Project Number 260041

SUPPORTING ACTION

EnRiMa

Energy Efficiency and Risk Management in Public Buildings

Deliverable D2.1: Sankey Diagrams that Link the Energy Resources to the Loads

Start date of the project: 01/10/2010
Duration: 42 months
Organisation name of lead contractor for this deliverable: UCL
Revision: 1.0

Project funded by the European Commission within the Seventh Framework Programme (2007-2013)		
Dissemination Level		
PU	Public	**X**
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Table of Contents

Table of Figures

Executive Summary

In order to improve energy efficiency in buildings, it is essential to understand how energy flows from resources to loads. We first construct general energy-balance equations that are flexible enough to describe energy flows in most buildings' current and future configurations. Next, using data collected from two test sites and a back-up test site, we populate the energy-balance equations and obtain energy consumption, production, and purchase at each site's current system configuration. Based on these equations, we create a Sankey diagram for each site that illustrates energy flows and dependencies. Finally, we demonstrate how our approach will be useful for future deliverables by creating Sankey diagrams for alternative system configurations.

EnRiMa Deliverable D2.1: Sankey Diagrams that Link the Energy Resources to the Loads
(Lead Contributor: UCL; Other Contributors: CET, HCE, Tecnalia)

1. *Introduction*

Optimising how a building's energy requirements are met necessitates modelling energy flows. Establishing a mathematical relationship between building energy requirements and available resources provides a deeper understanding of the ways in which the existing system is configured and may be open to improvement. The existing state-of-the-art in modelling energy flows tracks how energy loads may be met by given resources at given efficiencies (see King and Morgan, 2007 and Marnay *et al.*, 2008). It formalises these links algebraically before providing a visual representation of the structure in the form of a Sankey diagram (see Figure 1).

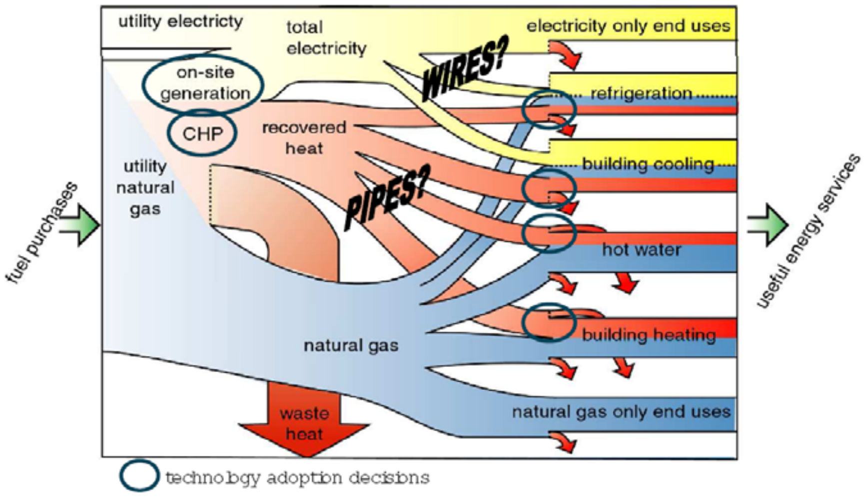

Figure 1. Typical Sankey Diagram (Marnay *et al.*, 2008)

In the EnRiMa project, we first use the current state-of-the-art in order to establish a mathematical relationship between energy requirements and resources for existing building configurations at our test sites and a back-up test site. This is what we mainly report in this deliverable. However, since the innovative aspect of the EnRiMa project is to incorporate the impact of building retrofits or technology adoption on energy flows and to facilitate the calculation of energy transfer efficiencies (to be provided in Deliverable D2.2), we must also consider general energy-balance equations by taking into account possible future configurations of buildings at test sites. In order to provide structure for modelling energy flows and to ensure a good platform to meet the objectives for Deliverable D2.2, we also do a preliminary iteration of energy-balance equations and envisage how to model energy flows in possible future configurations at each site. Although these steps are not required in Deliverable D2.1, they are good modelling practice because they provide a basis for critical appraisal and identification of deficiencies by partners leading the work in WP 4.

The structure of this document is as follows:

- Section 2 provides a snapshot of energy flows in existing building configurations at test sites and a back-up test site along with an initial

- Section 3 provides examples of how energy flows in possible future building configurations at each test and back-up test site may be modelled by our approach
- Section 4 puts the work of this deliverable in context to that in subsequent deliverables
- Section 5 provides references for the work mentioned here

2. *Current Energy System Configurations*

2.1. *General Energy-Balance Relations*

Prior to introducing the energy-balance equations and Sankey diagrams for each site's current system configuration, we first present a general approach to energy modelling. The purpose of this effort is to provide a basis for tackling changes to system configurations, which may be proposed as part of EnRiMa's strategic optimisation. In this subsection, we proceed by listing the possible parameters (which are outside the control of the building manager) and variables (which are within the control of the building manager), which will be refined further in Deliverable D2.2. Each parameter is also classified as being constant, deterministic, or stochastic. We next list and explain the general energy-balance equations that could hold for current and possible future configurations of the kinds of energy systems we have analysed.

Nomenclature
CCA: concrete core-activated heating and cooling
CHP: combined heat and power
DEC: desiccant evaporative cooling
HP: heat pump
HS: heat storage
ICT: information and communication technologies
NGB: NG-fired boiler
PV: photovoltaic
$AuxPump_{HP}$: heat-source-side and heat-sink-side auxiliary pump
$AuxPump_{heating}$: main heat distribution auxiliary pump
$AuxPump_{cooling}$: main cooling distribution auxiliary pump
$AuxPump_{CCA}$: distribution auxiliary pumps for CCA
$AuxPump_{solar}$: auxiliary pumps on primary and secondary sides of the solar system
C: constant
D: deterministic
S: stochastic

Indices
i : current electricity resource, $i = \{CHP, PV\}$
j : current heat resource, $j = \{DistrictHeating, CHP, NGB, HP, Solar, HS\}$
k : current cooling resource, $k = \{Well\}$
l : current end use, *l={ICT, Lighting, ServerRoomCond, HotWaterPrep, AirCond, IndoorIllum, CirculationSys, ElecOnly, VentilationSys}*

m: current electricity-based technology, m={HP, $Well$, $AuxPump_{HP}$, $AuxPump_{heating}$, $AuxPump_{cooling}$, $AuxPump_{CCA}$, $AuxPump_{solar}$}
t : time period, $t = 1,\ldots,T$

