Title

Systemic impacts of low-carbon transition policies for housing in Innsbruck: Mapping the intersections of vulnerability and social justice with affected citizens and stakeholders

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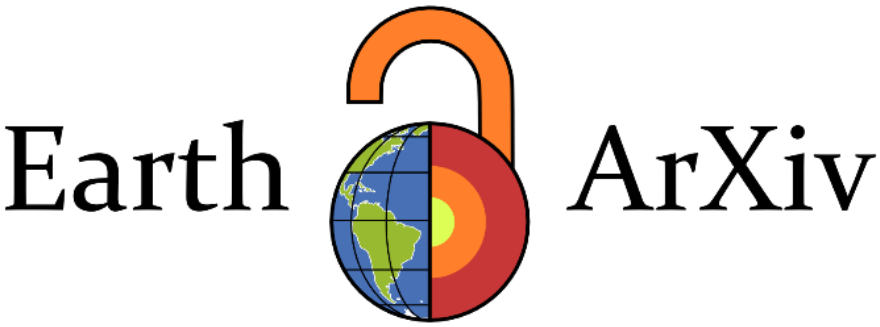

Abstract

Decarbonizing the building sector is a key priority in the European energy transition, as it is responsible for more than a third of the EU's GHG emissions. To boost energy renovation rates and efforts to phase out fossil fuel-based heating systems, current energy policy directives target in particular the promotion of energy efficiency. However, implementing technology-oriented solutions for low-carbon energy and heating transitions raises a variety of issues, bearing also the risk of exacerbating energy and housing vulnerability.

This preprint-article explores potential synergies and trade-offs between climate neutrality and social justice, advocating for deliberative democracy and participation in co-designing systemic perspectives for low-carbon policy interventions. We focus on the city of Innsbruck, where both rents and shares of installed fossil fuel-based heating systems are among the highest in Austria. Our data builds on stakeholder interviews, policy analysis, and participatory systems mapping with citizens in a deliberation panel setting. We identify several structural key conditions that increase exposure to housing and energy vulnerability in Innsbruck, particularly among tenants and low-income households in Innsbruck. From a systemic perspective, we show how sharply rising rent and energy costs not only affect the disposable household income, but also reinforce dynamics that develop within the relationship between income, stress, renunciation, and mental health. We discuss the shortcomings of a narrow focus on energy efficiency policies, which may hinder the full potential of alleviating energy poverty and lead to adverse distributional impacts on vulnerable groups. Finally, we link a range of potential leverage points for socially just policy interventions to address the challenges of housing and energy vulnerability, including measures such as the highly debated social policy of rent control.

Keywords

Low-carbon transition; energy and housing vulnerability; social justice; systems mapping; policy intervention

1 Introduction

Decarbonizing the building sector is a key priority in the European energy transition, as it is responsible for more than a third of the EU's GHG emissions (European Environment Agency, 2024). The EU's long-term strategy addresses a myriad of interlinkages with policies and initiatives, most notably the ambitious Renovation Wave initiative (EU COM, 2020) as part of the EU Green Deal (EU COM, 2019a), which contribute significantly to achieving the 2030 climate objectives as well as climate neutrality by 2050 (EU, 2018). In order to boost current energy renovation rates and efforts to phase out of fossil fuel-based heating systems, EU energy policy directives target in particular the promotion of energy efficiency (EU, 2023) and the energy performance of buildings (EU, 2024). In addition, energy efficiency is considered a key area for enhancing the living conditions of households, including the alleviation of energy poverty (Papantonis et al., 2022).

With an estimated 10.6% of the EU population (i.e. 47 million, Eurostat, 2023) unable to afford to adequately heat their homes in 2023, and 8.7 % spending 40 % or more of their household disposable income on housing in 2022 (Eurostat, 2024), however, the implementation of transition policies faces major challenges in overcoming intersecting vulnerabilities. Despite the European Green Deal's pledge to "leave no one behind" (EU COM, 2019b) and promote socially inclusive decarbonization, mainstream just transition approaches tend to underestimate the inherently plural and multi-scalar nature of energy systems' transition (Bouzarovski, 2022; S. Williams & Doyon, 2019). Phasing out of fossil energy carriers is politically challenging, place-dependent, and fraught with issues of power, political legitimacy, and equity, alongside economic and social losses (Bogner et al., 2024; Rinscheid et al., 2021). In this context, achieving a systemic perspective on vulnerability to housing as well as energy affordability, availability and quality that bridges socio-technical and social justice dimensions in low-carbon transitions will address a key research gap (Iwińska et al., 2021; Rice et al., 2020; Sareen & Haarstad, 2018). This is of specific relevance as recent studies have pointed out that energy efficiency policies can have adverse distributional impacts on vulnerable groups such as low-income tenant households, thus potentially exacerbating social inequality (Egner et al., 2021; Kaufmann et al., 2023; Woods et al., 2024). Furthermore, measures to improve the energy efficiency of buildings have been increasingly connected to the emergence of 'grey greening' as a form of low-carbon gentrification (Bouzarovski et al., 2018a; Checker, 2011; Quinton & Nesbitt, 2024). Especially in urban transition efforts, the link between energy efficiency renovation and changes in rental prices is gaining traction in terms of socio-spatial segregation, including forced displacement or eviction of low-income communities as a form of systematic 'renoviction' (Bouzarovski et al., 2018b; Busà, 2024; Long & Rice, 2019; Papantonis et al., 2022).

This study focuses on the city of Innsbruck, Austria, and explores the intersecting dimensions of vulnerability and social justice in the context of housing and the energy and heating transition by examining the social impacts of transition policies to improve energy efficiency, in particular thermal building renovation and the phasing out of oil and gas heating systems. Innsbruck provides a pertinent example for studying the intersecting vulnerabilities linked to the housing and energy cost burden in the context of the energy and heating transition, as it is the city in with one of the highest real estate prices and residential vacancy rates in Austria (Statistik Austria, 2023a, 2023b). Furthermore, with 29% it has one of the highest shares of installed fossil fuel-based heating systems in Austrian cities (Statistik Austria, 2023c), which exacerbates the issue of energy poverty. We apply a transdisciplinary approach developed within the EU Horizon project "Transdisciplinary ANd Deliberative equity appraisal of transition policies in Energy and Mobility" (TANDEM) to promote exchange and facilitate co-design and

reflective policy making with stakeholders and affected citizens to achieve more inclusive and equitable decision-making processes and outcomes. Our research integrates stakeholder interviews and policy analysis as well as the application of participatory systems mapping (Barbrook-Johnson & Penn, 2021; Sedlacko et al., 2014) and arts-based methods (Finley, 2008; McNiff, 2008; Turnhout et al., 2010) during a citizens' deliberation panel in Innsbruck to promote systems thinking, multi-actor problem identification, and co-design of policy interventions.

We pose the following main research questions: What are the challenges and obstacles to promoting a socially just energy and heating transition in Innsbruck's residential building sector? How is social vulnerability manifested and experienced by affected citizens from a systemic perspective? What are potential leverage points for policy interventions?

Our study found a wide range of challenges and obstacles to promoting a socially just energy and heating transition in Innsbruck. These relate primarily to structural conditions of the local housing, such as the lack of affordable housing options in a private real estate market driven by speculation and the lower availability of non-profit social housing compared to other Austrian cities, which increase the exposure to housing and energy vulnerability, especially for tenants and low-income households. Furthermore, from a systemic perspective of affected citizens our results show how strongly the disposable household income is affected by rising rent and energy costs, exerting serious pressure on both mental and physical health. Prioritizing income increase, however, triggers long-term balancing dynamics and lock-in effects, which calls for socially just policy interventions such as rent caps and regulations in tenancy law adapted to low-carbon transitions.

2 Materials & methods

2.1 Case study description

Innsbruck, regional capital of Tyrol in Western Austria, is one of the largest urban agglomerations in the European Alps. The development of urban tourism and the commercialization of mountain landscapes have dominated the trend towards the creation of a postmodern leisure city for years (Andexlinger et al., 2005; Haller et al., 2020). In 2024, 132,594 inhabitants, including 37,304 students, reside in the permanent settlement area of Innsbruck, which is reduced to 34% of the total municipal area due to its geographical location in the Inn valley. In addition, 27,448 people have registered a secondary residence (Stadt Innsbruck, 2024). In the first quarter of 2024, the building stock totaled 11,415 buildings with apartments, which corresponds to 79,396 residential units (Behmann, 2024a).

Although the rapidly rising demand for housing has led to significant investment in the private real estate market in Western Austria (Razen et al., 2023), the strong interest in purchasing apartments for capital investment coincides in particular with an increase of apartments held off the housing market for speculative reasons (Herrmann, 2023; Innsbruck Informiert, 2024). In the wake of this development, the city government of Innsbruck declared a "housing emergency"[1] (Balgaranov, 2022) and requested the first direct intervention in the housing market in 50 years through the Land Protection Act (RIS, 2004; Pichler, 2022). The Tyrolean Leisure Residence and Vacancy Levy Act has also been in

[1] This declaration allows the city government to conclude purchase agreements for building plots and, ultimately, even to resort to expropriation. However, the requested declaration of a housing emergency was rejected by the formally responsible Tyrolean state government in July 2024.

force since January 1, 2023 (RIS, 2023), however, the residential vacancy rate[2] remains at 8.8% in February 2024, i.e. +0.1% compared to July 2023 (Behmann, 2024b).

In addition, the state of Tyrol including the city of Innsbruck maintains one of the highest shares of installed fossil fuel-based heating systems (40% oil, and 30% gas for space and water heating) in Austria. This is important in the context of the energy and heating transition, since buildings, including fossil fuel heating systems, dominate the net CO_2 exchange in Innsbruck, alongside transport (Stampfer, 2023). Although these emissions have decreased in recent years (Lamprecht et al., 2021), the residential building sector of Innsbruck, for instance, still accounts for 40% of energy consumption (Behmann, 2023). Local and regional plans such as the "Energieplan Innsbruck 2050" (Dobler et al., 2017) or the initiative "Tirol 2050 Energieautonom" (Ebenbichler et al., 2021) aim to become independent of fossil fuels, but pursue a longer time horizon and do not contain binding political strategies. In addition to phasing out fossil fuel use, and integrating renewable energy sources, a reduction in emissions in the building sector can be achieved primarily through the thermal renovation of existing buildings and through energy-efficient new buildings in passive or nearly zero-energy building quality (Behmann, 2023, p. 31). This is further relevant with regard to energy poverty, as approximately 10,000 households in Tyrol cannot afford to heat their dwellings adequately (Stigger, 2021). The provision of affordable but also climate-friendly housing and heating is therefore a key challenge for a socially just transition pathway in Innsbruck.

2.2 Data selection, collection and analysis

Our data cover the first empirical phase (09/2023-03/2024) of the EU Horizon project TANDEM, providing information on local socio-economic context and policy settings as well as on the experiences and knowledge of affected citizens, gained during the first citizens' deliberation panel in Innsbruck.

Stakeholder interviews

In total nine stakeholder interviews were conducted between March and May 2023 (Supplementary Table 1). The composition of the interview partners reflects different expert opinions from the fields of public services and administration, energy supply and consultancy, technological innovation and research, social and non-profit housing, as well as civil and tenancy rights. The semi-structured interview guide (see Supplementary Table 2) includes case study-specific problem and opportunity questions in the area of energy and heating transition, policy targets and potential impacts on social vulnerability. Interviews were recorded with permission, transcribed verbatim, and analyzed using the software MAXQDA (version 2022.8) and a theme-centric qualitative approach as described by Braun and Clarke (2021).

