hothouse

Hot water provision in homes: consumption, storage and lifestyle

Modelling and Calibration of Domestic Building with High-Resolution Measured Data

iSTUTE Meeting 20th June 2016
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Why do we need a calibrated model ?

- To reduce the gap between simulation and measurements
- Create a model that present (nearly) real building and system operation
- Use calibrated model results to tune measured data (useful to input in neighbourhood level models)
- Estimate potential energy demand reduction when replacing a boiler with heat pump system.
- Investigate demand side management strategies when switching from gas to whole house electricity (heat pump) demand
- Investigate the impact of TES on load shifting and demand side management

Modelling and Calibration of Domestic a Building

3D - view of building model

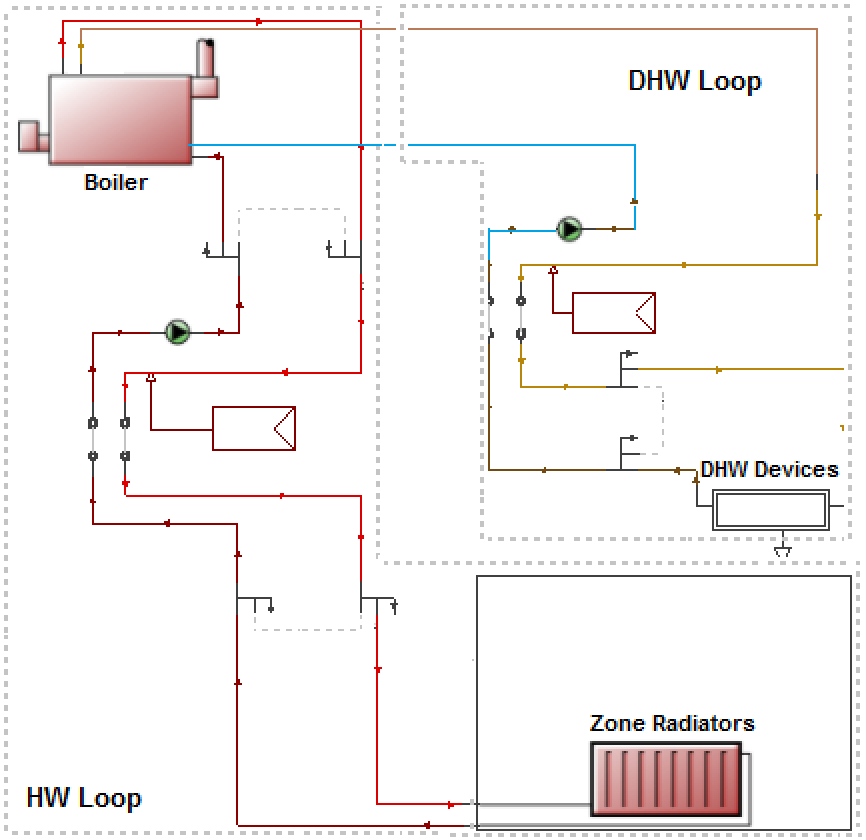


Diagram of heating and domestic hot water loops

Design and Operation Schedules for base-line model

Design input parameters for base-line model

Design Parameter	Unit	Zones				
		Kitchen	Livingroom	Bedroom	Bathroom	Hall
Heating setpoint	°C	19	22	19	21	20
Infiltration	ac/h	1.5	1	0.5	1.5	1.3
Ventilation	l/s/person	10	10	10	12	10
Equipment Power	W/m^2	3	3.9	3.6	1.7	1.6
Lighting Power	W/m^2	5	5	5	5	5
Occupancy	$people/m^2$	0.017	0.017	0.03	0.019	0.016
Hot Water	l/m^2/ day	1.05	0.72	0.53	4.85	0.53

