Modeling the Water-Energy Nexus in Households – Supplementary Information

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We provide here additional information and complementary figures for the publication "Modeling the Water-Energy Nexus in Households".

1 Materials and Method

1.1 Water Pipe Model Calibration

Of all the models contained in the WaterHub Modelica Library used throughout the publication, only the water pipe model required an explicit calibration process. Other models either did not require calibration (e.g., ideal tap and shower models) or their thermal characteristics were set to values provided in the literature (e.g., tank boiler).

The water pipe model follows a discretization method (Hanby et al. 2002) with ideally mixed nodes. Its thermal dynamics are governed by the overall heat transfer coefficient *UA*:

$$UA^{-1} = \frac{1}{h_w A_i} + \frac{\ln\left({}^{r_o}/_{r_i}\right)}{2\pi L k} + \frac{1}{h_a A_o} \quad . \tag{1}$$

where $h_{w,a}$ are the convection heat transfer coefficient of water and air, respectively, and k the thermal conductivity of the pipe material. For copper, k was set to k = 400 W K^{-1} m^{-1}. Because it is difficult to derive h_w and h_a theoretically, they were manually calibrated to fit data provided by Hiller (2006) on the steady-state temperature drop and heat loss rates at various flowing conditions in a copper pipe (30.5m in length, 13 mm in diameter). The calibrated curves are shown in Figure S1 and reflect h_w = 3000 W K^{-1} m^{-2} and h_a = 15 W K^{-1} m^{-2}.

We note that the water pipe model overestimates the steady-state temperature drop slightly, although the error lies well within 10% for low flow regimes (< 0.15 L s^{-1}). At larger flows, the relative error increases but remains acceptable in absolute terms: around 0.4 °C at 0.3 L s^{-1}. Furthermore, the steady-state heat loss rate is consistently underestimated by the water pipe model, up to 15% for larger flow regimes (> 0.15 L s^{-1}).

Because the analyses presented in this publication were developed for the purpose of demonstration, these calibration results, although improvable, were considered acceptable.