Policy analysis

The aim of the policy analysis was to produce a record of key policies, including the identification of problems or issues, actors, and decision-making procedures related to the case study (see Supplementary Table 3). The analysis is based on a review of literature and documents (policies, decrees, local reports) and supported by semi-structured interviews with decision makers, policy experts and civil

[2] Based on the information from the vacancy monitoring system, the apartments surveyed (total of 40,042 corrected units) are only designated as 'vacant' if no main or secondary residence has been registered for a period of at least six months. However, due to data limitations, the analysis of vacant apartments is uncertain and may be higher.

servants. The selection of policies and regulations addresses multiple levels of governance, supranational (EU), national (Austria), regional (Tyrol), and local (Innsbruck). We focused primarily on the consistency of policy aims and proposed measures, targeted groups, governance mechanisms, and expected impacts (Supplementary Table 3). The analysis of policy documents and stakeholder interview data were then synthesized into an aggregate description of key transition policies, anticipated or unintended impacts, main political and social tensions, including the potential to exacerbate social vulnerabilities.

First citizens' deliberation panel

To involve affected citizens in the co-creation process of potential policy interventions, the first citizens' deliberation panel (three in total) was held in a local community center (ISD Stadtteiltreff Reichenau)[3] from March 2nd to 3rd, 2024. It served as a platform for citizens to voice their experiences and concerns, particularly in the context of the energy and heating transition in Innsbruck, to define significant evaluation criteria, and to identify potential policy interventions for a socially just energy and heating transition.

Recruitment and sample strategy

Recruitment for the panel started in February 2023 by drafting a stakeholder engagement strategy, which incorporated the representation of affected citizens and vulnerable groups such as low-income households, single mothers or students (Sovacool, 2021, p. 7). An online survey was distributed over two rounds of mailshots (between 12/2023-01/2024) with a total of 12,500 postal brochures to collect specific household information in neighborhoods of higher socioeconomic vulnerability, including the status of housing, building renovation, heating systems, energy poverty, impact of energy and heating transition measures. The brochures also contained information about the aims of the project and a link to register for the first deliberative citizens' panel in Innsbruck. In addition, the survey was distributed via newsletters from local initiatives, posters in ISD community centers, newspapers and posts on social media. The response rate of fully completed surveys was very low at 0.5%, but due to the heterogeneous characteristics of the respondents, a varied sample of participants was ensured for the first deliberation panel (Tables 1-2). Over the course of two days 23 citizens participated in the panel, who were compensated with 90€ worth of vouchers for a local currency (Inn-Taler GmbH, 2024).

System mapping and model analysis

The methodological design builds on the transdisciplinary research toolkit and guide developed in the TANDEM project, containing guidelines for facilitating participatory systems-mapping with arts-based methods (Pässilä et al., 2023).

The development of CLDs helps to make mental models explicit from the perspective of affected citizens by promoting the visual representation of hypothesized system elements, their interconnections within certain system boundaries, and the purposes that drive the system (Meadows, 2009; Sterman, 2002). Given that identified circular chains of causal connections between elements do not necessarily follow a linear path, feedback loops emerge from connecting multi-variables with causal links within the mapped system (B. Williams & Hummelbrunner, 2010). In addition, they indicate the ultimate effect of an action on a variable, defined as either reinforcing (positive polarity, i.e. circular chain maintains reinforcing changes) or balancing (negative polarity, i.e. the circular chain ends in a different

[3] The ISD (Innsbrucker Soziale Dienste GmbH: www.isd.or.at) covers a comprehensive care program of social services in the provincial capital of Innsbruck. The district work is concentrated in nine community centers, which are places of encounter, exchange and networking.

direction from where it has started) mechanisms (Schaffernicht, 2010). By disclosing feedback loops, CLDs can further exhibit potential leverage points (i.e. places to intervene in a system) for policy support (e.g., Han et al., 2023; Suno Wu et al., 2021). Here, we applied a combination of the systems thinking oriented leverage point framework proposed by Meadows (1999) and Abson et al. (2017) and the network theory guided framework by Murphy and Jones (2020).

The facilitation script for the first citizens' deliberation panel (Supplementary Table 6) further integrated collective voicing through polyphony, valuing the diversity of participants' backgrounds, opinions, and interpretations. Arts-based methods (Finley, 2008; McNiff, 2008) such as the introduction of personas (Ali & Rogers, 2022), games and visual media were used to motivate the experience of system dynamics and to create shifts in deliberation through metaphor and symbolism that encourage creative and meaningful engagement rather than purely cognitive discussions. The incorporation of arts into research has proven fruitful to the requirements of intersectional research, as creative engagement allows for deeper emotional integration, comprehension and articulation of "tacit, embodied, and complex experiences of exclusion" (Margolin et al., 2017, p. 386). The playful approach, adding to one's own position the use of four different personas, allowed participants to communicate further perspectives on local challenges, problems and needs, exploring both current realities and future possibilities, without the pressure for consensus. This ensured that a diversity of human and non-human voices was heard, and new ideas surfaced organically. A visual documentation of the panel is shared on Recapsy (link).

The sequence of the first citizens' panel is outlined as follows:

In a first step, the citizens formed groups of four to five people based on similar housing situations. Commonly experienced personal challenges and problems related to housing and/or domestic energy use were discussed in these groups and documented as possible variables, after which the variables were presented in plenary and clustered. In this process, the facilitation team inquired about explicit and implicit effects to enable a translation of the listed challenges into mappable variables with as little deviation as possible from the citizens' formulations. A total of 54 variables underlying the problem descriptions were translated and bundled into main problem clusters. In a second step, three individual citizens' groups subsequently developed CLDs, focusing on one of the following systemic problem clusters: (A) How do the housing emergency and rising rents affect my own housing situation?; (B) How do high energy costs affect my everyday life?; (C) What options do I have for shaping my living environment? Citizens had the option to prioritize the variables underlying the problem description, including the addition or exclusion of variables during the mapping exercise. Each citizens' group was facilitated by one to two research team members, who were instructed to encourage a structured approach.

The developed system maps were then digitized and analyzed using the Vensim PLE software (version 10.1.3) and the online relationship mapping tool KUMU (kumu.io) (see Supplementary Table 5 for full description of the feedback loops). Model simplification was achieved by labelling the exogenous variables and focusing on feedback loop procedures corresponding to selected dynamic behavior (Asif et al., 2023; Eberlein, 1989). In addition, to visually enhance CLD simplicity and comprehensibility of systemic issues, we applied color coding and realigned the dynamics in Adobe Illustrator 2024.

3 Results

3.1 Challenges and obstacles to promoting a socially just energy and heating transition in Innsbruck

In total, we have identified nine thematic clusters and 46 associated factors for challenges and obstacles to promoting a socially just energy and heating transition, including references to the impact dimensions 'housing vulnerability' and 'energy vulnerability'. The explicit perspective of stakeholders and citizens is visualized in Fig. 1 and Fig. 2 respectively, with the main thematic clusters of challenges shown in the innermost circle and the associated sub-challenges in the outer rings. Furthermore, challenges are linked to five key dimensions of social justice: distributive, procedural, recognitional, and intergenerational justice as well as intersectionality (for details see Supplementary Table 4).

The first key finding highlights structural conditions that significantly increase the exposure to housing and energy vulnerability in Innsbruck, particularly for tenants, low-income households, elderly and chronically ill people, migrants, single mothers and young people. Escalating housing expenses, including rents and costs for electricity and heating, the lack of affordable housing options, and the lower availability of non-profit social housing compared to other Austrian cities such as Vienna, are articulated as a bundle of key challenges by both stakeholders and citizens. The unequal distribution of capital power is particularly reflected in the relationship between property and apartment owners, landlords, investors and speculators on the one hand and tenants on the other. Based on this precondition, the current and planned energy and heating transition policies are interpreted – both potentially positively and adversely – in terms of their additional impact dimension on housing and energy vulnerability. From a social justice perspective, these issues are highly intersectional and distributional, particularly in terms of access to affordable housing or the distribution of costs between landlords and tenants. Citizens and civil society organizations also underline the issue of recognition, which calls for a stronger representation of the needs and demands of vulnerable groups such as low-income households.

While both stakeholders and citizens recognize operational housing expenses and transition costs – especially in terms of investment – as key challenges, their perspectives differ in terms of priorities and approaches. Despite acknowledging various technological and infrastructural boundaries, there is a broad consensus among the stakeholders interviewed on the overarching goal of implementing technology-oriented solutions for the energy and heating transition. The lack of incentives for landlords and residential property owners to refurbish buildings and to exchange heating systems, however, is cited a core affordability concern (Fig. 1). Here, stakeholders address a broad range of interlinked, mostly hindering factors at policy, law/regulation level: (1) multi-level policy target deviation and political lagging especially at local scale; (2) legal barriers, e.g. the Residential Property Act (P12) poses challenges in decision-making in co-owned multi-unit houses; construction codes and monument protection law restrict the potential of solar panel or heat pump installation in inner-city areas; and bureaucracy and data protection hinder the development of efficient measures to curb the residential vacancy rate. Furthermore, the current situation between non-binding political strategies (e.g. P4, P6, P7, P8, P10) and, in other cases, rigid regulations (e.g. P1, P12) create planning and decision-making uncertainties, slows down and individualizes the energy and heating transition in Innsbruck, by relying primarily on financial incentives and owners' and landlords' willingness to initiate and finance heating exchanges or thermal renovations.

The citizens who participated in the deliberation panel reflected above all the impact on their own living situation. The rising costs of rent and energy (heating/cooling, electricity) in particular have a

negative impact, creating a constant situation of uncertainty. They can deteriorate the financial situation and increase exposure to vulnerability in case of rent debts, back payments and energy debts. In this context, citizens mentioned an increasing fear of losing their home and, due to a lack of affordable housing, the need to consider moving to neighboring districts of Innsbruck. The 'quality of life' cluster most strongly illustrates the citizens' perspective by mapping the relationship between energy and housing vulnerability with significant health concerns (Fig. 2). Mental strain, as voiced particularly by vulnerable citizens is exacerbated by the current legal situation and the relatively low agency of tenants in contrast to landlords, apartment and property owners: their options for claiming thermal building renovation or heating replacement are practically excluded, should the latter be reluctant – indicating procedural issues due to the low level of agency in decision-making on household level. Yet, citizens also acknowledge a lack of incentives for landlords to actively promote energy efficiency in buildings by renovating and/or replacing heating systems. In addition, the quality of life is also affected by physical health problems, e.g. mold, extreme temperatures, and drafts. The options for action are in practice very limited to implementing energy-saving measures individually (e.g. energy sufficiency by renunciation of cooling/heating) or applying for public subsidies for rent, electricity or gas. In summary, the concerns expressed by citizens primarily reflect the immediate impacts on daily living conditions and accentuate, particularly manifest in the example of health, not only concerns about intersectionality, distributional, procedural and recognitional injustice, but also a pronounced form of intergenerational inequity, which is underlined primarily by concerns over the future of their own children.

3.2 Systemic perspectives

Due to strong thematic overlaps and complementarity within the systemic problem cluster groups (A) regarding rising rents and availability of housing and (B) regarding rising energy costs, the allocated variables and dynamic relationships were merged in Fig. 3 (see Supplementary Fig. 1-2 for individual CLDs). This extended CLD A+B contains 31 variables (including one exogenous variable) and 529 causal links, resulting in 180 differentiable dynamics, of which 75 are balancing and 105 are reinforcing feedback loops (see Supplementary Table 5).

Overall, CLD A+B is characterized by nested loops and counteracting reinforcing and balancing dynamics, indicating a strong presence of lock-in effects. The first key variable affected by rising costs of rent and energy (heating, electricity) is disposable household income, from which a series of direct and indirect effects are captured in 161 dynamics. The second key variable is mental health, captured in 152 dynamics. By aggregating the dynamics containing these two key variables, all 30 of the endogenous variables are covered. They primarily influence dynamics that exert pressure to save money and regulate the available budget for household expenses and leisure activities.

