Presentation of system performance calculation Educational material

A technical report of subtask D

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IEA Solar Heating and Cooling Programme

The *International Energy Agency* (IEA) is an autonomous body within the framework of the Organization for Economic Co-operation and Development (OECD) based in Paris. Established in 1974 after the first "oil shock," the IEA is committed to carrying out a comprehensive program of energy cooperation among its members and the Commission of the European Communities.

The IEA provides a legal framework, through IEA Implementing Agreements such as the *Solar Heating and Cooling Agreement*, for international collaboration in energy technology research and development (R&D) and deployment. This IEA experience has proved that such collaboration contributes significantly to faster technological progress, while reducing costs; to eliminating technological risks and duplication of efforts; and to creating numerous other benefits, such as swifter expansion of the knowledge base and easier harmonization of standards.

The *Solar Heating and Cooling Programme* was one of the first IEA Implementing Agreements to be established. Since 1977, its members have been collaborating to advance active solar and passive solar and their application in buildings and other areas, such as agriculture and industry. Current members are:

Australia	Finland	Singapore
Austria	France	South Africa
Belgium	Italy	Spain
Canada	Mexico	Sweden
Denmark	Netherlands	Switzerland
European Commission	Norway	United States
Germany	Portugal	

A total of 49 Tasks have been initiated, 35 of which have been completed. Each Task is managed by an Operating Agent from one of the participating countries. Overall control of the program rests with an Executive Committee comprised of one representative from each contracting party to the Implementing Agreement. In addition to the Task work, a number of special activities—Memorandum of Understanding with solar thermal trade organizations, statistics collection and analysis, conferences and workshops—have been undertaken.

Visit the Solar Heating and Cooling Programme website - **www.iea-shc.org** - to find more publications and to learn about the SHC Programme.

Current Tasks & Working Group:

Task 36	*Solar Resource Knowledge Management*
Task 39	*Polymeric Materials for Solar Thermal Applications*
Task 40	*Towards Net Zero Energy Solar Buildings*
Task 41	*Solar Energy and Architecture*
Task 42	*Compact Thermal Energy Storage*
Task 43	*Solar Rating and Certification Procedures*
Task 44	*Solar and Heat Pump Systems*
Task 45	*Large Systems: Solar Heating/Cooling Systems, Seasonal Storages, Heat Pumps*
Task 46	*Solar Resource Assessment and Forecasting*
Task 47	*Renovation of Non-Residential Buildings Towards Sustainable Standards*
Task 48	*Quality Assurance and Support Measures for Solar Cooling*
Task 49	*Solar Process Heat for Production and Advanced Applications*

Completed Tasks:

Task 1	*Investigation of the Performance of Solar Heating and Cooling Systems*
Task 2	*Coordination of Solar Heating and Cooling R&D*
Task 3	*Performance Testing of Solar Collectors*
Task 4	*Development of an Insolation Handbook and Instrument Package*
Task 5	*Use of Existing Meteorological Information for Solar Energy Application*
Task 6	*Performance of Solar Systems Using Evacuated Collectors*
Task 7	*Central Solar Heating Plants with Seasonal Storage*
Task 8	*Passive and Hybrid Solar Low Energy Buildings*
Task 9	*Solar Radiation and Pyranometry Studies*
Task 10	*Solar Materials R&D*
Task 11	*Passive and Hybrid Solar Commercial Buildings*
Task 12	*Building Energy Analysis and Design Tools for Solar Applications*
Task 13	*Advanced Solar Low Energy Buildings*
Task 14	*Advanced Active Solar Energy Systems*
Task 16	*Photovoltaics in Buildings*
Task 17	*Measuring and Modeling Spectral Radiation*
Task 18	*Advanced Glazing and Associated Materials for Solar and Building Applications*
Task 19	*Solar Air Systems*
Task 20	*Solar Energy in Building Renovation*
Task 21	*Daylight in Buildings*
Task 22	*Building Energy Analysis Tools*
Task 23	*Optimization of Solar Energy Use in Large Buildings*
Task 24	*Solar Procurement*
Task 25	*Solar Assisted Air Conditioning of Buildings*
Task 26	*Solar Combisystems*
Task 27	*Performance of Solar Facade Components*
Task 28	*Solar Sustainable Housing*
Task 29	*Solar Crop Drying*
Task 31	*Daylighting Buildings in the 21st Century*
Task 32	*Advanced Storage Concepts for Solar and Low Energy Buildings*
Task 33	*Solar Heat for Industrial Processes*
Task 34	*Testing and Validation of Building Energy Simulation Tools*
Task 35	*PV/Thermal Solar Systems*
Task 37	*Advanced Housing Renovation with Solar & Conservation*
Task 38	*Solar Thermal Cooling and Air Conditioning*

Completed Working Groups:

CSHPSS; ISOLDE; Materials in Solar Thermal Collectors; Evaluation of Task 13 Houses; Daylight Research

IEA Heat Pump Programme

This project was carried out within the Solar Heating and Cooling Programme and also within the *Heat Pump Programme*, HPP which is an Implementing agreement within the International Energy Agency, IEA. This project is called Task 44 in the *Solar Heating and Cooling Programme* and Annex 38 in the *Heat pump Programme*.

The Implementing Agreement for a Programme of Research, Development, Demonstration and Promotion of Heat Pumping Technologies (IA) forms the legal basis for the IEA Heat Pump Programme. Signatories of the IA are either governments or organizations designated by their respective governments to conduct programmes in the field of energy conservation.

Under the IA collaborative tasks or "Annexes" in the field of heat pumps are undertaken. These tasks are conducted on a cost-sharing and/or task-sharing basis by the participating countries. An Annex is in general coordinated by one country which acts as the Operating Agent (manager). Annexes have specific topics and work plans and operate for a specified period, usually several years. The objectives vary from information exchange to the development and implementation of technology. This report presents the results of one Annex. The Programme is governed by an Executive Committee, which monitors existing projects and identifies new areas where collaborative effort may be beneficial.

The IEA Heat Pump Centre

A central role within the IEA Heat Pump Programme is played by the IEA Heat Pump Centre (HPC). Consistent with the overall objective of the IA the HPC seeks to advance and disseminate knowledge about heat pumps, and promote their use wherever appropriate. Activities of the HPC include the production of a quarterly newsletter and the webpage, the organization of workshops, an inquiry service and a promotion programme. The HPC also publishes selected results from other Annexes, and this publication is one result of this activity.

