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Economic and environmental analysis of central solar heating plants with seasonal storage for the residential sector

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Tesis Doctoral

ECONOMIC AND ENVIRONMENTAL ANALYSIS OF CENTRAL SOLAR HEATING PLANTS WITH SEASONAL STORAGE FOR THE RESIDENTIAL SECTOR

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Doctoral Thesis

Economic and Environmental Analysis of Central Solar Heating Plants with Seasonal Storage for the Residential Sector

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Abstract

Economic and Environmental Analysis of Central Solar Heating Plants with Seasonal Storage for the Residential Sector.

Buildings represent 40% of the Union's final energy consumption; the member states should establish a strategy to improve the energy performance in buildings and reduce the consumption of non-renewable primary energy. In Spain, the implementation of the Technical Building Code (CTE) compels to install solar thermal collectors in new buildings providing a minimum solar contribution of domestic hot water (DHW). In north and center European countries, e.g. Denmark, Germany and Austria, new installations also supply heat for the space heating needs. The approach of central solar heating plants with seasonal storage (CSHPSS) is the storage of solar thermal energy from the period of higher offer (summer) to be consumed in the periods of higher demand (winter). These installations are integrated into district heating systems that supply heat for a large number of dwellings and reach a solar fraction of 50% or higher. In this thesis the experience gained in Europe on centralized solar district heating systems with seasonal storage will be transferred to the Spanish situation, in order to establish the conditions and criteria for installing these systems in Spain in the midterm.

The main objective of this thesis is the proposal and design of CSHPSS that could be able to provide a high fraction of thermal energy demand with solar thermal energy for different climatic areas. These systems should be feasible from a technical viewpoint, economically acceptable, and with a low environmental impact. That is, this thesis unveils the requirements for the feasibility of CSHPSS and is intended to foster their development in Spain.

In order to reach this objective, it has been performed a revision of the state of the art of district heating systems, with emphasis to: i) solar district heating systems and CSHPSS; ii) design and calculation methods that could be used for new systems in Spain; iii) economic data and results from existing solar district heating systems and CSHPSS in Europe and worldwide; and iv) environmental assessment methodologies and analysis performed for solar thermal components and systems.

An original calculation method for the analysis, design and evaluation of these installations from technical, economic and environmental points of view has been developed. The variation of solar radiation along the day and the year and the monthly distribution of the residential sector demand are considered. The main advantage of the method developed, compared to other methods, is the simplification of the calculation process and the utilization of simple climatic and demand data. The method developed has also been used to perform parametric analyses that have served to obtain new design criteria for different locations.

The technical viability of these installations is not enough argument to motivate their development. The investment cost of these installations has therefore been analyzed according to the main design parameters (area of solar collectors and seasonal storage

volume) and validated with results from real projects in north European countries. Moreover, this thesis analyzes the environmental impact of these installations using the Life Cycle Assessment (LCA) methodology. This impact assessment not only considers the consumption of fuels and electricity for the production of energy but also the consumption of materials for the construction of the plant. Three different environmental assessment methods have been used to determine the impacts generated and avoided by a CSHPSS: i) emission of greenhouse gases and their contribution to the global warming; ii) consumption of primary energy; and iii) environmental indicator IMPACT 2002+, which encompasses a significant range of environmental burdens.

Based on the previous thermal, economic and environmental models and analyses developed, appropriate design criteria for CSHPSS in different geographical areas have been established. It has been concluded that design criteria are strongly dependent on the local climatic and demand conditions. Therefore, CSHPSS designs for north European countries cannot be applied in south Europe.

Furthermore, it has also been concluded that CSHPSS have a considerable potential in Spain; i.e. it is interesting to build CSHPSS in those regions of Spain with significant heating demand, because they can supply heat to large communities at a competitive cost with a low environmental impact.

Finally, from the calculation and analysis tools developed in the thesis, a software application with a friendly user interface has been developed to pre-design CSHPSS. The software is mainly oriented to European locations and provides the thermal performance, economic cost and environmental impact of the evaluated CSHPSS.

Resumen

Análisis Económico y Ambiental de Centrales Solares Térmicas con Acumulación Estacional para el Sector Residencial

Los edificios representan el 40% del consumo de energía final de la Unión Europea; los estados miembros deben establecer una estrategia para mejorar la eficiencia energética de los edificios y reducir el consumo de energía primaria no renovable. En España con la entrada en vigor del Código Técnico de la Edificación (CTE) se ha pretendido sustituir energía procedente de combustibles fósiles por energía solar y se obliga a la instalación de sistemas solares térmicos para proporcionar una contribución solar mínima anual a la demanda de agua caliente sanitaria (ACS). Sin embargo en los países del centro y norte de Europa como Dinamarca, Alemania y Austria, que destacan por su aprovechamiento de la energía solar, vemos que parte de sus nuevas instalaciones aportan energía solar térmica para cubrir también las necesidades de calefacción. El interés de las centrales solares térmicas con acumulación estacional consiste en el aprovechamiento del exceso de captación solar en el periodo de mayor oferta (verano) para su consumo en el periodo de mayor demanda (invierno). Estas instalaciones se integran en sistemas de calefacción de distrito que proveen energía térmica a un elevado número de viviendas alcanzando una fracción solar elevada (> 50%). En esta tesis se adapta al caso de España la experiencia obtenida en Europa acerca de los sistemas de calefacción solar de distrito con acumulación estacional y se esclarecen las condiciones y criterios que harían interesante su implantación a medio plazo en nuestro país.

El principal objetivo de esta tesis consiste en proponer y prediseñar sistemas de calefacción solar de distrito con acumulación estacional para distintas zonas climáticas y diferentes tamaños de distrito, que sean: i) técnicamente viables, ii) económicamente rentables, y iii) con bajo impacto ambiental. En otras palabras, esta tesis desvela y establece los requisitos para que los sistemas de calefacción solar de distrito con acumulación estacional sean una alternativa interesante, contribuyendo de este modo al desarrollo de estas instalaciones en España.

Para poder alcanzar este objetivo se ha llevado a cabo una revisión del estado del arte de los sistemas de calefacción de distrito, haciendo especial énfasis en: i) sistemas de calefacción solar de distrito con acumulación estacional; ii) métodos de cálculo y diseño que puedan ser empleados para la propuesta de sistemas de estas características en distintas zonas geográficas de España; iii) datos y resultados económicos de sistemas de calefacción solar de distrito con acumulación estacional actualmente existentes en Europa y en el mundo; y iv) datos y metodologías para su evaluación ambiental y análisis de ciclo de vida (ACV).

Se ha desarrollado un método de cálculo original para el análisis, diseño y evaluación de estas instalaciones desde un punto de vista técnico, económico y ambiental. El método desarrollado considera la variación de la radiación solar a lo largo del día y del año y la distribución mensual de la demanda térmica en el sector

residencial. La principal ventaja del método desarrollado frente a otros trabajos es la simplificación del proceso de cálculo y la utilización de datos climáticos y de demanda fáciles de encontrar. Con el método desarrollado se han realizado análisis paramétricos que han servido para definir nuevos criterios de diseño para distintas localizaciones.

La comprobación de la viabilidad técnica de estas instalaciones no supondría por si solo un argumento suficiente para impulsar su desarrollo, por tanto se analiza el coste de inversión en función de las principales variables de diseño de la instalación (área de captación solar y volumen del acumulador estacional). Más allá, esta tesis analiza el impacto ambiental de estas instalaciones utilizando la metodología del análisis de ciclo de vida. La evaluación ambiental realizada considera los efectos de los consumos de combustibles y electricidad para la producción de energía térmica, y además el consumo de materiales para la construcción de la planta. Se han utilizado tres métodos diferentes para determinar los impactos ambientales generados y los beneficios ambientales alcanzados: i) emisión de gases de efecto invernadero y su contribución al cambio climático; ii) consumo de energía primaria; y iii) cálculo del indicador ambiental IMPACT 2002+ que abarca una gran variedad de aspectos ambientales.

Gracias a los modelos desarrollados y a los análisis llevados a cabo considerando el comportamiento físico, económico y ambiental de los sistemas de calefacción solar de distrito con acumulación estacional, se han definido criterios de diseño adecuados para diferentes zonas geográficas. Una de las principales conclusiones alcanzadas es que el diseño correcto de estos sistemas depende fuertemente de las condiciones climáticas y de la demanda de las viviendas. Por tanto, los diseños aplicados en el norte de Europa no pueden ser trasladados al sur de Europa.

Asimismo se concluye que los sistemas de calefacción solar de distrito con acumulación estacional son viables técnica y económicamente en las zonas de España con elevado consumo de calefacción; es decir, estos sistemas cuentan en nuestro país con un potencial elevado para atender las necesidades de calefacción de grandes comunidades a un coste competitivo y además con bajo impacto ambiental.

Finalmente indicar que a partir de los modelos y herramientas de análisis elaborados se ha desarrollado una aplicación informática de fácil manejo para el pre-diseño de sistemas de calefacción solar de distrito con acumulación estacional, principalmente orientado a localidades europeas, que proporciona el comportamiento térmico del sistema y estima su coste económico e impacto ambiental.

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List of Acronyms

Acronym	*Description*
ADHAC	Spanish association of district heating and cooling
AEMET	*Asociación Española de Meteorología*
ASHRAE	American Society of Heating Refrigeration and Air Environment
ATES	Aquifer Thermal Energy Storage
BOE	Spanish Official State Gazette
BTES	Borehole Thermal Energy Storage
CBM	Bare Module Cost
CED	Cumulative Energy Demand
CHP	Combined Heat and Power
CPC	Compound Parabolic Collector
CRF	Capital Recovery Factor
CSHPSS	Central Solar Heating Plants with Seasonal Storage
CTE	Technical Code for Edification (Spanish Normative)
DALY	Disability Adjusted Life Year
DB-HE	Basic Document on Heating Efficiency of the CTE
DH	District Heating
DHC	District Heating and Cooling
DHW	Domestic Hot Water
DLSC	Drake Landing Solar Community
EC	European commission
EES	Engineering Equation Solver
EHI	European Heating Index
EHP	Euroheat & Power
EN	European Normative
EPS	Expandable Polystyrene
ESTIF	European Solar Thermal Industry Federation

Acronym	*Description*
ESTTP	European Solar Thermal Technology Platform
ETC	Evacuated tube solar collector
ETFE	Ethylene tetrafluoroethylene
EU	European Union
FBM	Bare Module Factor
FEP	Fluorinated ethylene propylene
FPC	Flat Plate Collector
GHG	Green house gases
GWP	Global Warming Potential
HDPE	High Density Polyestyrene
HE	Heat Exchanger
IDAE	*Instituto para la Diversificación y el Ahorro Energético Español*
IEA	International Energy Agency
IMP	IMPACT 2002+
IMPACT	IMPact Assessment of Chemical Toxics
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LPG	Liquefied Petroleum Gas
NZEB	Nearly Zero Energy Building
PDF	Potentially Disappeared Fraction
PTES	Pit Thermal Energy Storage
PUR	Polyurethane
PV	Photovoltaics
PVC	Polyvinyl Chloride
REE	Spanish Electric Grid

Acronym	*Description*
SAIC	Science Application International Corporation
SDH	Solar District Heating
SF	Solar Fraction
SH	Space Heating
SHC	Solar Heating and Cooling
TRNSYS	Transient System Simulation
TTES	Tank Thermal Energy Storage
UG	Unglazed solar collector
UNE	*Una Norma Española*
UNEP	United Nations Environment Program
UP	Unsaturated Polyester
WGTES	Water gravel thermal energy storage
XPS	Extruded Polystyrene

List of Nomenclature

Nomenclature	*Description*	*Units*
$(\alpha\tau)_{av}$	Average transmittance times absorptance	
A	Solar collector field area	m^2
A	First empirical factor for the utilizability correlation	
A_{acu}	Seasonal storage envelope surface	m^2
a_k	Coefficients of Erbs correlation for ambient temperature	
AEI	Annualized environmental impact	1/yr
B	Second empirical factor for the utilizability correlation	
b_k	Coefficients of Erbs correlation for ambient temperature	
c	Third empirical factor for the utilizability correlation	
c_{aux}	Auxiliary system heat cost	€/MWh
c_{ele}	Electricity cost	€/MWh
c_{fixed}	Fixed costs of natural gas	€/month
c_p	Specific heat capacity	J/(kg·K)
$c_{p,sf}$	Specific heat capacity of the solar field flow	J/(Kg·K)
$c_{p,w}$	Water specific heat capacity	J/(Kg·K)
c_{sol}	Solar heat cost	€/MWh
c_{sys}	System heat cost	€/MWh
$c_{variable}$	Variable costs of natural gas	€/MWh
$CED_{displaced}$	CED displaced by the system	MWh
CED_k	Cumulative energy demand of the component k	MWh
$CED_{operation}$	CED consumed in operation	MWh
$cf_{mic,k}$	Conversion factor of the component k to the middle impact category, mic	
CI_{DHW}	Domestic hot water consumption index	
D	Seasonal storage diameter	m
DD	Degree-days	K·day
DD_{15}	Degree-days in base 15ºC	K·day

Nomenclature	*Description*	*Units*
DD_{ave}	Average degree-days in Europe	K·day
DD_{DHW}	Degree-days of domestic hot water	K·day
DD_{SH}	Degree-days for space heating	K·day
df_{mic}	Damage factor of the middle impact category, mic	
DHW_{day}	Consumption of hot water per person per day	l/(p·day)
E	Energy produced by a system	MWh
E_P	Energy consumed by pumps	MWh
E_{P1}	Energy consumed by pump number 1	MWh
E_{P2}	Energy consumed by pump number 2	MWh
E_{P3}	Energy consumed by pump number 3	MWh
E_{PS}	Energy consumed by the solar field pump	MWh
EA	Energy accumulated in the seasonal storage	MWh
EA_{max}	Maximum energy that can be accumulated in the energy storage	MWh
EA_{max}	Maximum energy that can be accumulated in the seasonal storage	MWh
Ec_k	Unitary Environmental impact of the stream 'k'	
Eff	Heat exchanger effectiveness	%
EHI	European Heating index	
EI_{CED}	Environmental impact to the consumption of resources	MWh
EI_{dam}	Environmental impact for the damage category, dam	
EI_{GHG}	Environmental impact to the greenhouse effect	kg CO_{2-eq}
EI_{IMP}	Environmental impact according to IMPACT 2002+	Points
EI_{mic}	Environmental impact for the middle impact category, mic	
E_{pdh}	Electricity consumption for distribution	MWh/yr
E_{psf}	electricity consumption on the solar field	MWh/yr
f_{aux}	Auxiliary equipment investment factor	
f_{ind}	Indirect costs factor	
f_{ope}	Operation and maintenance costs	1/yr

Nomenclature	*Description*	*Units*
F_R	Heat removal factor	
G	Natural gas consumed	MWh
G_1	Natural gas consumed by boiler 1	MWh
G_2	Natural gas consumed by boiler 2	MWh
GWP_k	Global warming potential factor of the component k	$kgCO_{2\text{-}eq}$
H	Seasonal storage height	M
$\bar{H}$	Daily radiation on a horizontal surface	$MJ/(m^2 \cdot day)$
H_f	Operating hours of the pump	h/yr
$\bar{H}_t$	Daily radiation on a tilted surface	$MJ/(m^2 \cdot day)$
i	Interest rate	
I_0	Horizontal irradiance	W/m^2
I_{TC}	Minimum level of irradiance required by the solar collector	W/m^2
Inv	Investment required	€
Inv_{acu}	Investment required for a seasonal storage	€
Inv_{coll}	Investment required for a solar collector field	€
k_1	First heat loss coefficient	$W/(m^2 \cdot K)$
k_2	Second heat loss coefficient	$W/(m^2 \cdot K^2)$
$\bar{K}_t$	Clearness sky index	
K_{tot}	Building Heat loss coefficient	
Lat	Latitude	º
LCI_k	Inventory of the component k	Unit
M	Month, 1 = January, 12 = December	
m_s	Solar field flow rate	$kg/(h \cdot m^2)$
N	Number of days per month	days
n	length of time	yr
N_{dwe}	Number of buildings	
N_{heat}	Operating hours of the heating system	h
Na	Lifetime solar collector field	yr

Nomenclature	*Description*	*Units*
Nv	Lifetime seasonal storage	yr
Occ	Occupants per dwelling , persons per house	p/dwe
P1	Pump number 1 power	kW
P2	Pump number 2 power	kW
P3	Pump number 3 power	kW
Payback	Energy payback	yr
PEF	Primary Energy factor	MWh/MWh
Psol	Solar field pump power	kW
Q_{aux}	Auxiliary energy required	MWh
Q_b	Solar heat that can be used without seasonal storage	MWh
Q_c	Production of solar collector field	MWh
q_c	Production of thermal energy by the solar collector	Wh/m^2
q_{coll}	Solar collector performance	W
Q_d	Annual thermal energydemand	MWh
Q_{DHW}	Demand for Domestic Hot Water	MWh
Q_e	Thermal energy charged in the storage	MWh
Q_{gas}	Natural gas consumed	MWh
Q_l	Heat loss of the seasonal storage	MWh
q_r	Solar irradiance on the solar collector	W/m^2
$q_{r,op}$	Radiation received during operation period	Wh/m^2
Q_s	Discharged heat from the storage	MWh
$Q_{s,max}$	Maximum amount of energy that can be discharged	MWh
Q_{SH}	Space heating demand	MWh
Q_{sol}	Solar heat delivered to the demand	MWh
Q_{sx}	Maximum amount of heat that can be discharged	MWh
Q_x	Heat rejected from the solar field	MWh
Q_l	Annual thermal losses of the storage	MWh
$\bar{R}$	Ratio between daily tilted and horizontal radiation	

Nomenclature	*Description*	*Units*
$\bar{R}_n$	Ratio between tilted and horizontal irradiance at midday	
RAD	Ratio solar Collector Area per unit of Demand	m^2/(MWh/yr)
RHD	Ratio storage height divided by diameter	m/m
RVA	Ratio Storage volume per Area of solar collector	m^3/m^2
RVA_c	Critical Volume Area Ratio	m^3/m^2
S	Radiation absorbed	W/m^2
T	Monthly average storage temperature	ºC
Ta	Ambient temperature	ºC
Ta_{ave}	Average ambient temperature on a typical day	ºC
Ta_{max}	Maximum ambient temperature on a typical day	ºC
Ta_{min}	Minimum ambient temperature on a typical day	ºC
Ta_{op}	Ambient temperature during operation period	ºC
T_{acu}	Storage temperature at the end of the month	ºC
$T_{acu,Max}$	Maximum temperature reached in the Seasonal storage	ºC
T_c	Solar collector temperature	ºC
T_{CW}	Cold water supply temperature	ºC
T_{DHW}	Hot water supply temperature	ºC
T_{dwe}	Comfort temperature in buildings	ºC
T_{gr}	Ground temperature	ºC
T_{in}	Inlet temperature of the solar collector	ºC
T_{max}	Maximum storage temperature	ºC
T_{min}	Minimum storage temperature	ºC
t_{op}	Duration of operation period	h
T_{out}	Outlet temperature of the solar collector fluid	ºC
T_{ret}	Return temperature from the DH system	ºC
T_{sup}	Supply temperature of the DH system	ºC
U	Heat transfer coefficient	$W/(m^2 \cdot K)$
U_{acu}	Storage heat transfer coefficient	$W/(m^2 \cdot K)$

Nomenclature	*Description*	*Units*
U_L	Solar collector heat transfer coefficient	$W/(m^2 \cdot K)$
UA_{acu}	Seasonal storage heat loss coefficient	W/K
UA_{dwe}	Heat transfer coefficient to the dwelling from the heating system	W/K
V	Volume of the seasonal storage	m^3
V_c	Critical Volume	m^3
V_i	Nominal flow pump 'i'	m^3/h
VH_{P3}	Volume of water displaced by pump 3	m^3/yr
$\overline{X}_c$	Radiation factor for utilizability correlation	
Z	CSHPSS annual costs	€
Z_{acu}	Seasonal storage annual costs	€
Z_{coll}	Solar collector field annual costs	€
A	Seasonal storage cost reduction factor	
Aτ	Solar collector absorptance times transmittance	
B	Solar collector tilt	º
Γ	Solar collector orientation	º
ΔP_k	Pressure drop in component 'k'	kPa
ΔP_{Pi}	Pressure drop to overcome by pump 'i'	kPa
ΔT	Seasonal storage temperature amplitude	K
ζ_{dam}	Weighting factor for the damage category	
η_0	Optic efficiency	
η_{acu}	Efficiency of the seasonal storage	MWh
η_{BH}	Efficiency of the boiler	
η_{coll}	Efficiency of the solar collector field	MWh
η_p	Mechanical efficiency of pump	
η_{SH}	Efficiency of Space Heating system	
η_{sys}	Efficiency of the system	MWh
P	Density	Kg/m^3

Nomenclature	*Description*	*Units*
ρ_{sf}	Density of the solar field flow	Kg/m^3
ρ_g	Ground reflectance	
ρ_w	Water density	Kg/m^3
σ_{dam}	Normalization factor for the damage category	
Φ	Utilizability factor	

Chapter 1: Introduction

1. Introduction

1.1 Solar thermal energy for the residential sector

An increasing interest can be observed with regard to the consumption of non-renewable primary energy. Rising prices, international commitments for the reduction of CO_2 emissions and proximity to a horizon in which petrol, coal and natural gas will not be available, at current levels, trigger strategies for the present and for the future in order to swift towards a new energy model.

The European Union has committed to achieve important improvements by 2020: 1) energy efficiency, obtaining a reduction of 20% of the Union´s primary energy consumption, 2) increase production from renewable energy sources to 20% and 3) reduce the emission of GHG by 20% (Directive, 2009/28/EC). Furthermore, the energy efficiency directive (Directive, 2012/27/EU) establishes that it would be preferable to achieve these improvements by cumulative implementations promoting energy efficiency in different fields.

Buildings represent 40% of the Union´s final energy consumption; the member states should improve the energy performance in buildings and reduce the consumption of non-renewable primary energy. Directive 2010/31/EU set the framework for energy efficiency in buildings and nearly zero energy buildings (NZEB) which will require not only energy efficiency measures to reduce energy consumption but also the production of energy from renewable energy sources (e.g. solar thermal, PV).

To achieve these goals, it might be useful to analyze the consumption of energy in buildings. In Europe, more than 75% of the energy consumed in buildings is used to maintain the comfort temperature and to produce domestic hot water (ESTTP, 2009). To cover heating needs, natural gas, electricity, oil, biomass and other fuels are used in small boilers, electric heaters and heat pumps with low efficiency.

Small solar thermal systems can produce part of the domestic hot water (DHW) needs. Since 2006, in Spain the technical code for edification (CTE) requires for new buildings to produce a share of the domestic hot water needs with solar thermal energy. The update of the CTE (2013) allows producing this share with other renewable energy sources but solar thermal is still the most common solution. Nevertheless, this application only covers a small share of the total heating needs because the consumption of energy for the production of space heating is larger than the consumption for DHW.

Currently, less than 18% of the energy consumed for heating in the Spanish residential sector comes from renewable energy sources, while most of the heat is produced from electricity, natural gas, oil, LPG and other fuels (IDAE, 2011). These resources are consumed to produce thermal energy at low temperature while they could be used to produce electricity or thermal energy at high temperature making a better use of their thermodynamic potential.

District heating systems have been used in north and center European countries to cover the heating needs of the residential sector. District heating systems deliver heat from production centers to consumers using a network of pipes that transport hot water or steam. Several energy sources and many strategies in operation can be used to produce heat with low cost and low environmental impact.

The EU has planned to increase the application of district heating and highly efficient cogeneration plants which have a significant potential to save primary energy in the Union. The platform Euroheat & Power has elaborated a plan for Europe 2050 (Euroheat & Power, 2013a) in which by increasing energy efficiency in buildings and enlarging the application of district heating and cooling systems, European CO_2 emissions will be reduced at least by 80% at a low cost. District heating systems might become a key player in the future of the EU energy plan.

District heating systems have been reducing their supply temperature in order to use residual heat from industry and solar thermal energy while thermal losses in distribution are reduced (Lund et al., 2014). Most European systems deliver hot water at 90ºC or 70ºC but to maintain the comfort temperature in buildings, low temperature district heating systems, with supply temperature as low as 50ºC or even 35ºC, can be used as has been tested in some of the newest solar district heating systems.

Centralized solar thermal plants supply heat to district heating systems in Denmark, Sweden, Germany and Austria, producing thermal energy for a large number of customers. The production of thermal energy in these plants depends on the availability of the solar resource and the energy produced should be complemented by other energy sources to secure supply. To cover a considerable share of the space heating and domestic hot water needs with solar thermal energy is more difficult than to cover a small share due to the un-matching periods of demand and production, but nowadays it is a reality for Central Solar Heating Plants with Seasonal Storage (CSHPSS). CSHPSS harvest solar radiation producing thermal energy. The thermal energy produced is transferred to the district heating system or is accumulated in the seasonal storage for its later consumption. The seasonal storage is a large size thermal energy storage in which temperature rises and decreases along the year because of a seasonal charging and discharging process.

Remarkable examples of CSHPSS are operating in Denmark (Marstal and Braedstrup), Germany (Crailsheim) and Canada (Drake Landing Solar Community). Each system is unique and has been designed according to the specific characteristics of the location: demand for thermal energy, supply temperature, solar radiation and ambient temperature. CSHPSS have been tested in north European countries where district heating systems are available but they could be much more profitable in Spain and south European countries where solar radiation is higher. However, it is necessary to redesign these systems for the specific conditions of Spain and south European countries.

1.2 Energy analysis

Several technologies for energy production can be applied in district heating systems i.e. heat pump, biomass, cogeneration, waste incineration, residual heat from industry, heat and cold storage and electric heat to cover peaks of demand (Serra et al., 2009). Due to the variability of district heating demand, solar resource and electricity price to design an energy system with minimum cost becomes a complex optimization problem. Each design alternative or operating strategy can be simulated, calculating sequentially the performance of the system along the calculation period, typically a year, but to compare several technologies it is convenient to use simplified calculation methods to reduce the calculation effort.

Connolly et al. (2010) reviewed computational tools for the integration of renewable energy sources concluding that there is no energy tool that addresses all issues related to the integration of renewable sources in energy systems, the ideal computational tool is dependent on the objectives that must be fulfilled.

The performance of an energy system is affected by load profiles for household heating, cooling, electricity and hot water. Widén et al. (2009) worked on household load evaluation; the efforts that can be applied on thermal modelling are limited and are based on simulation tools or measured results from previous experiences. Some authors claim that design requires non-deterministic demand modelling methods that consider the demand uncertainties (Calleja, 2015). Other projects try to simplify the demand characterization as the European Heating Index (Werner, 2006). The simplification of the demand characterization not only reduces the calculation effort but also the accuracy of the calculation method.

Simulation models can be used to estimate the performance of any energy system. In this direction Persson et al. (2009) validated a dynamic model for wood pellet boilers and stoves, Niknia and Yaghoubi (2012) used TRNSYS to develop a combined solar thermal power plant, Kalogirou (2009) simulated solar heaters and many other authors simulated different alternatives. However, simulation models can only be used in advanced stages of the project when the energy system has already been predesigned.

For preliminary analysis and selection of alternatives simplified calculation methods are required. Lindenberger et al. (2000) proposed a method to design optimum solutions for district heating systems with seasonal storage, heat pumps and cogeneration. Lozano et al. (2010a) solved design and operation problems of trigeneration systems with thermal storage under legal constraints.

In this thesis a simplified calculation method for CSHPSS has been developed as no other method has been found in the literature that fulfills the current needs for preliminary analysis. The tool will be used to predesign CSHPSS for different locations according to specific climatic and demand conditions. The method will be used to design systems with minimum cost and minimum environmental impact.

