

Response to reviewers

To the editor and reviewers,

Thank you for taking the time to consider our paper for *Sustainable Energy, Grids and Networks*. The detailed feedback received has allowed the paper to be improved considerably. The suggestions and feedback have been incorporated into the revised manuscript, and a point-by-point response to feedback with changes made is detailed below. We hope the revised manuscript can be considered for publication.

Best regards,

Sebastian Zwickl-Bernhard, Hans Auer, Antonia Golab

List of responses

Reviewer #1:

This paper presents research on a very relevant topic of equitable subsidy allocation for decarbonising heat supply.

The topic is an important one and relevant to the E&B journal. A strong background and literature section are presented. The scope, methods, and findings of the research are relevant and consistent, although I have some remarks on the calculation (see below).

However, there are problems with how the work is presented which results in it being somewhat hard to follow, I therefore recommend the following issues be addressed before the paper can be ready for publication.

Reviewer's comment: Firstly, there seems to be a lack of discussion of relative fuel costs. The tenant heat charges seem to be calculated based on current charges and system change investment, but do not seem to take into account different energy prices that one would assume from switching from gas to electricity or district heating - this should be more clearly addressed (if it is not included in the model this should be explained also).

Author's response: We agree with the review comment addressing the importance of relative fuel costs in the analysis. We do take into account different energy prices for (natural) gas, electricity and district heating. The variable $p_{\text{init},y,m}$ is the price of the conventional fuel initially supplying heat demands. Besides, $p_{\text{alt},y,m}$ is the fuel price of the sustainable heating system alternative. A detailed explanation of the assumptions of relative fuel costs (including price development assumptions, etc.) is presented in Section 3.2.2 in the revised manuscript as we moved Appendix A into the main text. In addition, we added a sentence highlighting the fuel costs of the alternative heating system below equation 11 (numbering of the revised manuscript).

Reviewer's comment: The title of Section 2 should be simply 'state of the art' while the subsection 'progress beyond' should instead be headed 'aim and scope' (usually included at the end of the introduction). Several elements of the paper would then be moved there, e.g. L114-116, L363-366. The paragraph from L131 would make more sense as the start of section 2.1.

Author's response: We thank the reviewer for this comment. We would like to mention explicitly that we have dealt in detail with the raised concern as part of the revision process. In principle, we agree with the review comment that a section 'aim and scope' at the end of the introduction is useful. We also want to keep the introduction deliberately short and lean. Therefore, against the background of this study, we see some advantages in introducing the subsection 'State-of-the-art and progress beyond'. In the original manuscript,

we aimed to follow the tie principle regarding the structure of the sections. From our perspective, the review of the existing literature in sections 2.1 to 2.3 particularly is the knot of the tie. Building upon, the intention of the following subsection 'progress beyond state-of-the-art' is to build the arc of suspense. The reader discovers the novelties of the study and the methodological approach. Thus, the ordering of the subsections can motivate the reader to follow the manuscript and read the next section about the methodology (i.e., mathematical formulation) in detail. With this in mind, the structure of the original and revised manuscript is the same but we thank the reviewer once again for the comment. We hope that our explanations above nevertheless take sufficient respond to the comment.

Reviewer's comment: The bigger issues are in the presentation of the model - since it is quite complicated it's crucial that this be well explained. Firstly, figure1 could be expanded and improved to more clearly illustrate the inputs/outputs/inter-relation of the different model elements, possibly with reference to the equations or data inputs. In the description of the model, I think using words or abbreviations/subscripts for some of the parameters instead of greek symbols would make it easier to follow what is going on (e.g. using something G_{owner} , G_{tenant} for governance grants instead of Φ & Ω). The model constraint section is also hard to follow in that it does not provide much explanations (rather only a few descriptive sentences). Perhaps condensing the equations into a table with a brief description in the table and a more high-level explanation in the text would improve this.

Author's response: We agree with the review comment that the presentation of the model is quite complicated in the original manuscript and needs more explanations. In the revised manuscript, we followed the review comment and have done the following changes:

- We scanned through the methodology section and added text below equations (as suggested rather high-level explanation)
- Expansion of Figure 1 to include the variable names and equations (i.e., their numbering) of the model.
- Adding a new table (Table 1 in the revised manuscript), where we show an overview of the mathematical formulation of the model (equations/constraints, dimension, keyword, etc.).

