Making stakeholder knowledge on SDG interaction explicit – a Causal Loop Diagram (CLD) approach

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Abstract

This study explores stakeholder knowledge on interactions between Sustainable Development Goals (SDGs) through participatory system mapping and Causal Loop Diagrams (CLDs). We focus on SDG1/10 (reduce poverty/reduce inequality), SDG8 (decent work and economic growth), and SDG13 (climate action), aiming to make implicit mental models of SDG interactions explicit and compare them with the iSDG-AT model for Austria. A participatory workshop involving diverse stakeholders was conducted to elicit variables and dynamics underpinning five key indicators: energy poverty (SDG1/10), real GDP per capita (SDG8), work satisfaction (SDG8), total greenhouse gas (GHG) emissions (SDG13), and GHG emissions from the building sector (SDG13). The CLDs developed by the participants were digitalized, refined and connected to highlight feedback loops, synergies, and trade-offs. Results indicate that household income acts as a central variable linking multiple SDGs, with significant synergies between economic and social indicators but notable trade-offs with environmental outcomes. This paper provides insights into integrating stakeholder knowledge to support more informed policy decisions. It also establishes a shared system understanding to guide further research within the ACRP-funded SDGVisionPath project.

1 Introduction

In 2015, two important international agreements were adopted: (1) The 2030 Agenda and its 17 Sustainable Development Goals (SDGs) and (2) the Paris Agreement, aiming to keep global warming below 1.5°C compared to the pre-industrial era (UNFCCC 2015). In 2016, a corresponding decision was made in Austria by the Council of Ministers to implement the 2030 Agenda (Bundeskanzleramt 2017). Despite significant efforts towards the SDGs and combat climate change, countries are not on track with achieving the set targets (Alvaredo et al., 2018; Haberl et al., 2020a; Otero et al., 2020; Steffen et al., 2018; Wiedenhofer et al., 2020). Following UN level indicators, Austria currently has an SDG Index Score of 82.5 and a score of 77.2 when considering EU level indicators (Sachs et al., 2024). This results, among other reasons, from the many positive and negative interactions between the SDG entities, i.e. targets, goals and indicators. On the one hand, the complex interactions pose a specific challenge and on the other hand, focusing on the interactions and formulating integrated approaches towards the targets provides an opportunity to accelerate progress (Pradhan et al., 2024).

To seize the opportunity and enable a transformation towards a more sustainable system, it is important to identify and implement measures and investments that enable synergies (i.e. simultaneous achievement of several goals) and avoid trade-offs. Researchers have made numerous efforts to capture interactions between the SDGs and thus support decision-makers in their choice of measures (Allen et al., 2016; Bennich et al., 2020; Breuer et al., 2019; Horvath et al., 2022; Miola et al., 2019; Nilsson et al., 2016; Pedercini et al., 2020a, 2020b; Pradhan et al., 2024). As the SDGs are a global framework that needs to be implemented at the national level, country specific circumstances need to be considered when modelling potential future pathways of the SDGs.

A commonly applied approach to aid policy design and decision-making is to apply quantitative models that can simulate the interaction of SDGs and the impacts of socio-economic pathways on SDG indicators. Recently, a lot of progress has been made in this field (Allen et al., 2016; Doelman et al., 2022; Pedercini et al., 2019; Soergel et al., 2021; Spittler, 2019; van Soest et al., 2019), and efforts are underway to apply such an analysis with the System Dynamics based iSDG model (Allen et al., 2024; Li et al., 2024; Pedercini et al., 2018) for Austria (Spittler and Kirchner, 2022). However, models will never be able to capture all interactions and, necessarily, turn a blind eye to certain aspects. Hence, there are approaches that aim to utilize the implicit knowledge of stakeholders and experts to improve our knowledge on sustainability issues (Hirsch Hadorn et al., 2010), such as SDG interactions. A very promising approach for this is the use of system mapping methods (Hanger-Kopp et al., 2024), specifically Causal Loop Diagrams (CLDs) (Perrone et al., 2020; Sterman, 2000), which rank high in their ability to identify SDG interactions and as a method of collaboration (Horvath et al., 2022).

We aim to apply CLDs in the context of the 2030 Agenda in Austria. To not overburden stakeholders and experts we focus on the interaction of four (out of 17) SDGs that are considered to be at odds in many instances (Campagnolo and Davide, 2019; Gagnebin et al., 2019; Wiedenhofer et al., 2020): SDG13 (climate action), SDG8 (decent work and economic growth) and SDG1/10 (no poverty/reduced inequality). Our first objective is to make the implicit mental models (Jungermann and Thüring, 1987) that stakeholders and experts have on SDG interactions explicit by applying CLDs. Our second objective is to contrast theses CLDs with the iSDG model structure in order to show how the current iSDG-AT model can or cannot support stakeholders' perspectives and their decision-making for achieving the SDGs. Hence, we address the following research questions:

- How do stakeholders conceptualize the dynamics that drive SDG1/10, SDG8 and SDG13?

- Can the iSDG-AT reflect the stakeholders' understanding of the SDGs and their interactions?

In the remaining part of the paper we will present, in section 2, the materials and methods we used to elicit stakeholders understanding of the relevant dynamics and relations between the SDGs and provide a brief description of the iSDG-AT model against which it is contrasted. The results are presented in section 3 and discussed, with a focus on a comparison with the iSDG-AT model structure, in section 4. We finish with conclusions and outlook for further research (section 5).

This study is conducted as part of the ACRP-funded SDGVisionPath project, which seeks to apply a stakeholder-driven, holistic systems-thinking approach for Austria. The project focuses on the interactions between SDG13 (climate action), SDG8 (decent work and economic growth), and SDG1/10 (no poverty/reduced inequality) to ultimately derive policy recommendations for achieving these goals. The results of this study establish a shared systems understanding among participants and researchers, forming the foundation for subsequent research steps.

2 Material and method

Based on the understanding that each of the SDGs is part of a system and together they represent important parts of our socio-economic and environmental systems, we decided to root our methodology in Systems Thinking, more explicitly relying on different tools of System Dynamics, which provides a framework to comprehend all three domains of sustainability (Sterman, 2000; United Nations, 2015). System Dynamics offers quantitative and qualitative methods for comprehending and investigating complex systems (Sterman, 2000). For our research we apply the qualitative tool of Causal Loop Diagrams (CLDs) and refer to the quantitative System Dynamics iSDG-AT model, which are both explained below.

2.1 Participatory system mapping and Causal Loop Diagrams (CLDs)

System dynamics does not only offer a set of tools to develop models or model structures for modelers and researchers by themselves, but the tools are well suited for and should ideally be used in a participatory setting (Barbrook-Johnson and Penn, 2022; Videira et al., 2010). Hence, this enables expert as well as stakeholder engagement in the model development process. Different frameworks and methods for participatory modelling exist, for example group model building (Vennix, 1996) or community-based system dynamics (Hovmand, 2013). These two examples, among others, provide a framework on how to conduct participatory modelling processes that start with a problem definition, cover computational model development and lead to scenario analysis, in which stakeholders are involved in each step of the process. Of course, more approaches and combinations of them can be found in practice (Gray et al., 2017; Hanger-Kopp et al., 2024; Meinherz and Videira, 2018; Tourais and Videira, 2021). Additionally, it is also possible to employ individual tools of System Dynamics in a participatory setting to support problem or system understanding and extract stakeholder knowledge without following each step of an entire group model building process.

One tool that is well suited for participatory expert and stakeholder engagement is that of Causal Loop Diagrams (CLDs) creating CLDs (Olivar-Tost et al., 2020), especially in comparison to other methods available for analyzing SDG interactions (Horvath et al., 2022). It is well suited for extracting knowledge on systems' dynamics from experts. Due to time and resource constraints, only a subset of indicators that are relevant to the broader topic of each SDG and at the same time are dynamically linked, could be investigated in this process. The selected indicators for which the dynamic structures were elaborated with stakeholders were: i) Energy poverty (SDG1/10); ii) Real GDP per capita (SDG8); iii) Work satisfaction (SDG8); iv) Greenhouse gas emissions (SDG13); and v) Greenhouse gas emissions for the building sector (SDG13). Although these are not explicit SDG indicators, we decided to take advantage of the vagueness of the SDGs that leaves room for interpretation and manoeuvre in stakeholder processes (Saiz and Donald, 2017, p. 1031). Dynamics relevant to all five of these indicators and thereby the four selected SDGs were elicited with stakeholders. For a detailed description of the mapping process see the next section.

2.2 The participatory development of CLDs

The following tasks, in chronological order, were necessary to develop the CLDs for the SDGs 1/10, 8 and 13 in a participatory setting:

1. Stakeholder mapping and identification; sending out workshop invitations,
2. Preparation of reference modes for the indicators,
3. Conduct a trial workshop,
4. Carry out a preliminary survey on the most relevant variables,
5. Conduct the workshop,

6. Post-Process of workshop results,

2.2.1 Stakeholder mapping and identification

We invited 65 potential stakeholders to the workshop, of whom 25 confirmed their participation and 21 attended and actively engaged. To facilitate discussions, we grouped the stakeholders based on their expertise and organized them into five tables aligned with the SDG indicators, with approximately 4 to 6 participants per table. The workshop included a diverse group of stakeholders, representing various sectors: administration (7 participants), academia (6), NGOs (4), social partnership institutions (e.g., Chamber of Labour; 2), and business representatives (2). Detailed information about the stakeholders can be found in Table 1 in Annex 8.2

2.2.2 Preparing reference modes for the indicators

The research team preselected five indicators and their reference modes for the workshop. A reference mode represents the past development of an indicator. The indicators were chosen based on the expertise of the researchers responsible for their respective SDGs and the availability of relevant data. The selected indicators were:

(1) Energy poverty (SDG1/10),
(2) Real gross domestic product (GDP) per capita (SDG8),
(3) Work satisfaction (SDG8),
(4) Total greenhouse gas emissions (SDG13),
(5) Greenhouse gas emissions in the building sector (SDG13).

Each table received a visually prepared handout to facilitate discussions (see Figure 7 in Annex 8.1.1). English translation of these indicators is provided in Figure 8 to Figure 12 in Annex 8.1.1.

2.2.3 Trial Workshop

Approximately one month before the stakeholder workshop, we conducted a trial workshop with students and colleagues to evaluate the suitability of the agenda, script, and methods. This exercise provided valuable feedback on facilitation techniques, including identifying when and where support might be needed, how to effectively present technical concepts, what to include (and omit) in the introduction, and the optimal number of participants per table. Additionally, it highlighted potential challenges that could arise during the workshop. This feedback significantly enhanced the final scenario script and facilitation strategies.

2.2.4 Survey on variables

Around the time of the trial workshop, we distributed an online survey asking stakeholders to identify drivers related to the SDG indicators. Stakeholders received questions corresponding to their area of expertise, focusing on the indicators for SDG1/10, SDG8, or SDG13 (see 8.1.2). In total, we collected over 20 variables per indicator, amounting to 143 variables overall. These variables were then processed, clustered and, if necessary, renamed to meet the criteria of the CLD method. For example, variables were formatted as nouns, referred to quantities that could vary over time, avoided directional implications, and did not reference time itself. The finalized variables were printed on small cards, which stakeholders used during the CLD process in the workshop.

2.2.5 Workshop

A finalized agenda script was developed and agreed upon by the research team for the workshop (see Table 2 in Annex 8.2). Each table was assigned at least one facilitator from the research team to support participants with the tasks. In total, 8 people assisted in conducting this workshop.

The workshop began with a brief introduction to the project and the CLD method. For the first task, participants reviewed the variables collected from the survey and added new ones if necessary. They then clustered the variables into meaningful groups. Following a short break, participants worked on identifying linkages between the variables. After reflecting on the resulting CLD, they prepared to present their findings to the plenum. After a second break, each group shared their insights with the entire workshop. The final task focused on identifying possible connections between the individual CLDs. The workshop concluded with a group discussion, reflection, and feedback from the stakeholders.

2.2.6 Post-processing of workshop results

After the workshop, the research team post-processed the CLDs, which involved digitizing them in the Vensim software, refining their structure, and identifying feedback loops, trade-offs, synergies, and connections between the individual CLDs. This process also included merging the individual CLDs to an overarching CLD.. A few months later, a webinar was organized to present and discuss the finalized CLDs with the stakeholders, which helped to clarify remaining issues. The results were shared with the stakeholders in a user-friendly handout and published on the project website[1]. The finalized CLDs are described and analyzed in detail in the results section 3.