1.3 Economic analysis

In order to produce solar thermal energy for district heating at low cost, large solar fields must be installed in locations where the land is cheap and the solar resource is abundant. But other factors, as the average district heating price or the interest rate, determine the economic viability of the project. In Denmark, achieving small solar fractions in district heating systems has become viable for most networks; loans at 3% annual interest rate for large solar fields and a price system in which using conventional fuels is highly taxed support an economically viable solar heat.

The Danish company Arcon-Sunmark (2015) has built 19 of the 25 largest solar plants in the World; its data has been used to estimate the cost of large solar fields in this thesis. While achieving a small solar fraction is economically viable, reaching a high solar fraction is required in order to accumulate the summer overproduction for its later consumption in winter. The accumulation of thermal energy from summer to winter greatly increases the initial investment required.

Storing thermal energy for a large number of consumers increases the efficiency of the storage and reduces the accumulation cost due to important economies of scale. New technologies of seasonal storage have been developed that further reduce the required investment. Pit thermal energy storage and borehole thermal energy storage are tested technologies that can store thermal energy at half the cost of conventional thermal energy storages. Solites (2014a) is the major expert in design and construction of seasonal thermal energy storages and the results from its projects have been used in this thesis to estimate the investment cost.

The economic viability of CSHPSS is controversial. Demonstration projects as Marstal (2014) or Drake Landing Solar Community (SAIC, 2012) proved that it is possible to reach a high solar fraction without increasing the cost of the heat produced using low cost seasonal storage technologies (SDH, 2012a). It might be necessary to check the results obtained with more demonstration projects looking for optimal operation strategies and even lower cost.

The economic result of solar district heating has already been determined and tested in cold climates. Nevertheless, in south European countries or in locations with better conditions for solar harvesting, this technology has not been evaluated yet. It is expected that locations with high radiation and high heating demands will improve the thermal performance of CSHPSS reducing the heat cost.

This assumption will be validated in this thesis with a CSHPSS designed for Spain and with economic evaluations based on the results from previous experiences. An economic model for CSHPSS based on the main design variables is required to perform this analysis and also will be useful to make preliminary analysis for new plants. The results obtained from this research enlighten this economic problem but it should be validated with further demonstration projects.

1.4 Environmental assessment

The growing awareness about the environmental impact of the products consumed has increased the number of methodologies to evaluate the impacts with the aim of reducing them. In this thesis the Life Cycle Assessment (LCA) methodology, described in the standard ISO 14040 (2006), has been applied. This tool assesses the environmental impacts of a process or product along its life from the extraction of the materials consumed to the disposal at the end of the life cycle.

The LCA has been applied in many research projects in recent years to analyze and compare the environmental impact of different energy efficiency measures. García (2010) proposed an application for buildings in the residential sector in Andalusia. Rivela (2012) proposed another application for the whole building sector in Spain. Other works consider a wider point of view; Jones (2011) evaluated the life cycle energy consumption and environmental burdens associated with energy efficiency measures and supply technologies for buildings. It is necessary to continue characterizing energy supply technologies and energy efficiency measures for the buildings with the LCA in order to compare alternatives, from an environmental point of view, using this comprehensive method.

In this thesis the LCA methodology is completely described, based on the four stages required in the standard ISO 14040. An important part of the LCA is to describe the inventories of the components and materials considered. Inventories for the main components of CSHPSS (large solar collectors and seasonal thermal energy storage) have been described in detail.

Environmental assessment can be performed with single parameter evaluation methodologies (e.g. emission of greenhouse gases quantified in equivalent kg of CO_2 emitted to the atmosphere, consumption of primary energy in MWh calculated with the cumulative energy demand method) or with general evaluation methods as the IMPACT 2002+ that consider several impact categories and indicators. In this thesis these three methodologies have been applied.

The results obtained from the LCA can be used to compare different design alternatives from an environmental point of view. The optimization of a design based on minimizing the environmental burdens of a system is comparable to the economic optimization analysis but in this thesis two objectives will be minimized: 1) environmental impact and 2) economic cost. Some authors have faced the multiobjective optimization problem converting the multiobjective problem into a series of single objective optimization problems (Carvalho, 2011; Rangaiah, 2009). The multiobjective optimization has never been applied in the design process of a CSHPSS. The results from this analysis determine in which situations a seasonal storage is justified from an economic and environmental point of view and in which conditions it does not reduce the economic cost and the environmental impact.

1.5 Objectives

The revision of the state of the art showed that CSHPSS have been exploited in north European countries and in locations with cold climates but not in south European climates where they might produce heat for the residential sector with low environmental impact and cost. The starting hypothesis for this thesis is “CSHPSS can produce thermal energy for the residential sector in Spain with low cost and low environmental impact”.

As a first step, it has been analyzed the current state of the art for large solar fields and seasonal thermal energy storages. It is analyzed the experience obtained in north and center European countries. Also, it has been studied the state of the art of calculation and design tools. This knowledge founds the development of the thesis.

To verify the hypothesis proposed it is necessary not only to evaluate the technical, economic and environmental viability, but also to have an appropriate evaluation tool for feasibility analysis, for any location, to foster the development of this technology. It is necessary to create an economic model to estimate the cost of CSHPSS according to the main design parameters and an environmental model for the assessment of the environmental burdens provoked by CSHPSS.

Therefore, considering the previous aspects presented, the objectives proposed in this thesis are:

1) To gather the knowledge achieved about CSHPSS and to analyze if these systems might be used in Spain and other south European countries.

2) To analyze how different climate conditions affect the plant design and to define new design criteria that could be applied at new locations.

3) To generate a debate about current calculation and design tools. Define which methods and models are required to make the development of this technology easier.

4) To develop a calculation method for CSHPSS and tools to transform simple climatic and demand data into input requirements for the calculation tool.

5) Determine the economic cost of these systems; create an economic model based on simple design parameters and compare with the results obtained in real plants.

6) Determine the environmental impact of this technology along its life cycle by performing a comprehensive environmental assessment applying the Life Cycle Assessment method.

7) To develop a software tool, easy to use, that would be able to evaluate CSHPSS from a technical, economic and environmental point of view for different locations in Europe.

The objectives in this thesis search to fulfill the hypothesis established, CSHPSS are suitable to supply heat for the residential sector for south as well as north European countries from a technical, economic and environmental point of view.

1.6 Structure

The document has eight chapters. The first chapter of the thesis (Chapter 1, this one) introduces the thematic and the framework as well as the objectives of the thesis and the structure of the document. The document's main body is divided in two parts. Part I: State of the art gathers the knowledge in which this thesis is founded; this part includes Chapter 2 and Chapter 3. Part II: Design and analysis presents the main results obtained along the thesis encompassing Chapters 4 to 7. The last chapter, Chapter 8, summarizes the conclusions of the thesis.

Chapter 2 is divided into 6 sections. Section 2.1 is used to present the energy consumed by the residential sector. Data sources available in the literature to estimate heating demands are also introduced. Section 2.2 presents information about district heating networks: general design literature, statistics about application and most common supply technologies. Information about large scale solar thermal plants is given in Section 2.3. In Section 2.4 large size solar collectors applied in large size solar fields are presented and experiences about seasonal storage are discussed in Section 2.5. Finally, in Section 2.6 remarkable examples of CSHPSS are presented.

Chapter 3 discusses design, modelling and characterization methods that can be used. First experimental characterization methods for solar collectors in Section 3.1 are presented. Then, the utilizability method that can be used to estimate the performance of solar thermal systems is described, Section 3.2. Simulation tools for solar thermal systems are presented in Section 3.3. Section 3.4 presents simplified calculation methods based on results from simulations or semi-empirical methods. Short-cut simulations also simplify the calculation process but are based on the physics of the equipment (Section 3.5). Section 3.6 presents economic and environmental analysis that will be used in this thesis: economic analysis, thermoeconomic analysis, environmental assessment and multiobjective optimization. The last section (Section 3.7) shows the conclusions obtained from the discussion of the design, modelling and characterization methods.

Chapter 4: Simple Method, presents an original calculation method developed in this research work to predesign and calculate the behavior of CSHPSS based on simple climatic, design and demand data and with low calculation effort (Section 4.1-4.5). The *Simple Method* has been compared, as design tool, in Section 4.6 and 4.7 with TRNSYS (dynamic simulation tool) and five simple calculation methods available in the literature.

Chapter 5: Economic Analysis, presents an economic model developed for CSHPSS based on the results obtained from experiences in north and center European countries. The economic model proposed (Section 5.1) is validated by stages and considers the main design parameters. This economic model is used in this chapter to obtain appropriate design criteria. Section 5.2 analyzes the economies of scale of a system that delivers heat for a community between 100 and 5000 dwellings. Section 5.3 shows a design criterion, named critical volume that can be applied to design CSHPSS based on the thermal performance along the year. Sections 5.4 and 5.5 consider different design criteria that can be applied and Section 5.6 explores the economic viability of these systems, determining the conditions required for their commercial development.

Chapter 6: Environmental Analysis, evaluates the environmental impact of CSHPSS using the LCA methodology, which is described in Section 6.1. For the very first time the environmental burdens of these systems along with their life cycle have been determined for a case study, Section 6.2. This Section includes detailed inventories for the plant components. Solar collector inventory and impacts are compared with other authors. The seasonal storage inventory and impact is analyzed for different designs. The environmental impact is calculated for three evaluation methodologies (emission of GHG, consumption of primary energy CED and points of IMPACT 2002+). The thermoeconomic theory has been merged with the environmental results obtained from this analysis and used to evaluate the environmental impact of the internal energy flows. Results from Section 6.2 have been used in Section 6.3 to make a simplified impact assessment for CSHPSS based on the LCA.

Chapter 7 joins the results obtained in the previous chapters to obtain further results. Section 7.1 uses the *Simple Method* (Chapter 4), the economic analysis (Chapter 5), and the simplified environmental assessment (Chapter 6) to design systems from an environmental and economic point of view, solving a multiobjective optimization problem. Section 7.2 extends the demand data required for the *Simple Method* to other locations by transforming common climatic data into demand data. Section 7.3 presents a software application that has been developed to design CSHPSS based on: the *Simple Method*, the economic analysis, the simplified impact assessment and the extended climatic and demand data. This software application has been used in Section 7.4 to study the effect of location on the design of CSHPSS.

The conclusions of the thesis are presented in Chapter 8 with the following sections: synthesis, contributions and perspectives. Section 8.1 synthesizes the research work developed, Section 8.2 summarizes the main contribution obtained and Section 8.3 explores the future perspectives.

Part I:

STATE OF THE ART

Part I: State of the art

Part I of the thesis gathers knowledge about Central Solar Heating Plants with Seasonal Storage (CSHPSS) i.e. it shows the state of the art. Chapter 2 describes installations, components and demands while Chapter 3 presents calculation and simulation models used by engineers to design and evaluate new installations.

CSHPSS is a technology in development, the number of operating plants and the knowledge of these systems is limited. Moreover, these systems have been developed only for north European climates and there is no presence of this technology in south European countries or warmer climates. These systems might produce an important share of the residential sector heating needs in locations with high demands of heating and large amounts of solar radiation along the year.

Climatic differences make it impossible to translate completely the results from previous experiences in high latitude locations to south European countries. Therefore it is necessary to learn from the projects developed in such locations and to analyze the differences between those cases and possible cases in Spain where the solar radiation and the heating demands are different.

Chapter 2 of the thesis analyzes the demand of thermal energy in the residential sector in Europe and presents some methods, available in the literature, to estimate the demands of hot water and space heating along the year and their distribution using climatic and demand data. This chapter also explains district heating systems used to deliver thermal energy. A district heating system is a network of insulated pipes located underground to distribute thermal energy to consumers in different buildings from one or several production centers as CSHPSS. Components and pieces of equipment in CSHPSS are presented in Sections 2.3-2.6 where large scale solar thermal plants, large size flat plate collectors, seasonal storage and CSHPSS are presented showing an overview of the existing systems and the most common practices.

The objective of this thesis is to perform economic and environmental analyses of CSHPSS for new locations. Chapter 3 presents characterization methods for solar thermal collectors, semi-empirical methods to determine the daily production of solar thermal systems, simulation methods for thermal systems and design methods for large scale solar thermal systems. In Chapter 3 the economic and environmental analyses that will be used to design systems with minimum cost and minimum environmental impact are presented.

Part I gathers all the information and knowledge that has been required to develop Part II of the thesis, therefore Part I studies the state of the art of CSHPSS and in Part II are designed and analyzed new systems.

Chapter 2:
Residential Sector, District heating and Solar Thermal Plants

2 Residential Sector, District Heating and Solar Thermal Plants

The energy needs of the residential sector are diverse and depend on many factors. They can be analyzed from the supply side, fuels and resources consumed and from the consumption side, utilities that consume the energy supplied.

According to statistical studies the electricity consumed in the Spanish residential sector is 216,000 TJ/yr (IDAE, 2011). The white-goods (refrigerator, washing machine…) consume 62% of the electrical energy, space heating and domestic hot water (DHW) consume 15%, 12% lighting systems, 9% kitchen and cooling equipment represent a small 2% in the statistical average.

In addition to the electricity demand, the residential sector consumes 398,000 TJ/yr of fuel (almost twice the consumption of electricity), shared as follows: 69% consumed for space heating, 25% DHW, 6.5% kitchen and 0.03% cooling. It can be concluded that even in south European countries most of the energy consumed in buildings is used to produce space heating and DHW.

District heating and cooling systems (DHC) are well known in most European countries and supply an important part of the energy demand in the buildings sector (residential, commercial and service buildings). District heating systems deliver hot water or steam from centralized production plants to buildings or houses using distribution pipes located underground. Thermal energy is transferred from the district heating system to the buildings heating systems and the district heating fluid returns to the production plant at a lower temperature to be heated again.

District heating systems were developed to use several energy sources with high efficiency and low cost in urban areas. In Iceland most of the houses are connected to district heating systems that deliver heat from geothermal sources at very low price, 11 €/MWh (Euroheat & Power, 2013b), but most European countries use other energy sources such as cogeneration or biomass for the production of heat with an average price between 50 €/MWh (Austria) and 100 €/MWh (Denmark). It is remarkable that statistically in Spain district heating and cooling systems represent a negligible amount of the heating needs (ADHAC, 2014).

Solar thermal energy has been used widely to cover the DHW demand of the residential sector (IEA, 2011). In Spain the normative on buildings (CTE, 2013) requires for new buildings, depending on the climatic location, a production with solar energy from 30% to 70% of the thermal needs for domestic hot water. This production represents a small fraction of the total thermal energy demand in buildings but it is a first step in the right direction to reduce the energy dependency. Considering also the coverage of other heating demands in buildings as space heating in winter or even cooling with absorption machines in summer, the real potential of the solar thermal energy source is very high, almost 75% of the energy consumed in buildings.

Centralized solar systems have already proved that they can produce thermal energy for district heating networks, integrating also seasonal storage and heat pumps to increase the share of renewable resources utilization. Large solar collectors have been developed to reduce the consumption of materials, maintenance problems and electricity consumption in operation. Different strategies have been tested to accumulate thermal energy from summer to winter to obtain high solar fraction with low cost. Available technologies are: water tank thermal energy storage, pit thermal energy storage, borehole thermal energy storage and aquifer thermal energy storage.

In this chapter are presented: residential sector energy demands, characteristics of district heating and cooling networks, large scale solar thermal plants, large size solar collectors, seasonal thermal energy storage technologies and examples of CSHPSS that are operating nowadays.

2.1 Residential sector

According to statistics of the International Energy Agency (IEA, 2013), the final energy consumption in Europe (EU-25 considered) is 1100 Mtoe and 24% of it is consumed by the residential sector. Moreover, the European Solar Thermal Technology Platform (ESTTP, 2009) estimated in 2008 that the energy consumption in buildings (including residential, commercial and service sectors) might represent a share of 35% from the final energy consumption in Europe. On average for Europe, 75% of the energy consumed in buildings is used for the production of space heating (SH) and domestic hot water (DHW). Therefore, the demand of low temperature thermal energy for SH and DHW in buildings represents about 26% of the final energy consumption in Europe.

The demand of thermal energy for buildings in Europe depends on two factors: climate and energy efficiency. Big differences can be observed between different locations in Europe. As a general rule, the consumption of energy is higher in countries with cold climates and lower in countries with warm or temperate climates but the consumption of energy depends also on energy efficiency and other factors: constructive characteristics, local normative, average size of the houses, occupation rate and habits of consumption.

Focusing on Spain the final energy consumption of the residential sector is 18% and buildings in the commercial and the public sector consume 12% of the final energy consumption (IEA, 2013), which does not represent significant differences compared to the European average.

According to statistical studies performed by the Spanish Institute for Diversification and Energy Efficiency (known as IDAE) the energy consumed by the residential sector in Spain is 600,000 TJ/yr, distributed as follows: 35% electricity, 25% natural gas, 17% petrol products (diesel oil 14%, and LPG 2.6%), 17% biomass, 0.9% solar thermal energy and other energy resources (coal and geothermal). For more details, see Table 2.1.

Table 2.1: Final energy consumption of the residential sector in Spain (IDAE, 2011)

Final energy consumption (TJ/yr)	Electricity	Natural gas	Petrol products	Biomass	Solar thermal	Others
- Space heating	15,907	70,977	101,363	99,135	432	760
- Domestic hot water	16,129	65,568	26,864	2097	5402	182
- Kitchen appliances	20,063	16,704	7730	1079		74
- Cooling	5042					107
- Lighting	25,366					
- White goods	133,470					
Total	215,977	153,249	135,957	102,311	5834	1123

Heating demand in buildings depends on climate and location. The document for the certification of energy efficiency in buildings determines the reference value of final heating demand in Spain. According to location and climate, reference value for new buildings varies from less than 20 kWh/(m^2·yr) to over 70 kWh/(m^2·yr) (IDAE, 2009).

Radiation levels also change significantly with location making more or less suitable solar thermal energy. Frago (2011) analyzed the wide number of climatic conditions in Spain considering these factors, see Fig.2.1.

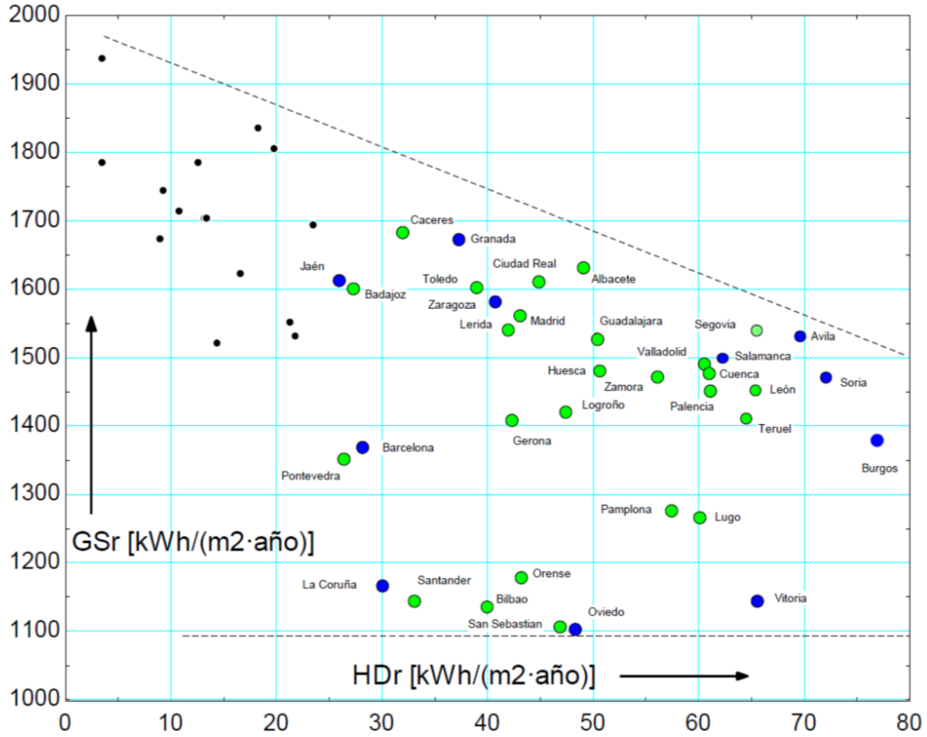

Figure 2.1: Final heating demand (HDr) vs solar radiation (GSr) in Spain (Frago, 2011)

The knowledge of heating and cooling demands in buildings with some detail is necessary in order to design heating and cooling devices. The knowledge of peak demands of thermal energy is required to size conventional heating equipment. To analyze the economic cost of the heating and cooling systems is necessary to estimate the consumption of fuel and/or electricity along the year.

In the case of systems with solar production and/or thermal energy storage it is also necessary to know the annual and even daily demand distribution to determine the accumulation requirements. To accurately design systems it is required to have detailed climatic and demand data.

The demand of thermal energy in existing buildings can be obtained using direct measures on the heating and cooling production devices or measuring periodically the fuel and electricity consumed. For refurbished or new buildings, the estimation of the heating demand can become a challenge and different methodologies can be applied.

2.1.1 Determination of space heating needs

Thermal simulation tools for buildings can be used to estimate the final heating and cooling demand of existing or planned buildings according to:

1) Local climate.
2) Building geometry.
3) Thermal properties of the building envelope (including the effect of windows).
4) Internal loads (electric equipment, people occupation and others).
5) Ventilation system.
6) Space heating and cooling system to supply thermal energy.

This method, while quite accurate, requires especial software and a deep knowledge of the calculation process. It also requires detailed information from the building and its environment and a considerable amount of time and effort to estimate the heating and cooling demand for a single building.

On the other hand, empirical methods can be used to estimate the demand with lower accuracy and lower calculation effort. This is the case of the degree-days method that estimates the space heating demand (Q_{SH}) knowing the annual or monthly degree-days (DD_{SH}) and the building overall heat loss coefficient (K_{tot}) (ASHRAE, 2009).

$$Q_{SH} = K_{tot} \cdot DD_{SH} / \eta_{SH} \qquad (1)$$

The software LIDER-CALENER (2014) is used in Spain for the certification of new buildings for energy consumption (IDAE, 2009). The reference demand of thermal energy depends on the location and type of building. For the Spanish certification normative, buildings from the residential sector are sorted in two big groups: single family houses and multifamily buildings.

Single family houses not only take up a bigger piece of land but also require more thermal energy per built area kWh/(m^2·yr) to maintain the comfort temperature. Compact cities in which people live in multifamily buildings consume less energy and land (Rogers, 1997) and are also more suitable for centralized and district heating systems. Most locations in south Europe (e.g. Spain, Portugal or Italy) have a very high share of multifamily buildings (VHK, 2007). These buildings might be connected to efficient and economic district heating systems due to their high density.

The annual demand of thermal energy for SH, DHW and cooling for new buildings (New build.) and existing buildings (Exist. Build.) for different locations are presented in Table 2.2. This information is not enough to design solar thermal systems; however, it is a necessary starting point for distributing the annual demand. The degree-days method and other methods can be used to distribute the SH demand.

Table 2.2: Final energy consumption for multifamily buildings in Spain (kWh/(m^2·yr)) (IDAE, 2009)

	Heating		Cooling		DHW
Location	New build.	Exist. build.	New build.	Exist. build.	All build.
Albacete	49.1	135.9	9.7	17.1	13.1
Alicante	13.2	49.2	16.7	29.4	12.3
Almería	10.8	36.5	19.1	33.7	12.1
Ávila	69.5	187.5	0.0	0.0	13.7
Badajoz	27.4	85.4	17.1	30.2	12.6
Barcelona	28.3	87.4	8.0	14.6	12.8
Bilbao	40.0	106.1	0.0	0.0	13.0
Burgos	77.1	193.6	0.0	0.0	13.8
Cáceres	32.1	92.5	19.0	33.5	12.7
Cádiz	9.0	33.7	14.6	25.7	12.3
Castellón	21.4	64.3	13.1	23.1	12.5
Ceuta	18.3	60.6	5.7	10.1	12.6
Ciudad Real	45.0	116.2	13.2	23.3	13.0
Córdoba	23.5	64.2	22.4	39.5	12.4
Cuenca	60.9	156.2	5.6	10.2	13.3
Gerona	42.4	110.2	6.4	11.7	13.0
Granada	37.4	106.6	12.5	22.0	12.9
Guadalajara	50.4	132.2	7.8	13.8	13.1
Huelva	12.6	43.0	18.3	32.2	12.3
Huesca	50.6	137.9	7.9	14.5	13.1
Jaén	26.2	83.5	22.3	39.4	12.3
La Coruña	30.0	93.1	0.0	0.0	13.0
Las Palmas de Gran Canaria	3.5	-	11.1	19.6	11.8
León	65.5	179.1	0.0	0.0	13.6
Lérida	42.0	117.9	12.4	21.9	13.0
Logroño	47.4	132.2	5.9	10.8	13.2
Lugo	60.2	154.8	0.0	0.0	13.5
Madrid	43.2	121.2	10.8	19.1	13.0
Málaga	13.4	41.4	16.1	28.4	12.3
Melilla	9.3	31.6	14.2	25.1	12.2
Murcia	19.8	59.8	12.5	22.0	12.5
Orense	43.2	105.4	5.7	10.5	13.0
Oviedo	48.3	122.8	0.0	0.0	13.3
Palencia	61.2	160.7	0.0	0.0	13.5
Palma de Mallorca	14.4	51.0	15.9	28.1	12.4
Pamplona	57.5	152.5	0.0	0.0	13.3
Pontevedra	26.5	86.1	0.0	0.0	12.9
Salamanca	62.3	161.0	2.7	4.9	13.5
San Sebastián	46.9	118.8	0.0	0.0	13.2
Santander	33.0	96.2	0.0	0.0	13.0
Santa Cruz de Tenerife	3.5	-	15.6	27.5	11.8
Segovia	65.7	162.0	4.2	7.6	13.5
Sevilla	16.6	52.9	23.4	41.2	12.3
Soria	72.1	187.1	0.0	0.0	13.7
Tarragona	21.8	62.8	16.4	28.9	12.4
Teruel	64.5	163.8	2.8	5.2	13.5
Toledo	39.0	106.2	18.9	33.4	12.8
Valencia	21.3	64.5	12.6	22.3	12.5
Valladolid	60.6	155.1	4.5	8.3	13.3
Vitoria	65.4	163.6	0.0	0.0	13.5
Zamora	56.3	148.4	5.3	9.7	13.3
Zaragoza	40.6	116.0	11.4	20.1	12.9

The heating demand of buildings also depends on the year of construction. Thus, district heating systems connected to old buildings have higher demands than systems connected to new neighborhoods or refurbished buildings with higher insulation levels.

New highly efficient buildings have much lower demand than average buildings. Communities with the standards of passive house (Passive House Institute, 2009) present annual space heating demands as low as 15 kWh/(m^2·yr) in locations where the average annual demand is 80 kWh/(m^2·yr) or even higher. This feature affects to the annual consumption of energy in buildings as well as its distribution.

2.1.2 Domestic hot water consumption

According to the certification for buildings in Spain the annual demand of domestic hot water can be estimated according to the location and size of the dwelling, but other factors as the occupancy must be considered to estimate it more accurately. This annual demand of DHW should be distributed for each month to analyze the solar fraction that can be covered each month with the solar production available.

The domestic hot water demand, Q_{DHW} (MWh), can be monthly calculated using the method proposed by the standard UNE 94002 (UNE, 2005). The DHW demand is estimated as a function of the number of occupants (Occ), the average consumption of hot water per person (DHW_{day}), number of days (N), hot water temperature (T_{DHW} = 60ºC) cold water temperature (T_{CW}), and water properties (density ρ (kg/m^3) and specific heat capacity c_p (J/(kg·K)).

$$Q_{DHW} = Occ \cdot DHW_{day} \cdot N \cdot (T_{DHW} - T_{CW}) \cdot \rho \cdot c_p / (3.6 \cdot 10^9) \quad (2)$$

The production of DHW with solar energy is one of the most profitable applications for solar energy today (IEA, 2011). It represents the bulk of the market of solar heating and cooling. In Spain, new and refurbished buildings must produce between 30% to 70% of the DHW needs with solar thermal energy according to the Basic Document of Energy Efficiency (known as DB-HE) included in the Spanish Technical Code of Edification (CTE, 2013).