Operation Schedules for base-line model

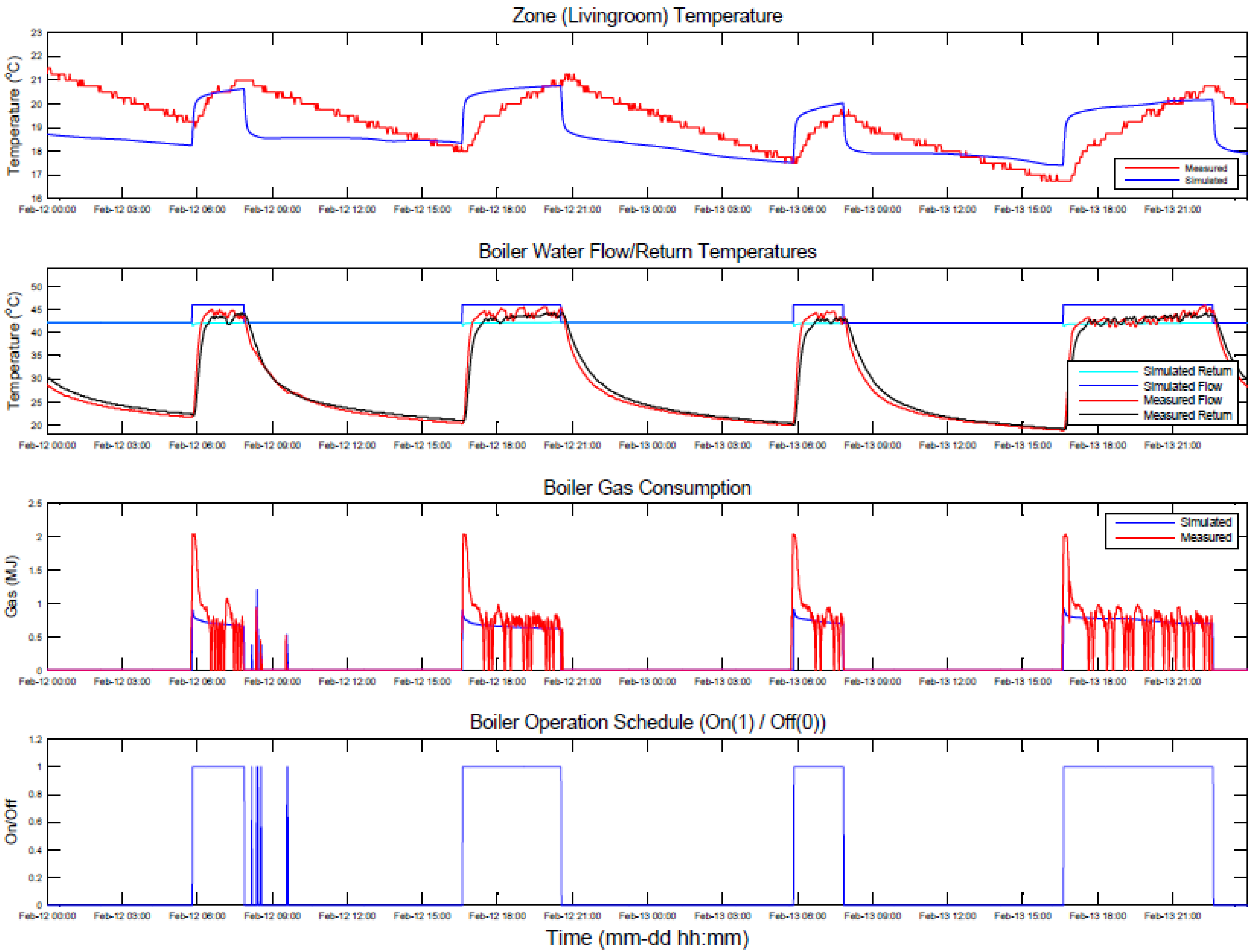
Schedule	Zone	Time of Day (hour)																							
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Heating [°C]	Kitchen	12	12	12	12	19	19	19	19	19	19	12	12	12	12	12	12	19	19	19	19	19	19	12	12
	LivingRoom	12	12	12	12	12	12	12	12	12	12	12	12	12	12	22	22	22	22	22	22	22	22	22	12
	BedRoom	19	19	19	19	19	19	19	19	19	12	12	12	12	12	12	12	12	12	12	22	19	19	19	19
	BathRoom	21	21	21	21	21	21	21	21	21	21	12	12	12	12	12	12	12	21	21	21	21	21	21	21
	Hall	12	12	12	12	21	21	21	21	21	10	12	12	12	12	12	12	21	21	21	21	21	21	21	12
Occupancy [-]	Kitchen	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0.2	0.2	0.2	0.2	0
	LivingRoom	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	1	1	1	1	0.7	0
	BedRoom	1	1	1	1	1	1	1	0.5	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.7
	BathRoom	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0.2	0.2	0.2	0.2	0
	Hall	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0.2	0.2	0.2	0.2	0.3
Equipment [-]	Kitchen	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.3	1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.5	1	0.3	0.1	0.1
	LivingRoom	0.1	0	0	0	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.5	1	1	1	1	0.7	0.1
	BedRoom	0.1	0.1	0	0	0.1	0.1	0.3	1	1	0.5	0.1	0.1	0.1	0.1	0.1	0.1	0.5	1	1	0.3	0.2	0.1	0.2	0.1
	BathRoom	0.1	0.1	0	0	0.1	0.1	0.3	1	1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1	0.3	0.1	0.1
	Hall	0.1	0.1	0	0	0.1	0.1	0.1	0.5	1	0.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.5	0.7	1	1	0.7	0.3
Lighting [-]	Kitchen	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	0	0
	LivingRoom	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0
	BedRoom	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0.2	0.2	0.2	0.2	0
	BathRoom	0	0	0	0	0.5	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	0
	Hall	0	0	0	0	0.5	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	0