2.3 iSDG-AT model

Based on World3, the Millennium Institute built the Threshold21 (T21) model, to support integrated national planning efforts for the Millennium Development Goals (MDGs) in the Global South (Pedercini and Barney, 2010). From this the integrated Sustainable Development Goals (iSDG) model was developed. This means the iSDG's structure relies on a System Dynamics model structure that has by now been improved over several decades. The model captures interactions of domains relevant to analyzing the dynamics among the SDGs and their sub-targets (Allen et al., 2021, 2019). It has been applied in different countries, with very different socio-economic and environmental contexts (e.g. Allen et al., 2019, 2022; Collste et al., 2017; Li et al., 2024; Pedercini et al., 2018, 2019). It was also calibrated for Austria in 2022 (Spittler and Kirchner, 2022) and has since been adapted for applying it to different projects (*Earth4All: Austria*, 2024; Wretschitsch et al., 2024) – this version will be referred to as iSDG-AT. The iSDG-AT model has been evaluated as covering the broadest range of SDGs at the national level, and its existing application in Austria makes it particularly suitable for this analysis. Furthermore, the iSDG-AT model, being a System Dynamics model, is well-suited for use in stakeholder processes.

Computational System Dynamics modelling is a simulation-based modelling approach. The main characteristics and elements underlying this modelling approach make it suitable for comprehending complex system structures, by focusing on the causal relationships (Sterman, 2000). Based on this, arising dynamics are modelled over time, which allows to model and explore “what-if” scenarios. This means that the effects of policies, which one wants to implement, and their effects on individual variables but also system-wide behaviors can be investigated. Due to the way relationships between variables are formulated, the four main elements of the System Dynamics method are feedback, accumulation, delay and non-linearity (Sterman, 2000).

3 Results

In this section we present the CLDs for each indicator that resulted from the stakeholder participation process, which are then compared to the iSDG-AT model structure and discussed in

[1] https://sdg.visionpath.at/materialien/#ergebnisse

terms of available literature and other modelling approaches. Finally, we provide some concluding remarks and an outlook.

3.1 Energy poverty interactions from a stakeholder perspective

As shown in Figure 1, energy poverty is a direct function of purchasing power (real income), which is negatively linked to energy poverty, meaning that the energy poverty rate falls when purchasing power increases and the energy poverty rate rises when purchasing power drops. All feedback loops in the energy poverty system are balancing except for one. The balancing dynamics of energy poverty can explain the oscillating behaviour of the energy poverty indicator (see Figure 8). In general, balancing dynamics do not only stabilize a system but can also create lock-in effects. However, the reinforcing dynamics of inflation and rents can lead to an increasing or decreasing trend in energy poverty. In this system diagram, the large number of balancing feedback loops all revolve around energy prices and all but two (B3a & B3b) are connected to purchasing power. If income increases, so does purchasing power, which is directly linked to energy demand (increases when income increases) and thus energy consumption (increases when energy demand increases), as well as energy price (rises directly when energy consumption increases). Purchasing power decreases with higher energy prices due to the direct negative link of energy prices on purchasing power (B1a), but also indirectly, with rising energy prices increasing food prices, inflation and rental costs (B1b, B1c, B1d). Here, inflation and rental costs are mutually reinforcing each other in a reinforcing feedback loop (R1). The balancing feedback loops described above are influenced by another balancing effect between energy consumption, energy supply and energy prices. While, as described above, more energy consumption leads directly to higher energy prices, this effect is initially intensified because more energy consumption leads to a lower supply of energy, which means that energy prices continue to rise. However, rising prices lead to lower energy consumption, which in turn will lead to falling prices directly (B3a), as well as indirectly via the supply of energy (B3b). The dampening effect of energy prices on energy consumption can lead to the balancing feedback loops described above being weaker.

Even though many balancing feedback loops could in principle keep the system stable (which could be a negative effect if the energy poverty level is very high), the reinforcing feedback loop between inflation and rent prices could throw the system out of balance. An effect that was strongly felt due to the energy crisis and the rising inflation rate starting in 2021 (Bardazzi et al., 2024). However, the CLD also points out (or allows the interpretation) that an inflationary spiral is a greater factor in energy poverty than energy prices (which do not directly affect inflation in this system and lead to less energy consumption through a balancing feedback loop, which would cause prices to fall again). Thus, the energy price cap demanded by many political parties and organizations could lead to a short-term reduction, but energy poverty would level off again at a high level. In terms of System Dynamics, this would be a system intervention with a shallow leverage point (Abson et al., 2017; Meadows, 1999), since only a single parameter (in this case: the energy price) is changed. A higher and more effective leverage point would be implemented by decoupling the inflationary spiral between rents and inflation, as this would change the interrelationships in the system itself.

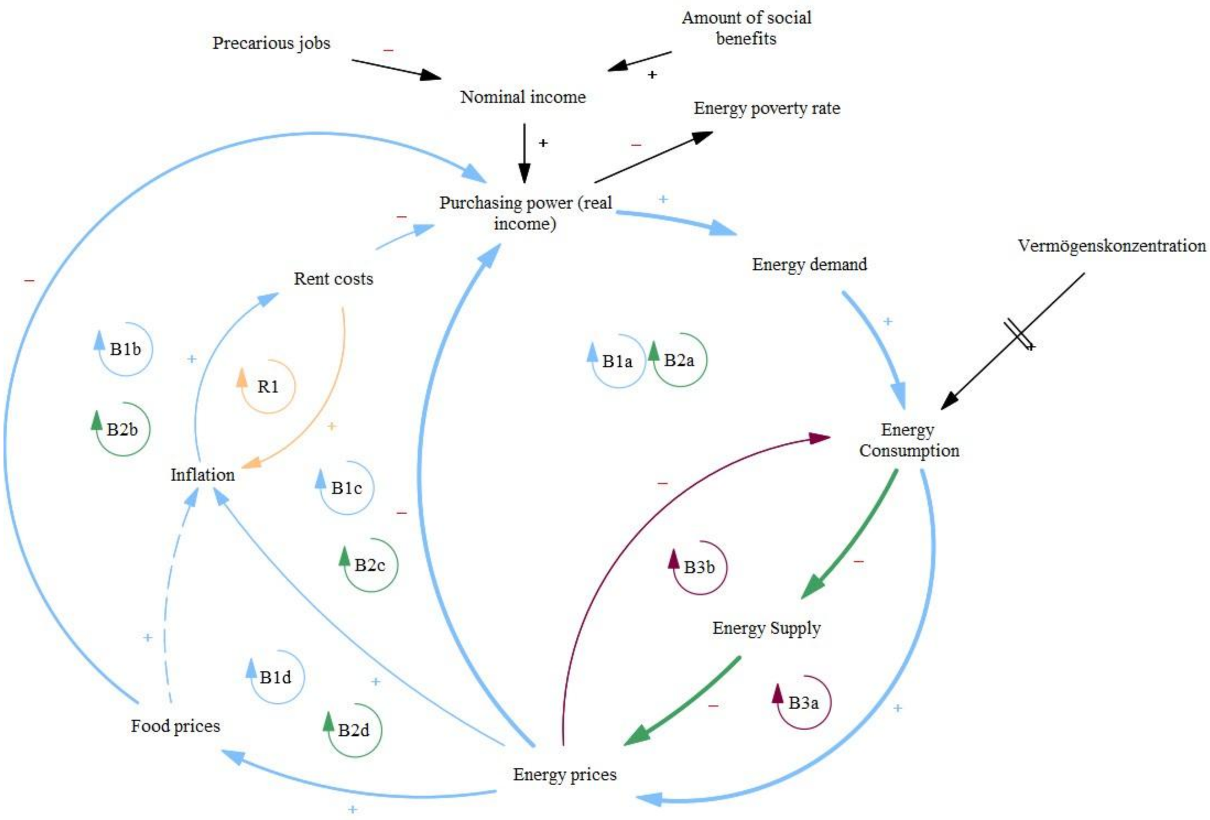

Figure 1: Stakeholder CLD on energy poverty

3.2 Real GDP per capita interactions from a stakeholder perspective

Figure 2 displays that, according to our stakeholders, real GDP per capita can reinforce itself through a number of different feedback loops. In particular, the positive effect on tax revenues and household income creates a reinforcing dynamic. These causal effects are indirect and unfold through the quality of the education system and labour productivity (R2a), consumption (R2b, R2c), innovation and productivity (R2d), as well as a reduction in poverty (R3a1, R3a2) and insecurity (R3b1, R3b2, R3c). The chain of effects via resource consumption must be viewed in a differentiated way. Although there is a direct reinforcing feedback loop (R1: GDP positively influences resource consumption and resource consumption positively links to GDP), more resource consumption also leads to more pollution, and thus to more uncertainty. More uncertainty causes real GDP per capita to fall, as it has a reducing effect on consumption (B1a, B1b) and innovation (B1c).

As long as limiting factors such as pollution and uncertainty do not prevail, real GDP per capita will continue to grow, as has been seen over time so far (excluding exogenous shocks such as epidemics, see Figure 9 in Annex 8.1.1). All balancing dynamics relate to uncertainty. In this CLD picture, it is therefore an important factor that can tip the system in a different direction.

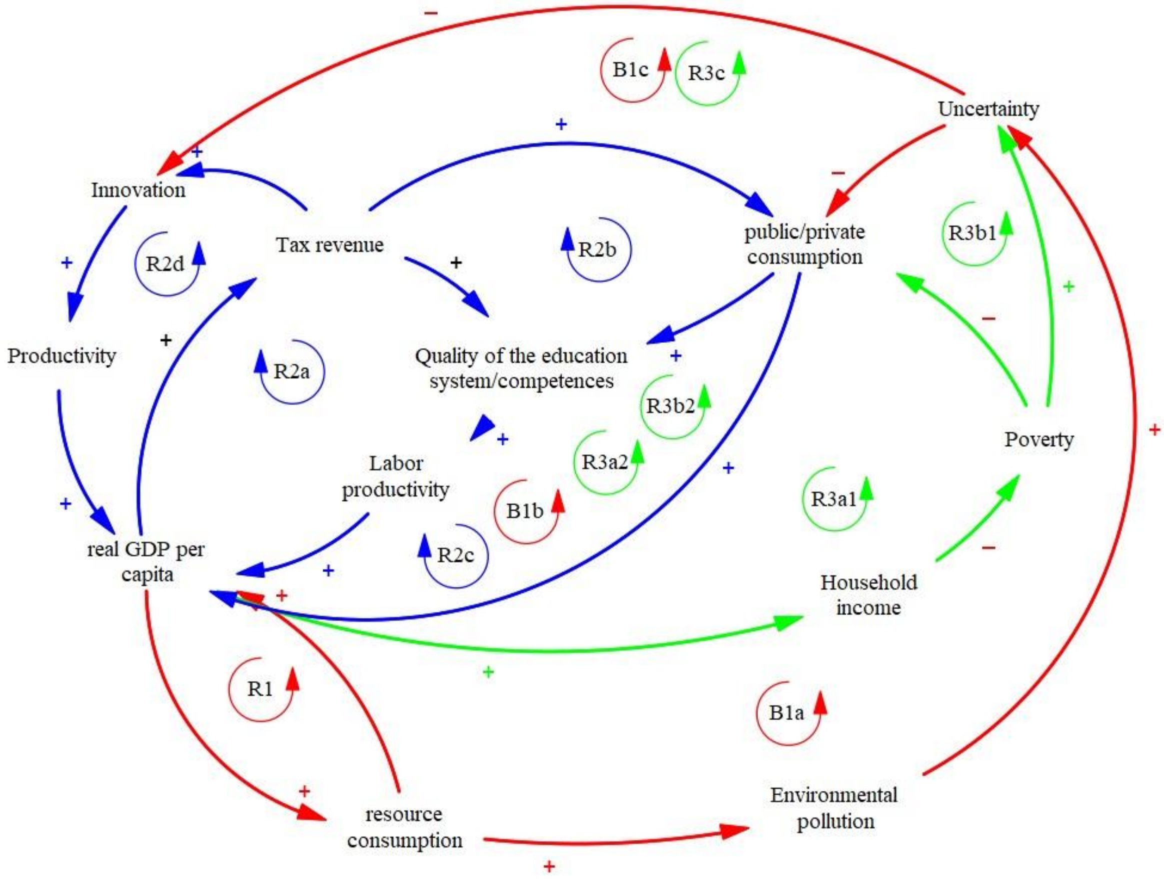

Figure 2: Stakeholder CLD on real GDP per capita

3.3 Work satisfaction from a stakeholder perspective

The CLD for work satisfaction (see Figure 3) reveals numerous reinforcing feedback loops. Two directly reinforcing loops are identified through *loyalty/identification with the company* (R1a) and *recognition* (R2a, R4). Additional positive feedback loops with extended causal chains also emerge. Greater recognition reinforces loyalty/identification with the company, which, in turn, enhances the management's scope for decision-making, ultimately improving the company's financial situation.