For further information about the IEA Heat Pump Programme and for inquiries on heat pump issues in general contact the IEA Heat Pump Centre at the following address:

IEA Heat Pump Centre
Box 857
SE-501 15 BORÅS
Sweden
Phone: +46 10 16 55 12
Fax: +46 33 13 19 79

Visit the Heat Pump Programme website - **http://www.heatpumpcentre.org/** - to find more publications and to learn about the HPP Programme.

Contents

1 Introduction

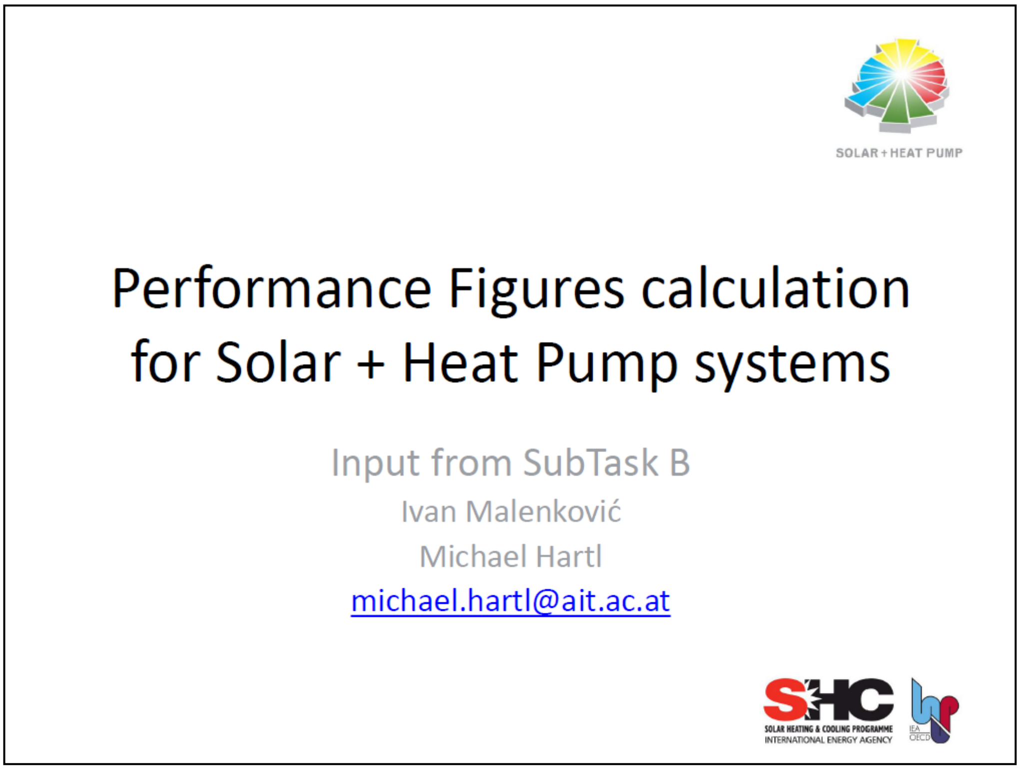
IEA Task 44 / Annex 38 has produced free available educational material on the subject of performance figures evaluation for Solar plus Heat Pump (SHP) systems. The aim is to develop supporting material useful during teaching activities on the topic of Solar plus Heat Pump systems.

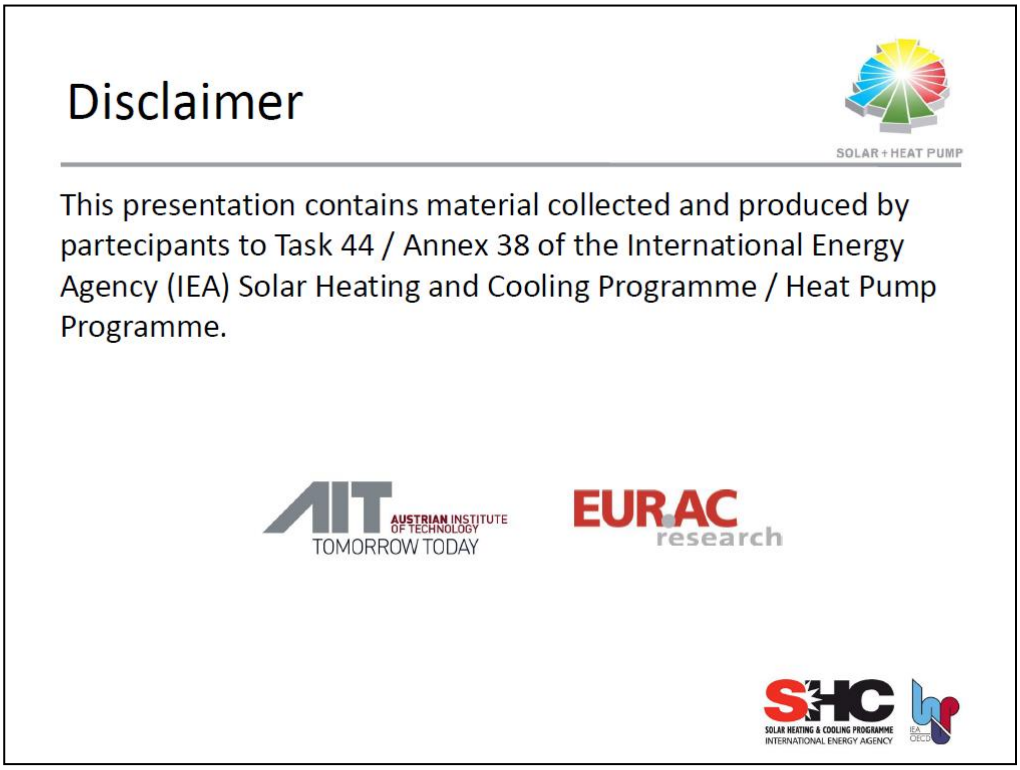
The content addresses the definition of several performance indicators developed within Task 44 / Annex 38. The material has been derived from the activities of Subtask B. More detailed information on this topic can be found in the deliverable B1. In the final slides an example is additionally presented for clarifying the relevance and the meaning of each single performance figure.

The material has a form of a presentation. Since the idea is to guide hand-in-hand the reader in the process of SHP analysis, the format is clear and communicative and clarifying text and graphs correlate indicator's definition.