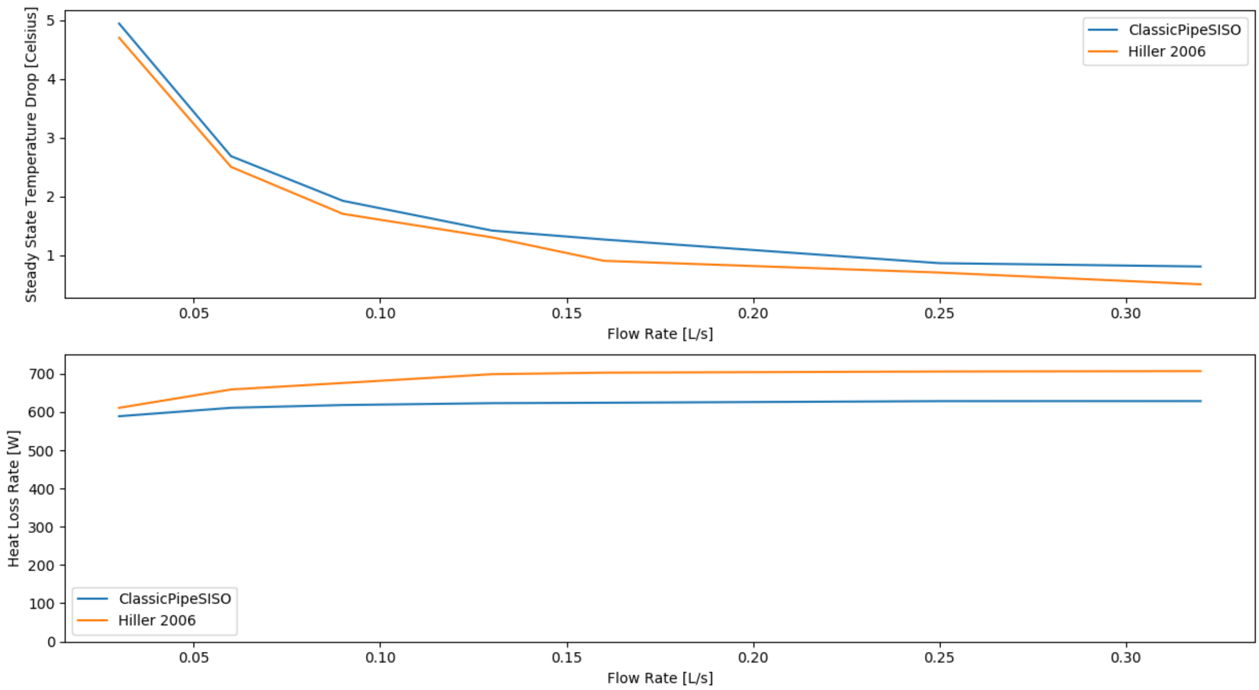

Figure S1. Calibration of the water pipe models. ClassicPipeSISO is the discretized water pipe model used in the analyses presented in this publication. Experimental data is from Hiller (2006).

1.2 Model Comparison

Table S1. Components of the DHW system and remarks.

Name	*Hot Water Connection*	*Energy Connection*	*Remark*
Hot Water System	No	Yes	Tank boiler with constant losses
Shower	Yes	No	
Bath	Yes	No	
Tap Adults	Yes	No	In Kenway et al. (2012), taps form a single appliance “Taps Indoor”
Tap Children	Yes	No	In Kenway et al. (2012), taps form a single appliance “Taps Indoor”
Tap Household	Yes	No	In Kenway et al. (2012), taps form a single appliance “Taps Indoor”
Washing Machine	No	Yes	
Dishwasher	No	Yes	
Kettle	No	Yes	Water sinks in “Human Sink”, not “Wastewater”
Toilet	No	No	

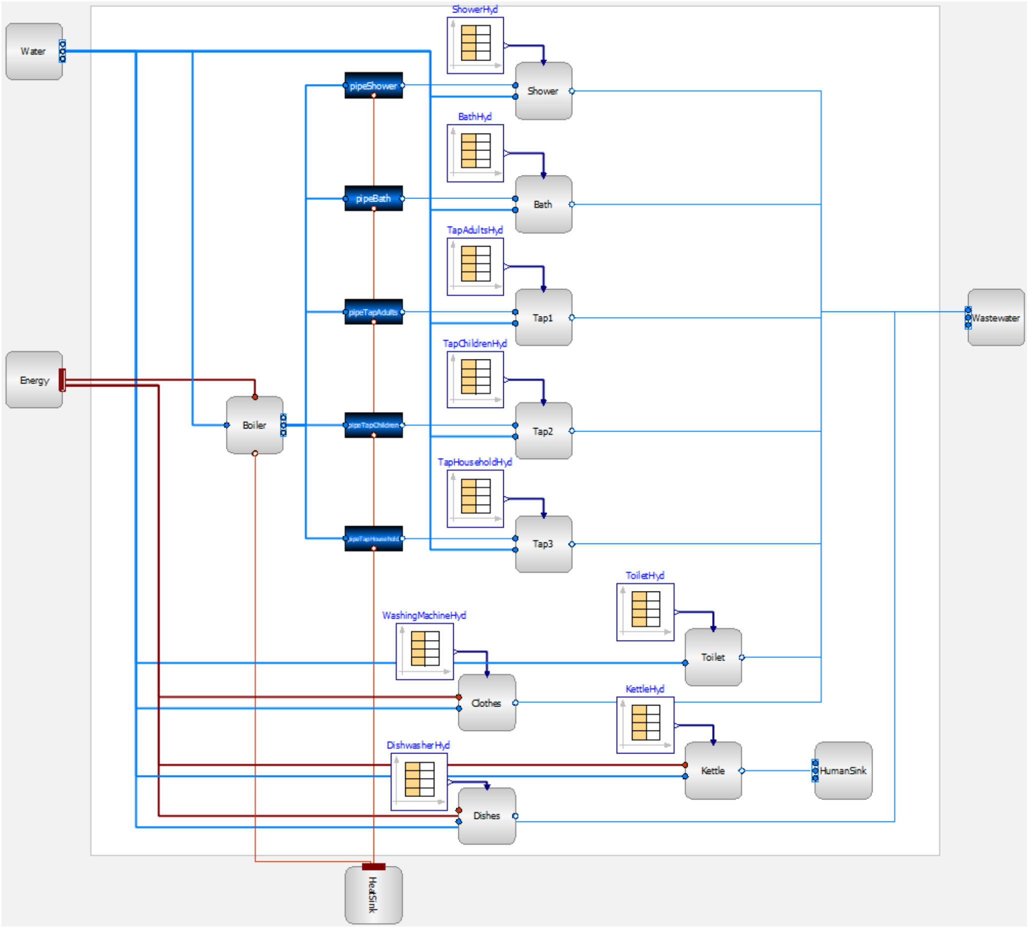

Figure S2. Schematic modeling of the DHW system in the OpenModelica OMEdit software tool. Blue connections are water flows, red connections are energy flows.

