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The 15th International Symposium on District Heating and Cooling

Assessing the feasibility of using the heat demand-outdoor temperature function for a long-term district heat demand forecast

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Abstract

District heating networks are commonly addressed in the literature as one of the most effective solutions for decreasing the greenhouse gas emissions from the building sector. These systems require high investments which are returned through the heat sales. Due to the changed climate conditions and building renovation policies, heat demand in the future could decrease, prolonging the investment return period.

The main scope of this paper is to assess the feasibility of using the heat demand – outdoor temperature function for heat demand forecast. The district of Alvalade, located in Lisbon (Portugal), was used as a case study. The district is consisted of 665 buildings that vary in both construction period and typology. Three weather scenarios (low, medium, high) and three district renovation scenarios were developed (shallow, intermediate, deep). To estimate the error, obtained heat demand values were compared with results from a dynamic heat demand model, previously developed and validated by the authors.

The results showed that when only weather change is considered, the margin of error could be acceptable for some applications (the error in annual demand was lower than 20% for all weather scenarios considered). However, after introducing renovation scenarios, the error value increased up to 59.5% (depending on the weather and renovation scenarios combination considered). The value of slope coefficient increased on average within the range of 3.8% up to 8% per decade, that corresponds to the decrease in the number of heating hours of 22-139h during the heating season (depending on the combination of weather and renovation scenarios considered). On the other hand, function intercept increased for 7.8-12.7% per decade (depending on the coupled scenarios). The values suggested could be used to modify the function parameters for the scenarios considered, and improve the accuracy of heat demand estimations.

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Keywords: Heat demand; Forecast; Climate change

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1. Introduction

District heating networks are commonly proposed in the literature as an environmentally friendly solution for providing heating services for urban environment. Centralized heat production located outside municipalities, utilization of renewable heat sources (biomass, solar, geothermal etc.) and comfort for the consumers are usually stated as the main benefits of such systems. The subject has been widely researched in several scientific reports [1-4]. The conclusions were that the district heating should be considered as an essential cost effective technology for the EU energy system decarbonization. The construction of such infrastructure requires significant investments costs, which are returned through the heat sales. However, due to the changed weather variables caused by the climate change, the amount of heat required to maintain comfort indoor conditions could decrease in the future. Additionally, new governmental policies that tackle the refurbishment of the existing building stock (such as EPBD - Energy Performance of Buildings Directive, or the Directive 2010/31/EU), along with the implementation of advanced construction and insulation for new buildings, could decrease the heat loss through the building envelope. Consequently, heat demand could decrease even further. Thus, modelling the future heat demand evolution in the decades to come could be the crucial aspect for assessing the district heating networks construction/expansion project feasibility.

Nomenclature

T_{ht}	heating threshold temperature [°C]
T_{ct}	cooling threshold temperature [°C]
$Q_{h,i,j}$	hourly heat demand of the i -th building for the regarded j -th hour [W]
α_i	heat demand – outdoor temperature function slope for the corresponding i -th building [W/°C]
θ_i	heat demand – outdoor temperature function intercept for the corresponding i -th building [W]
$t_{o,j}$	outdoor air temperature for the regarded j -th hour [°C]
θ	heat demand – outdoor temperature function intercept for the corresponding building [W]
Δ	annual heat demand percentage error [%]
σ	standard deviation between the hourly demand values [-]
$Q_{hdf,j}$	hourly district heat demand estimated by the heat demand-outdoor temperature function [W]
$Q_{hdRC,j}$	hourly district heat demand estimated by the RC model [W]

The impact of climate change on building heat demand was already addressed within the existing bibliography. Based on the study scale and weather scenarios considered, these studies can commonly be categorised into three major groups:

- **Building scale, one location** – one representative building was selected for the location studied, with weather scenarios developed based on the local climate [5-6];
- **Building scale, multiple locations** - one representative building from the national building stock was selected, with weather scenarios developed for all major climate types found within that particular country [7-10];
- **Large scale (district/city/country level)** – methodologies developed were applied on a large building sample (that vary in both type and construction period), with single or multiple weather scenarios considered [11,12];