From our perspective, we were able to improve the quality of the manuscript based on your very helpful comment.

Reviewer's comment: Equation 17 is a key part of the paper approach and needs to be presented earlier in the text and with more explanation, since it operationalises the concept of equitability in the paper as a subsidy balance - this is important to make explicit since other views of what is equitable also exist, which could be addressed in the discussion.

Author's response: We agree with the review comment that Equation 17 (in the original manuscript) is a key part of the paper approach. Therefore, we followed the reviewer and present this equation earlier in the revised manuscript (now Equation 2). We added text to the paper explicitly stating that the concept of equitability in the paper is defined as a subsidy balance. We agree that it is important to make this aspect clear in the paper. Thank you for the hint.

Reviewer's comment: Section 3.3.3 would more conventionally be titled 'data', 'input data' or similar. The input parameters in Table2 should be associated with their variable names in the model equations (add a 'symbol' column to the table). The source for all values should be stated explicitly (are they all from openENTRANCE? if so this should be stated). There is a very large price difference between the heat pump and district heating costs, it would be good to better understand how these costs are derived and what they include (i.e. do they consider a part of the construction of the whole DH network or do they assume that the network is connected anyway).

Author's response: In the revised manuscript, Section 3.3.3 is titled 'Input data' and Table 2 is expanded by a 'Symbol' column and source description. The costs of district heating and heat pump are calculated based on a representative old building from the building stock in Vienna, Austria. Nevertheless, it is important that

the cost values need to be checked for each building (i.e., case study) separately since they can vary significantly. To give one example, district heating requires a connection between the network and each individual building. If there is a shaft in the building, the pipes can be laid relatively easily and the costs for the building are comparatively low. If not and it has to be built first (exemplarily for a building with several floors), the connection costs for the building can increase significantly.

In any case, we fully agree with the review comment since the empirical scaling is often challenging for academic research due to data accessibility. In the revised manuscript, we tried to highlight that the costs for district heating and heat pumps are rough estimates and should be checked in detail for each building individually.

Reviewer's comment: The 'model validation' section should be in the results section, although it is not entirely clear to me what these results add that are not in the results already. In Figure 2, writing the fractions on the plot is rather confusing. Since the yearly payback is anyway linear, it would be easier to just show a single bar for the total values over the period where the relative size of the bar immediately communicate the relative fractions of NPV.

Author's response: We fully agree with the review comment that the model validation section does not add any new results that are not in the results already. However, the intention here is to validate (or rather verify) the developed model and to present the functionalities and results of the model. We followed the suggestion from the review comment and updated Figure 2. However, we do not present a single bar for the linear yearly payback (i.e., rent-charge related revenues) in order to ensure consistency in terms of result presentation (e.g., Figure 3). Please note that we moved the model validation into Appendix A in the revised manuscript and named it 'Illustration of the model' (as suggested by Reviewer #2).

Reviewer's comment: In S4.1 the explanation of the figure L482 should be in the figure caption while the text instead provides the synthesis of the results. In the discussion of the reference Gas scenario, it seems this scenario does not consider the ongoing maintenance costs of a legacy gas system - since old boilers at some point need investment for repair or replacement this can significantly change the relative merits of new low carbon system. Please clarify this point.

Author's response: We checked L482 and the caption of Figure 3. Moreover, we thank the reviewer for the attentive comment related to the maintenance costs of a legacy gas system. We do not explicitly consider maintenance costs in the reference gas scenario as a separate cost component. However, we assume a price of the conventional fuel initially supplying the heat demand, which implicitly includes the maintenance costs. We added this information to the revised manuscript. Moreover, it is important to note that only the difference in maintenance costs between the gas reference scenario and the sustainable alternative one influences the results since the optimal solutions takes into account the relative difference between the two net present values of the scenarios. Consequently, one can assume that adding maintenance costs explicitly does not influence the results significantly.

Reviewer's comment: In S4.2, I am not convinced that there can be no feasible solution for a non-retrofitted HP installation, since according to the input data this would cost ~6000€ per dwelling which is not so extreme. Furthermore, there is nothing in the model definition to apply a constraint on the maximum governance grant (i.e. it could be 100% of the costs). The calculations for this section should be reviewed in detail and the discrepancy explained.