It is free downloadable from the Task 44 / Annex 38 webpage (http://task44.iea-shc.org).

2 Educational material




Disclaimer
SOLAR + HEAT PUMP
This presentation contains material collected and produced by partecipants to Task 44 / Annex 38 of the International Energy Agency (IEA) Solar Heating and Cooling Programme / Heat Pump Programme.
AUSTRIAN INSTITUTE OF TECHNOLOGY
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EURAC research
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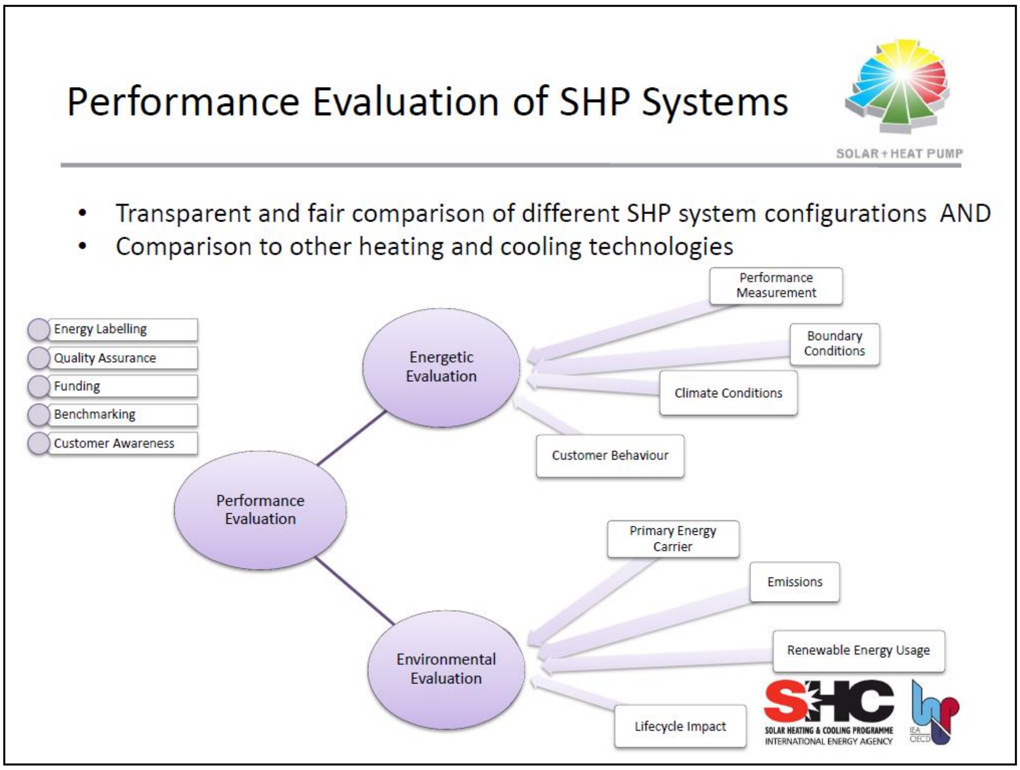
Performance Evaluation of SHP Systems
SOLAR + HEAT PUMP
• Transparent and fair comparison of different SHP system configurations AND
• Comparison to other heating and cooling technologies
Energy Labelling
Quality Assurance
Funding
Benchmarking
Customer Awareness
Performance Evaluation
Energetic Evaluation
Environmental Evaluation
Performance Measurement
Boundary Conditions
Climate Conditions
Customer Behaviour
Primary Energy Carrier
Emissions
Renewable Energy Usage
Lifecycle Impact
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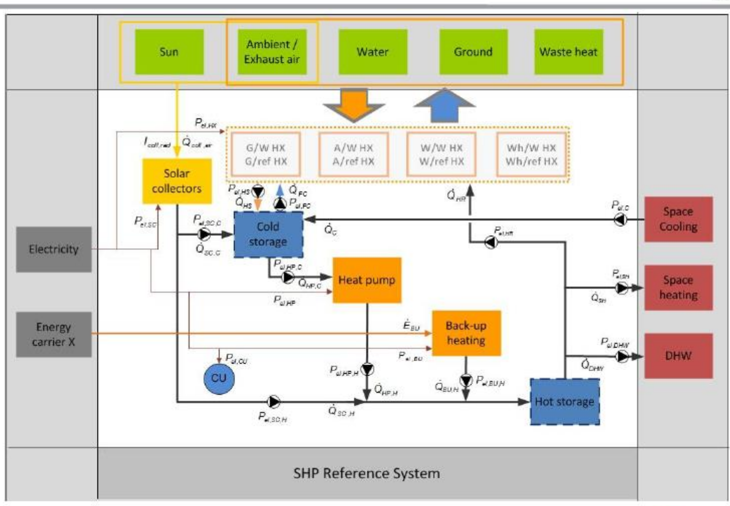
Seasonal Performance factor - SPF

The SPF gives the efficiency of the whole system or a defined subsystem, calculated as the **overall useful energy output** to the **overall driving final energy input.**

$$SPF = \frac{\int (\dot{Q}_{SH} + \dot{Q}_{DHW} + \dot{Q}_C) \cdot dt}{\int \sum P_{el} \cdot dt}$$

- Difficult to determine if system is operated simultaneously in different operation modes, e.g. heating and cooling, cooling and DHW etc.
- The SPF accounts for the system performance depending on the boundary conditions such as heat source temperature, solar irradiation, supply temperature etc.
- It does not take into account the depletion of non-renewables or CO_2 emissions caused during the lifetime etc.