Within these studies, to calculate the heat demand, the authors either used detailed simulation software such as Energy Plus and TRNSYS (for the case studies on a building scale), or estimations based on the statistical data (for large-scale case studies). However, urban environment is usually consisted of various building types originating from different construction periods that can differ significantly in both size and geometry. Thus, up-scaling the heat demand calculated for a representative building or downscaling the demand calculated on a statistical basis could

provide misleading results. Consequently, this motivated the authors of the present study to develop a dynamic model that is capable of calculating heat demand for a large number of buildings without significant calculation time or computing power required, and that is yet able to take into account all significant building properties (geometry, thermal properties, occupancy profiles etc.). The dynamic aspect is particularly important from the district heating network operator point of view (for the production units and storage optimisation). Model description, validation and possible limitations were described in detail within the previous publications by the authors [13, 14].

However, the model requires multiple input data for each building within the district. For the previous case study [13], input data was obtained by using different tools (such as Geographical Information System (GIS), Light Detection and Ranging (LiDAR)), bibliography, as well as local municipality database. Since the source and data availability can vary from one location to another, the margin of error for using a less complex approach (that requires less detailed inputs) for estimating the heat demand in the future is considered within this study.

Heat demand - outdoor temperature function (Fig.1) is commonly used to represent the dependency of energy consumed in buildings on the outdoor temperature. The main assumption in this approach is that the energy demand for heating use the same set-point temperature over the year, and that the change in energy demand corresponds to a change in the outdoor temperature (i.e., sensible heat exchange through the building envelope has significantly higher impact on energy demand compared to other heat losses/gains such as heat gain from the occupants/lighting/appliances and infiltration loss). In the study of Hekkenberg et al. [15], the authors suggested that the function angles could prove to be suitable for expressing the change in heat demand caused by the climate change in the future. This V-shaped linear symmetric relationship between the building energy demand and outdoor temperature was also addressed in the paper of Brown et al. [16]. The authors addressed both linear symmetric and non-linear asymmetric relationships between temperature and energy use in buildings, as well as semi-parametric and non-parametric models. However, the authors focused on the electricity demand for meeting the cooling demand (due to a higher non-linearity in electricity consumption-outdoor temperature correlation compared to heating). Additionally, building renovation was not considered.

The main scope of this study is to assess the feasibility of using the heat demand-outdoor function for heat demand forecast on a district scale, taking into account climate and building renovation scenarios for the future.

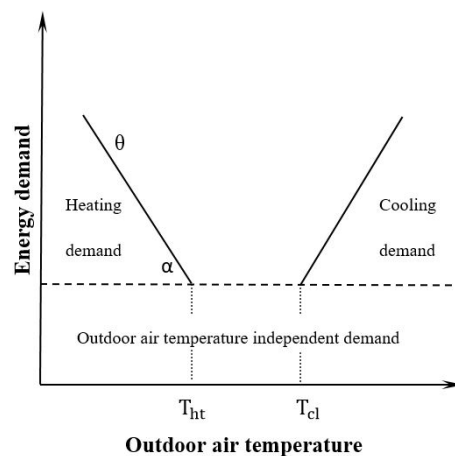


Figure 1. Energy demand – outdoor temperature function

2. Methodology

Primarily, heat demand was calculated on an hourly basis for each building within the district (for the reference district state and weather scenarios) by using RC (resistance-capacitance) model based on the thermo-electrical

analogy. With the reference district heat demand calculated, the heat demand – outdoor temperature function for each building was expressed as:

$$Q_{h,i,j} = \alpha_i \cdot t_{o,j} + \theta_i \quad (1)$$

where $Q_{h,i,j}$ [W] is the hourly heat demand of the i -th building for the regarded j -th hour, α [W/°C] and θ [W] are the function slope and intercept (respectively) for the corresponding i -th building, and $t_{o,j}$ [°C] is the outdoor air temperature for the regarded j -th hour.