Solar thermal is a profitable energy source for DHW applications in the residential sector. This technology produces four times more final energy than all solar electric technologies combined (IEA, 2011). Nevertheless, the Spanish market for solar thermal energy has been contracting since 2008 because the new building sector is frozen. While in 2008 there were installed 440,000 m^2/yr in 2013 a significant smaller area (225,000 m^2/yr) was installed (ESTIF, 2013).

2.2 District heating

District heating and cooling (DHC) systems connect production plants and disperse consumers using steam, hot water or cold water through networks of pipes. District heating systems are scalable and can connect small communities of 30 to 40 houses up to big cities as the district heating network of Manhattan in New York that has been operating for over 180 years.

District heating and cooling systems are very standardized worldwide and specific bibliography can be found. The publication *District Heating and Cooling* (Frederiksen and Werner, 2013) is a detailed academic guide about district heating and cooling, analyzing global market, production centers, distribution systems and methods to determine their operation and performance.

ASHRAE (American Society for Heating Refrigeration and Air-conditioning Engineers) has specific bibliography for district heating systems, *District Heating Guide* (ASHRAE, 2013a), and district cooling systems, *District Cooling Guide* (ASHRAE, 2013b).

Danfoss as one of the major producers of district heating components has elaborated manuals for recommended solutions in: substations, piping and controlling systems: *District Heating application handbook* (Danfoss, 2014a) and *The heating book - 8 steps to control heating systems* (Danfoss, 2014b).

In Spain DHC networks are registered by ADHAC (2014). In the year 2015 there were 202 systems supplying a maximum power of 1109 MW (792 MW for heat and 317 MW for cooling). Most of these networks (124 networks) are small size networks that connect commercial and service sector buildings, 47 networks connect residential buildings, 18 networks connect residential and other sector buildings and 13 networks supply energy to industry with or without third sector buildings.

Figure 2.2: Preinsulated district heating pipes installed underground (Danfoss, 2015)

The geographical expansion of DHC networks is quite irregular in Spain, it is focused in the most industrialized areas, Madrid, Cataluña, Navarra and Basque Country, as shown in Fig. 2.3 (ADHAC, 2014).

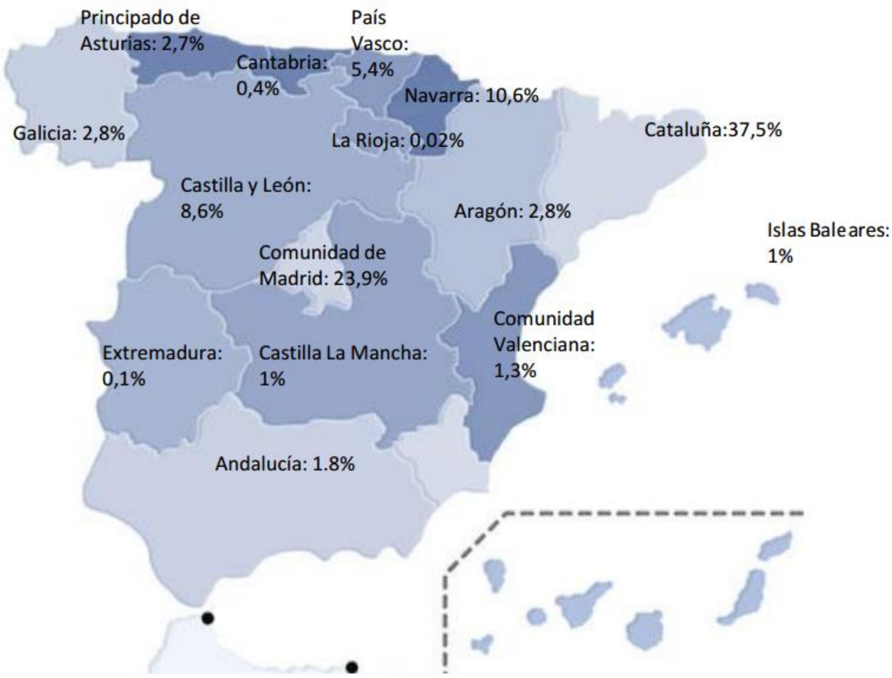

Figure 2.3: Geographic distribution of DHC networks in Spain, rated by installed power (ADHAC, 2014)

From the listed networks it is remarkable that most of the networks are fed by renewable energy sources (biomass) but natural gas and electricity represent a big share. There is a potential for renewable energy in existing DHC systems but also a big potential to increase the size and the number of networks.

According to a report elaborated by Aiguasol for the IDAE (2015a) Barcelona DHC networks have a big potential for renewable energy and especially solar thermal energy. For the district heating network of *Ecoenergies* has been proposed to install 1500 m^2 of linear Fresnel collectors, or 5000 m^2 of flat plate collectors and a seasonal storage of 8000 m^3. For the district heating network of *Districlima* solar thermal energy will be viable in a few years if the heating demand continues rising.

The heat used in district heating systems typically comes from very low cost thermal energy sources such as cogeneration, waste incineration or geothermal energy (Euroheat & Power, 2013b). Austria, Czech Republic, Denmark, Estonia, Finland Latvia, Lithuania, Poland, Slovakia and Sweden have a share of served citizens greater than 20% with an average district heating price between 40 €/MWh and 100 €/MWh.

For the biggest countries in Europe and those with a higher production of solar thermal energy, district heating statistics are presented in Table 2.3 (Euroheat & Power, 2013b) and compared with the data available in Spain about district heating systems (ADHAC, 2015). Two main conclusions can be obtained from this comparison: 1) the number of citizens connected to district heating is especially low in Spain and 2) Spanish systems use less direct renewables or recycled heat than the European average.

Table 2.3: Situation of district heating in Europe (Euroheat & Power, 2013b; ADHAC, 2015; VHK, 2007)

	DE	FR	UK	IT	ES‡	SE	AT	DK
Population (2005) 10^6p*	82.8	60.9	59.8	57.3	41.3	8.9	8.1	5.4
Ratio of dwellings in multifamily buildings*	54%	43%	19%	75%	48%	52%	52%	39%
Percentage of citizens served by district heating†	12%	7.4%	1%	5%	<1%	48%	21%	61%
Average district heating price (€/MWh) †	73	66	---	---	---	74	50	100
Energy supply composition†								
- Recycled heat	90%	47%	---	68%	---	70%	64%	70%
- Direct renewables	0.1%	11%	---	7%	30%	23%	23%	19%
- Others	9.7%	42%	---	24%	70%	7%	13%	11%

* Population and its distribution obtained from VHK (2007).
† DHC data obtained from Euroheat & Power (2013b), except Spain.
‡ Data from Spanish DHC networks extracted from ADHAC (2015).

The objective of district heating systems is to offer low cost thermal energy with low environmental impact. To achieve this double objective most systems incorporate different energy sources, technologies and modes of operation. Energy integration strategies and energy efficiency measures can be applied from both the demand side and the production side decreasing the cost and the environmental impact.

From the demand side, characteristics of the supply temperature can be adjusted according to the heating needs or the outside temperature reducing the district heating supply temperature which increases the efficiency of the energy system and reduces thermal losses in transport (Lund, 2014). From the first generation of district heating systems, based on steam there is a general tendency in reducing the supply temperature and increasing the efficiency in transport. Currently most systems in Europe operate between 90ºC and 70ºC (supply/return temperature). But the supply temperature is not constant along the year and reaches the maximum value only when the outside temperature is very low and therefore the maximum power is required. In Denmark some of the new systems use lower supply temperature (70ºC-50ºC) in the path to 4th generation district heating (see Fig. 2.4). Supply temperature can be reduced drastically if heating systems for buildings are prepared like in Drake Landing Solar Community where the district heating system supplies heat at a temperature lower than 40°C in a system almost 100% solar (Sibbitt et al., 2012).

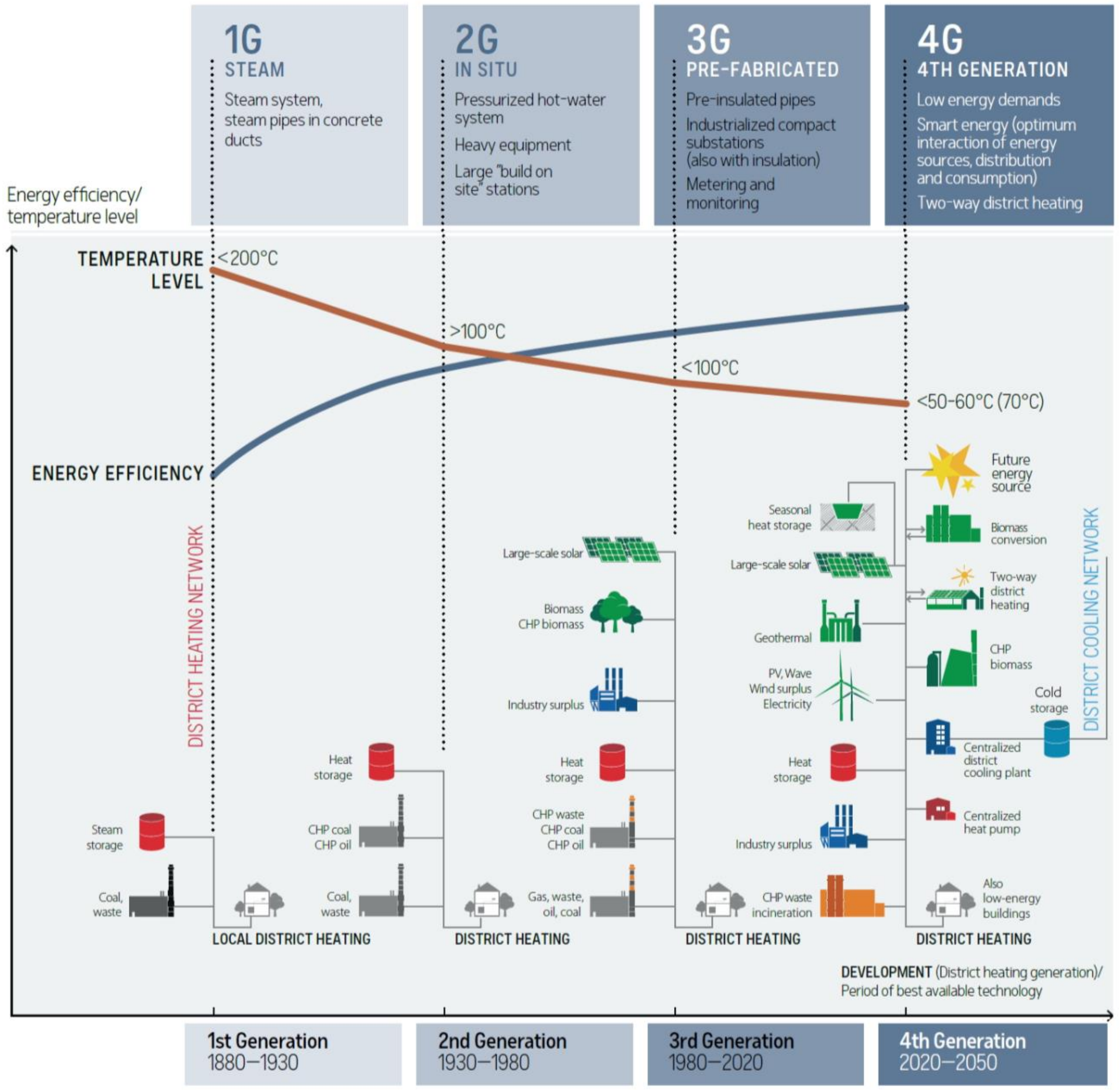

Figure 2.4: Historical development of DHC networks (UNEP, 2015)

From the production side, different energy sources can be used in combination to produce thermal energy with low cost and low environmental impact. See in Fig. 2.5 the conceptual illustration of a DHC system with several energy sources (cogeneration, biomass, waste incineration, heat from industry, heat pumps and geothermal, solar thermal and thermal energy storage) supplying heating and cooling to a network that connects industries, residential areas and other buildings in the city.

DHC systems enable to use renewable energy sources as biomass or solar heating in cooperation with other residual energy sources assisted by conventional fuels if required. The distribution system allows reaching a large number of consumers with highly efficient production plants. These systems use economic and environmental friendly energy sources as, cogeneration, biomass, residual heat from industry and solar heat. The district heating system is a local market of thermal energy that connects consumers and producers using a network of pipes.

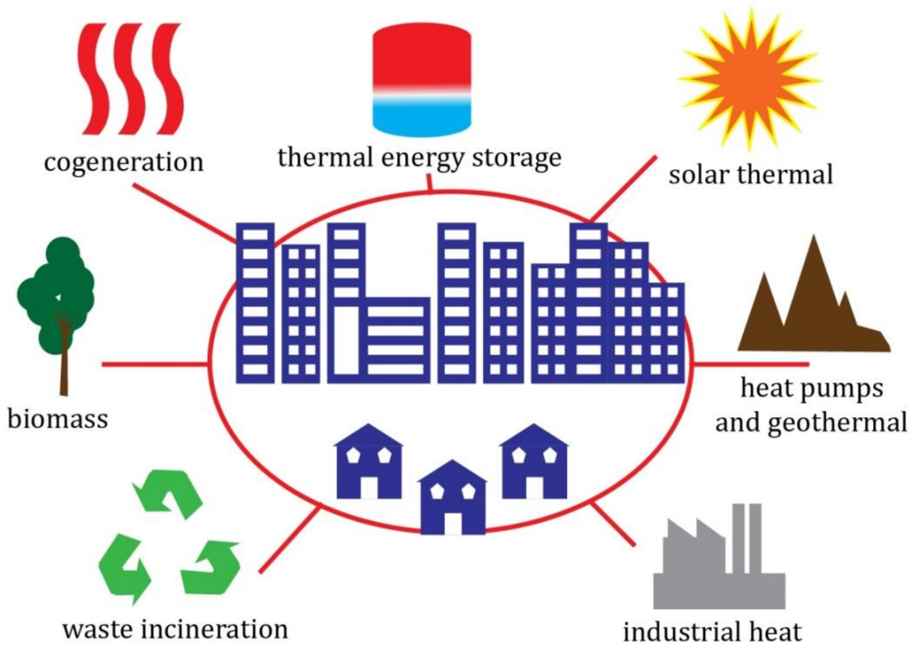

Figure 2.5: District heating system (based on illustration from IEA, 2009)

2.2.1 Cogeneration

Cogeneration (also known as CHP, combined heat and power) has been the base for the whole idea of district heating systems (Frederiksen and Werner, 2013). In the production of electricity from fossil fuels or biofuels using a water-steam cycle or a gas turbine cycle a large amount of heat is produced that should be discharged to the ambient or that can be used for district heating. This heat can also be used to produce cooling using absorption machines. The production of several services, e.g. heating, cooling and power, is known as polygeneration and can be more efficient than producing the different services separately (Serra et al., 2009; Lozano et al., 2010a; Ramos, 2012).

2.2.2 Biomass

Heat generation plants in district heating systems (heat-only boilers and CHP plants) can handle a wide variety of fuels, e.g. oil, coal, natural gas, bark, peat, plastics, waste or biomass. District heating systems have diversified their energy sources since the two international oil embargoes in 1973/74 and 1978/79 to make supply less dependent on imports. In the period from 1980 to 1990 Sweden reduced from a 90% oil dependent district heating system to only 10% by increasing the consumption of biomass and waste incineration. In the last two decades, due to the increased awareness on climate change, the use of biomass and alternative sources has increased again (Frederiksen and Werner, 2013). Biomass is the renewable energy resource in Spain with the highest share in the residential sector (IDAE, 2011). In individual boilers only certain types of biomass fuels as pellets can be used but in centralized boilers for district heating any biomass resource can be valorized for the production of thermal energy for district heating (Vallios et al., 2009).

2.2.3 Waste incineration

Incineration of waste reduces the volume of waste significantly. The residual non-combustible waste can be disposed more easily with less problems from an environmental point of view. The heat generated in the incineration can be recovered for useful purposes. Large incineration plants can release the heat generated to a district heating system or it can be used to generate electricity in a thermal power plant. A third option would be to produce heat and power in a cogeneration plant.

2.2.4 Heat from industry

Industrial plants can capture the heat produced in the plant to be reused in the process reducing the energy consumption. Some heat might be used by the plant but a surplus might be suitable for selling to the district heating company as a byproduct of the industrial process to increase the value of the industry and even reduce cooling needs (Frederiksen and Werner, 2013).

2.2.5 Heat pump

Heat pumps can be used to produce thermal energy using different energy sources or sinks e.g. geothermal, air, ground, rivers or lakes. Several authors have proposed different strategies in which heat pumps can be used in district heating systems, many of the systems proposed combine heat pumps with thermal energy storage and solar thermal collectors (Henning and Miara, 2010; Frank et al., 2010; Lozano et al., 2013; Task 44, 2013). There are several available options for the integration of heat pumps with solar thermal systems:

1) Heat pump between solar plant output and district heating system in order to increase the temperature to the required value.
2) Heat pump working in parallel to the solar collector field, charging the thermal energy storage at high temperature (Lerch et al., 2014; Carbonell et al., 2014).
3) Return water with low temperature from the district heating system can be raised taking advantage of the low temperature to have a higher electrical performance.
4) Heat pump working in series with the solar collector field rising the output temperature from low temperature solar collectors as unglazed collectors (Fraga et al., 2015; Carbonell et al., 2014).
5) In parallel with the solar collector field a heat pump can cover peak periods using a thermal reservoir (geothermal, lake, river or air) to produce thermal energy (Lerch et al., 2014, Carbonell et al., 2014).

Thermal energy storages can accumulate the thermal energy produced by solar collectors or a heat pump to cover the heating needs. The thermal energy storage enables optimizing the operation of a system with heat pump in which the electricity price is variable.

2.2.6 Solar district heating

Thermal energy can be produced from solar radiation in a wide range of temperature from low temperature as 50°C to high temperature as 450°C, see Fig. 2.6.

Uncovered solar collectors, also known as unglazed collectors, can produce thermal energy at low temperature with low cost. This type of solar collectors has been used for low temperature applications such as swimming pool heating or in series with a heat pump (Qi et al., 2008) in solar-electrical feed systems for space heating and domestic hot water (Fraga et al., 2015).

Flat plate collectors and evacuated tube collectors are the most common solutions for solar thermal systems obtaining a maximum temperature of 120°C. Many applications can be found in literature for flat plate and evacuated tube collectors in district heating; see Section 2.3 and Section 2.4. These types of solar collectors are also very popular in industry: IEA-SHC Task 33, *Solar Heat for Industrial Processes* (Task 33, 2014), and IEA-SCH Task 49, *Solar Process Heat for Production and Advanced Applications* (Task 49, 2014a).

Large parabolic trough and Fresnel collectors can be used for higher temperature production, over than 250°C. The thermal energy produced can be used in Organic Rankine Cycles producing electricity and obtaining important fuel savings (Niknia and Yaghoubi, 2012). Residual heat from such process can be used for district heating applications.

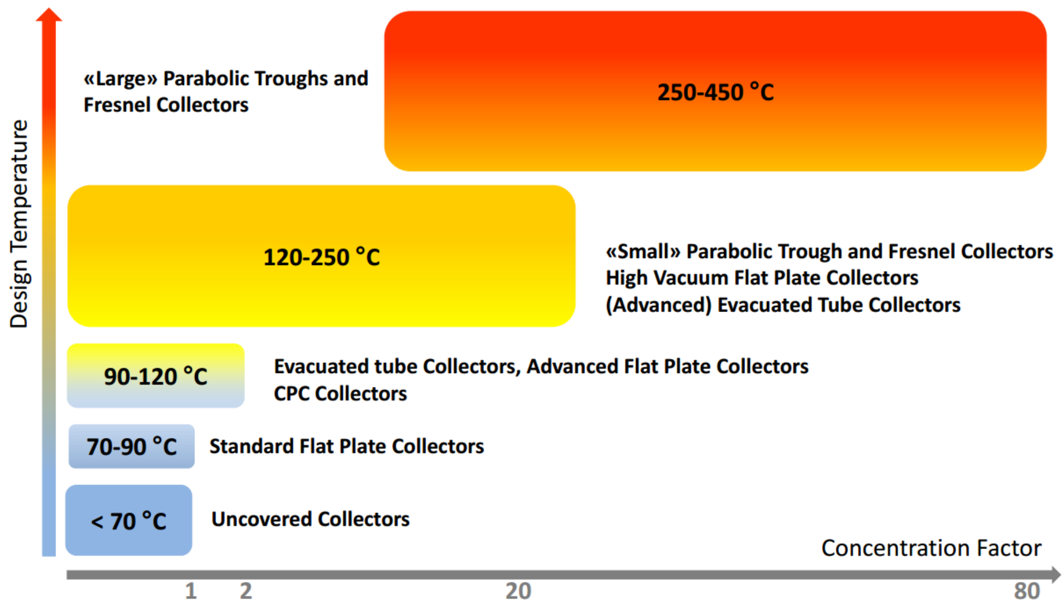

Figure 2.6: Solar collectors and operating temperature (Frank, 2012)

2.2.7 Heat and cold storage

Large scale thermal energy storage for district heating networks can be divided into seasonal storage and short term storage. Seasonal storage is very appropriate for solar thermal systems but is still in development phase; further details are presented in Section 2.5.

Short term storage can be used to shift loads away from hours of peak demand to hours of lower demand. A second application for short term storage is to provide rapid heat or cold supply to meet sudden load changes that generating equipment cannot fulfill and to avoid losses associated with quick starts and stops (Frederiksen and Werner, 2013).

2.2.8 Electric boilers

Electric boilers for district heating systems can be used in countries where electricity is occasionally available at low price. The excess of power on the electric grid can be used in large electric boilers for direct consumption or accumulation supporting the expansion of wind power and other renewable energy sources. Usually district heating loads are met by at least two energy sources to avoid the risk of non-supply. Electric boilers can be used as support systems and to cover demand peaks to avoid oversizing in CHP plants and boilers.

2.3 Large scale solar thermal plants

Solar thermal plants can produce thermal energy for district heating systems and other applications. Solar thermal plants with an area of solar collectors larger than 500 m^2 are considered large scale solar thermal plants by IEA-SHC Task 45. These installations can produce heat or hot water for the following applications: domestic hot water, swimming pools, space heating, heat for industry and can be even used to produce cooling with absorption machines for industry or buildings (Nielsen, 2014).

The performance of these plants is more efficient than solar domestic applications due to economies of scale and better strategies of operation and maintenance. On the other hand, to install these systems a wide place having many hours of solar radiation and a low cost is required, e.g. cheap land, tilts on roads, noise protection walls or building roofs. See examples in Fig. 2.7 from Crailsheim (Germany) and Braedstrup (Denmark).

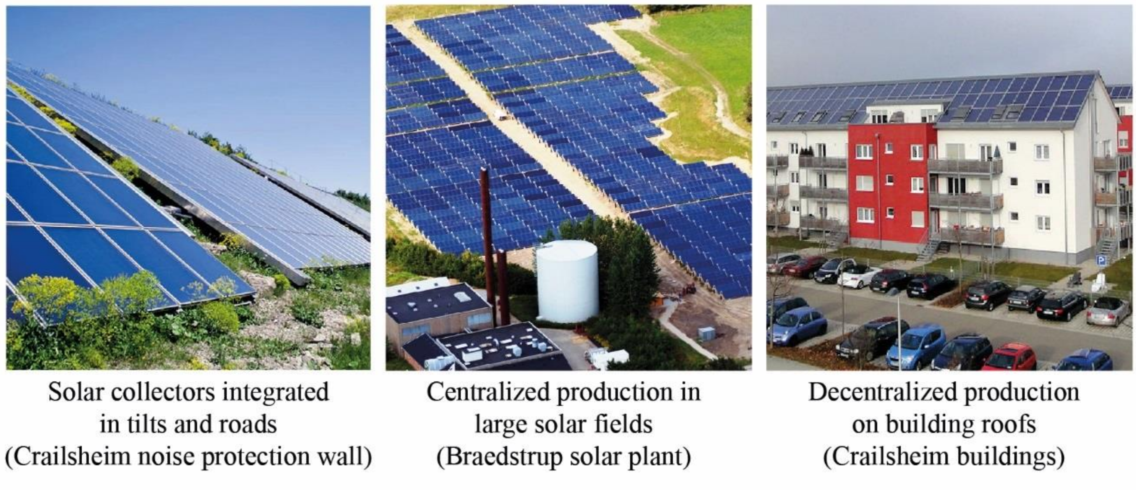

Figure 2.7: Installation place for large scale solar thermal plants (pictures from Solites, 2014a)

Low temperature applications increase the efficiency of solar collectors. Low temperature DH systems, known as 4th generation DH systems, are being developed to make a better use of the solar resource and other low temperature energy sources as well as to increase the efficiency of the DH system (Lund, 2014). Advantages of 4th generation DH are illustrated in Fig. 2.4 (UNEP, 2015).

Production of solar thermal plants depends on the solar radiation. In summer, periods of high radiation and low demand for district heating applications might produce overheating in the solar field and damage to the hydraulic equipment. To avoid overheating periods, it is necessary to correctly size the thermal energy storage and to choose appropriate control strategies to prevent damage.

The consumption of electricity during operation is important in large scale solar thermal plants. The design of the hydraulic circuit is decisive, pressure drops in joints and pipes should be minimized to increase efficiency and reduce operating costs.

2.3.1 Worldwide distribution of large scale solar thermal plants

The *International Energy Agency* (IEA) has a program dedicated to promote the use of solar thermal energy, *Solar Heating and Cooling* (SHC). The program SHC primary activity is to develop research projects, denominated Tasks, to study fundamental aspects of solar thermal energy.

IEA-SHC Task 45: Large Scale Solar Heating and Cooling Systems, was launched in January of 2011, with the aim of fostering and supporting the development of a strong and sustainable market of large scale solar heating and cooling systems (Task 45, 2013).

One of the obtained results from IEA-SHC Task 45 has been the characterization and analysis of large scale solar thermal systems worldwide. In the last ten years, both the number and the size of large installations have grown exponentially due to the interest in renewable energy sources.

The production of thermal energy with solar thermal collectors is an economically viable option that is rising year by year. Thus, in the year 2012, the number of large scale solar thermal installations worldwide was 244 and in the year 2014 the number of installations raised to 290 (see Fig. 2.8). Because of favorable political conditions for renewable energy systems the European countries are leaders of the market with 220 installations in 2014.

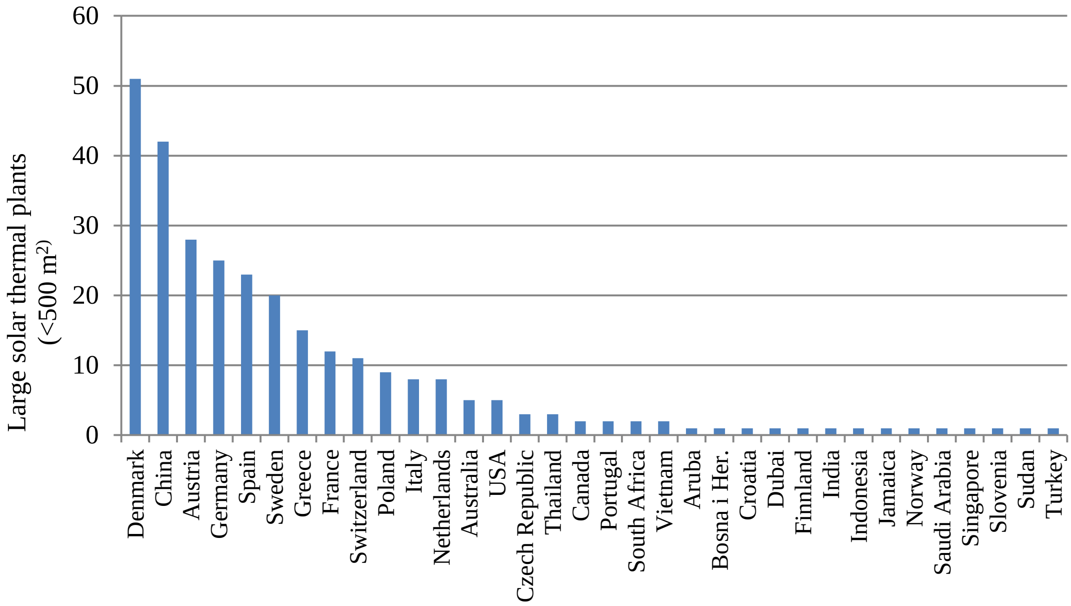

Figure 2.8: Worldwide distribution of large scale solar thermal plants (Task 45, 2014d)

2.3.2 Large scale solar thermal plants in Europe

Denmark is the country with the highest number of large scale solar thermal systems and has almost 50% of the total collector area installed because the Danish installations are also the largest ones. Austria, Germany, Spain and Sweden also have a considerable number of large scale solar thermal systems. Data are presented in Fig. 2.8.