1.3 Water Demand Scenarios

The water consumption was simulated using data provided by Kenway et al. (2012). In all scenarios, the daily average water consumption was identical. In addition, similar water consumption events (e.g., tap event for shaving) had identical average temperatures. We summarize the daily water consumption of each appliance in Table S2.

Table S2. Water consumption and temperature averages used in the non-stochastic, semi-stochastic and fully-stochastic scenarios.

Appliance	*Water Consumption [Liters per Event]*	*Temperature [°C]*	*Usage*
Shower	*44*	*41*	*Adults*
	52.25	*38*	*Children*
Bath	*50*	*41*	*Adults*
	37	*38*	*Children*
Tap Adults	*0.83*	*32*	*Handwash*
	0.3	*27*	*Teethbrush*
	2.5	*45*	*Shave*
Tap Children	*0.83*	*32*	*Handwash*
	0.3	*27*	*Teethbrush*
Tap Household	*7*	*46*	*Dishwash*
	15	*35*	*Clothes Wash*
	7	*47*	*Cleaning*
	1.3	*30*	*Other Uses*

Washing Machine	*62* *62*	*40* *65*	*Warm* *Hot*
Toilet	*4.7*	*-*	*All*
Dishwasher	*18*	*50*	*All*
Kettle	*1.2*	*95*	*All*

Table S3. Full Scenario description for the water demand scenarios. Time interval (in seconds) between subsequent water consumption events.

Appliance	*Scenario 1*	*Scenario 2*	*Scenario 3*	*Scenario 4*	*Scenario 5*	*Scenario 6*
Shower	*600*	*1200*	*2400*	*4800*	*9600*	*19200*
Bath	*1200*	*2400*	*4800*	*9600*	*19200*	*38400*
Tap Adults	*20*	*40*	*80*	*160*	*320*	*640*
Tap Children	*20*	*40*	*80*	*160*	*320*	*640*
Tap Household	*20*	*40*	*80*	*160*	*320*	*640*
Washing Machine	*2000*	*4000*	*8000*	*16000*	*32000*	*68000*
Toilet	*600*	*1200*	*2400*	*4800*	*9600*	*19200*
Dishwasher	*2000*	*4000*	*8000*	*16000*	*32000*	*68000*
Kettle	*600*	*1200*	*2400*	*4800*	*9600*	*19200*