SHP Reference System – Square View



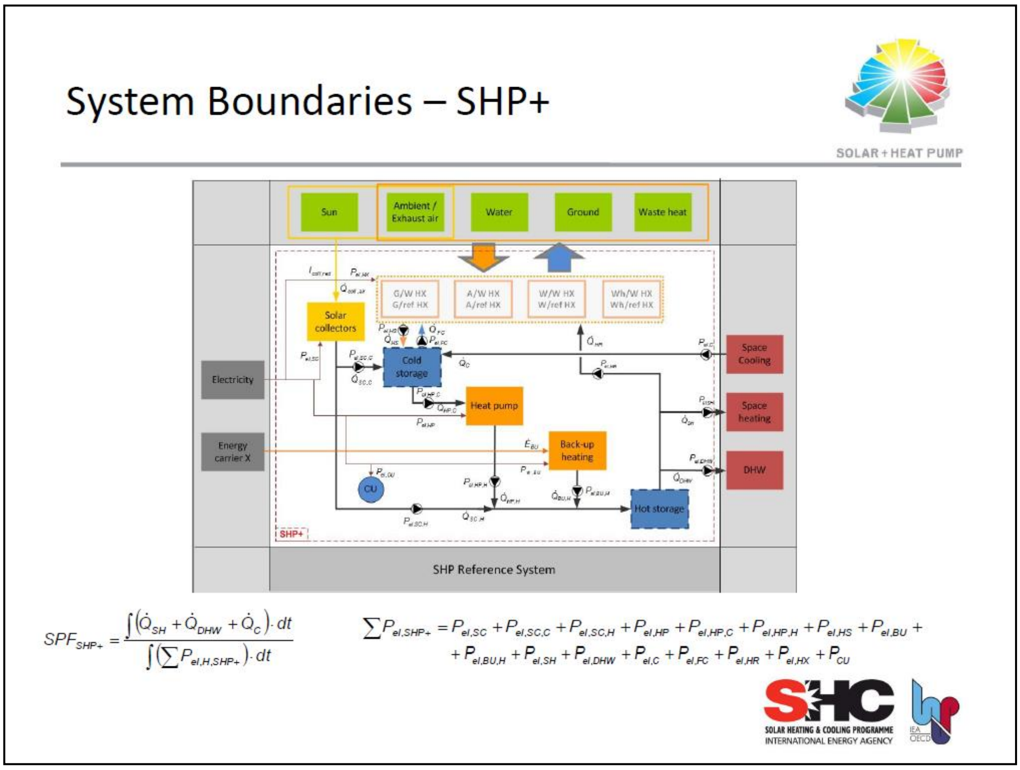
SHP Reference System - Simplifications

- Ambient and Exhaust Air, Ground Water, Ground and Waste Heat can all be considered as heat source for the heat pump ($\dot{Q}_{HS}$) or heat sink in the case of free cooling or energy dissipation for active cooling. They, as well as the respective heat exchangers, were put together as “free energy sources” with an orange frame (slashed for heat exchangers);
- Solar collectors can generally transform both solar radiation and ambient air heat (including condensation) into useful heat or heat source for the heat pump (either directly or for the regeneration of the ground, air pre-heating etc.). This fact has been considered by putting Air and Sun together with the yellow frame. The energy input to the collector is denominated as $I_{coll,rad}$ for the solar radiative part and $\dot{Q}_{coll,air}$ for the energy input from the ambient air;
- Traded energy includes Electricity and other energy carriers, denominated by “Energy carrier X”.
- Energy flows are represented in their physical direction, from higher to lower temperatures;
- The connections between the components do not reproduce the hydraulic configuration of the system. They however provide information on possible interactions between the components, due to the hydraulics and the controls of the system;
- The connections between components with a pump symbol represent energy consumption needed to transport the heat transfer medium and overcome the pressure losses within the system;
- The components presented with a slashed frame (both storages) can be ignored if not a part of a particular system or if direct connections possible (e.g. the solar energy can be either stored or used directly in the evaporator of the heat pump);
- Although presented as one component, the “storage” can actually consist of more than one unit (e.g. one storage for heating and one for DHW). This implies, that e.g. the energy input $P_{el,SC,H}$ can in reality consist of more than one consumer (pumps);
- In analogy, one pump can be used to transport the heat transfer medium e.g. from one “heat source” component to several “heat sink” components. For example, one pump can be used to circulate the fluid from the collector both to the evaporator of the heat pump and to the heat storage. This implies, that this pump would be consuming both $P_{el,SC,H}$ and $P_{el,SC,C}$. This has to be considered for the evaluation of the data accordingly.
- Defrosting for air source HPs:
  - Direct electric defrosting: Should be included in $P_{el,HP}$;
  - Hot gas defrosting: The energy consumption should also be included in $P_{el,HP}$;
  - Reverse cycle defrosting: the heat energy taken from the storage/building has to be subtracted from the useful energy output at the appropriate boundary, if not automatically executed by the heat meter.

System Boundaries

Four different boundaries have been defined to evaluate a SHP system:

1. **„SHP+“** Solar and Heat Pump System with Useful Energy Distribution System
   a. Systems without additional heating of the distribution pipes
   b. Systems with additional heating of the distribution pipes
2. **„SHP“** Solar and Heat Pump
3. **„bSt“** Before Storage
4. **„HP + HS (HR)“** Heat Pump with Heat Source (Heat Rejection)
5. **„HP, SC, BU“** Heat Pump, Solar Collector, Back-Up Unit