Besides SHC other platforms gather information of large scale solar thermal systems. The platform Solar District Heating (SDH, 2015) supported by the program Intelligent Energy Europe of the European Union compiles information of large scale solar thermal plants connected to DH systems in Europe, but in this case the minimum size considered is 1000 m^2. In this database, managed by Jan-Olof Dalenbäck (Chalmers University, Gothenburg), technical data from large scale solar installations can be found. This database gives information about: location, solar collector field area, type of solar collector and, if available, type of thermal energy storage and volume. According to this database, the largest installation in Europe is located in Vojens (Denmark). The plant has flat plate collectors with an area of 70,000 m^2 and a hot water tank of 203,000 m^3.

The most common technology for large scale solar thermal systems in Europe is flat plate collector (SDH, 2015; Task 45, 2014d). Only few installations use unglazed collectors or vacuum tube collectors. Conversely, in the Asian market almost half of the collectors installed are vacuum tube collectors or heat pipe collectors.

2.3.3 Large scale solar thermal plants in Spain

Task 45 has registered 17 large scale solar thermal plants in Spain. These installations provide heating for swimming pools, sport facilities and Aquaparks (Haro, Llefra, Bac de Roda, Cerdeda Park, Parcbit and Daoiz y Velarde). Also some hotels and day care centers have large scale solar thermal systems for heating and DHW (Centro San Juan de Dios Residence for elders in Sant Feliu de Guixols, Bitacora Appartments, Hotel San Antonio) and even cooling (Belroy Palace hotel). Four examples in the industry sector are registered by Task 45 (El Oso in Avila, Inditex in Arteixo, Nissan Motor Iberica in Avila, Contank in Barcelona) but more examples for industry can be found in Task 33 (2014) and Task 49 (2014a). From this list of large scale solar thermal plants in Spain only three installations have more than 1000 m^2 and are also included in SDH list (SDH, 2015)

1) Solar cooling installation in Arteixo with 1500 m^2 connected to Inditex buildings.
2) Solar heated swimming-pool in Haro with 1500 m^2, unglazed collectors.
3) Solar thermal system in Badalona with 1216 m^2 for a sport centre with swimming pool.

Two large scale solar thermal plants have been proposed for DH networks in Spain (*Districlima* and *Ecoenergies*) to increase the production from renewable energy and to displace the consumption of conventional fuels (IDAE, 2015a). The viability of this technology for district heating in Spain will be validated in the following years.

2.4 Large size flat plate collectors

Large size flat plate collectors are the most common solution for large scale solar thermal plants worldwide, except in Asia and Australia where there are also a considerable number of plants with evacuated tube solar collectors and other technologies. The main suppliers of large size flat plate collectors in Europe are Arcon (2014) and Sunmark (2014) which have recently joined into Arcon-Sunmark (2015). Large size flat plate collectors, similar to that one shown in Fig. 2.9, have an area of about 14 m^2 per collector and have been designed to be connected in series minimizing joints and connections to reduce the installation, maintenance and operation costs.

Figure 2.9: Large size flat plate collector (Arcon, 2014)

The absorber is built with copper tubes with lateral flaps made with aluminum and it has a selective coating treatment to increase the absorbance and reduce the emittance. The glass is located at a certain distance over the absorber to generate an air gap that reduces thermal losses to the environment. To reduce thermal losses even more, an intermediate transparent layer of ETFE (Ethylene tetrafluoroethylene) or FEP (Fluorinated ethylene propylene) is used in some versions to generate a second air gap between the absorber and the transparent cover. Insulation material, mineral wool or other, is located below the absorber and on the laterals with a thickness between 30 and 80 mm to reduce heat transfer from the collector to the environment. Aluminum housing protects the solar collector from outdoor conditions.

Large size flat plate collectors have an entrance for the heating fluid on one lateral and an outlet on the other lateral so solar collectors can be easily connected in series of 7 to 14 solar collectors, each array reaching a total area between 100 and 200 m^2. This connection in array reduces the piping connections, increasing the efficiency and reducing the cost.

Large size flat plate collectors are characterized by the same standard as regular flat plate collectors following the European Standard EN 12975-2:2006 Thermal solar systems and components – Solar Collectors Part 2: Test methods (EN, 2006). This standard describes the following reliability testing methods: 1) internal pressure test for absorbers; 2) high temperature resistance test; 3) exposure test; 4) external thermal shock test; 5) internal thermal shock test; 6) rain penetration test; 7) freeze resistance test; 8) mechanical load test; 9) impact resistance test; and 10) thermal performance test of liquid heating collectors (glazed and unglazed) under steady state conditions and under quasi dynamic conditions.

The investment cost of large size solar thermal collectors has been reduced in the last years, as most renewable energy technologies, due to the technological development and the production at bigger scale. The cost per area of solar collector for large applications obtained in some of the last projects remains between 200 and 300 €/m^2 (Arcon, 2014) with very low installation costs due to the relatively simple installation, as shown in Fig. 2.10.

Figure 2.10: Flat plate collector installation (Arcon, 2014)

Large scale solar thermal systems can be installed on the ground, on the roof of buildings or on tilted surfaces as shown in Fig. 2.7. For installations on ground it is very important to have available land at low price. Installations on roof are more demanding due to the technical difficulty of integration with the building envelope.

Contribution of thermal energy to DH systems from large scale solar thermal plants is very often limited to relatively low solar fractions (10% - 25%) due to the un-matching availability of the solar resource and the demand of thermal energy. Increasing the solar fraction requires the use of seasonal thermal energy storage.

2.5 Seasonal Thermal Energy Storage

Solar thermal production and demand do not match in time and thermal energy storage is required to accumulate the thermal energy produced. In order to increase the solar fraction in these systems, large thermal energy storage for long term applications "seasonal storage" is used to accumulate the thermal energy produced in summer to cover the heating demand in winter. Otherwise, solar collectors are underused in summer and stagnation problems might harm the equipment along the overproduction periods. Moreover, the cost of the solar heat rises when a seasonal storage is required.

Thermal energy can be stored in three different forms: 1) sensible heat storage, 2) latent heat storage and 3) chemical energy storage.

1) Sensible heat storage is the accumulation of thermal energy by changing the temperature of a material without changing its phase or chemical composition. The capacity to accumulate thermal energy in sensible heat storage depends on the temperature amplitude between the minimum and maximum temperatures in the thermal energy storage. It also depends on the storage volume and the specific heat of the storage material.
2) Latent heat storage is the accumulation of thermal energy by changing the phase of a material without changing its temperature or its chemical composition. Latent heat storage capacity depends on the energy required to change the state from solid to liquid.
3) Chemical heat storage is the accumulation of energy by activating a reversible chemical reaction. Reversible chemical reactions can be used to accumulate thermal energy without thermal losses to the environment during the period in which energy is accumulated as chemical energy.

The most common thermal energy storage technology used for the residential sector is sensible heat storage in hot water tanks but other technologies might be applied (Pinel et al., 2011). For large applications with higher requirements of thermal energy storage, such as solar heating plants for district heating systems, specific sensible heat storage technologies have been developed to accumulate thermal energy at low cost based on hot water, hot water and gravel or even heating the underground soil.

For large applications, the following systems (also presented in Fig 2.11) are being used: Tank Thermal Energy Storage (TTES), Pit Thermal Energy Storage (PTES), Borehole Thermal Energy Storage (BTES) and Aquifer Thermal Energy Storage (ATES).

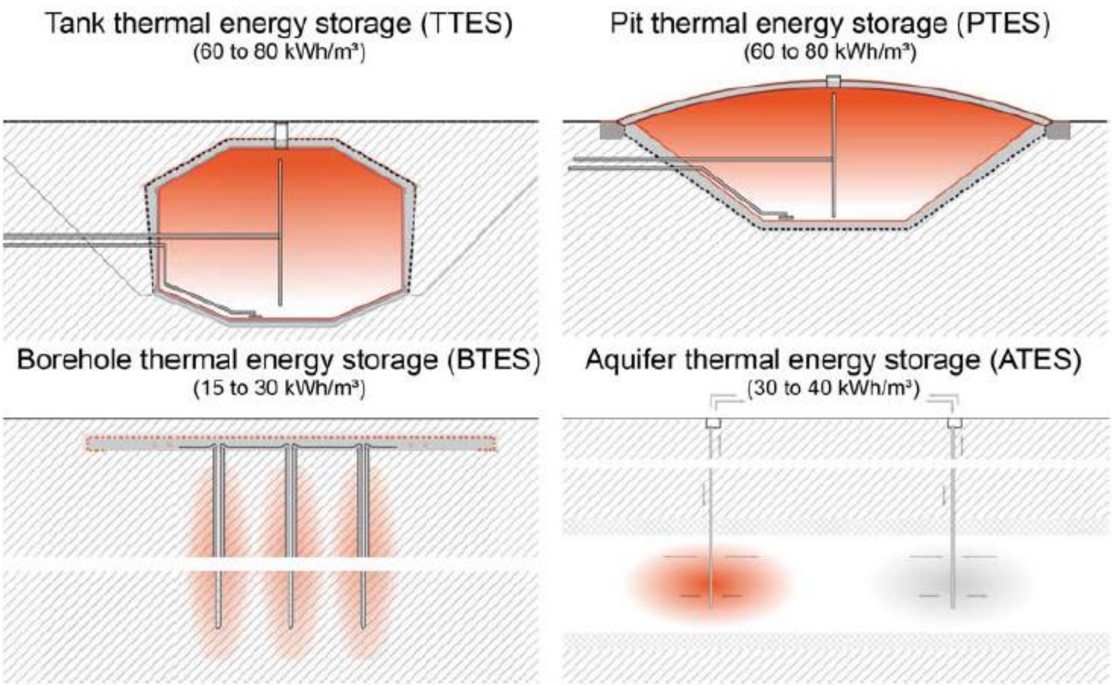

Figure 2.11: Types of seasonal thermal energy storage (Solites, 2014a)

2.5.1 Tank thermal energy storage

Water tank thermal energy storage is a tank filled with water to store thermal energy. It can be located on ground, partially buried or underground. It is built as a reinforced concrete tank, or as a cylindrical steel tank. The tank can be insulated on the top, sides or bottom to reduce the thermal losses to the environment. Usually a vapor diffusion liner is required to avoid vapor diffusion. Hot water tanks can be used under almost any circumstance but the economic cost is significantly higher than other available technologies for seasonal storage due to the consumption of structural materials as reinforced concrete. Fig. 2.12 shows a picture from the construction of a hot water tank.

Figure 2.12: Construction of hot water tank (Solites, 2014a)

2.5.2 Pit thermal energy storage

In order to reduce the cost of the seasonal storage, for large size applications, the pit thermal energy storage was developed to substitute the water tank construction. The pit does not have a solid structure; it is built only by moving land. The storage is partially insulated on the sides, and on the top with a watertight floating lid. This storage is filled with water or with water and gravel. The sides of the pit are tilted and supported over the soil and the cover usually floats or is supported over gravel. The construction of the storage is cheaper than the TTES but the efficiency is also lower.

Pictures from the construction process are presented in Fig. 2.13: land moving to make tilted walls, installation of the waterproof membrane, installation of the floating cover, and final result of the PTES.

Figure 2.13: Marstal pit construction (Ellehauge and Pedersen, 2007)

2.5.3 Borehole thermal energy storage

Thermal energy can be stored in the ground directly with a Borehole Thermal Energy Storage (BTES), avoiding the construction of a PTES or a TTES. A BTES is made of U pipes located in vertical boreholes to create a large heat exchanger with the underground soil. Hot water goes from the production centre to the U pipes to heat the underground during the charging season and on the opposite direction in the discharging season. Usually, U pipes are connected from the central part of the storage to the lateral sides, as shown in Fig. 2.14) creating a radial temperature gradient in the seasonal storage. Thermal properties of the soil, conductivity and heat capacity affect the efficiency of the storage.

Figure 2.14: Drake Landing Solar Community borehole construction (canmet ENERGY, 2015)

2.5.4 Aquifer thermal energy storage

In some locations underground caverns or aquifers can be used to store thermal energy. In these cases, the natural underground water is heated along the charging season and used in winter to produce thermal energy with a heat pump, due to the low accumulation temperature. Besides the virtually no cost for the storage medium, other costs, as heat pump investment and heat pump electricity consumption, have to be considered since their economic effect might be significant.

2.5.5 Technical and economic viability of seasonal storage technologies

The larger is the seasonal storage, the better the thermal performance. A cylindrical hot water tank with height equal to its diameter that reaches a maximum average temperature of 90ºC at the end of the charging season and a minimum average temperature of 30ºC at the end of the discharging season ($T_{max} - T_{min} = 60$ K) can accumulate 70 kWh/m^3 (see Table 2.4).

The tank will have thermal losses to the ambient proportional to the envelope area and the heat transfer coefficient. For a tank with 25 cm of insulation (U = 0.12 W/(m^2·K)) the annual thermal losses to the environment can be estimated along the 8760 h of the year at the average storage temperature (60 ºC) with the ambient at its yearly average temperature (15ºC). Storage capacity and thermal losses per cubic meter have been calculated for a wide range of volumes in Table 2.4.

Table 2.4: Efficiency of a cylindrical seasonal storage with height equal to its diameter

Volume (m^3)	0.1	1	10	100	1000	10,000	100,000
A (m^2)	1.19	5.54	25.7	119	554	2570	11,900
A/V (m^2/m^3)	11.9	5.54	2.57	1.19	0.554	0.257	0.119
EA_{max} (MWh)	0.007	0.07	0.7	7	70	700	7000
EA_{max}/V (kWh/m^3)	69.6	69.6	69.6	69.6	69.6	69.6	69.6
Q_l (MWh/yr)	0.056	0.26	1.2	5.6	26	120	560
Q_l/V ($kWh/yr/m^3$)	560.0	260.0	120.0	56.0	26.0	12.0	5.6

Envelope area and thermal losses per cubic meter are significantly reduced when the size is increased. TTES is the most common solution for thermal energy storage but cheaper solutions as PTES and BTES are becoming very competitive even when they have lower efficiency and temperature range (see Fig. 2.15).

Different data sources can be used to analyze the cost of the seasonal storage (Hadorn, 1990; SAIC, 2012; Schmidt et al., 2004, 2009, 2012; Task7, 1983) but there is still a lack of contrasted models to estimate the investment cost based on the size of the storage. In Chapter 5 a capital investment function for seasonal storage based on data from several sources will be detailed.

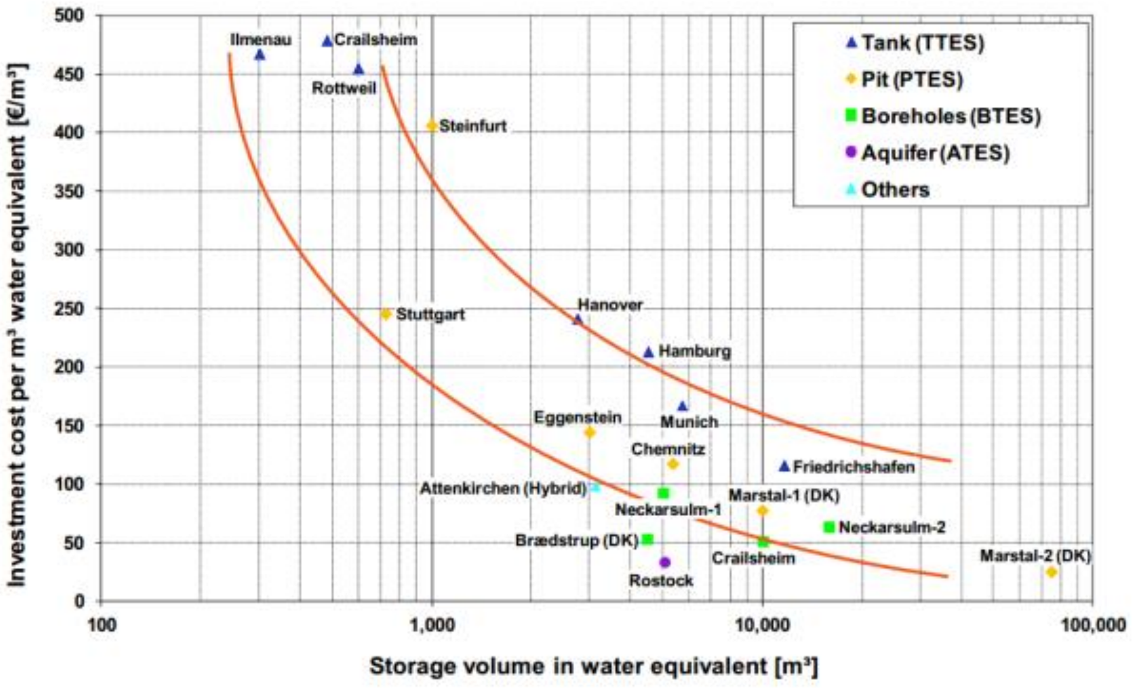

Figure 2.15: Specific storage cost of seasonal storage demonstration projects (Solites, 2014a)

2.6 Central Solar Heating Plants with Seasonal Storage

The number of Central Solar Heating Plants with Seasonal Storage (CSHPSS) is still limited and their future development will be defined by the results obtained in demonstration projects as Marstal, Braedstrup, Crailsheim and Drake Landing. The objective of these plants is to provide thermal energy for large communities with high solar fraction, at least 50%. The design of each CSHPSS is unique and depends on the specific heating needs, climatic conditions and characteristics of the district heating system. In Table 2.5 a brief description of CSHPSS in operation is summarized and in the following pages a complete description of four plants that hold up the banner of CSHPSS as a technical and economically viable option are presented.

Table 2.5: Description of Central Solar Heating Plants with Seasonal Storage in operation

Name*	Built	Area (m^2) †	Volume (m^3) ‡	Solar Fraction	Investment (€)
Friedrichshafen	1996	FPC 4050	TTES 12,000	47%	3,200,000
München	2007	FPC 2900	TTES 5700	47%	2,900,000
Mongolia	2012	CPC 5000	TTES 5000		
Hamburg	1996	CPC 3000	TTES 4500	49%	2,200,000
Rise Fjernvarme	1998	FPC 3582	TTES 4000	80%	697,200
Hannover Kronsberg	2000	FPC 1350	TTES 2750	39%	1,200,000
AEroeskoebing	1998	FPC 4875	TTES 1400	20%	1,200,000
Neuchatel	1997	UG 1120	TTES 1000		
Tubberupvaenge	1991	FPC 1030	TTES 1000		1,270,000
Marstal Fjernvarme	1996	FPC 33,000	PTES 75,000 PTES 10,340 TTES 2000	55%	9,440,000
Ottrupgaard	1995	FPC 565	PTES 1500		
Chemnitz	2000	ETC 540	WGTES 8000	30%	1,400,000
Augsburg	1998	FPC 2000	WGTES 6000		5,100,000
Eggenstein	2008	FPC 1600	WGTES 4500	37%	1,100,000
Sonderborg Vollerup	2008	FPC 7681	WGTES 4000	20%	
Steinfurt Borghorst	1999	FPC 510	WGTES 1500	34%	500,000
Neckarsulm Amorbach	1997	FPC 5670	BTES 63,000	50%	3,500,000
Anneberg	2002	FPC 2400	BTES 60,000		
Crailsheim	2003	FPC 7464	BTES 37,500	50%	4,500,000
Drake Landing, DLSC	2007	FPC 2164	BTES 34,000	96%	2,600,000
Braedstrup	2011	FPC 18,600	BTES 19,000 BTES 7500	30%	12,300,000
Attenkirchen	2002	FPC 800	BTES 9350	55%	760,000
Rostock Brinckmanshöhe	2000	FPC 980	ATES 20,000	62%	700,000

* Data obtained from different sources: Arcon, 2014; Dalenbäck, 2014; SAIC, 2012; Schmidt and Mangold, 2009; Schmidt and Miedaner, 2012; SDH, 2015; Solarge, 2013; Solvarmedata, 2013; Task 45, 2014d.

† FPC: Flat Plate Solar Collector, UG: Unglazed Solar Collector, ETC: Evacuated tube solar collector, CPC: Compound parabolic collector.

‡ TTES: Tank Thermal Energy Storage, PTES: Pit Thermal Energy Storage, WGTES: Water Gravel Thermal Energy Storage, BTES: Borehole Thermal Energy Storage, ATES: Aquifer Thermal Energy Storage.

2.6.1 Marstal

Some of the biggest solar thermal installations in the World are located in Denmark. A large scale solar thermal plant for a district heating system was installed in Marstal in 1996 (Marstal, 2014). The solar collector field area installed had a total area of 8000 m^2 and a hot water steel tank of 2100 m^3 as thermal energy storage. In 1999 the solar field was enlarged by 1000 m^2 and a pilot PTES of 3500 m^3 filled with water and gravel was built. With the knowledge of this first pit thermal energy storage, a second PTES of 10,000 m^3 was built in 2003, complemented by 8000 m^2 of solar collectors. The last expansion was accomplished in 2012-2013 reaching a total solar collector field area of 33,000 m^2 and including a third PTES of 75,000 m^3.

For auxiliary energy production the system has a 4 MW wood chips boiler and a thermal oil boiler connected to an organic Rankine cycle of 3.25 MW. A CO_2 driven heat pump of 1.5 MW extracts heat from the storage cooling it down to 10°C producing hot water at 75-90°C for the DH system.

The demand of the DH system is 19,039 MWh/yr and currently a solar fraction of 55% is achieved. The investment required to accomplish the whole project has been 9.4 million € and has been funded by the Danish government.

Figure 2.16: Solar thermal plant in Marstal (Sunstore-4, 2014)

Marstal solar thermal plant has been part of different research European projects: SUNSTORE 2 and SUNSTORE 4 (Sunstore-4, 2014). Along the project SUNSTORE 2 the following results were obtained: a PTES can be built with an investment lower than 67 €/m^3 for a size of 10,000 m^3 and for a size of 100,000 m^3 a PTES can be built at 31 €/m^3. Along the project SUNSTORE 4 energy integration solutions were compared considering different components: solar collectors, wood chip boiler, PTES, heat pumps and electricity production with an organic Rankine cycle.

2.6.2 Braedstrup

Braedstrup solar plant was installed in 2007 with a solar collector field of 8000 m^2 and a hot water tank of 2000 m^3. The district heating system supplied heat to over thousand buildings with an annual demand of 40,000 MWh/yr. The solar plant initial investment was 1.6 million €, and produced 4000 MWh/yr of solar energy (solar fraction 10%). The plant produced part of the heating demand with a cogeneration plant of 7.8 MW and in the periods of maximum demand the thermal energy required was supplied by auxiliary boilers 22 MW.

In 2012 the size of the solar collector field was extended with an area of 8600 m^2 rising the production of solar thermal energy to 8900 MWh/yr. A new system to accumulate thermal energy was installed consisting of a hot water tank of 5500 m^3 and a BTES. The BTES was composed by 48 boreholes arranged in hexagonal symmetry. The total area affected by the boreholes had a diameter of 24 m and a depth of 45 m, therefore the volume of the thermal energy storage was 19,000 m^3. The BTES has lower investment than TTES, for the same capacity, but accumulates the thermal energy at a lower temperature. A heat pump with a power of 1 MW produces heat at 85ºC using the BTES as a thermal source.

The cogeneration plant, the solar plant and the heat pump can produce thermal energy in any moment of the day or accumulate the thermal energy in the hot water tank, uncoupling production and demand. Several strategies of production can be applied: 1) production of electricity with the cogeneration plant to run the heat pump and extract the maximum amount of thermal energy from the system; 2) production of electricity to be sold along the periods of high price; 3) run the heat pump during low electricity price periods. This plant is an interesting example of energy integration using different energy sources, production technologies and thermal energy storages.

Figure 2.17: Braedstrup solar thermal plant (Solarge, 2013)

2.6.3 Drake Landing Solar Community

Drake Landing Solar Community (DLSC) is a master planned neighborhood in the town of Okotoks, Alberta (SAIC, 2012). This community produces more than 95% of the space heating needs with solar thermal energy. The solar system is the first of its kind and produces thermal energy for a 52 house community with 800 solar thermal flat plate collectors mounted on array over the garage roof of the houses with a total collector area of 2300 m^2.

The facility combines short term storage with seasonal storage. The seasonal storage is a BTES with a volume of 34,000 m^3. The community is supplied from the short term storage, composed by two TTES of 120 m^3, through the district loop. The district heating system supplies thermal energy at low temperature: supply 55ºC and return 32ºC. To use this low temperature energy source each house has an air handler unit that heats the house supply air. The BTES is basically a large, underground heat exchanger which consists of 144 boreholes with a depth of 35 m. The process of charging the BTES took several years, the plant started to operate in July 2007 and it took three years to charge completely the seasonal storage. The solar fraction obtained during the first year of operation (July 2007 - July 2008) was 55%, the following years were obtained 60%, 80%, 86% and finally 97% in 2011-2012. For the production of DHW all the houses are equipped with a stand-alone solar domestic hot water unit that operates with self-regulated solar panels installed on the roof of the homes.

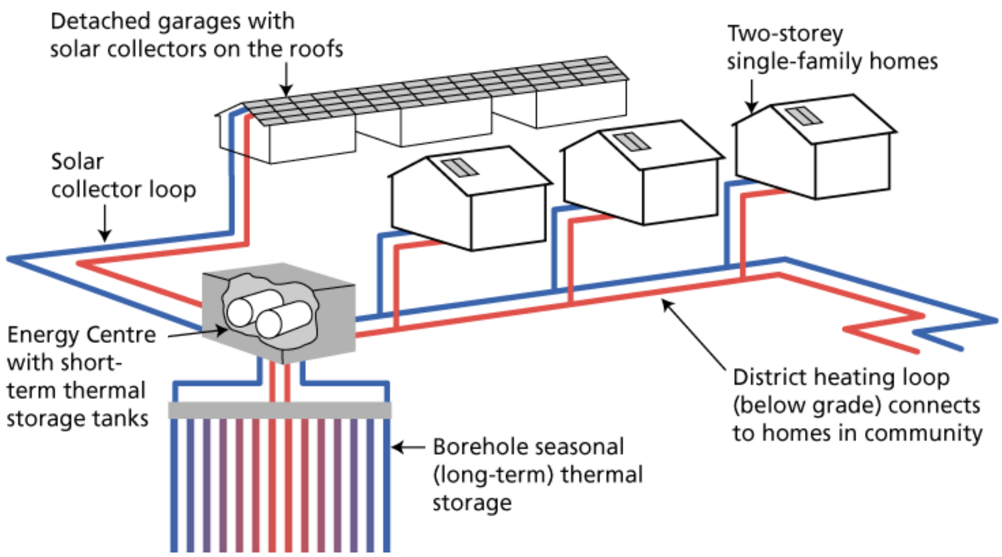

Figure 2.18: System scheme of Drake Landing Solar Community (SAIC, 2012)

Each house had the following extra costs compared to standard house to achieve this result: 1) energy efficiency upgrades in the houses 6400 $\$_{USA}$; 2) solar collector system 14,800 $\$_{USA}$; 3) garage upgrades 4000 $\$_{USA}$; 4) short term storage system 6000 $\$_{USA}$; 5) district loop 6000 $\$_{USA}$; vi) borehole thermal energy system 12,000 $\$_{USA}$. In total the extra charges per house has been around 50,000 $\$_{USA}$ but now they own a clean and renewable energy system first of its kind. The project driving agents are looking for a new community of bigger size to prove the economic viability of this kind of system.