An improved financial situation generates reinforcing feedback loops by leading to higher income (R1b, R2b). This, in turn, strengthens the company's financial situation directly (R6) and indirectly through increased work satisfaction, which fosters greater innovation (R5).

Finally, work satisfaction is further reinforced as higher satisfaction contributes to a better social work environment, reducing the subjective perception of stress and resulting in even greater work satisfaction (R3).

Since this CLD contains only reinforcing feedback loops, exogenous shocks determine the direction in which work satisfaction is reinforced. The oscillating changes in the indicator over time (see Figure 10 in Annex 8.1.1) were thus most likely driven by fluctuations in exogenous factors (e.g., government measures, labor market competition, work-life balance).

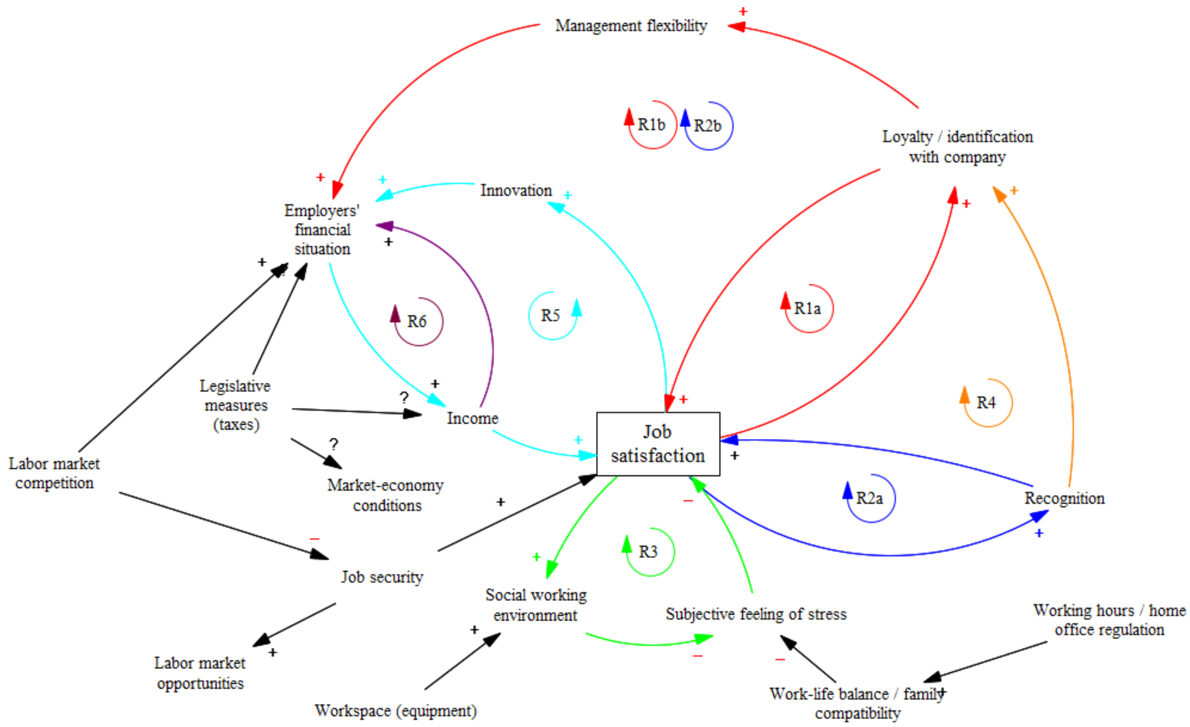

Figure 3: Stakeholder CLD on work satisfaction

3.4 Total GHG emissions interactions from a stakeholder perspective

Figure 4 shows that the feedback loops in the CLD are mainly centered around the indicator burning of fossil fuels as a proxy for GHG as a whole (in addition to process emissions) and via the two variables heat waves and goods production. There is a variety of both amplifying and balancing feedback loops. Almost all balancing feedback loops are due to the dampening effect of heat waves on labour productivity, which reduces the production of goods. This has a direct (B1b, B2a) and indirect reducing effect on the combustion of fossil fuels (all B1 feedback loops) or process emissions (all B2 feedback loops). Indirect paths run through, for example, the decline in air conditioning systems (B1a), less advertising expenditure (B1c) and thus less meat (B2b) and status consumption (B2c). A decline in the latter also has a reducing effect on kilometres driven (B1d), urban sprawl (B1e), and living space requirements (B1f). At the end of these balancing feedback loops, the combustion of fossil fuels or process emissions and thus also heat waves decrease. These feedback loops described above also have an amplifying effect, as more heat waves increase the demand for air conditioning systems and thus also boost the production of goods, which ultimately increases the combustion of fossil fuels or process emissions and thus also heat waves (R1a to R1f and R2a to R2c). These two feedback effects are reversed by green roof façades: Heat waves reduce labour productivity, which reduces the production of goods and reduces status consumption due to less budget for advertising spending. This leads to less green roof façades and thus further increases heat waves. This results in an amplifying feedback loop (R5). At the same time, the increased demand for air conditioning systems due to more heat waves and the resulting increase in goods production results in more advertising expenditure, increased status consumption and thus more green roof façades, which leads to a reduction in heat waves (B3). Further reinforcing feedback loops can be found for the important variables of goods production and heat waves: (i) If the production of goods increases, this leads to an increase in the combustion of fossil fuels (R3) due to more heat waves and thus more installation of air conditioning systems. (ii) An increase in the production of goods goes hand in hand with an increase in advertising spending. Therefore, consumption (status and meat consumption) and thus the production of goods (R4a, R4b, R4c) also increases.

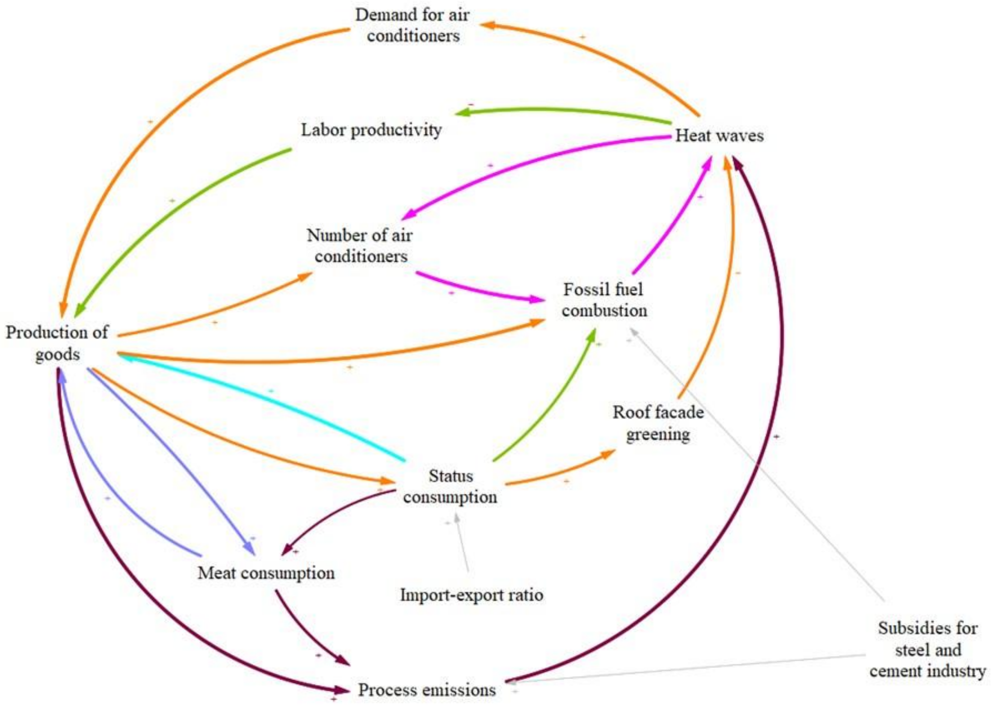

Figure 4: Stakeholder CLD on total greenhouse gas emissions

3.5 GHG emissions in the building sector interactions from a stakeholder perspective

In the CLD presented in Figure 5, most of the feedback loops are due to the amplifying effects of emissions in the building sector on heat waves. The (delayed) increased pressure of more heat waves on climate protection policy has a balancing effect. More climate protection leads to fewer CO_2 footprints (B1a), less fossil heating (B1b), less fossil energy generation (B1c), higher renovation rates and thus less cooling (B1d) and heating (B1e) requirements, as well as more densification. Densification has a reducing effect on emissions in the building sector via a variety of channels: fewer single-family homes (B1f) and commercial space (B1g), less construction activity and thus less steel and cement production (B1f1, B1g1) as well as less income and assets and a reduced usable living space per person (B1g2, B1g3, B1g4, B1g5, B1f2, B1f3, B1f4, B1f5). All these climate mitigation paths ultimately reduce emissions in the building sector. However, there are also reinforcing feedback loops: (i) Since more emissions generate more heat waves, this also increases the cooling demand and thus the emissions (R1); (ii) Since more construction activity leads to more income and assets, this leads to increased construction activity (R2a, R2b) on the one hand through increased mobility and thus more single-family houses and, on the other hand, it also leads to more construction activity (R3a, R3b) via a higher usable living space per person.

The existing system picture could explain the reduction of GHG emissions in the building sector due to the pressure on climate policy. It could also point to a typical "fixes that fail" archetype of system dynamics (Kim, 1995; Meadows, 2008): In principle, falling emissions result in higher emissions in this system picture (because the pressure on politics decreases again, but with a time lag). This is even reinforced by the reinforcing feedback loop of construction activity. This may partly explain the flattening of the reduction curve in recent years.