Three future weather scenarios were created by using the CCWeather Generator tool (developed at the University of Southampton) for morphing reference .epw weather files. The software uses the .epw files as a primary input. Other required inputs are the output climate scenario files (for A2 family of IPCC scenarios) from the HadCM3 (Hadley Centre Coupled Model, version 3) - coupled Atmosphere-Ocean General Circulation Model (AOGCM) developed at the Hadley Centre located in the United Kingdom. As an output, CCWorldWeatherGen produces morphed weather data for three years: 2020, 2050 and 2080. However, within this study, obtained results were used to develop three weather scenarios: low scenario (weather data calculated for the year 2020 is used as the weather data for the year 2050), medium scenario - weather data calculated for year 2050 is used as the weather data for the year 2050) and high scenario (weather data calculated for year 2080 is used as the weather data for the year 2050). For all three scenarios, weather data for the years 2020, 2030 and 2040 was linearly interpolated between the values for a reference year (2010) and the values for the year 2050. We found that our low, medium and high scenarios correspond to RCP2.6, RCP6.0 and RCP8.5 IPCC (Intergovernmental Panel on Climate Change) scenario (respectively), within the range of uncertainty defined within the IPCC report [17].

Additionally, three district renovation paths for the future were developed to account different depths of district renovation (i.e. the amount of building renovated) and levels of building renovation (different levels of building envelope improvements). Three main criteria were considered for renovation scenarios:

- **Building selection criteria** – defining which buildings are renovated;
- **Renovation depth** – defining the amount of buildings renovated out of the total buildings selected by the first criteria;
- **Renovation level** - level of improvement in the building envelope that defines new thermal properties;

Finally, for each year considered in scenarios (2020, 2030, 2040 and 2050), hourly demand of each building within the district was calculated by using two approaches:

- **RC model simulation** – for each year of the scenarios, hourly heat demand for each building within the district was calculated by using the detailed input data from weather scenarios (outdoor air temperature, solar radiation) and renovation scenarios (new building envelope thermal properties, improved after the renovation);
- **Heat demand-outdoor air temperature function estimation** – primarily, function parameters (slope and intercept) for each building were calculated based on the RC model heat demand results for a reference year (2010, reference weather and district state). Then, for each year of the regarded scenarios, hourly district heat demand for each building within the district was estimated by using these function parameters (see eq.(1)) and forecasted outdoor air temperatures.

To estimate the difference between the results obtained from these methods, two parameters were used: annual heat demand percentage error Δ ([%], eq.(2)) and standard deviation between the hourly demand values (σ [SD], eq. (3)):

$$\Delta = \frac{(\sum_{j=1}^n Q_{hdf,j} - \sum_{j=1}^n Q_{hdRC,j})}{\sum_{j=1}^n Q_{hdRC,j}} \cdot 100 \quad (2)$$

$$\sigma = \sqrt{\frac{\sum_{j=1}^n (Q_{hdf,j} - Q_{hdRC,j})^2}{n}} \quad (3)$$

where the $Q_{hdf,j}$ [W] and $Q_{hdRC,j}$ [W] are the hourly district heat demands (sum of hourly heat demands of all buildings within the district for the regarded j -th hour of total n hours during the heating season) estimated by the heat demand-outdoor temperature function and calculated by the RC model, respectively.

3. Case study

The district of Alvalade, located in Lisbon (Portugal), was used as a case study. The district is consisted of 665 buildings that vary in both construction period and typology (single-family houses, multi-apartment buildings, offices, educational buildings and hotels). Reference building database (building geometry, position, shading etc.) was created by using ArcGIS and remote sensing (LiDAR), as well as already existing database from the local municipality. Thermal properties for the reference buildings state were obtained from the BPIE (Building Performance Institute Europe) online database [18] and a specific case study for Portugal [19], based on the construction period and type considered. For the reference weather data, .epw weather file for Lisbon from Energy Plus weather database [20] was used. Weather scenarios were developed by using the CCWeather Generator tool. For the building renovation scenarios, building selection criteria (i.e. the definition of which buildings will be selected for renovations) was based on the administrative division of the district, while the values for the amounts of buildings renovated each year within the sections were obtained from the BPIE report [21]. Thermal properties for the improved envelope elements after renovation measures were estimated based on the available bibliography [22]. In this case study, first renovation step would be to refurbish the existing building stock to the current commercial level (the U-values for the buildings built around 2010, as given in [22]) before upgrading it to higher levels of insulation. Thus, for each building type (and for its elements), upgrade to 2010 values is considered as a minor renovation, while for the nearly-zero energy buildings level the values from the previously mentioned study ([12]) were assigned. Accordingly, the values for the moderate and deep renovations are derived through the linear interpolation between these values. For more detailed description of the district data collection and creation of weather and renovation scenarios, please refer to a previous study by the authors [13].