Parameters
Δt (C): length of decision-making period (h)
$HofOperation$ (C): annual hours of operation (h)
$NGBoilerCap$ (C): natural gas boiler capacity (MW)
$GenCap_i$ (C): generation capacity of electricity resource i (MW_e)
$ThermalPower_j$ (C): thermal power capacity of heat resource j (MWh_{th})
$CoolingPower_k$ (C): cooling power capacity of cooling resource k (MWh_{th})
$HeatDemand_t$ (D/S): heating demand for period t (MWh_{th})
$BuildHeating_t$ (D/S): building heating demand for period t (MWh_{th})
$OtherHeating_t$ (D/S): other heating demand for period t (MWh_{th})
$HeatforTech_{DEC,t}$ (D/S): heat required for use in DEC system during period t (MWh_{th})
$ElecDemand_t$ (D/S): electricity demand over all end uses for period t (MWh_e)
$ElecEndUse_{l,t}$ (D/S): electricity demand by end use l for period t (MWh_e)
$CoolingDemand_t$ (D/S): cooling demand for period t (MWh_{th})
β (C/S): gas-to-heat conversion efficiency of the NGB based on higher heating value (HHV) (MWh_{th}/MWh)
ε_i (C/S): gas-to-electricity conversion efficiency of electricity resource i based on HHV (MWh_e/MWh)
φ_i (C/S): useful heat produced by each unit of electricity generated via resource i based on HHV (MWh_{th}/MWh_e)
δ_j (C/S): heat-to-heat conversion efficiency of heat resource j (MWh_{th}/MWh_{th})
γ_m (C/S): electricity required by electricity-based technology m for each unit of heating/cooling (MWh_e/MWh_{th})
$SolarInsolation_t$ (C/D/S): fraction of maximum solar insolation incident upon location for period t

Variables
$SolarHeat_t$: heat from solar thermal before losses through storing system for period t (MWh_{th})
$HeatSupp_{j,t}$: heat supplied by heat resource j during period t (MWh_{th})
$DistrictHeating_t$: heat purchased during period t (MWh_{th})
$UsefulDistrictHeating_t$: useful heat purchased for period t (MWh_{th})
$NGforHeat_t$: natural gas purchased for use in the boiler during period t (MWh)
$NGforElec_{i,t}$: natural gas purchased for use in electricity resource i during period t (MWh)

$ElecforTech_{m,t}$: electricity required for use in electricity-based technology m during period t (MWh_e)
$ElecGen_{i,l,t}$: electricity generated by electricity resource i for use in end use l during period t (MWh_e)
$ElecGen_{i,m,t}$: electricity generated by electricity resource i for use in electricity-based technology m during period t (MWh_e)
$ElecExp_{i,t}$: electricity generated for sales by electricity resource i during period t (MWh_e)
$ElecPur_{l,t}$: electricity purchased for use in end use l during period t (MWh_e)
$ElecPur_{m,t}$: electricity purchased for use in electricity-based technology m during period t (MWh_e)
$CoolingSupp_{k,t}$: cooling supplied by resource k during period t (MWh_{th})
$Demand\mathrm{Re}sponse_{l,t}$: demand response for end use l during period t (MWh_e)

Energy-balance equations
Eq. (1) is the heat-balance equation: it states that the heat supplied by all on-site resources plus any heat provided by district heating has to satisfy the system's demand for heat.

$$\sum_j HeatSupp_{j,t} + UsefulDistrictHeating_t = HeatDemand_t + HeatforTech_{DEC,t}, \forall t \quad (1)$$

Eq. (2) provides the heat supplied by a gas-fired boiler based on how much natural gas is used for it.

$$HeatSupp_{NGB,t} = \beta \cdot NGforHeat_t, \forall t \quad (2)$$

Eq. (3) constrains the natural gas that can be used by a gas-fired boiler by its capacity size, which is given for existing buildings.

$$NGforHeat_t \le \Delta t \cdot NGBoilerCap, \forall t \quad (3)$$

Eq. (4) constrains heat from solar thermal based on available solar thermal power and the fraction of solar insolation, which is given for existing buildings.

$$SolarHeat_t \le \Delta t \cdot ThermalPower_{Solar} \cdot SolarInsolation_t, \forall t \quad (4)$$

Eq. (5) constrains the heat supplied by solar sources.

$$HeatSupp_{Solar,t} = SolarHeat_t, \forall t \quad (5)$$

Eq. (6) links the electricity requirement of the heat pump to its output.

$$ElecforTech_{HP,t} = \gamma_{HP} \cdot HeatSupp_{HP,t}, \forall t \quad (6)$$

Eq. (7) constrains the heat output of HP based on its capacity, which is given for existing buildings.

$$HeatSupp_{HP,t} \le \Delta t \cdot ThermalPower_{HP}, \forall t \quad (7)$$

Eq. (8) links the heat supplied by the CHP unit to the electricity generated.

$$HeatSupp_{CHP,t} \le \varphi_{CHP} \cdot \left(ElecGen_{CHP,t} + ElecExp_{CHP,t}\right), \forall t \quad (8)$$

Eq. (9) corrects for any losses incurred from district heating purchases.

$$UsefulDistrictHeating_t = \delta_{DistrictHeating} \cdot DistrictHeating_t, \forall t \quad (9)$$

Eq. (10) is the balance equation for each electricity end use: electricity generated on-site plus electricity purchased and demand response must meet the electricity end-use demand of each type.

$$\sum_i ElecGen_{i,l,t} + ElecPur_{l,t} + Demand\,\mathrm{Re}\,sponse_{l,t} = ElecEndUse_{l,t},\ \forall l,t \quad (10)$$

Eq. (11) is an analogous balance equation for electricity used by each technology: electricity generated on-site plus electricity purchased must meet the electricity needed by each technology.

$$\sum_i ElecGen_{i,m,t} + ElecPur_{m,t} = ElecforTech_{m,t},\ \forall m,t \quad (11)$$

Eq. (12) sums the total electricity generated on-site for either end-use demands or technologies.

