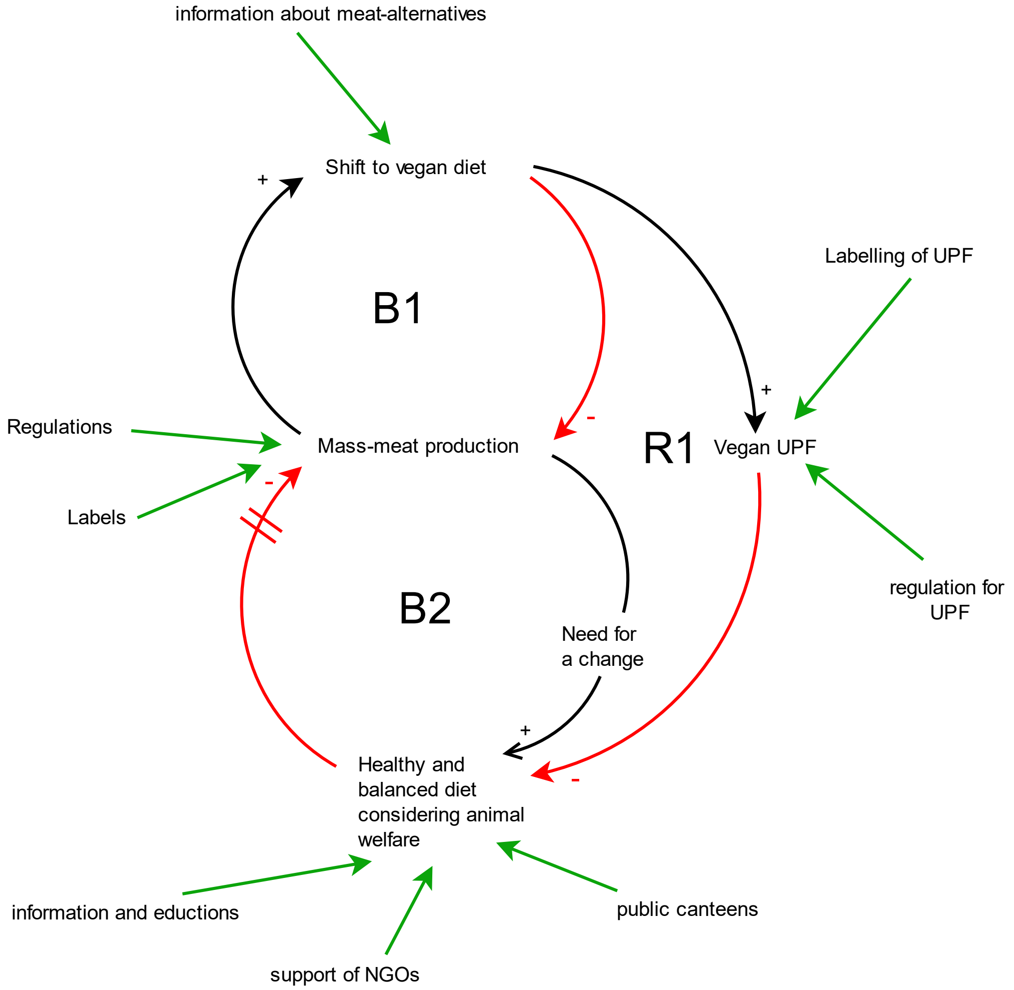
It must be stated clearly that this is a very reduced and simplified CLD. Factors like social status, spending power, the social peer group and knowledge also play a role in the decision-making process. On top of that, there is a particular interest of all actors in the food value chain and marketing (nudging) should be considered. This archetypical behaviour reduces complexity and is comparable to the rebound effect sketched in Figure 13. However, the mechanism is visible already today and should not be neglected. For policy intervention, the following options can be identified :

1. addressing the delay
2. strengthening the balancing loops
3. dumping down the reinforcing loop

Two basic types of policy instruments might be applied as examples: first, education and information, and second, regulations about the quality of UPF and/or limiting mass-meat production. ‘Education and information’ would help the general public understand a healthy and balanced diet (e.g., EAT-Lancet recommendations[4]). Labels would empower the decisions of the populations. Animal welfare Regulations would indirectly affect mass meat production; a revision of EU animal welfare legislation has been announced for 2023. There are some voluntary animal welfare labels by food retailers/supermarkets.

4 EAT-Lancet Commission Brief for Everyone - EAT (eatforum.org), accessed November 2023

Figure 16: CLD including leverage points for the policy instruments



Note: The Causal Loop Diagram (CLD) illustrates the dynamics between meat production, dietary choices, and interventions to promote healthier and more sustainable diets. Balancing Loop B1 (Mass-meat production): Regulations and labels targeting mass-meat production aim to reduce it. The shift to a vegan diet is encouraged as regulations increase, reducing mass-meat production over time. Balancing Loop B2 (Need for a change): As mass-meat production decreases, the need for a dietary change to a healthier and more balanced diet, considering animal welfare, increases. This loop is supported by information, education, support of NGOs, and public canteens promoting such diets. Reinforcing Loop R1 (Vegan UPF): The rise in vegan ultra-processed foods (UPF) is driven by the shift to vegan diets and the labelling and regulation of UPFs. As vegan UPFs become more popular, their need increases, potentially reinforcing the uptake of a vegan diet. The green arrows represent policy interventions such as providing information about meat alternatives, requiring labels for both meat and vegan UPFs, regulating UPFs, promoting healthy diets, and supporting NGOs and public canteens. These interventions are designed to create a sustainable shift

Source: author's sketch.

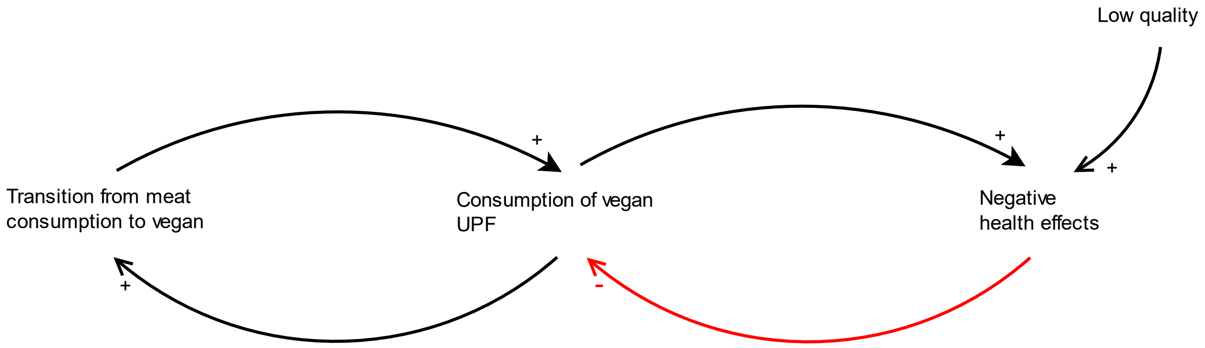
As already mentioned in the EEAs report 'Transforming Europe's food system — Assessing the EU policy mix' (EEA, 2022d), Tools based on information have the potential to impact consumer decisions when individuals possess the required skills (such as understanding labelling), have access to sustainable food options, and are motivated to choose healthy products. Additionally, these tools will likely shape behaviour when consumers face a shift in their routine habits, such as relocating, changing employment, or becoming a parent (Verplanken and Roy, 2016). In various scenarios, different types of cues often influence consumer decisions.

2.2.3 Limits to Growth

In the context of a shift towards vegan lifestyles based on ultra-processed food, the limits to the growth archetype can help to think about (1) the driving forces of an increasing share of vegan food, (2) the balancing force, and (3) the limiting condition. The question is not if and how the share of vegan food can grow limitless. This archetype helps to identify policies.

Figure 17 shows a very condensed form of the Limits to Growth archetype.

Figure 17: 'Limits to growth', looking at ultra-processed vegan food consumption



Note: The figure depicts a causal loop diagram ('Limits to Growth' archetype) showing how transitioning from meat consumption to a vegan diet affects health outcomes. As individuals shift to a vegan diet, the consumption of vegan ultra-processed foods (UPF) may increase, which are often perceived as low quality. This rise in UPF consumption can lead to negative health effects, which create a feedback loop as these health outcomes can deter or influence future dietary choices.

Source: Author's representation.

The 'growth engine' is the loop on the left side: the more people start to transition to eating more vegan, the more vegan processed food will be produced and consumed. As the consumption of UPF is convenient and cheap (Steele et al., 2017), more people are making this choice. Respectively, the share of the consumption of vegan UPF will increase significantly (see also section 2.2.2). However, there are adverse health effects related to the consumption of UPF. As the adverse health effects become more apparent, it is at least possible that the consumption of vegan UPF would be limited/reduced (see Shifting the Burden, section 2.2.3). Of course, there are more boundary factors, or in the case of limited nutrients (see definition of UPF), people might start to consume additives to the food, which might limit the adverse health effects. Unfortunately, it is also possible that people are not changing their behaviour due to the adverse health effects. Nonetheless, the archetype as such could be defined like this, and a consequence for policy-making might be identifying measures that support reducing the adverse health effects or shifting to fresh and unprocessed food instead.

2.3 A short reflection on vegan and vegetarian lifestyles in the light of the systemic thought experiment

Notarnicola et al. (2017) state in their article "Environmental Impacts of Food Consumption in Europe": "Food consumption is among the main drivers of environmental impacts. On the one hand, there is the need to fulfil a fundamental human need for nutrition, and on the other hand, this poses critical threats to the environment." However, many factors have an impact on food choices and lifestyles. In Europe, the food system is based on an extensive and complex value chain, creating many environmental pressures (EEA, 2017a). Nonetheless, consumers have a variety of diets to choose from and – if not limited by economic reasons – have access to healthy and locally produced food.

The thought experiment intended to specifically explore what could happen when meat consumption was replaced by vegan ultra-processed food. This is obviously an extreme, and this situation will not occur in this pure form. Therefore, this analysis does not come up with concrete and exact data, but it does challenge (hidden) assumptions about causes and effects in the food consumption-production system.

While it is clear that nobody intends to switch off meat production from one day to another, it is worthwhile to think through the potential implications for the system and to get an idea about the potential for 'improvement'. Feedback loops and delays in the complex system make quick fixes hard, and potential results might be hard to see.

However, considering the speculative nature of this thought experiment, some conclusions could be made:

- The intention to completely reduce the consumption of meat in order to reduce the environmental impact will only create a slow change in the system. There might be a risk of disappointment and a lack of self-efficacy.
- Additional political measures along the food value chain need to support individual efforts.
- The good intention of switching to no-meat consumption could be compensated or dumped by a rebound effect when switching to vegan or vegetarian meat replacements.
- Vegan UPF is a Fix to Fail and is Shifting the Burden, making it harder to follow a balanced and healthy diet.

From a methodological point of view, CLDs can help identify levers in the system and identify measures to support sustainable food consumption and production (see Figure 12). However, the food system is highly complex, and many factors, like affordability, knowledge, and availability in the market, influence consumer decisions. The CLDs presented here are partly too simplistic to address the full complexity of the system. Nonetheless, the archetypical behaviour can be identified, and this perspective can help build policy mixes and understand feedback mechanisms that would have offset possible gains.