System Boundaries – SHP+
SOLAR + HEAT PUMP
Sun
Ambient / Exhaust air
Water
Ground
Waste heat
G/W HX G/ref HX
A/W HX A/ref HX
W/W HX W/ref HX
Wh/W HX Wh/ref HX
Solar collectors
Cold storage
Heat pump
Back-up heating
Hot storage
CU
Electricity
Energy carrier X
Space Cooling
Space heating
DHW
SHP+
SHP Reference System
$$SPF_{SHP+} = \frac{\int (\dot{Q}_{SH} + \dot{Q}_{DHW} + \dot{Q}_C) \cdot dt}{\int (\sum P_{el,H,SHP+}) \cdot dt}$$
$$\sum P_{el,SHP+} = P_{el,SC} + P_{el,SC,C} + P_{el,SC,H} + P_{el,HP} + P_{el,HP,C} + P_{el,HP,H} + P_{el,HS} + P_{el,BU} + P_{el,BU,H} + P_{el,SH} + P_{el,DHW} + P_{el,C} + P_{el,FC} + P_{el,HR} + P_{el,HX} + P_{CU}$$
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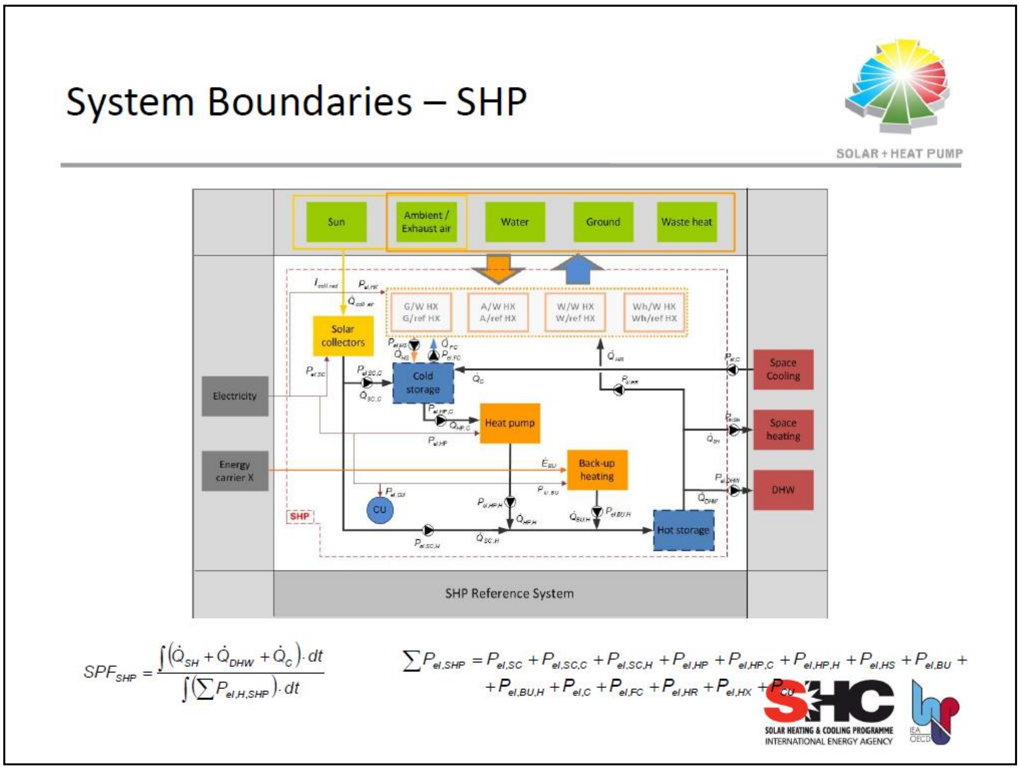
System Boundaries – SHP
SOLAR + HEAT PUMP
Sun
Ambient / Exhaust air
Water
Ground
Waste heat
G/W HX G/ref HX
A/W HX A/ref HX
W/W HX W/ref HX
Wh/W HX Wh/ref HX
Solar collectors
Cold storage
Heat pump
Back-up heating
Hot storage
CU
Electricity
Energy carrier X
Space Cooling
Space heating
DHW
SHP
SHP Reference System
$$SPF_{SHP} = \frac{\int (\dot{Q}_{SH} + \dot{Q}_{DHW} + \dot{Q}_C) \cdot dt}{\int (\sum P_{el,H,SHP}) \cdot dt}$$
$$\sum P_{el,SHP} = P_{el,SC} + P_{el,SC,C} + P_{el,SC,H} + P_{el,HP} + P_{el,HP,C} + P_{el,HP,H} + P_{el,HS} + P_{el,BU} + P_{el,BU,H} + P_{el,C} + P_{el,FC} + P_{el,HR} + P_{el,HX} + P_{CU}$$
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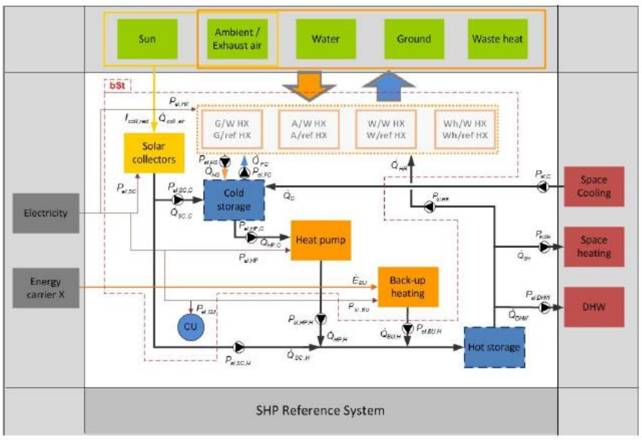
System Boundaries – bSt

SOLAR + HEAT PUMP



$$SPF_{bSt,Heat} = \frac{\int\left(\dot{Q}_{SC,H} + \dot{Q}_{HP,H} + \dot{Q}_{BU,H}\right)\cdot dt}{\int\left(\sum P_{el,bSt,Heat}\right)\cdot dt} \qquad \sum P_{el,bSt,Heat} = P_{el,SC} + P_{el,SC,C} + P_{el,HP} + P_{el,HP,C} + P_{el,HS} + P_{el,FC} + P_{el,BU} + P_{el,HX} + P_{CU}$$

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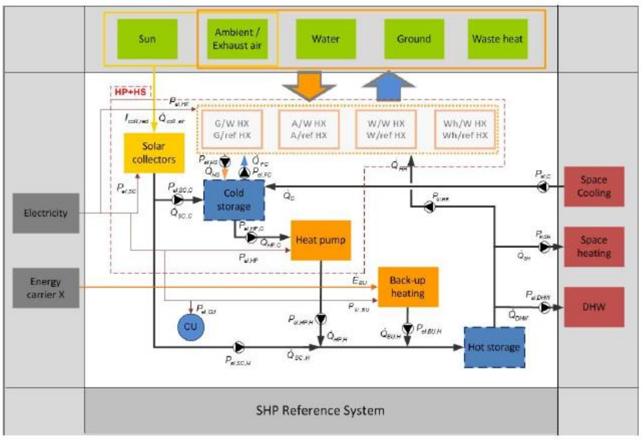
System Boundaries – HP + HS

SOLAR + HEAT PUMP



$$SPF_{H,HP+HS} = \frac{\int \dot{Q}_{HP,H}\cdot dt}{\int\left(P_{el,HP} + P_{el,HP,C} + P_{el,SC} + P_{el,SC,C} + P_{el,HS} + P_{el,HX} + P_{el,FC}\right)\cdot dt}$$