2.6.4 Crailsheim

The German government funded several research and demonstration plants for solar assisted district heating since 1996. One of these plants was installed in Crailsheim, located in the state of Baden-Württemberg, south/west of Germany. The system delivers heat to a community of 260 apartments, a gym and a school. The plant started to operate in 2005 with a solar field of 1500 m^2 installed over buildings and a 100 m^3 TTES as buffer storage. In 2007 an additional solar collector field of 3500 m^2 was installed over road/city noise protection walls. To manage the extra thermal energy production a new TTES of 480 m^3 was installed. To accumulate the summer overproduction, in the following year a BTES of 37,500 m^3 was installed. To increase the potential of the solar plant, in 2010 a heat pump with an electric power of 530 kW was installed. Other extensions for the solar production have been installed reaching a total collector area of 7,300 m^2. See in Fig. 2.19 the location where the solar collectors were installed, on the left side over buildings, and on the right side on the noise wall.

Figure 2.19: Solar collectors integrated in the community of Crailsheim

The Crailsheim project deals with an urban district aiming to shift its energy consumption from fossil fuels to renewable energy sources. The roof integration of the solar thermal collectors was realized during the renovation of old buildings and allowed to use the maximum area of the roof. The solar collectors installed on the noise protection walls are a great example of urban planning, as an apparently useless space was finally utilized to install the solar collectors. The ground showed good prerequisites for BTES: thermal conductivity between 1.95 W/(m·K) and 2.46 W/(m·K) (deeper area), volumetric heat capacity between 2.4-2.6 MJ/(m^3·K). This plant produces heat for a community with high solar fraction getting a final solar heat cost of 190 €/MWh, calculated for long term operation with 6% interest over the investment costs (Schmidt and Miedaner, 2012).

Chapter 3:
Design, modelling and characterization

3 Design, modelling and characterization

In this chapter a review of characterization, modelling, simulation and calculation methods for solar thermal collectors and solar thermal systems is presented.

Solar energy can be used by the residential sector to produce heat for domestic hot water or space heating. Solar assisted energy systems for DHW are very common and can be calculated with simple correlations based on empirical methods validated by a long-term application.

On the other hand, designing CSHPSS systems, with highly dynamic behavior, is a complex process in which climatic and demand data are required. Dynamic simulation methods can be used to calculate the performance of solar thermal systems with high accuracy but requiring a lot of detailed climatic and demand data. These methods have become very popular in the last years since they can be used even on personal computers with an acceptable calculation effort. They are accepted tools for the performance design and optimization of thermal processes (Nafey, 2005). Nevertheless, other design methods are available.

Simple calculation methods can be used to perform feasibility and pre-design studies enabling an estimation of the annual result with simpler input data (Lund, 2009). These design methods calculate the average performance of the system with reduced calculation effort, they are faster than simulation methods and are useful in preliminary analysis, general survey studies and system design when simulations are too expensive or when climatic and demand data is limited.

This chapter presents both characterization methods for solar collectors and calculation or predesign methods for solar systems. The chapter closes with a short presentation of the economic analysis applied to these systems and with the environmental analysis required to estimate the environmental impact of a solar assisted energy system. Some of the methods presented in this chapter will be used in Chapter 4.

3.1 Characterization of solar collectors

In steady state, the performance of a solar collector q_{coll} (W), whose area is A_c (m^2), can be described as an energy balance between the irradiance absorbed S (W/m^2) and the thermal losses, which depend on the heat loss coefficient U_L ($W/(m^2 \cdot K)$), the collector temperature (T_c) and the ambient temperature (Ta) (Duffie and Beckman, 2006).

$$q_{coll} = A_c \cdot [S - U_L \cdot (T_c - Ta)] \qquad (1)$$

Hottel and Woertz (1942) proposed a method to characterize the irradiance absorbed as the irradiance or incident solar radiation q_r (W/m^2) times the transmittance of the cover (τ) times the absorptance of the absorber (α).

$$q_{coll} = A_c \cdot [\ \tau\alpha \cdot q_r - U_L \cdot (T_c - Ta)] \qquad (2)$$

In this equation, thermal losses depend on the collector temperature, which depends on the solar incident irradiance and the entering fluid conditions. The average transmittance absorptance product ($(\tau\alpha)_{av}$) and the solar collector heat removal factor (F_R) can be used to use the inlet temperature (T_{in}) instead of the collector temperature. The heat removal factor relates the actual useful energy gain of a collector to the useful gain if the whole collector surface were at the fluid inlet temperature (T_{in}).

$$q_{coll} = A_c \cdot F_R \cdot [(\tau\alpha)_{av} \cdot q_r - U_L \cdot (T_{in} - Ta)] \qquad (3)$$

In the mid-1970s many new collectors appeared on the market and it became necessary to set characterization standards for solar thermal collectors. The standard was developed by the National Bureau of Standards and a further modification was developed by ASHRAE (2003). Currently the standard in Europe is EN 12975-2 (EN, 2006) equivalent to the international standard ISO 9806 (1992). This characterization method determines: optic efficiency η_0, first heat loss coefficient k_1 ($W/(m^2 \cdot K)$), and second heat loss coefficient k_2 ($W/(m^2 \cdot K^2)$) based on the average absorber temperature.

$$q_{coll} = A_c \cdot (\ \eta_0 \cdot q_r - \ k_1 \cdot (T_c - Ta) - k_2 \cdot (T_c - Ta)^2\ ) \qquad (4)$$

This characterization method for solar collectors (EN, 2006) has been used in this thesis. The experimental coefficients of the large size solar collector used, ARCON HT/SA 28/10, are presented in Fig. 3.1 (Arcon, 2013).

Data

External dimensions:	2.27 x 5.96 x 0.14	m
Gross area:	13.57	m²
Aperture area:	12.52	m²
Weight, excl. fluid:	250	kg
Fluid cintent:	9.3	litre

Efficiency

$$\eta = \eta_0 - \frac{a_1 \cdot (T_m - T_a)}{G} - \frac{a_2 \cdot (T_m - T_a)^2}{G}$$

where:

T_a = Ambient temperature [°C]
T_m = Mean fluid temperature [°C]
G = Irradiance [W/m²]

Efficiency based on aperture area of 12.56 m², a flow of 25 ltr/min and a wind velocity of 3 m/s:

η_0 = 0.817
a_1 = 2.205 [W/(m²K)]
a_2 = 0.0135 [W/(m²K²)]

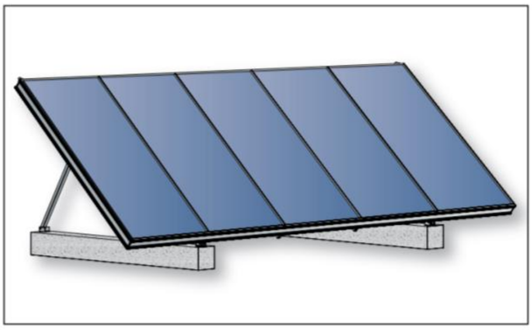

Figure 1: HT-SA collector mounted on concrete foundations

Figure 3.1: Datasheet of Arcon solar collector HT-SA 28/10 (Arcon, 2013)

The standard EN 12975-2 also defines the characterization of other factors as: incidence angle modifier (K_θ), time constant (τ_c) and effective thermal capacity (C). Besides, other factors that produce a minor effect might be considered: shading, dust and heat capacity effect.

The experimental characterization of a solar collector requires to measure: solar incident radiation, inlet flow, inlet temperature, outlet temperature and ambient temperature. The characterization can be done under steady state conditions or under dynamic conditions. At steady state conditions it is necessary to have a clear sky day, but in climates with few clear sky days, solar collectors can be tested using the quasi dynamic test method that requires a more complex characterization of the solar collector including one node thermal capacitance (Perers, 1993) but can use any outdoor condition. Indoors solar collectors can be characterized along the whole year using a solar simulator and the steady state method.

The characterization of solar collectors is useful to determine their instantaneous performance but it does not shed light on daily, monthly or annual production of thermal energy.

3.2 Utilizability methods

The daily amount of solar radiation that can be transformed into thermal energy can be estimated from generalized utilizability methods which depend on the cloudiness, latitude and collector tilt. The utilizability method estimates the thermal performance of solar collectors on an hourly, daily or monthly basis (Duffie and Beckman, 2006). The utilizability correlation was proposed to estimate the daily fraction of utilizable radiation (Hottel and Whillier, 1958). Different utilizability methods can be used as the *generalized utilizability* method (Liu and Jordan, 1963) or the *average utilizability method* (Klein, 1978).

3.2.1 Daily utilizability

The production of thermal energy from a solar collector field can be determined using the daily radiation received on a tilted surface $\bar{H}_t$ (MJ/(m^2·day)) and the daily utilizability factor Φ. For a month of N days, the thermal production Q_c (MWh) is obtained as follows,

$$Q_c = A \cdot \eta_0 \cdot \bar{H}_t \cdot N \cdot \Phi / 3600 \qquad (7)$$

where η_0 is the fraction of radiation received that will be absorbed and Φ is the fraction of radiation absorbed that can be extracted from the solar collector. The minimum level of solar radiation I_{TC} (W/m^2) required to produce a net amount of energy in the solar collector is evaluated to obtain the utilizability factor.

$$I_{TC} = F_R \cdot U_L \, (T_{in} - T_a) / (F_R \cdot (\tau\alpha)_{av}) \qquad (8)$$

The ratio between this minimum radiation level and the radiation at midday is defined as $\bar{X}_c$. Being r_{tn} the ratio between midday hour radiation and daily radiation on the tilted surface for an average day of the month.

$$\bar{X}_c = I_{TC} / (r_{tn} \cdot \bar{H}_t \cdot 10^6 / 3600) \qquad (9)$$

The daily utilizability factor is obtained by Klein (1978) as a function of $\bar{X}_c$, daily distribution factors of the solar radiation ($\bar{R}$ and R_n) and empirical factors (a, b and c).

$$\Phi = \exp\left[(a + b \cdot R_n / \bar{R})(\bar{X}_c + c \cdot \bar{X}_c^2)\right] \qquad (10)$$

$\bar{R}$ is the ratio between the monthly average daily incident radiation on a tilted surface and on a horizontal surface.

$$\bar{R} = \bar{H}_t / \bar{H} \qquad (11)$$

R_n is the ratio of the hour centered at noon of radiation on the tilted surface to that on a horizontal surface for an average day of the month.

The factors a, b and c depend on the monthly average clearness sky index $\bar{K}_t$.

$$a = 2.943 - 9.271\, \bar{K}_t + 4.031\, \bar{K}_t^2 \quad (12)$$

$$b = -\,4.435 + 8.853\, \bar{K}_t - 3.602\, \bar{K}_t^2 \quad (13)$$

$$c = -\,0.170 - 0.306\, \bar{K}_t + 2.936\, \bar{K}_t^2 \quad (14)$$

These correlations are completely described in Duffie and Beckman (2006) and a complete example can be found in page 132 of his book.

3.2.2 Drew and Selvage

Drew and Selvage (1980) proposed a methodology to size the volume of the seasonal storage V (m^3) and the solar collector field area A (m^2), for the specific case of 100% solar fraction using the utilizability method to calculate the performance of the solar collector field. The methodology considers a predicted temperature profile in the seasonal storage (T_{acu}) for the ideal performance along the year with charge and discharge following a sinusoidal function of amplitude $\Delta T = T_{max} - T_{min}$.

$$T_{acu}[m] = T_{min} + 0.5 \cdot \Delta T \cdot (1 - \sin(\pi \cdot (m - 1) / 6)) \quad (15)$$

As the storage temperature is known, the monthly solar production Q_c (MWh) can be obtained following Eq. 7. The monthly thermal losses from the seasonal storage are obtained with the heat loss coefficient U_{acu} (W/K) and the storage surface A_{acu} (m^2), which depends on the storage volume.

The seasonal storage will be charged from its minimum temperature (T_{min}) to its maximum temperature (T_{max}) accumulating EA_{max} (MWh) according to the volume and thermal properties of water ρ (kg/m^3) and c_p (J/kg/K).

$$EA_{max} = V \cdot \rho \cdot c_p \cdot \Delta T / (3.6 \cdot 10^9) \quad (16)$$

This charging process will be produced between April and September. The energy balance for the system during this period of time is

$$EA_{max} = \sum_{m=4..9} (Q_c[m] - UA_{acu} \cdot (T_{acu}[m] - T_a[m]) \cdot 24 \cdot N \cdot 10^{-6} - Q_d[m]) \quad (17)$$

However, in the following months of October to March the storage will be completely discharged. The energy balance for the system during this period of time is

$$- EA_{max} = \sum_{m=10..12;1..3} (Q_c[m] - UA_{acu} \cdot (T_{acu}[m] - T_a[m]) \cdot 24 \cdot N \cdot 10^{-6} - Q_d[m]) \quad (18)$$

These two equations are obtained to size the solar collector field area and the seasonal storage volume. This method can be used to pre-size the system but only for a CSHPSS with 100% solar fraction, based on the assumption that the storage has a uniform charging and discharging process.

3.2.3 Braun

Braun et al. (1981) proposed a method to calculate CSHPSS, of any fraction, using the monthly utilizability method and common climatic data. This method requires for the month *m* the monthly average storage temperature (T[m]), as well as the temperature at the beginning (T_{acu}[m-1]) and the end of the month (T_{acu}[m]).

$$T[m] = (T_{acu}[m] + T_{acu}[m-1]) / 2 \quad (19)$$

The monthly discharge of thermal energy from the seasonal storage $Q_{s,max}$ (MWh) is limited according to the monthly average seasonal storage temperature, comfort temperature in the buildings T_{dwe}, heat transfer coefficient from the district heating to the house UA_{dwe} (W/K), number of houses (N_{dwe}), and monthly number of hours in which is operating the heating system (N_{heat}).

$$Q_{s,max}[m] = UA_{dwe} \cdot N_{dwe} \cdot N_{heat}[m] \cdot (T[m] - T_{dwe}) \cdot 10^{-6} \quad (20)$$

The restriction between the limit in discharge and the monthly demand (Q_d) defines the discharged heat (Q_s).

$$Q_s[m] = min\,(Q_{s,max}[m]; Q_d[m]) \quad (21)$$

The auxiliary energy required (Q_{aux}) is the difference between demand and discharged heat.

$$Q_{aux}[m] = Q_d[m] - Q_s[m] \quad (22)$$

The model also considers thermal losses to the ambient from the storage Q_l (MWh) at the average storage temperature for the month of N days.

$$Q_l = UA_{acu} \cdot (T - T_a) \cdot N \cdot 24 \cdot 10^{-6} \quad (23)$$

being UA_{acu} (W/K) the storage heat transfer coefficient.

An energy balance with restrictions in charge is used to determine the thermal energy accumulated EA (MWh) and the storage temperature (T_{acu}) at the end of the month.

$$EA[m] = min\ (EA[m\text{-}1] + Q_c[m] - Q_l[m] - Q_d[m];\ EA_{max}) \quad (24)$$

$$T_{acu}[m] = T_{min} + (T_{max} - T_{min}) \cdot EA[m]/EA_{max} \quad (25)$$

If the storage reaches the maximum temperature ($EA = EA_{max}$) then part of the heat collected will be rejected to the ambient Q_x (MWh).

$$Q_x[m] = EA[m\text{-}1] + Q_c[m] - Q_l[m] - Q_d[m] - EA[m] \quad (26)$$

This method determines the monthly system performance with a system of non-linear equations whose resolution requires an iterative process. It is recommended to solve this problem with a solver of equations as EES (2013).

The utilizability method is used to determine the production of the solar field based on the storage temperature and the daily average radiation. This correlation is based on empirical studies for a certain number of locations and collectors but its accuracy for different locations or new solar collectors is not clearly defined.

Instead of using the utilizability correlation to calculate the performance of the solar field along the day, other methods use the characterization correlation for the solar collector. The performance of the solar collector can be calculated for short periods of time and the daily performance can be obtained by the sum of those periods.

The method of Braun considers complete mixture in the storage temperature which limits the discharge of thermal energy. The assumption of complete mixture underestimates the positive effects of stratification. If the solar field produces thermal energy in winter or early spring while the storage is discharged the hot water produced is accumulated on the top of the storage at a temperature higher than the average storage temperature. Thermal energy at high temperature can be discharged to the houses increasing the amount of energy discharged and the solar fraction in the period of higher demand.

3.2.4 Lund

Lund, 1989 uses the utilizability correlation to calculate the monthly performance of a CSHPSS. The solar radiation, the ambient temperature and the heating demand are estimated as a sinusoidal function along the year. The annual performance is calculated integrating uniform functions by tranches.

This method simplifies the non-linear equations reducing the iterative process but is based on uniform functions for heating demand and solar radiation simplifying the effects of climate on the system performance. Models should be sensitive to design conditions. Lund method, as well as Drew and Selvage method, do not consider demand and solar radiation annual distribution among different locations.

3.3 Simulation tools

Simulation and modelling methods represent mathematically the performance of components and systems to predict their output supporting the design process (Löf, 1993). The performance of a CSHPSS can be calculated with simulation tools hourly or even further detailed with a sequential process from an initial state.

3.3.1 TRNSYS

TRNSYS (TRansient SYstem Simulation) is a thermal process simulation program that uses a list of component libraries including: climatic data, radiation models, thermal equipment (solar collectors, pumps, heat exchangers, boilers…), controlling components, demand profiles, and mathematical operators, to simulate thermal systems (TRNSYS, 2010). TRNSYS has been validated for thermal energy systems including CSHPSS (Raab et al., 2005; Lundh and Dalenbäck, 2008).

The simulation of a CSHPSS requires at least hourly climatic data of ambient temperature and solar radiation for the desired location. Climatic data from EnergyPlus (2012) can be used to simulate systems in most locations worldwide. Components included in TRNSYS can be used to estimate radiation over tilted surfaces with different correlations available in literature. The solar collector can be introduced as a component that heats a fluid entering at a determined temperature and flow rate. Pumps and controllers are required to define the flow rate in the different hydraulic circuits. Controllers reduce the flow in periods with low radiation and increase the flow when the outlet temperature reaches very high values.

The components of the system are connected using the outputs from some units as inputs for others. Heat loss in pipes, efficiency and effectiveness in heat exchangers can be included as well as stratification in thermal energy storages. Many thermal components are available in TRNSYS including heat pumps, residual heat from other energy sources or different technologies for production of electricity. The demand of thermal energy can be introduced as an input value generated by other sources or created through the thermal simulation of a building (Guadalfajara et al, 2012).

Simulations of CSHPSS with TRNSYS provide an evaluation of the performance with high accuracy but require exhaustive and detailed information. The amount of work required to create a TRNSYS model is quite long but afterwards these models can be reused for similar applications adjusting the input data (climatic and demand) and the design parameters.

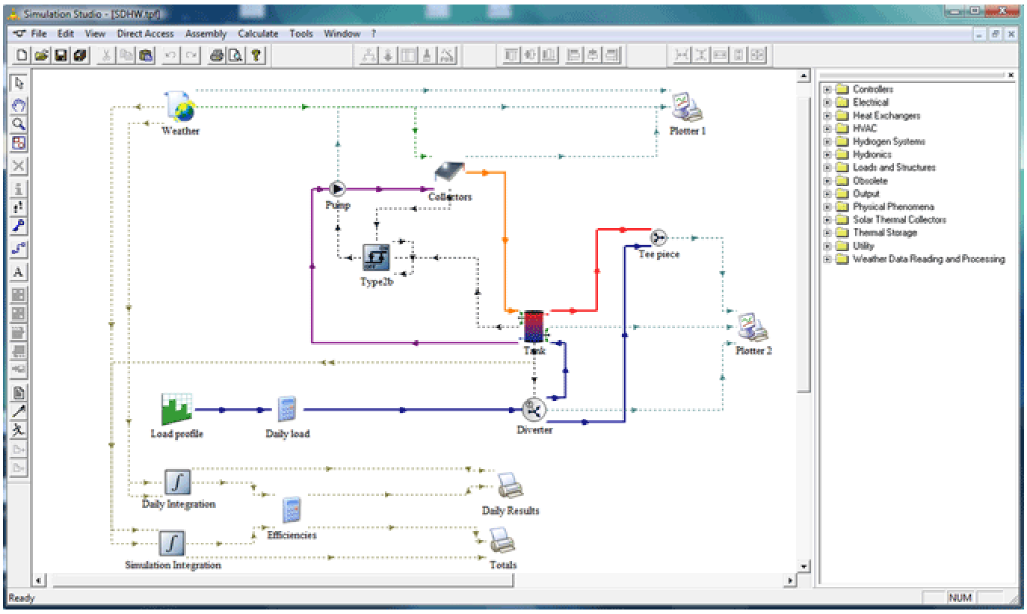

Figure 3.2: TRNSYS software (TRNSYS, 2010)

3.3.2 Polysun

Polysun (2014) is a simulation software developed to design different technologies of renewable energy systems e.g. photovoltaics, solar thermal or geothermal. Polysun is very appropriate to design common energy systems; it requires lower calculation effort and simulation knowledge than general purpose simulation programs. It enables the user to effectively simulate small common pre-elaborated systems in a user friendly way. It has several installations predefined but lower level of component detail compared with TRNSYS models.

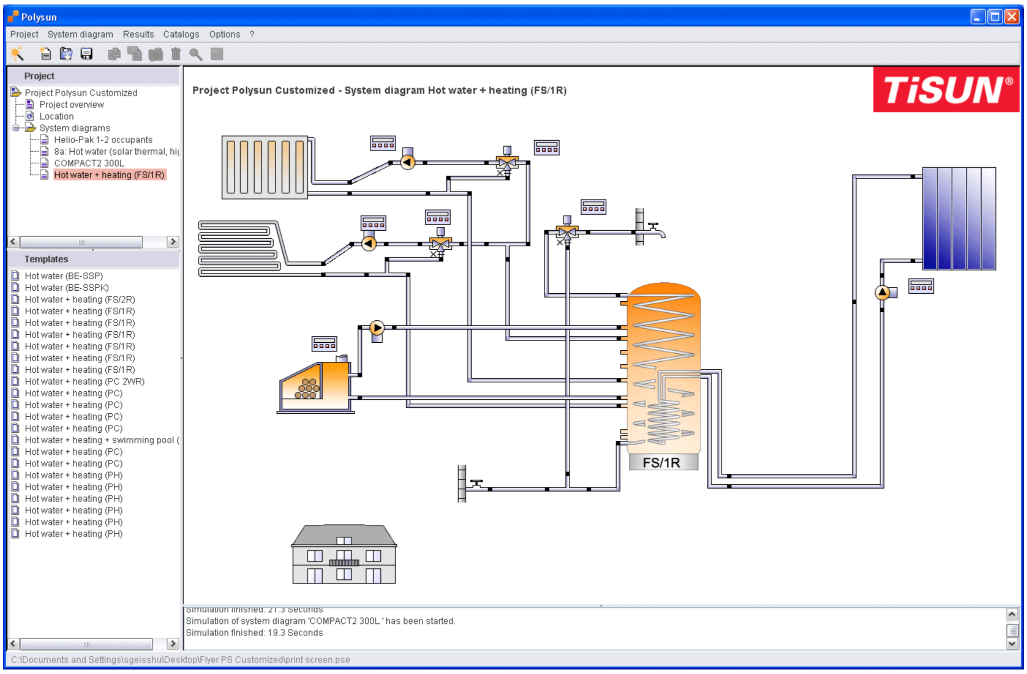

Figure 3.3: Polysun software (Polysun, 2014)

3.3.3 MINSUN

MINSUN is a Solar Simulator tool developed by Task 7 (Task 7, 1985) organized by the platform Solar Heating and Cooling (SHC) of the International Energy Agency (IEA). MINSUN is a set of FORTRAN programs that model different components and subsystems of a centralized solar heating system. The program provides thermal simulations, costing and economic analysis based on models developed by Task 7 in 1983 (Task 7, 1983). It is no longer possible to find this software and probably all the knowledge has been lost except for documentation that can be found in IEA-SHC Task 7 website (Task 7, 1985).

3.3.4 Other applications

Matlab (2014) can be used to simulate dynamic systems such as solar thermal systems with latent or sensible thermal energy storage. The diagram tool Simulink (2014) facilitates the modeling process enabling the connection of components. A sort of models and libraries in which the different components are mathematically described can be found online (Task 44, 2013).

EnergyPro (EnergyPro, 2014) is a flexible modelling software for the design, simulation, and optimization of energy systems. It also allows making detailed technical and financial planning. This software models different kinds of energy projects such as co-generation, tri-generation, biogas, geothermal or solar projects but it does not include seasonal storage, which makes the software unable for our purposes.

Many other computer tools to simulate energy systems can be found in Connolly et al. (2010) but in this section only the most appropriate tools to simulate solar assisted energy systems have been presented.

3.4 Semi-empirical methods

Simulation models obtain the result for different environmental conditions and design parameters. From a large number of results correlations based on the ambient conditions and the design parameters can be generated. These correlations can be used to design new systems based on the design parameters included in the simulation method that for solar systems can be among others: solar collector coefficients, solar collector field area, inclination, orientation, storage volume and location.

The most well-known semi-empirical methods for solar thermal system, based on pre-elaborated simulations, is the f-Chart method (f-Chart, 2015) but it is limited to systems for domestic hot water with short term energy storage.

3.4.1 f-Chart

The f-Chart method developed by Klein et al. (1976, 1977) and Beckman et al. (1977) is a semi-empirical method developed to estimate the annual fraction of solar thermal energy that will be delivered to the load. This method is the result of hundred simulations of solar heating systems for domestic hot water with different design and environmental conditions.

The method was developed using climatic data from various locations in USA and a solar collector with two adjustment coefficients, which was the standard in the period in which the method was developed. This method has been used widely to design solar domestic hot water systems. Other semi-empirical calculation methods based on simulations have been developed using climatic data from a broader number of cities and climates.

3.4.2 CHEQ4

The application CHEQ4 (IDAE, 2015a) has been developed to design solar domestic hot water systems in Spain (Aiguasol, 2011) considering seven configurations (i.e. centralized, semi-centralized, de-centralized and with or without thermal energy storage). This software, based on 69,000 TRNSYS simulations, can be used to check if a designed installation fulfills the requirements on solar domestic hot water defined by the Spanish technical normative on buildings (CTE, 2013).

This method is more appropriate to design systems in Spain than f-Chart method. While the f-Chart method was developed using climatic data from cities in the USA, the CHEQ4 method uses climatic data for most of the big cities in Spain. Also, design options for solar assisted systems are based on current needs of designers that should compare alternatives as centralized or semi-centralized systems for multifamily buildings in Spain. Moreover, the method can be used as a validation tool for the national normative on solar hot water systems.

Figure 3.4: CHEQ4, certification software for solar thermal systems in Spain (IDAE, 2015a)

The option of a system with seasonal storage is not included among the design options for solar thermal systems. The highest ratio volume of hot water storage per area of solar collector that can be selected is 0.18 m^3/m^2. This ratio is very small for CSHPSS and the application can only be used for systems without seasonal storage.

3.4.3 SDH online calculation tool

SDH online calculation tool based on TRNSYS simulations is a user friendly web-application that uses a first approach for sizing a solar district heating plant centralized or de-centralized with or without seasonal storage (Solites, 2014b). The tool calculates the annual solar fraction with multi-linear interpolation between the outputs of 100,000 TRNSYS simulations (Deschaintre, 2014). The method allows selecting among three supply/return temperature for the DH system. Four alternatives of solar collector can be selected and six locations for the climate condition in Europe. Also it is not possible to define or adjust the annual profile of demand, which has a considerable effect on seasonal storage needs.