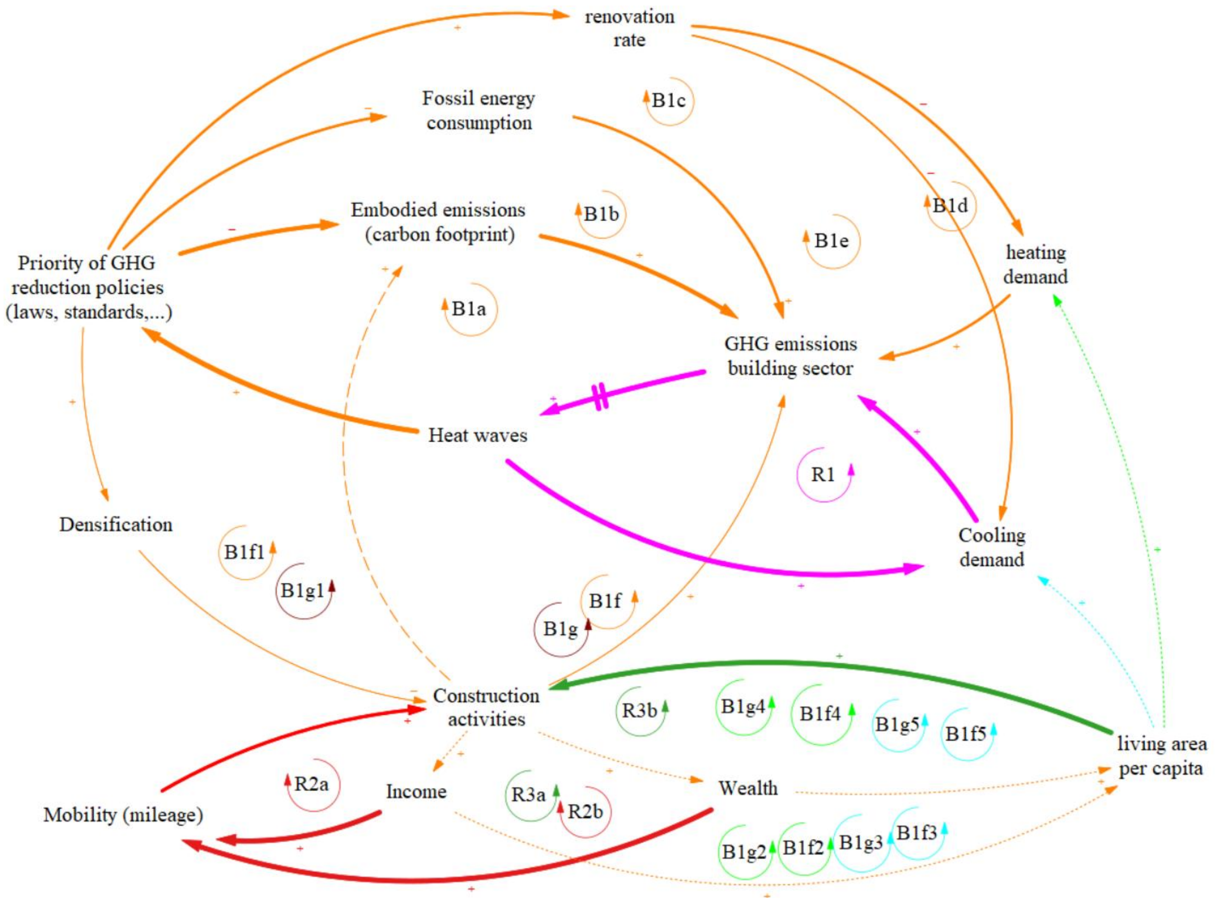

Figure 5: Stakeholder CLD on greenhouse gas emissions in the buildings sector

3.6 Combined SDG dynamics interactions from a stakeholder perspective

Figure 6 depicts a simplified version of the resulting overall CLD while still providing the most essential information regarding synergies, trade-offs, potential conflicts and feedback loops in the respective systems created by stakeholders. Notable, all CLDs are connected via one central variable, i.e. household income. This clear connection is, on the one hand, a coincidence, as we neither demanded nor required that all CLDs developed by the various stakeholders be interconnected. On the other hand, it is not entirely surprising, given that household income is a central and influential variable in most SDG systems. From this CLD we can identify the most important synergies and trade-offs at a macro level according to our stakeholders' knowledge:

- There is **synergy between real GDP per capita (SDG8), work satisfaction (SDG8) and energy poverty (SDG1/10)**: First, there is a positive feedback loop connecting (i) real GDP per capita and household income and (ii) work satisfaction and household income, i.e. increases in real GDP per capita / work satisfaction increase household income and vice versa. Real GDP per capita and work satisfaction thus mutually reinforce each other. Second, higher household income always directly reduces energy poverty, which results from the CLD on energy poverty.
- However, higher household income will directly lead to increases in GHG emissions (SDG13), thus leading to a clear **trade-off between SDG13 and the other SDG indicators**.

Hence, making stakeholders' knowledge and mental models explicit via CLDs revealed that they see possible synergies between the indicators from SDG1/10 and SDG8 but none with SDG13. Furthermore, the impacts of climate change and environmental pollution on real GDP per capita indicate that the stakeholders see some "limits to growth". The same applies to the positive effect of income on energy consumption.

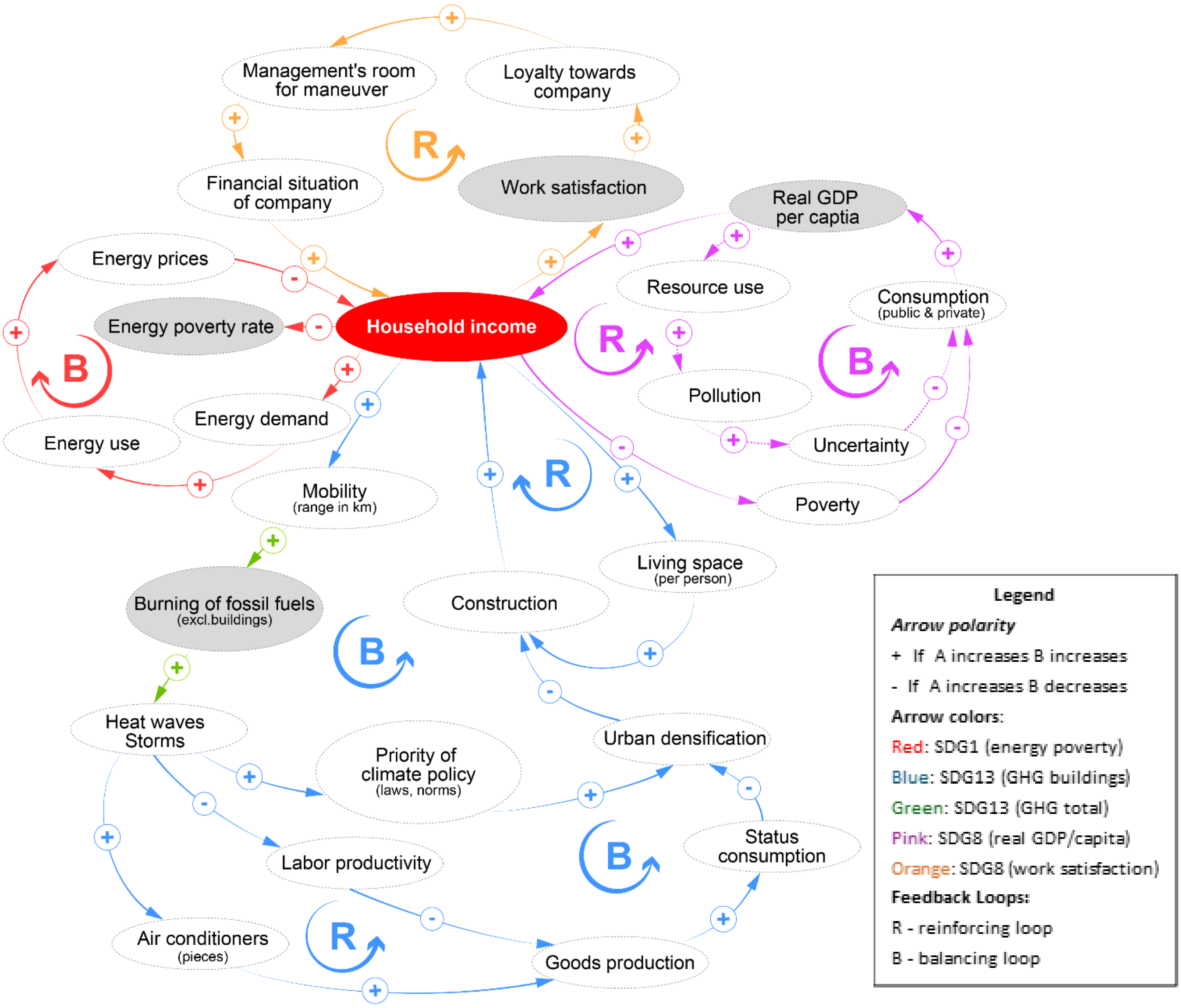

Figure 6: Synthesized overall stakeholder systems understanding

4 Discussion

4.1 Comparing CLDs with the iSDG-AT model structure

4.1.1 Energy poverty interactions in the iSDG-AT model

In the model, two kinds of energy prices can be distinguished: First, there are the international fuel prices for oil, gas and coal. These prices are world market prices which cannot be determined by a national model and thus are also not influenced by energy demand. Second, the price for electricity in the model depends on the energy mix, their generation and investment cost. So, with an increase in electricity demand more expensive technologies need to be used which also increase the average electricity price for households. The other option would be to import electricity to cover the domestic electricity demand. The price for imported electricity is assumed to be the same as the domestic price. Both options would increase the energy bill for households and thus increase the energy poverty rate. Further, it impacts the real income via the effect of expenditures on imported electricity on productivity. Inflation in the model is exogenous and therefore not influenced by variables that are part of the model structure. Real income, also in the model, impacts energy consumption. Also, there is the effect of energy prices on energy consumption. However, the feedback which is caused by the impact of energy consumption on energy prices might not be as strong as indicated by the stakeholders according to the iSDG-AT model.

The model structure does not allow for detailed analysis concerning energy poverty since the household groups are distinguished by income classes but not by differences in their energy consumption. Therefore, by analyzing energy poverty we have to assume that all households consume the same amount of energy. In absolute numbers, energy consumption increases with disposable household income. Still, data on the use of energy in the year 2021 and 2022 highlighted that the ratio of energy cost to income corresponds to 9.6% for low-income households in contrast to only 3.5% for high-income households (Statistics Austria, 2024).

Regarding the systems understanding of the stakeholders, the main dynamics for the energy poverty rate are caused by changes in real income which is depicted in the iSDG-AT model and also differentiated by income percentiles.

4.1.2 Real GDP per capita interactions in the iSDG-AT model

In the systems understanding of the stakeholder, the variable "uncertainty" is of major importance. However, in the model, there is no such variable. This caps a lot of feedback mechanisms that were identified and assumed by the stakeholders.

Real GDP in the iSDG-AT model is derived by a production-based approach in the model. The production function in the model only considers capital and labor as input factors. Resource use is not taken into account.

The link from poverty to public/private consumption is not so clearly shown in the iSDG-AT model structure. For example, public expenditure is defined as a percentage of GDP and therefore not explicitly linked to poverty. If poverty is caused by a general decrease in household income, without a change in income distribution, then reduced income will most likely also lead to lower public consumption. Also, the effect on private consumption is caused by a change in household income, irrespective of whether poverty is increased or not.

4.1.3 Work satisfaction interactions in the iSDG-AT model

Unfortunately, work satisfaction is currently not represented at all in the iSDG-AT model. Also, most variables contained in this CLD are qualitative in nature making it challenging to integrate them in a simulation model like the iSDG.

4.1.4 Total GHG emission interactions in the iSDG-AT model

Overall, heat waves are a central variable in the CLD explaining the trend in total greenhouse gas emissions. In the further refinement of the CLDs during the follow-up webinar, this was clarified as an exemplary variable for climate change impacts in general. Still, climate change impacts in the iSDG-AT model are based on the exogenously defined expected temperature change in Austria depending on the assumed shared socio-economic pathway (SSP) which describes a scenario of climate change with underlying socio-economic developments. (IPCC, 2021; O'Neill et al., 2017). The only way climate change impacts can be influenced in the model is by the expenditures for and investments in adaptation capital. In case no investment in adaptation is made, negative impacts on productivity and infrastructure might occur. However, in contrast to the stakeholders' CLD, national greenhouse gas emissions have no direct effect on climate change impacts in the iSDG-AT model.

The effect of temperature change on productivity is indicated to be negative in the CLD which is part of a balancing feedback loop. In the iSDG-AT model, the elasticity of productivity to changes in temperature is derived in the calibration process based on historic data.

4.1.5 Building GHG emission interactions in the iSDG-AT model

In the iSDG-AT model, emissions in the building sector are mainly driven by population growth, income growth and average energy cost. An important influence is also the energy mix which is influenced by relative energy prices (energy taxes) and an from the calibration resulting suitability factor, which describes the attractiveness of using a certain energy source in the buildings sector.

In contrast to the CLD where the priority of climate policy is increased with the occurrence of heat waves, policy interventions are exogenous in the iSDG-AT model.

Further, also climate change impacts are exogenous in the model and not influenced by national emission levels. Instead, a climate scenario is exogenously assumed and independent from the national mitigation pathway which then determines the extent of climate impacts in Austria (see 4.1.4 above).

4.1.6 Combined SDG dynamics in the iSDG-AT model

Although the causal mechanisms and integrated variables differ between the CLDs and the iSDG-AT model structure, the dynamics for energy poverty, GHG emissions and real GDP per capita also link to each other via various mechanisms in the model: Instead of household income, real GDP in this case is one of the most important variables that relates to multiple dynamics in the model: First, real GDP has a great impact on GHG emissions mostly via an increase in (fossil) energy consumption. Without decoupling production and GHG emissions and the transition to renewable energy system, an increase in real GDP causes higher GHG emissions. Thus, the trade-off between real GDP per capita and GHG emissions as identified by the stakeholders is also apparent in the iSDG model. Second, real GDP leads to higher household incomes and thus also lower energy poverty in the iSDG model, which is indicated by the average energy cost relative to disposable income. This was identified as synergy effect by the stakeholders' CLDs which will also appear in model simulations. Finally, work satisfaction is not considered in the model as the main focus is on qualitative aspects, that can hardly be captured by quantitative simulation models. However, with respect to other work-related indicators as the unemployment rate, synergy effects can be observed in the model since rising real GDP also leads to higher demand for workers.