Focusing on disposable household income, six dynamic clusters emerge that contain both reinforcing and balancing feedback loops regarding the availability of money for leisure activities and food as well as pressure to save money, especially for rent and energy dispenses. While there are several balancing dynamics that indicate a system's stability (see for instance feedback loop B73: the higher the disposable household income, the lower the pressure to save money), they can also be counterproductive by promoting lock-in effects. Most strikingly, if rent increases only slightly and disposable household income falls as a result, this can have a negative effect in the long-term as a negative dynamic is set in motion. This is particularly critical for low-income households, as the pressure to save and earn more money will increase notably if income continues to fall (B15B). This situation leads to either spending less money on, for example, food and pleasant leisure activities and/or increasing the number of working hours to raise the disposable household income. At the same time, prioritizing the increase in

household income only shows a positive effect in the short-term, as it is connected to balancing dynamics that can reverse this effect, resulting in a deterioration in the systemic conditions for health and quality of life. Hence, income related lock-in effects due to balancing dynamics are often directly linked to the pressure to save energy, which can specifically cause freezing (B18E) or mold formation (B19E) in the home, and in turn has a direct negative effect on physical health.

Although health issues are generally linked to the household's disposable income, citizens made a clear distinction between physical and mental health, emphasizing that the latter is directly linked to stress, worries (distress), and the need for psychological support. Once mental health is triggered to increase or decrease, it shows great potential to create a virtuous or vicious cycle, continuously reinforcing the initial signal of the trigger, thus emphasizing the characteristics of reinforcing behaviors. Other elements of the total 70 reinforcing dynamics linked to mental health are, for instance, a sense of insecurity and helplessness, fear of excessive costs, including the cost of psychological counselling. However, all these elements are part of rather vicious short or long feedback loops whose reinforcing capacity can ultimately lead to fear of losing one's apartment (loss of existence) and stress (R97), as well as constantly mounting pressure to save and earn more money while reinforcing worries or distress (R75B).

As a result, mental health is also part of a bigger reinforcing structure through disposable household income, renunciation of pleasant leisure activities, and pressure to earn or save more money, which affects how much people worry and develop existential anxiety impacting stress levels. Since several reinforcing dynamics are linked to balancing ones, there is a potential that the dynamics of the balancing loop (B38B) can also be reinforced (R5E), amplifying the oscillation, and/or at some point the reinforcing dynamics take over the balancing dynamics and drive the system towards one direction, following an overall growing or decreasing trend (potentially with oscillations). Other balancing effects, such as physical health and the ability to spend money on pleasant leisure activities, also set limits to the reinforcing dynamic of earning more money.

In the CLD of the systemic problem cluster group (C) regarding agency in shaping one's living environment, the citizens mapped 21 variables (including 12 exogenous variables) in a total of 16 feedback loops, all of which represent reinforcing dynamics (see Fig. 4; Supplementary Table 5 for a full description). This means that once the system gets triggered in one direction, it continuously replicates this dynamic until either a limit is reached, or another exogenous trigger starts driving the dynamics in the other direction. The structure of the CLD C shows two parallel dynamics: a short reinforcing loop addressing the building's community and the importance of social contacts for creating a sense of community (R13); and a cluster of various intertwinements ranging from health to conflicts with the landlord, strongly defining the personal satisfaction with the current housing situation. The two dynamics are connected by variables outside of these feedback loops in a reciprocal behavior, i.e. the emergence of one vicious cycle drives the others (see violet links and variables in Fig. 4).

In general, CLD C demonstrates dynamics that are embedded in very strong structures. The energy efficiency of a building and the need for thermal renovation, for instance, have a direct influence on personal satisfaction with the housing situation; the worse the building's condition, the lower the satisfaction, which can lead to conflicts with the landlord and consequently affect both direct (R9) and indirect (R6A) mental health. Ultimately, mental health is also a key variable in CLD C, directly connected to 13 of the 16 loops. The dynamic between mental health and stress (R10), for example, also highlights the dominant character of direct dynamics (six loops) of CLD C.

The second key variable connected with nine loops and specific to this cluster group is personal satisfaction with the housing situation. It is directly influenced by six variables, including endogenous variables such as conflicts with the landlord, mental health and stress, as well as by variables exogenous of feedback loops. Therefore, despite not being part of a loop, the sense of dependency on the landlord's decision-making is deliberated by citizens also as a key variable, as it is not only influenced by many other variables exogenous of feedback loops, but affects stress and satisfaction with the housing situation, and thus significantly drives the reinforcing dynamics of the system. Furthermore, variables such as sense of dependency on the landlord's decision-making and willingness of the landlord to cooperate illustrate the often-asymmetrical power relationship and the tenant's lack of agency in decision-making, which in turn determines the potentially tense and conflict-prone relationship between tenants and landlords. The feeling of powerlessness was emphasized by the participants several times regarding the request for thermal renovation or the replacement of fossil heating systems, which in summary suggests that the influence of system dynamics on the variables linking the feedback loops tends to be less than their influence on the system.

3.3 Assessing leverage points promoting a socially just energy and heating transition

For policy development, it is critical to align reinforcing dynamics with the desired goal and to break causal relationships with external variables to initiate changes in direction. Furthermore, breaking systems structures that drive vicious circles or lock-in the system through balancing behaviors, for instance, can create long-lasting transformative change. In general, targeting highly connected variables and those that are linked to many dynamics can affect the system on a larger scale and strongly drive system behavior. Following the question of how to influence the behavior of a system, we follow Meadows' (1999) twelve leverage points, which Abson et al. (2017) further aggregated to four broad types of system characteristics that interventions can target: parameters, feedbacks, design, and intent. These leverage points are embedded in a hierarchical order, ranging from 'shallow' (e.g. subsidies, taxes) to 'deep' (e.g. power to transcend paradigms) transformational structural changes.

Based on our results, different potential leverage points targeting systemic behavior emerge. They stem from stakeholder perspectives as well as deliberated interventions proposed by citizens, and span from implemented or planned policies and measures to community building activities (see Table 3, and Supplementary Table 3 for specific policy information). In summary, the following findings can be derived with respect to the four aggregated system characteristics:

- **Parameters:** The effects of changing parameters are generally limited, depending on the size of the change and which loops are affected by it. If a parameter of a reinforcing dynamic is changed, this alteration perpetuates itself and can have a larger effect in the long run (Abson et al., 2017, p. 32). Interventions proposed by both stakeholders and citizens range from subsidies for rents, energy-efficient devices including VAT reduction, and energy cost caps to structural changes such as district heating network expansion and improvement. Subsidies are considered 'shallow' leverage points having immediate, albeit limited, impact on the system's behavior by adjusting certain economic incentives or cost factors.
- **Feedbacks:** Due to the high number of lock-in effects in CLD A+B, leverage points are particularly important where a large number of feedbacks are potentially producing negative or positive social effects. Promoting the enforcement of policies, such as the Renewable Heating Act (P3) or the Act on the Improvement of Energy Efficiency (P5) which include subsidies for the replacement of fossil heating systems and thermal building renovation, focus on negative feedback loops. Instead, many stakeholders propose more research on technological

fixes and energy efficiency or an adaptation of spatial zoning for social housing units for driving positive feedback loops.

- **Information flows and rules (design):** Interventions focus on improving the structure of information flows in terms of obligation to transparency and information exchange for various actors, including local governments, landlords and tenants. The examples for changing the rules of the system are more powerful than parameters and feedbacks, as they have greater influence on the decision-making and the behavior of key stakeholders, such as landlords. They range from energy cost caps to legislative adjustments for the mandatory replacement of fossil fuel heating systems in existing buildings to obligations to thermally refurbish buildings. Citizens also emphasize the need to strengthen community building and create more consumption-free common spaces in the neighborhood. In terms of decision-making power, the need to institutionalize mechanisms for meaningful public participation in policymaking was raised by both stakeholders and citizens.
- **System goals and paradigms (intent):** Changing system goals or paradigms represent 'deep' leverage points and require a redefinition of the system's underlying objectives, such as a shift from a market-driven towards a sustainability and equity driven energy and housing policy. Measures such as a dividend waiver for electricity suppliers require a radical mindset shift from maximizing economic efficiency to acknowledging energy as a common good that is essential to the long-term societal well-being.

4 Discussion and conclusion

4.1 Low-carbon energy and heating transition faces vulnerability and social justice issues for disadvantaged groups in rental housing

This study focused on the decarbonization efforts in Innsbruck's housing sector, which demonstrates potential for inadvertently contributing to increased vulnerability and injustices, particularly for low-income households with rental contracts in buildings with low energy performances.

Among the interviewed stakeholders, technological innovation and infrastructural expansion dominated suggested pathways to promoting the energy and heating transition. The focus on energy efficiency and the promotion of research and development in technology mirrors the national and regional transition strategies, building on partial regulation (P3, P5), information (P7-P10), and targeted incentives for improving the energy efficiency of buildings (P4, P6). Nevertheless, studies have also explored the risk of energy efficiency policies hindering the alleviation of energy poverty (Papantonis et al., 2022) and leading to adverse distributional impacts on vulnerable groups (Woods et al., 2024). In this context, there is lack of deeper understanding how vulnerability is experienced by affected citizens from a systemic perspective. We found that rising costs of rent, utilities and energy consumption are exerting considerable financial pressure on disadvantaged groups, driving them into precarious situations that can lead to worry, existential fears of loss and health problems. Our findings with the increasing presence of emotional experiences in housing and energy vulnerability, emphasizing emotions as relational practices (Ambrose et al., 2016; Grey et al., 2017; Longhurst & Hargreaves, 2019). In addition to the distributional issues targeting mainly costs, there are also procedural issues raised by tenants (Seebauer, 2021). Our findings on systemic problems resonate here, emphasizing that vulnerable groups frequently bear a disproportionate brunt of energy transition costs and experience a lack of decision-making opportunities and misrecognition, for example through exclusion from policy support schemes (Heffron, 2022; McCauley et al., 2019; Papantonis et al., 2022). Finally, our results show several potential leverage points for socially just policy interventions to bridge the

challenges of housing and energy vulnerability, including measures such as the highly debated social policy of rent control (Kholodilin, 2024).

In the context of housing, we draw specific attention to the "landlord-tenant dilemma" or "investor-user dilemma" (Ástmarsson et al., 2013; Gillingham et al., 2012), as the limited agency of tenants in decision-making coupled with the reluctance of private landlords' behavior to cooperate and invest in energy efficiency upgrades (Hope & Booth, 2014; Miu & Hawkes, 2020), can lead to severe deterioration in living conditions (Müller et al., 2024). The dilemma's causes are complex and, to some extent, under-researched. However, the problem of asymmetric information and 'split incentives' between landlord and tenant, which emphasizes the former as the 'principal agent' of investment (Ambrose & McCarthy, 2019) but does not directly benefit from the advantages of energy-saving or thermal comfort, is crucial (Gillingham et al., 2012; Melvin, 2018). From the landlord's perspective, insufficient financial incentives for implementing energy efficiency measures, combined with regulatory barriers such as local heritage protection or Austria's Tenancy Rights Act (P12), exacerbate the issue by limiting the landlord's capability to act – which ultimately raises the question of who is willing to pay (Bird & Hernández, 2012; März et al., 2022). These challenges highlight the broader systemic issue of financial and legal frameworks that fail to align the interests of both landlords and tenants with the goals of a just energy transition.

In accomplished cases of energy renovation, a recurring phenomenon of 'green gentrification' has been observed. Here, energy efficiency improvements lead to rising property values and potentially to socio-spatial segregation and displacement of low-income tenants (Bockarjova et al., 2020; Bouzarovski et al., 2018b). Furthermore, Rice et al. (2020) and von Platten et al. (2022) highlighted how associated transition costs are often transferred to tenants, for instance, via rent increases. Despite expected energy savings from improved building efficiency, the total household expense finally outweighs the financial low carbon induced benefits. While there is clearly a lack of studies to support this claim for the city of Innsbruck, the panelists and stakeholders reported increased exposure of social segregation due to rising rents associated with higher building standards and energy efficiency upgrades. This particularly affects vulnerable groups as Innsbruck confronts a situation of limited social housing alternatives in comparison to other Austrian cities, ultimately exacerbating both housing and energy poverty.