3 Energy – the case of Hydrogen

By Javad Keypour and Ullrich Lorenz

3.1 Introduction

With its Climate Law and the associated climate targets, the European Union committed to becoming the first carbon-neutral economy by 2050 (EU, 2021). Meeting such targets entails furthering and implementing its commitments to energy efficiency, renewable energy production, and carbon sequestration. From a systemic perspective, it is important to consider the effects of introducing and upscaling specific technologies on the European energy system and its viability. An energy system encompasses all aspects of energy supply and consumption shaped by economic, political, technical, and societal factors. This system exhibits significant diversity in the EU, including variations in energy sources, market structure, and infrastructure age, leading to varying carbon emissions and market competitiveness (EEA, 2019b). Understanding the systemic interconnections between its components and the functions it delivers to society is paramount.

In addition to climate concerns (emissions of greenhouse gases), the EU energy system is, to some extent, also related to public health impacts.

The energy transition towards an energy system primarily based on renewable energy could be highly synergistic: On the one hand, dependency on the import of fossil fuels is reduced (concerns about the security of supply have been raised again since the energy price hike started in the fall of 2021 and then in the aftermath of the Russian invasion of Ukraine in early 2022). Moreover, the emissions of greenhouse gases and other pollutants can be reduced, particularly for particulate matter, NOx and VOCs (EC, 2023).

The drawback associated with renewable energy technologies is the variability of electricity production. For example, wind and solar power do not constantly produce electricity. Windmills only produce when there is wind, and solar panels only create electricity when the sun shines. An energy system based purely on such infrastructure without any base-load-backup-system requires short-term, mid-term and long-term buffering systems and flexible load management (to ramp up and regulate down production depending on available energy). In addition, the larger and better regulated the power grid, the better and easier it is to balance the whole system. Electromobility might play a significant role as a buffer system with the available battery capacities. While the EU is accelerating the transition to an efficient, renewables-focused energy supply, energy efficiency, demand management, and higher contribution from the "prosumers" (individuals who produce and consume electricity) will reshape the energy demand and, therefore, the whole energy system landscape and governance (EEA, 2019a).

In any case, the capacity of RE facilities needs to balance at least the peak electricity demand in the system plus a reserve. The installed capacity must be high enough to produce electricity to meet the current demand and store energy for days without wind and sun. The systems must be scaled so that the reserve can be built up, even on a regular day in winter. Given that all RE facilities are producing electricity at full capacity (e.g. strong winds and sunny periods in summer), there will be a lot more energy in the system than can be consumed and, at times, even be stored. In such a case, e.g. windmills are 'powered down'.

Hydrogen (electrolysis) can play a significant role in an energy system increasingly dependent on RE. It could be an ideal means to store the surplus electricity for later use. Water electrolysis creates the potential to "store" energy by simply splitting water and capturing H2. This energy is then available for later use and even transferable to different locations. Such a characteristic makes hydrogen interesting as a fuel, offering a sustainable alternative to fossil fuels. Despite today's inefficiencies in converting energy from renewables to H2 and back to power, it can become a versatile energy carrier and a central element in storing energy to capture overcapacities in a fully renewable energy system. Next to its potential relevance for the energy system, hydrogen is an essential compound in the chemical industry and can play an increasing role, e.g. in steel production (Lambert, 2020).

However, hydrogen must be produced, stored and transported securely and reliably. The final use for a consumer or in any industrial or technical process must be safe. Different technologies are already available today for all the different stages. However, most of the infrastructure still needs to be installed, while the processes and governance of the energy system must be reconfigured. Such reconfigurations are mainly a question of the economy (investments/production), society (acceptance/cost/organisation) and policy (regulations of the transition/incentives).

The EU Hydrogen Strategy of 2020 is a framework to support the uptake of renewable and low-carbon hydrogen to help decarbonise the EU and reduce its dependence on imported fossil fuels. It proposed 20 key actions in five areas: investment support, production and demand, market and infrastructure, research and cooperation, and international cooperation (EC, 2020a). Already, by the first quarter of 2022, these actions were implemented and delivered. Some of the main achievements included setting targets for renewable hydrogen in industry and transport by 2030, creating a dedicated infrastructure for hydrogen, establishing an efficient hydrogen market, and fostering international partnerships on hydrogen.

Hydrogen is a promising energy carrier that can be produced from renewable sources and used in various applications. However, hydrogen also poses some health- and security-related and environmental risks that must be considered before implementing a hydrogen-based energy system. Some of these risks are:

- Hydrogen is highly flammable and explosive, requiring special safety measures for production, storage, transport, and use. If it leaks or accumulates in confined spaces, it can cause fires or explosions if it reaches an ignition source.
- Hydrogen production from fossil fuels, such as steam methane reforming or coal gasification, generates greenhouse gas emissions and other pollutants, contributing to climate change and air quality problems. These emissions can be reduced by using carbon capture and storage technologies, but they are not yet widely available or cost-effective. This option cannot be the goal for the energy transition. However, during the transition, it is likely and possible that hydrogen demands might be met by fossil fuels or nuclear hydrogen production. As any energy conversion creates losses in efficiency, as a rule of thumb, these conversions must be avoided in the long run.
- Hydrogen production from water electrolysis requires large amounts of electricity, which can have environmental impacts depending on the source of the electricity. For example, if the electricity comes from coal-fired power plants, it produces greenhouse gas emissions and other pollutants. On the other hand, if the electricity comes from renewable sources, such as solar or wind, it will have lower environmental impacts but also face challenges of intermittency and variability.
- Hydrogen use in power systems, transportation, industry and agriculture can have positive or negative environmental impacts depending on the type and efficiency of the devices that convert hydrogen into useful energy. For example, fuel cells can produce electricity from hydrogen with high efficiency and low emissions, but they also require rare and expensive metals as catalysts (however, recent innovations point to different solutions). Internal combustion engines can run on hydrogen (blended) with lower efficiency and higher emissions but are cheaper and more widely available (Markiewicz et al., 2015; Ugurlu, 2020). However, in the last example, there is still a dependency on carbon-based fuels (fossil, synthetic or bio-based).

- Hydrogen use can also affect the atmospheric chemistry and climate by altering the concentrations of some trace gases, such as ozone, methane, water vapor and nitrogen oxides (Pearman and Prather, 2020).

Therefore, a comprehensive analysis of hydrogen production, storage, transport and use is needed to assess a Hydrogen-based energy system's net environmental and health impacts. Such an analysis should consider the direct emissions and impacts of hydrogen activities and the indirect emissions and impacts of the upstream and downstream processes linked to them. In the following sections, some systemic considerations are presented, by focusing on:

- Potential rebound effects associated to the introduction of hydrogen energy technologies;
- The limitations for upscaling hydrogen infrastructure in reason of potential impacts of hydrogen combustion;
- The limitations to green hydrogen deployment stemming from continued reliance on fossil fuels (e.g. blue hydrogen).

3.2 Examples of Systemic Properties Concerning the Hydrogen Economy

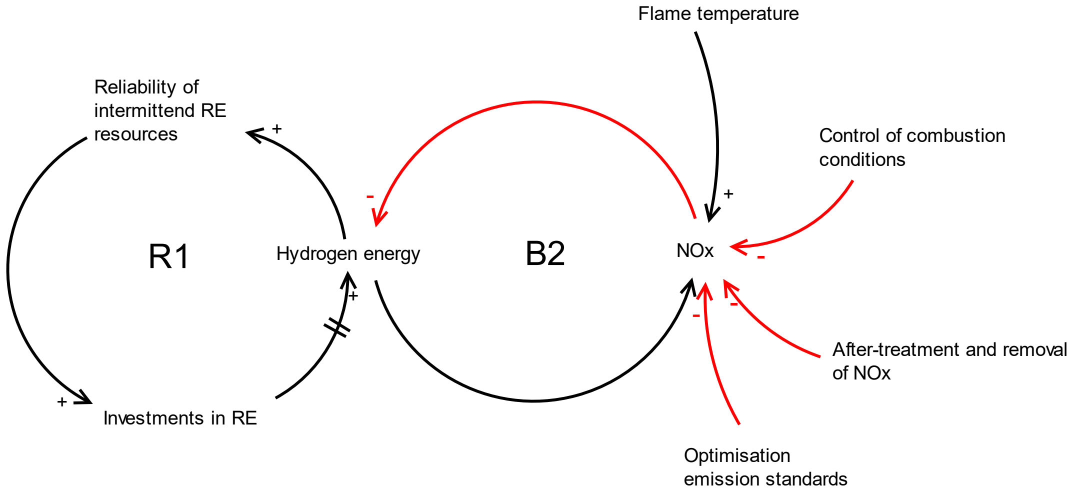
3.2.1 Limits to Growth

This archetype describes a situation where an initial growth in a variable (e.g. hydrogen demand) is slowed down or reversed by a balancing feedback loop (e.g. market saturation). Yusaf and colleagues (Yusaf et al., 2022) are addressing the potential of hydrogen energy as an alternative to fossil fuels for decarbonising the energy sector. A potential environmental challenge associated with using hydrogen as a combustion fuel may increase the risk of environmental deterioration due to the production of NOx and PMx, which would only be the case when hydrogen is blended into fossil fuel or burned as fuel. If the energy would be transformed based on fuel cells, no emissions in the form of NOx or PM would be formed.

According to Yusaf et al., the archetype consists of a reinforcing loop (R1) and a balancing loop (B2), visually represented in Figure 18. Hydrogen will be the means for mid-term to long-term buffer systems. Such buffer systems are the prerequisite for a possibly highly volatile renewable energy system. Building a hydrogen storage and re-powering system must go hand in hand with the growth of renewable energy production (wind, solar power). From a systemic point of view, hydrogen and renewable energy infrastructure depend on each other to create a positive feedback relationship.

The authors further claim that, as the capacity for (renewable) hydrogen generation expands, it would be used in more appliances, where it might be directly burned (blended or in pure form). Any thermal burning process using ambient air will create NOx and, depending on the burning conditions, small particles (PMx). Nonetheless, adjusting combustion conditions (e.g., flame temperature) and post-treatment measures can mitigate the adverse effects. Consequently, stringent emissions regarding NOx-emission standards may constrain the growth of hydrogen utilisation. While fuel cells might be used in mobility, especially in the glass or steel industry, hydrogen would be directly burned for thermal and chemical reasons. Avoiding carbon dioxide emissions comes at the price of elevated (or at least comparably high) NOx and PM emissions. However, recent research proposes certain correction factors, stating that compared to pure methane combustion, blended or pure H2 burning has relatively lower levels of NOx (Wagman, 2023).

Figure 18: Structure and behavioural graph of the Limits to Growth (hydrogen energy)



Note: The figure illustrates a causal loop diagram that highlights the interactions between renewable energy (RE) investments (R1) and hydrogen energy (B2). It shows how investments in RE increase the reliability of intermittent RE resources, influencing hydrogen energy production. The diagram further outlines the impact of hydrogen energy on NOx emissions through various factors such as flame temperature, control of combustion conditions, after-treatment, and optimisation of emission standards. The structure follows the 'limits to growth' archetype.

