**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, Daniel Huppmann, Antonia Golab, Hans Auer

**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 consistant, 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, I 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 pinit,y,m is the price of the conventional fuel initially supplying heat demands. Besides, palt,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 Appendix A.   
Hier einen Satz nach Gleichung (10) einfügen.

**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. However, 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 built the arc of suspense. The reader discovers the novelties of the study and which methodological approach was developed. 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 Phi & Omega).  
**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 expanded Figure 1. Particularly, we tried to link the Figure with the variables and equations of the model. Furthermore, we added a table in the revised manuscript where we provide an overview of the model (variables, constraints, equations, etc.) where we added abbreviations/subscripts on order to make it easier to follow the method. Thank you for the hint.

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 completely agree with the reviewer and the raised issue. As stated above, we followed the suggestion of adding a table to provide an overview of the model. In addition, we tried to add more high-level explanations in the text in order to make it easier to understand the equations. We do think that we could improve the quality of the manuscript based on the reviewer comment.   
Sidewaytable einfügen über eine ganze A4 Seite.

**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. We added text to part of the paper explicitly stating that the concept of equitability in the paper is defined as a subsidy balance. We agree that is important to make this aspect clear in the paper. Thank you for the hint.   
Gleichung (17) weiter vor in der Methode und explizit schreiben, dass wir Equitability als subsidy-balance verstehen.

**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' and 'Reference' column. 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 but 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.  
Satz dazu schreiben, dass das grobe Schätzungen waren. Vielleicht zum Anhang was hinzufügen von der Berechnung.

**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. The 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).  
Figure 2 update machen (Fractions entfernen).

**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 removed L482 into 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. Nevertheless, we include the raised issue as future work of the study.   
pinit,y,m berücksichtigt auch die Maintenance costs (see Appendix A).  
Future work: explizit hinzufügen von maintenance costs.  
**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) can not be satisfied. We added this information to Section 4.2 in the revised manuscript. Thank you for this helpful comment.  
Erklärung noch mal nachschärfen zur no feasible solution. Hohe Energiekosten.

**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. The use names and abbreviations instead of Case A, B… in the revised manuscript. Moreover, we significantly updated the 3D graphic in Figure 6. We hope that the updated presentation of the results in Figure 6 is now easier to follow since there important results of the analysis are presented.  
3D Graphic/Plot nochmals überarbeiten!!

**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 could be removed as they do not add important information. In particular, we removed L107 and L120-122.   
Zeilen löschen wenn sie nicht wichtig sind.

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:

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.

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.

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), is 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.

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

Specific comments

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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).

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).

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).

\* 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?

\* 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.

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?

Sec 3.3.2

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

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%).

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).

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

\* 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?

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).

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:

\* 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).

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

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.

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).

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?

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

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

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

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).

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)?

Sec 4.3:

As commented above, it would be nice to have results like Fig. 5 also for the diverse levels of envelope retrofit.

Fig. 5 (and lines 559 - 562): rent related revenues to the owner should not appear on this figure, since the 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).

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.

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.

\* 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 to 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.

\* Further sensitivity to the main parameters (investment costs, amortisation period, heat demand level of the reference case, …) could be worthwhile.

\* What about the operational burden (and cost) of the subsidy scheme, with amounts which need to be re-evaluated every year?

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 = yo"

Eq. 17: As currently written, symbol "a" is missing on the left-hand side of the equation.