The WaterHub Modules: Material and Energy Flow Analysis of Domestic Hot Water Systems

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Abstract

Domestic Hot Water (DHW) systems are large energy consumers in newly-built residential buildings. Mitigation measures involve more efficient hot water appliances and distribution systems, waste heat recovery systems, or changes in consumer habits. However, the implementation of these measures must be investigated carefully, as combinations may lead to unforeseen systemic interactions limiting their potential. In this article, we present tools to identify and optimize these interactions. The WaterHub modules were developed for Material and Energy Flow Analyses (MEFA) of domestic hot water systems. Two modules are available: (i) the WaterHub Modelica library includes models for MEFA system definition, and (ii) The HydroGen Python module provides methods for the stochastic generation of appliance-specific hydrographs, used as input data for the simulation of the system energy and water flows. First, we describe the technical aspects of these modules. Second, we provide an example of how they may be used in a didactic scenario analysis of a heat recovery device.

Keywords: Domestic Hot Water Systems, Material and Energy Flow Analysis, Modelica Library, stochastic demand modeling

1 Introduction

If space heating is historically the largest energy consumer in Swiss households, the share of Domestic Hot Water (DHW) is growing larger as the energy-efficiency of buildings envelopes dramatically increased over the last decades (Meggers and Leibundgut, 2011). In the Netherlands, with a climate similar to Switzerland, Frijns, Hofman, and Nederlof (2013) have shown that 50% of the natural gas demand of newly-built houses is attributed to warm water production.

A broad range of technologies is available to reduce the share of DHW primary energy consumption at household level: improvements regarding hot water production and distribution, measures targeting warm water demand, and wastewater heat recovery strategies may positively impact the system efficiency (Lazarova, Choo, and Cornel, 2012).

However, the energetic system integration of upcoming DHW technologies must be investigated carefully. Sitzenfrei, Hillebrand, and Rauch (2017) highlighted inter-level competition when decentralized heat recovery appliances at shower-level were implemented simultaneously to sewer-level energy recovery facilities. The simulated performance drop of the latter reached in this case 40%. We hypothesize that other system combinations at household level may show similar competitive or synergetic behaviors that shall be identified in order to promote optimal strategies.

In addition to technological interactions, behavioral interactions impact system integration strategies. It is widely recognized that energy and water consumption at household level are strongly influenced by consumer behavior (Pakula and Stamminger, 2015). Nevertheless, the influence of consumption patterns on the systemic energy-efficiency and cost-efficiency of selected technologies is seldom acknowledged. Hendron et al. (2009) were among the first researchers to recognize the issue. Later, Kenway et al. (2012) performed one of the first Material and Energy Flow Analysis (MEFA) of water-related energy flows in households, making use of stochastic demand equations. Although reliable models of water consumption are emerging (Weber et al., 2005; Blokker et al., 2010; Hendron et al., 2010; Penn et al., 2017), many energy-focused investigations of DHW systems still lack the handling of realistic consumption flows.

We hypothesize that investigations of system integration of DHW technologies will be significantly facilitated by the development of a modeling tool fulfilling the following requirements:

1. Flexible and straight-forward definition of complex DHW systems. The modeler should be able to graphically construct technical models, integrating and combining DHW technologies from a library of submodels.

2. The modeling environment should follow the formalism of MEFA approaches as first described by Brunner and Rechberger (2004), to allow for scenario analyses and provide a standard framework for additional comparisons, e.g., Life Cycle Assessments (LCA) or Multi Criteria Decision Analysis (MCDA).

3. In the model, consumer interaction with DHW appliances (showers, taps, dishwasher, etc.) should trigger

upstream (water heaters, distribution systems) and downstream (heat recovery systems, water recycling units) energy and water flows. The model is demand-triggered.

4. The modeler should have full control of water consumption patterns, feeding either (i) stochastic flows or (ii) deterministic flows to single DHW appliances in the technical model.

Tools specifically designed to model DHW systems have emerged within the TRNSYS (Maguire et al., 2011) or the Microsoft .NET environments (Springer et al., 2008), with state-of-the-art treatment of heat losses in pipes. However, these tools do not fulfill all above requirements, as they lack the flexibility of a library of models the modeler can pick from (1), the MEFA formalism (2), and full control over the consumption scenarios to be fed to the model (3).