4. Results and discussion

Primarily, the results for a reference year (2010) are compared to verify the suitability of the heat demand – outdoor temperature function to estimate building heat demand based only on the calculated function parameters for the reference year and outdoor temperature. The precision was quite high, with the annual error of $\Delta=0.25\%$ in estimated heat demand and standard deviation between the hourly demand of $\sigma=0.06$ (as it can be seen on Fig.2). To further estimate the ability of the function to represent the dependency between the heat-demand and outdoor temperature, Pearson's product-moment correlation coefficient was used (commonly used in the bibliography as a measure of linear correlation between two variables). The coefficient is defined as the covariance of the two variables divided by the product of their standard deviations. The value of the coefficient was $\rho=-0.91$, which proves high linearity (on scale from 0 to -1 for total negative correlation (negative due to the fact that the heat demand decreases with a temperature increase)). The results proved that, in our context, the major factor in heat demand are clearly sensible heat losses through the envelope (due to the high linearity).

However, in the case of heat demand forecast with developed weather scenarios accounted (without any renovations considered), the error and deviation increased (Fig. 2). The average error increase is within the range of 0.4 - 2.5% per decade (depending on the weather scenarios considered), while the standard deviation slightly increases within the range of 0.061 - 0.064. Considering that within the bibliography it is stated that for the

simplified building models, acceptable margin of error is 20% [23], and taking into account that in this case the highest margin of error is less than 20% (11.9%, high weather scenario, year 2050), this approach could be suitable for simplified estimations of heat demand in the future. However, since the acceptable margin of error further depends on the scope of the study (stage and the value of the project in development etc.), in some instances the error of 12% could be considered as quite high. Thus, depending on the margin of error expected by the decision-makers, dynamic models (such as mentioned RC model) could be necessary.

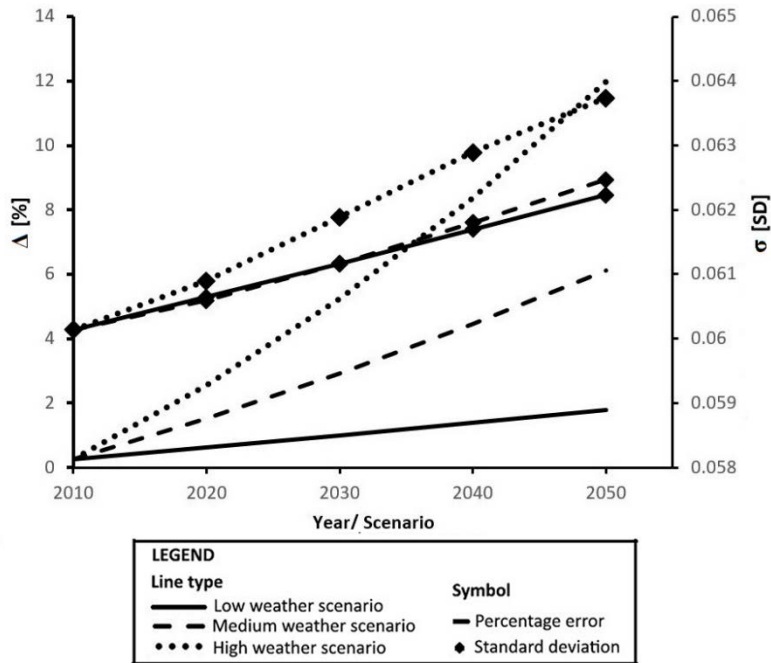


Figure 2. Percentage error and standard deviation between the two approaches considered (only weather scenarios)

As presented in the paper by the authors for the previous International Symposium on District Heating and Cooling [23], the number of heating hours has the crucial effect on the function perimeter values. As a result of shifted temperature values for the future weather conditions, the number of heating hours (n_{hh}) is decreased, and the hour dataset that is consisted of these values and used for the heat demand calculations is consequently not the same. The effect of decreased number of hours that require heating on district heat demand function parameters (calculated for the demand of the whole district) can be observed on Fig.3 and Fig.4.