Author's response: We agree with the review comment that the (investment) costs per dwelling are not the reason for the infeasibility of the non-retrofitted HP installations. Instead, the main reason for the infeasibility here lies in the increase of the monthly energy costs for the tenants. Particularly, the high electricity demand (resulting from the low coefficient of performance of the heat pump) and the increasing electricity price (mainly driven by the increase of the CO₂ price) require high subsidy payments. At the same time, as you stated, the comparable investment costs for the property owner (~6000€ per dwelling) are not so extreme

and thus the equitability constraint (i.e., subsidy balance) cannot be satisfied. We added this information to Section 4.2 in the revised manuscript. Thank you for this helpful comment.

Reviewer's comment: In table 4, the different cases should use names or abbreviations instead of Case A, B... to make it easier to follow in the text. It is not really possible to follow what is going on in Figure 6, the 3D perspective doesn't allow to understand the results.

Author's response: Thank you for the hint. We use names and abbreviations instead of Case A, B... in the revised manuscript. We removed the 3D graphic in Figure 6. We had a lot of discussion in the process and development of Figure 6. The issue here is that the result presentation needs four different dimensions (three for the different shares of opportunity costs among parties and one for the objective value). From our perspective, it is really challenging to improve Figure 6. Therefore, we decided to add Table 6. We hope that the updated presentation of the results using a table are now easier to follow.

Reviewer's comment: Finally, in terms of overall writing style, while the language etc. are very good I suggest editing for brevity. For instance there are various introductory sentences at the start of sections/paragraphs that don't really add anything (e.g. p6 L107, L120-122), sometimes there is an overuse of adjectives, etc. This is however a minor point.

Author's response: Thank you for the hint. We checked the manuscript for introductory sentences that can be removed.

Otherwise, the final discussion and conclusions sections do a good job of extracting the key findings from the work.

Reviewer #2:

General comment: Very interesting and pertinent topic, suited for Energy and buildings.

However, the paper currently suffers from major drawbacks:

Reviewer's comment: 1) Currently, the issue of the paper is related to equity between tenants and owner, rather than overall societal equity. The private economic deficit of owner and tenants with respect to fuel switch is currently completely born by the state (governance). At the state level, no constraint is modelled on the deficit level, which could lead to a snowball-effect, and a major public deficit, which would need to be solved by public finance (ex. taxes). Therefore, even if the model has a solution, the equity problem is transferred to a fiscal policy problem, which is currently not addressed.

Author's response: Thank you for this critical comment. We fully understand the concerns regarding a fiscal policy problem. However, several aspects are important here that need to be considered:

- This work presents an approach to define and examine equity on the building level in the context of a sustainable heat system switch. We are aware that there exist also other ways to define equity. The question ultimately always narrows down to where the system boundary for equity is drawn. Our expertise, and therefore the focus of this work, is on local and distributed energy systems. From our perspective, a rapid and effective decarbonization of building heat (incl. particularly ownership structure) requires, among others, practicable and realizable actions since otherwise we will run out of time with an eye on the remaining CO₂ budget for limiting the increase of global average temperature below 2.0°C. We agree that in any case there is a trade-off between complexity (i.e., system boundary), feasibility (i.e., heating system switch) and the overall costs (i.e., fiscal policy

problem) involved. Therefore, we added related aspects raised in the review comment above to future work since further research in this context is important.

- The raised issue regarding a possible snowball-effect is important. We agree that the model does not explicitly include a constraint that considers the deficit level at the governance level. However, it is important to note that the model includes constraints ensuring that (1) the net present value of the property owner and the heating system switch investment is set to zero which means that no profit is gained at the expense of the governance (equation 8 in the revised manuscript), and (2) the net present value of the tenant remains the same between the initial (reference gas scenario) and the alternative heating system (equation 12 in the revised manuscript). Both equations are crucial in order to limit the mentioned snowball-effect. Accordingly, we completely agree with the review comment and can state that we have already considered this aspect. We added explanations in the methodology of the revised manuscript, where we address the issue related to the snowball-effect. Thank you for this helpful comment.
- In the default mathematical formulation, the private economic deficit of owner and tenants with respect to fuel switch is completely born by the state. However, particularly the sensitivity analysis in Section 4.4 *Allocation of CO₂ pricing related costs between the governance, property owner, and tenant* (incl. more explanations in Appendix D) elaborates in detail on this. We discuss the possibility to allocate the monetary burden of the fuel switch among the governance, property owner, and tenant. From our perspective, the reviewer concern is completely justified but at addressed and discussed in the sections mentioned before.