$$ElecGen_{i,t} = \sum_l ElecGen_{i,l,t} + \sum_m ElecGen_{i,m,t},\ \forall i,t \quad (12)$$

Eq. (13) analogously sums the electricity purchases for either end-use demands and technologies.

$$ElecPur_t = \sum_m ElecPur_{m,t} + \sum_l ElecPur_{l,t},\ \forall t \quad (13)$$

Eq. (14) is analogous to Eq. (6) for the auxiliary heat pump linking the electricity required to the heating demand it satisfies.

$$ElecforTech_{AuxPump_{HP},t} = \gamma_{AuxPump_{HP}} \cdot HeatSupp_{HP,t},\ \forall t \quad (14)$$

Eq. (15) links the electricity required for auxiliary heating to the heating demand.

$$ElecforTech_{AuxPump_{heating},t} = \delta_{HS} \cdot \gamma_{AuxPump_{heating}} \cdot HeatDemand_t,\ \forall t \quad (15)$$

Eq. (18) does the same as Eq. (15) for the cooling demand.

$$ElecforTech_{AuxPump_{cooling},t} = \gamma_{AuxPump_{cooling}} \cdot CoolingDemand_t,\ \forall t \quad (16)$$

Eq. (17) does the same as Eq. (15) for solar heating.

$$ElecforTech_{AuxPump_{solar},t} = \gamma_{AuxPump_{solar}} \cdot SolarHeat_t,\ \forall t \quad (17)$$

Eq. (18) does the same as Eq. (15) for auxiliary CCA pumps.

$$ElecforTech_{AuxPump_{CCA},t} = \gamma_{AuxPump_{CCA}} \cdot (CoolingDemand_t + \delta_{HS} \cdot BuildHeating_t),\ \forall t \quad (18)$$

Eq. (19) constrains the amount of electricity generated via CHP both for on-site consumption and sales by the amount of installed capacity, which is given for existing buildings.

$$ElecGen_{CHP,t} + ElecExp_{CHP,t} \leq \Delta t \cdot GenCap_{CHP},\ \forall t \quad (19)$$

Eq. (20) constrains the amount of electricity generated via PV for both on-site consumption and sales by the amount of installed capacity and fraction of solar insolation.

$$ElecGen_{PV,t} + ElecExp_{PV,t} \leq \Delta t \cdot GenCap_{PV} \cdot SolarInsolation_t,\ \forall t \quad (20)$$

Eq. (21) calculates the amount of natural gas required for electricity generated using the electricity-conversion efficiency.

$$NGforElec_{CHP,t} = \frac{1}{\varepsilon_{CHP}} \cdot \left(ElecGen_{CHP,t} + ElecExp_{CHP,t}\right),\ \forall t \quad (21)$$

Eq. (22) is an energy-balance equation for cooling demand: the cooling supplied by all possible resources must match the cooling demand.

$$\sum_k CoolingSupp_{k,t} = CoolingDemand_t, \forall t \quad (22)$$

Eq. (23) constrains the cooling supply by the capacity of the cooling resource that is installed.

$$CoolingSupp_{k,t} \leq \Delta t \cdot CoolingPower_k, \forall t, k \quad (23)$$

Eq. (24) does the same as Eq. (16) for the cooling well.

$$ElecforTech_{Well,t} = \gamma_{Well} \cdot CoolingSupp_{Well,t}, \forall t \quad (24)$$

Eq. (25) decomposes the heating demand into building heating and heat for the DEC system.

$$HeatDemand_t = BuildingHeating_t + OtherHeating_t, \forall t \quad (25)$$

2.2. Sankey Diagrams

2.2.1. Pinkafeld

The University of Applied Sciences ("Fachhochschul Studiengänge Burgenland") in the eastern-most province of Austria, Burgenland, consists of two campuses. We analyse energy flows in the buildings of the Pinkafeld campus (http://www.fh-pinkafeld.ac.at/), which was renovated in 2011. Energy end uses are indicated on the right-hand side of Figure 2 starting with the electricity ones at the top and the heating ones at the bottom. Since Pinkafeld has only a 1.28 kW_p PV system installed on-site, it is considered a rather passive building. Given its current configuration, all of the electricity end-uses are met via utility purchases (indicated by yellow in the left-hand side of Figure 2). Similarly, district heating is used to meet all of its heating demand. Finally, the installed PV is used exclusively for electricity sold into the grid. Therefore, it is not relevant for the Sankey diagram.

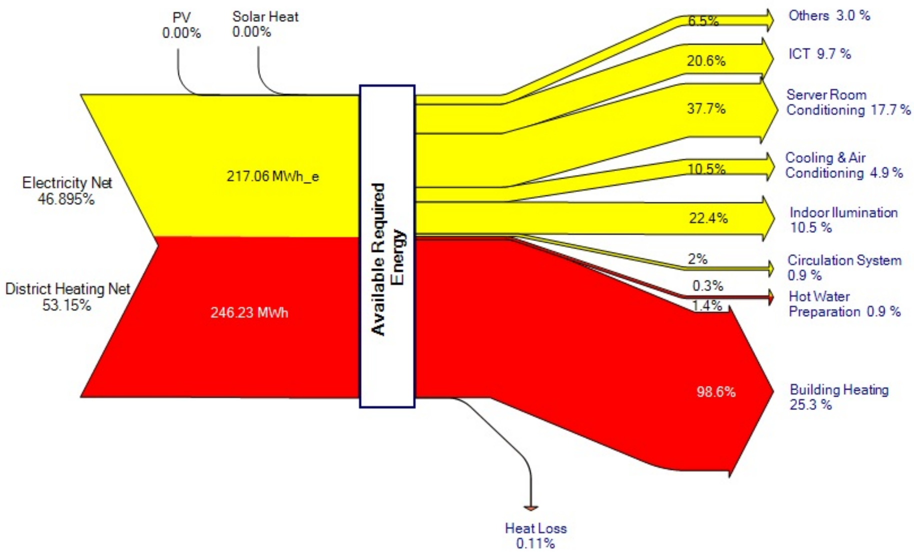

Figure 2. Sankey Diagram for Pinkafeld in 2006

The general energy-balance relations in Eqs. (1)-(25) are populated with the data for Pinkafeld as indicated in Table 1. We use annual values for the electricity and heating demand for illustrative purposes, but such constraints can be specified for any time interval over which data are available. During 2006, the electricity and heating demand were 217 MWh_e and 246 MWh_{th}, respectively. The former is partitioned into seven end uses. As for the latter, it is met exclusively via district heating with a loss of 0.2%. The available thermal heat capacity is 162.8 kWh_{th}, i.e., the district heating system can meet 162.8 kWh_{th} of heating demand each hour. Finally, approximately 1 kWh_e of electricity are produced annually by the PV system and sold into the grid.