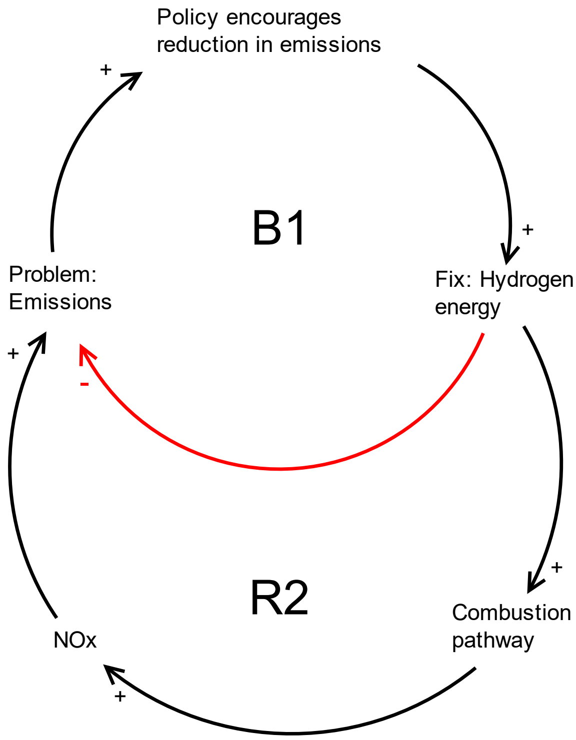
Source: Adapted from Yusaf et al. (2022).

3.2.2 Fixes that Fail

This archetype describes a situation where a short-term solution to a problem (such as increasing hydrogen production or consumption) creates unintended consequences that worsen the problem in the long term (such as increasing greenhouse gas emissions, energy insecurity or social inequality). A possible example of this archetype in the renewable energy transition is the reliance on blue or grey hydrogen as a bridge technology to green hydrogen, which could delay the development of renewable energy sources and lock in carbon-intensive infrastructure and practices.

Yusaf et al. (2022) describe an example of this archetype. It consists of a reinforcing (R2) and a balancing loop (B1), as illustrated in Figure 19. To mitigate emissions, the government is investing in hydrogen energy (loop B1). While investing in hydrogen is essential to mitigate CO_2 emissions, hydrogen as a combustion fuel may lead to further emissions (NOx) and PMx depending on the technology used. This will, in turn, increase the net of emissions (represented by loop R2).

Figure 19: Fixes that Fail archetype linking hydrogen burning and emissions



Note: The figure illustrates a causal loop diagram depicting the relationship between emission reduction policies and hydrogen energy adoption. The balancing loop (B1) indicates how policies encouraging emission reductions promote using hydrogen energy as a solution. The reinforcing loop (R2) highlights the increase in nitrogen oxide (NOx) emissions due to the combustion pathway of hydrogen energy.

Source: Yusaf et al. (2022)

The solution to this failed fix is to avoid blending or the pure combustion of hydrogen under ambient air conditions. While this sounds trivial, several applications in industry and for heating in private households suggest precisely the blending of natural gas or the burning of hydrogen as a heat source.

So, instead of moving directly from the current natural gas energy systems to pure hydrogen, an incremental blending of hydrogen with natural gas is seen to support a seamless transition. Current studies focus on blending to natural gas pipeline networks (Tran et al., 2022).

For example, Diesel and Hydrogen can be blended, which offers great potential in agricultural vehicles. However, pilot studies show both increased or decreased levels of NOx (Gheorghe et al., 2019).

However, fuel cells are certainly the better solution to fix the challenge of the combustion pathway. Various studies see the potential of hydrogen fuel, for example, for maritime transportation applications (Stark et al., 2022), heavy-duty vehicles (Yaïci and Longo, 2022), fuel cell electric vehicles (Gómez and Santos, 2023) and even in aviation (Sarkar et al., 2023).

It is becoming clear that further research is needed to minimise the above-sketched “fix that fails”. A more integrated view taking into account air quality and mitigating greenhouse gas emissions is key.

3.3 Discussion and Reflection

Energy transition aimed at reaching the current EU climate mitigation targets or, more ambitiously, striving towards a carbon neutral—or even carbon negative—economy without significant adverse environmental or social side effects is a demanding and essential challenge.

Hydrogen technology could play a central role in a renewable energy system, both as a means of buffering the overproduction of renewable energy and as a mobile fuel in selected modes of transport.

Hydrogen is a carrier of energy, not an energy source; thus, it is comparable to electricity (Oberdorf, 2023).

However, in light of the findings found in the literature, it is imperative to recognise the interrelations between hydrogen combustion technologies and the potential elevation of NOx emissions. Direct hydrogen burning, blended with fossil fuels or in pure form, would not resolve the air quality problem. This calls for the application of fuel cell technology. While a fuel cell creates independence from electric plugs and batteries and could play a key role as a mid-term buffer, the technology and infrastructure for managing and using hydrogen still need to be built and tested.

4 Mobility – The case of navigating mobility and accessibility

by Nike Sudikatis

4.1 Introduction

The mobility system plays a vital role in modern society, enabling individuals to fulfil their essential mobility needs by connecting them to crucial services, opportunities, and experiences. As societies continue to expand and urbanise, the mobility needs of individuals are on the rise, which has resulted in a notable surge in the demand for mobility and a continuous increase in transportation activities in recent years (EEA, 2022c). At the same time, spurred by the COVID-19 pandemic, this growing demand for mobility coincides with a noteworthy shift away from collective transport modes in favour of individual means of transportation, such as private vehicles (EEA, 2022c). However, this increase in demand has significant environmental and social implications, particularly as the transport sector is a major contributor to greenhouse gas emissions (EEA, 2022c). Beyond the evident challenges of accidents, congestion, and air pollution associated with heightened mobility, a subtler issue emerges. Often, in the ambition to satisfy mobility needs, the concept of accessibility has taken a back seat. While meeting these needs is vital for economic and social well-being, it is crucial to recognise that mere transportation volume does not automatically translate into improved accessibility.

Mobility serves as a bridge between individuals and locations. It involves the convenience of moving from one place to another using various modes of transportation. Accessibility concerns how easily we can reach vital destinations such as schools, hospitals, and shops. These intertwined concepts, mobility and accessibility, collectively shape how we interact with our environment and accomplish our daily activities and how the environment is structured and functions. However, a complex issue arises when focusing on improving mobility, potentially affecting access to local areas. Mobility as a functional domain is not a stand-alone entity but is part of a complex socio-technical system. A systemic perspective captures the dynamics and mechanisms of change that arise from the interplay and co-evolution of technologies with socio-economic and institutional developments. Here, the aim is to provide more insights into these dynamics by highlighting several systemic properties and approaching the topic from transport and urban planning angles. The examples of systemic properties have been selected to align with the primary objectives outlined in the OECD report on transportation (OECD, 2021). The report aims to ensure accessible mobility within a sustainable transport system. To achieve this aim, it calls for re-evaluating priorities, moving away from focusing solely on efficiency and technological advancements. Instead, it emphasises the importance of systems redesign, including street design, spatial planning, and the development of robust, sustainable transport networks (OECD, 2021). Within this overarching framework, specific systemic properties closely associated with the report's objectives will be highlighted here. These properties are situated within the context of the three main drivers identified as influential in mobility dynamics: induced demand, urban sprawl, and the decline of active and shared modes of transportation (OECD, 2021).

This approach also resonates with the European Commission's 2020 introduction of the 'Sustainable and Smart Mobility Strategy,' which outlines the path for greening and digitising the EU's transportation system. This strategy is aligned with the European Green Deal's objective of reducing emissions by 90% by 2050 (EC, 2019). It emphasises the development of a smart, accessible, and affordable transport system to realise this target (EC, 2019). This case analysis of the mobility-accessibility dynamic corresponds to the strategy's main pillars that emphasise sustainability, accessibility, and systemic transformation within the mobility system. The systemic approach adopted here can shed more light on how different factors in the mobility system interact and influence people's ability to get to different locations. The power of embracing a systems approach in policymaking also becomes apparent when recognising that individual decisions do not solely shape people's behaviours. Instead, their choices are influenced by the structures of the larger system they function within. This approach acknowledges that the context, environment and culture in which individuals operate significantly impact their choices. Therefore, redesigning systems is crucial in making choices available (Buckle et al., 2020).

The following section will establish the context of the selected case by introducing the key concepts of mobility and accessibility and the challenges of the prevailing assumption that these are interchangeable concepts.

4.1.1 Key concept: Mobility

Mobility plays a vital role in linking spaces and people together. Historically, transport policies have focused on increasing mobility by making travel faster (Chapman, 2019). Mobility measures are commonly based on high traffic volumes and the ability of individuals to cover greater distances in shorter periods. Mobility is often connected with having many vehicles on the road and achieving more trips (Buckle et al., 2020). In addition, high levels of mobility have been linked to the success of a well-functioning transport system and contributing to overall well-being (OECD, 2019). However, it is important to note that increasing travel efficiency does not necessarily result in reduced travel time. Increased efficiency often stimulates increased demand, maintaining the overall time spent on travel at approximately 70 minutes per day (Ahmed and Stopher, 2014). New approaches are emerging that rethink the conventional ideas of mobility, viewing the movement of people and goods in urban areas as more than just an economic matter (López et al., 2020). These approaches consider urban challenges related to the environment and overall quality of life. In this context, accessibility plays a critical role.

4.1.2 Key concept: accessibility

A broader perspective on well-being directs attention away from just mobility and towards accessibility. Accessibility refers to the combination of mobility and proximity. It involves the ease of movement and the convenience of having important destinations and opportunities nearby. This means that accessibility considers both the ability to travel and the practicality of reaching essential places, offering a more comprehensive perspective on an effective transportation system (Silva and Larsson, 2018a). As such, moving from focusing solely on mobility to one centred on accessibility and its connection to sustainable transportation has gained traction. The concept has increasingly been recognised as a promising approach towards a more holistic mobility system (Silva and Larsson, 2018a).

4.1.3 Mobility as a proxy for accessibility: an assumption revisited

The common assumption in transportation planning holds that higher mobility levels naturally result in improved accessibility (OECD, 2021). This belief rests on the idea that enhancing mobility, often measured by the ability to cover more extensive distances quickly, automatically leads to more accessible access to various destinations. However, high overall transport volumes (measured in vehicles, passengers, and kilometres travelled) often occur due to limited accessibility (OECD, 2019). Research with European planning practitioners has shown a lack of understanding of accessibility concepts in policy contexts (Silva and Larsson, 2018). In many contexts, accessibility and mobility are used interchangeably, or mobility is used to achieve accessibility. However, using mobility as a direct substitute for accessibility presents a significant concern, as emphasised by the OECD (OECD, 2019). While analysing transportation volumes is crucial to understanding factors influencing emissions and demand patterns, it falls short of offering a comprehensive evaluation of the overall effectiveness of the transport sector.

In practice, this mobility focus has been accompanied by various trade-offs and knock-on effects that have implications for accessibility-related factors, highlighting several systemic properties at play. These include decreased accessibility levels and unsustainable settlement and travel patterns, like increased car dependency, loss of local activities, and urban sprawl (OECD, 2021). In addition, the pursuit of high mobility has increased emissions, traffic congestion, road safety issues, poor air quality, and adverse health effects (OECD, 2019). Moreover, the current prevailing mobility perspective has led to policies that overlook the crucial aspect of proximity (Silva and Larsson, 2018a) This is problematic as well-being is more closely associated with convenient access to places rather than the ability to travel long distances (OECD, 2021). Currently, the issue of accessibility remains insufficiently addressed, particularly for individuals with lower incomes who face substantial challenges when it comes to accessing transportation services (OECD, 2021). At the same time, private vehicle owners benefit from policy-driven privileges, such as convenient and flexible mobility, shorter travel times, and enhanced comfort. This contributes to accessibility disparities compared to lower-income groups relying on public transportation systems with limited service options and longer commute times.