Reviewer's comment: 2) The above equity between tenants and owner is further subject to a so-called "parity" constraint (eq 17) which seems unnecessary and is misleading.

Author's response: The equity between the property owner and tenants is in the foreground of this analysis. This is achieved by defining subsidy parity between both parties within the system boundary, which is set to at building level. As stated above, it is possible to define alternative system boundaries and to derive alternative parity constraints. We take a practical perspective in this work. Nevertheless, we do not agree with the review comment that equation 17 is unnecessary and misleading. Instead, equation 17 is crucial in the mathematical formulation of the model and ensures subsidy parity at the building level. We would like to refer to the comment from reviewer#1 suggesting to move equation 17 to the beginning of the methodology section since it is a key part of the paper approach. We followed this suggestion and moved the equation to the beginning of Section 3.2.2. In addition, we added further explanations and text in this context to make the importance of the equation clearer in the revised manuscript. We hope that these changes result in a better understanding of this relevant part of the methodology.

Reviewer's comment: 3) There is a strong confusion between "macro-economic/environmental" scenarios (DT, SC, GD) and technological options / decision variable (DH, HP). As stated here (sec.3.3.2), it looks like the DT scenario will/should bring about a technical change towards DH, while the SC scenario will/should bring about a technical change towards HP. This is not straight forward, and would actually be interesting/necessary to see how both technical options react to the diverse macro-economic/environmental scenarios (what is actually partially done in sec. 4.3). Similarly, the issue of envelope retrofit should be explored for both technical options.

Author's response: We agree with the review comment that this (= DT brings a technical change towards DH and SC towards HP) is not straightforward. However, with an eye on the scope of this work, the following points are important to keep in mind. We focus on the sustainable heating system change at the local level. Thereby, we use the macro-economic/environmental scenarios to put the investigated local energy system into a larger context (i.e., high-level empirical decarbonization framework that is projected at the building level). From our point of view, it is becoming increasingly important to put decarbonization and its concrete measures into practice, which is done ultimately, at the local level. We examine in detail the aspect of the heating system change in the context of different macro-economic/environmental scenarios defining both a

narrative storyline and the underlying parameter assumptions (CO₂ and energy prices, etc.). As mentioned in the review comment, Section 4.3 aims exactly at the comparison of the different concrete implementation options of the heating system change in the different macro-economic/environmental scenarios.

Additionally, it should be mentioned that this work is done as part of the European H2020 project openENTRANCE (<https://openentrance.eu/>). Therein, in total four different narrative storylines/scenarios are developed including the three scenarios of this work. They describe decarbonization pathways at the European level. A key part of the project is also to bridging the gap between aggregate and local levels. Against this background, this work aims to break down the European decarbonization pathways to the building level.

Furthermore, several clarifications / modifications need to be done, and the paper needs partially be restructured.

Specific comments

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Reviewer's comment: Sec. 3.1 (Fig. 1 and line 337 - 344). The authors should clarify that the social equity between tenants and owner consists in both agents bearing no economic burden of the energy transition (see eq. 7 and 11), which is all born by the state, possibly with an important drawback (see comment above). Unlike what Fig 1 shows, the subsidy to owner and tenant is not equal (see further down, discussion of eq. 17 and of fig. 2).

Author's response: Thank you for this hint. In the revised manuscript, we clarified that the social equity between tenants and owner includes in general that both agents bearing no economic burden of the energy transition, which is all born by the governance (below equation 2).

Reviewer's comment: Sec. 3.2.2, Eq. 2 and onwards: Are you actually working at monthly level? If so, there is missing indication in your case study (sec. 3.3.3) on how you break down the yearly heat demand in monthly values. From an operational point of view, it seems extremely burdensome (unfeasible?) to calculate the subsidies to tenants on a monthly basis (calculation at a yearly basis is already very burdensome).

Author's response: Thank you for the comment. The model has a monthly temporal resolution. We added information regarding the breakdown of the yearly heat demand in monthly values in the revised manuscript (Section 3.3.3). We fully agree with the review comment that the operational point of view is an issue here. However, this issue is not within this work's scope but could be included in future work.

