Energy Signature Modeling Towards Digital Twins – Lessons Learned From a Case Study With TRV and GAHP Technologies

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Abstract

In building refurbishment projects, efficient technologies such as heat pumps are increasingly being used as a substitute for conventional technologies such as condensing boilers, with the aim of reducing carbon emissions and determining operational energy and cost savings. Measured building performance, however, often reveals a significant gap between the predicted energy use (design stage) and actual energy use (operation stage). For this reason, a scalable energy signature modeling approach is presented in this paper to verify building energy performance from measured data. Regression models are built with data at multiple temporal resolutions (monthly and daily) and are used to verify the performance improvement due to smart heating controllers (TRV) and Gas Absorption Heat Pumps (GAHP). The capabilities of energy signature analysis are enhanced by including additional variables in the modeling process and by running the models as "digital twins" with a rolling horizon of 15 days of data. Finally, a regression model for GAHP technology is developed to validate the results measured in the monitoring process in a comparative way. The case study chosen is Hale Court sheltered housing, located in the city of Portsmouth (UK). The results obtained are used to illustrate possible extensions of the use of energy signature modeling, highlighting implications for energy management and innovative building technologies development.

1. Introduction

The necessity of achieving high energy efficiency targets while maintaining an adequate level of services in the building stock is one of the topics driving the built environment today. Innovative heating technologies are part of this research and Gas Absorption Heat Pump (GAHP) can be used as an alternative to conventional and condensing boilers. Additionally, smart heating controllers, such as Smart TRVs (Thermostatic Radiator Valves) are often reported as a promising technology, even if this depends on multiple factors and, in particular, operational patterns and user behavior (Manfren et al., 2021a, 2021b and 2022; Tronchin et al., 2018).

The case study of Hale Court, considering intervention in the North Block allows testing of the new methodology in question. In particular, the area was monitored before and after the retrofit intervention – namely, first with the installation of Smart TRVs (Thermostatic Radiator Valves) and then with the installation of Gas Absorption Heat Pumps (GAHPs). The monitored data are split into three periods: explicitly before retrofit, after the installation of TRVs and after the installation of GAHPs and plant room upgrade. The performance before retrofit represents for us the baseline for evaluation. Data are summarized and aggregated at different time scales (monthly and daily), energy signatures are calculated from energy metering data and piecewise linear regression models are fitted for the different monitoring periods to enable performance comparison. Finally, the savings monitored are compared to the ones calculated by a regression model of GAHP performance

2. Methods

First of all, the methods used in this research are aimed at giving primarily a reliable assessment of the actual impact of different technologies in terms of efficiency. For this reason, the regression-based approaches proposed by state-of-the-art Measurement and Verification (M&V) protocols such as ASHRAE 14 (ASHRAE, 2014), Efficiency Value

Organization (EVO, 2003), Federal Energy Management Program (FEMP, 2008), frequently indicated with the term M&V 2.0 (Gallagher et al., 2018), are included. This is crucial because of the necessity of performing an initial screening analysis before proceeding with more in-depth evaluations. Technical state-of-the-art standardization was used as a basis and some innovative elements were introduced. The starting point is a regression-based analysis of energy signatures (i.e., average power in a certain interval of analysis).

Sample models for the whole-building approach (ASHRAE 14:2014 Measurement of Energy, Demand, and Water Savings) are used:

- mean, or one-parameter model, (electricity);
- two-parameter model;
- three-parameter heating model (similar to a variable-base degree-day VBDD model for heating);
- three-parameter cooling model (VBDD for cooling);
- four-parameter heating model;
- four-parameter cooling model;
- five-parameter model.

Energy signature regression is proposed in standardization as a way of "normalizing " energy performance with respect to the main influencing factors - outdoor air temperature in this case. Models can then be used to track performance in time (Manfren et al., 2019 and 2021b).

3. Case Study

Hale Court is a sheltered housing development run by Portsmouth City Council, built in 1984. Hale Court consists of 80 flats with a mix of studio flats, 1 bedroom-, 2 bedroom- and 3-bedroom-flats.