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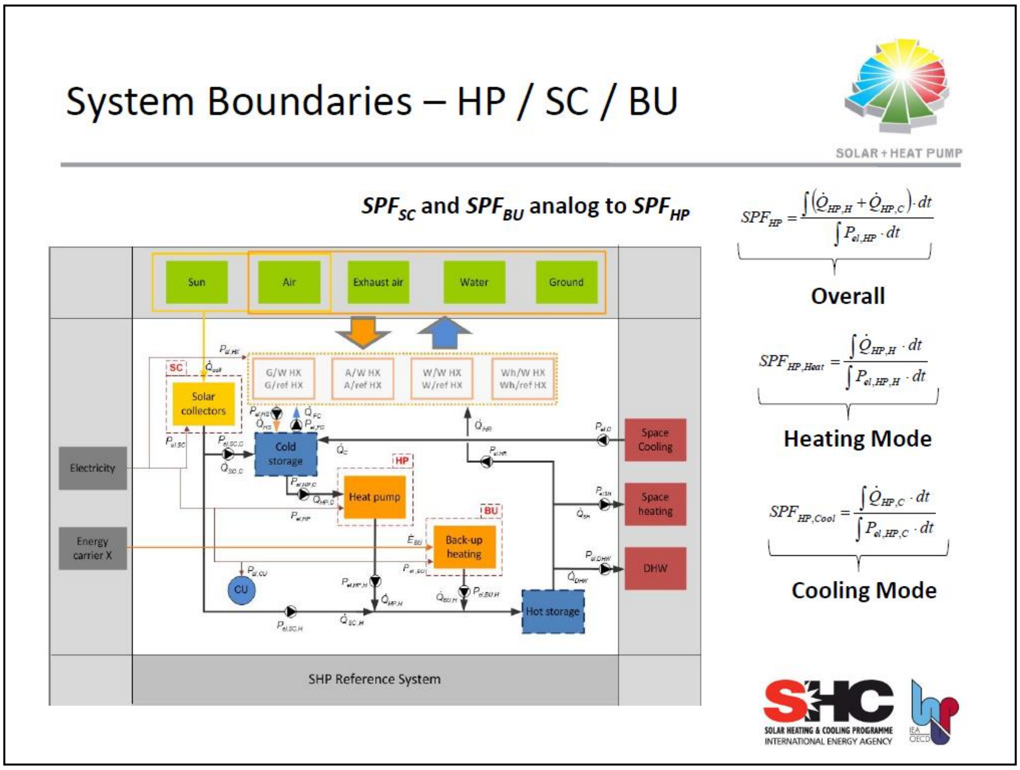
System Boundaries – HP / SC / BU
SOLAR + HEAT PUMP
SPF_SC and SPF_BU analog to SPF_HP
$SPF_{HP} = \frac{\int (\dot{Q}_{HP,H} + \dot{Q}_{HP,C}) \cdot dt}{\int P_{el,HP} \cdot dt}$
Overall
$SPF_{HP,Heat} = \frac{\int \dot{Q}_{HP,H} \cdot dt}{\int P_{el,HP,H} \cdot dt}$
Heating Mode
$SPF_{HP,Cool} = \frac{\int \dot{Q}_{HP,C} \cdot dt}{\int P_{el,HP,C} \cdot dt}$
Cooling Mode
Sun
Air
Exhaust air
Water
Ground
G/W HX
G/ref HX
A/W HX
A/ref HX
W/W HX