Reviewer's comment: Sec. 3.2.2., Eq. 17: The meaning and the pertinence of this equation is unclear and misleading:

- Unlike what the authors are stating, this equation does not offer equal support to owner and tenants, since the second term of the left-hand side is not a financial support (see discussion of Fig. 2 and Fig. 5).

Thank you for this comment. With an eye on the current legislative background, the second term of the left-hand side in equation 17 (numbering in the original manuscript) can be interpreted as a financial support. Particularly, this includes the fact that the governance gives the property owner the permission to increase the rent price because of the alternative heating system switch. This is not currently the standard case on this scale. It is important to note that the discussed term is an indirect financial support from the governance for the property owner. Specifically, the tenant pays the higher rent price to the property owner but is at the same time compensated by the

governance, which is why this can be interpreted as a financial support. We added this explanation to the methodology section.

- By using eq. 6 and 7, the left-hand side is the sum of the investment grant (by the state) and the investment by the owner, i.e. the total investment. Why should the subsidy to tenants, which covers increase in heating cost and in rent (eq. 10 and 11), cover the total investment?
Equation 6 shows that the rent-related revenues of the property owner (permission for that because of the heating system switch) is calculated primarily on the basis of the model decision variable $r_{y,m}$ (rent-charge adjustment per year and month). In addition, equation 7 calculates the net present value of the alternative heating system option. Particularly, the first term reflects the overnight investment costs and investment grant by the governance. The second term shows the additional rent-related revenues due to the heating system switch. From the property owner's perspective, this equation ensure economic viability.
- It seems to us that the parity between owner and tenants is guaranteed by eq. 7 and 11, which states that neither party will suffer from the decarbonization action (which is completely born by the state). Eq. 17 hence seems unnecessary and misleading.
We agree that equation 7 and 11 guarantee that neither party will suffer from the decarbonization action. We agree that one can argue that those two equations could be an appropriate approach to model equity. However, from our perspective, equation 17 is crucial and a key part of the work. Particularly, the equation ensures that both parties at the building level (i.e., property owner and tenants) receive the financial support (net present value). In general, a mathematical framework of the model without equation 17 does not necessarily ensure an equity result with an eye on the financial support. In sum, we do not agree with the review comment that equation 17 is unnecessary but we do agree that the original manuscript did not provide enough information on this key part. We added additional information to the revised manuscript and hope that this improves the quality of the manuscript. Therefore, we thank the reviewer for this comment.

Reviewer's comment: Sec. 3.3.1 (in particular line 370-373): Does the heat demand include space heating (SH) and domestic hot water (DHW), or only SH? This question is in particular linked to the issue of individual gas-fired heating system. Is the air-source HP individual (one per dwelling) or centralized?

Author's response: Thank you for the comment. We do consider both space heating and domestic hot water in the total heat demand. We clarified this in the revised manuscript. From the techno-economic perspective of this analysis, we assume that each unit/dwelling implements its own air-source heat pump (e.g., at the rooftop of the building) but it is also possible that a centralized one is implemented (e.g., in the basement). We would like to refer to footnote nine in the manuscript.

Reviewer's comment: Sec 3.3.2

Disentangle macro-economic/ environmental scenarios (sec 3.3.2) from technological options (sec 3.3.3).

Author's response: Thank you for the comment. The macro-economic/environmental scenarios define the framework of the local decarbonization study and heating system change at the building level. As mentioned above, we aim with our study to break down and map European decarbonization scenario to the building level. However, we fully agree with the review comment that this explanation was been missing in the original manuscript. Based on the review comment, the following changes have been made:

- Changed the order of the input data and the scenario description. In the revised manuscript, Section 3.3.2 is dedicated to the input data of the multi-apartment building, while Section 3.3.3 explains the scenarios.
- Additional text at the beginning of the scenario section in order to (1) state explicitly that the scenarios define the empirical framework for the local analysis of this work, (2) clarify that we try to map abstract European decarbonization scenarios to the local levels.

Reviewer's comment: Sec. 3.3.3

- Table 1 is confusing / unnecessary (see general comment on macro-economic/environmental scenarios, versus technical options). On the other hand, data relative to the economic and environmental parameters (Tables A1 and A2) would fit very well here rather than in an appendix, and help fluent reading. You should also add here some info (or refer to appendix B) concerning the envelope retrofit measures (with heat reduction of 10, 20 or 30%).