Table 1. Energy-Balance Equations for Pinkafeld in 2006

Parameter	Value/year	Calculation	Equation
$HeatDemand$	245.738	=	$\sum_t \left(HeatSupp_{Solar,t} + UsefulDistrictHeating_t \right)$
$ElecDemand$	217.063	=	$\sum_t \sum_l ElecEndUse_{l,t}$
$HofOperation$	8760		
End Use			
$ElecPur_{ICT}$	44.72	=	$\sum_t ElecEndUse_{ICT,t}$
$ElecPur_{ServerRoomCond}$	81.83	=	$\sum_t ElecEndUse_{ServerRoomCond,t}$
$ElecPur_{Cooling\&AirCond}$	22.79	=	$\sum_t ElecEndUse_{Cooling\&AirCond,t}$
$ElecPur_{IndoorIllum}$	48.62	=	$\sum_t ElecEndUse_{IndoorIllum,t}$
$ElecPur_{CirculationSys}$	4.34	=	$\sum_t ElecEndUse_{CirculationSys,t}$
$ElecPur_{HotWaterPrep}$	0.65	=	$\sum_t ElecEndUse_{HotWaterPrep,t}$
$ElecPur_{Others}$	14.11	=	$\sum_t ElecEndUse_{Others,t}$
$\sum_t \sum_l ElecEndUse_{l,t}$	217.063	=	$\sum_l ElecPur_l$
District Heating System			
$\delta_{DistrictHeating}$	0.998		
$DistrictHeating$	246.230		
$UsefulDistrictHeating$	245.738	=	$\delta_{DistrictHeating} \cdot \sum_t DistrictHeating_t$
PV			
$GenCap_{PV}$			
$ElecExp_{PV}$	0.001	≤	$GenCap_{PV} \cdot \Delta t \cdot \sum_t SolarInsolation_t$

2.2.2. *FASAD*

FASAD (http://www.fasad.es/) is the Asturian Foundation for Attending Handicapped People ("Fundación Asturiana de Atención y Protección a Personas con Discapacidades y/o Dependencias"). Among various facilities, it runs a residential centre for adults called La Arboleya located in Siero, Spain. Unlike Pinkafeld, FASAD's residential centre has installed technologies that are used to meet on-site electricity and heating demands. In particular, it has two gas-fired boilers with a total capacity of over 3 MW and a CHP system with a 5 kW capacity. However, all the electricity generated by the latter is sold to the grid. Thus, the Sankey diagram in Figure 3 illustrates the current situation at FASAD: all of the electricity consumed on-site is met via utility purchases, while building heating and hot water requirements are met mostly via the boilers with a modest contribution from the CHP unit. Losses due to energy conversion in both technologies are also reflected in the Sankey diagram. All details on the parameters and energy balances on an annual basis are reported in Table 2.

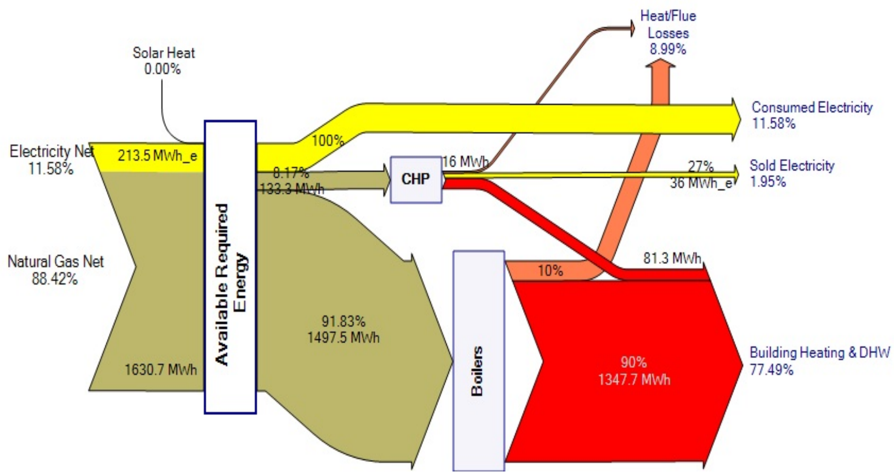

Figure 3. Sankey Diagram for FASAD

Table 2. Energy-Balance Equations for FASAD

Parameter	**Value/ year**	**Calculation**	**Equation**
$HeatDemand$	1429	=	$\sum_t \left(HeatSupp_{CHP,t} + HeatSupp_{NGB,t} + HeatSupp_{Solar,t} \right)$
$ElecDemand$	213.5	=	$\sum_t \sum_l ElecEndUse_{l,t}$
End Use			
$ElecPur_{Consumption}$	213.5		
$HofOperati\ on$	6500		
2 NG-Fired Boilers			
$ThermalPower_{NGB}$	3.0234		
β	0.9		
$NGBoilerCap$	3.3593	$\frac{ThermalPower}{\beta}$	
$NGforHeat$	1497.46	$\leq$	$HofOperation \cdot NGBoilerCap$

Parameter	Value/ year	Calculation	Equation
$HeatSupp_{NGB}$	1347.71	=	$\beta \cdot \sum_t NGforHeat_t$
Micro-CHP (Dachs)			
$GenCap$	0.0055		
φ_{CHP}	0.61		
ε_{CHP}	0.27		
$NGforElec_{CHP}$	133.25	=	$\frac{1}{\varepsilon_{CHP}} \cdot \sum_t \begin{pmatrix} ElecGen_{CHP,t} \\ + ElecExp_{CHP,t} \end{pmatrix}$
$ElecGen_{CHP} + ElecExp_{CHP}$	35.98	$\leq$	$HofOperation \cdot GenCap_{CHP}$
$HeatSupp_{CHP}$	81.28	$\leq$	$\varphi_{CHP} \cdot NGforElec_{CHP}$

2.2.3. *ENERGYbase (Back-Up Test Site)*

ENERGYbase (http://www.energybase.at/) is a passive office building constructed in 2008 and located in Vienna, Austria. We have included it as a back-up test site in order to have another building in which to test our DSS. There are different decentralised energy supply technologies in use to meet the heating and cooling demand. For building heating, two water/water heat pumps (2x170 kW_{th}) in combination with the 285 m² of solar collectors are used. For building cooling, a ground water cooling system is used. The distribution of the cold or hot water is done by concrete core activation (CCA, see http://www.enob.info/en/analysis/analysis/details/concrete-core-temperature-control).