Modelica, an equation-based, object-oriented programming language, offers high flexibility, hierarchical libraries of models and easy graphical definition of complex systems. Existing Modelica libraries developed for whole building simulation purposes are very powerful and versatile tools that meet (and usually exceed) requirement (1), such as the *Buildings Library* (Wetter, Zuo, and Nouidui, 2014), or more generally IEA Annex 60 based libraries (Christoph et al., 2015). However, these libraries were not developed to follow the MEFA formalism (2), lack the demand-triggered model behavior (3) and full control over domestic hot water flows (4).

Although these libraries may be adapted to meet the above requirements, the purpose of using MEFA formalism (requirement 2) is to provide environmental researchers, already acquainted with similar analyses such as LCA, tools that do not require extensive knowledge in building simulation practices. In this sense, the MEFA requirement allows for significant simplification of the models developed in libraries originally meant for building or district simulations. We thus considered more appropriate to build a dedicated Modelica library rather than downgrading and complementing existing libraries. However, work is conducted to assess the use of the Annex 60 library base interfaces, in order to facilitate potential future integrations. We add that the choice of outsourcing the generation of model water flows to an external Python module was motivated by the complexity of stochastic modeling in Modelica.

We present in this article the WaterHub modules, combining a custom Modelica library for DHW technologies and a Python module for the modeling of demand flows. We describe the implementation and typical use of the tools, and provide an implementation example.

2 The WaterHub Modules

Figure 1 shows a typical workflow using the WaterHub modules for the simulation of DHW system properties, for instance the systemic energy efficiency. We present in this section the MEFA formalism overarching the WaterHub modules and technical descriptions of the modules. The early stage of development of the modules does not yet allow for an open release, however access to the Git repositories will be granted on request.

2.1 MEFA Formalism

Material Flow Analysis (MFA) and its extended version Material and Energy Flow Analysis (MEFA) are described by Brunner and Rechberger (2004) as the "systematic assessment of the flows and stocks of materials [and energy] within a system defined in space and time". The main idea of MEFA is to quantify all flows of *materials*, i.e. conserved quantities, between *processes* (any transport, transfer, transformation or storage of materials) present in a given system. Energy and mass conservation governs the system:

$$E_{in} - E_{out} = E_{stored} \quad (1)$$

$$M_{in} - M_{out} = M_{stored} \quad (2)$$

This approach has the advantage of clearly separating *flows* (or *fluxes*) and *processes*. A process can hence be as complex as required by the application without impacting the nature of the flows, as it essentially sets the value of its output flows using transfer coefficients on input flows. Moreover, an MFA often form the basis of LCA, as they share part of their formalism.

2.2 WaterHub Modelica Library

The WaterHub Library contains models for the definition of MEFA systems, using a bottom-up modeling approach. Although inspired by the Modelica Standard Library (MSL) *Fluid* library, the models inputs and outputs were simplified to water and energy flows only, in an attempt to stick to the MEFA formalism. The following packages are available:

- **Base Classes**: Defines the *WaterPort* and *HeatPort* connectors, for the water and energy flows, respectively. Water flows are described by a volumetric *flow* in liters per second and a *temperature*. Expressing flows with volume instead of mass units is standard in DHW studies. The specific volumetric heat capacity of water is set to 4179.6 J $l^{-1}K^{-1}$, corresponding to water at 25 °C. Energy flows are expressed in Watts and have no related effort variable.
- **Blocks**: Contains the interface models with the Python HydroGen module (see Section 2.3). Most used is the `Sources.HydrographFromFile` model that connects the output file from HydroGen to appliances from the End-Use package.
- **Appliances**: Technologies at the interface between the water consumer and the DHW system: showers, taps, washing machines, dishwashers, WC, etc. In

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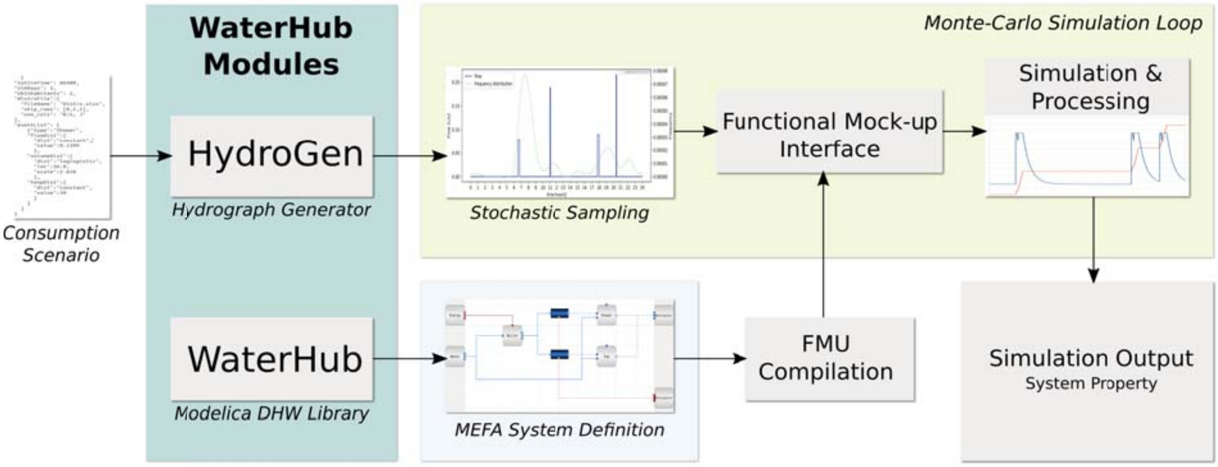