Thank you for this comment. We removed Table 1 in the revised manuscript. In addition, we followed the review suggestion and moved Table A1 and A2 into the main text. Additionally, we explicitly refer there to Appendix B as well.

Reviewer's comment: Table 2 (or in the text):

- Please add a short note (or appendix) regarding HP and DH construction costs. What does that include, in particular in terms of heat distribution and the question of centralized / individual heat production (gas boiler, HP, DH).

We added a short note regarding HP and DH construction costs below Table 2 in the revised manuscript.

- Initial rent price: does that include amortization of the technical equipment, in particular of heat production and distribution.

The initial rent price does not include amortization of the technical equipment (= heating system alternative). Instead, the rent-charge adjustment reflects the amortization of the investment in DH or HP.

- Are the additional costs due to retrofit (active and passive) all amortized over 15 years (see example of Fig. 3), and this for all macro-economic/environmental scenarios?

Yes, we do consider an amortization of the retrofit measure within 15 years for all macro-economic/environmental scenarios.

Reviewer's comment: Sec. 3.4 is confusing and should be removed or adapted:

- Should you keep this section, the title should be "illustration" rather than "validation". Why work with another setup (single family house / appendix C) than the case study you are focusing on? If you keep this section, I would recommend illustrating the model on hand of one of the scenarios used in sec. 4.2 or 4.3 (for example SC with 20% retrofit, HP and/or DH case).

Thank you for this comment. We moved this section from the revised manuscript to Appendix A in the revised manuscript. We renamed the section to "Illustration of the model" as suggested. Intentionally, we aimed with the section to present the basic functionality and results of the model since it was developed from scratch and reviewers often ask for such illustrations during the review.

- **Reviewer's comment:** Fig. 2 (p. 23): The explanation of Fig. 2 (line 449 - 457) is not clear. If I get it right: i) the owner receives an investment grant of 2'750 EUR (20% of the total investment of 13'750 EUR), the rest of the investment being paid by the tenants through their rent charges; ii) over the 15 years of operation, the tenants receive a total subsidy of 13'750 EUR (NPV), which corresponds to the increase of heating costs due to system change; iii) the total subsidy of the governance hence amounts to 16'500 EUR. Hence:

We agree with the statement of the reviewer – this is completely correct and describes the basic functionality of the model. The total subsidy of the governance amounts to 16,500 EUR.

Nevertheless, some aspects are important here – we response in detail after each bullet point below.

- Unlike what is stated (line 449, but also Fig. 1), owner and tenants do not receive an equal financial support (each party gets a subsidy which enables no additional burden due to the decarbonization action, which is fully supported by the governance).

The property owner and tenant receives subsidy payments that amount to 13,750 EUR (i.e., net present value equals to 13,750). It is important to note that the property owner's net present value

reaches zero by the 20% investment grant and the (additional) rent-related revenues within 15 years of operation. In addition, the same financial support (i.e., net present value equals to 13,750) for the tenant by the governance ensures that the total spending (more precisely the net present value) between the existing and alternative heating system remains constant. We thus assume that the energy and rent costs for tenants will not increase in the future compared to today, as otherwise the social compatibility of decarbonization could not be guaranteed. The ultimate question here is to which reference (i.e., net present value) the subsidy payments for the tenant are referred. We decided to use the current energy and rent spending as reference.

- Why not allocate the entire 16,500 EUR to the owner, who would reduce the rent adjustment accordingly?

Thank you for this comment. Two aspects are very important in this context. (1) If the governance would allocate the entire 16,500 EUR to the property owner, this results in the fact that the property owner has in total a net present value greater than 0 (i.e., profits). This becomes evident as one compares the total overnight investment costs (14,000 EUR) with the total subsidies. However, the intention here is to ensure that the property owner does not gain profits through the heating system switch. If one wants to satisfy both aspects (i.e., allocate the entire 16,500 EUR to the property owner and sets the property owner's net present value equals to zero), this can only be achieved if the rent price adjustment is negative.