The number of hours with heat demand during the heating season decreases for an approximately 14h, 46h and 108h per decade (for low, medium and high weather scenario, respectively). The values of the slope coefficient α increase for 0.01 to 0.08MW/°C per decade, while the values of the intercept θ decrease for 0.18 to 1.92MW per decade (depending on the weather scenario considered). Thus, it can be concluded that for the decrease in number of heating hours of 4% per decade (that correspond to an average of all weather scenarios increase in outdoor temperature of 0.4°C per decade), the value of the slope increase for 0.04MW/°C, while the intercept values decrease for 0.74MW.

However, due to the new building renovation policies, the probability of envelope retrofitting over the district in the future is relatively high, and thus, the effect of renovation scenarios should be also considered. Consequently, we have recalculated the error in results between the two models, taking into account both weather and renovation scenarios. The percentage error increased significantly, and for all combinations of weather and renovation scenarios, the margin of error was higher than 20% in year 2030.

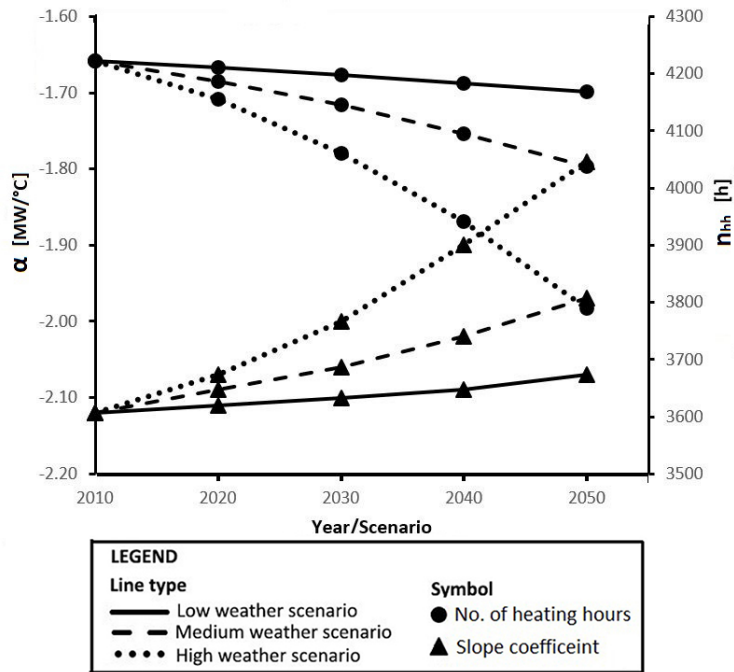


Figure 3. The impact of decrease in heating hours on the district heat demand function slope coefficient (only weather scenarios)

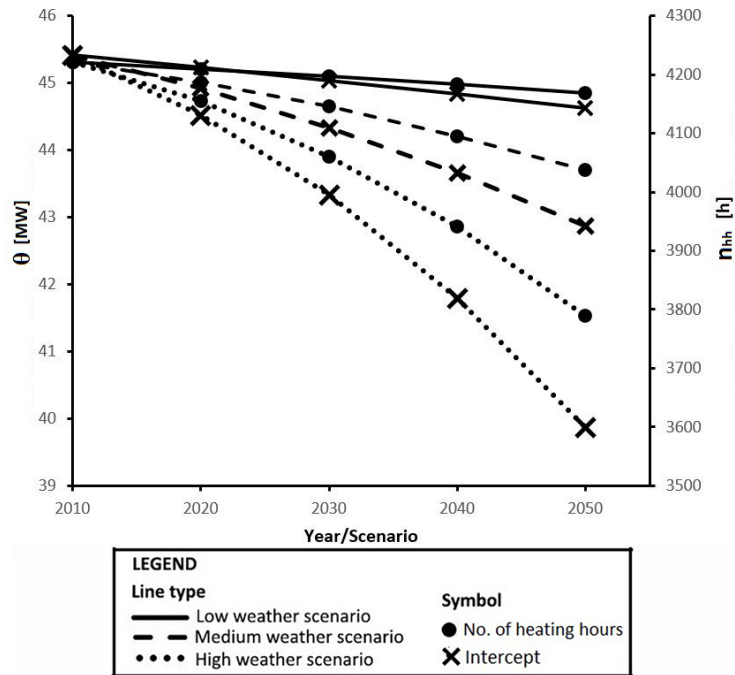


Figure 4. The impact of decrease in heating hours on the district heat demand function intercept (only weather scenarios)