This is the only semi-empirical method available that can be applied to systems with seasonal storage but it has several limitations on climate, load selection and design parameters.

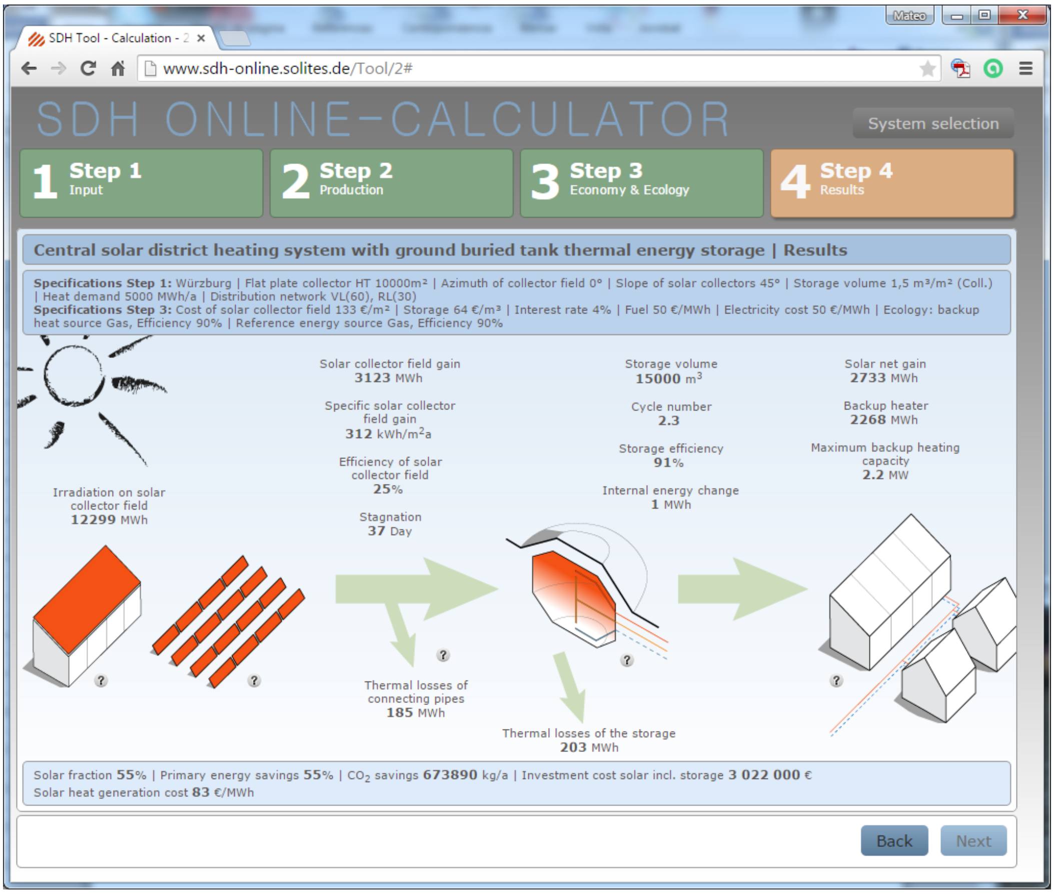

Figure 3.5: SDH online calculator (Solites, 2014b)

3.4.3 *f-Easy*

f-Easy (2014) is a feasibility tool developed by PlanEnergi (2014) to provide pre-sizing of solar plants in district heating systems. The calculation process estimates the performance of the solar collector field proportional to the annual radiation and calculates the solar field area to obtain a specific solar fraction.

The method includes adjusting coefficients for the supply temperature and for the solar collector model based on the results obtained from multiple simulation runs. The seasonal storage size is obtained using a ratio volume of storage per area of solar collector that is function of the desired solar fraction and based on the results of designing CSHPSS. The design factors were obtained by the experience of designing systems in the climate of Denmark. The application of the obtained results to locations with different climate may lead to wrong conclusions.

For more specific calculations in Denmark, PlanEnergi prepared a more elaborated tool than f-Easy based on Excel to compare different scenarios. Fjernsol (2014) provides an estimation of the performance of a solar collector field, estimates the energy price for different solar solutions in €/MWh and compares between several cases. The calculation methodology has been designed for installations in north and center European countries in which the solar production represents a small fraction of the district heating load.

3.5 Short-cut simulations

Instead of doing an annual complete simulation, a short-cut simulation can be used to estimate the performance of a CSHPSS with lower calculation effort. Compared with semi-empirical methods, the main difference is that while semi-empirical methods use the result of cases previously defined to determine the performance of other systems by interpolation, short-cut simulations use specific climatic and demand data as well as user defined parameters.

One of the main problems with short-cut simulations of CSHPSS is the seasonal storage. Along the calculation period, in which the system's performance is considered uniform, the storage temperature changes, rising during the seasonal storage charge or decreasing during the seasonal storage discharge.

For short term storages the calculation process should consider the hourly charging and discharging process along the day. The knowledge of the daily distribution of the heating demand is crucial in order to determine the performance. On the other hand, the daily performance does not affect the storage temperature of long term storage due to their big thermal inertia. Nevertheless, the seasonal charging and discharging process affects the thermal performance of the system.

Simulation of thermal systems with seasonal storage requires calculating at least the hourly performance of a system with many variables for several years. This process might take several minutes in current computers, which is an acceptable amount of time for designers to calculate one case.

If the effect of design variables is to be analyzed, then it might be required to calculate hundreds or thousands of cases with different input parameters. The time required for such application might be in the order of days, which might be a problem. If the number of design variables to optimize is high, the number of cases to simulate increases exponentially.

To analyze the design of solar heating systems with seasonal storage a short-cut simulation model has been used to perform parametric analysis finding the design space (Kulkarni et al., 2007). The calculations were performed with hourly simulations of several days per month reducing the calculation effort compared to a complete annual simulation. The design space generated by Kulkarni analyzes the design variables area of solar field *A* and volume of the seasonal storage *V*, with the solar fraction achieved.

Recently, short-cut simulations have been also used to find economic optimized designs using micro-genetic algorithms (Kim et al., 2012).

3.5.1 SOLCOST

The SOLCOST method was developed for solar thermal systems to determine the monthly performance of solar thermal collectors simulating the hourly performance of two typical days per month (Connelly et al., 1976). It calculates a cloudy and a clear day and weights the monthly results to the average cloudiness. The calculation effort is significantly reduced, i.e. SOLCOST calculation method requires the calculation of 24 days per year instead of 365 days as in a complete simulation.

3.5.2 Lunde

Integrated equation developed by Lunde (1979) for solar thermal systems with seasonal storage predicts the performance of solar thermal collectors for a certain period. This method uses pre-processed climatic data that simplifies the sum of equations for each period of time into one equation for the whole month. Elaborated climatic data is required to calculate the monthly production of the solar field Q_c (MWh): incident radiation $q_{r,op}$ (Wh/m^2) and ambient temperature ($T_{a,op}$) along the operation period (t_{op}). The operation period contains hours with solar radiation higher than a certain value. These data are specific for a location and a collector inclination-orientation.

$$Q_c = A \cdot (\eta_0 \cdot q_{r,op} - k_1 \cdot (T - T_{a,op}) \cdot t_{op} - k_2 \cdot (T - T_{a,op})^2 \cdot t_{op}) \cdot 10^{-6} \qquad (27)$$

being T the average storage temperature.

The method calculates the seasonal storage temperature at the end of the month as a result of an energy balance similar to the methods presented in the utilizability section. The system of equations can be simplified into a second degree equation that can be solved for each month sequentially.

The simplicity of the equations reduces the calculation effort but is preceded by the need of elaborated climatic data. To extend the use of this method to new locations, it will be required to transform a large amount of climatic data into pre-processed data for the calculation process.

3.5.3 Simple method

In this thesis a simple calculation method for CSHPSS based on the physics of the solar collector field and the thermal energy storage is presented. For each month, it estimates the hourly performance of the solar collector field on a typical day and the monthly performance of the seasonal storage and auxiliary systems, considering limits to the seasonal storage charge and discharge.

This method uses simple climatic and demand data that can be easily obtained for any location or case. The load is defined by the consumption of DHW and the needs of SH and can be adjusted by the user, being possible to calculate systems with different load profiles.

The performance of the solar collector is calculated according to the performance coefficients obtained from ISO 9806 (1992) utilizing the collector temperature, which depends on the storage temperature and the effectiveness of the heat exchanger in the solar field. Limitations on the charging process are considered as in the method developed by Lunde (1979).

The mathematical model of the *Simple Method* is completely described in Chaper 4. The *Simple Method* has been validated with dynamic simulation models generated with TRNSYS and with other calculation methods available in literature.

The *Simple Method* has been used to perform a parametric analysis that determines the performance of the system under different design conditions. In Chapter 5 an economic model for CSHPSS is generated. The economic model is used with the *Simple Method* to determine the cost of the solar heat, performing parametric analyses and finding minimum cost designs.

In Chapter 6 a simplified environmental assessment for CSHPSS is presented. The environmental assessment based on the design parameters is used with the *Simple Method* to find designs with minimum environmental impact. To conclude and to improve its dissemination, in Chapter 7 of the thesis a software application based on the *Simple Method*, developed by the author in EES in the framework of IEA-SHC Task 45, (download available) is presented. The application can be used to pre-design CSHPSS in Europe obtaining economic and environmental impact results.

3.6 Economic and environmental analyses

Meeting the needs of the present generation without compromising the ability of future generations to meet their own needs (Brundtland Commission, 1987). This definition of sustainable development can be applied to the economic and environmental levels. Energy is a commodity of prime necessity and to secure energy supply for the future at an affordable price without compromising our ecosystem must be an international priority.

In this thesis energy systems that use local and renewable energy sources supply heat without increasing the cost of the energy for present and future generations are analyzed. The environmental burdens generated or avoided by these systems are investigated and compared to the use of conventional energy systems.

3.6.1 Economic analysis

Energy services such as hot water, heating or cooling require an initial investment in equipment that will transform the energy resources into the services. The initial investment should be amortized along the expected life of the equipment. Boilers require fuel to produce heat and compressors in cooling machines require electricity to produce cooling. Besides the basic operation costs, the plant suffers deterioration during its expected life; maintenance tasks are required to keep the plant in good operation. The operation and maintenance (op&m) costs must be included in the annual costing evaluation. For big plants other costs might be included in the operation costs such as the expenses for personnel and equipment to operate and control the plant. An economic analysis of a thermal energy system should consider at least these three expenses to estimate the economic cost: amortization, operation and maintenance and the non-renewable resources consumed.

For renewable energy systems the initial investment is usually higher than in conventional energy systems, but the cost of commercial energy is considerably lower due to the reduced consumption of fuels and electricity. If the increase in the amortization cost is compensated by the fuel reduction and the reduction in maintenance and operation costs, then the economic investment becomes viable. Other variables can be considered, as the payback period for an investment, the expected rise for fuel and electricity prices or the interest rate for a long-period loan.

3.6.2 Thermoeconomic analysis

Thermoeconomics merges economic analysis and thermodynamics with the purpose of revealing opportunities in energy and cost savings when designing and operating energy conversion systems. It can be used to calculate the cost formation process in CSHPSS, large scale solar thermal plants and any other thermal system.

In thermoeconomic analysis, the unit cost of internal flows and products of a system is calculated for each stream with cost balances and auxiliary equations for allocation criteria in case of multiproduct systems. A general methodology for calculating efficiencies and costs in thermal systems was proposed by Lazzaretto and Tsatsaronis (2006) and a cost allocation method based on the exergy of products was developed by Lozano and Valero (1993). Verda et al. (2001) applied the thermoeconomic analysis to design district heating systems. CSHPSS systems have been analysed from a thermoeconomic point of view by our research group in previous years (Lozano et al., 2010c) and also for solar air heating systems (Lozano et al., 2014). In this work this analysis will no longer be explored, but used to evaluate the environmental impact for internal flows.

3.6.3 Environmental analysis

In order to have a complete vision of the interest and advantages of large scale solar thermal systems it is necessary to gain a better understanding of the environmental impacts caused or avoided by the system during its whole life cycle. To this end, the Life Cycle Assessment (LCA) procedure, standardized by ISO 14040 (2006), can be utilized to analyze the entire range of environmental damages associated with a product or a service through the life cycle, from the consumption of raw materials to the final disposal.

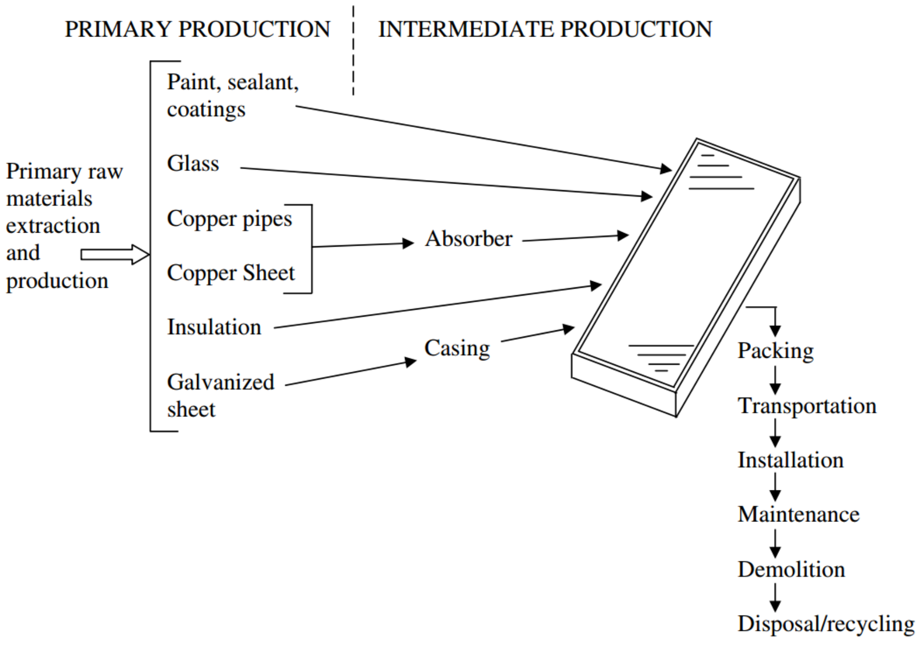

Figure 3.6: Processes considered in the LCA of a solar collector (Kalogirou, 2009)

Environmental burdens generated by the system are estimated based on relevant emissions to the atmosphere, e.g. greenhouse gases, NO_x, SO_x, and cumulative energy demand (CED), as well as with other environmental indicators as the IMPACT 2002+.

There is a relatively limited number of studies which focuses on solar thermal systems and most of these studies analyze the life cycle of solar systems for residential houses (2-5 people). Verda and Colella (2011) explored primary energy savings in district heating systems and Oró et al. (2012) compared the environmental impact of thermal energy storages for solar power plants.

Hang et al. (2012) carried out a comparative LCA of thermal solar systems focused on the analysis of flat plate collectors and vacuum tubes. Oró et al. (2012) focused on the DHW storage systems (molten salt and solid medium) and only few works (Simons and Firth, 2011) analyze solar thermal application for several dwellings.

3.6.4 Multiobjective optimization

Energy systems can be designed to produce useful energy services with a minimum investment required or with a minimum unit product cost. It is also possible to design energy systems with the lowest environmental impact; however, if two different design objectives are searched at the same time (i.e. minimum cost and minimum environmental impact) then very likely there will not be an optimum solution fulfilling both requirements at the same time. Pareto-optimal solutions can be obtained if one of the optimization variables is set as a constant value and the optimization objective is to minimize the other variable. Carvalho et al. (2012) applied multiobjective optimization for the synthesis of trigeneration systems and Gebreslassie et al. (2012) designed absorption cooling cycles for the reduction of global warming and cooling cost.

3.7 Conclusions

Calculation and design methods have been classified by different authors in different categories. Duffie and Beckman (2006) classified design methods for solar thermal systems according to the assumptions required for the calculation process and Löf (1993) classified design methods in semi-empirical correlations, simplified simulation methods or utilizability methods. In this chapter, they have been classified in six categories according to the focus, detail of characterization and complexity of the calculation process.

1) Characterization of solar collectors: methods to estimate the performance of the solar collector from experimental results.
2) Utilizability methods: empirical correlations that can be used to estimate the performance of solar thermal collectors along a day or a month based on the expected distribution of the radiation.
3) Simulation tools: calculation methods based on a detailed dynamic simulation of the system components using at least hourly climatic and demand data.
4) Semi-empirical methods: correlations generated from a large number of detailed simulations, or from empirical results, to estimate the performance of solar thermal systems.
5) Short-cut simulations: design and calculation methods that estimate the performance of typical days each month or with data series instead of doing detailed simulations along the whole year reducing the calculation effort.
6) Economic and environmental analysis: complementary analyses are required to design and evaluate solar thermal energy systems.

It is claimed in this chapter that there is a lack of simple calculation methods for CSHPSS. They have been developed in the early 80´s but they have been forgotten for a long time. Currently there is a demand for simple calculation tools to predesign these systems. Some applications have been presented based on semi-empirical methods, or on the experience of experts that can only be applied to specific locations and climates.

A simple calculation tool that could be applied to any location and climate would be very useful for the development of these systems. Furthermore, simple calculation tools could also be used to perform parametric analyses with significant lower calculation effort to find optimized designs based on economic and environmental assessments.

Table 3.1: Classification of calculation methods for solar thermal systems

Category	Methods	Description
Characterization of solar collectors	Hottel and Woertz, 1942	Characterization model with two coefficients.
	Jordan and Liu, 1977	ASHRAE correlation.
	EN 12975-2:2006 1) Steady state 2) Quasi dynamic test	Current standard for solar collector. 1) Difficult to do in outdoor conditions. 2) Difficult data treatment.
Utilizability methods	Drew and Selvage, 1980	Sizing for 100% solar fraction systems.
	Braun et al, 1981	Monthly performance with utilizability.
	Lund, 1989	Integrating uniform functions by tranches.
Semi-empirical methods	f-Chart, 1976-1977	Tool to design solar DHW systems.
	CHEQ4	Simple tool for Spanish solar DHW.
	SDH online calculation tool	Based on TRNSYS simulations, centralized and decentralized SDH systems.
	f-Easy, 2014	Feasibility tool for presizing solar plants based on simple coefficients and ratios.
	Fjernsol, 2014	Compare scenarios in Denmark.
Short-cut simulation	SOLCOST	Simulate cloudy and clear sky day each month.
	Lunde, 1979	Integrated equations with elaborated data.
	Kulkarni et al., 2007	Hourly simulation of few days per month.
	Simple method	Hourly simulation of one day per month.
Simulation	TRNSYS	Dynamic simulation of thermal systems.
	Polysun	Predesigned solar thermal systems.
	Matlab	Generic tool with solar thermal library.
	EnergyPro	Flexible modelling software for the design, simulation and optimization of energy systems.
	Minsun	Solar simulator tool developed by Task 7, 1985.

Very few environmental impact analyses of CSHPSS have been performed. An appropriate approach for this analysis is the Life Cycle Assessment technique, which accounts all the environmental burdens along the life cycle of the analyzed system. A LCA for a CSHPSS and a simplified method to parametrize the environmental impact of the most important components to make it extendible to other installations is presented in Chapter 6.

Part II:
DESIGN AND ANALYSIS

Part II: Design and analysis

Central Solar Heating Plants with Seasonal Storage (CSHPSS) can supply heat for space heating and domestic hot water demands of big communities at an affordable price. These systems already supply heat through district heating systems in north and center European countries. The evaluation of the performance and the design of these centralized solar systems is a complex process, due to their dynamic behavior, both during the day and along the year.

The production of the solar collector field depends on the solar radiation and the ambient temperature, changing along the day, as well as on the operation temperature of the seasonal storage tank, changing along the year. The behavior and operation temperature of the seasonal storage depend on the demand and solar production distributions along the year. Further, location and demand size affect the performance of the system in such way that the sizing between the north and south of Europe might be very different. As a result, the process of pre-design and study in initial stages of the project becomes a real challenge.

Dynamic simulations with TRNSYS (TRNSYS 16, 2010) of CSHPSS provide an evaluation of the performance of its behavior with a high accuracy (Guadalfajara et al., 2012; Guadalfajara, 2013; Lozano et al., 2010b; Lundh and Dalenbäck, 2008; Raab et al., 2005) but it requires exhaustive and detailed information and a high computational effort. Simple calculation methods requiring less detailed data and a lower computational effort can complement TRNSYS for a preliminary quick evaluation of the size of the main components of an installation, facilitating the design task and providing an estimate of its annual performance (Braun et al., 1981; Guadalfajara et al., 2013a, 2013b, 2014a, 2014b, 2014c, 2014d, 2014e; Lunde 1979).

In Part II of this thesis, tools to design and evaluate CSHPSS from different points of view are presented: technical, economical or environmental. These tools are completely described and applied to different locations and cases in Spain and Europe in order to obtain appropriate design criteria and to evaluate the potential of this technology.

In Chapter 4 an original calculation method for CSHPSS is presented, based on simple climatic and demand data. In Sections 4.1 to 4.4 the calculation method (*Simple Method*) divided in the four modules is presented. The calculation method has been built using the Engineering Equation Software (EES, 2013) and public climatic and demand data that can be easily obtained. The *Simple Method* calculates the behavior of the system on a monthly basis and can be used to pre-design the solar field and the volume of the seasonal thermal energy storage of CSHPSS. Then in the following sections of Chapter 4, a case generated with TRNSYS for a location in Spain has been used to validate the results of the *Simple Method.* The results obtained for that case are also compared with other calculation methods and design tools.

The *Simple Method* is useful to perform feasibility studies in preliminary stages of a project, as well as to establish optimization and design criteria of CSHPSS. In Chapter 5 CSHPSS cost is analyzed based on the size of the main pieces of equipment. The economic analysis considers the operation & maintenance cost and the effect of paying the installation along the amortization period with an interest rate applied over the initial investment required. The economic analysis is used to define new design criteria to obtain CSHPSS with minimum cost according to specific climatic and demand data.

In Chapter 6 an environmental analysis is performed for CSHPSS applying the Life Cycle Assessment (LCA) method. LCA is an objective methodology that evaluates the environmental loads associated with a product, process, or activity, identifying and quantifying the use of mass and energy as well as environmental emissions over its life cycle. It provides a comprehensive view of the environmental aspects of the energy produced in the CSHPSS and a more accurate picture of the true environmental trade-offs in process selection.

To finalize Part II of the Thesis, in Chapter 7 applications of the work developed are presented. Section 7.1 presents parametric analyses of CSHPSS based on the *Simple Method* and the environmental assessment to design systems with minimum environmental impact. Section 7.2 presents an extension of the climatic and demand data required by the *Simple Method* to be used in different locations. A software application is presented in Section 7.3. This software is based on the *Simple Method* and on the economic and environmental procedures presented in Chapters 5 and 6. The software application, available online, has been developed in the context of this thesis and the collaboration in Task 45 (Task 45, 2013). This software application overcomes one of the barriers found by the expert group of the Task 45 for the development of large solar heating plants with seasonal storage: the lack of simple design methods for CSHPSS. This software application is presented in this section and used to analyze the effect of climate over the design, cost and environmental impact of CSHPSS for different locations in Europe. Finally in Section 7.4 a geographic analysis of CSHPSS is presented, comparing different design requirements, economic costs and environmental impact of installations located in several cities of Europe.

Chapter 4: Simple Method

4 Simple Method

The *Simple Method* is based on the possibility of performing an approximate calculation on a monthly basis of the solar collector field production and the capacity of the seasonal thermal energy storage to match production and demand. Fig. 4.1 shows the system scheme and identifies the main energy flows that appear in the *Simple Method*.

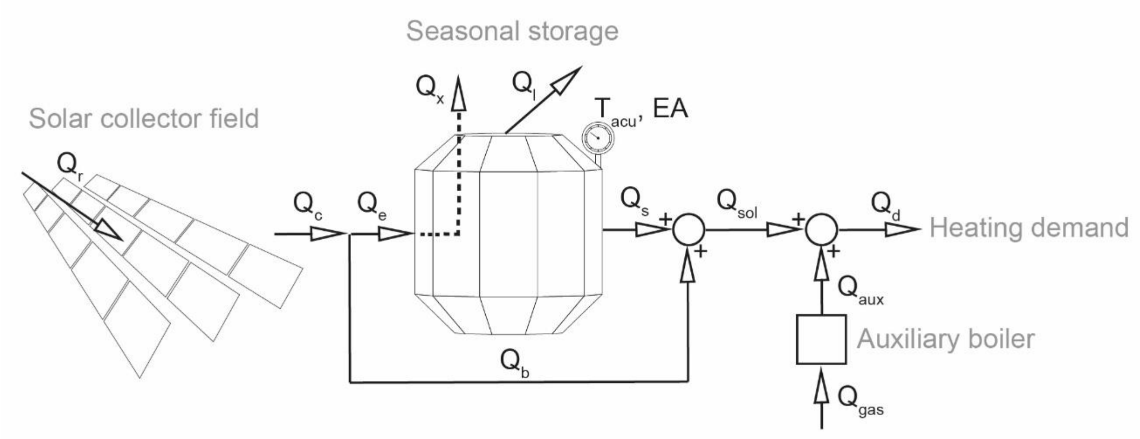

Figure 4.1: Energy flow chart of the *Simple Method*

The radiation received, Q_r, over the solar collector is harvested and the production of the solar field, Q_c, is calculated simulating its hourly operation during a representative day of the month. A complete mixture in the thermal energy storage is considered, i.e. without stratification; so the accumulator temperature is uniform, T_{acu}, along the calculation period, which is a month in the proposed method. Thus, the solar collector performance and the heat losses, Q_l, of the seasonal storage are calculated considering the tank temperature at the beginning of the month. In a seasonal storage tank, the assumption of constant water tank temperature along the month is reasonable due to the high thermal inertia (high volume) of the tank. A monthly energy balance is used to calculate the temperature in the thermal energy storage at the end of the month. The water tank temperature at the end of the month is used to calculate the solar collector performance the following month.

The monthly operation of the seasonal storage tank has two different operation modes during the year: i) charge and ii) discharge.

The charge operation mode occurs when the production of the solar field, Q_c, is higher than the heat demand, Q_d. Then part of the collected heat will be used to attend the immediate demand, Q_b, and the surplus collected heat will be sent to the seasonal storage for its later consumption, Q_e.

In the discharge operation mode, the heat demand, Q_d, is higher than the production of the solar collector field, Q_c, and the seasonal storage tank is first discharged, Q_s, and if it is still not enough, then the auxiliary system, Q_{aux}, provides the required heat to cover the demand.

The thermal energy storage operation is constrained by two temperature limits, T_{min} and T_{max}. When the limit of the minimum temperature is reached, the thermal energy storage cannot be discharged anymore and the auxiliary system provides the required heat, Q_{aux}, to fulfil the demand. The thermal energy storage cannot be charged over the maximum temperature. When it reaches this maximum temperature limit, part of the heat production is rejected, Q_x, to avoid overheating and equipment damage. As the thermal energy storage is warm, the heat losses to the environment, Q_l, are also calculated. The thermal energy accumulated in the storage tank is denoted by the variable EA.

As shown in Fig. 4.2, the *Simple Method* consists of four sequential modules for the calculation of the annual and monthly performance of a CSHPSS.