Therefore, researchers have increasingly advocated adopting a more comprehensive mobility perspective considering broader societal well-being. This approach aligns with the primary objective outlined in the OECD report on transportation (OECD, 2021): to ensure accessible transportation for a sustainable transport system. This approach is grounded in a well-being perspective, emphasising the significance of safe and sustainable access to essential locations. Evaluating performance and shaping policy decisions based on accessibility measures can offer a more accurate reflection of how effectively transportation systems serve the needs of the wider population.

4.2 Systemic properties: unintended consequences and trade-offs in mobility-centred approaches

Building upon the understanding of the complex interplay between accessibility and mobility, this section explores the inherent systemic properties that underlie this dynamic in more detail. The examples of systemic properties discussed here have been selected to align with the primary objectives outlined in the OECD Report on Transportation (OECD, 2021). The report's central goal is to ensure accessible transportation within a sustainable transport system. Achieving this aim calls for re-evaluating priorities and moving away from solely focusing on efficiency and technological advancements (OECD, 2021). Instead, it emphasises the importance of systems redesign, including street design, spatial planning, and the development of robust, sustainable transport networks.

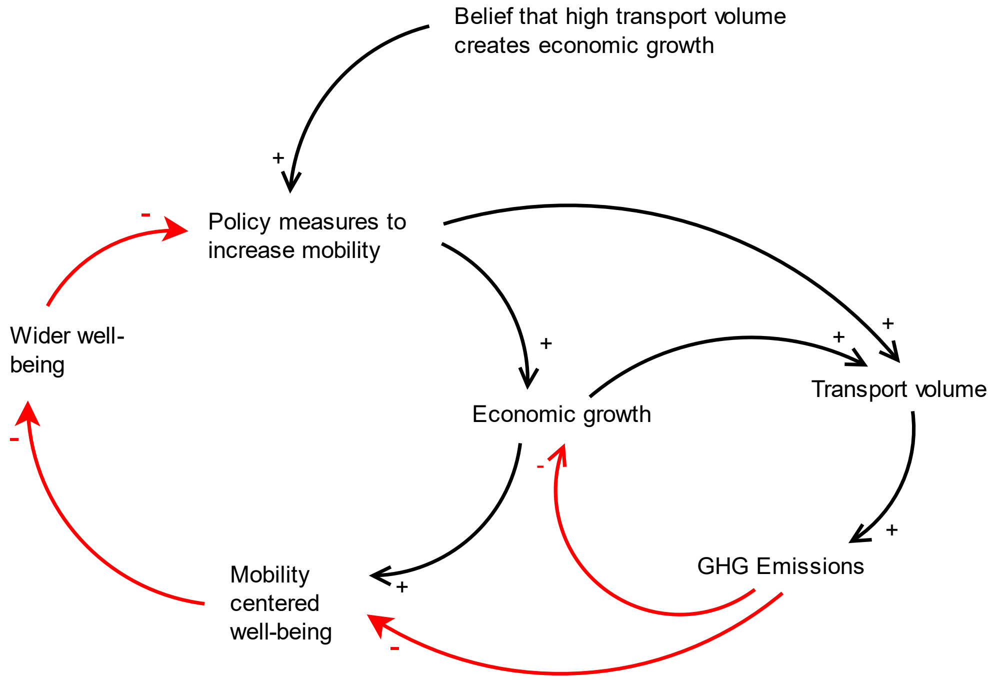
This analysis will highlight specific systemic properties closely related to the report's objectives within this context. These properties are situated within the three main drivers identified as playing a role in mobility: induced demand, urban sprawl, and the erosion of active and shared transport modes.

Adopting a systems perspective reveals that decisions centred solely on enhancing mobility can trigger unintended consequences, affecting aspects as diverse as economic well-being, land use, public spaces, and urban structures. Several issues emerge that will be explored further in the following sections.

4.2.1 Fixes that fail: economic growth vs societal well-being

Chapman (2019) highlights how historical transportation policies have predominantly centred on promoting mobility to drive economic advancement. Approaches that prioritise economic growth as a core objective often build on the assumption that a higher volume of transportation is necessary to sustain GDP growth. This perspective emphasises mobility performance indicators primarily rooted in physical movement metrics, such as passenger numbers, distance travelled, and speed (OECD, 2019). However, viewed systemically, this focus constitutes the Fixes that Fail archetype, where the emphasis on economic growth comes at the expense of factors relating to wider societal well-being. Public welfare, health, and climate change concerns are often relegated to a lower priority (Buckle et al., 2020). This perspective sheds light on the inherent trade-offs within policy decisions regarding economic growth versus societal well-being.

Figure 20: Causal loop diagram of highlighting economic growth and well-being dynamics



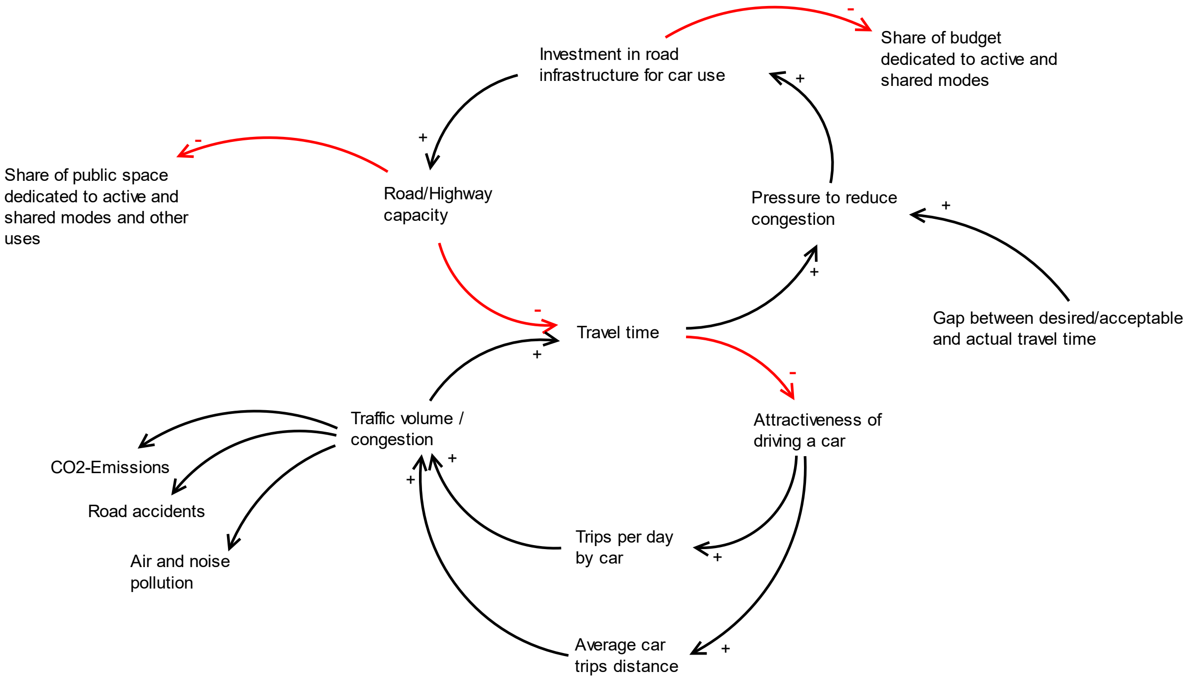
Note: This CLD follows the shape of a Shifting the Burden Archetype but has more of the logic of Fixes that Fail. Arrows with a '+' indicate an increasing effect, while red arrows with a '-'symbolise a decreasing effect. A 'wider well-being' approach also takes accessibility into the equation. However, increased mobility does not contribute to a 'wider well-being' and decreases mobility-centred well-being.

Source: author's sketch.

4.2.2 Shifting the burden: faster travel vs land use and public space

Another aspect to consider within this mobility-focused framework is the fixation on transportation volume. This focus downplays the essential role of land use and the delicate balance between optimising travel speeds and allocating space for various purposes and opportunities, including housing, businesses, schools, and parks (Buckle et al., 2020). This challenge becomes apparent when transportation policies prioritise faster travel without adequately addressing the arrangement and use of public spaces. This illustrates another example of "shifting the burden," where the focus on swift mobility, without considering the spatial arrangement and design of roadways and urban areas, can lead to crowded and congested streets. The resulting congestion not only hampers efficient movement but also diminishes the quality of life for residents due to longer commute times, heightened stress levels, and negative environmental impacts such as air pollution (OECD, 2019). Adopting a systemic lens highlights the interdependencies between transportation policies, urban planning, and the overall well-being of communities.

Figure 21: CLD of shifting the burden showing consequences of prioritising traffic volume growth



Note: Arrows with a '+' indicate an increasing effect, while red arrows with a '-'symbolise a decreasing effect. The figure displays a causal loop diagram showing the impact of investment in road infrastructure for car use on travel dynamics and environmental factors. It illustrates how increased investment boosts road/highway capacity, which affects travel time and the attractiveness of driving a car. The diagram also highlights the relationships between traffic volume, CO2 emissions, road accidents, air and noise pollution, and the competition for public space and budget allocation between car use and active/shared modes.

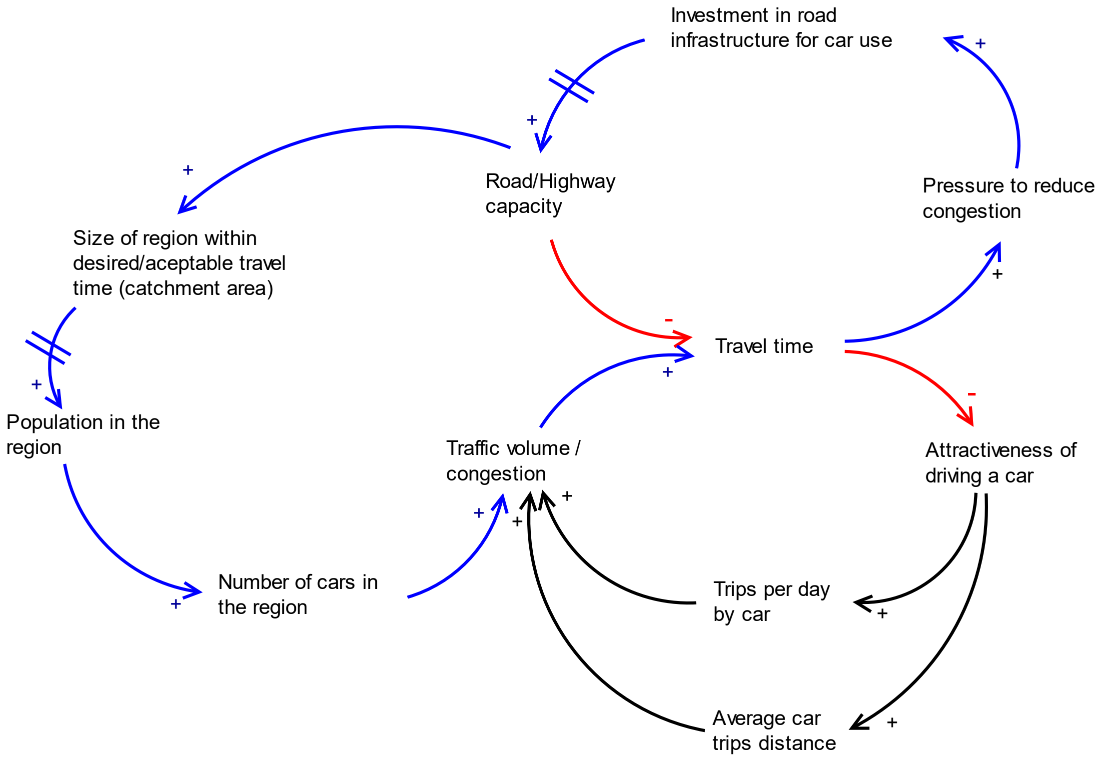
Source: (OECD, 2021)

4.2.3 Fixes that Fail: urban sprawl, infrastructure dependencies, and inequality

A similar pattern emerges concerning the issue of urban sprawl and infrastructure lock-ins. On the one hand, enhancing transportation speed and capacity may increase economic growth and operational efficiency. On the other hand, such efforts tend to contribute to urban sprawl, wherein communities expand outward (OECD, 2021). As people move away from urban centres, often influenced by increasing living and housing costs in cities, daily travel distances tend to increase. This shift towards suburban living is often accompanied by a rise in private vehicle usage, driven by convenience and safety factors. However, longer travel distances discourage walking, cycling, or micro-mobility options, as an increase in private vehicle use inevitably leads to reduced space for other activities (OECD, 2019). This constitutes a 'Fixes that Fail' archetype, as growing urban expansion makes it more challenging for individuals to conveniently access crucial destinations within reasonable proximity. This can lead to longer commutes, aggravated traffic congestion, and a notable decline in overall quality of life (OECD, 2019). In contrast, a more holistic approach to the urban environment focuses on creating neighbourhoods where daily necessities are within easy reach, reducing the need for long commutes and enabling a better balance between work, leisure, and family time.