Calibrated Parameters in base-line Model with Measured Data

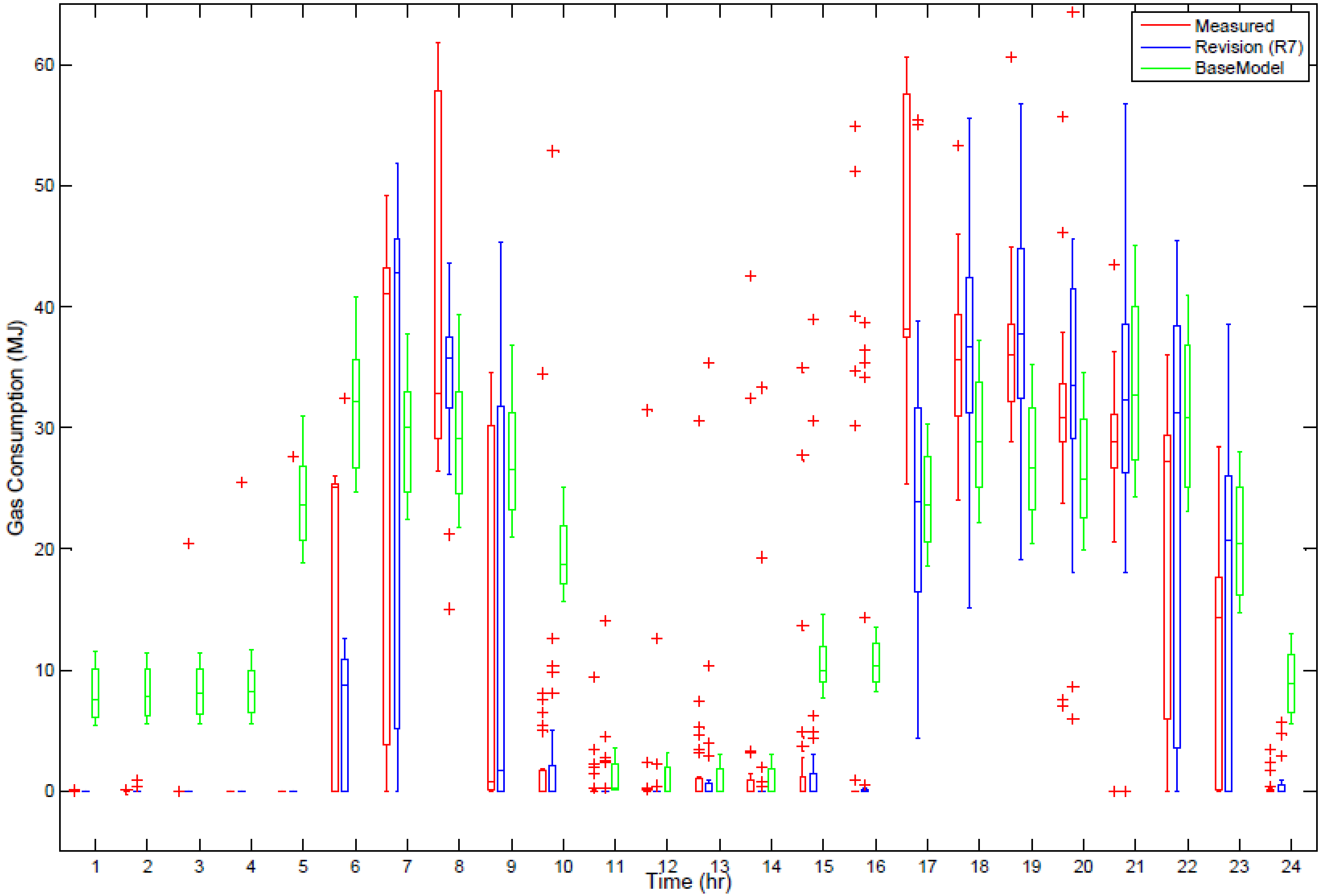
- Power consumption
- Hot Water use
- Weather data
- Boiler schedule and zones temperature
- Boiler efficiency
- Infiltration and ventilation
- Radiators water flow