For the year 2050, for the lowest heat demand reduction scenario combination (low weather scenario and shallow

renovation path), the margin of error is 27.6%, while for the highest demand reduction scenario (high weather scenario and deep renovation path) the margin of error is 59.5%. Thus, the margin of error increases significantly when renovation scenarios are considered, due to the inability of the function to account for the changes in the thermal performance of building envelope elements (please see eq.(1)). Consequently, it can be concluded that the use of solely reference function parameters and future weather conditions is not suitable for heat demand forecast. Hence, the impacts of coupled weather and renovation scenarios on the reference function parameter values (calculated for the whole district demand) are explored.

The impact of coupled scenarios on the number of heating hours (and consequently demand function slope and intercept) are illustrated on Fig 5 and Fig.6. The values of the function slope coefficient increase on average within the range of 3.8% up to 8% per decade, that correspond to the decrease in the number of heating hours of 22-139h during the heating season (depending on the combination of weather and renovation scenarios considered). On the other hand, function intercept increases for 7.8-12.7% per decade (depending on the coupled scenarios). Comparing the results from Fig. 3/Fig.4 and Fig.5/Fig.6, it is clear that the renovation of buildings within the district has a higher impact on the function parameters, and consequently on the number of heating hours and errors in heat demand estimations by using the reference values of slope and intercept. Thus, the values of the slope and intercept coefficients (α, θ) would have to be corrected in order to decrease the margin of error and make the heat demand-outdoor temperature function feasible for a long-term district heat demand forecast.

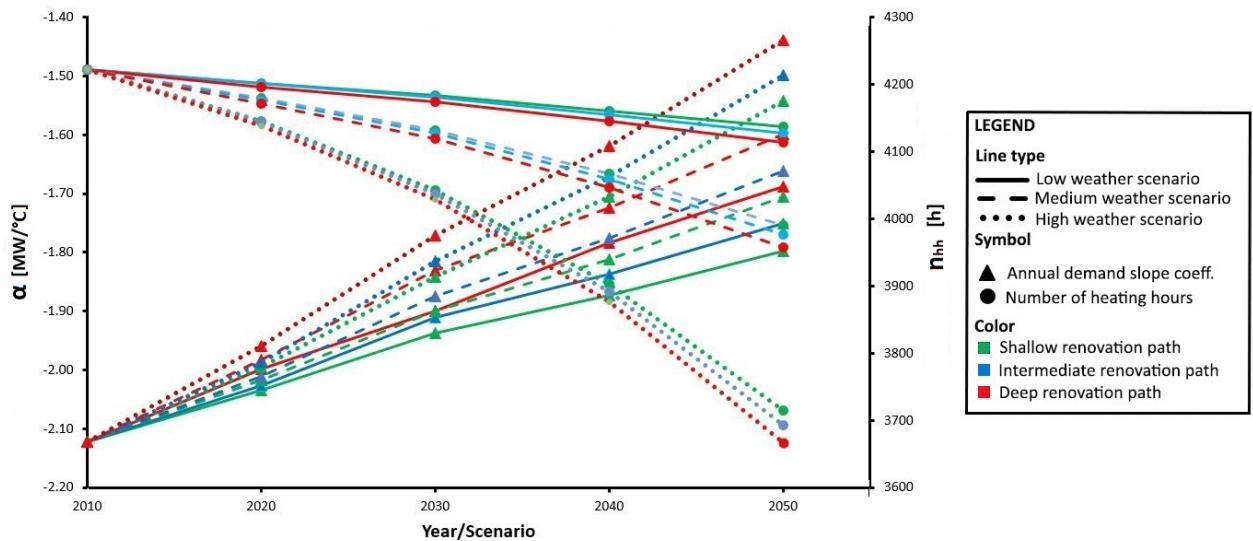


Figure 5. The impact of decrease in heating hours on the district heat demand function slope coefficient (both weather and renovation scenarios considered)

5. Conclusion

The main scope of this paper was to explore the feasibility of using a simplified numerical approach based on the heat demand – outdoor temperature function to estimate the heat demand in the future on a district scale. The impact of climate change was considered through the developed weather (low, medium, high) and renovation (shallow, renovation, deep) scenarios. The results were compared with an output from a dynamic heat demand model, previously developed and validated by the authors. Proposed methodology was applied on the district of Alvalade, located in Lisbon (Portugal), that is consisted of 665 buildings that vary in both typology and construction period. Three weather scenarios were considered (low, medium and high), along with three building renovation scenarios (shallow, intermediate, deep renovation path).