Figure 1. Typical workflow highlighting the use of the WaterHub modules for the simulation of DHW system properties (e.g., energy efficiency, absolute water or energy consumption, etc.). The HydroGen module and WaterHub Modelica library provide the tools for straightforward Monte-Carlo processes.

addition to the energy and water inputs and outputs, these models have a data port, allowing the modeler to link the model flows to an external file containing the flows demanded by the appliance (outputs of the HydroGen module, for instance, see section 2.3).

- **ImportExport**: Includes infinite sources and sinks for imported/exported water and energy flows (flowing in/out of the system). We note here that the flows are not strictly mono-directional, but the existence of sources and sinks suggests a natural flow direction.
- **Pipes and Carriers**: Contains models for water and energy carriers. Note that water pipe models are usually based on first principles, although this is not mandatory.
- **DHW Systems**: Building blocks of DHW systems, e.g., boilers, reservoirs, etc. Includes also water or wastewater-related technologies aiming at recovering resources from wastewater, e.g., wastewater heat exchangers or heat pumps, greywater treatment units, etc. Depending on the needed complexity, models may be based on first principle heat exchanges or emulate steady-state performance. Similarly, additional energy requirements due to pressure losses or pumping subsystems may be modeled with appropriate detail.

2.3 HydroGen Python Module

The module provides methods for the stochastic generation of appliance hydrographs, i.e. time-resolved flow curves. *Events* for a specific appliance are uniquely characterized by (i) a starting time, (ii) a flow rate, (iii) a temperature and (iv) a total event volume. These properties are sampled from distributions defined by the modeler, as described by Scheepers and Jacobs (2014). The modeler provides a *consumption scenario*, a JSON-formatted file containing information for the HydroGen module to generate appliance-resolved domestic water events. The purpose of the following code is to exemplify the JSON structure of a consumption scenario. Here, HydroGen will stochastically generate shower events for a family of five:

```
{
"totSimTime": 86400,
"simDays": 1,
"nbInhabitants": 5,
"distroFile":{
  "fileName": "DistroFile.xlsx",
  "skipRows": [0,1,2],
  "useCols": "B:G, J"
},
"eventList": [
    {"type":"Shower",
    "flowDist":{
      "dist":"loglogistic",
      "loc":0.127,
      "scale":4.158
      },
    "volumeDist":{
      "dist":"loglogistic",
      "loc":55.97,
      "scale":2.828
      },
    "tempDist":{
      "dist":"normal",
      "loc":39,
      "scale":2
      }
    }
  ]
}
```

The following sections describe the variables and parameters present in this exemplary consumption scenario.

2.3.1 Simulation variables

`totSimTime`, `simDays` and `nbInhabitants` are general simulation variables. `totSimTime` defines the time span, in seconds, over which the events should be generated (default is 86400, i.e. 1 day). Note that this number must be consistent with the simulated period in the consequent simulation of the system energy and water flows. `simDays` defines the number of days the flows should be aggregated upon (default is 1). Lastly, `nbInhabitants` defines the number of consumers for the modeled appliance. In the present version of HydroGen, the number of events is sampled from a truncated normal distribution with parameters based on the number of inhabitants. Next step will be to implement a modeler-defined discrete distribution for a full control of the number of events.

2.3.2 distroFile

The `distroFile` key lets HydroGen compute the frequency distributions from an excel or comma-separated values (`.csv`) file. `distroFile` contains the average time-resolved flows (liters per time-step) for each appliance. Flows are converted into frequencies, and the starting time of events is sampled using an inverse transform sampling process as described by Devroye (1986).