The ventilation system is divided into two parts. The ground and first floors are supplied by the ventilation system, LA03, and the remaining area at the upper floors is supplied by the ventilation systems LA01 and LA02 with a solar-assisted desiccant evaporative cooling (DEC, see http://www.technologyreview.com/energy/25623/page1) system. To cover parts of the electrical consumption, a PV system with 48 kW_p is installed at the southern façade. Figure 4 summarises the energy flows at ENERGYbase. All details on the parameters and energy balances on an annual basis are reported in Table 3.

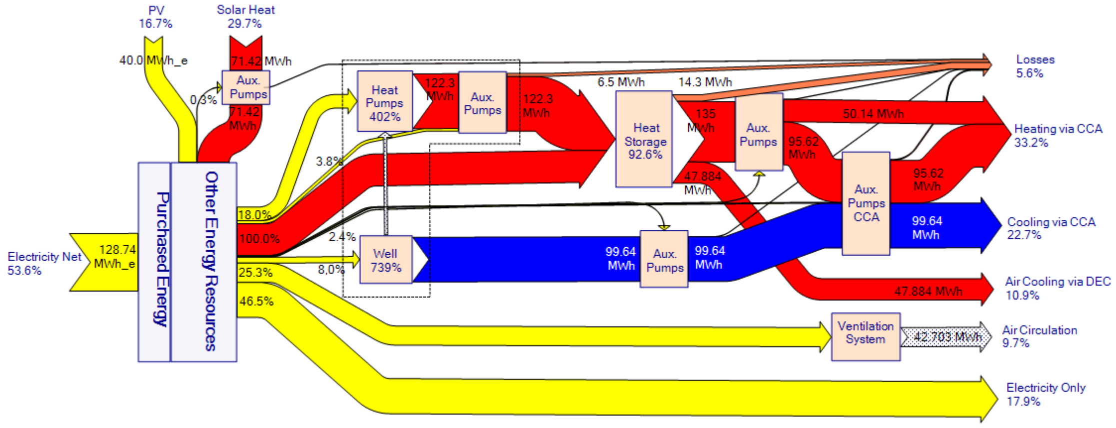

Figure 4. Sankey Diagram for ENERGYbase

Table 3. Energy-Balance Equations for ENERGYbase

Parameter	Value/ year	Calculation	Equation
$HeatDemand + HeatforTech_{DEC}$	193.656	=	$\sum_t (HeatSupp_{HP,t} + HeatSupp_{Solar,t})$
$HeatDemand$	145.757	=	$BuildingHeating + OtherHeating$
$ElecDemand$	168.740	=	$\sum_t \sum_l ElecEndUse_{l,t} + \sum_t \sum_m ElecforTech_{m,t}$
$CoolingDemand$	99.640	=	$\sum_t CoolingSupp_{Well,t}$
End Use (hypothetical data)			
$ElecPur_{ElecOnly}$	78.400	=	$\sum_t ElecEndUse_{ElecOnly,t}$
$ElecPur_{VentilationSys}$	42.703	=	$\sum_t ElecEndUse_{VentilationSys,t}$
$HofOperation$	8760		
Elec-Based Technology (Calculations)			
γ_{HP}	0.249		
γ_{Well}	0.068		
$\gamma_{AuxPump_{HP}}$	0.053		
$\gamma_{AuxPump_{heating}}$	0.005		
$\gamma_{AuxPump_{cooling}}$	0.007		
$\gamma_{AuxPump_{solar}}$	0.008		
$\gamma_{AuxPump_{CCA}}$	0.011		
$ElecforTech_{HP}$	30.446	=	$\gamma_{HP} \cdot \sum_t HeatSupp_{HP,t}$
$ElecforTech_{Well}$	6.745	=	$\gamma_{Well} \cdot \sum_t CoolingSupp_{Well,t}$

Parameter	Value/ year	Calculation	Equation
$ElecforTech_{AuxPump_{HP}}$	6.482	=	$\gamma_{AuxPump_{HP}} \cdot \sum_t HeatSupp_{HP,t}$
$ElecforTech_{AuxPump_{heating}}$	0.675	=	$\delta_{HS} \cdot \gamma_{AuxPump_{heating}} \cdot \sum_t HeatDemand_t$
$ElecforTech_{AuxPump_{cooling}}$	0.698	=	$\gamma_{AuxPump_{cooling}} \cdot \sum_t CoolingDemand_t$
$ElecforTech_{AuxPump_{solar}}$	0.579	=	$\gamma_{AuxPump_{solar}} \cdot \sum_t SolarHeat_t$
$ElecforTech_{AuxPump_{CCA}}$	2.068	=	$\gamma_{AuxPump_{CCA}} \cdot \sum_t \left(CoolingDemand_t + \delta_{HS} \cdot BuildHeating_t \right)$
ElecPur/ElecGen (hypothetical data)			
$ElecPur_{AuxPump_{HP}}$	6.482	=	$ElecforTech_{AuxPump_{HP}}$
$ElecPur_{AuxPump_{heating}}$	0.675	=	$ElecforTech_{AuxPump_{heating}}$
$ElecPur_{AuxPump_{cooling}} + ElecGen_{PV,AuxPump_{cooling}}$	0.698	=	$ElecforTech_{AuxPump_{cooling}}$
$ElecGen_{PV,Well}$	6.745	=	$ElecforTech_{Well}$
$ElecGen_{PV,HP}$	30.446	=	$ElecEndUse_{HP}$
$ElecGen_{PV,AuxPump_{solar}}$	0.579	=	$ElecEndUse_{AuxPump_{solar}}$
$ElecGen_{PV,AuxPump_{CCA}}$	2.068	=	$ElecEndUse_{AuxPump_{CCA}}$
PV			
$GenCap_{PV}$	48		
$ElecGen_{PV}$	40	≤	$GenCap_{PV} \cdot \Delta t \cdot \sum_t SolarInsolation_t$
Heat Pumps			
$ThermalPower_{HP}$	0.340		
γ_{HP}	0.249		
δ_{HP}	0.926		
$HeatSupp_{HP}$	122.252	=	$\frac{1}{\gamma_{HP}} \cdot ElecforTech_{HP}$
$HeatforTech_{DEC}$	47.884		
$BuildingHeating$	95.616		
$OtherHeating$	50.140		
Well			
γ_{Well}	0.068		
$CoolingSupp_{Well}$	99.640	=	$\frac{1}{\gamma_{Well}} \cdot ElecforTech_{Well}$
		≤	$HofOperation \cdot ThermalPower_{Well}$