Tied closely to both the issues of energy efficiency and green gentrification are rebound effects, in which the expected reductions in energy consumption from efficiency measures are partially offset by increases in energy use due to behavioral or systemic responses (Papantonis et al., 2022). For example, households may use more energy as a result of lower operational costs from energy-efficient technologies, negating the intended environmental benefits (Müller et al., 2024). The rebound effect thus complicates the relationship between energy efficiency improvements and social outcomes. As Galvin (2015) notes, these effects are significant because they disrupt the straightforward reciprocal relationship between energy efficiency gains and reductions in energy consumption. Linked to green gentrification, these rebound effects may also be reproduced by new incoming upper-income residents, who demonstrate a higher consumption behavior of energy than low-income households (Rice et al., 2020). Instead of focusing solely on reducing rebound effects, policymakers need to address the underlying issue of high energy consumption itself, which remains prevalent even in more energy-efficient buildings (Guzzo et al., 2023). This suggests that more comprehensive policies are needed, not only to improve building and appliance energy performance but also to ensure that behavioral adaptations align with energy-saving goals.

Another compelling finding is the role of mental health in exacerbating or alleviating the impacts of energy transition. Mental health is strongly interconnected with the aforementioned factors, in particular rising costs and poor housing conditions, forming a feedback loop that amplifies vulnerability. This aligns with studies showing that low socioeconomic status is associated with higher prevalence rates of mental disorders (and therefore need for psychological counselling) and lower treatment access (Niemeyer & Knaevelsrud, 2023). Mirroring Longhurst and Hargreaves's (2019) findings, citizens partaking in the deliberation panel expressed feelings of stress, anxiety, and fear of existential loss, which were exacerbated by rising rents and energy costs. This stress, in turn, negatively impacted their mental and physical health, creating a reinforcing cycle of financial and emotional hardship. The reinforcing dynamics associated with poor mental health thus create a vicious cycle where financial strain and psychological stress feed into one another, exacerbating social vulnerabilities. This is in line with existing research showing that individuals with lower income are more prone to mental health issues, and the financial burden of accessing therapy can lead to higher dropout rates from treatment (Bugatti et al., 2023).

4.2 Addressing limitations and their potential impact on the results

The first limitation of our study relates to the response rate in recruitment, which is relatively low compared to the number of invitations distributed. The results are not representative from a quantitative perspective, but they do offer a strong qualitative insight into local vulnerability experiences due to the focus on disadvantaged groups.

The second limitation relates to the chosen participatory approach to systems mapping, which affects quality and consistency and sometimes also contains contradictory or implausible causal relationships, largely due to the inclusion of non-experts and time constraints in the panel sessions. Furthermore, the developed CLDs do not contain information on the individual loop strength, which is an empirical shortcoming. Understanding how strong the reinforcing behavior is compared to the balancing one and how large the interventions should be at certain points, can be useful to better clarify points and strengths of interventions. According to Meadows (1999) driving reinforcing loops into the desired direction leads to more transformative results than strengthening balancing loops. This means that changes should target reinforcing dynamics by changing their direction. Combining this approach with Murphy and Jones' (2020) insights on connectivity of certain variables, makes mental health a point of high leverage in all the groups, as this is highly connected to the potential of virtuous or vicious dynamics. In addition, according to Meadow's (1999) changing system's structure, physical and social structures (e.g. information flows) can also lead to transform systems. In our case, this could mean providing citizens with more information and thereby also reducing their anxiety and increasing mental health.

4.3 Implications for further research and policy suggestions

The study highlights structural lock-in effects that perpetuate housing and energy vulnerabilities, driven by systemic inequalities and policy gaps. Moving forward, policies need to gradually shift their focus from energy efficiency towards ensuring equitable access to affordable housing and energy services. The participatory systems mapping, and deliberative citizens' panel used in this study can help to ensure that the voices and experiences of vulnerable groups are heard and included in policy design. Moreover, reinforcing community-building initiatives and enhancing tenants' agency in energy decision-making processes could foster more resilient and inclusive energy systems. Health issues, in particular mental health strain, which are associated with poor housing quality, distress and worries, emerged as a very sensitive topic that is largely overlooked by current policies. From a systemic point

of view, reducing the mental distress of vulnerable population groups is one of several options for breaking negative feedback loops that exacerbate social vulnerability. According to Bugatti et al. (2023), measures to reduce the costs associated with mental health support and ensure faster access to therapies are considered particularly efficient in alleviating some of these reinforcing negative cycles. This directly addresses mental health, but also influences income dynamics, which in turn has short term-positive effects and does not alter the system's behavior in the long-term.

Improving energy efficiency of buildings by retrofitting energy-saving measures requires a significant change in the investment behavior of private landlords (Ambrose & McCarthy, 2019). Policymakers need to address the challenges faced by landlords, provoked particularly by high upfront costs and low prospective returns on refurbishment investments, coupled with bureaucracy and lack of knowledge (Hope & Booth, 2014; Miu & Hawkes, 2020). New incentives guaranteeing that not only landlords and property owners, but also tenants potentially benefit from these improvements could offset the disproportionate cost burden currently shouldered by tenants. In addition, addressing rent control and ensuring that energy efficient renovations and upgrades do not disproportionately impact low-income tenant households are essential steps in mitigating green gentrification dynamics (Bengtsson & Kopsch, 2019) and consequently promoting a socially just transition. Although there is a great consensus in scholarship that rent control is effective in fostering resilience for low-income households, it is also tied to undesired effects such as potential deterioration in the quality of housing due to less market-based incentives, resulting in less interest in investment in housing by the private sector (Kholodilin, 2024). As a counter-strategy, we see a need for a transformative paradigm shift that orientates more towards Abson's (2017) 'intent' leverage points, such as spatial zoning for the construction of social housing (Granath Hansson, 2019). In addition, strong legal standards and financial incentives for the energy efficient construction of public housing and support for private investors engaged in social housing development are necessary to fulfill benefits of both energy efficiency and social inclusion (Desvallées, 2022).

Finally, approaches that support a participatory and careful analysis of these specific challenges are very beneficial to reveal existing blind spots of systemic relationships, while also promoting dialogue and social learning which is a key part of sustainability transitions. Despite the above-mentioned methodological challenges of conducting participatory systems mapping with non-experts mentioned above, we assert that these formats, if well-designed, can promote procedural and recognitional aspects of justice and contribute to improving policy design processes that lead to more fair, balanced and legitimate approaches.

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6 Declaration of Interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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8 Tables

Table 1. Sample comparison of recruitment survey respondents and citizens' deliberation panel participants

QUESTIONS	MEAN		STANDARD DEVIATION		P-VALUE
	Respondents	**Participants**	**Respondents**	**Participants**	
AWARENESS	3.114754098	3.0666667	1.2	1.1	0.879668
INTEREST	1.6	1.6875	0.9	0.9	0.731957
HOUSING SIZE*	70.84166667	28.4	72.71875	27.5	0.000466
HOUSEHOLD SIZE	2.283333333	2.0625	1.1	0.9	0.411692
HOUSEHOLD COMPOSITION	0.767857143	0.4	1.1	0.8	0.141714
SPACE	0.879310345	0.8	0.6	0.5	0.592429
OWNERSHIP LODGING	0.95	0.75	0.6	0.6	0.246671
TENANCY CONTRACT	1.044444444	1	1.3	0.9	0.874438
OWNERSHIP II	2.050847458	1.4	1.875	1.6	0.173889
BUILDING FABRIC*	1971.027273	30.3	1971.6786	23.4	$1.19307e^{-10}$
BUILDING CONDITION	2.309090909	2.25	1.1	1	0.838201
RENOVATION HOUSING COST CHANGE*	0.272727273	0	0.6	0	0.000683
RENOVATION ANNOUNCEMENT COST CHANGE*	0.333333333	0	0.5	0	$2.039e^{-06}$
HEATING SYSTEM	2.049180328	2.25	1.6	1.8	0.688327
HEATING EXCHANGE	0.107142857	0.3333333	0.4	0.7	0.231359
IMPACT RISING ENERGY COSTS ON INCOME	1.535714286	1.1333333	0.9	1	0.158061
INCOME	1953.965116	1750.5	997.5	1,000.0	0.475178
DISPOSABLE INCOME	1.527777778	1.7272727	0.9	0.7	0.347756
IMPACT RISING RENTS ON INCOME	1.979166667	1.75	1.3	1.4	0.559765
EMPLOYMENT	1.3	2.2666667	1.8	1.8	0.067984
EDUCATION	3.929824561	4.1333333	2.2	2.2	0.744469
GENDER	0.474576271	0.625	0.5	0.5	0.294449
AGE	39.25	35.78125	12.7	15.07416358	0.407450

*) Statistically relevant differences between the two sets, determined with a two-sample t-test for each of the questions with a p-value below 0.05.

868 **Table 2.** Demographics of the citizens' deliberation panel participants

AGE	GENDER	HOUSE-HOLD SIZE	HEATING SYSTEM	BUILDING COMPLITION	INCOME PER MONTH	INCOME COVERING BASIC EXPENSES (DISPOSABLE INCOME)	IMPACTED BY RISING ENERGY COSTS	IMPACTED BY RISING HOUSING COSTS
55-64	male	2	fossil	1991-2000	2001-3000	Exceeds (low)	yes	no
25-34	female	3	fossil	1991-2000	1001-2000	Equals (none)	yes	yes
25-34	female	2	fossil	(old)	2001-3000	Exceeds (medium)	no	yes
25-34	male	4	-	1971-1980	3001-4000	Exceeds (medium)	yes	yes
25-34	male	2	solar	(new)	501-1000	Exceeds (low)	no	no
25-34	female	2	-	1981-1990	2001-3000	Exceeds (high)	no	n/a
18-24	female	3	combination	1941-1950	501-1000	Exceeds (medium)	no	no
35-44	male	1	fossil	1971-1980	3001-4000	Exceeds (medium)	no	no
45-54	female	2	fossil	1951-1960	-	Equals (none)	yes	no
65+	female	1	biofuel	1961-1970	501-1000	Equals (none)	no	no
18-24	female	2	electric	1961-1970	501-1000	-	no	yes
25-35	female	1	biofuel	Before 1940	-	Equals (none)	n/a	n/a
-	male	3	district	1951-1960	-	Equals (none)	yes	n/a
18-24	female	2	electric	1981-1990	1001-2000	Equals (none)	no	n/a
55-64	female	1	district	2011-today	501-1000	Does not cover (none)	yes	yes
55-64	male	1	fossil	1961-1970	1001-2000	Equals (none)	no	no

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871 **Table 3.** Matrix of potential leverage points in the context of housing and the energy and heating
872 transition