Focusing on enabling greater regional mobility in reaction to the expansion of urban areas can also increase congestion and reinforce existing inequalities (Buckle et al., 2020). Investing in road infrastructure alleviating congestion can lead to an unintended feedback loop. While the goal is to reduce congestion, this can unintentionally stimulate greater private vehicle travel demand. As congestion lessens due to improved roads, people might find it more convenient to use their private vehicles, leading to increased overall traffic. This pattern of increased vehicle usage intensifies congestion challenges and prompts further road construction that creates more infrastructure lock-ins (OECD, 2021). Lower population density often corresponds to a lack of adequate public transportation options. Expanding road infrastructure further exacerbates this issue as it reduces competitiveness for public transport while making private vehicle transport faster. This has the potential to further privilege those with access to private vehicles while marginalising those dependent on alternative modes of transportation. As a result, individuals without access to private transportation might find themselves at a disadvantage when it comes to reaching essential destinations and opportunities. These interconnected patterns demonstrate how changes in urban planning can influence transportation choices, impacting not only individual travel behaviours but also the broader transportation system's functioning.

Figure 22: CLD highlighting road infrastructure and urban sprawl interdependencies



Note: The blue colour marks a reinforcing loop: more Investment in road infrastructure leads to more investments in the long run. Arrows with a '+' indicate an increasing effect, while red arrows with a '-' symbolise a decreasing effect. The double lines on an arrow mark a delay.
The figure presents a causal loop diagram that explores the dynamics between road infrastructure investment and regional travel patterns. It depicts how investments in road infrastructure increase road/highway capacity, subsequently influencing travel time, population size within an acceptable travel area, and the number of cars in the region. The diagram further illustrates the feedback loops affecting travel time, traffic volume, the attractiveness of driving a car, and congestion.

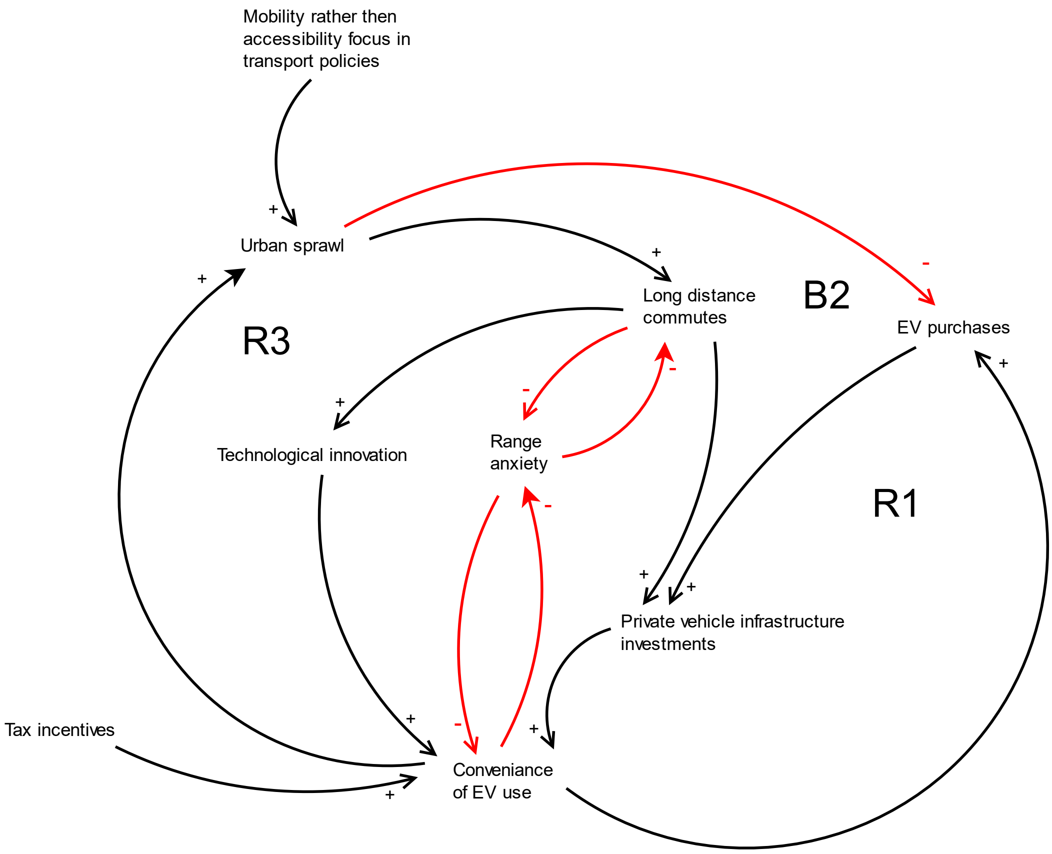
Source: (OECD, 2021).

4.2.4 Electric vehicles, environmental misperceptions, and range anxiety

Electric vehicles (EVs) have been positioned as key players in reshaping the mobility landscape (Hoerler et al., 2021). This transformation has been facilitated through various strategies, including tax incentives designed to encourage EV purchases and infrastructure investments that foster the convenience of car usage. However, the perception that EVs are zero-emission solutions has created a misconception that their usage carries no environmental impact. This misunderstanding can downplay the actual environmental footprint associated with this technology. While EVs play a role in the context of more sustainable mobility solutions, their overall environmental benefits are only modest (Litman, 2021a).

Nevertheless, there is a concerted effort to integrate EVs into the mobility landscape as a cleaner alternative. However, this push for EV adoption coexists with resistance fuelled by extended commutes resulting from urban sprawl. Longer travel distances increase range anxiety, a phenomenon where drivers worry about running out of battery charge before reaching their destination (Hoerler et al., 2021). These concerns can diminish the overall attractiveness of EVs as sustainable mobility solutions. This paradoxical situation highlights the complex interplay between mobility strategies, environmental considerations, and the societal challenges posed by urban development patterns (Hoerler et al., 2021).

Figure 23: Causal loop diagram highlighting urban sprawl and EV adoption interdependencies



Note: Arrows in black with a '+' symbolise an increasing effect, while red arrows with a '-' symbolise a decreasing effect. The figure illustrates a causal loop diagram depicting the complex interactions between electric vehicle (EV) adoption, transport policies, and urban sprawl. It shows how a focus on mobility rather than accessibility promotes urban sprawl and long-distance commutes, which increases range anxiety and affects EV purchases. The diagram highlights reinforcing loops (R1, R3) and balancing loops (B2), illustrating how factors like technological innovation, private vehicle infrastructure investments, and tax incentives interplay to influence the convenience of EV use and overall EV adoption rates.

Source: own sketch.

4.3 Discussion and conclusion

4.3.1 Embracing systemic approaches – integrating mobility and proximity

A prevailing challenge emerges in the pursuit of transforming mobility—a disproportionate emphasis on technological innovations and incremental enhancements, often at the expense of holistic, systemic change. Neglecting systemic approaches in transport policies leads to a narrow focus on isolated elements, such as targeting the combustion engine as the primary concern (OECD, 2021) coupling', places excessive emphasis on optimising only one aspect of the system (OECD, 2021). However, this approach overlooks the complex interactions of various elements within the system. It falls short of embracing sufficiency principles and considering measures to reduce travel distances. As a result, the deep-seated dependency on cars remains untouched. Such a strategy continues to focus on patterns of car-centric transportation that limit broader transformative changes that could lead to a more sustainable and equitable mobility system. In addition, electrification's advantages show signs of being offset by a rebound effect, marked by a rise in travel demand and larger vehicle sizes (Lamb et al., 2021). This highlights the complex nature of mobility dynamics and emphasises the need for a more comprehensive and integrated approach beyond isolated solutions.

Adopting more systemic approaches also involves discovering more significant synergies between urban and transport planning, traditionally regarded as distinct fields. Yet, it is becoming increasingly evident that urban settlement and mobility patterns are inherently interconnected and cannot be examined in isolation. This connection becomes crucial in accessibility, highlighting the importance of looking at both the convenience of travelling and the proximity of essential destinations. Achieving sustainable urban development is closely linked to how people move around the city. Additionally, it prompts questions about how public spaces are used, thereby facilitating the reallocation of space for various functions beyond private vehicle use (OECD, 2020). This holistic view is crucial for creating a system that improves accessibility by strengthening the link between urban planning and mobility. This approach redefines priorities and objectives and significantly emphasises societal well-being (Buckle et al., 2020).

Aligned with this perspective, the OECD has adopted a well-being lens to drive transformative change (OECD, 2019). This involves shifting away from focusing solely on GDP-centric objectives and prioritising well-being. This approach strives for a significant transformation within transport systems. Such a transformation aims to increase the proportion of shared and active trips in the overall transportation mix (Buckle et al., 2020). This transformative shift also challenges the idea that more consumption equals a better quality of life, reflected in recommended policy objectives that include reducing overall demand. Additionally, shifting towards systems thinking in policymaking involves moving away from short-term goals and narrow approaches to achieve more comprehensive and sustainable outcomes.

*4.3.2 Policy implications – **bridging mobility and accessibility***

In transportation, focusing on accessibility, measured by the ease of reaching crucial destinations, opens up a broader perspective that considers the impact of mobility choices on both the environment and social equality. By embracing accessibility as a primary measure and incorporating it into policy decisions, the potential drawbacks associated with increased regional mobility can be addressed. Central to this approach is the formulation of measures to alter the relative costs of different transportation modes, guided by vulnerability indicators to inform these choices. An accessibility-centred approach ensures a more comprehensive evaluation of transportation outcomes and offers a proactive approach to reducing inequalities and promoting sustainable practices over the long term.