Parameter	Value/ year	Calculation	Equation
Solar Heat			
$ThermalPower_{Solar}$	0.228		
$SolarHeat$	71.42	$\leq$	$HofOperation \cdot ThermalPower_{Solar}$
$HeatSupp_{\ Solar}$	71.42	$=$	$SolarHeat$

3. *Examples of Future Energy System Configurations*

The purpose of this section is to illustrate the capabilities of our general modelling approach to decomposing a building's energy flows. By proposing alternative configurations at each site, we populate Eqs. (1)-(25) with new equipment characteristics in order to produce new Sankey diagrams. Thus, this section provides a basis for the mathematical formulation of energy-balance constraints as part of an optimisation in subsequent work.

3.1. Pinkafeld

We consider two alternative configurations: one with a CHP system (Figure 5) and another with both electricity and heat storage (Figure 6). The former illustrates how Pinkafeld may be able to meet its electricity and heating demands if a gas-fired CHP system were installed. However, this results in a reliance on extensive purchases of natural gas to run the CHP system, which displaces utility purchases of electricity and the use of district heating. Enough electricity and heat is produced on-site in order to meet all end-use demands. The second alternative configuration installs storage technologies in order to facilitate the use of the PV and solar heating systems.

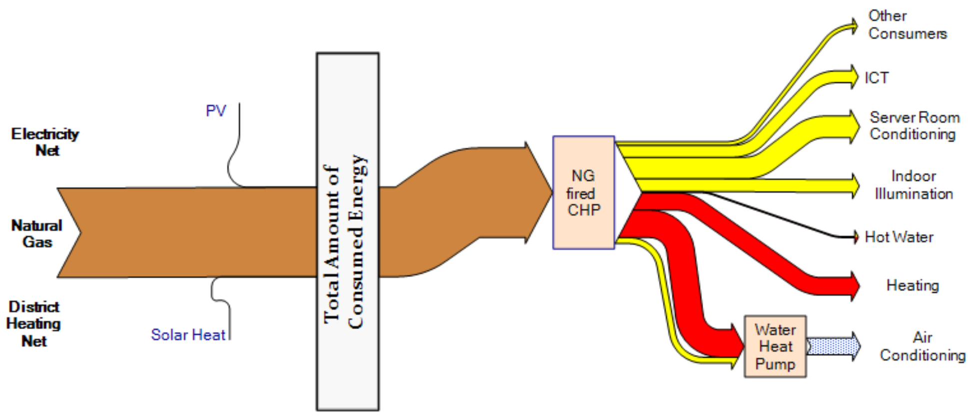

Figure 5. Alternative System Configuration for Pinkafeld with CHP

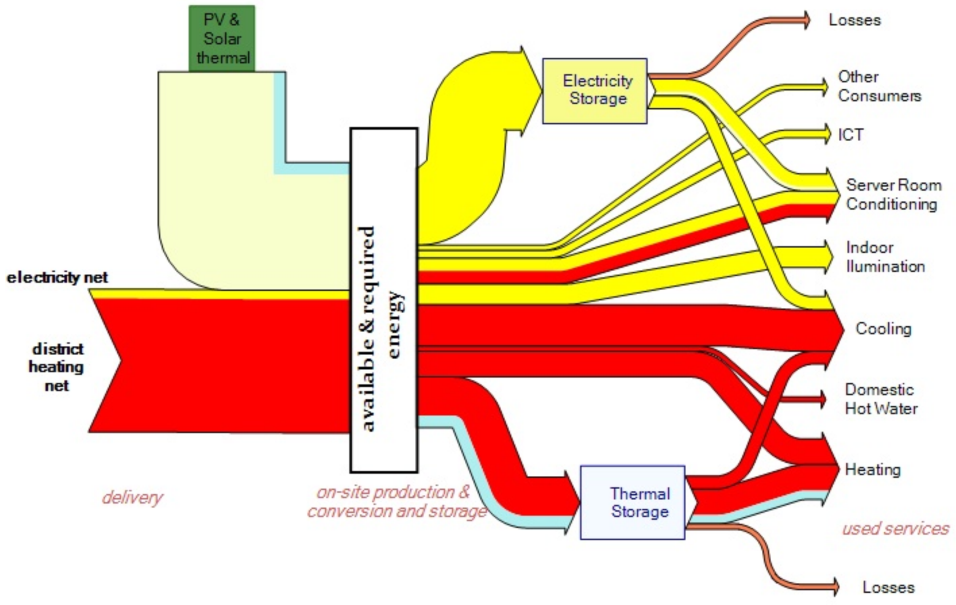

Figure 6. Alternative System Configuration for Pinkafeld with Storage

3.2. FASAD

We consider three alternative configurations: one with a heat pump (Figure 7), one with a combination of a solar thermal system and a large CHP system (Figure 8), and another with electricity storage (Figure 9).