Revision No.	Calibrated performance aspect	Calibration description
R1	Power consumption	The power consumption and the hourly schedules for equipment and lighting are replaced with measured data. The power consumption was measured at five circuits and the equipment/lighting loads were obtained at zone level. The maximum power load values at zone level are used as design values. The fraction factors (as a function of maximum design values) are inserted in a corresponding schedule at a minutely timestep. This revised input was necessary in order to calibrate the power consumption and the internal heat gains in terms of the heating demand for space heating.
R2	Hot water use	The design values of the baseline model are replaced with the measured hot water use in the building. Similar to the power consumption, the fraction factors are inserted as a function of maximum design value (at corresponding timestep). The hot water supply outlet temperature was considered to be 50 ℃ (combi-boiler). This revision calibrate the volume of hot water use and as well influence the estimated gas consumption for domestic hot water production.
R3	Weather data	Weather data was measured close to the building site and is used to generate a weather simulation file for EnergyPlus. This revision influenced the outdoor conditions and therefore led to adapted heating energy demand and zones' temperatures.
R4	Boiler schedule and zone temperatures	The baseline model assume that boiler operate continuously to maintain design heating setpoint temperature presented at Table 2. The boiler operation schedule in the baseline model was calibrated by using an on/off schedule retrieved from measured data. The schedule is obtained based on the measured water supply outlet temperature from the boiler. The zonal heating design set point temperatures (dual setback) are calibrated using 21℃ in all zones during the entire period. This revision influence heating system operation and zones design heating set points, consequently gas consumption.
R5	Boiler efficiency	The efficiency of the combi-boiler when producing hot water was estimated to be about 68% (rather than 90% as suggested in the regulations) as based on measured gas consumption and estimated supplied thermal heat (Buswell et al., 2013). For heating operation, the water mass flow rate in heating loop was not measured, so the supplied heat (consequently efficiency) was not able to be estimated based on measured data. The technical manual of the boiler (Worcester-boiler-manual) indicates that the seasonal boiler efficiency is about 89% for this model. ASHRAE (2012) provides a boiler efficiency curve (ranging from 82% to 99%) as a function of the inlet water temperature. The EnergyPlus simulation tool can model space heating and hot water production in two separate loops. Therefore, the estimated efficiency from measures was used hot water production, whilst the ASHRAE efficiency curve was used to estimate boiler efficiency during heating operation. This revision has a direct impact on the estimated gas consumption for space heating and hot water production.
R6	Infiltration and ventilation	For a more realistic estimation of infiltration and ventilation, the airflow network method is applied. This method provide the ability to simulate multi-zone airflow network driven by movement of openings (windows/doors) and wind speed/directions from weather data. When the airflow network is implemented, the EnergyPlus tool disregards the design infiltration and ventilation design values (from the baseline model) and estimates ventilation flow rates based on the windows/doors opening surface area and the operation schedule (as obtained from windows/doors monitoring). The amount of air infiltrated into the building is then estimated from the program based on crack surfaces area and air infiltration crack factor (the default values for the infiltration coefficient suggested by the program were taken). The windows/doors opening surface area is not a practical measurement and difficult to estimate. In the simulation, a factor of 20% (for windows) and 70% (for doors) of the total surface area is considered as opening surface area. This revision impacted the heating demand (and therefore gas consumption) as well as zones air temperature.
R7	Radiators water flow	For the baseline model, the water mass flow rate through the radiators was auto-sized by the simulation tool. For auto-sized method, the water mass flow rate is distributed in a sequential way, meaning that the first radiator in the heating loop has the maximum mass flow rate (to meet zone heating demand) followed by the second radiator with highest water mass flow rate and so on until the last radiator. The water flow rate was not measured, however based on the zonal design heating loads estimated from the simulations and considering a temperature difference through the heating system, a maximum design flow rate can be estimated for each radiator in each zone. Using this method, the supplied heat in the system is expected to be distributed in a more uniform way. The maximum boiler water supply temperature for the heating system is set to 47 ℃ (as observed from the measured data). The simulation tool modulates the water mass flow rate through the radiators in order to meet the heating demand in each zone. This revision impact supplied heat from the radiators, zones temperatures and gas consumption from boiler.