4.2 Comparing CLDs with findings in literature

4.2.1 Energy poverty interactions in the literature

In the literature, multiple causes for energy poverty have been identified (Rodriguez-Alvarez et al., 2021). In accordance with the systems picture shown in the CLD, low-income was most frequently found to characterize vulnerable groups for energy poverty (Niks et al., 2022): This is explained by less financial capabilities to (i) pay energy bills, (ii) to afford to live in energy efficient buildings and (iii) to invest in energy efficiency improvements themselves. Furthermore, households with higher energy consumption (e.g. households with children) have also been identified as at risk for energy poverty. Also, the type of housing tenure was found to be relevant for explaining energy poverty, as tenants were found to be more vulnerable to energy poverty, which also links to low-income and low energy-efficiency cases.

The literature further points out for the case of Austria that measuring energy poverty as the share of energy expanses to income would underestimate the occurrence of energy poverty as households already "self-restrictedly" reduce their energy consumption (Eisfeld and Seebauer, 2022).

From their analysis on causes of energy poverty in Europe, Rodriguez-Alvarez et al. (2021) propose financial support for vulnerable groups, reductions on energy prices and increasing energy efficiency as effective measures against energy poverty.

In the context of Austria, Seebauer et al. (2019) argue for integration of climate and social policies to simultaneously address climate and social goals and tackle energy poverty, especially with regards to the housing sector.

4.2.2 Total GHG emission interactions in the scientific literature

The relationship of temperature increases and more frequently occurring heatwaves is also found in the literature, while for Europe countries in the south are found to be affected more severely, also compared to Austria. To adapt to this climate change impact, space cooling is proposed to weaken the impact on labor productivity (Day et al., 2019). While cooling is influenced by heat waves in the CLD, the effect on labor productivity has not been considered. Also, in the iSDG-AT model, climate change adaptation mitigates the potential negative impacts on production.

The CLDs derived by the stakeholders do not highlight stocks and flows, however, this distinction is highly relevant with respect to GHG emissions and climate change impact (IPCC, 2021). In the CLDs, it was not considered that GHG emissions accumulate, and the stock of emissions determines climate change impacts such as heat waves. Unlike as stated in the CLDs, a decline in fossil fuel consumption will not lead to less heat waves, until emissions are reduced to zero.

4.3 Limitations

While no full group model building process was carried out as for example described in (Antunes et al., 2006; Videira et al., 2010). It enabled participants of the workshop to combine their knowledge and expertise relevant to the problematic dynamics underlying the selected indicators. This fostered the participants' learning as they could explore connections between individual system components and enabled us to understand the limitations of the current SDG modelling approach. Additionally, the results provided us with a basis for enhancing model structure developments.

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CLDs capture stakeholders' mental models (Hanger-Kopp et al., 2024) and, like scientific models, are simplified representations that omit certain factors and may contain inaccuracies. Nonetheless, the key findings from these CLDs align with the scientific literature. For instance, studies have documented the trade-offs between economic growth and GHG emissions (Haberl et al., 2020b; Vogel and Hickel, 2023; Wiedenhofer et al., 2020) as well as between climate action and energy poverty (Fragkos et al., 2021; Priesmann et al., 2022).

5 Conclusions and outlook

This study demonstrates the utility of Causal Loop Diagrams (CLDs) as a participatory tool to capture stakeholder perspectives on SDG interactions. By integrating diverse knowledge systems, we revealed critical feedback loops, trade-offs, and synergies that influence the dynamics of key indicators like energy poverty, economic growth, and greenhouse gas emissions. Notably, the centrality of household income emerged as a crucial nexus connecting social, economic, and environmental domains.

The comparison between stakeholder-derived CLDs and the iSDG-AT model highlighted both alignments and gaps. For instance, while stakeholders identified dynamic feedback effects between variables such as energy prices and energy poverty, these were underrepresented in the quantitative model. Similarly, qualitative dimensions like work satisfaction were absent, emphasizing the need to expand existing models to better reflect stakeholder realities.

The results of this paper are the basis for further stakeholder knowledge integration process within the SDGVisionpath project, i.e.: co-creating a future vision (Hinterberger et al., 2024b, 2024a) and transformation pathways (Bukowski et al., 2024b), simulating these pathways with the iSDG-AT model (Wretschitsch et al., 2024), assessing conflict potentials with the IPAM model (Bukowski et al., 2024a) and the identification of policy recommendations for achieving Austria's SDG goals (Kirchner et al., 2024).

Future research should prioritize:

1. **Enhancing model granularity:** Incorporating variables like work satisfaction and capturing heterogeneity in household energy use to improve policy relevance.
2. **Bridging qualitative and quantitative insights:** Integrating participatory tools like CLDs with simulation-based approaches to offer a more comprehensive understanding of SDG interactions.
3. **Addressing systemic leverage points:** Exploring interventions at deeper structural levels, such as decoupling inflation from housing costs, to achieve sustainable outcomes.

Ultimately, this research underscores the value of participatory methods in complementing traditional modelling approaches, enabling more inclusive and actionable pathways for achieving the SDGs. Future efforts should aim to institutionalize such participatory frameworks to foster collaboration and adaptability in the face of complex sustainability challenges.

To mitigate undesired effects, such as conflicts between climate action and energy poverty, interventions are required to alter reinforcing feedback loops, adjust causal mechanisms, or set alternative targets, such as indicators beyond real GDP per capita. Furthermore, future lifestyle changes may shift the structure of these systems, leading to the emergence of new synergies and trade-offs.

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8 Annex

8.1 Workshop preparation

8.1.1 Reference modes

The first graph is an example of the handout stakeholders received at their respective group tables in the workshop. All other graphs here are translated in English for an international audience.

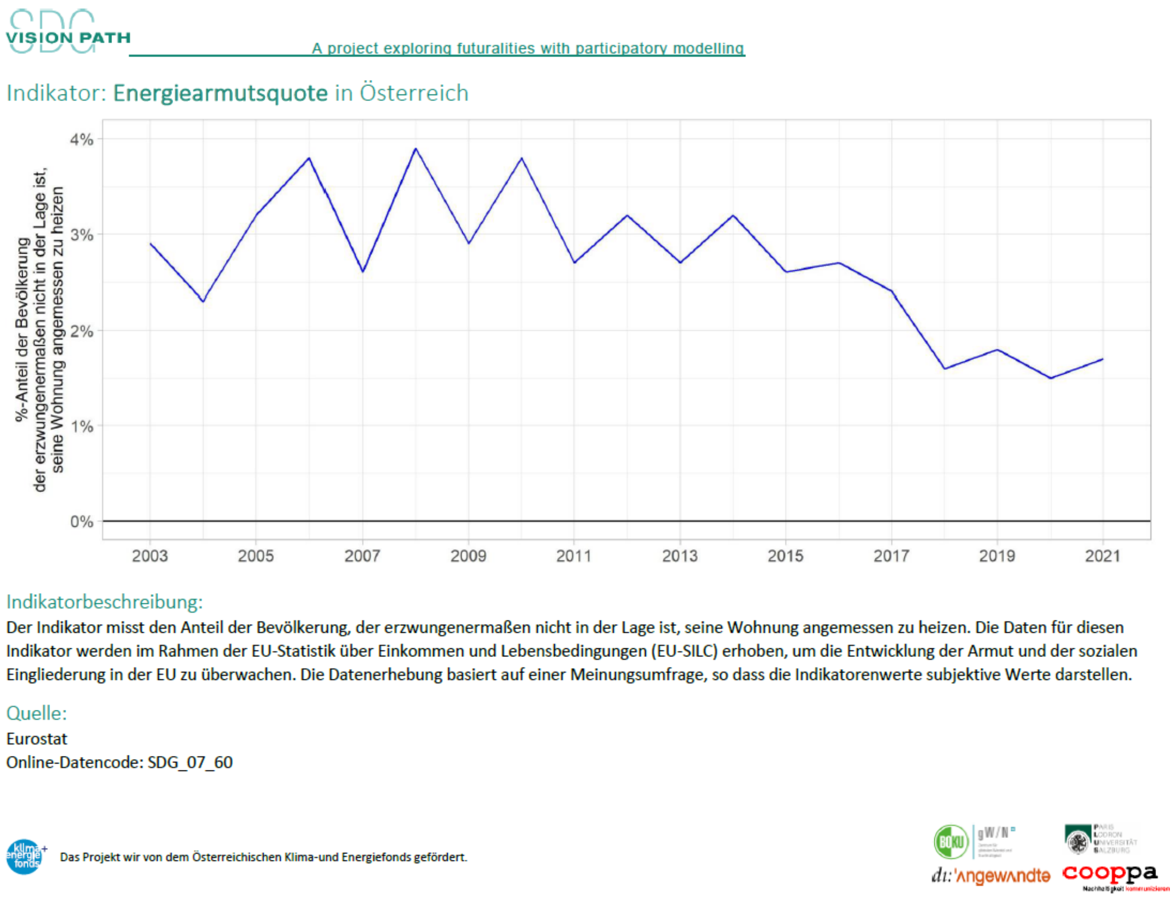

Figure 7: Example of a reference mode made available for stakeholders at the workshop (energy poverty)

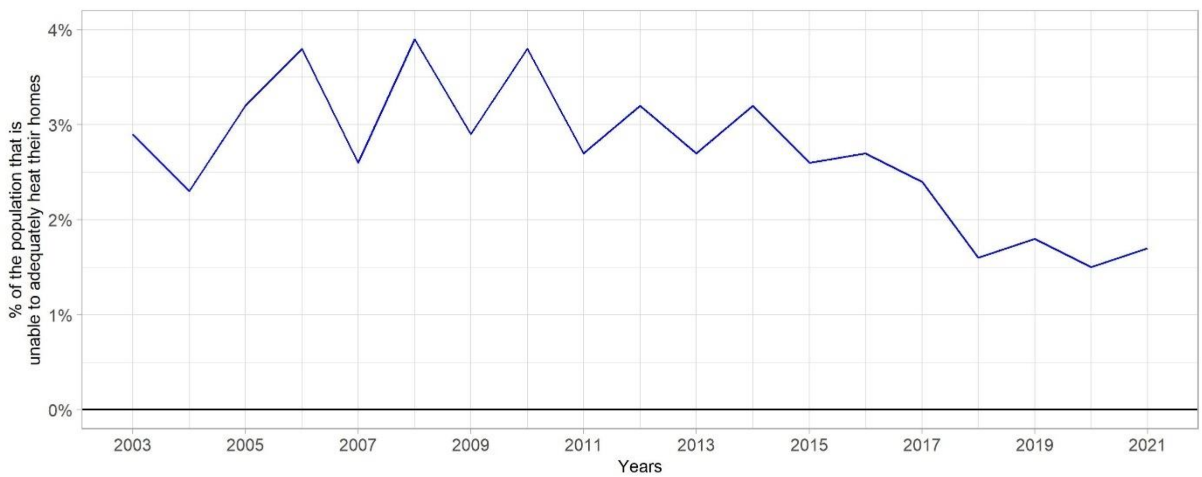

Figure 8: Energy Poverty Rate in Austria measured as "% of the population that is unable to adequately heat their homes"

***Indicator description**: This indicator measures the proportion of the population that is unable to adequately heat*

their homes due to economic constraints. The data for this indicator is collected as part of the EU Statistics on Income and Living Conditions (EU-SILC) to monitor poverty and social inclusion in the EU. The data collection is based on a survey, meaning the indicator values are subjective.
Source: *Eurostat; Online Data Code: SDG_07_60*