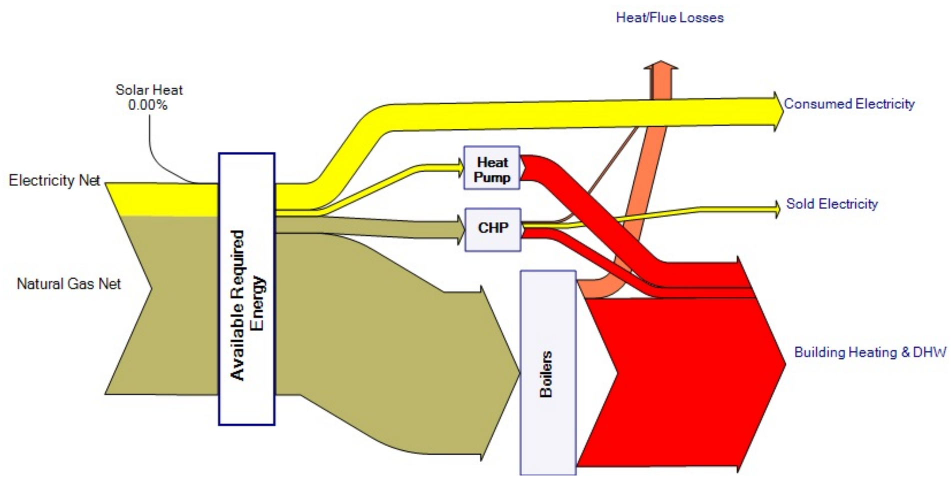

Figure 7. Alternative System Configuration for FASAD with Heat Pump

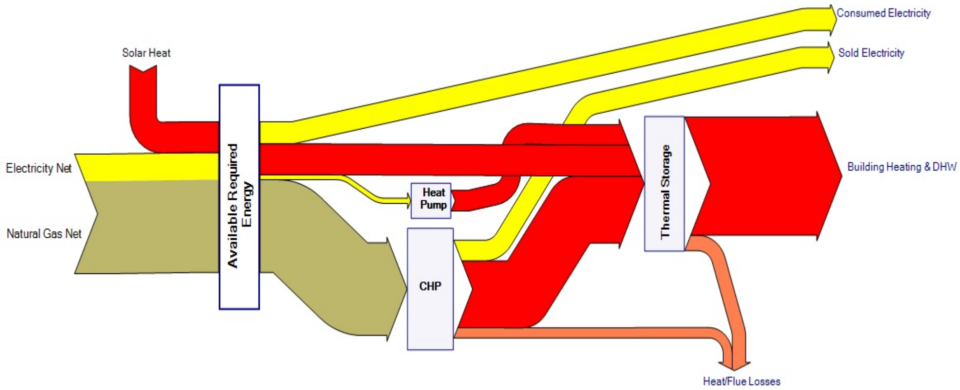

Figure 8. Alternative System Configuration for FASAD with Solar Thermal System and a Large CHP System

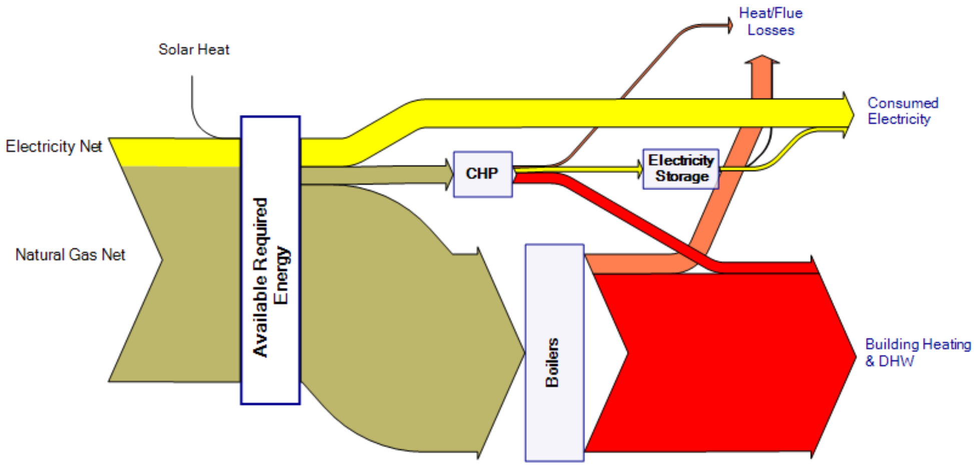

Figure 9. Alternative System Configuration for FASAD with Electricity Storage

3.3. ENERGYbase (Back-Up Test Site)

We consider three possible future system configurations for ENERGYbase and illustrate how to model their energy flows using our approach. In the first one (Figure 10), district heating and solar heating are used to meet the heating demand. For cooling purposes, an adsorption chiller is used, which deploys heat for cooling. The second alternative configuration (Figure 11) explores the use of a CHP system for heating and electricity generation. The cooling demand is covered by an absorption chiller, which is supplied by both the solar system and the CHP system. Additionally, electric storage is used. A third possible future configuration (Figure 12) has a CHP system used for heating purposes. Meanwhile, cooling is done by “free cooling” with ground water. As in the previous configuration, electric storage is used.

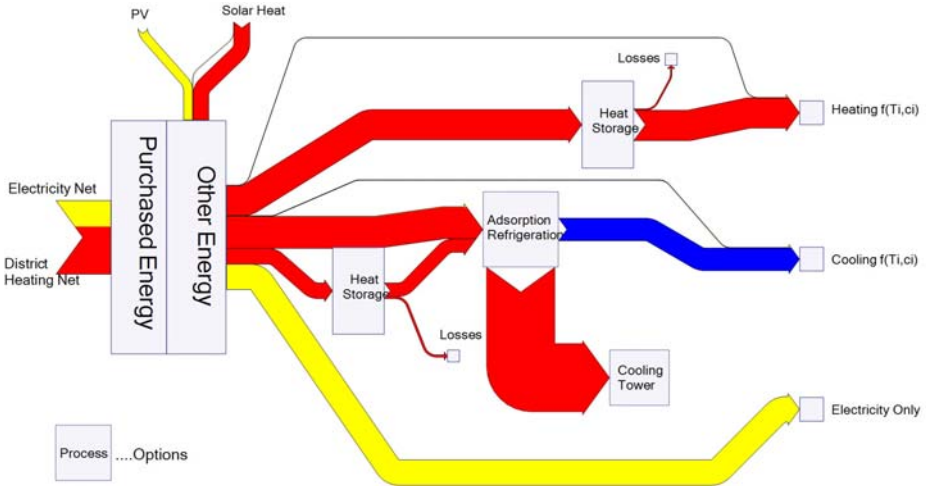

Figure 10. Alternative System Configuration for ENERGYbase with District Heating, Heat Storage, and an Adsorption Chiller