2.3.3 eventList

`eventList` describes the type of events to be generated. In the above example, HydroGen will generate "Shower" events. The events types are organized as a list, each component of the list containing four fields:

- `type` is a string and describes the event type. It should correspond to one column of `distroFile`. Types can for instance be shower, WC, kitchen, wash basin, etc.
- `flowDist` is the flow distribution, from which the event flow is sampled.
- `volumeDist` is the total volume distribution, from which the event total volume is sampled.
- `tempDist` is the event temperature distribution, from which the event temperature is sampled.

Each distribution contains a `dist` field describing which distribution should be used for the sampling of the event parameter, and the required parameters describing the distribution shape. The distributions are constructed based on the `NumPy.random` Python package, and the shape parameters are consistent with their NumPy counterparts. In the present version, the modeler can select one of the following distributions: log-logistic, Weibull, Gamma, lognormal, normal, Rayleigh or uniform. The modeler can also set `dist` as `constant`, and the software will return a constant value that overrides the stochastic sampling procedure.

2.3.4 Output

HydroGen2.0 produces a `.csv` file that can be used with models from the WaterHub Appliances package, as described in Section 2.2. The file is formatted to be compatible with the `WaterHub.Blocks.Sources.HydrographFromFile` model, inspired by the `CombiTimeTable` from the MSL. The file contains three columns: (i) time, (ii) demanded flow (liters/second) and (iii) demanded temperature (K). We provide here an example (with default `totSimTime` = 86400 seconds):

```
#1
float FlowTable(86400, 3)
0, 0.1, 311.0
1, 0.1, 311.0
2, 0.0, 0.0
    ...
86399, 0.0, 0.0
86400, 0.0, 0.0
```

2.4 Typical Workflow

The HydroGen Python module and the WaterHub Modelica library are designed to ease the workflow of DHW systems MEFAs and allow fast scripting of single simulations or Monte-Carlo processes. The workflow is schematically shown in Figure 1. Using the WaterHub Modelica library, the modeler defines the DHW system, including all appliances, sources, sinks and water-related technologies contained in the system following the MEFA formalism. The model is saved as a Modelica file (`.mo`). Within a Python simulation environment, the model is compiled into a Functional Mock-up Unit (FMU). In this work, the JModelica.org platform from Modelon was used (Åkesson et al., 2010). HydroGen methods are used for the stochastic generation of hydrographs, based on the modeler-defined *consumption scenario*, and fed as input for each of the DHW system appliances using the Functional Mock-up Interface (FMI) standard (the open-source PyFMI python package, part of the JModelica.org platform, was used) (Blockwitz et al., 2012). Each Monte-Carlo iteration provides the FMU with a new set of hydrographs through the FMI. Average system properties and their associated distribution are consequently computed, giving insights into the dynamics of the system flows.

The variability across Monte-Carlo iterations is currently dominated by the user consumption behavior, as the variability intrinsic to the system, for instance system parameters, is considered negligible. Future versions of the modules will account for system variability through the implementation of weather variables and/or cold water temperature profiles, for instance.

3 Example Scenario Analysis

Typical questions about system integration of water technologies are: (i) how has the system performance changed with the implementation of the technology, and (ii) how does the rest of system react, i.e. whether the performance of upstream or downstream technologies is impacted by