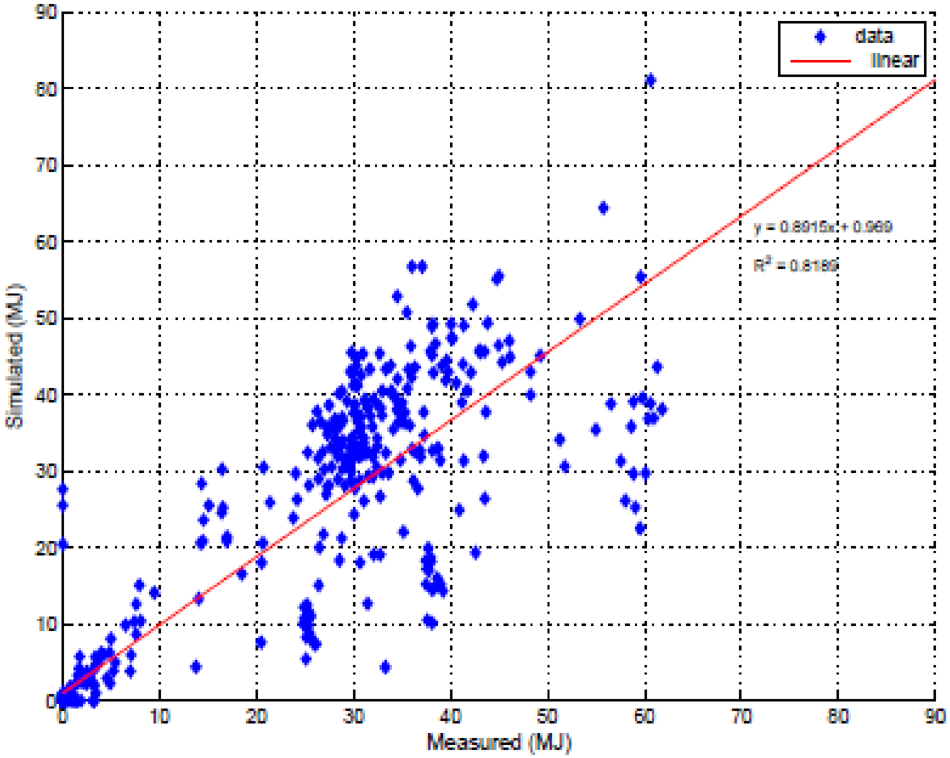
Comparison between Measured and Simulated Results