System characteristics (Abson et al. 2017)	Places to intervene in a system (Meadows 1999)	Degree of effectiveness (12=lowest; 1= highest)	Leverage points indicated by		
			Stakeholders (S)	Stakeholders & Citizens (S/C)	Citizens (C)
Parameters	Parameters (e.g. subsidies, taxes, standards)	12	- Full coverage of energy-efficient appliances particularly for low-income households	- Heating and energy-saving allowances - Increase in subsidies for fossil-fuel heating exchange and building renovation for landlords	- Heating and energy-saving subsidies - Reduced VAT on energy-efficient devices - Rent subsidies
	The size of buffer stocks, relative to their flows	11	n/a		
	The structure of material stocks and flows	10	- Expansion of social housing	- Expansion and improvement of the district heating network	- Renewable energy supply for all public buildings
Feedbacks	The length of delays, relative to the rate of system change	9	n/a		
	The strength of feedback loops with negative polarity	8			- Promoting the enforcement of transition policies (e.g. EWG, EEffG)
	The gain around driving feedback loops with positive polarity	7	- Research on technological fixes and energy efficiency		
Design	The structure of information flows (access to information)	6	- Transparency obligation to improve planning of district heating networks - In-house publication of energy consumption to ensure comparability and incentivize energy-savings	- Information for tenants on energy conserving behavior (public energy consultancy) - Information of viable transition pathways for local governments	- Provision of information for landlords and property owners on current policies and subsidies - Organization of joint activities for tenants of a building, including the provision of common spaces
	The rules of the system (such as incentives & constraints)	5	- Subsidies for residential construction linked to life cycle costs instead of construction costs - Linking rent increases to energy efficiency (increases only permitted above a certain energy standard) - Rent regulations in new buildings	- Energy cost caps (e.g. via price-limit for feed in) - Update of building regulations (e.g. passive house standards for newly constructed buildings) - Obligation for landlords to thermally renovate buildings - Law for the mandatory exchange of fossil heating systems in existing buildings - Stricter rent regulations: rent increases; prohibition of increases for the duration of the tenancy proposed by citizens; ban of rent increases after renovation) - Regulation of district heating (prices, expansion)	- Financial incentives to save energy - Provision of space for leisure activities without the compulsion to consume - Development of residential meeting points in the neighborhood without the compulsion to consume - Organization of get-togethers in neighborhoods with free activities for children
	The power to add, change or self-organize system structure	4	- Institutionalize mechanisms for citizens to participate in policy-making - Increased recruitment and training of labor for energy and heating transition		- Institutionalize mechanisms for enhancing information exchange for tenants of a building
Intent	The goals of the system	3	- Dividend waiver for electricity suppliers		
	The mindset/paradigm out of which the system arises	2	- Spatial zoning promoting the construction of social housing - Promotion of energy sufficiency - Set national targets for reducing energy poverty		
	The power to transcend paradigms	1	n/a		

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9 Figures

List of (short) figure captions

Fig. 1 Stakeholders' perspective on local challenges and obstacles of the energy and heating transition

Fig. 2 Citizens' perspective on local challenges and obstacles of the energy and heating transition

Fig. 3. Merged causal loop diagram (CLD A+B) on housing and energy vulnerability from an affected citizens' perspective

Fig. 4. Causal loop diagram (CLD C) on the citizens' capability to influence the own housing situation

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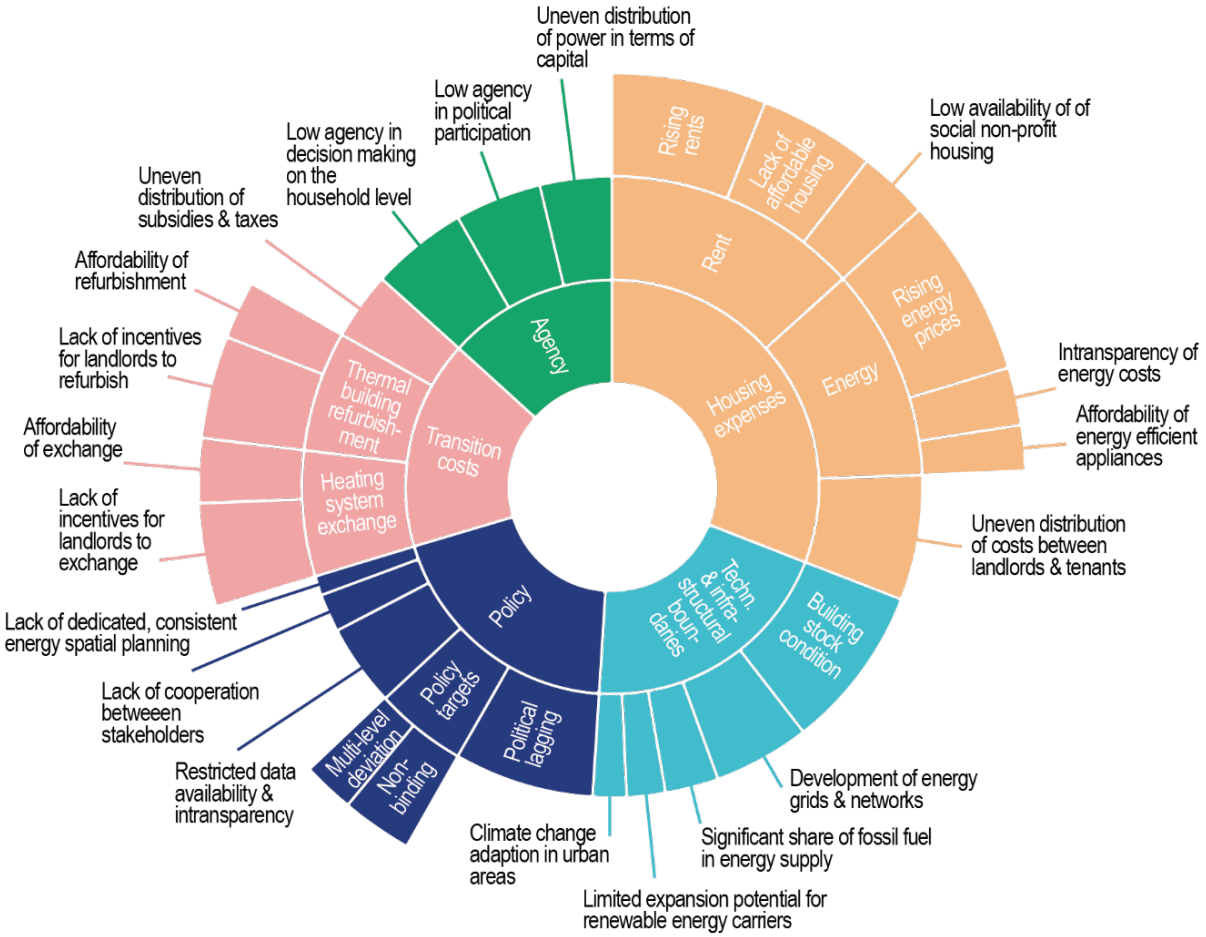

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885 **Fig. 1** Stakeholders' perspective on local challenges and obstacles of the energy and heating transition

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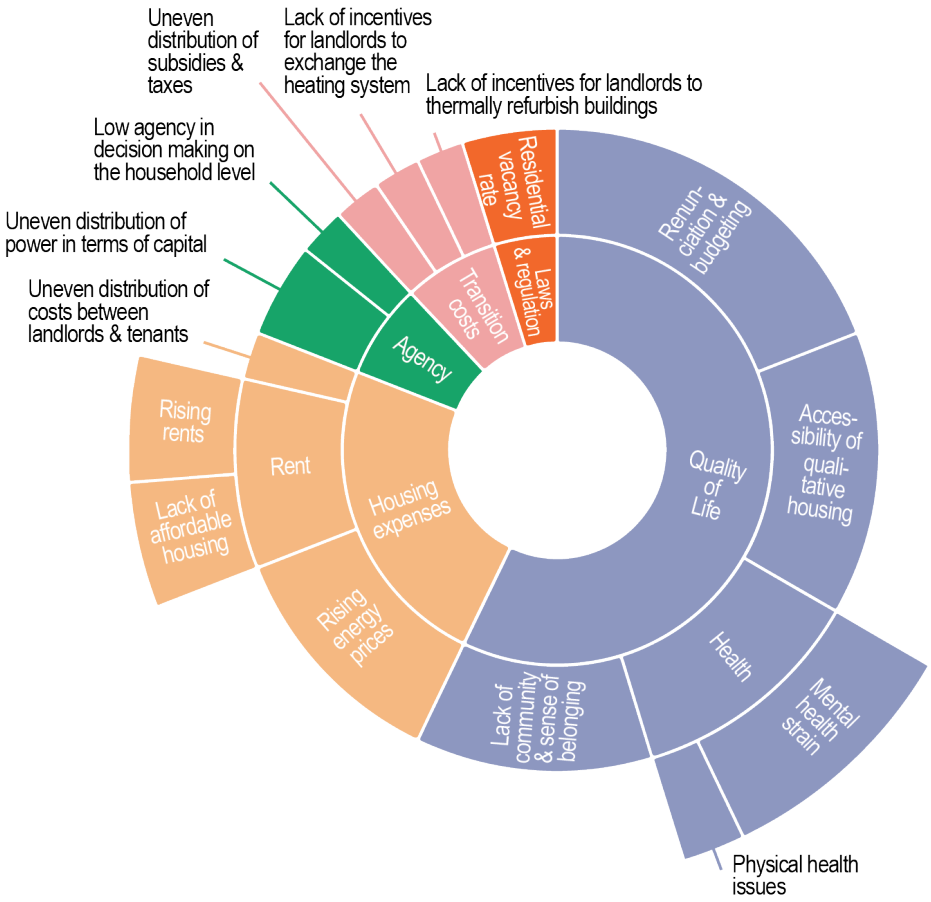

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891 **Fig. 2** Citizens' perspective on local challenges and obstacles of the energy and heating transition

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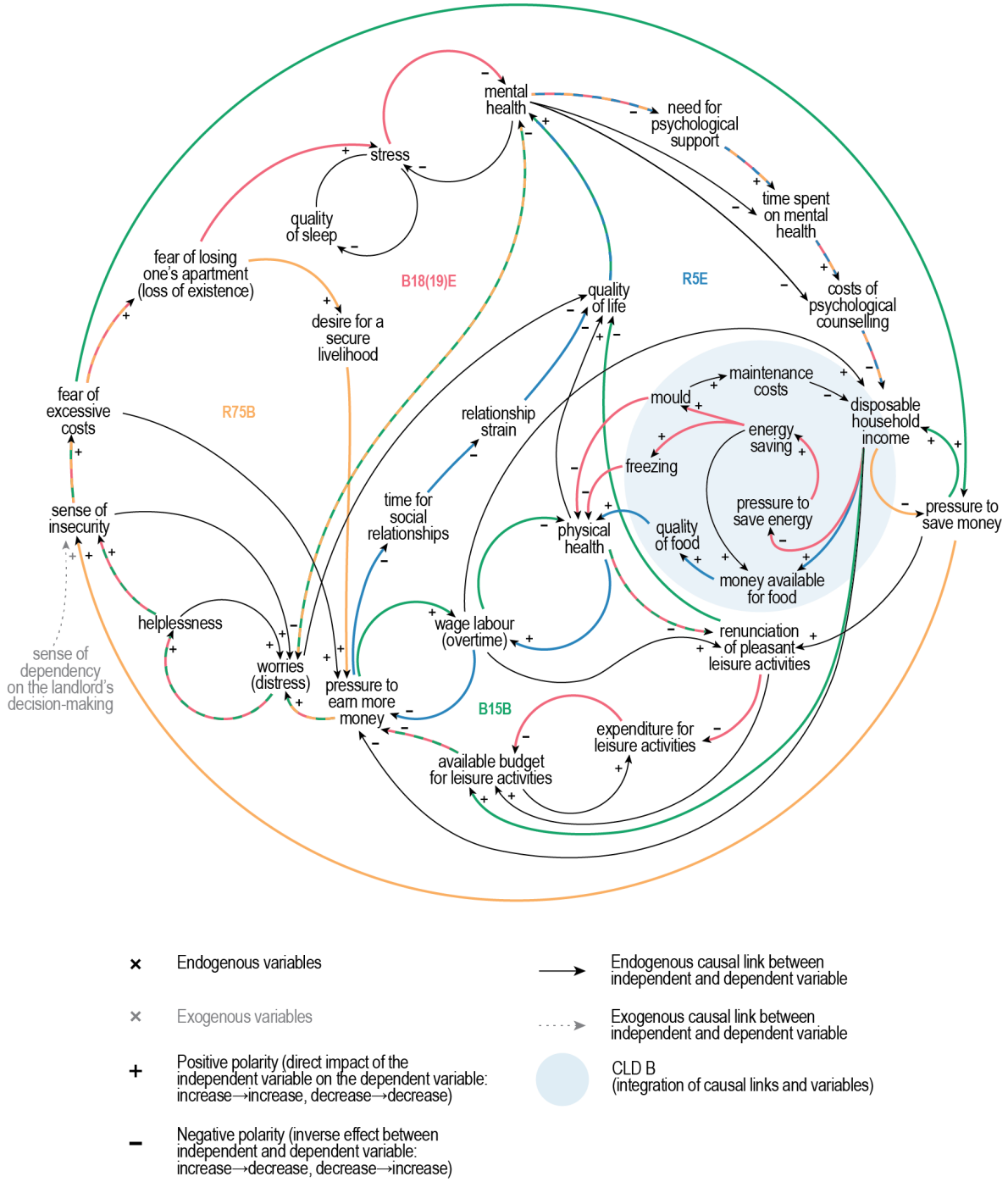

894

895 **Fig. 3.** Merged causal loop diagram (CLD A+B) on housing and energy vulnerability from an affected
896 citizens' perspective. Causal links couple the independent variables to dependent variables by using
897 positive (i.e. direct impact of the independent variable on the dependent variable, or as the cause
898 increases, the effect will also increase) or negative (i.e. the inverse effect between independent and
899 dependent variables) polarities. Color coding refers to four exemplary feedback loops (R75B, B15B,
900 R5E, B18(19)E), dashed colored lines represent overlapping dynamics.