Reviewer's comment: Section 4: Generally speaking, it would be extremely insightful to simulate the DH and HP scenarios for the diverse macro-economic/environmental scenarios (DT, SC, GD), as well as for the diverse levels of envelope retrofit (0-30%). Without such, it is very difficult to differentiate HP and DH options, as well as to disentangle the specific sensitivity to the macro-economic/environmental scenarios, or to envelope retrofit. Such a reorganization will probably induce some reorganization of section 4.

Author's response: Thank you for this hint. We completely agree with the review comment that such an expansion of the results could be probably insightful. However, the intention with our work is primarily to present a newly developed open-source model in the context of an equitable decarbonization of local heating systems. Thereby, we used the three different macro-economic/environmental scenarios (DT, SC, and GD) to presenting the model. Nevertheless, we followed your suggestion and added the raised issue to future work as it could be a starting point for further analyses.

Reviewer's comment: Line 478 (p. 24): "Following Table 2 ..." should be adapted to "Following Table 2 and Appendix A ..." (or any proper reformulation with respect to a re-organisation of the text).

Author's response: Thank you for this hint. We rephrased this part of the text.

Reviewer's comment: Fig. 3 (p. 25):

- Are the heating cost and rent charge of the tenants total values, or additional costs as compared to the reference case?

The heating cost and rent charge of the tenant in Figure 3 are total values.

- Does the sum of heating cost and rent charge correspond to the (additional) rent revenue of the owner?

The sum of heating cost and rent charge of the tenant is related to the additional rent-charge related revenues of the property owner but generally not equally for each year and month.

- Why is it necessary to subsidize the tenant only during the first years?

Particularly, this becomes necessary as the underlying three different macro-economic/environmental scenarios (DT, SC, and GD) include a linear decrease of the specific emissions of electricity and district heating, which is why the influence of the CO₂ is high at the beginning (i.e., first years) and low at the end of the time horizon.

Reviewer's comment: Line 495 (and Appendix A): is the gas price for the reference scenario considered constant over the entire life span? Why?

Author's response: Thank you for this comment. Yes, the gas price for the reference scenario is constant over the entire life span. Accordingly, the heating system switch is compared with the current energy and rent spending of a tenant. From our perspective, this assumption is highly relevant as it ensures that the alternative heating system switch is socially compatible.

Reviewer's comment: Sec. 4.2:

- How much are the investments for envelope retrofit? Should be detailed in Appendix C or sec. 3.3.3. Does the investment (and corresponding investment grant) depicted in Fig. 4 comprise both the active decarbonization (change in heat production) and passive decarbonization (envelope retrofit)? Please add a table (possibly in appendix) describing the separate shares of investment for active/passive measures. If possible, show the results for HP and DH (if needed using an appendix).
Thank you for this comment. We added the value derived from Fina et al. [54] to Appendix B in the revised manuscript. The investment grant in Figure 4 is the financial support for both the active and passive decarbonization of the building. Accordingly, the optimization model does not separate the investment grant between active and passive measures since it is a single decision variable in the modeling framework.
- Line 512-518: Why is the HP implementation in the SC scenario "unfeasible" without envelope retrofit? Is governance subsidy (whatever its value) intrinsically unable to cover the additional economic burden of owner and tenants, or does the model integrate a subsidy limit (how much)?
Thank you for the comment. The main reason lies in the high energy costs for tenants and the equity constraint. In particular, the low building standard and corresponding high heat demand results in high energy spending of the tenant. The governance aims to compensate high energy costs of the sustainable heating system. However, the required amount of subsidy payments for the tenant result in an overcompensation of the property owner (i.e., net present value greater than zero). For a feasible solution, the property owner would have to gain profits in order to satisfy the subsidy balance constraint (equation 2) in the non-retrofitted building. We added this explanation into the revised manuscript (footnote twelve).

Reviewer's comment: Sec 4.3: As commented above, it would be nice to have results like Fig. 5 also for the diverse levels of envelope retrofit.

Author's response: Thank you for this comment. We agree with the reviewer that such a figure would be helpful in order to extend the already presented results of this work. However, from our point of view, the results of the paper are already comparatively extensive, which is why we have refrained from adding these results in the interest of keeping the paper lean and readable. Nevertheless, we followed the review comment and added this suggestion to future work.

Reviewer's comment: Fig. 5 (and lines 559 - 562): rent related revenues to the owner should not appear on this figure, since they are not part of the subsidy scheme. If my understanding is correct, they are covered (or partially covered) by the subsidy to the tenants (see comment above).