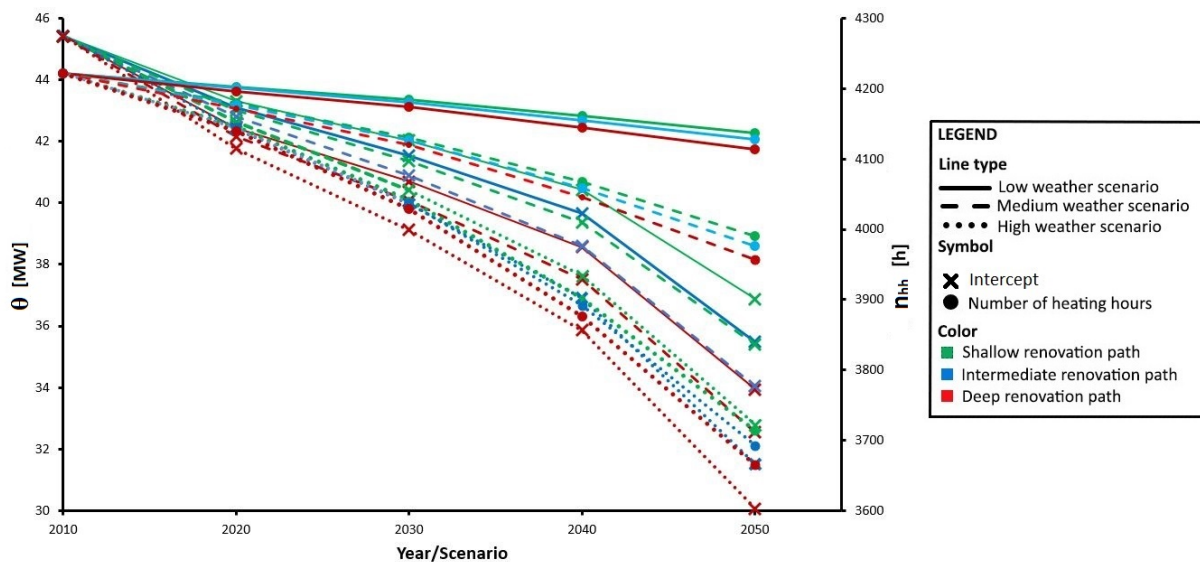


Figure 6. The impact of decrease in heating hours on the district heat demand function intercept (both weather and renovation scenarios considered)

The results indicated that for the reference year (reference weather and district state), the precision of estimated demand values through the proposed function was satisfactory. After taking into consideration weather scenarios, the margin of error was still below 20% on all occasions, and the approach could be considered accurate enough for some applications, if no district renovation measures are planned. However, after introducing the renovation scenarios, the error value increased up to 59.5% (depending on the weather and renovation scenarios combination considered). Considering the values of function parameters, slope coefficient increased on average within the range of 3.8% up to 8% per decade, that correspond to the decrease in the number of heating hours of 22-139h during the heating season (depending on the combination of weather and renovation scenarios considered). On the other hand, function intercept increased for 7.8 - 12.7% per decade (depending on the coupled scenarios).

The values suggested could be used to modify the function parameters for the scenarios considered, and improve the accuracy of heat demand estimations (by correcting the function parameter values for the regarded year and considered weather and/or renovation scenarios). However, the coefficient correction values presented are based on the findings for a particular case study addressed in this paper and renovation scenarios considered. The impact of changed weather variables could be different for locations in different climate and building stocks, as well as renovation parameters. Furthermore, behind the renovation scenarios, three aspects are considered (building selection, renovation depth and renovation level). Instead of connecting the function parameters to renovation scenarios, a deeper insight on the impact of envelope element U-values improvements and element surface on the function parameters, combined with weather variables change, could be useful for future estimations. However, these complex relationships between multiple parameters should be presented in a clear and simplified manner, which is a challenging task itself.

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