As part of the EU Horizon 2020 project THERMOSS), Smart Thermostatic Radiator Valves were installed and the heating system plant room was refurbished with the installation of Gas Absorption Heat Pumps (GAHP). A monitoring system was set-up to enable detailed building energy performance analysis.

The proposed refurbishment of the heating system for the North Block plant room involves: (1) keeping the existing gas boilers (2) removal of the water heaters (3) addition of a 3-GAHP cascade (4) incorporation of thermal storage and (5) reconfiguration of the piping layout.

Table 1 – Characteristics of the thermal systems

HEAT GENERATORS	
Gas Boilers x2	**REMEHA GAS 110 Eco**
Capacity	115 kW (per boiler)
Boiler design Temperature	80 °C
Typology	Condensing
Gas Absorption Heat Pump	**GHP AWO 38 Three appliance cascade**
Thermal power output A7W50	114.9 kW
Gas Utilization Efficiency A7W50	1.52
Natural gas power input A7W50	75.6 kW
Max. heating water flow temperature	65 °C
Permissible Ambient Temperature	-20 to +40 °C

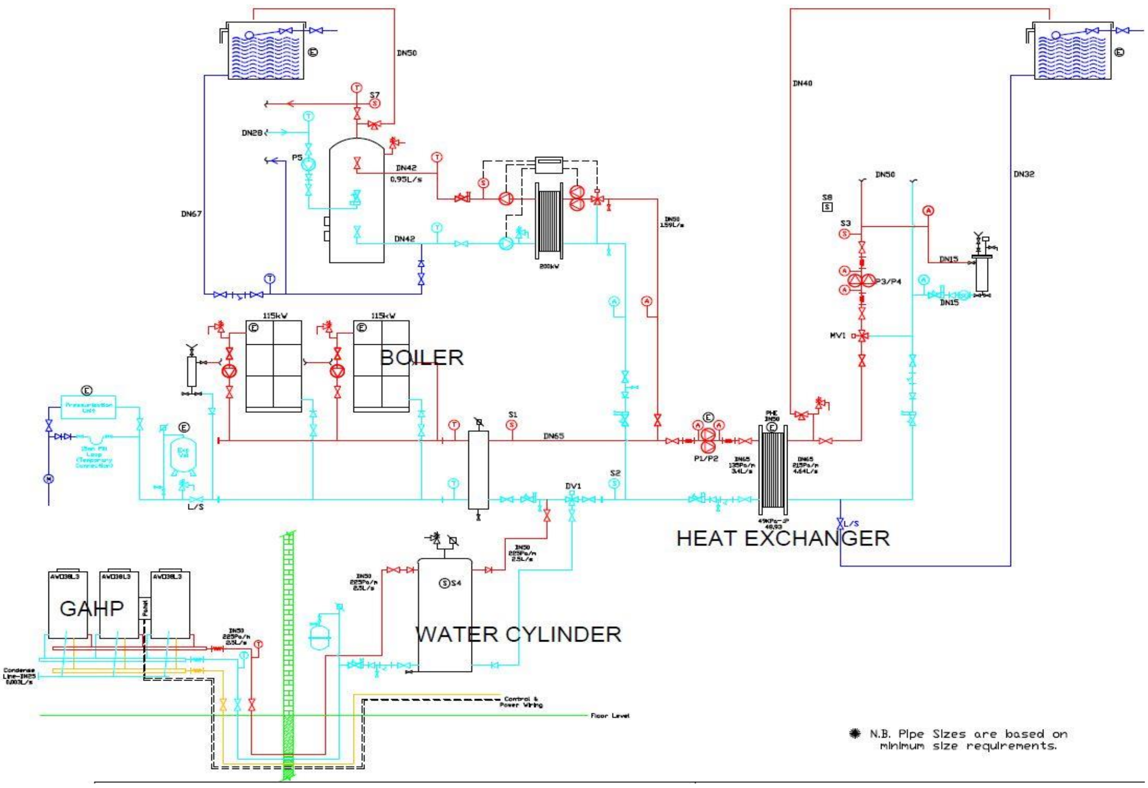

Fig. 1 – Technological scheme of the case study – Hale Court

4. Results and Discussion

Energy signature analysis of natural gas and electricity requires using piecewise linear regression for Hale Court, North Block.