Author's response: Thank you for the comment. As stated in the original manuscript, Figure 5 shows the explicit and implicit subsidy payments by the governance to the property owner and tenants. We refer here to the following paragraph in the manuscript:

When comparing Table 4 and Figure 4, it is important to note that the property owner's rent-related revenues (orange bar) are an "implicit" subsidy. Hence, the governance's total financial support is equal to the sum of the tenants' heating costs subsidy (purple bar) and the property owner's investment grant (blue bar).

Reviewer's comment: Sec. 4.4: This section remains quite unclear. Instead of analysing the cost of inaction (which could be the object of further work), we strongly suggest to use this section for addressing the issue of possible public deficit. This could be done by comparing i) the total subsidy by the state with ii) the increase in CO₂ tax revenue due to inaction (i.e the difference between CO₂ tax without fuel change and with fuel change). Such should / could be done for all combinations of macro-economic scenarios, technical

options, and level of envelope retrofit.

Author's response: Thank you for this comment. We fully agree with the review comment, that investigating the total governance's costs is very important. Against this background, the intention in Section 4.4 is to show how the total governance's subsidy payments can be reduced by allocation the costs of inaction between the three agents/parties (i.e., governance, property owner, and tenants). We removed Figure 6 since it was quite complicated and added Table 6 to the revised manuscript. From our perspective, Section 4.4 is in consistency with the results presented in Sections 4.1 to 4.3 and rounds off the result section of the manuscript. However, we followed the review comment and made the following changes:

- We extended Table 4 with respect of the CO₂ tax-related revenues and public financial deficit (as suggested). Based on this, we added a bullet point to the key results in Section 4.3 regarding the scenario with the lowest public financial deficit.
- Moreover, we added this very important aspect of a detailed analysis related to the public financial deficit to future work.

In general, we completely agree with the review comment regarding in-depth analyses of the public financial deficit. Against the background of this work, this would need a modification of the mathematical formulation of the model. In particular, the objective function would need to be adapted since the CO₂ tax-related revenues of the governance are currently not included in the cost-minimizing function of the work. We will consider this very relevant issue in future work and thank the reviewer for the comment.

Reviewer's comment: Conclusions and outlook:

- Comparison between DH and HP should be done on a common basis, with an overview of the diverse macro-economic/environmental scenarios and envelope retrofit rates.
Thank you for this comment. We added this aspect to future work.
- To the contrary of air-soil HP, DH cannot be developed in dense urban centres unless presently already, due to crowded use of the subsurface and extensive use of the ground surface (namely for traffic) which makes interventions unfeasible or much too costly. In the case of presently available DH network of a certain size, decarbonization of the heat-mix usually occurs over several decades, making an "overnight" decarbonization (as assumed in the model) unfeasible. Further work would be needed to take into account such phenomena.
Thank you for the hint. We added this important aspect to the conclusions of the work. However, this work rather investigates an overnight replacement of end-user gas boilers than decarbonization of the energy mix, fueling district heating or electricity.
- Further sensitivity to the main parameters (investment costs, amortisation period, heat demand level of the reference case, ...) could be worthwhile.
Thank you for the hint. We added this aspect to future work.
- What about the operational burden (and cost) of the subsidy scheme, with amounts which need to be re-evaluated every year?
The operational burden and cost of the subsidy scheme are out of this paper's scope.

Reviewer's comment: Miscellaneous

- P. 11, line 245: "... the investment costs to adapt existing buildings" (instead of "to adopt"?)
- P.12, line 275-277: not clear (check syntax?)
- P. 21, line 412: "The GD scenario aims at limiting the global temperature increase ..."
- Eq. 6: As defined here (and as used in eq. 7), this is the adjustment of the rent related revenue (not the total rent-related revenue). The initial rent price (does not enter this definition (see line below eq. 6)).

- Eq. 8, Eq. 9 and first line after Eq. 9: symbol for initial annual spending of tenants not coherent
- Eq. 15: drop the mathematical symbol "for all" (reversed A) and write " $y = y_0$ "
- Eq. 17: As currently written, symbol "a" is missing on the left-hand side of the equation.

Thank you for the hints. We rephrased the parts in the revised manuscript.