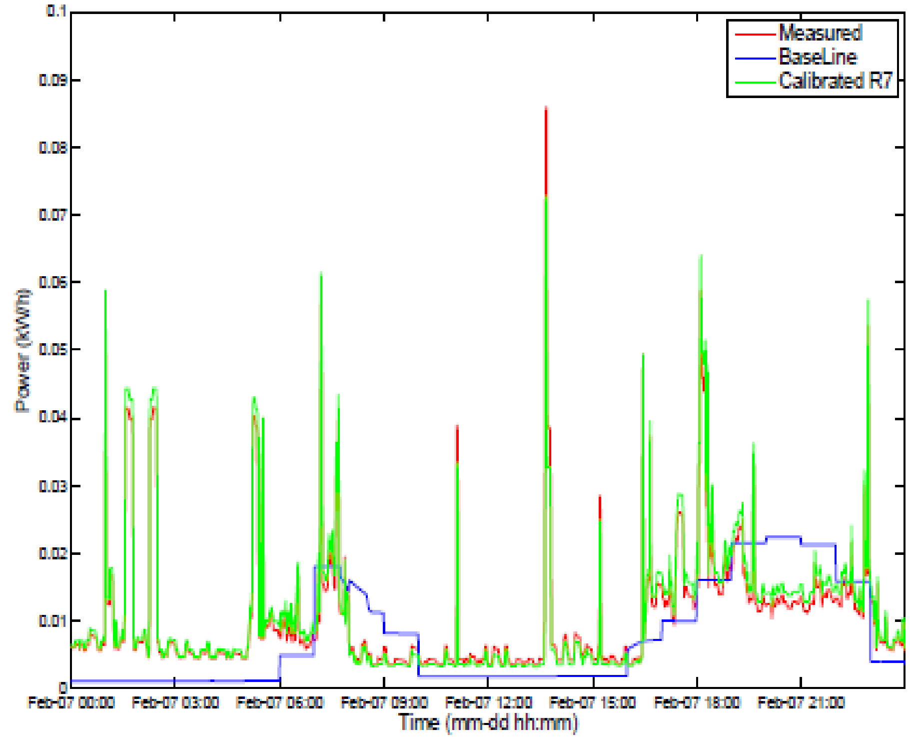
Variation of Gas Consumption Normalized at Hourly time-step