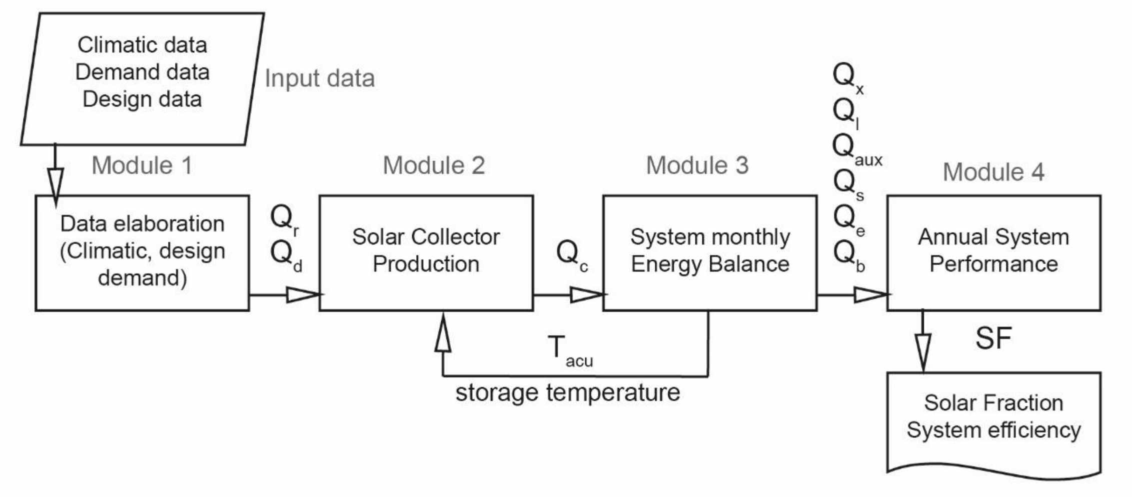

Figure 4.2: Information flow chart and scheme of the *Simple Method* calculation modules

Using public data that can be easily obtained, Module 1 elaborates the hourly and monthly climatic and demand data required to calculate the system performance (hourly radiation over tilted surface, hourly ambient temperature, monthly demand…).

Module 2 calculates the monthly production of the solar field based on the hourly radiation and hourly ambient temperature of a typical day each month calculated in Module 1, and on the tank temperature at the beginning of the considered month. The calculation of the solar collector field is based on the performance equation of the solar collector. The effectiveness of the heat exchanger that connects primary and secondary circuits (between the solar field and the seasonal storage tank) is also considered.

Each month an energy balance, considering production, demand and losses, is used to calculate the energy charged/discharged/accumulated in the seasonal storage and if required the auxiliary energy, as well as storage temperature at the end of the month and the heat rejected, in case the storage tank would be fully charged (Module 3).

Module 4 calculates the technical results: annual energy balance, global efficiency of the system and of the considered components, solar fraction, as well as an estimation of the investment, operation and maintenance costs of the system and the solar heat cost if the economic analysis is included (Chapter 5).

A base case has been used to present the *Simple Method*. The base case corresponds to a CSHPSS that supplies thermal energy for a 1000 dwellings community in Zaragoza (Spain), thermal energy for space heating and domestic hot water. The base case is calculated and the details of the calculation process are presented to explain the *Simple Method*.

The *Simple Method* has been compared with other design methods in literature and with dynamic simulation models, for validation purposes. A model generated in TRNSYS has been calculated with the *Simple Method* and with other design methods in order to compare the results obtained with each design method. The results obtained with the *Simple Method* are slightly conservative compared to the TRNSYS model but more accurate than many other modern simple design methods due to the capacity of using specific climatic data.

4.1 Base case

To make the evaluation of CSHPSS easier with the *Simple Method* a few public available data are used. The minimum input data required are: annual demand of domestic hot water, Q_{DHW}, and space heating, Q_{SH}; latitude of the location; monthly average of daily global radiation on a horizontal surface, $\bar{H}$ (monthly data); monthly average of daily medium, minimum and maximum ambient temperatures, Ta_{ave}, Ta_{min} and Ta_{max} (monthly data); monthly degree-days, DD_{15} (base 15ºC, monthly data); cold water temperature from the network, T_{CW} (monthly data); ground temperature, T_{gr}; and ground reflectance, ρ_g.

In the considered base case the installation is located in Zaragoza (latitude 41.6º) and it supplies heat for space heating and domestic hot water for a community of 1000 dwellings of 100 m^2 each. The considered demand has been taken from the reference values in Spain for new multifamily buildings (IDAE, 2009). In Zaragoza the annual demand for space heating in multifamily buildings is 40.6 kWh/m^2 and the domestic hot water demand is 12.9 kWh/m^2. Data shown in Table 4.1 have been obtained from multiple sources: radiation (UNE 94003, 2007), degree-days (UNE 100-002-88, 1988), average medium, minimum and maximum ambient temperatures (AEMET, 2010) and cold water temperature of the supply network (UNE 94002, 2005).

Table 4.1: Climatic data for Zaragoza used by the *Simple Method*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$\bar{H}$ (MJ/(m^2·day))	6.4	9.8	13.8	17.4	21.5	23.8	25.3	22.5	16.5	11.6	7.5	5.7
DD_{15} (K·day)	285	222	187	99	26	1	0	0	3	52	176	286
Ta_{min} (ºC)	2.4	3.5	5.2	7.4	11.2	14.8	17.6	17.8	14.7	10.3	5.8	3.5
Ta_{ave} (ºC)	6.4	8.4	10.9	13	17.2	21.3	24.5	24.4	20.7	15.5	10.0	7.1
Ta_{max} (ºC)	10.3	13.3	16.6	18.7	23.2	27.7	31.5	31.0	26.7	20.7	14.3	10.7
T_{CW} (ºC)	8	9	10	12	15	17	20	19	17	14	10	8

Primary design variables considered in the *Simple Method* are the following: area of solar collector, A (or RAD which is the ratio solar field area, m^2, divided by the annual demand in MWh/year); volume of the seasonal storage tank, V (or RVA, which is the ratio volume of the seasonal storage tank, m^3, divided by the solar field area in m^2).

Secondary design variables are: solar collector efficiency curve (η_0, k_1, k_2); tilt, β, and orientation, γ, of the solar collector field; specific mass flow rate of the solar field, m_s; solar field´s heat exchanger effectiveness, E_{ff}; supply, $T_{sup,}$ and return, $T_{ret,}$ temperature from/to the district heating network; minimum, T_{min}, and maximum, T_{max}, temperature in the seasonal storage; and storage global heat transfer coefficient to the ambient, U_{acu}, to calculate thermal losses. The parameters for the base case are presented in Table 4.2.

Table 4.2: Design parameters for the base case

	Parameter	Value
Solar Collector Field	RAD: ratio area of solar collector per unit of demand	0.6 m^2/(MWh/yr)
	A: area of solar collectors	3210 m^2
	η_0: optical efficiency	0.816
	k_1: 1st order heat loss coefficient	2.235 W/(m^2·K)
	k_2: 2nd order heat loss coefficient	0.0135 W/(m^2·K^2)
	β: tilt	45º
	γ: orientation	0º
	m_s: solar field flow rate	20 kg/(h·m^2)
	$c_{p,sf}$: specific heat capacity of the solar field fluid	4180 J/(kg·K)
	ρ:density of the solar field fluid	1000 kg/m^3
	Eff: heat exchanger effectiveness	0.9
Seasonal Storage	RVA: ratio volume / area	6 m^3/m^2
	V: volume of seasonal storage	19,260 m^3
	T_{min}: minimum storage temperature	30ºC
	T_{max}: maximum storage temperature	90ºC
	RHD: ratio storage height divided by diameter	0.6 m/m
	U_{acu}: heat transfer coefficient to the ambient	0.12 W/(m^2·K)
	A_{acu}: heat transfer area	4101 m^2
	ρ·c_p: heat capacity	4.18·10^6 J/(m^3·K)
Heating Demand	Q_{SH}: annual space heating demand	4060 MWh/yr
	Q_{DHW}: annual DHW demand	1290 MWh/yr
	Q_d: annual demand	5350 MWh/yr
District Heating	T_{sup}: supply temperature	50 ºC
	T_{ret}: return temperature	30 ºC
	T_{DHW}: DHW temperature	50 ºC

The seasonal storage is assumed as an underground cylindrical tank with a shape ratio RHD = 0.6 (height, H, divided by diameter, D). Once the volume is known the other dimensions can be calculated as well: accumulator area A_{acu} and maximum energy stored EA_{max} (MWh).

$$D = (4 \cdot V/(\pi \cdot RHD))^{1/3} \quad (1)$$

$$H = RHD \cdot D \quad (2)$$

$$A_{acu} = (RHD+0.5) \cdot \pi \cdot D^2 \quad (3)$$

$$EA_{max} = V \cdot \rho \cdot c_p \cdot (T_{max}-T_{min}) / (3.6 \cdot 10^9) \quad (4)$$

The ground temperature, T_{gr}, has been considered constant along the year and equal to the average ambient temperature (15.0 ºC in Zaragoza) due to its low response to ambient temperature variations at storage depth.

4.2 Module 1: Data elaboration

In the Module 1 the hourly ambient temperature Ta[m,h] for a representative day of each month and the hourly radiation over tilted surface q_r[m,h] in W/m^2 are calculated. The Erbs´s correlation for the ambient temperature (Erbs et al., 1983) is used to estimate the hourly ambient temperature along the day; it uses the minimum (Ta_{min}), maximum (Ta_{max}) and monthly average daily temperatures (Ta_{ave})

$$Ta[m,h] = Ta_{ave}[m] + (Ta_{max}[m] - Ta_{min}[m]) \cdot \sum_{k=1..4} a_k \cdot cos(k \cdot \tau[h] - b_k) \qquad (5)$$

where h is the solar hour (h = 12 is the solar high noon) and

$$\tau[h] = 2 \cdot \pi \cdot (h - 1) / 24 \qquad (6)$$

The sky clearness index can be obtained from the average daily horizontal radiation and the extraterrestrial radiation, which depends on the city latitude and the date (Duffie and Beckman, 2006). This index is used to calculate the daily diffuse radiation with Erbs's correlation (Erbs et al., 1982).

The total horizontal radiation is hourly distributed with the Collares-Pereira and Rabl's (1979) correlation, and the diffuse horizontal radiation is hourly distributed with Liu and Jordan's (1960) correlation. The difference between total radiation and diffuse radiation is the direct (beam) horizontal radiation. The radiation in tilted surface is calculated using the isotropic sky model (Duffie and Beckman, 2006).

For the month of May (m=5) in Zaragoza Table 4.3 shows the estimated hourly: ambient temperature Ta[5,h], horizontal irradiance I_0[5,h], and irradiance over tilted surface q_r[5,h], at β = 45º and south oriented γ = 0º with a ground reflectance ρ_g = 0.2.

Table 4.3: Hourly ambient temperature and irradiance for a typical day in Zaragoza in May

Hour	Ta (ºC)	I_0 (W/m^2)	q_r (W/m^2)
5:00 – 6:00	11.8	65	31
6:00 – 7:00	12.0	182	112
7:00 – 8:00	13.0	316	253
8:00 – 9:00	14.6	453	402
9:00 – 10:00	16.7	577	541
10:00 – 11:00	18.8	671	648
11:00 – 12:00	20.6	722	706
12:00 – 13:00	21.9	722	706
13:00 – 14:00	22.8	671	648
14:00 – 15:00	23.4	577	541
15:00 – 16:00	23.5	453	402
16:00 – 17:00	22.9	316	253
17:00 – 18:00	21.8	182	112
18:00 – 19:00	20.3	65	31

Further in the Module 1, the annual space heating demand (Q_{SH}) is monthly distributed according to the monthly degree-days (Lozano et al., 2010a). As centralized systems tend to be unplugged when the demand is low, the space heating demand supplied is considered 0 in those months in which the degree-days, DD_{SH}, are lower than the monthly days, N.

$$DD_{SH}[m]: \text{ If } DD_{15}[m] > N[m] \text{ Then } DD_{SH}[m] = DD_{15}[m] \text{ Else } DD_{SH}[m]=0 \quad (7)$$

$$Q_{SH}[m] = Q_{SH} \cdot DD_{SH}[m] / \sum_{m=1..12} DD_{SH}[m] \quad (8)$$

The domestic hot water demand (Q_{DHW}) is monthly distributed with the method proposed by the standard UNE 94002 (UNE 94002, 2005), in which the demand depends on the cold water temperature, T_{CW}, and the number of days in each month.

$$DD_{DHW}[m]= N[m] \cdot (T_{DHW} - T_{CW}[m]) \quad (9)$$

$$Q_{DHW}[m] = Q_{DHW} \cdot DD_{DHW}[m] / \sum_{m=1..12} DD_{DHW}[m] \quad (10)$$

The system monthly demand is the sum of both SH and DHW demand.

$$Q_d[m] = Q_{SH}[m] + Q_{DHW}[m] \quad (11)$$

The obtained results of the monthly demand are shown in Table 4.4.

Table 4.4: Monthly demand obtained with Module 1 for the analyzed base case

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	*Year*
Q_{SH} (MWh)	885	690	581	308	0	0	0	0	0	162	547	888	4060
Q_{DHW} (MWh)	125	110	119	110	104	95	90	92	95	107	115	125	1290
Q_d (MWh)	1011	800	700	417	104	95	90	92	95	269	662	1014	5350

Note that the *Simple Method* does not require the elaboration data performed in the Module 1 for the evaluation of CSHPSS if equivalent data are provided (monthly demand and hourly ambient temperature and radiation over tilted surface for a representative day for each month).

4.3 Module 2: Solar collector field production

The solar collector production, $q_c[m,h]$ (Wh/m^2), is calculated for each hour using the solar collector efficiency curve (η_0, k_1, k_2) of the large solar collectors employed (Arcon, 2013). This calculation requires the solar radiation $q_r[m,h]$ and the temperature difference between the solar collector, T_c, and the ambient temperature, Ta. Note that only the heat collected when the efficiency value is positive is considered (Eq. 12).

$$q_c[m,h] = Max\,(\eta_0 \cdot q_r[m,h] - k_1 \cdot \Delta T[m,h] - k_2 \cdot \Delta T[m,h]^2\ ;\ 0) \qquad (12)$$

$$\Delta T[m,h] = T_c[m,h] - Ta[m,h] \qquad (13)$$

The solar collector temperature is the average value between the inlet and the outlet temperature of the fluid in the solar collector.

$$T_c[m,h] = (T_{in}[m,h] + T_{out}[m,h])/2 \qquad (14)$$

The fluid circulating through the solar collector transfers the collected heat to the seasonal storage through a countercurrent plate heat exchanger. Considering that the heat capacity of the fluids circulating through the primary circuit (solar collector) and through the secondary circuit (load circuit charging the accumulator) is the same, and that the temperature of the water in the accumulator remains constant during the whole month, the next equation is obtained:

$$T_{in}[m,h] = T_{out}[m,h] - E_{ff} \cdot (T_{out}[m,h] - T_{acu}[m-1]) \qquad (15)$$

The outlet temperature of the solar collector fluid depends on its inlet temperature, the mass flow rate m_s, and its specific heat capacity $c_{p,sf}$.

$$T_{out}[m,h] = T_{in}[m,h] + q_c[m,h] \cdot 3600 / (m_s \cdot c_{p,sf}) \qquad (16)$$

The five variables (q_c, ΔT, Tc, T_{in}, T_{out}) are obtained from Eqs. 12 to 16.

The hourly performance for the typical day in May is presented in Table 4.5.

Table 4.5: Hourly performance of the solar collector field for a typical day in Zaragoza in May

Hour	Ta (ºC)	T_{in} (ºC)	T_{out} (ºC)	q_r (W/m^2)	q_c (W/m^2)
5:00 – 6:00	11.8	29.1	29.1	31	0
6:00 – 7:00	12.0	29.3	31.3	112	46
7:00 – 8:00	13.0	29.8	36.5	253	155
8:00 – 9:00	14.6	30.4	42.3	402	274
9:00 – 10:00	16.7	30.9	47.5	541	385
10:00 – 11:00	18.8	31.3	51.6	648	471
11:00 – 12:00	20.6	31.6	54.0	706	520
12:00 – 13:00	21.9	31.6	54.1	706	524
13:00 – 14:00	22.8	31.4	52.1	648	482
14:00 – 15:00	23.4	31.0	48.3	541	402
15:00 – 16:00	23.5	30.5	43.2	402	296
16:00 – 17:00	22.9	29.9	37.7	253	180
17:00 – 18:00	21.8	29.4	32.4	112	70
18:00 – 19:00	20.3	29.1	29.3	31	4

The monthly production of the solar field $Q_c[m]$ is the sum of the hourly values multiplied by the solar collector field area A and the number of the days of the month.

$$Q_c[m] = A \cdot N[m] \cdot 10^{-6} \sum_{h=1..24} q_c[m,h] \qquad (17)$$

The monthly radiation $Q_r[m]$ received by the solar field is calculated in a similar way, changing $q_c[m,h]$ for $q_r[m, h]$ in Eq. 17.

For the month of May in Zaragoza, the system harvests a total radiation $Q_r[5]$ = 536 MWh, generating a total production of thermal energy $Q_c[5]$ = 379 MWh.

4.4 Module 3: Monthly energy balance

The monthly energy balance of the system requires a control of the minimum and maximum seasonal storage temperature. These limits guarantee the calculation of the charge and discharge fulfilling the physical constraints of the storage, which affect the auxiliary energy required to cover the demand, when the tank is empty, and the heat rejected, in the case of the tank being fully charged. All the thermal energy flows appearing in Module 3 are expressed in MWh/month.

The system is operated in such a way that each month the heat harvested in the solar collector field, Q_c, will firstly fulfill the demand, Q_b, and, once it has been covered, the remaining heat, Q_e, will be introduced into the thermal storage (see Fig. 4.1).

$$Q_e[m] = Max\,(Q_c[m] - Q_d[m];\,0) \qquad (18)$$

$$Q_b[m] = Q_c[m] - Q_e[m] \qquad (19)$$

Heat loss of the seasonal storage tank, Q_l, is calculated by multiplying the global heat transfer coefficient of the accumulator U_{acu} in $W/(m^2 \cdot K)$ by the tank area A_{acu} in m^2, by the temperature difference between the tank T_{acu} and the ground T_{gr}, and by the number of hours of the month. The considered tank temperature is the temperature at the beginning of the month (temperature at the end of the previous month).

$$Q_l[m] = U_{acu} \cdot A_{acu} \cdot (T_{acu}[m-1] - T_{gr}) \cdot 24 \cdot N[m] \cdot 10^{-6} \qquad (20)$$

In order to calculate the tank discharge, an auxiliary variable, Q_{sx}, which expresses the maximum amount of heat that could be discharged, is used. This maximum amount depends on the accumulated energy, EA, the heat introduced, Q_e, and the thermal losses, Q_l.

$$Q_{sx}[m] = Max\,(EA[m-1] + Q_e[m] - Q_l[m];\,0\,) \qquad (21)$$

The monthly auxiliary energy required, Q_{aux}, is calculated as follows:

$$Q_{aux}[m] = Max\,(Q_d[m] - Q_b[m] - Q_{sx}[m];\,0) \qquad (22)$$

Finally, the discharged heat, Q_s, is calculated as a difference between demand, solar direct production, and auxiliary energy required.

$$Q_s[m] = Q_d[m] - Q_b[m] - Q_{aux}[m] \qquad (23)$$

The monthly solar heat consumed, Q_{sol}, is

$$Q_{sol}[m] = Q_b[m] + Q_s[m] \qquad (24)$$

The theoretical energy accumulated, EA_x, at the end of the month is calculated without considering the temperature limit. In real installations there are security systems that stop the solar field pumps when the maximum seasonal storage temperature is reached, $T_{acu} = T_{max}$. In the simple method this effect is modeled calculating the heat rejected, Q_x. Thus, the theoretical energy accumulated, EA_x, at the end of the month is

$$EA_x[m] = EA[m\text{-}1] + Q_e[m] - Q_l[m] - Q_s[m] \qquad (25)$$

If this energy is higher than the storage capacity, part of the solar production will be rejected. The final energy accumulated, EA, and the heat rejected, Q_x, are given by the following equations:

$$EA[m] = Min\ (EA_x[m];\ EA_{max}) \qquad (26)$$

$$Q_x[m] = EA_x[m] - EA[m] \qquad (27)$$

The accumulator temperature at the end of the month is calculated considering the real energy stored.

$$T_{acu}[m] = T_{min} + (T_{max} - T_{min}) \cdot EA[m] / EA_{max} \qquad (28)$$

All the calculations are performed for an annual cycle in which the accumulator temperature at the end of the year is the same as that at the beginning.

$$T_{acu}[0] = T_{acu}[12] \qquad (29)$$

The consumption of electricity in pumps and heat losses in pipes, heat exchangers and in the district heating network have not been considered in the calculation. In Table 4.6 the monthly results for the analyzed case are shown.

4.5 Module 4: Annual results

The annual energy flows of the system Q_i (Q_d, Q_r, Q_c, Q_b, Q_e, Q_x, Q_l, Q_s, Q_{aux} and Q_{sol}) are calculated as follows,

$$Q_i = \sum_{m=1..12} Q_i[m] \qquad (30)$$

and the annual net energy balance should be equal to zero.

$$Balance_{annual} = Q_c + Q_{aux} - Q_d - Q_l - Q_x \qquad (31)$$

The solar fraction, SF, and the solar collector efficiency, η_{coll}, can be calculated on a monthly and annual basis.

$$SF = Q_{sol} / Q_d \qquad (32)$$

$$\eta_{coll} = Q_c / Q_r \qquad (33)$$

The thermal energy storage efficiency, η_{acu}, and the annual system efficiency, η_{sys}, can be calculated only on an annual basis.

$$\eta_{acu} = Q_s / Q_e \qquad (34)$$

$$\eta_{sys} = Q_{sol} / Q_r \qquad (35)$$

In Table 4.6 monthly and annual results for the analyzed case are shown.

Table 4.6: Monthly and annual results for the base case

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Q_d (MWh)	1011	800	700	417	104	95	90	92	95	269	662	1014	5350
Q_r (MWh)	305	359	458	470	536	543	610	605	501	446	338	288	5458
Q_c (MWh)	181	232	305	320	379	359	382	341	229	168	103	126	3124
Q_b (MWh)	181	232	305	320	104	95	90	93	95	168	103	126	1911
Q_e (MWh)	0	0	0	0	275	264	293	248	134	0	0	0	1213
Q_s (MWh)	0	0	0	0	0	0	0	0	0	101	559	407	1067
Q_l (MWh)	5.5	4.9	5.3	5.1	5.2	9.3	13.7	18.3	21.3	23.9	21.2	12.4	146
Q_x (MWh)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Q_{sol} (MWh)	181	232	305	320	104	95	90	93	95	269	662	533	2979
Q_{aux} (MWh)	830	568	396	98	0	0	0	0	0	0	0	480	2372
EA (MWh)	-6	-10	-16	-21	249	503	782	1012	1125	1000	419	0	---
T_{acu} (ºC)	29.8	29.5	29.3	29.1	41.1	52.5	65.0	75.3	80.3	74.7	48.8	30.0	---
SF (%)	18	29	44	77	100	100	100	100	100	100	100	53	56
η_{coll} (%)	59	65	67	68	71	66	63	56	46	38	30	44	57
η_{acu} (%)	---	---	---	---	---	---	---	---	---	---	---	---	88
η_{sys} (%)	---	---	---	---	---	---	---	---	---	---	---	---	54

4.6 Design methods

A CSHPSS has been designed and calculated using different methods and equivalent input data to make a fair comparison among them. The comparison case is located in Zaragoza (Spain) and supplies heat for a community of 1000 dwellings achieving a solar fraction of 50% for space heating.

The comparison case has been simulated with TRNSYS and the results used to validate the *Simple Method* presented in this chapter and other calculation methods: Lunde (1979), Braun et al. (1981), Drew and Selvage (1980), f-Easy (2014) and SDH-online calculation tool (Solites, 2014b). The outcomes obtained from the TRNSYS simulation are used as input data (climatic conditions and thermal demand) as well as results from the plant for the validation process.

4.6.1 TRNSYS model

TRNSYS is an accepted and validated tool to calculate CSHPSS with high accuracy (Raab et al., 2005; Lundh and Dalenbäck, 2008). The TRNSYS model used for this validation (see Fig. 4.3) is completely described in Guadalfajara et al. (2012) and Guadalfajara (2013). The CSHPSS comparison system has been simulated in short periods of time for two consecutive years using hourly climatic data from EnergyPlus (2012). The results from the second year have been used as final results for the system.

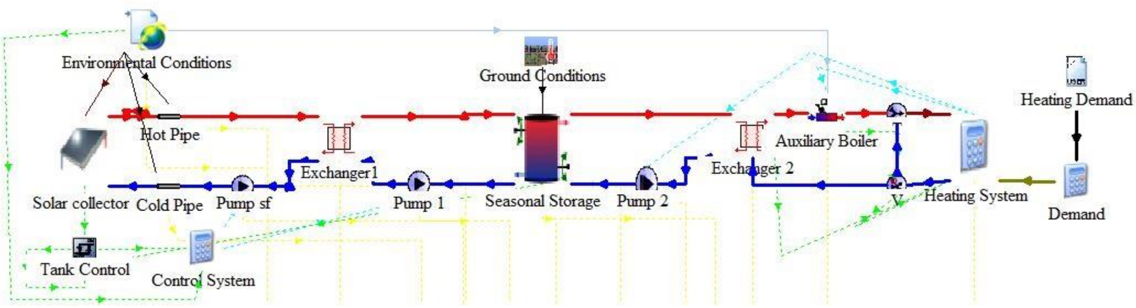

Figure 4.3: Dynamic model elaborated in TRNSYS of the analyzed CSHPSS (SHC, 2012)

The TRNSYS model developed elaborates climatic data to calculate the performance of the solar collector and the other pieces of equipment in short periods of time. The model defines the operation of the pumps according to the tank temperature and the solar field temperature. In the tank, the temperature is calculated in different nodes considering the thermal stratification. According to the demand and the supply temperatures are defined: operation of the pumps and flow rate in the discharging side of the storage. The auxiliary boiler produces thermal energy when the supply temperature is lower than the control value. The TRNSYS model use the space heating demand of a standard multifamily building model that was developed with TRNBuild following the Spanish standards for new buildings (CTE, 2013).

The main design characteristics of the plant are presented in Table 4.7.

Table 4.7: Main parameters of the comparison case

	Parameter	Value
Solar Collector Field	RAD: ratio area of solar collector per unit of demand	0.52 m^2/(MWh/yr)
	A: area of solar collectors	2854 m^2
	η_0: optical efficiency	0.817
	k_1: 1st order heat loss coefficient	2.205 W/(m^2·K)
	k_2: 2nd order heat loss coefficient	0.0135 W/(m^2·K^2)
	β: tilt	45º
	γ: orientation	0º
	m_s: solar field flow rate	20 kg/(h·m^2)
	$c_{p,sf}$: heat capacity fluid of the solar field	3840 J/(kg·K)
	ρ_{sf}: density of the solar field fluid	1020 kg/m^3
	Eff: heat exchanger effectiveness	0.95
Seasonal Storage	RVA: ratio volume / area	8 m^3/m^2
	V: volume of seasonal storage	22,829 m^3
	T_{min}: minimum storage temperature	30ºC
	T_{max}: maximum storage temperature	100ºC
	RHD: ratio storage height divided by diameter	0.6 m/m
	U_{acu}: heat transfer coefficient to the ambient	0.12 W/(m^2·K)
	A_{acu}: heat transfer area	4604 m^2
	$\rho \cdot c_p$: heat capacity	4.18 MJ/(m^3·K)
Heating Demand	Q_{SH}: annual SH demand	5488 MWh/yr
	Q_{DHW}: annual DHW demand	0 MWh/yr
	Q_d: annual demand	5488 MWh/yr
District Heating	T_{sup}: supply temperature	50ºC
	T_{ret}: return temperature	30ºC
	T_{DHW}: DHW temperature	50ºC

The results obtained for the main energy flows and the storage temperature, summarized by months are presented in Table 4.8: heating demand Q_d, radiation Q_r, solar heat collected Q_c, solar heat $Q_{sol,}$ auxiliary energy Q_{aux} and storage temperature T_{acu}. These results have been compared with the results that can be obtained for the same case using the simple calculation methods. Some outcomes from the thermal simulation, monthly demand and even hourly radiation have been used as input data for some calculation methods.