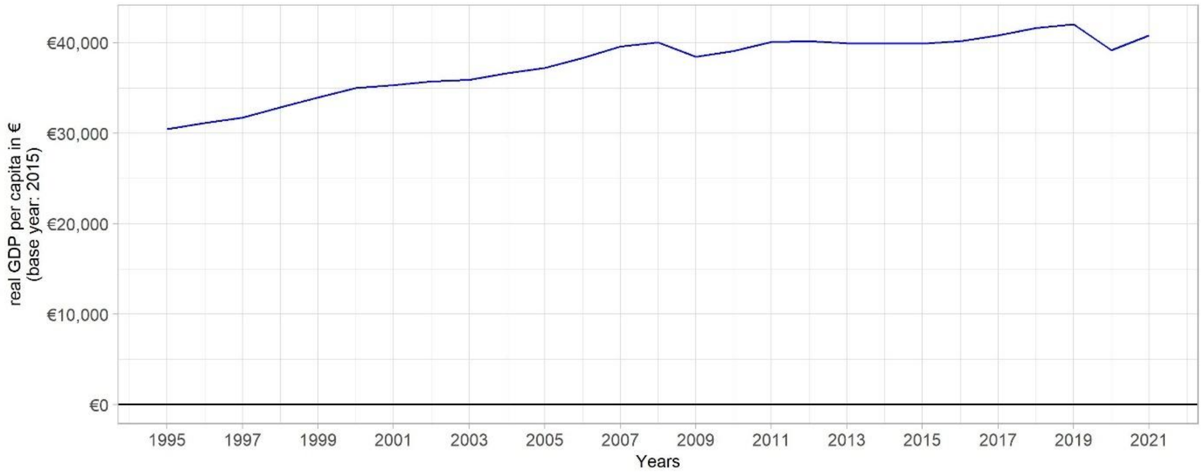

Figure 9: Real GDP per capita in Austria
Indicator description*: GDP measures the total value of final goods and services produced by an economy over a specific period. It is a measure of economic activity and serves as an approximation of the material standard of living in a country. "Real" indicates that the values are adjusted for inflation based on a specific year. Real GDP per capita is calculated as the ratio of real GDP to the average population of a specific year.*
Source: *Statistics Austria*

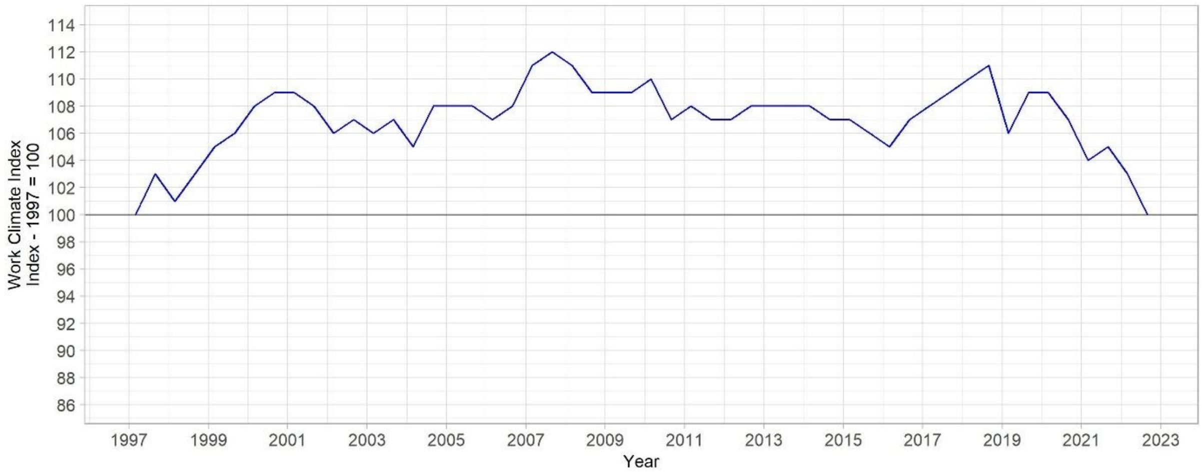

Figure 10: Work Climate Index in Austria
Indicator description*: The Work Climate Index is based on surveys of samples of employed persons across Austria. Data is collected quarterly through interviews with 900 employees, conducted by IFES staff using a standardized questionnaire in face-to-face interviews. The questionnaire covers 26 topics, including working time regulations, company size, satisfaction with company-provided social benefits, etc...*
Source: *Chamber of Labour Upper Austria; see http://db.arbeitsklima.at/*

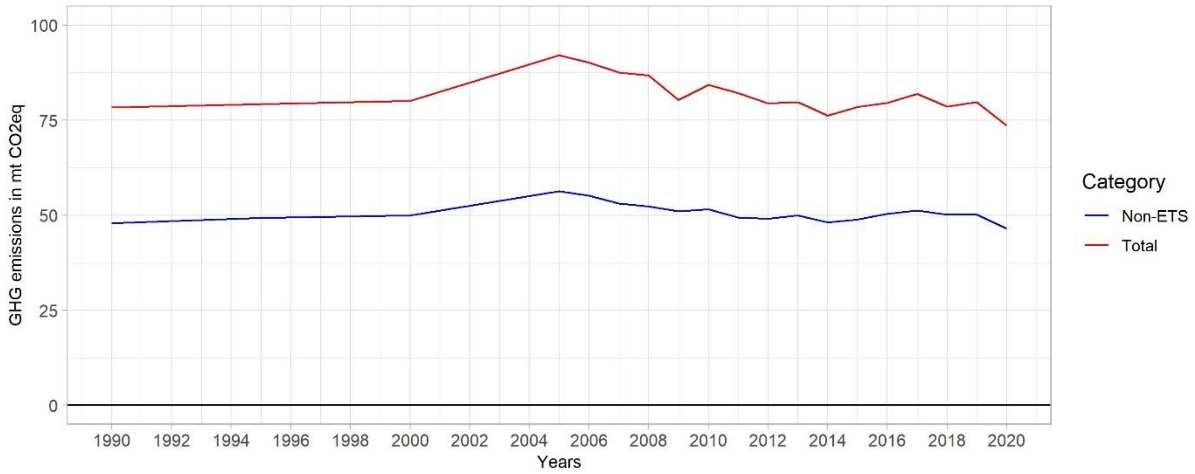

Figure 11: Total Greenhouse Gas Emissions in Austria
***Indicator description**: The greenhouse gas (GHG) emissions indicator measures the amount of climate-damaging gases caused by human activities: CO_2, CH_4, N_2O, and fluorinated gases. To calculate GHG emissions, the emissions of all gases are converted into CO_2 equivalents (CO_2eq). "Total" refers to all Austrian GHGs according to IPCC accounting ("production-based"). "Non-ETS" refers to all emissions not covered by the European Emissions Trading System (ETS). These include sectors such as transport, buildings, agriculture, waste management, non-energy-intensive industries, and fluorinated gases. The ETS covers the energy sectors and energy-intensive industries (e.g., steel, cement).*
***Source:** Environment Agency Austria (Austria's National Inventory Reports)*

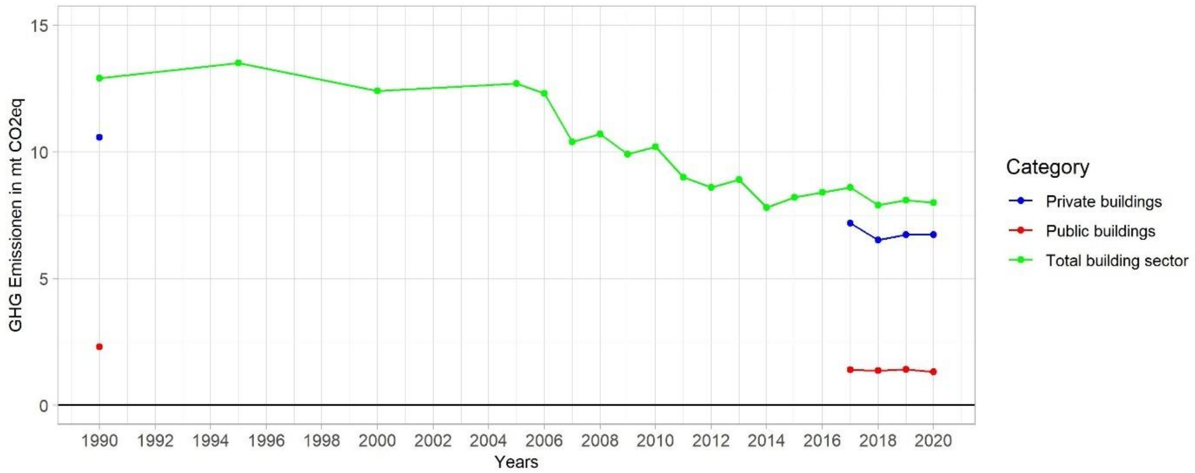

Figure 12: Greenhouse Gas Emissions in the Building Sector in Austria
***Indicator description**: The GHG emissions indicator measures the amount of climate-damaging gases caused by human activities: CO2, CH4, N2O, and fluorinated gases. To calculate GHG emissions, the emissions of all gases are converted into CO2 equivalents. The building sector includes all emissions that occur in private and public buildings.*
***Source:** Environment Agency Austria (Climate Protection Reports)*

8.1.2 Pre-workshop survey

These questions were asked during the survey:

1. SDG1/10 (12 answers received, 6 of them fully answered):
   a. Which drivers influence the development of energy poverty the most?
   b. Which drivers influence the development of risk of poverty the most?
2. SDG8 (19 answers received, 8 of them fully answered):

   a. Which drivers influence the development of work satisfaction the most?
   b. Which drivers influence the development of real GDP per capita the most?
3. SDG13 (11 answers received, 7 of them fully answered):
   a. Which drivers influence the development of total GHG emissions the most?
   b. Which drivers influence the development of GHG emissions in the buildings sector the most?

Note that stakeholders only received the survey specific to their expertise (i.e. a climate expert would only receive the survey related to SDG13) and could name at maximum seven variables per question.

8.2 Workshop participants & agenda

Table 1: Characteristics of the participants

Note: "Sozialpartnerschaft" ("social partnership") refers to the cooperative framework between employers' organizations, trade unions, and the government in Austria. It comprises chambers of commerce and labor, as well as associated lobby organizations and trade unions.

Groups	Participants	Administration	Sozialpartnerschaft	Academia	NGO	Business
Total	21	7	2	6	4	2
Energy Poverty	6	3	1	1	1	0
Work Satisfaction	4	0	1	1	1	1
Economic Growth	4	1	0	1	1	1
Total GHG emissions	4	2	0	2	0	0
GHG emissions buildings	3	1	0	1	1	0

Table 2: Workshop agenda script

Start	End	Time (min.)	Setting	What
9:00	10:00	60	Plenary	Introduction Project & CLD example
10:00	10:30	30	Groups	Discuss variables from survey (15 mins), add new ones if necessary Cluster variables (15 mins)
10:30	10:40	10		Break
10:40	11:25	45	Groups	Work on linkages (start with a cluster, then add components)
11:25	11:35	10	Groups	Reflect on own work + prepare presentation
11:35	11:50	15		Break (team puts CLDs on the wall)
11:50	12:10	20	Plenary	CLDs are presented by group representative
12:10	12:40	30	Plenary	Identify connections between the individual CLDs
12:40	13:00	20	Plenary	Reflection