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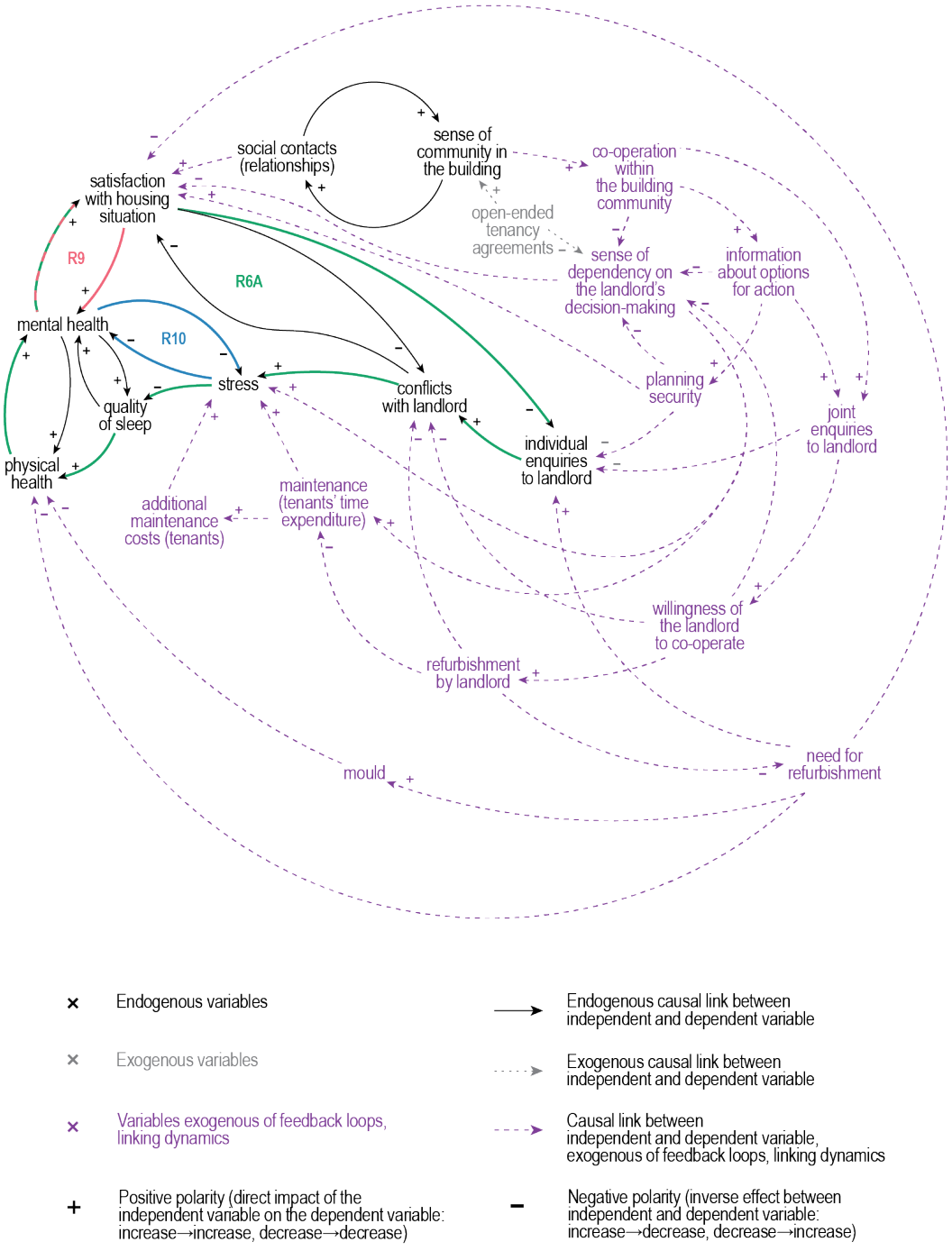


Fig. 4. Causal loop diagram (CLD C) on the citizens' capability to influence the own housing situation. Causal links couple the independent variables to dependent variables by using positive (i.e. direct impact of the independent variable on the dependent variable, or as the cause increases, the effect will also increase) or negative (i.e. the inverse effect between independent and dependent variables) polarities. Color coding refers to three exemplary reinforcing feedback loops (R9, R10, R6A).

10 Supplementary information

Supplementary Table 1. List of stakeholder interviews

#	STAKEHOLDER	DESCRIPTION	DATE	DURATION
S1	Innsbrucker Kommunal Betriebe	Service provider (energy sector)	2023-05-11	100 min
S2	Tyrolean Chamber of Labor	Chamber of Labor	2023-05-10	120 min
S3	Tyrolean Energy Agency (Energieagentur Tirol)	Service Provider (energy consultancy)	2023-03-02	95 min
S4	Tyrolean Tenants' Association (Mietervereinigung Tirol)	NGO (tenancy consultancy)	2023-04-19	84 min
S5	Tyrolean Regional Government	Administration (regional)	2023-04-27	180 min
S6	University of Innsbruck	Scientific hub and university	2023-04-19/20	140 min
S7	Neue Heimat Tirol	Social housing real estate sector	2023-05-03	155 min
S8	TIWAG	Service provider (energy sector)	2023-05-10	65 min
S9	Stadt Innsbruck	Administration (local)	2023-02-09	20 min

Supplementary Table 2. Semi-structured stakeholder interview guide

PHASE 1: INTERVIEW

Can you tell us something about your professional background and your role in relation to the city of Innsbruck and the specific context of the low-carbon transition process?

1) Can you explain what is going on in the case area?
   a) *Problem and opportunity framing*
      - What are the main problems and issues?
      - How have these problems and issues evolved over time?
      - What has been driving these problems and issues?
      - Which future developments can be expected in this context?
      - Which opportunities for action are conceivable?
   b) *Policy focus*
      - Which government policies or regulations are relevant to the transition process?
      - What is the intended effect of the policies on the problem and its drivers?
      - From the interviewee's perspective to what extent is the implementation and potential impact of the above transition policy just or unjust (from an equity perspective)?
      - How supportive are these policies?
      - What are possible or already observed unintended or undesirable side effects the policy might cause?
   c) *Vulnerability focus*
      - Which social groups in the case area have or will be most affected in the transition process?
      - How does the transition process affect these social groups?
      - To what extent can these groups influence the transition process?

PHASE 2: STAKEHOLDER MAPPING

1) Starting with the full categorization of the interviewed stakeholder
2) Identification of other key stakeholders
3) Drawing relations between stakeholders

PHASE 3: SYNTHESIS

→ After concluding the network map, we finish the interview with further questions focusing on the identified vulnerable stakeholders[4].

1. Which groups might become vulnerable or are particularly at risk of negative impacts in the future?
2. What is the capacity of the identified vulnerable groups to overcome potential negative impacts?
3. How are vulnerable groups involved in the decision-making processes?
4. What is stopping them from having a greater impact on the transition process?
5. Which new relationships need to be made, or strengthened, between the vulnerable groups and other stakeholders to increase their influence?

[4] Definition of vulnerability: Stakeholders who are most affected and have low power to influence the process.

Supplementary Table 3. Policies, regulations and strategies for housing and the energy and heating transition

#	NAME	ISSUING AUTHORITY	STATUS	TYPE	MAIN AIMS	INSTRUMENTS	EXPECTED IMPACTS
P1	EU Taxonomy	European Commission (2023)	implemented (latest update 2023)	EU regulation	Establishing common definitions for what is sustainable, promoting sustainable investment, setting criteria for sustainability (= reduce greenwashing), support climate objectives of the EU, encouraging sustainable business practices, informing consumers and investors (= transparency), supporting transition activities, and policy coherence.	market-based	Improved transparency and consistency provided by the taxonomy criteria will likely reduce costs for investors to identify, and for corporates to fund, sustainable initiatives.
P2	Klimaschutzgesetz (KSG)	Austrian Parliament (2017)	issued (2011; update 2017)	Federal law	- Compliance with greenhouse gas emission ceilings and the elaboration of effective climate protection measures - intended to enable the coordinated implementation of effective measures for climate protection - installing a National Climate Protection Committee	regulatory, market-based	- Increased energy efficiency, share of renewable energy sources in final energy consumption, and overall energy efficiency in the building sector - Integration of climate protection into spatial planning, mobility management, waste prevention, protection and expansion of natural carbon sinks as well as economic incentives for climate protection
P3	Bundesgesetz zum Ausstieg aus der fossil betriebenen Wärmebereitstellung (Erneuerbare-Wärme–Gesetz - EWG)	Austrian Parliament (2024)	implemented	Federal (constitutional) law	Phase-Out Oil, Liquified Gas and Coal (no set time frame), by no longer authorizing such heating systems	regulatory	Phase out via prohibition of new installation of fossil-based heating systems, and subsidies for heating system exchange.
P4	Sanierungsoffensive	Austrian Financial Ministry (2023/24)	implemented	subsidy program	Incentivizing the renovation of the building stock (thermal renovation) to increase energy efficiency.	market-based	- Increased interest in/incentives for the renovation of building stock, thereby reducing CO2 emissions - Increased energy efficiency of building stock
P5	Bundesgesetz über die Verbesserung der Energieeffizienz (Bundes-Energieeffizienzgesetz 2023 – EEffG 2023)	Austrian Parliament (2023)	implemented	Government bill - Federal (constitutional) law	- Not to exceed the final energy consumption of 920 petajoules for a control year in the calendar year 2030 - Achieving annual cumulative final energy-savings of at least 650 petajoules by 31 December 2030 achieve at least 650 petajoules. - Expanding the pioneering role of the federal government, set further federal measures, and strengthen the principle of "energy efficiency first". - Supporting households, especially beneficiary households (social), and businesses to implement energy efficiency measures. and businesses to implement energy efficiency measures, which will reduce energy costs for households and businesses and reducing energy poverty.	regulatory for businesses, federation, federal states, and energy providers; informational for citizens	- Positive fiscal effects that lead to increased public demand (e.g. for energy services, energy-efficient products, etc.) - By 2027 buildings of the federal state will be heated by a sustainable source - Conservation-orientated effects in the sense of improving energy efficiency through consumption-based monitoring - Reduction in energy demand and the associated increased consumption due to the associated cost savings - Additional employees through investments in energy efficiency measures, such as thermal building renovation - Investment incentives will have positive effects on the innovative strength of companies - Reduction of GHG emissions and emissions of air pollutants
P6	raus aus Öl und Gas	Austrian Financial Ministry (2023/24)	implemented	Subsidy program	incentivizing the exchange of fossil heating systems to sustainable alternatives.	market-based	Increased interest in/installation of renewable/sustainable heating systems, thereby reducing CO2 emissions.
P7	Tirol2050	Tyrolean Regional Government & Tyrolean Energy Agency (2021)	issued	Strategy, and scenario evaluation	Creating an as generally agreed as possible "Our Way to 2050" target scenario, which should serve as a guide for the political direction of travel for the next five to ten years.	informational	The described scenarios lead to changes in political decisions, towards a more sustainable future.
P8	Tiroler Nachhaltigkeitsstrategie	Tyrolean Regional Government (2022)		Strategy	Promoting the sourcing of renewable energy locally, building renovation, and resource-saving spatial planning, monitoring local energy consumption, and production, installing regional energy spatial planning, as well as energy consultation offices, and increasing awareness. Furthermore, the	market-based (subsidies), informational	- Reduction in greenhouse gases and energy transition - Improved governance - Higher level on education on climate change issues - Improved crisis aversion capabilities and resilience - Protection of biodiversity