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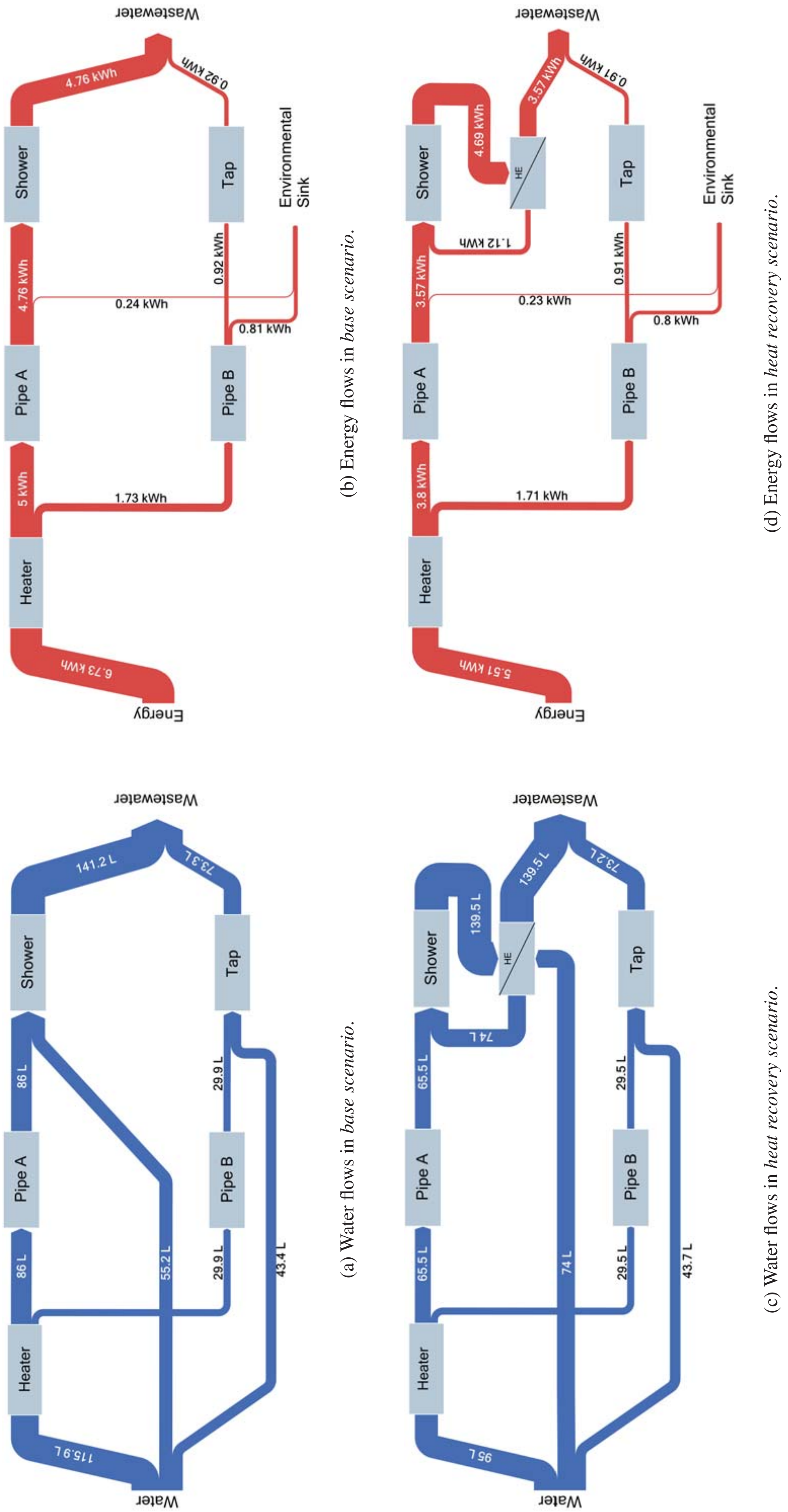

(a) Water flows in *base scenario*.

(b) Energy flows in *base scenario*.

(c) Water flows in *heat recovery scenario*.

(d) Energy flows in *heat recovery scenario*.

Figure 2. Sankey diagrams of DHW systems, daily averages of water and energy flows for the 2000-iteration Monte-Carlo process. MEFA processes are shown as grey boxes, system imports and exports are not outlined.

the implementation. We present here an example scenario analysis. The objective is to provide a usage example of the WaterHub modules for the analysis of a heat exchanger implementation at shower-level. We investigate how the heat exchanger impacts the system energy efficiency and the systemic consequences of its integration.

Two technical scenarios were constructed graphically using the models contained in the WaterHub Modelica library. The *base scenario* includes the following models:

- Sources and sinks (MEFA *imports* and *exports*):
  - Infinite water and energy supply
  - Infinite wastewater sink
  - Infinite energy (or environmental) sink.
- An ideal instantaneous water heater
- Two ideal appliances, a shower and a kitchen tap. Appliance flows are sampled from data generated by Butler et al. (1995); Friedler and Butler (1996); Scheepers and Jacobs (2014)
- Two 15m water pipes, losing energy to the surrounding environment (temperature = 23 °C). The plug-flow modeling of the pipes followed the methodology described by Hanby et al. (2002). The model was validated by computing values similar to experimentally measured overall heat transfer factors in flowing conditions (about 0.62 $Wm^{-1}K^{-1}$ for a 1/2" copper pipe of type L)(Hiller, 2006).