The two models for natural gas demand signature (three-parameter heating model) and electricity signature are in the boundaries fixed by the ASHRAE 14:2014 guidelines.

Table 2 – Results of analysis for natural gas demand signature

Period	Energy indicator			Statistical indicator			
	Energy Measured (M)	Energy Predicted (P)	Relative differences	R^2	MAPE	NMBE	Cv(RMSE)
1	293464	299273	-1.98	93.0	14.3	1.98	11.9
2	93466	93544	-0.08	91.1	15.9	0.08	12.2
3	242586	243004	-0.17	88.3	13.9	0.17	13.3

The energy demand reduction regression model of GAHP performance shows a reduction of 20 %.

Table 3 shows the energy demand reduction using a prediction model, with standard weather and normalized occupant behavior.

Table 3 – Reductions

Period	Description	Overall reduction	Relative reduction
1	Before retrofit	0 (baseline)	-
2	TRVs installation	7.2 %	0 (baseline)
3	GAHPs and plant room upgrade	25.8 %	20.0 %

In order to characterize GAHP performance, we need to consider the *GUE* (Gas Utilization Efficiency), which is the parameter describing its thermal conversion efficiency. *GUE* is defined as the ratio between the delivered thermal energy and the fuel energy (and substantially similar to the COP for an electric heat pump).

Prediction of thermal power output P_{th} and *GUE* in full load conditions as a function of outdoor air temperature and supply water temperature used multivariate regression.

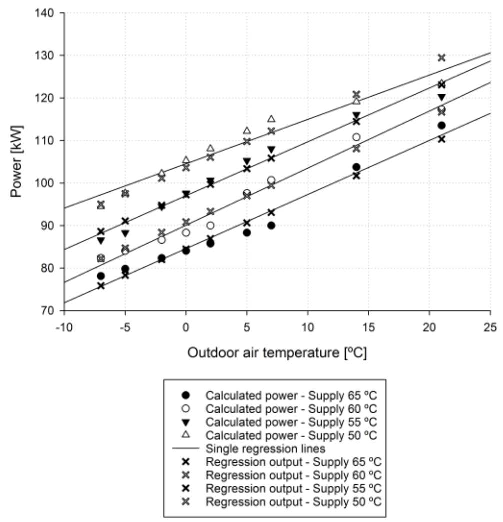

Fig. 2 – Thermal power output as a function of outdoor air temperature

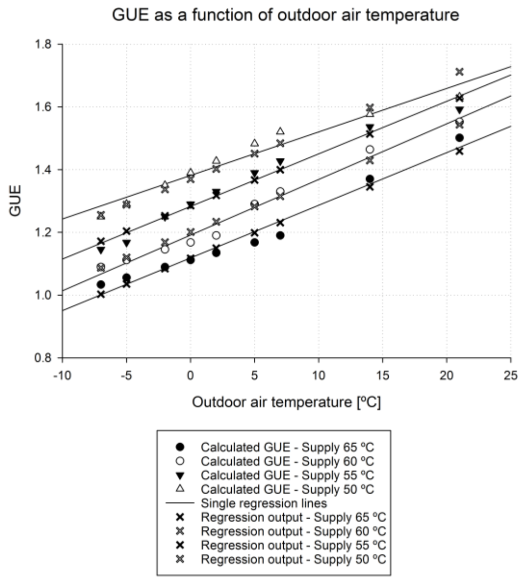

Fig. 3 – GUE as a function of outdoor air temperature

5. Conclusions

Energy signature modeling is a powerful tool for a first screening using monthly data. GAHP performance linearization enables the estimation of performance variability (*P_{th}, GUE)* as a function of outdoor air and supply temperatures and the calculation of part-load performance. Feedback from data analysis can help to improve management and control of GAHP.

Further research concerns application to daily and hourly data, to derived daily and hourly energy signature analysis and performance tracking:

1. Calculation of part-load performance ratio for GAHP using the regression model as reference.
2. Analysis of average thermo-physical properties of building to support detailed energy model calibration.

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