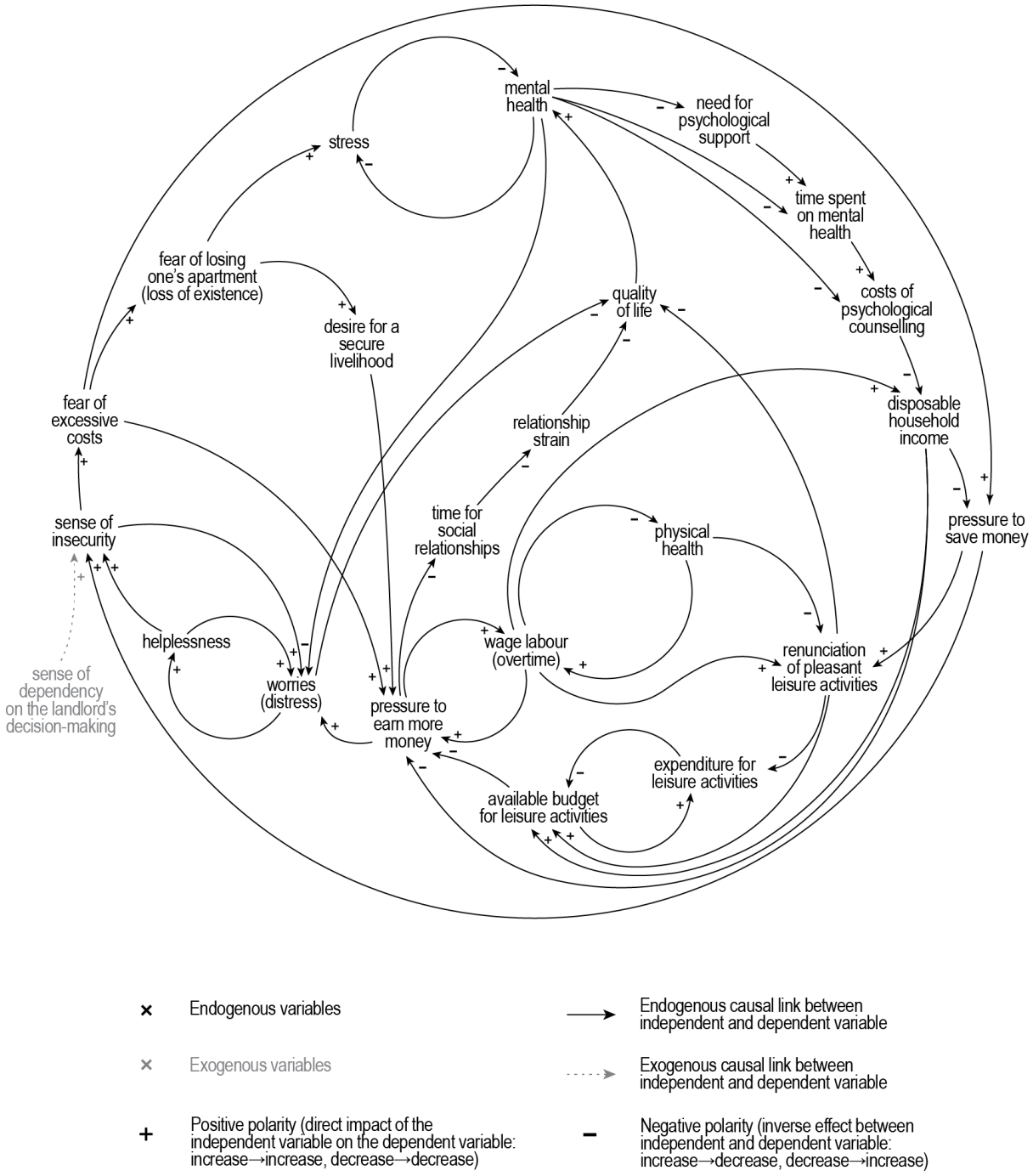
				strategy aims to protect biodiversity, save water, foster inter-regional co-operation, and addresses protection from natural hazards, and disaster management.		- Improved health - Social innovation and economic benefits through digitalization - More social inclusion, and improved conditions for vulnerable groups - Economic benefits through regionality - Improved spatial and resource efficiency
P9	Doppelplus	alpS GmbH	Program	Raising awareness of the target group on the subject of climate protection, and supporting vulnerable households with information on energy conservation.	informational	- Raising awareness of the target group on the subject of climate protection - Average annual energy-savings 2,091 kWh per consulted household. This corresponds to a reduction of 667 kg CO2eq.
P10	Energieplan Innsbruck	Government of Innsbruck & University of Innsbruck (2017)	Strategy	Illustrating pathways to cohere to the regional energy autonomy strategy, and showing alternative pathways of development.	informational	- basic development scenario: the required energy reductions cannot be fulfilled, small energy demand reduction until 2050 - intermediate development scenario: the required energy reductions are off by 10% in regards to the "Tirol 2050" goal, mainly due to lagging in the phase-out of fossile fuels - best-case scenario: energy demand reduced by 49,1%, full energy supply via renewable resources by 2050, only feasible, if the transition measures are implemented from 2021 onwards
P11	Wohnschirm	Austrian Federal Ministry for Social Affairs, Health, Care and Consumer Protection (2021)	Subsidy program	Supporting low-income tenant households who can no longer pay their rent/energy costs financially to avoid evictions.	market-based (subsidies), informational	Alleviation of existential stress for vulnerable households, through financial support.
P12	Mietrechtsgesetz	Austrian Parliament (1981)	Federal law	Regulation of the conditions for the provision of premises for rent.	regulatory	-

Supplementary Table 4. List of challenges and obstacles from the perspective of stakeholders and citizens

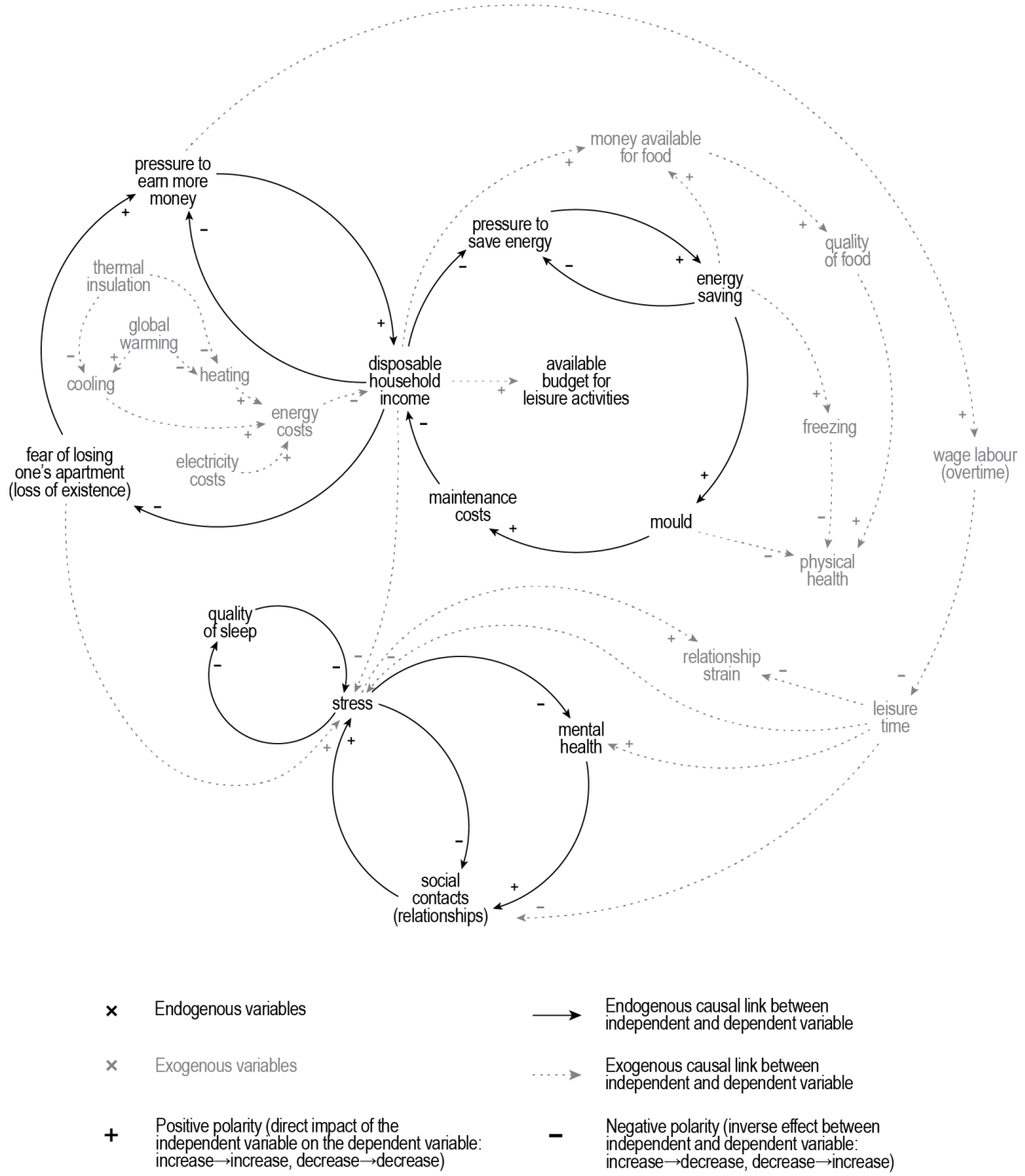
	Stakeholders									Citizens	Impact dimension			Social justice dimension				
	A	B	C	D	E	F	G	H	I		Housing vulnerability	Energy vulnerability	Energy & heating transition	Distributional	Procedural	Recognitional	Inter-generational	Inter-sectional
Policy																		
Multi-level policy target deviation (EU, AUT, Tyrol, Innsbruck)	●		●				●●		●				✓				✓	
Non-binding policy targets	●		●				●●	●	●				✓				✓	
Political lagging	●		●	●●●	●	●●●	●●		●		✓	✓	✓				✓	
Lack of cooperation between stakeholders		●	●●		●		●		●			✓	✓		✓			
Restricted data availability (e.g. due to data protection) and intransparency	●			●		●	●●	●●●			✓	✓	✓		✓			
Lack of consistent, dedicated spatial energy planning				●			●						✓				✓	
Laws & regulation																		
Low flexibility in maintenance costs			●	●	●													
Energy price regulation and feed-in tariffs		●																
Construction codes (e.g. monument protection law)	●	●	●		●			●	●				✓				✓	
High degree of bureaucracy		●	●	●		●	●				✓	✓	✓		✓			
Lack of restrictions on rents (esp. for privately financed new buildings)				●	●	●●	●		●		✓				✓			
High complexity and low flexibility of tenancy and housing laws						●●			●		✓							
High residential vacancy rate										●	✓			✓		✓		✓
Housing expenses																		
Rising energy costs (including potential back payments and energy debts)		●●●	●	●●	●●	●	●●			●●		✓	✓	✓		✓		✓
Intransparency of energy costs (esp. district heating)		●	●	●	●		●					✓			✓			
Rising rents (including potential rent debts)	●			●●●	●	●●	●	●	●	●	✓		✓	✓		✓		✓
Lack of affordable housing	●	●		●	●●	●●	●	●	●	●	✓			✓		✓		✓
Low availability of non-profit social housing	●			●●		●		●	●		✓			✓		✓		✓
Affordability of energy-efficient appliances			●	●	●							✓	✓	✓		✓		✓
Uneven distribution of costs between landlords and tenants	●	●		●●	●	●●●			●●●	●	✓	✓	✓	✓		✓		✓
Transition costs																		
Affordability of thermal building renovation					●	●	●		●			✓	✓	✓		✓		✓
Lack of incentives for landlords to refurbish	●		●●●	●	●	●		●	●	●	✓	✓	✓	✓				
Affordability of heating system exchange			●		●	●●	●		●			✓	✓	✓		✓		✓
Lack of incentives for landlords to exchange heating systems	●		●	●●	●	●		●	●	●	✓	✓	✓	✓				
Uneven distribution of subsidies and taxes			●	●	●	●	●		●	●	✓	✓	✓	✓		✓		✓