Gas and Power Consumption: Simulated vs. Measured

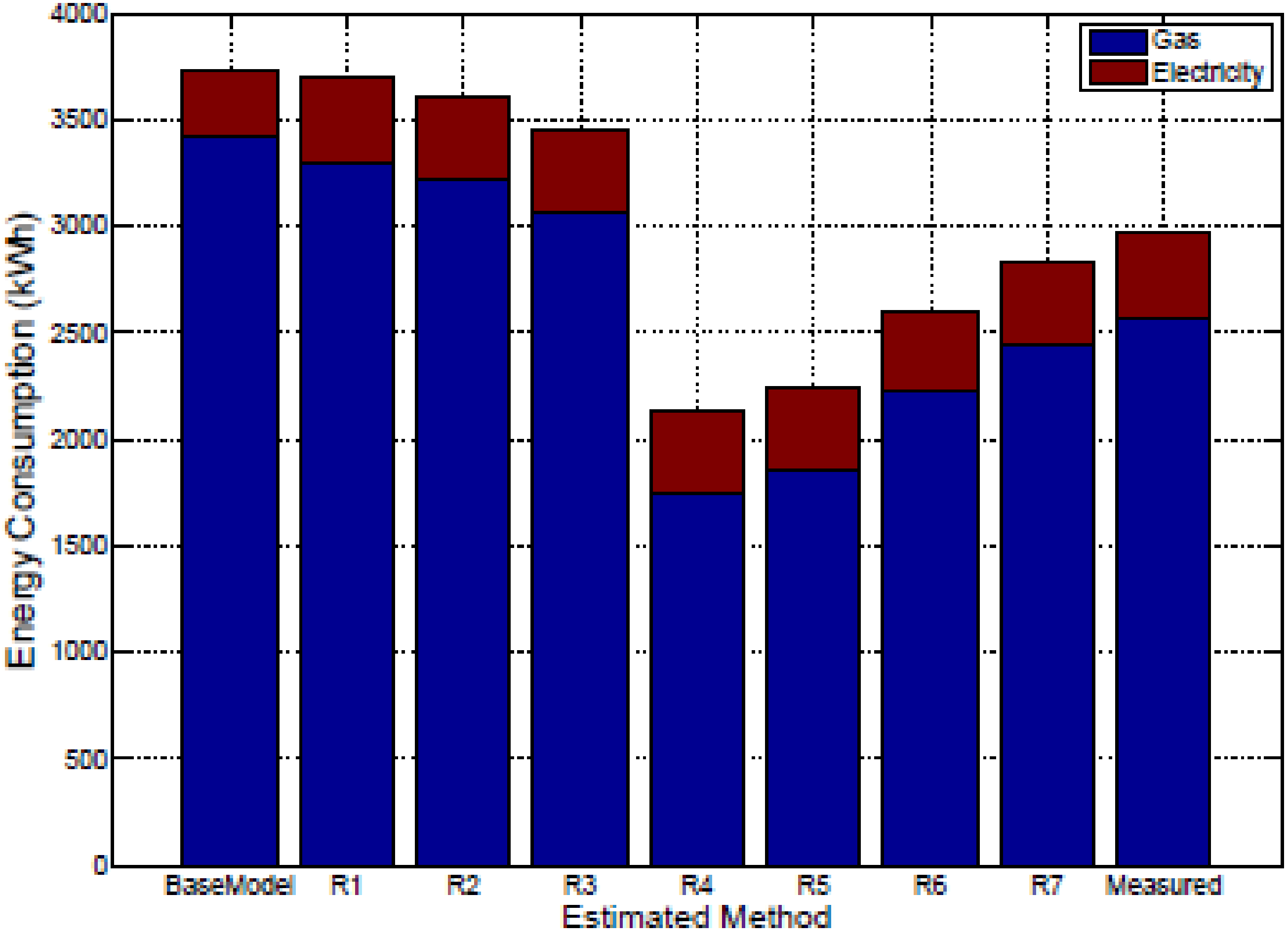


Gas consumption: simulated vs. measured



Power consumption: simulated vs. measured

Estimated Energy Consumption: Baseline, Calibrated and Measured



Validation Method and Error Gap: Simulated vs. Measured

$$MBE = \frac{\sum_{i=1}^{N_p}(M_i - S_i)}{\sum_{i=1}^{N_p}(M_i)}$$

$$CVRMSE_{(p)} = \frac{\sqrt{\sum_{i=1}^{N_p}((M_i - S_i)^2/N_p)}}{\overline{M_p}}$$

$$\overline{M_p} = \frac{\sum_{i=1}^{N_p}(M_i)}{N_p}$$

where: M_i and S_i are measured and simulated data at instance i respectively; p is the interval (e.g., monthly, daily, hourly); N_p is number of values at interval p (e.g., number of month, days, hours); and $\overline{M_p}$ is the average of measured data, i.e.,

MBE: Mean Bias Error (estimate the error gap for monthly results)

CVRMSE: Cumulative Variation Root Mean Square Error (estimate the error gap for hourly results)

Error Analysis: Simulated model vs. Measured Results

Model	Error Gap (%)					
	Gas			Electricity		
	MBE(m)[1]	CVRMSE(d)[2]	CVRMSE(h)[3]	MBE(m)	CVRMSE(d)	CVRMSE(h)
BaseLine model	+35.2	+42.4	+110.6	-22.3	-27.8	-82.6
R1	+30.3	+39.2	+108.7	+0.8	+1.3	+4.6
R2	+27.4	+32.6	+102.4	+0.4	+1.1	+5.6
R3	+20.6	+23.2	+96.4	+0.4	+1.1	+5.2
R4	-26.3	-29.8	-56.2	-5.2	-5.8	-6.6
R5	-22.4	-26.3	-51.4	-4.9	-5.3	-5.7
R6	-15.2	-20.3	-48.7	-3.8	-4.2	-4.9
R7	-3.7	-15.5	-46.7	-2.3	-3.1	-4.2

[1](m) monthly; [2](d) daily; [3](h) hourly; positive (+) values indicate that simulated results over-predict actual measured consumption, vice versa for negative (-) values.

Summary

- Base-line model overestimate 35% gas consumption while power consumption was underestimated by 22 %
- Calibration process reduced error gap considerably (-4 % gas and -2 % power) as compared to measurements
- Boiler operation schedule and infiltration/ventilation have the highest impact on error gap
- Simulation tool needs to improve it's capability to capture delayed system dynamics and time delay

Planned Future Work …

- Working towards submit journal paper (focused on hot water system modelling and analytical analysis)
- Use calibrated model to simulate domestic hot water system with heat pumps and storage tank.
- Develop and investigate possible energy demand reduction and load shifting with heat pump system

Thank you for your attention

Questions ?

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