2 Results

2.1 Model Comparison

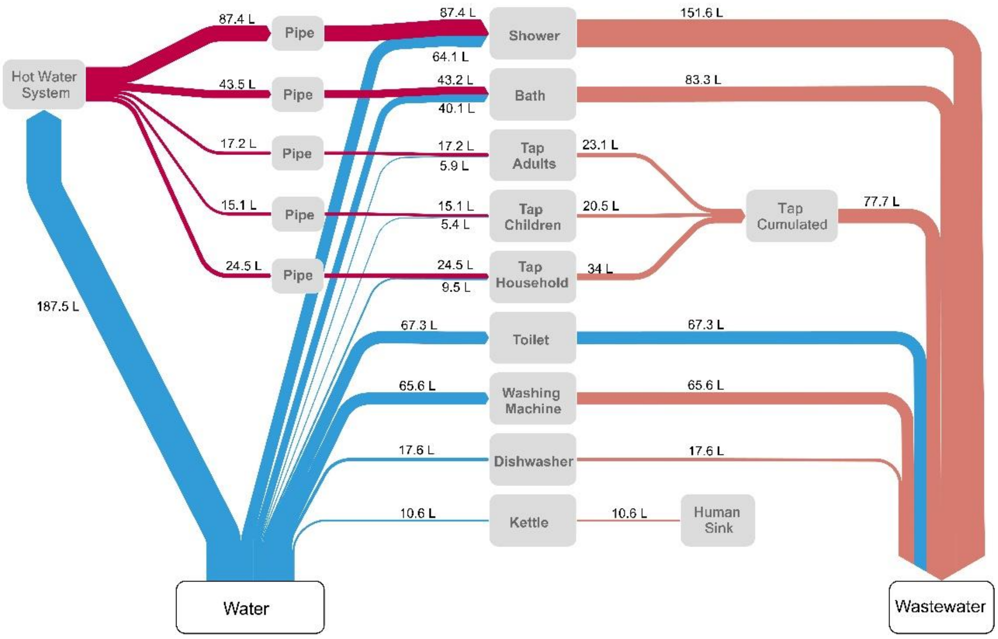

Figure S3. Sankey diagram representing the daily average water flows across the DHW system. Blue is cold water, red is hot water and orange is warm water.

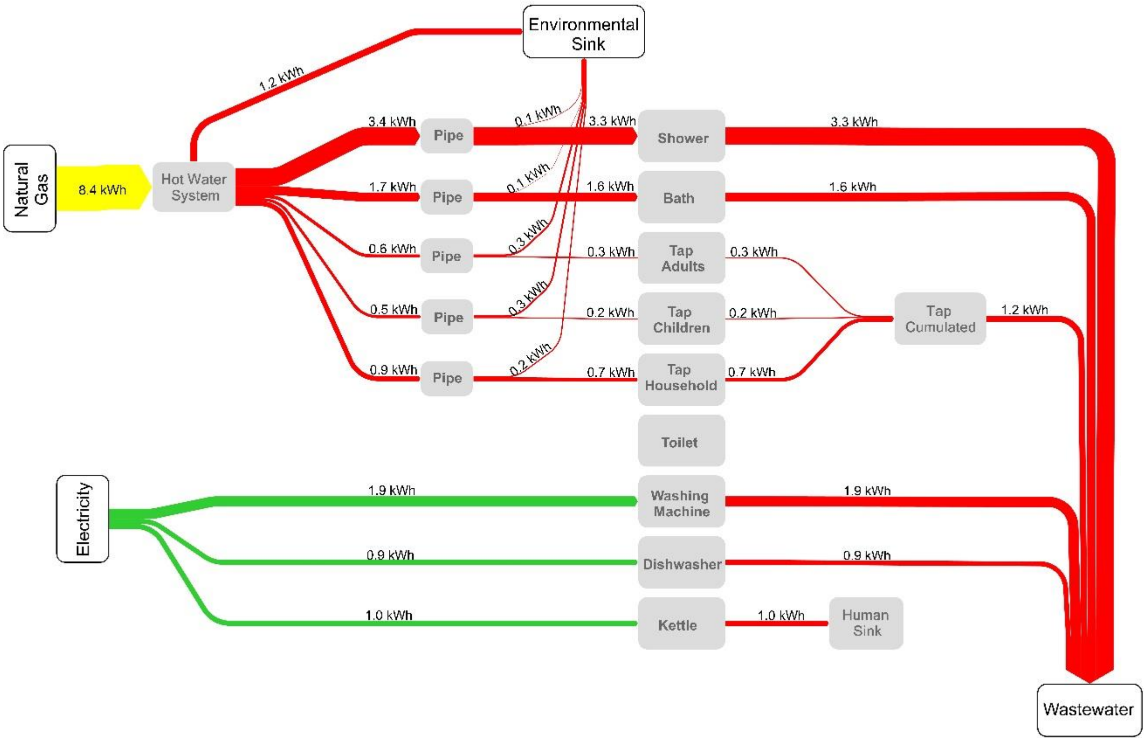

Figure S4. Sankey diagram representing the daily energy flows across the DHW system. Green is electricity, yellow is natural gas and red is heat.

References

Hanby, V.I., Wright, J.A., Fletcher, D.W. and Jones, D.N.T. (2002) Modeling the dynamic response of conduits. HVAC & R Research 8, 1-12.

Hiller, C.C. (2006) Hot Water Distribution System Piping Heat Loss Factors - Phase I: Test Results, pp. 436-446.

Kenway, S.J., Scheidegger, R., Larsen, T.A., Lant, P. and Bader, H.P. (2012) Water-related energy in households: A model designed to understand the current state and simulate possible measures. Energy and Buildings 58, 378-389.