Social & knowledge boundaries																			
Energy literacy (e.g. energy saving and sufficiency; green techno-skepticism)				●	●			●●				✓	✓		✓				
Lack of technical staff (e.g. heat pump installation) & know-how (e.g. provision of technical expertise)		●						●	●				✓						
Climate awareness		●●		●	●		●	●		●			✓				✓		
Access to energy consultation and funding support			●	●●●	●	●			●		✓	✓	✓		✓				
Agency																			
Uneven distribution of power in terms of capital		●	●	●	●	●	●●		●	●	✓	✓		✓		✓			✓
Low agency in political participation	●	●	●		●	●	●●		●				✓		✓				
Low agency in decision-making on household level			●	●●●	●	●●	●		●	●	✓	✓	✓		✓				
Technological & infrastructural boundaries																			
Significant share of fossil fuels in energy supply		●	●	●			●	●	●				✓						
Limited expansion potential for renewable energy carriers (esp. in inner-city areas)		●●					●	●					✓						
Building stock condition (energy performance requirements in terms of construction period, building type etc.)	●	●●	●●	●●	●●		●●	●	●●	●		✓	✓						
Climate change adaptation in urban areas (e.g. cooling spaces)	●						●●	●		●		✓	✓				✓		
Development of energy grids and networks		●●●	●	●	●		●		●				✓				✓		
Quality of life																			
Physical health issues (e.g. mold, extreme temperatures, draft)					●	●	●	●	●	●	✓	✓	✓	✓		✓	✓	✓	
Mental health strain (e.g., stress and fear of existential loss)										●●	✓	✓		✓		✓	✓	✓	
Renunciation and budgeting		●			●	●				●●●		✓		✓		✓			
Lack of community and sense of belonging					●		●			●●	✓		✓		✓				
Accessibility of qualitative housing (e.g. adequate lodging size)		●	●		●	●●	●●	●	●●	●●	✓	✓		✓		✓		✓	
External factors																			
Ukraine war and volatile energy prices	●	●	●		●							✓							
Longer heating periods in Alpine regions				●								✓							
Inflation		●		●		●	●					✓							
Lower wages than national mean				●							✓	✓							

Supplementary Table 5. For the full description of the feedback loops follow this link to the zenodo platform (doi: 10.5281/zenodo.13748036).



Supplementary Fig. 1. CLD of the problem cluster A



Supplementary Fig. 2. CLD of the problem cluster B

Supplementary Table 6. Script for the first citizens' deliberation panel in Innsbruck

Day	Time	Duration	Agenda Point	Guiding Questions/Remarks	Goal	Setting
1	15:30:00	00:30:00	Arrival & Check-in		- participants have arrived, and received their vouchers; feel comfortable	
1	16:00:00	00:20:00	Welcome & Introduction	- words of welcome - introduction to location (facilities; water; snacks) - introduction of project (goals; processes) - open flipchart	- participants know who we are, what TANDEM is, and why we are here - Goal of the panel: shared understanding of i) main challenges; ii) their causes; iii) their impacts on daily life; iv) how policies interact with challenges; v) which interventions would be necessary to make the situation more socially just	Circle of chairs with PPT
1	16:20:00	00:10:00	Testimony	- introduction of guests/testimonials	- participants feel aknowledged and recognized	Circle of chairs with PPT
1	16:30:00	00:10:00	Agenda	- presentation of agenda - "always feel free to take a break, there will be no coersion"	- participants know what is coming, and that they are encouraged to respect their own boundaries	Circle of chairs with Flipchart
1	16:40:00	00:10:00	Q & A	- Which questions have already popped up? - transision: code of conduct	- participants' questions/preliminary insecurities are answered/tended to	Circle of chairs
1	16:50:00	00:15:00	Code of Conduct/ Agreement	- we have a common goal, we need rules how we would like to work together/treat each other to achieve this goal together	- participants share a community moment - we have a code of conduct/agreement we can refer to, should situations/discussions get out of hand	Circle of chairs with Flipchart
1	17:05:00	00:20:00	Icebreaker ("sociometry")	- Great, now that we've established that (hanging up the flipchart) - Ice-Breaker: We make a line-up, I ask a question, you position yourselves in the room (3 rounds, 2 people per round are asked to talk about why they positioned themselves where they have)	- participants get to know each other and the team members a little (advance of trust)	Participants move around the space
1	17:25:00	00:10:00	BREAK	- Introduction & arrival are done, let's have a short break	- give participants a chance to continue conversations from before, respite	Mingling
1	17:35:00	00:10:00	Introduction of key challenges	- affordable housing & energy - energy/heating transition	- participants get acquainted with our research scope and get a feel for the complexity of the challenges	Circle of chairs with PPT
1	17:45:00	00:45:00	Description of personal situtation	- guiding questions on PPT (3 rounds)	- participants have the opportunity to exchange experiences - formulation of common grounds - impacts/effects are documented on presentation cards	Participants sit in groups at tables (fotos on the tables)
1	18:30:00	00:40:00	Clustering	- How does XX affect your life? How? Why?	- participants (or representatives from each group) share their experiences and challenges with the group - facilitation team knows pain points (base for challenge clusters for CLDs)	Circle of chairs around "house" (taped silhouette on the floor)
1	19:10:00	00:05:00	Expectations	- What are your expectations for tomorrow/participating in the panel? - please leave your cards in the provided box - Thank you for your participation/engagement. - Whoever wants to is welcome to stay for dinner.	- participants have a chance to voice their expectations (we can adapt the script or be transparent about not being able to fulfill certain expectations)	Circle of chairs around "house" (taped silhouette on the floor)
1	19:10:00	00:40:00	Dinner & conclusion of day 1		- give participants a chance to continue conversations from before, informal exchange	Mingling
2	09:00:00	00:30:00	Arrival & Check-in			
2	09:30:00	00:10:00	"Mini-Recap"	- Welcome! It's great to have you back! - specfically welcome new people aswell - Recap of yesterday	- all participants know what we did yesterday - introduction of new panelists to the group	Circle of chairs with Flipchart
2	09:40:00	00:10:00	Recap: expectations	- We have gathered your expectations, …	- participants know what the panel will consist of, and which expectations will not be fulfilled	Circle of chairs with Flipchart
2	09:50:00	00:10:00	Triangle Game	- see triangle game sheet	- participants get to experience the complexity of systems playfully	Participants move around the space
2	10:00:00	00:15:00	Presentation of clusters	- Based on your accounts yesterday, we have clustered the addressed challenges in three groups …	- participants recognise their challenges in the workable clusters	Participants follow facilitator from table to table

2	10:15:00	00:05:00	Grouping	- Please go to the cluster, which interests you the most. - if needed: "Could one of you imagine working on cluster XY instead?"	- work groups/tables are established - participants get to work on a cluster they are interested in/affected by	Participants allocate themselves to tables (challenge clusters)
2	10:20:00	00:10:00	Introduction to personas	- Introduction to personas and why we use them	- participants understand that other people (who are not here) are also affected and may have different needs	Participants sit at tables
2	10:30:00	00:10:00	Persona Check: Herausforderungen	- Now, that you see these challenge clusters: do you see something persona XY would add to that?	- participants reflect from other perspectives	Participants sit at tables
2	10:40:00	00:10:00	Prioritisation of effects	- Which ones of these variables are the most crucial to answer the question of this challenge cluster?	- Participants get a starting point for their system map - appreciation through democratic decision	Participants sit at tables
2	10:50:00	00:15:00	BREAK	- break - meeting again in 15 min	- give participants a chance to continue conversations from before, respite	
2	11:05:00	00:20:00	Energizer		- participants discover system dynamics in a playful way and experience them with their own bodies	Participants move around the space
2	11:25:00	00:15:00	Introduction to system mapping	- Why do we work with system maps? - dynamics and systems thinking - focus on graspable metaphors/analogies	- participants understand the basics of system mapping	Participants sit at tables with flipchart
2	11:40:00	01:00:00	System map 1	ongoing facilitation: moderation of the discussion	- participants create a system map of their challenge cluster (faciliation supports)	Participants sit at tables with flipchart
2	12:40:00	00:30:00	System map 2: focus on feedback loops	- Looking at the system maps now: which relevant connections between variables are not there yet?	- participants finish the system maps (and draw them with a sharpie)	Participants sit at tables with flipchart
2	13:10:00	01:00:00	LUNCH BREAK	- introduce what there is to eat (options, markings, allergenes etc.)		Mingling
2	14:10:00	00:15:00	Gallery Walk		- participants feel a sense of accomplishment - opportunity to ask about other system maps/exchange	System maps are hanging on the wall, participants move around and can ask questions
2	14:25:00	00:25:00	Reflection system maps + persona check	- Check-In about current emotions - Regarding the personas, is there something you would like to add to the system maps?	- participants have a community moment, and feel like a group	Participants sit in a circle
2	14:50:00	00:05:00	Introduction: Policy, measures & future	- Taking off the wall of Thinking-Wickie (with Idea-Wickie stuck behind it) - We have now spent a long time looking at challenges and the current situation, now we are looking to the future and potential solutions	- transition from challenge-centred to future/solution-oriented	Participants sit at tables with flipchart
2	14:55:00	00:30:00	Effects of policy measures	- Introduction of the policies - Where in the system map do you see this policy coming in?	- participants get an idea of what current political measures support and who they support.	Participants sit at tables with flipchart
2	15:25:00	00:30:00	Brainstorming: flanking measures/interventions	- Which interventions would you like to see to alleviate XY/better the situation depicted in this system map?	- participants voice their wants and needs	Participants sit at tables with flipchart
2	15:55:00	00:10:00	Persona check	- Thinking of the personas: is there something one of these would need/want/add?	- participants reflect from another point of view	Participants sit at tables with flipchart
2	16:05:00	00:40:00	Check-Out	- How do you feel now? - What are you telling your friends/family about today when you get home?	- appreciation of the participants' emotions, and input - creation of a sense of community in the group - first opportunity for feedback	Circle of chairs
2	16:45:00	00:10:00	Summary & outlook	- Go through agenda, focus on accomplishments - outlook on upcoming panels	- participants go home with the feeling of having achieved something - participants know what to expect from the upcoming panels	Circle of chairs with Flipchart
2	16:55:00	00:10:00	The END	- Thank you for sharing your expertise! - Feel free to toast with us (non-alcoholic prossecco)		Circle of chairs with Flipchart/ then mingling