W/ref HX
Wh/W HX
Wh/ref HX
SC
Solar collectors
Cold storage
HP
Heat pump
BU
Back-up heating
CU
Hot storage
Electricity
Energy carrier X
Space Cooling
Space heating
DHW
SHP Reference System
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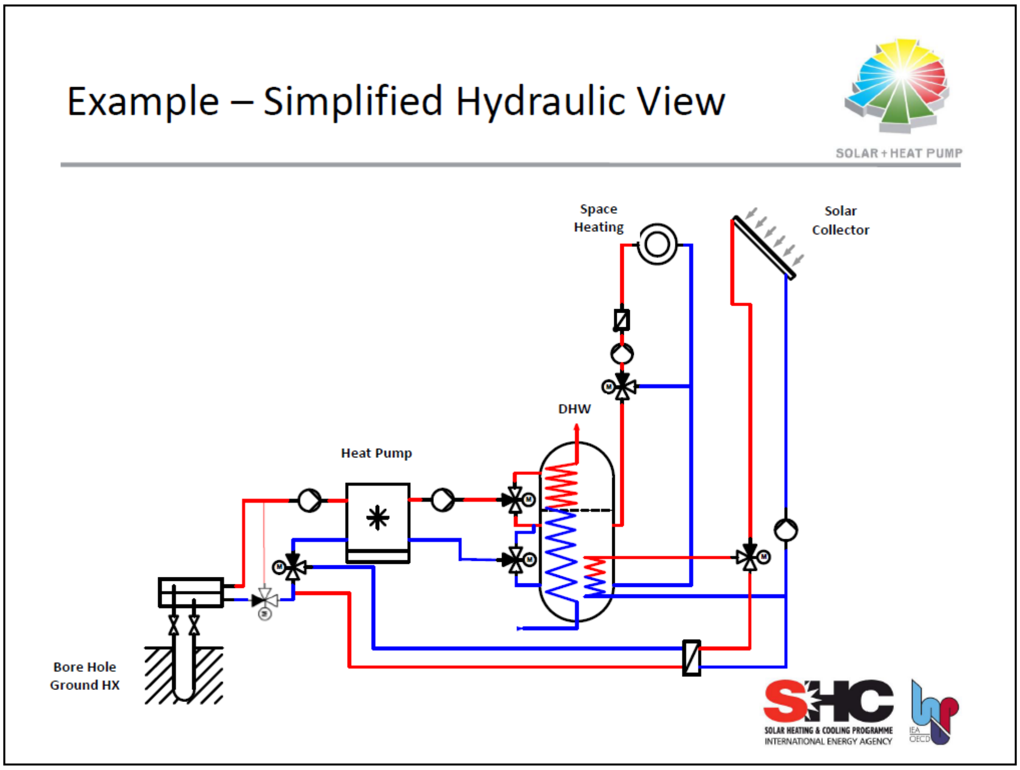
Example – Simplified Hydraulic View
SOLAR + HEAT PUMP
Space Heating
Solar Collector
DHW
Heat Pump
Bore Hole Ground HX
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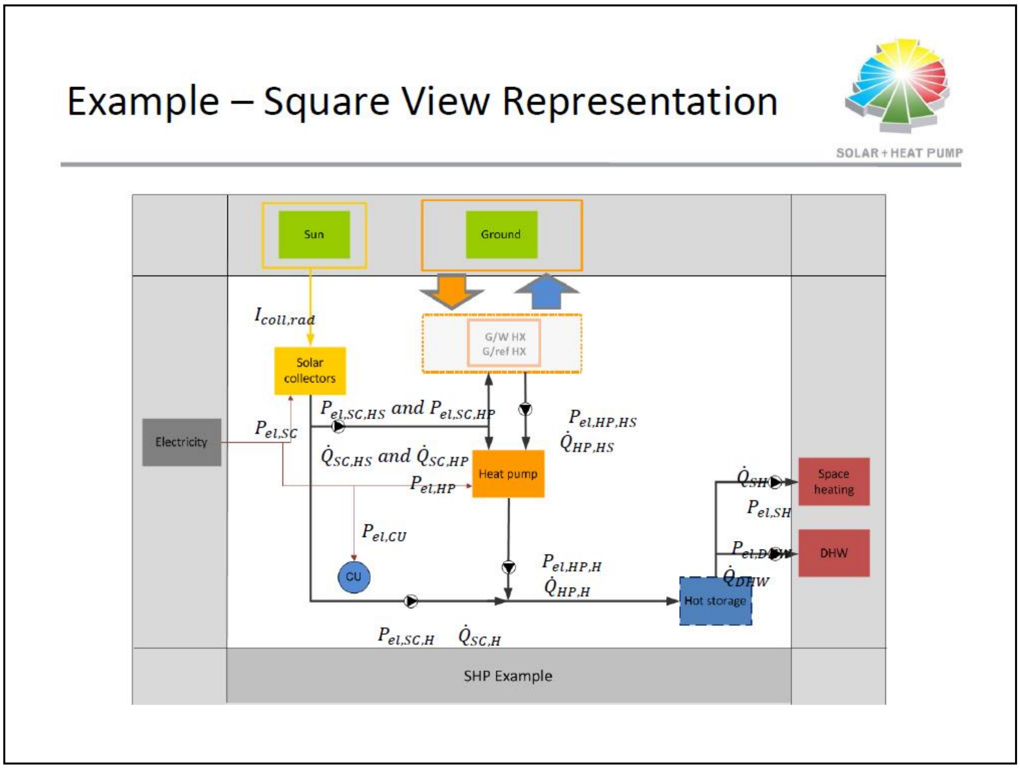
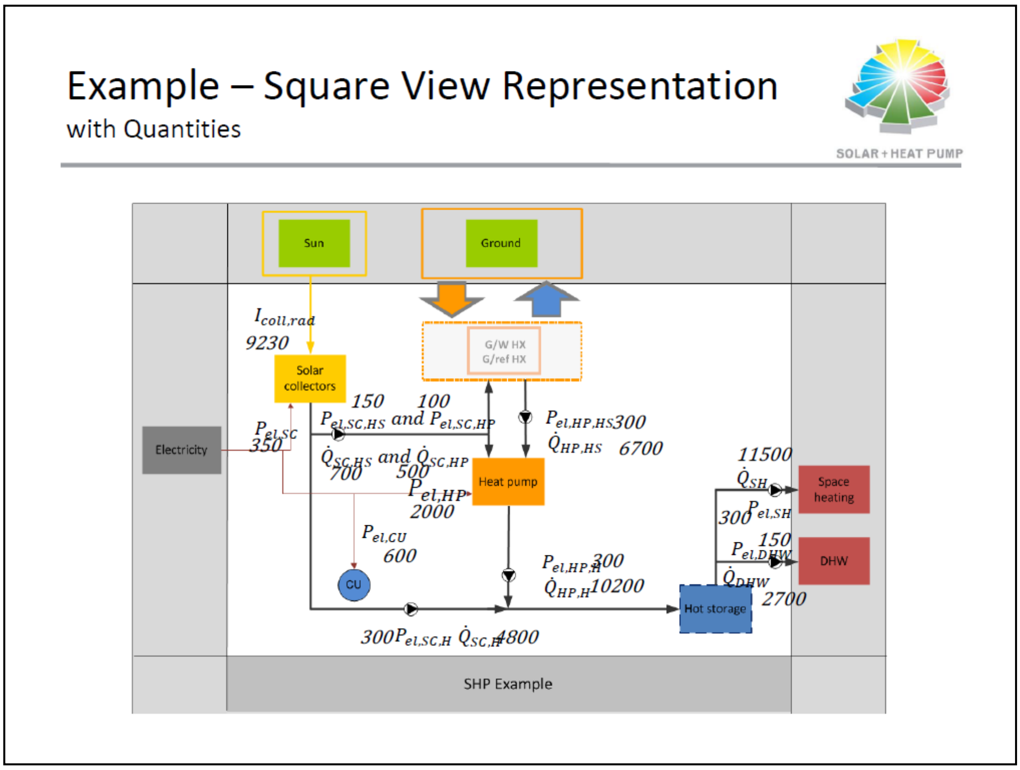