The *heat recovery scenario* includes all components from the *base scenario*, but the shower appliance is in addition connected to a simple local heat exchanger that preheats incoming cold water (set at 10 °C) with the shower outlet water. The heat exchanger was modeled with a constant steady-state performance curve, using Newton law of cooling and approximating the heat exchange by two thermally connected straight pipes with fluid flows in the same direction. The governing equations read

$$T_1^{out} = T_1^{in} + \frac{\Delta T}{(1 + j_1/j_2)}\alpha \qquad (3)$$

$$T_2^{out} = T_2^{in} - \frac{\Delta T}{(1 + j_2/j_1)}\alpha \qquad (4)$$

$$\alpha = (1 - e^{\frac{\gamma}{j_1+j_2}L}) \quad , \qquad (5)$$

with T_i^X being the temperature of pipe i at position X, ΔT the temperature difference at pipe inlets, and j_i the flow in pipe i. The variable α (Equation 5) describes the efficiency of the heat exchanger, a function of the heat exchange coefficients and exchange surface area (contained in parameter γ), length of pipes L, and flows j_i. In this fictitious example, α is approximated by a constant value. With $\alpha = 0$, no heat is transferred between the pipes, while all the available heat is transferred as $\alpha = 1$. We set $\alpha = 0.7$.

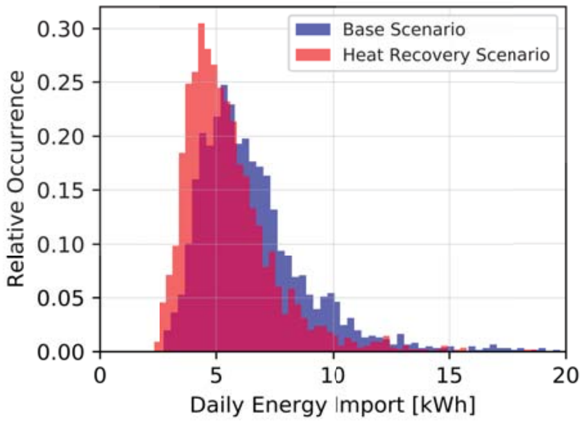

Figure 3. Daily energy imports in the *base scenario* and the *heat recovery scenario*.

The results of a 2000-iterations Monte-Carlo process following the workflow described in Section 2.4 are shown in Figure 2 as Sankey diagrams. The diagrams present the average daily water and energy flows of the *base scenario* and the *heat recovery scenario*. The small water consumption differences are numerical errors due to the limited number of Monte-Carlo iterations and can be neglected in the analysis. Under the assumptions of this didactic example, we recognize how the implementation of the heat exchanger has modified the average flows, increasing the cold/hot water ratio in the shower appliance from 0.64 to 1.13, saving on average 1.22 kWh per day for the heating of hot water (from 6.73 kWh to 5.51 kWh primary energy import). As the heater must now provide a daily average of 95 l of hot water instead of 115.9 l in the *base scenario*, we may suggest that a new dimensioning process is required to optimize the water heater to the new demand. In addition to mean flows, insights into system dynamics may be very important. The frequency analysis of the heater energy demand in Figure 3 shows that the daily energy import distribution is narrower when a heat exchanger is implemented, further indicating that as the heater will operate in a lower, narrower range, the power required by the heater may also be reduced. In addition, we note that the heat exchanger has no impact on the energy lost by the water pipe, indicating the two subsystems are not interacting.

4 Conclusions

The WaterHub modules are dedicated tools for the analysis of water and energy flows at household level, following the Materials and Energy Flow Analysis (MEFA) formalism, thus providing easy-to-use tools for Life Cycle Assessment (LCA) or stand-alone simulations of Domestic Hot Water (DHW) systems.

The WaterHub modules are useful for the identification and analysis of technological and behavioral interactions within DHW systems. In the simple application shown in the example of Section 3, we showed that the addition

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of appliance-level heat recovery systems may impact the design and dimensions of upstream water heaters.

The WaterHub Modelica library provides the modeler with sub-models for graphical MEFA system definition. The HydroGen Python module provides the modeler with methods for the stochastic generation of appliance-specific hydrographs. The hydrographs are linked to models from the Appliances package included in the WaterHub Modelica library. In this sense, the modeled DHW system is demand-based, triggering upstream and downstream flows by simulating human-appliance interactions. The clear distinction between technical scenarios (built with the WaterHub Modelica library) and consumption scenarios (processed into stochastic flows by the HydroGen Python module) facilitates scenario analyses, as shown in the provided example, by allowing the modeler full control over appliance flows and focusing solely on water and energy flows. The distinction is emphasized by the use of two separate modules: the Python module handles the stochastic modeling and the Modelica environment provides an excellent framework for the simulation of DHW flows.

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