8.3 Workshop documentation

8.3.1 Pictures of CLDs

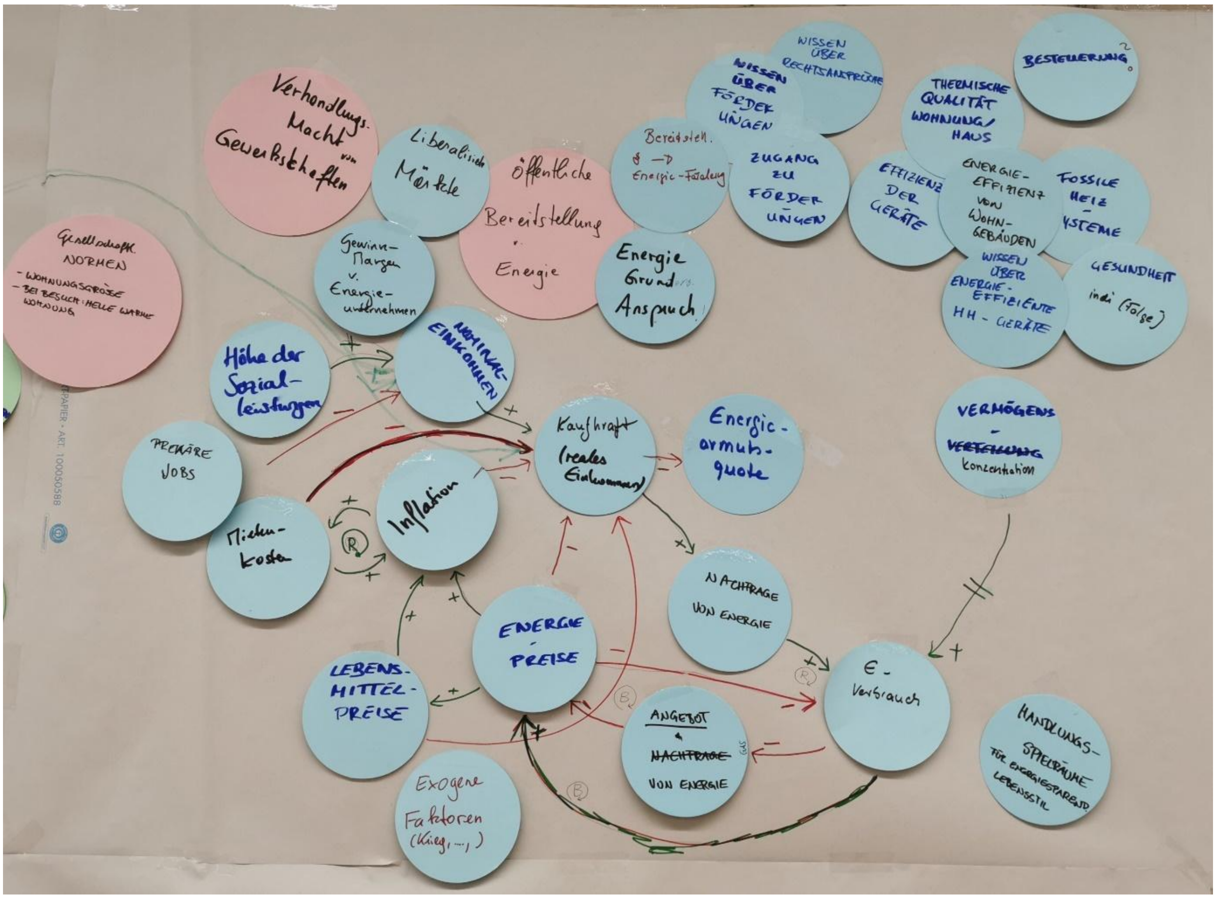

Figure 13: Stakeholder CLD of energy poverty

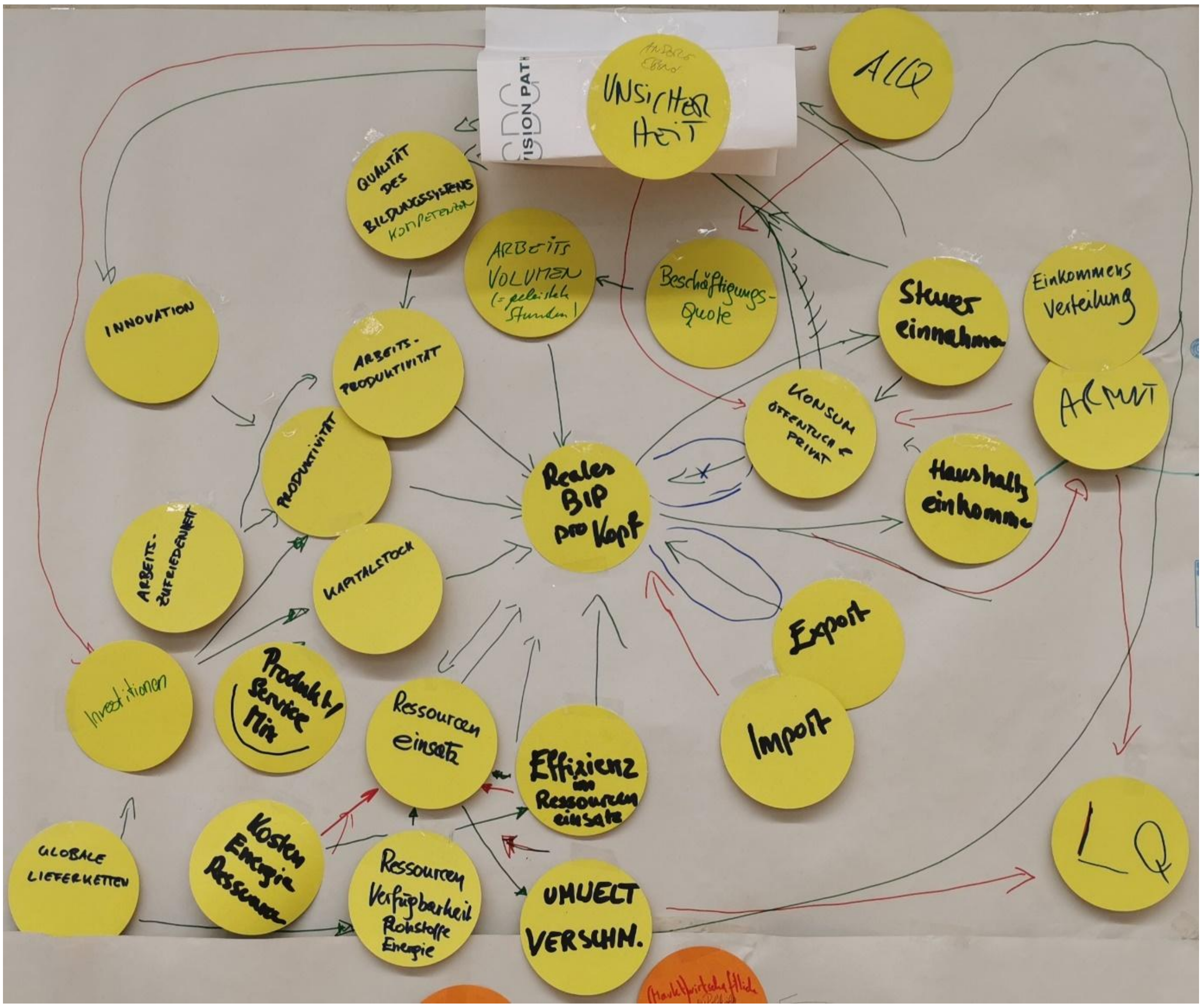

Figure 14: Stakeholder CLD of real GDP per capita

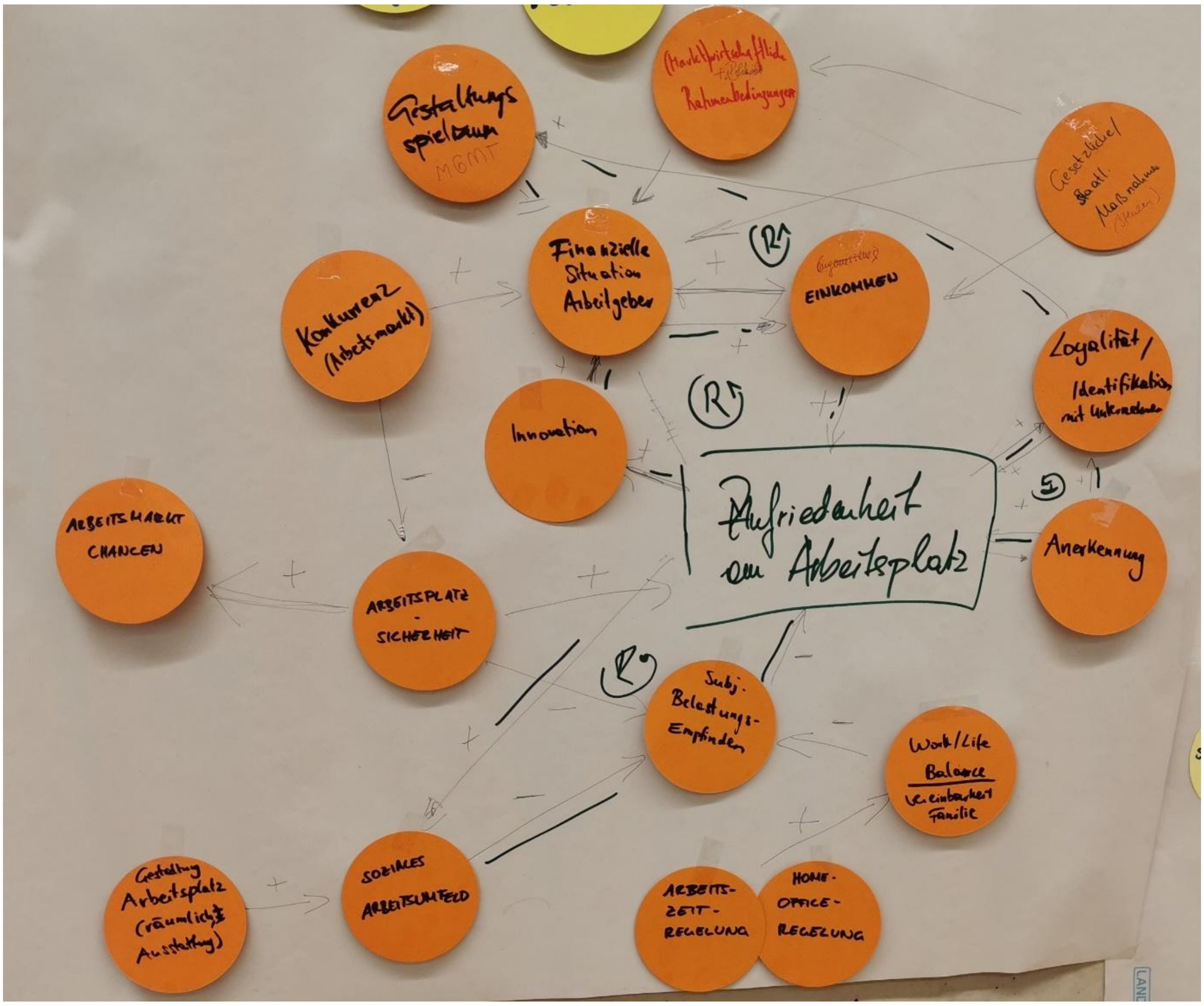

Figure 15: Stakeholder CLD of work satisfaction

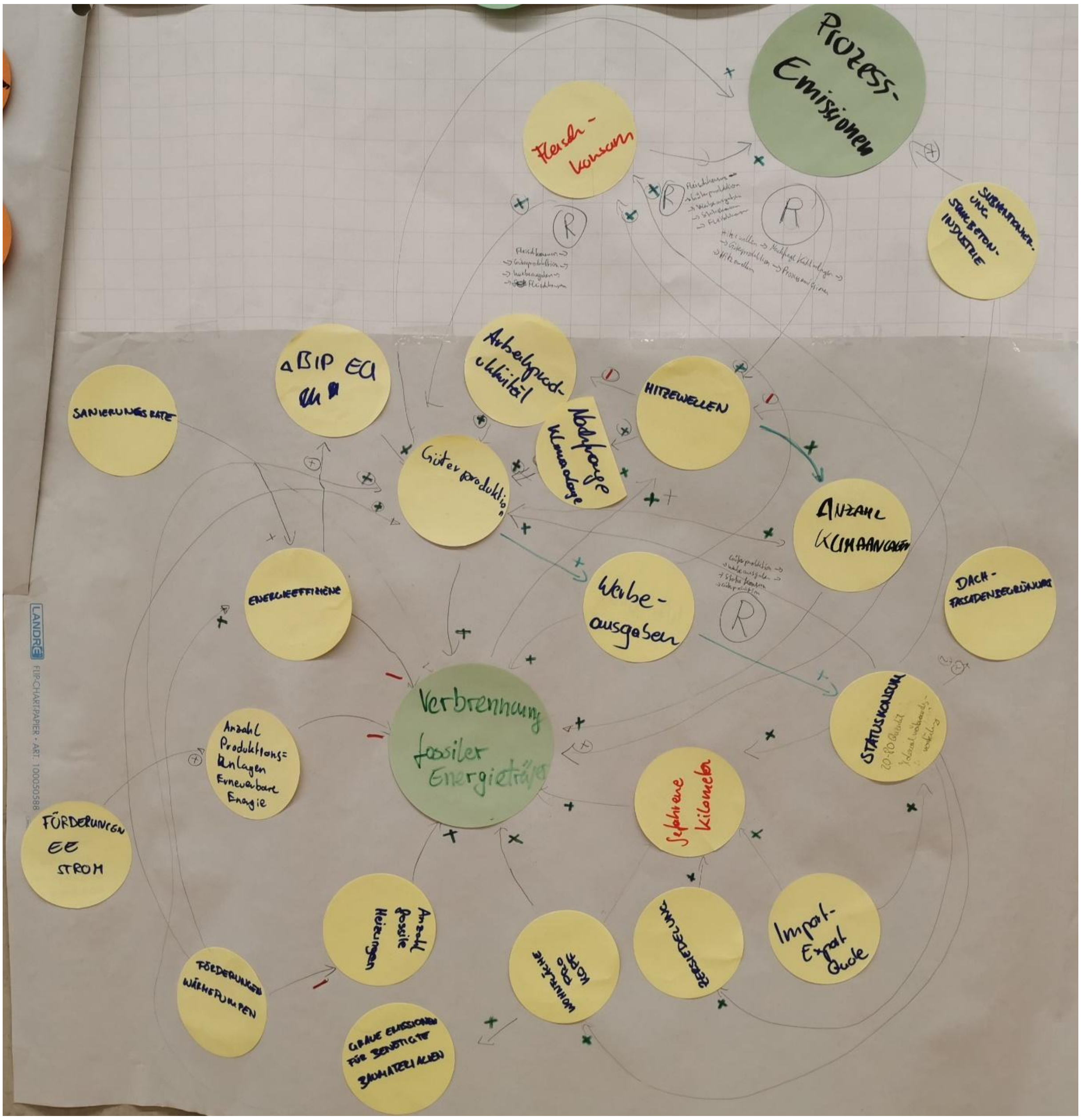

Figure 16: Stakeholder CLD of total GHG emissions

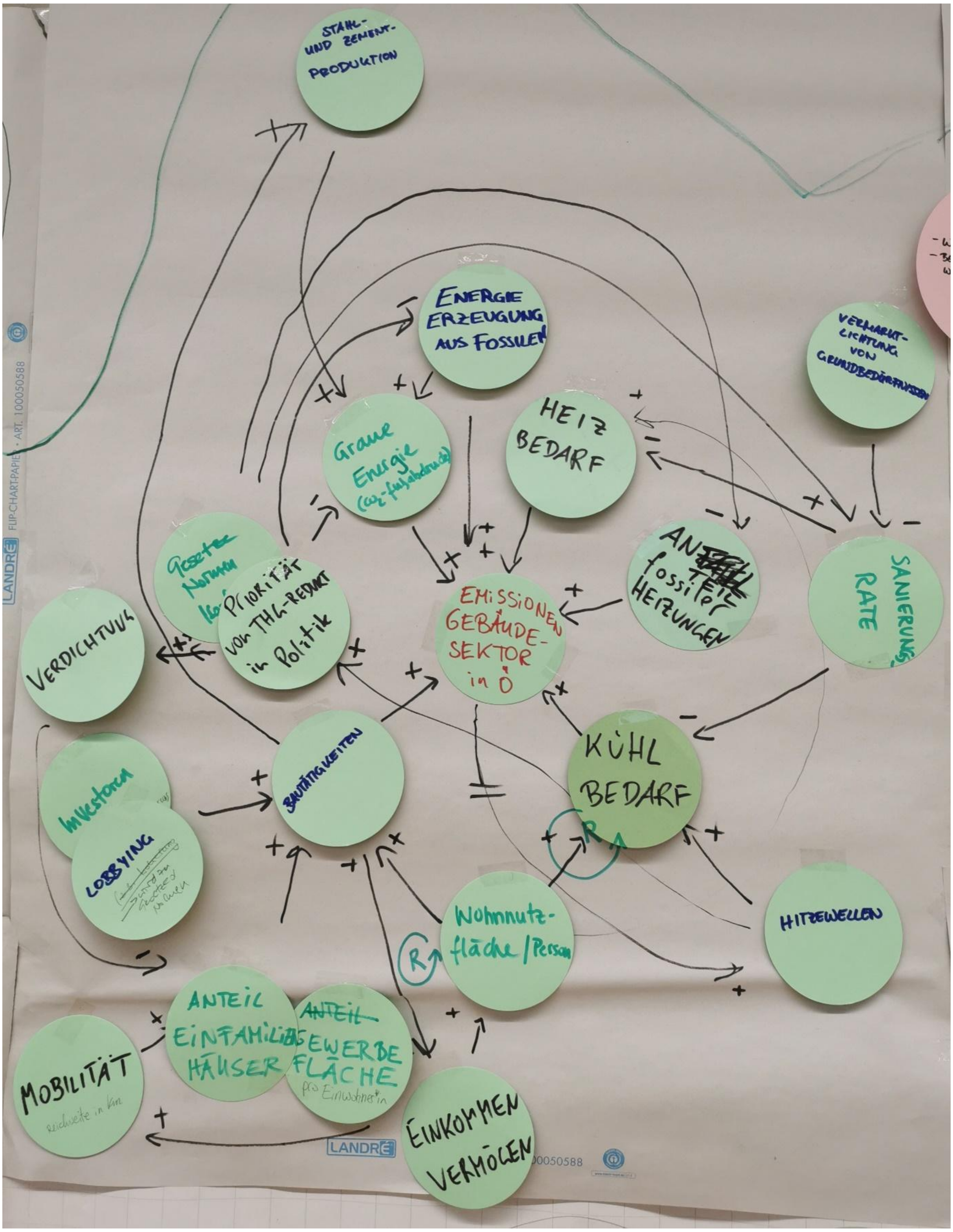