Example – Square View Representation
SOLAR + HEAT PUMP
Sun
Ground
G/W HX
G/ref HX
Solar collectors
Electricity
Heat pump
CU
Hot storage
Space heating
DHW
SHP Example
$I_{coll,rad}$
$P_{el,SC}$
$P_{el,SC,HS}$ and $P_{el,SC,HP}$
$\dot{Q}_{SC,HS}$ and $\dot{Q}_{SC,HP}$
$P_{el,HP}$
$P_{el,HP,HS}$
$\dot{Q}_{HP,HS}$
$P_{el,CU}$
$P_{el,HP,H}$
$\dot{Q}_{HP,H}$
$P_{el,SC,H}$ $\dot{Q}_{SC,H}$
$\dot{Q}_{SH}$
$P_{el,SH}$
$P_{el,DHW}$
$\dot{Q}_{DHW}$


Example – Square View Representation
with Quantities
SOLAR + HEAT PUMP
Sun
Ground
G/W HX
G/ref HX
Solar collectors
Electricity
Heat pump
CU
Hot storage
Space heating
DHW
SHP Example
$I_{coll,rad}$ 9230
$P_{el,SC}$ 350
150 100
$P_{el,SC,HS}$ and $P_{el,SC,HP}$
$\dot{Q}_{SC,HS}$ and $\dot{Q}_{SC,HP}$
700 500
$P_{el,HP}$ 2000
$P_{el,HP,HS}$ 300
$\dot{Q}_{HP,HS}$ 6700
$P_{el,CU}$ 600
$P_{el,HP,H}$ 300
$\dot{Q}_{HP,H}$ 10200
300 $P_{el,SC,H}$ $\dot{Q}_{SC,H}$ 4800
11500 $\dot{Q}_{SH}$
300 $P_{el,SH}$
150 $P_{el,DHW}$
$\dot{Q}_{DHW}$ 2700

Example – SPF according to the respective boundary

- SPF – SHP+

$$SPF_{SHP+} = \frac{\int \left(\dot{Q}_{SH} + \dot{Q}_{DHW}\right) \cdot dt}{\int \left(\sum P_{el,H,SHP+}\right) \cdot dt}$$

$$\sum P_{el,SHP+} = P_{el,SC} + P_{el,SC,HS} + P_{el,SC,HP} + P_{el,SC,H} + P_{el,HP} + P_{el,HP,HS} + P_{el,HP,H} + P_{el,SH} + P_{el,DHW} + P_{CU}$$

$$SPF_{SHP+} = \frac{11500 + 2700}{4550}$$

$$\int \left(\sum P_{el,H,SHP+}\right) \cdot dt = 350 + 150 + 100 + 300 + 2000 + 300 + 300 + 300 + 150 + 600$$

$$SPF_{SHP+} = 3.12$$

Example – SPF according to the respective boundary

- SPF – SHP

$$SPF_{SHP} = \frac{\int \left(\dot{Q}_{SH} + \dot{Q}_{DHW}\right) \cdot dt}{\int \left(\sum P_{el,H,SHP}\right) \cdot dt}$$

$$\sum P_{el,SHP} = P_{el,SC} + P_{el,SC,HS} + P_{el,SC,HP} + P_{el,SC,H} + P_{el,HP} + P_{el,HP,HS} + P_{el,HP,H} + P_{CU}$$

$$SPF_{SHP} = \frac{11500 + 2700}{4100}$$

$$\int \left(\sum P_{el,H,SHP}\right) \cdot dt = 350 + 150 + 100 + 300 + 2000 + 300 + 300 + 600$$

$$SPF_{SHP} = 3.46$$

Example – SPF according to the respective boundary

- SPF – bSt

$$SPF_{bSt} = \frac{\int \left(\dot{Q}_{SC,H} + \dot{Q}_{HP,H}\right) \cdot dt}{\int \left(\sum P_{el,H,bSt}\right) \cdot dt}$$

$$\sum P_{el,bSt} = P_{el,SC} + P_{el,SC,HS} + P_{el,SC,HP} + P_{el,HP} + P_{el,HP,HS} + P_{CU}$$

$$SPF_{bSt} = \frac{4800 + 10200}{3500}$$

$$\int \left(\sum P_{el,H,bSt}\right) \cdot dt = 350 + 150 + 100 + 2000 + 300 + 600$$

$$SPF_{bSt} = 4.29$$

Example – SPF according to the respective boundary

- SPF – HP+HS

$$SPF_{H,HP+HS} = \frac{\int \dot{Q}_{HP,H} \cdot dt}{\int \left(P_{el,HP} + P_{el,SC,HS} + P_{el,SC,HP} + P_{el,HP,HS}\right) \cdot dt}$$

$$SPF_{H,HP+HS} = \frac{10200}{2000 + 150 + 100 + 300}$$

$$SPF_{H,HP+HS} = 4$$

Example – SPF according to the respective boundary

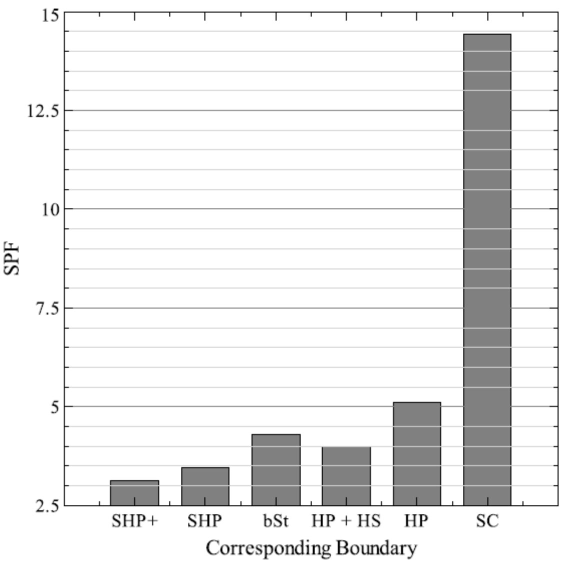
- SPF – HP and SC

$$SPF_{HP,H} = \frac{\int \dot{Q}_{HP,H} \cdot dt}{\int P_{el,HP,H} \cdot dt} \qquad SPF_{SC,H} = \frac{\int (\dot{Q}_{SC,H} + \dot{Q}_{SC,HS} + \dot{Q}_{SC,HP}) \cdot dt}{\int P_{el,SC} \cdot dt}$$

$$SPF_{HP,H} = \frac{10200}{2000} \qquad SPF_{SC,H} = \frac{4800+150+100}{350}$$

$$SPF_{HP,H} = 5.1 \qquad SPF_{SC,H} = 14.42$$

Example – comparison of different SPFs



Nomenclature

SOLAR + HEAT PUMP

CED	Cumulative Energy Demand	P	Power in W
$\dot{E}$	Energy flux in W	$\dot{Q}$	Thernal power in W
GWP	Global Warming Potential	PER	Primary Energy Ratio
$\dot{I}$	Solar irradiation in W	SPF	Seasonal Performance Factor
	Subscripts, capital		
BU	Back-up unit	HS	Heat source
C	Cooling, low temperature	HX	Heat exchanger
Cool	Cooling operation	NRE	Non-renewable
CU	Control unit	PE	Primary energy
DHW	Domestic hot water	SC	Solar collector(s)
FE	Final energy	SH	Space heating
H	High temperature	SHP	Solar and heat pump
Heat	Heating operation	SHP+	Solar and heat pump plus energy distribution system
HP	Heat pump	UE	Useful energy
HR	Heat rejection		
	Subscripts, small		
bSt	Before storage	el	Electrical
coll	Collector(s)	Rad	Radiative

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