Private vehicles are responsible for 75% of urban transportation emissions, and the trajectory indicates an anticipated growth in private vehicle ownership (ITF, 2021). It is crucial to recognise that this trajectory is not inevitable but rather a direct outcome of system design and policies that prioritise cars over alternative modes of transportation (Litman, 2021b). In promoting accessibility and well-being in transport systems, the concept of ‘scrapping schemes’ has gained prominence. These schemes, known as ‘cash-for-scrapping,’ can potentially incentivise sustainable transportation practices while addressing accessibility concerns (Buckle et al., 2020). They offer individuals incentives for using public transportation or purchasing a bicycle in exchange for retiring an older vehicle. For example, 71% of the Finnish car scrapping premium receivers in 2020 and 2021 used the money to purchase electrically assisted bicycles (Hytti et al., 2023). These strategies align with the broader effort to ensure transportation decisions that prioritise societal well-being and environmental sustainability.

In line with this perspective, the ‘complete streets’ concept, as advocated by Perk, (2015) presents an alternative approach to road space purpose and design. Rather than solely focusing on accelerating car travel, the shift lies in ensuring the safety and accessibility of streets for all users. This approach highlights the significance of accommodating diverse transportation modes and creating an inclusive urban environment that caters to pedestrians, cyclists, and public transportation users. Acknowledging the systemic interdependencies, transportation policies must navigate the complex interaction between mobility, land use, and public spaces to contribute to safe and sustainable urban landscapes.

In conclusion, this exploration has revealed the many systemic interdependencies within the transportation landscape. It has also highlighted the risks of unintended consequences from adopting one-sided perspectives that prioritise mobility alone. The challenges discussed – balancing economic growth and people's well-being, deciding between faster travel and land use, and handling urban sprawl and infrastructure dependencies – emphasise the need for a systemic approach in the context of the mobility system. In this context, the importance of accessibility emerges as a key measure that can guide policy decisions and mitigate the downsides of an exclusive emphasis on increased mobility. By connecting accessibility with mobility and considering vulnerability indicators, a transportation system can be shaped to cater to a broader range of societal needs.

5 Housing and Infrastructure - The Case of Renovation

by Ullrich Lorenz and Jens Konrad

5.1 Introduction

In 2020, energy use in buildings accounted for 42% of the EU's total energy consumption, 35% of energy-related greenhouse gas emissions, and a significant share of air pollutant emissions (EEA, 2021, 2022c). Reducing building energy consumption and decarbonising the heating, cooling, and electricity sectors are critical to achieving the EU's energy, climate, and air quality targets (EEA, 2023c).

The European Energy Efficiency Platform (E3P)[5] defines energy renovation as a broad term encompassing various building interventions in the energy and electricity sectors. These interventions range from modernisation, retrofitting, restoration, rehabilitation, maintenance, repairs, and routine upgrades. Often, energy renovation is carried out behind the scenes of these actions, each resulting in different levels of energy savings.

The Buildings Performance Institute Europe[6] suggests that minor renovations correspond to 0-30% of final energy savings, moderate renovations range from 30-60%, deep renovations achieve 60-90% savings, and renovations meeting nearly Zero-Energy Building (nZEB) standards go beyond 90% (Sibileau, 2021).

Similarly, the Global Buildings Performance Network states that deep renovations can lead to improvements of at least 75% in energy consumption or result in primary energy consumption after renovation of less than 60 kWh/m² per year, based on cross-regional analysis (Bindu, 2024).

An energy renovation can be categorised based on the type of intervention measures implemented in the building. These measures include:

- **Building envelope**: Insulation of external walls, roofs, lofts, and floors, replacement of windows and doors, draught-proofing, installation of solar shading systems, use of natural ventilation techniques, passive solar heating or cooling techniques.
- **Technical building systems**: Replacing inefficient boilers with condensing gas boilers or heat pumps, improving mechanical ventilation, air-conditioning, lighting, and auxiliary systems; installing heat recovery systems; enhancing emission/distribution systems of technical systems (e.g., pipework insulation), implementing building controls, integrating micro-cogeneration systems, photovoltaic systems, micro wind generation systems, micro-hydro systems, Energy-efficient and smart appliances.

The 'EU's renovation wave' aims to at least double the annual energy renovation rate of residential and non-residential buildings by 2030 and initiate deep energy renovations that could reduce buildings' energy consumption by at least 60% (EEA, 2023a).

Nonetheless, there is not necessarily a direct cause-impact-relation between the energy renovation of houses and the direct energy saving and, as a related effect, the reduced GHG emissions. Energy renovations require a more systemic perspective and the inclusion of economic, social and political factors.

[5] https://e3p.jrc.ec.europa.eu
[6] https://www.bpie.eu

5.2 Systemic properties in the case of energy renovation

5.2.1 Rebound effects

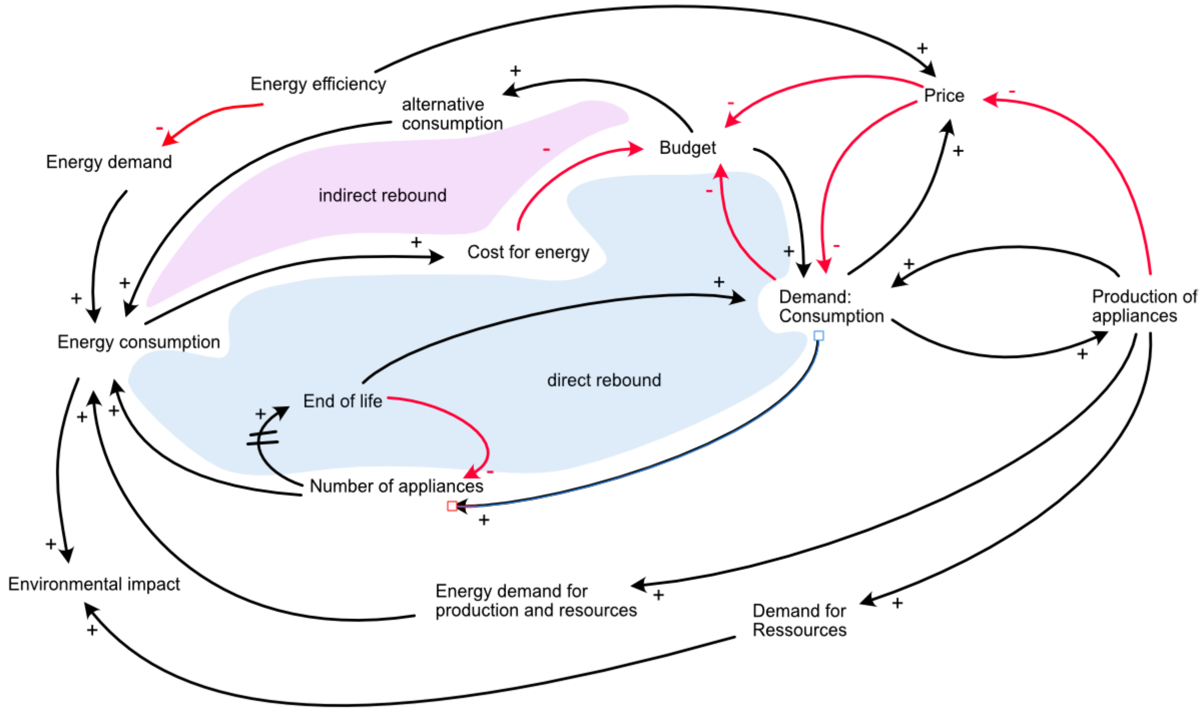
As outlined in section 1.3.2, the rebound effect is described as the loss in expected gains from efficiency-increasing technology caused by a behavioural change (Berkhout et al., 2000). Research has shown that technological improvements may lead to lower energy savings than expected due to the associated changes in consumer behaviour. The mechanism underlying this behavioural change relates to neoclassical economic theory: when the efficiency of a particular energy service is improved, households realise a reduction in the effective price of that service. Consequently, improved energy efficiency leads to an increase in energy service demand. This implicit price mechanism generates a so-called rebound effect, as it partially offsets the initial efficiency gains.

The direct rebound effect refers to the phenomenon where, e.g., energy efficiency improvements result in an overall increase in energy usage. The saved money results in a higher energy consumption or an extended use of energy-consuming activities, ultimately offsetting a portion of the initial energy savings achieved through efficiency improvements. The indirect rebound effect occurs when energy efficiency gains lead to savings (time, money) that might be used in other domains and create an adverse effect.

One should expect both types of rebound effects in the building sector. The energetic renovation leads to less energy consumption, which sets off capital for additional investments. This would refer to the indirect rebound effect. However, especially in the building sector, one must include the material flows in the calculation, the embedded energy into the resources, and the energy mix used for heating/cooling, illumination and ventilation.

For example, households' adoption of solar panels has increased significantly, mainly intending to reduce electricity bills. Solar photovoltaic (PV) systems allow households to generate their renewable energy and enjoy reduced marginal costs. A recent study (Aydın et al., 2023) utilising high-frequency data on household electricity consumption and production indicates a rebound effect of 7.7 per cent. This effect demonstrates that the reduced electricity consumption from solar panels may be partially compensated by increased overall energy demand from other sources. The identified rebound effect is robust and consistent across various samples and model specifications. One notable finding from the study is that households tend to shift their electricity consumption to periods when solar electricity production is higher. By aligning their demand with high solar irradiance periods, households seek to maximise the use and benefits associated with their PV systems.

Figure 24: Generic CLD about direct and indirect rebound effect



Note: The figure illustrates a complex causal loop diagram highlighting the feedback loops between energy efficiency, consumption, and rebound effects. The light blue shaded area represents the direct rebound effect, where improvements in energy efficiency reduce energy costs and subsequently lead to increased energy consumption as users take advantage of lower operational costs. Conversely, the rose-shaded area signifies the indirect rebound effect, where savings from energy efficiency are redirected towards alternative consumptions, increasing overall energy demand indirectly. Additionally, the diagram shows the broader impacts on budget allocation, the production and demand for appliances, and the associated environmental impacts, revealing the intricate network of factors influencing energy consumption.

Source: Ullrich Lorenz, 2024, own sketched, unpublished

The study highlights the heterogeneity of the rebound effect. It is observed that rebound effects vary across different seasons, primarily influenced by variations in solar irradiance levels. Seasons characterised by higher sunlight input exhibit a higher rebound effect, suggesting that households may be more inclined to increase their overall energy consumption during abundant solar power generation (Aydın et al., 2023).

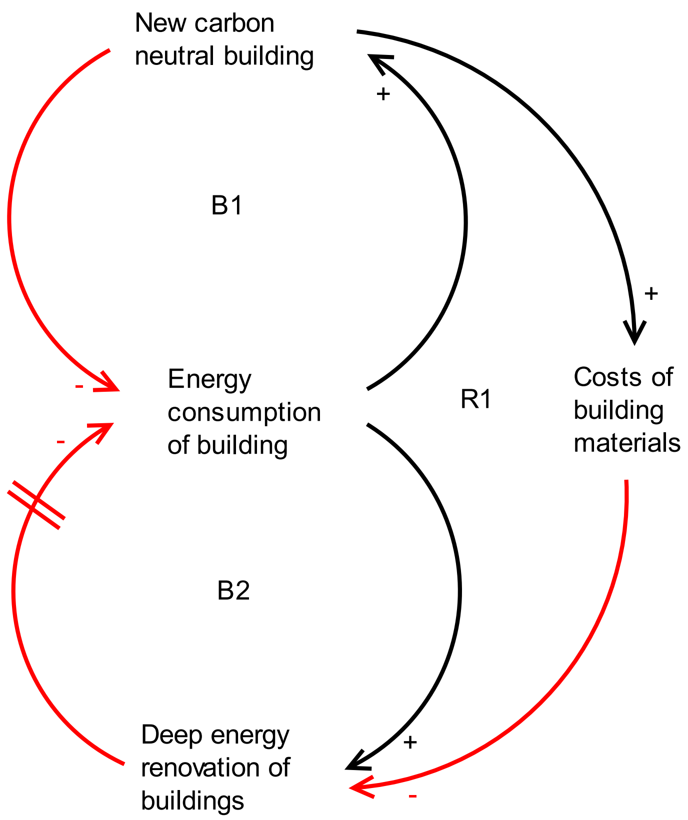
5.2.2 From energy to material demands - Shifting the Burden, Growth and Underinvestment, Limits to Growth

Reducing energy consumption for buildings relates to renovating existing buildings and constructing new carbon-neutral buildings (EEA, 2022a). The higher the number of new construction projects, the higher the demand for building materials, which leads to rising costs. This, in return, could ultimately lead to less energy renovation as the prices for homeowners are too high with too much financial risk involved. Costs of building materials are, therefore, a crucial and, at the same time, limiting factor for both new buildings and renovation (Kurmayer, 2023; Huber et al., 2022).