Figure 17: Stakeholder CLD on GHG emissions in the building sector

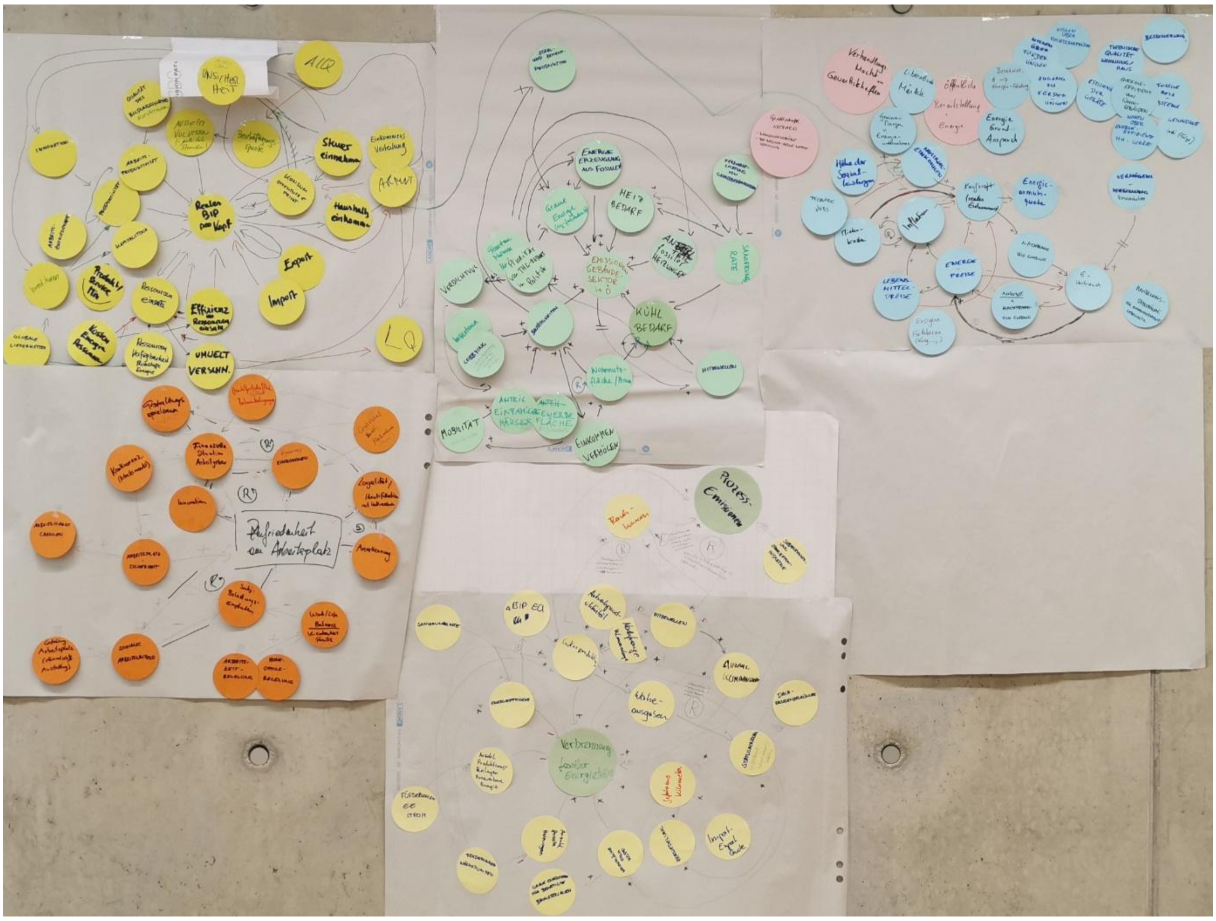

Figure 18: Connecting the individual CLDs during the stakeholder workshop

8.3.2 Picture of the workshop process

Figure 19: Discussing variables

Figure 20: Identifying linkages

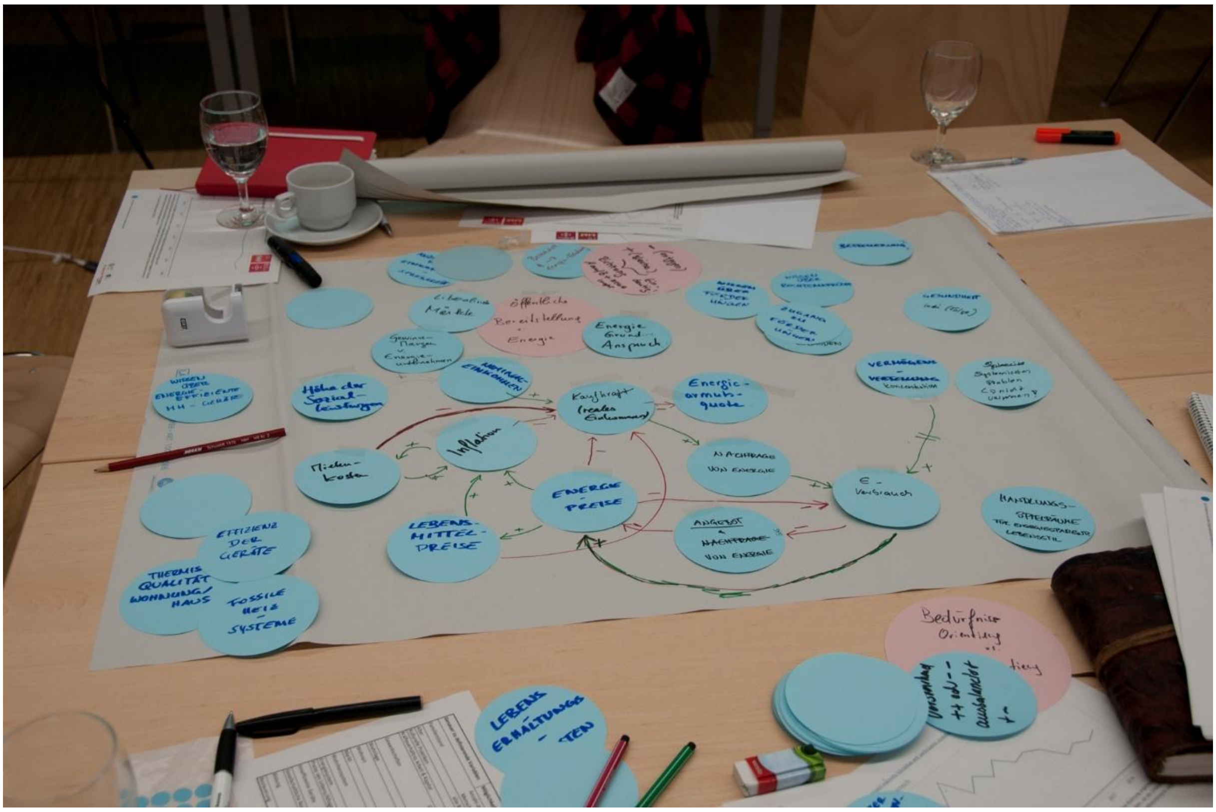

Figure 21: Finalizing and reflecting the CLDs

Figure 22: Workshop leaders (Nathalie Spittler & Mathias Kirchner) connecting the variables between the CLDs