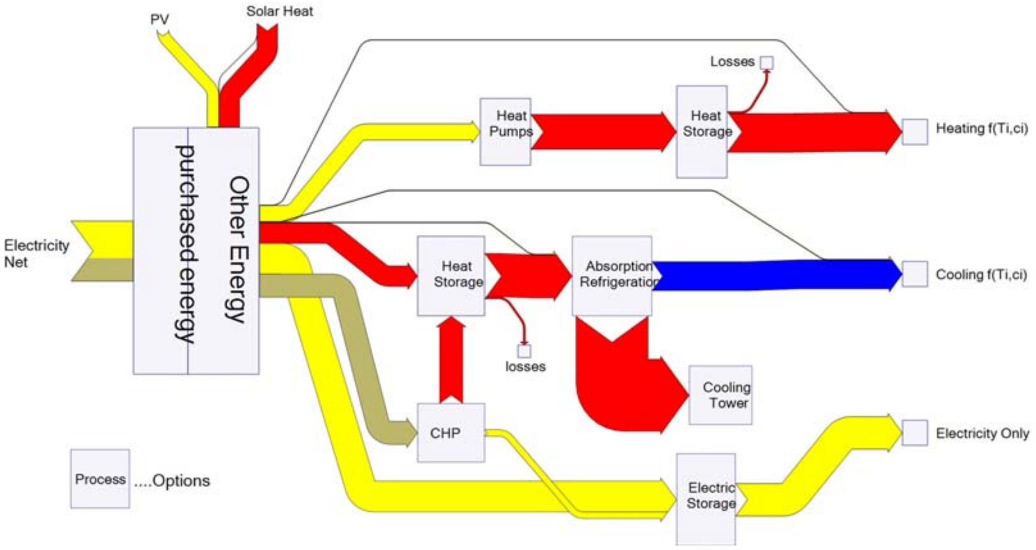

Figure 11. Alternative System Configuration for ENERGYbase with CHP, Electricity and Heat Storage, and an Absorption Chiller

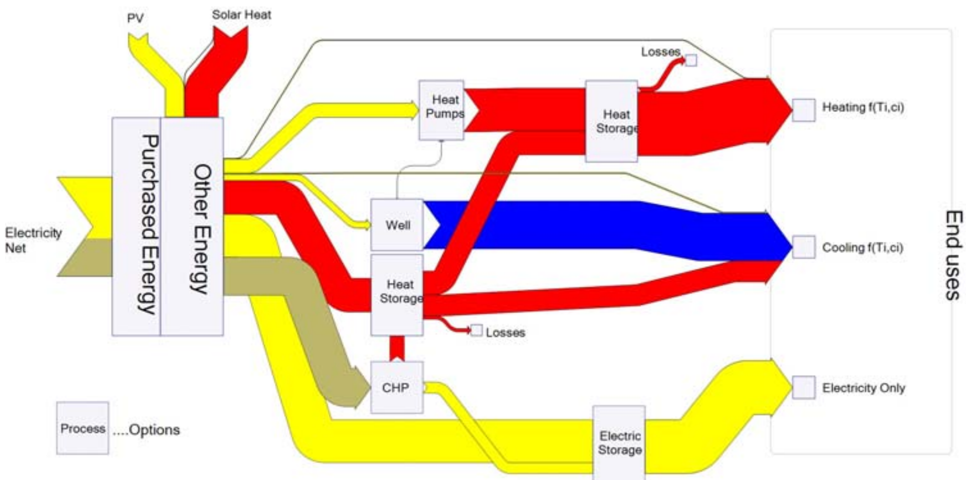

Figure 12. Alternative System Configuration for ENERGYbase with CHP and Storage

4. *Links to Subsequent Deliverables*

4.1. *Mathematical Formulation of Energy-Balance Constraints (Deliverable D2.2)*

Deliverable D2.2 will prepare a mathematical formulation of energy-balance constraints to be used in order to optimise energy-system operations and to provide strategic guidance for future system configurations. The effort made in Deliverable D2.1 to present a high-level, adaptive approach to model dependencies between energy demands and resources serves as a valuable platform to reach that goal. Enhancements to the modelling approach to be presented in Deliverable D2.2 will include relaxing the assumption that end-use demands are fixed. Instead, we will take the view that user requirements, e.g., temperature or ambient light, are specified, and set points of installed technologies are decision variables, which subsequently yield energy end-use demands. In addition to the parameters described in Section 2.1 of this document, we will also account for weather conditions, building characteristics, and internal heat gains and losses, some or all of which may be stochastic. Hence, we will proceed to tackle energy flows at a deeper level using the energy-balance equations outlined here as a starting point.

4.2. *Symbolic Model Specification (Deliverable D4.2)*

Deliverable D4.2 will consist of the symbolic model specification for optimisation problems to be solved for the test sites at both operational and strategic levels. The Sankey diagrams and energy-balance constraints will contribute to this work by linking energy resources with consumption. By creating high-level energy-balance constraints here and enhancing them to reflect a more expansive treatment of energy demands in Deliverable D2.2, we will provide a flexible approach to defining energy-balance constraints that take into account user requirements rather than fixed end-use demands and changes to the system configuration. Specifically, beyond the features described in this document and to be covered in Deliverable D2.2, the formulation will account for energy tariffs, regulatory conditions, and the availability of new energy technologies. Again, some or all of these aspects may be stochastic, which means that user preferences and risk management opportunities will be important. Overall, it is essential to indicate (for both short-term operational optimisation as well as for long-term strategic planning) how uncertainty will enter this representation, e.g., efficiency parameters (energy-transfer coefficients), energy flows (left-hand sides of Sankey diagrams), or demands (right-hand sides of Sankey diagrams). Representation of uncertainties in the energy system is, thus, one of the main challenges for operational and strategic optimisation.

5. *References*

King, D. and G. Morgan (2007), “Customer-Focused Assessment of Electric Power Microgrids,” *Journal of Energy Engineering* 133(3): 150–164

Marnay, C., G. Venkatarmanan, M. Stadler, A. Siddiqui, R. Firestone, and B. Chandran (2008), “Optimal Technology Selection and Operation of Commercial-Building Microgrids,” *IEEE Transactions on Power Systems* 23(3): 975-982