Consequently, renovation projects constitute only 54% of total building production in 2022 (48% in 2008 (van Sante, 2023)). This trend currently differs from the goal to double the renovation rate by 2030. Also, over the last 11 years, the development of the house price index (HPI) has enormously increased in Europe and the European Union (EU), making the ownership of real estate financially attractive (Eurostat, 2023b). The implications were a stronger focus on new house building and house ownership as investment and capital growth opportunities instead of energy renovations.

To break this cycle, one countermeasure for the **Shifting the Burden** archetypes is to focus more on the fundamental solution, which is the deep energy renovation, instead of quick fix responses. Over the last 20 years, much emphasis has been given to new buildings as a solution to cut energy and emissions from buildings. As an unintended consequence, the cost of house improvements has increased, surpassing the inflation rate in the European Union (van Sante, 2023). In addition, energy prices have increased even more, making energy efficiency measures more financially beneficial than in the past. Inflation and a sinking HPI also make it more difficult for homeowners to sell their houses, which leads to an increasing enhancement of existing living spaces to meet changing housing needs. This could lead to an increase or sustain the demand for renovation, which is also affected by other factors such as financing issues, interest rates, or changes in the legal framework.

Figure 25: Causal loop diagram showing the archetype 'Shifting the Burden'



Note: The figure depicts a causal loop diagram that illustrates the relationship between carbon-neutral building practices, renovation efforts, and energy consumption. The diagram highlights two balancing loops (B1 and B2) and one reinforcing loop (R1). Loop B1 shows how the construction of new carbon-neutral buildings can reduce energy consumption, while loop B2 demonstrates how deep energy renovation of existing buildings also contributes to lower energy consumption. The reinforcing loop R1 indicates that as energy consumption decreases, the demand for building materials may increase, leading to higher costs. This diagram underscores the interplay between building practices, material costs, and the overall energy efficiency of buildings.

Source: own sketch.

Research shows that it becomes evident that focusing on renovation actions that aim to directly increase buildings' lifespans has the most significant potential for both material and GHG savings. This is because increasing lifespans are translated into lower demand for new construction, which is very material and GHG intensive. Increasing the intensity of use also brings substantial CO2 savings (EEA, 2023a).

As illustrated in the previous paragraph, both ‘energy’ and ‘non-energy’ renovation require materials, which underlay intense price volatility in recent years. Therefore, it is necessary to consider how to simultaneously minimise emissions and costs for homeowners.

Adopting circular economy principles in building renovation can reduce the use of materials in existing buildings and minimise emissions embedded in building materials. Primary building materials like wood, stone, metal, or concrete are extracted from nature. Secondary building materials are recycled or reused from other sources, such as demolition waste or industrial by-products. Building-emissions are the greenhouse gases emitted from the operation of buildings, such as heating, cooling or lighting.

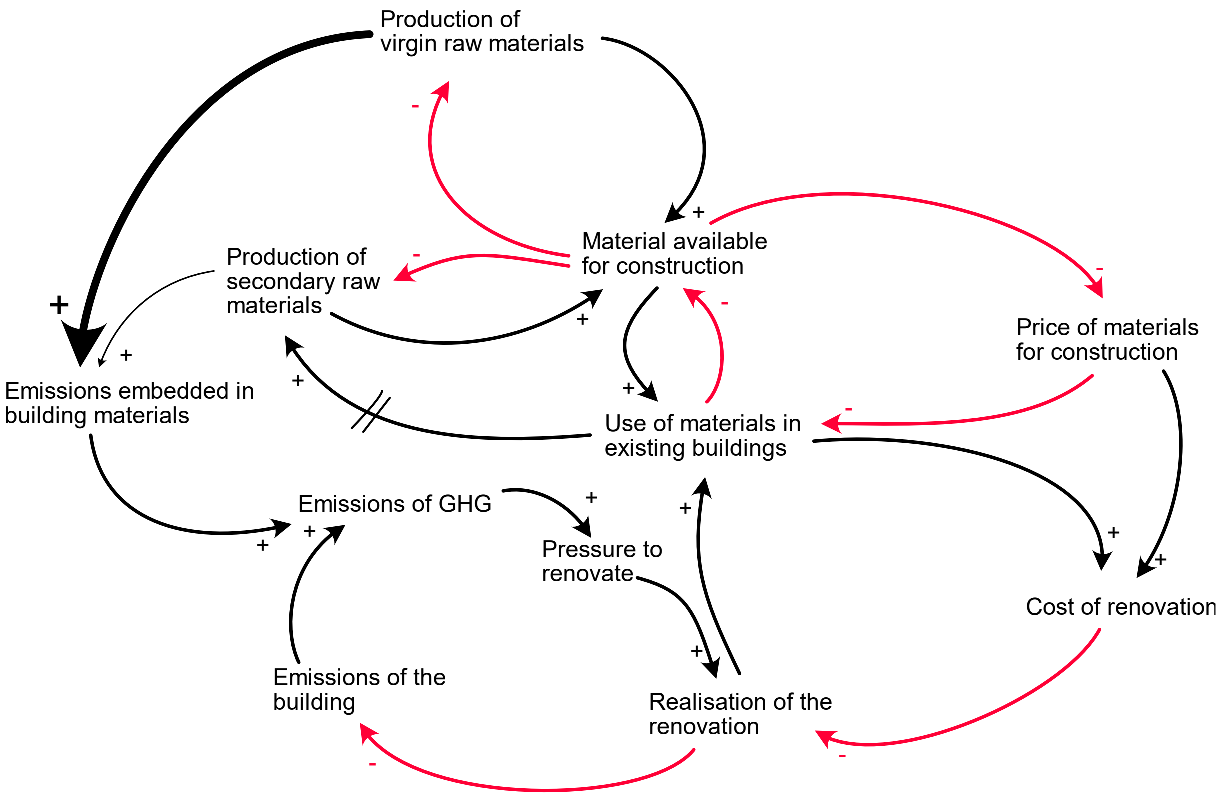
Using prefabricated facades (including cladding and insulation) saves around 25% of material compared with non-prefabricated options (EEA, 2022b). Circular economy-based renovation approaches can help reduce embedded greenhouse gas emissions by avoiding or delaying new materials in buildings.

Conversely, using virgin raw materials requires less time, leading to higher emissions and higher renovation costs due to more material usage. The Growth and underinvestment archetype can characterise this, whereas raw materials for an achievable price and emissions are limiting factors for renovating and building. Considering the high average lifespan of buildings, renovating with reusable materials constitutes a vital lock-in effect, influencing the goal of more energy-efficient buildings (EEA, 2022a).

One way to apply this archetype to the renovation of buildings is to consider the trade-off between the embedded emissions in primary and secondary building materials and the building emissions. Embedded emissions are the greenhouse gases emitted during the extraction, production, transportation, and installation of building materials. Primary building materials tend to have higher embedded emissions than secondary building materials because they require more energy and resources to obtain and process. However, primary building materials may also have higher performance and durability than secondary building materials, which can reduce the building emissions over the lifespan of the building. For example, a new window made of primary materials may have higher embedded emissions than a reused window made of secondary materials, but it may also have better insulation and ventilation properties, which can lower the heating and cooling needs of the building.

Therefore, one must balance the short-term and long-term impacts of choosing different building materials when renovating a building. If one chooses to use more primary building materials, one may increase the embedded emissions in the renovation process and decrease the building emissions in the operation phase. If one chooses to use more secondary building materials, one may reduce the embedded emissions in the renovation process and increase the building emissions in the operation phase. The optimal choice depends on various factors, such as the availability and cost of different materials, the design and function of the building, the local climate and energy sources.

Figure 26: Growth and underinvestment archetype for the renovation case



Note: The figure illustrates a causal loop diagram that explores the interactions between the production and use of building materials, the emissions embedded in these materials, and their impact on greenhouse gas (GHG) emissions from buildings. It highlights how the production of virgin raw materials and secondary raw materials affects the overall material availability for construction and the associated emissions. The diagram emphasises the pressure to renovate existing buildings due to emissions, which in turn influences the use of materials and the realisation of renovation projects, affecting the overall cost and price of construction materials. This system leads to multiple feedback loops where increased material use and renovation efforts can drive emissions, showcasing the complex interplay between construction activities and environmental impacts.

Source: own sketch

The problem arises when there is underinvestment or lack of renewal in the primary or secondary building materials. For example, suppose there is insufficient investment in sustainable extraction and production of primary building materials, such as using renewable energy sources or minimising waste and pollution. In that case, the environmental impact of using primary building materials will be too high and unsustainable. On the other hand, if there is not enough investment in recycling and reusing secondary building materials, such as developing efficient collection and sorting systems or ensuring quality and safety standards, then the supply and performance of secondary building materials will be too low and unreliable. In either case, the system's growth will be constrained by the scarcity or inadequacy of an essential resource that is underinvested or not renewed.

5.2.3 Fixes that fail – The case of heat pumps

The 'Fixes That Fail" systemic archetype can be applied to the renovation of buildings in several ways. This archetype is used to describe and analyse a situation where a fix, effective in the short-term, creates side effects for the system's long-term behaviour and may result in the need for even more fixes.

In the context of building renovation, a typical ‘Fixes That Fail” scenario might look like this:

- Problem Symptom: A building is not energy-efficient, leading to high energy costs and poor environmental performance.
- Short-Term Fix: The building owner decides to install a new heating system (heat pump) that is more energy-efficient. This seems to solve the problem in the short term as the energy costs decrease.
- Unintended Consequences: However, the new heating system might require a specific type of insulation to function optimally. If the building does not have this insulation, the heating system might not perform as expected, and the energy costs might increase again after some time. This forms a feedback loop that either worsens the original problem or creates a related one.
- Long-Term Failure: The building owner might then decide to install the required insulation, which could lead to other unforeseen problems, such as moisture build-up, leading to mould growth. This could then necessitate further fixes, leading to a cycle of fixes that fail.

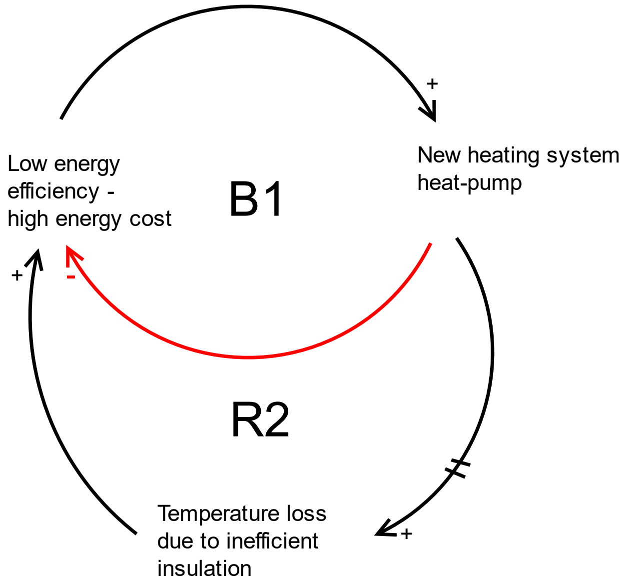
To avoid falling into this cycle, it is necessary to consider the long-term impacts of any fixes and to aim for comprehensive solutions that address the root causes of the problem.

Williams and Thomson (2023) have examined the context of heat pumps and the role of isolation in the UK. One of their results is that:

> *“*The space heating electricity demand is seven times higher than the case with good insulation, and heat pumps and resistive heating dominates all electricity demand.(...) *The effectiveness and economic sense of comprehensive installation of insulation and heat pumps has been shown.*
>
> *As well as making net zero a practical possibility for the UK, insulation has immediate benefits for almost all its citizens: warmer living spaces and reduced energy bills.*”

This context can be nicely captured in a CLD, as shown in Figure 27.

Figure 27: CLD showing shifting the burden concerning heating systems/heat pump



Note: The figure presents a causal loop diagram that depicts the relationship between energy efficiency, heating systems, and insulation quality. The balancing loop (B1) demonstrates how low energy efficiency and high energy costs can motivate the installation of new energy-efficient heating systems, such as heat pumps. Meanwhile, the reinforcing loop (R2) shows how temperature loss due to inefficient insulation exacerbates low energy efficiency, increasing energy costs and the necessity for advanced heating solutions. Although not directly shown in this particular diagram, similar systems often include concepts like the direct rebound effect, where improvements in energy efficiency might lead to increased energy use, and the indirect rebound effect, where savings from energy efficiency might be spent on other energy-consuming activities or goods.

Source: CLD-sketch: own elaboration, reflecting insights by (Williams and Thomson, 2023).

Rising temperatures, an ageing population, and urbanisation rapidly increase the demand for building cooling. The EU's heating and cooling needs in 2020 accounted for half of its total gross final energy consumption (Eurostat, 2023a). Despite many EU and national efforts to lower heating and cooling needs, this significant share has persisted for over a decade. Deep energy renovation of buildings can reduce the amount of energy used for cooling while decreasing greenhouse gas emissions (EEA, 2023c). A deep energy renovation ensures high-quality indoor comfort while minimising energy use and air emissions. The cooling system choice is made coherently with the insulation and ventilation. In particular, insulation significantly impacts the performance of an air-conditioning system, as it helps to keep hot and cold air from entering or escaping, thus reducing energy costs and maintaining optimal temperature levels. Without adequate insulation, a cooling and heating system unit will be forced to work harder than necessary to maintain desired temperatures. This extra strain can lead to higher utility bills and increased wear and tear on the system itself, resulting in more frequent repairs being needed over time.

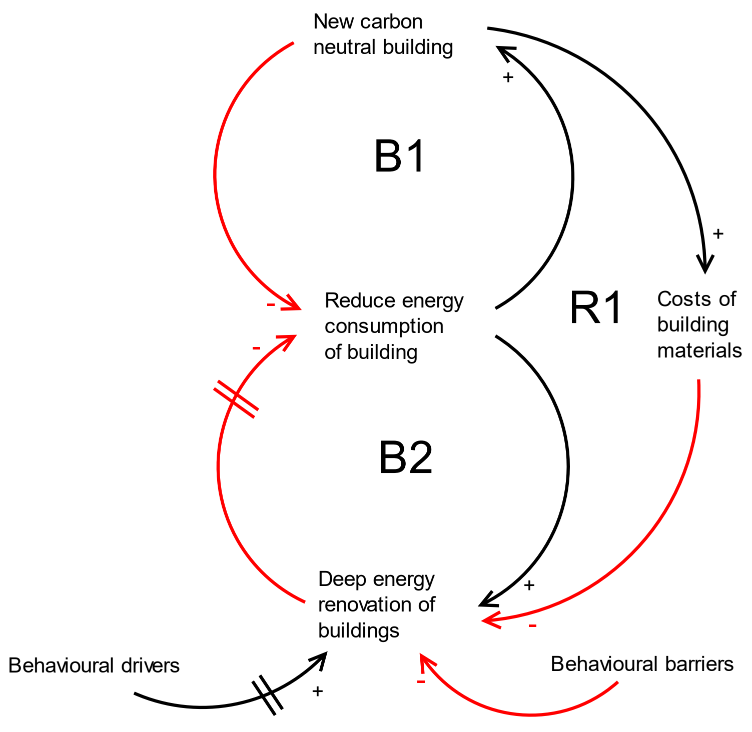
This systemic mechanism can be described with the Fixes that Fail archetype for buildings without deep energy renovation. Undesired temperatures in buildings lead to more heating/cooling systems (heat pumps), which lower or increase the temperature in the short term. However, the inefficient insulation is causing energy and temperature loss in the building, ultimately leading to temperature alterations and the need for more cooling at the aggregated scale (Efficiency Heating & Cooling, 2023). In addition, the short-term buying of cheap cooling systems in response to sudden heat waves is causing maladaptation of energy-inefficient systems.

Investing in high-insulation materials is more cost-effective than investing in expensive cooling technologies. According to the EU Climate Target Plan assessment, policy measures to improve the thermal insulation of buildings could reduce cooling needs by between 28% and 31% in the residential sector and 7% and 9% in services, compared with 2005 (EC, 2022). As a downside, insulation may increase demand for materials and associated embedded CO2 emissions (EEA, 2022a), but decrease demand for active cooling during building use.

5.2.4 Behavioural Factors Influencing Renovation

Besides the described external factors, deciding whether to invest in improving the energy efficiency of residential buildings is the starting point in the homeowner's decision, which is often complex and involves several stages and multiple barriers. First, a growing body of evidence suggests that behaviour, lifestyle and culture significantly impact energy demand in buildings and, thus, the homeowner's understanding of why energy renovation is needed in the first place. Secondly, the search for information and renovation alternatives is highly influenced by the social environment of homeowners, such as neighbours, which also affects social practices and appropriate behaviours. Thirdly, socio-psychological factors determine the cost-benefit relationship and prevent carrying out renovations. For example, one of the main barriers is the perceived level of effort and disruption that renovation can cause in the everyday lives of homeowners and residents, also called the 'hassle factor'. Factors here are lack of time or the breaking of daily routines due to construction work (van Bavel, 2020; Della Valle and Bertoldi, 2021). On the other side, monetary factors are access to loans and money and the financial uncertainties connected with the outcome of the renovation (EEA, 2023a).

Figure 28: CLD of the reduction of energy consumption of buildings (Shifting the burden)



Note: The figure presents a causal loop diagram illustrating the interplay between carbon-neutral building practices, energy consumption, and behavioural factors. The balancing loop (B1) shows how constructing new carbon-neutral buildings reduces energy consumption. The reinforcing loop (R1) captures the effect of building material costs on this process. Loop B2 highlights the impact of deep energy renovations on reducing energy consumption and the influence of behavioural drivers and barriers. Though not explicitly shown in this diagram, similar systems often involve direct rebound effects (light blue), where increased efficiency may inadvertently lead to higher energy use, and indirect rebound effects (rose), where energy cost savings are redirected to other energy-consuming activities.

Source: own sketch

These examples show that behavioural barriers are essential and can alter and change the diffusion of renovation. To counter these rebounds, the literature suggests promoting pro-environmental behaviours that raise awareness about home renovation's positive drivers and effects. Primarily, the improved living conditions and reduced energy costs are among the main incentives for homeowners. However, since the financial return on energy efficiency investments is often delayed, calculating the costs and benefits is an intricate task that might stop owners from investing (EEA, 2023a). In addition, reducing the 'hassle factor" is also crucial by providing one-shop concepts for homeowners to minimise time efforts.

5.3 Reflection

As illustrated in this report, the EU's goal to double the annual energy renovation rate of residential and non-residential buildings by 2030 is highly influenced by systemic properties. One of the most important factors is the reduction of costs by policy intervention or new construction principles, which impacts material usage and constitutes one of the main barriers for homeowners to start with renovation. The communication of long-term benefits has to balance out short-term behavioural barriers to motivate investments. One option is financial incentives, potentially supporting the transition during high inflation and interest rates. Besides, the choice of technologies and integration of circular economy principles are long-term beneficial elements to achieve this goal. Considering the long lifespans of buildings, promoting these elements is crucial to avoid adverse lock-in effects by using inefficient materials or heating/cooling systems in the context of changing climate and higher energy prices.

6 General Reflections and Recommendations - The use of system thinking in policy analysis

System thinking is a holistic approach to policy analysis that considers the interrelationships and feedback loops among different elements of a complex system. It can help identify the root causes of problems, the unintended consequences of policies, and the leverage points for effective interventions.

Sustainability topics like the transition to vegan food, the use of hydrogen energy, sustainable mobility and energetic optimisations in the housing area are systemic issues where system thinking helps to understand specific patterns of interaction of multiple stakeholders, trade-offs, uncertainties and nonlinearities that might challenge conventional policy making.

System archetypes can help diagnose the structure and dynamics of a system, reveal the underlying mental models and assumptions, and suggest potential solutions. However, an archetype's pure form (focus on one, two or three characteristic loops) might fall short of grasping the full complexity of the respective case. To overcome this, larger CLDs might be necessary, or even quantification might be done with the help of the System Dynamics approach.

System dynamics is a method of modelling and simulating the behaviour of complex systems over time. It can help understand the feedback loops, delays, and nonlinearities characterising complex systems over time. However, even system dynamics has some limitations when it comes to capturing the properties of complex adaptive systems, which are systems that can learn, evolve, and self-organize in response to their environment. Some of these properties are, according to :

- **Emergence:** Complex adaptive systems can exhibit emergent phenomena that arise from the interactions of their components but are not predictable or reducible to the properties of the components. System dynamics models tend to focus on the aggregate behaviour of the system and may not capture the emergent patterns resulting from the agents' diversity and heterogeneity.
- **Adaptation:** Complex adaptive systems can adapt to changing conditions by modifying their structure, behaviour, or rules. System dynamics models assume that the structure and parameters of the system are fixed or change according to predefined functions and may not account for the adaptive capacity of the agents or the system as a whole.
- **Co-evolution:** Complex adaptive systems can co-evolve with other systems or their environment, creating new feedback loops and interdependencies. System dynamics models often isolate the system from its context and may not reflect the co-evolutionary dynamics that shape the system and its environment over time.

Nonetheless, system thinking is an improvement compared to linear and deterministic thinking because it allows us to understand the complexity and interdependence of our world. Linear and deterministic thinking assumes that problems can be solved by finding and fixing their direct causes without considering the broader implications, feedback loops, ambiguities or trade-offs and synergies that may arise. System thinking recognises that problems are often embedded in larger systems with multiple dimensions, actors, and interactions.

The archetypes, however, are specifically helpful, as they help take different perspectives on the case studies. In this sense, they help to explore the topics, challenge one's mindsets and mental models and allow for testing what-if questions. If a combination of feedback loops associated with delays creates oscillation, this is already an insight that should be considered when designing policy responses.

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