Table 4.8: Monthly and annual results obtained with TRNSYS model

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Q_d (MWh)	1309	865	632	366	80	0	0	0	0	142	807	1287	5488
Q_r (MWh)	275	331	440	436	481	486	546	552	464	409	298	257	4978
Q_c (MWh)	165	210	289	289	326	317	335	304	160	143	166	152	2856
Q_{sol} (MWh)	179	206	285	204	80	0	0	0	0	142	807	898	2801
Q_{aux} (MWh)	1130	659	347	162	0	0	0	0	0	0	0	389	2687
T_{acu} (ºC)	33.6	33.7	33.8	37.1	46.4	58.5	71.1	82.5	88.2	87.8	63.0	34.2	---

4.6.2 Lunde method

Lunde (1979) proposed a method to calculate the performance of large scale solar thermal systems including a finite thermal energy storage in which the storage temperature rises or falls monotonically. The method predicts with an integrated equation the performance over an entire month of the solar collector using pre-elaborated climatic data. The integrated equation includes the effect of heating demand and thermal losses over the storage temperature and over the solar collector performance.

Hourly ambient temperature and radiation over tilted surface (obtained from the TRNSYS model) are used to generate the elaborated climatic data required in this calculation method. Climatic data are distributed by level of radiation: radiation received $q_{r,i}$ (kWh/m^2), average ambient temperature Ta_i (ºC) and number of hours, $t_{op,i}$ (h) for each radiation range i (W/m^2). Radiation ranges of 80 W/m^2 considered. For example, the elaborated climatic data for May is presented in Table 4.9.

Table 4.9: Climatic parameters by ranges of radiation in May, operation periods in grey

Radiation range (W/m^2)	< 2	2 - 80	80 - 160	160 - 240	240 – 320	320 - 400	400 - 480	> 480
q_r (kWh/m^2)	0	2.9	8.2	5.3	9.6	15.6	10.9	116.0
t (h)	291	92	68	26	34	45	24	164
Ta (ºC)	13.7	16.3	17.0	18.8	17.1	19.6	19.4	21.0

The operation period is defined as the sum of the periods with radiation that can produce a net amount of energy. In May, the radiation ranges between 2-80 W/m^2 having an average value lower than the minimum radiation required to produce net energy. Therefore the operation period, in May, is the sum of the ranges over 80 W/m^2 i.e. the operating period is t_{op} = 361 h and the radiation received along the operation period is $q_{r,op}$ = 165.6 kWh/m^2. From these values and the integrated equation, the monthly production of thermal energy is determined. From this production and the demand, the monthly energy balance and tank temperature at the end of the month are obtained. This calculation is performed sequentially, month by month, until the annual performance is obtained (final results on Table 4.10).

Table 4.10: Monthly and annual results obtained with Lunde method

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Q_d (MWh)	1309	865	632	366	80	0.0	0.0	0.0	0.0	142	807	1287	5488
Q_r (MWh)	275	331	440	435	481	486	546	552	465	409	299	257	4978
Q_c (MWh)	182	231	316	317	347	332	350	321	229	173	130	146	3075
Q_l (MWh)	4.9	4.1	4.0	3.4	3.7	5.0	7.0	9.7	12.0	14.3	12.5	7.9	88.5
Q_{aux} (MWh)	1132	638	320	53	0.0	0.0	0.0	0.0	0.0	0.0	0.0	359	2501
EA (MWh)	0.0	0.0	0.0	0.0	264	591	933	1245	1462	1479	790	0.0	---
T_{acu} (ºC)	30.0	30.0	30.0	30.0	39.9	52.2	65.1	76.9	85.0	85.7	59.7	30.0	---

4.6.3 Braun, Klein and Mitchell method

To calculate the monthly performance of a CSHPSS with simpler initial data than Lunde method, the utilizability correlation was used by Braun et al. (1981). The utilizability factor estimates the amount of radiation that can be transformed into thermal energy by a solar collector (Klein, 1978). The utilizability correlation and other climatic correlations required for this method can be found in Chapter 3 and are widely explained in common literature of solar systems (Duffie and Beckman, 2006).

Braun et al. (1981) proposed to calculate monthly the performance of the solar field and the charging and discharging process of the storage. The performance of the solar field is obtained from the daily utilizability correlation (see Chapter 3.2).

$$Q_c = A \cdot \eta_0 \cdot \bar{H}_t \cdot N \cdot \Phi \cdot 10^{-6} \qquad (39)$$

This method introduces a heat transfer limit between the seasonal storage and the demand $Q_{d,max}$, according to house heat transfer coefficient UA_{dwe}, number of houses N_{dwe}, amount of heating hours per month h_{heat} and difference between monthly average storage temperature and house comfort temperature T_{dwe}. For systems with high water supply temperature this condition is very appropriate to limit the discharge of thermal energy in months with high demand and low seasonal storage temperature.

$$Q_{d,max} = UA_{dwe} \cdot N_{dwe} \cdot h_{heat} \cdot (T - T_{dwe}) \qquad (40)$$

A second physical limit was introduced in this method for the charging process; if the seasonal storage reaches the maximum temperature, then part of the thermal energy produced by the solar collector field would be rejected.

An energy balance is used each month to calculate the system performance, as in other methods. However, to calculate the performance by this method an iterative process is required because the monthly performance of the solar collector is calculated with an estimated average storage temperature (storage temperature at the end of the month is calculated with the solar production, thermal losses and demand).

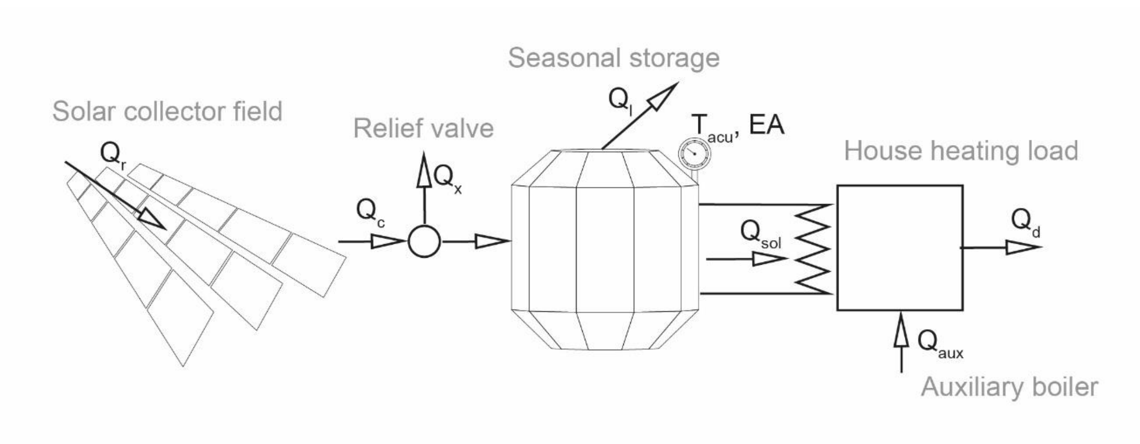

Figure 4.4: System diagram for Braun, Klein and Mitchel method

Final results obtained for the comparison case are shown in Table 4.11.

Table 4.11: Monthly and annual results obtained with BKM method

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
$\bar{H}$ (MJ/(m^2·day))	6.4	9.8	13.8	17.4	21.5	23.8	25.3	22.5	16.5	11.6	7.5	5.7	---
$\bar{K}_t$	0.45	0.50	0.52	0.51	0.54	0.57	0.62	0.62	0.56	0.54	0.48	0.45	---
$\bar{H}_t$ (MJ/(m^2·day))	11.2	14.9	17.9	18.3	19.6	20.5	22.2	22.5	19.5	16.6	12.5	10.5	---
Φ	0.78	0.85	0.87	0.88	0.88	0.83	0.78	0.70	0.57	0.48	0.48	0.64	---
Q_d (MWh)	1309	865	632	366	80	0	0	0	0	142	807	1287	5488
Q_r (MWh)	275	331	441	436	481	486	547	552	464	409	298	257	4978
Q_c (MWh)	175	229	313	313	345	329	349	315	217	160	117	134	2996
Q_l (MWh)	5.3	3.9	4.0	3.5	3.9	5.2	7.3	9.9	12.1	14.4	12.4	8.3	90.2
Q_{sol} (MWh)	324	218	257	277	80	0	0	0	0	142	807	770	2874
Q_{aux} (MWh)	985	647	375	89	0	0	0	0	0	0	0	517	2614
EA (MWh)	-28	-20	0	32	293	617	959	1264	1469	1472	770	126	---
T_{acu} (ºC)	31.9	29.1	29.6	30.6	35.6	47.3	59.8	72.1	81.7	85.6	72.4	47.0	---

Note that a result of this calculation method is that auxiliary energy in December is required while the energy accumulated at the end of the month is 126 MWh because the temperature in the seasonal storage is quite low and cannot supply the required power to the buildings. The limitation on the discharge of the storage increases the accuracy approaching more to the results obtained with the TRNSYS model, which also considers supply temperature.

4.6.4 Drew and Selvage method

Drew and Selvage (1980) proposed a method to calculate the required area of the solar field and the volume of the seasonal storage to reach 100% of solar fraction. The seasonal storage was sized to accumulate all the thermal energy produced in summer reaching the maximum storage temperature (see Chapter 3.2).

$$EA = \sum_{m=4..9} (Q_c[m] - UA_{acu} \cdot (T_{acu}[m] - T_a[m])\, 24 \cdot N \cdot 10^{-6} - Q_d[m]) \qquad (16)$$

$$-EA = \sum_{m=1..3;10..12} (Q_c[m] - UA_{acu} \cdot (T_{acu}[m] - T_a[m])\, 24 \cdot N \cdot 10^{-6} - Q_d[m]) \qquad (17)$$

The performance of the solar field is calculated with the utilizability factor as in the method proposed by Braun et al. (1981). For the comparison case, the optimum values of solar collector area and seasonal storage volume required to reach a 100% solar fraction are respectively A = 5794 m^2 and V = 46,690 m^3. This method cannot be used to design systems with different solar fractions.

4.6.5 f-Easy

The platform Solar District Heating (SDH) proposed the f-Easy (2014) method to perform feasibility studies of CSHPSS plants based on empirical design correlations (SDH, 2012a) and investment estimations. This method requires: annual radiation, annual demand, and solar collector field area or the desired solar fraction.

The estimated solar production is proportional to the annual solar radiation. Correction factors for the inlet temperature and type of solar collector can be applied. The appropriate ratio volume of seasonal storage divided by the area of the solar collector field (V/A) is proposed by the method, according to experience, to reach the desired solar fraction. Furthermore, the seasonal storage volume is calculated.

For the comparison case (location Zaragoza, space heating demand corresponding to 1000 dwellings) the feasibility tool estimates, as shown in Fig. 4.5, a solar collector field area of A = 3960 m^2 obtaining a 50% solar fraction. According to this solar fraction and the estimated solar collector field area the feasibility tool estimates a storage tank of V = 6732 m^3. The design ratios proposed by this tool were determined for north European cases and are not appropriate for other locations e.g. the ratio RAD obtained is quite high $RAD_{f\text{-}Easy}$ = 3960 / 5488 = 0.72 m^2/(MWh/yr) and the accumulation ratio proposed is rather low RVA = 1.7 m^3/m^2 compared to the comparison case ratio.

f-EASY (SDH)

Simple calculator for quick feasibility study of solar district heating

J.E.Nielsen, PlanEnergi *version 0.8* *21/9 2012*

Own or Calc	Parameter	Own input	Value used	Unit
Main inputs				
Own	Total load on network (= annual production)	5,488	5,488	MWh
Own	Solar irradiation on horizontal at location	1,540	1,540	kWh/m²
Own	Land area available	300,000	300,000	m²
Own	Price per m² land	3	3	€/m²
Own	Distance to network connection	-	-	km
Own	Average operating temperature - network side	50	50	°C
Own	Acceptable heat production price	60	60	€/MWh
Main results				
Own	**Collector area**	3,960	3,960	m²
Calc	**Land area used**	-	11,880	m²
Own	**Storage volume**	6,732	6,732	m3
Calc	**Total investment**		2.5	Mio €
Calc	**Simpel payback time**		16	Years

Figure 4.5: f-Easy results for the comparison case, f-Easy (2014)

The use of correlations to design CSHPSS is only recommended for countries or locations with climatic and demand characteristics similar to those of the place where the coefficients for sizing were fitted. The feasibility tool is straightforward and useful for preliminary studies but cannot be applied to any location. Nevertheless, it could be adapted to different climates increasing its usefulness.

4.6.6 SDH Online Calculation Tool

Solites (2014b) developed the SDH-Online Calculation Tool based on 100,000 TRNSYS simulations. It is a user-friendly tool to design and estimate the economics of two different models of solar district heating plants: central solar heating plants with thermal energy storage (not necessarily seasonal storage) and decentralized solar heating plants connected to district heating (see in Fig. 4.6 a screen from the website).

The first model estimates the performance of centralized solar heating plants with thermal energy storage that supply heat to a district heating network, the demand of which has been estimated from a building simulation with TRNSYS (including space heating and domestic hot water), whereas the second model estimates the performance of decentralized solar heating plants that deliver thermal energy to a theoretically infinite district heating network at a defined temperature.

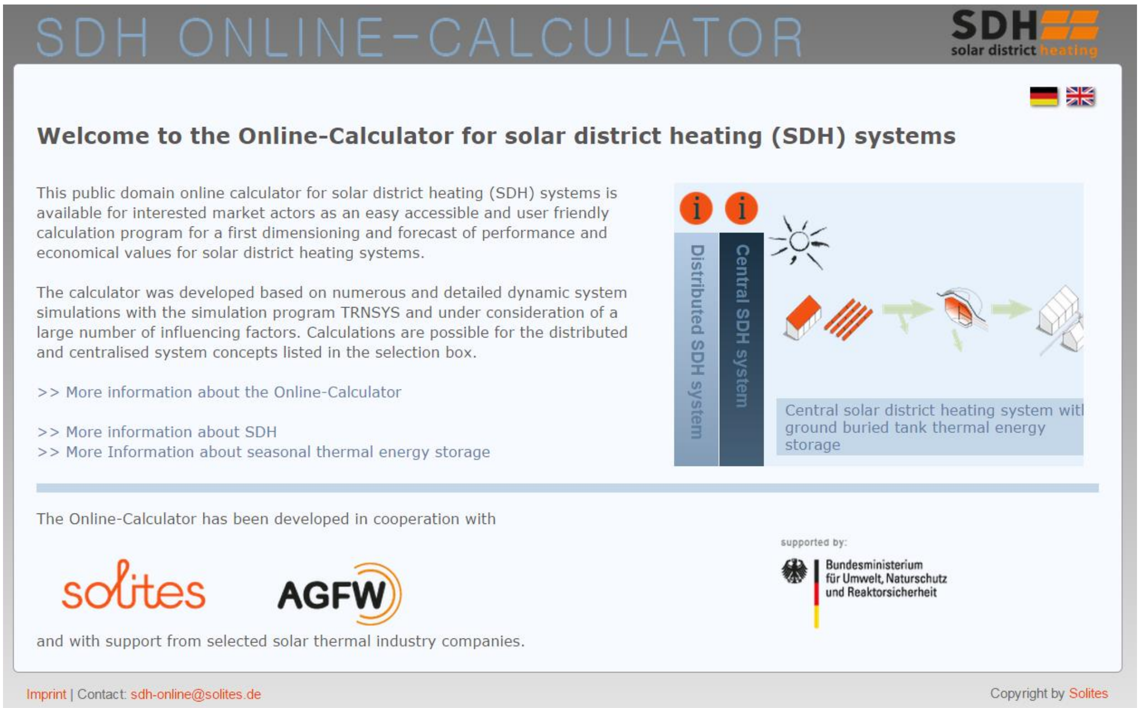

Figure 4.6: Solar district heating online calculation tool (Solites, 2014b)

The TRNSYS models have been calculated using different combinations of design parameters. Several calculation options are available: i) six locations in Europe; ii) four types of solar collectors; iii) three ranges of district heating temperature; iv) different collector area, azimuth and slope; v) different volume to area ratios 0.05-3 m^3/m^2; vi) different demand to area ratios 0.2-10 MWh/m^2.

From user defined parameters the online calculation tool calculates the annual performance by multilinear interpolation of the simulated cases. The online calculation tool estimates the solar fraction and the economics taking the main components of the systems into account.

As the closest location available to the comparison case is Barcelona, a system has been calculated for that location with a high temperature flat plate collector with an area of 2854 m^2, oriented to the south to deliver heat to a community with an annual demand of 5488 MWh. The tool calculates the systems that supply thermal energy for space heating and domestic hot water so the fulfilled demand is quite different from the comparison case. The obtained results are shown in Fig. 4.7.

The accumulation requirements are lower and the tool is limited to use a seasonal storage with a maximum size of 3139 m^3. The application considers a supply/return temperature of 60ºC/30ºC. It estimates an annual solar fraction of 43% but other results obtained are: 1) solar production of 2455 MWh; 2) stagnation period of 8 days; 3) 37 MWh of thermal losses in pipes; 4) seasonal storage thermal losses of 59 MWh; and 5) the backup heater produces 3125 MWh. The online calculation tool also estimates the solar collector field cost (piping included) at about 244 €/m^2 and estimates seasonal storage cost at about 214 €/m^3.

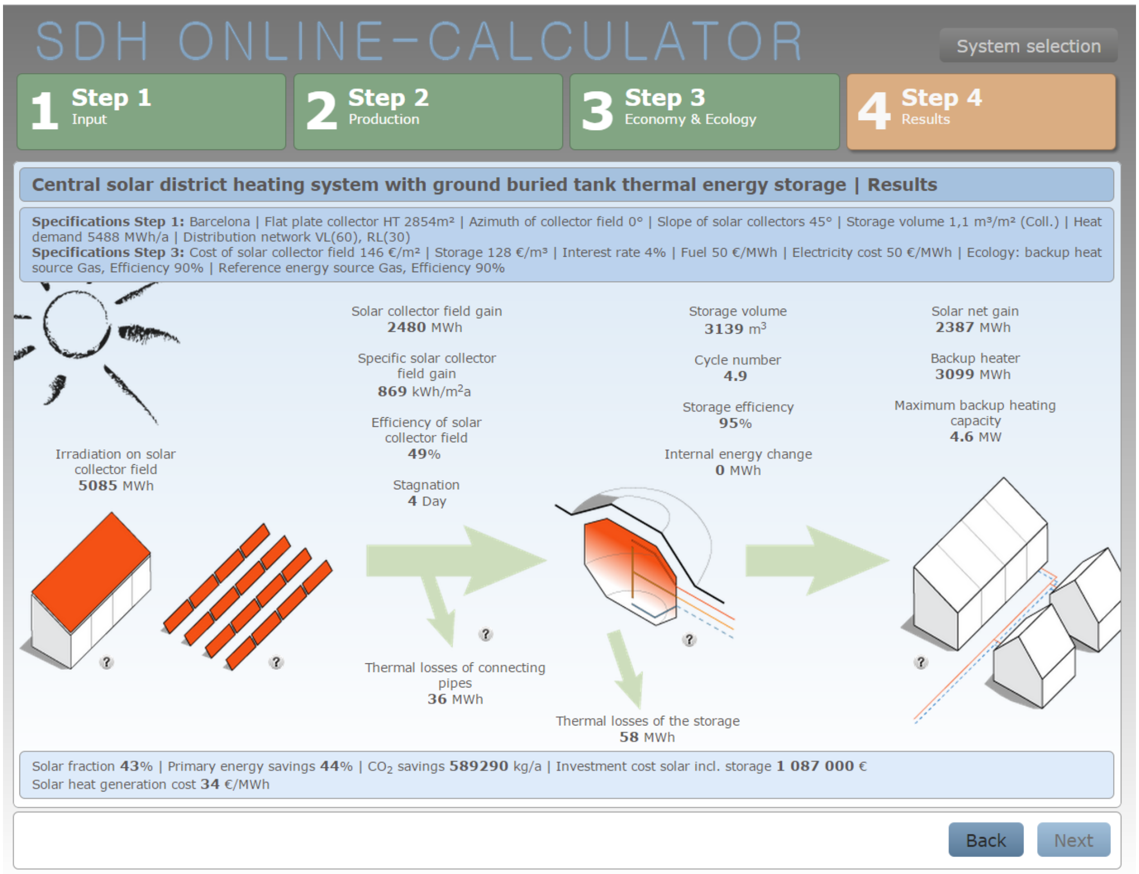

Figure 4.7: SDH online-calculator results for the comparison case (Solites, 2014b)

The limitations of input data in this method hinder its adjustment to the comparison case used to compare the calculation methods. Not only the climate in Barcelona is warmer than in Zaragoza, the calculation tool also takes into consideration the demand for domestic hot water, which make inappropriate to compare the results with the other calculation methods.

4.6.7 Simple Method

The *Simple Method* calculates the monthly and annual performances of a CSHPSS based on the physics of the equipment (Guadalfajara, 2013; Guadalfajara et al., 2014a). From simple and public climatic data (monthly average ambient temperature and daily horizontal radiation) the method elaborates the required climatic data, with well-known correlations (Duffie and Beckman, 2006), to calculate the hourly performance of the solar collector field in a typical day for each month.

The method distributes hourly the ambient temperature with Erbs's correlation (Erbs et al., 1982) and calculates the hourly radiation over a tilted surface with the isotropic sky model. The average ambient temperature and the monthly degree-days are used to distribute the annual demand for space heating and domestic hot water, simplifying the input of data. This monthly demand is used to calculate the system thermal performance. If equivalent data are known (hourly ambient temperature, hourly radiation over tilted surface or monthly demand) they can be introduced into the method.

The solar collector field performance is calculated for each hour and the effectiveness of the heat exchanger between the thermal storage and the solar field is considered. The hourly production of the solar collector is calculated using the average operation temperature, determined as the average temperature between the inlet and the outlet temperature of the solar collector. The system considers the rejection of heat in summer if the tank reaches the maximum temperature and calculates the auxiliary energy required to cover the demand when the storage reaches the minimum temperature.

The performance has been calculated with the *Simple Method* using the monthly demand generated by the TRNSYS model, the same design parameters and equivalent simple climatic data for radiation and temperature. Different results for the solar radiation over tilted surface have been obtained, as the *Simple Method* elaborates the climatic data with different correlations from the TRNSYS model. The results obtained for the comparison case with the *Simple Method* are presented in Table 4.12.

Table 4.12: Monthly and annual results obtained with the *Simple Method*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Q_d (MWh)	1309	865	632	366	80	0	0	0	0	142	807	1287	5488
Q_r (MWh)	271	319	407	418	477	483	542	538	445	397	300	256	4853
Q_c (MWh)	162	210	279	296	349	330	341	294	186	128	69	99	2744
Q_l (MWh)	4.8	3.7	3.3	2.4	1.3	3.3	5.8	9.1	12.3	15.2	15.2	9.9	87
Q_{aux} (MWh)	1147	655	353	70	0.0	0.0	0.0	0.0	0.0	0.0	0.0	606	2830
EA (MWh)	-5	-9	-12	-14	254	581	916	1201	1375	1345	592	0	---
T_{acu} (ºC)	29.8	29.7	29.5	29.4	40.2	53.4	66.9	78.4	85.4	84.2	53.8	30.0	---

4.7 Comparison of design methods

The following tables show an overview of the design methods that have been presented in Section 4.6. Table 4.13 presents a comparison of the design parameters that can be introduced in each design method. Design methods that require less input data are easier to use but present fewer opportunities to analyze the performance and evaluate different design alternatives.

The design method presented in this thesis (referenced as *Simple Method*) allows adjusting the most important design parameters, solar collector field area and seasonal storage volume, as well as secondary design parameters to adjust the performance of different solar collectors and the limits of the seasonal storage.

Table 4.13: Comparison of input data required

	A	V	η_0	k_1	k_2	β	γ	m_s	E_{ff}	T_{sup}	T_{ret}	T_{max}	UA_{acu}	UA_{dwe}	T_{dwe}	SF
Lunde	X	X	X	X	X	-	-	-	-	-	X	X	X	-	-	-
Braun et al.	X	X	X	X	X	X	-	-	-	X	X	X	X	X	X	-
Drew-Selvage	-	-	X	X	X	X	-	-	-	-	X	X	X	-	-	X
Simple Method	X	X	X	X	X	X	X	X	X	-	X	X	X	-	-	-
f-Easy	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X
SDH calculator	X	X	X	X	X	X	X	-	-	X	X	-	-	-	-	-

According to the results obtained from the comparison analysis, different calculation methods can be used to predesign CSHPSS. Integrated equations with elaborated data, the utilizability method, short-cut simulations or semi-empirical methods obtained from a large number of simulated cases can be used to calculate the performance of the solar collector field.

Different assumptions can be made for the performance of the storage and the charging and discharging processes. Some methods do not allow adjusting the heat transfer coefficient of the storage or the temperature limits. Such considerations are very important especially when different technologies for seasonal storage are compared.

Experimental coefficients obtained from operation might be used in the future to estimate the performance of seasonal storages with similar designs. The performance coefficients were obtained for BTES in Drake Landing Solar Community using the *Simple Method* and the experimental data from its operation (Guadalfajara et al., 2014f).

A short description of the correlations and equations used to calculate the performance of the equipment are presented in Table 4.14 as well as the results that can be obtained from each method.

Table 4.14: Main characteristic of the calculation process and results obtained

Design Method	Solar collector field	Thermal energy storage	Results
Lunde	- Integrated equation - Elaborated climatic data from hourly climatic data	- Thermal losses - Charge/Discharge	- Monthly performance
Braun et al.	- Utilizability correlation to estimate monthly solar collector performance	- Thermal losses - Charge/Discharge - Limit on max discharging	- Monthly performance
Drew and Selvage	- Utilizability correlation to estimate monthly solar collector performance	- Thermal losses - Charge/Discharge - Temperature profile	- Solar collector field area - Seasonal storage volume - Only for SF = 100%
Simple Method	- Hourly calculation of the solar collector field a typical day each month	- Thermal losses - Charge/Discharge - Rejection of heat	- Monthly performance - Economic cost - Environmental impact
f-Easy	- Solar production proportional to collector area and annual radiation	- Seasonal storage volume function of solar fraction	- Solar collector field area - Seasonal storage volume
SDH-online tool	- Detailed simulation - Interpolation of simulated cases with TRNSYS	- Stratification effect - Interpolation of simulated cases with TRNSYS	- Annual result - Economic cost - Environmental impact

Annual results are common for all the methods but detailed monthly results can only be obtained by some of them. For the comparison case the annual results obtained for each method as well as design values obtained/applied are presented in Table 4.15.

Table 4.15: Plant sizing and annual results for TRNSYS and design methods

Method	A (m^2)	V (m^3)	Q_r (MWh/yr)	Q_c (MWh/yr)	η_{coll} (%)	Q_{aux} (MWh/yr)	Q_{sol} (MWh/yr)	SF (%)
TRNSYS	2854	22,829	4978	2856	57 %	2687	2801	51%
Lunde	2854	22,829	4978	3075	62 %	2501	2987	54%
Braun et al.	2854	22,829	4978	2996	60 %	2614	2874	52%
Simple Method	*2854*	*22,829*	*4853*	*2744*	*56 %*	*2830*	*2658*	*48%*
Drew and Selvage	5794	46,690	10,076	5673	56 %	0	5488	100%
f-Easy	3960	6732	6907	2744	40 %	2744	2744	50%
SDH Online tool	2854	3139	5088	2455	48 %	3128	2360	43%

TRNSYS model estimated an annual solar fraction of 51%, Lunde method estimates an annual solar fraction slightly higher, 54%, and Braun et al. method estimates an annual solar fraction of 52%. The *Simple Method* estimates the most conservative solar fraction, 48%.

The monthly results obtained with the design methods of Braun et al., *Simple Method*, and Lunde are very similar, although in the Braun et al. method a demand limit has been introduced and in the *Simple Method* a more detailed tilted radiation is obtained (See Fig. 4.8).

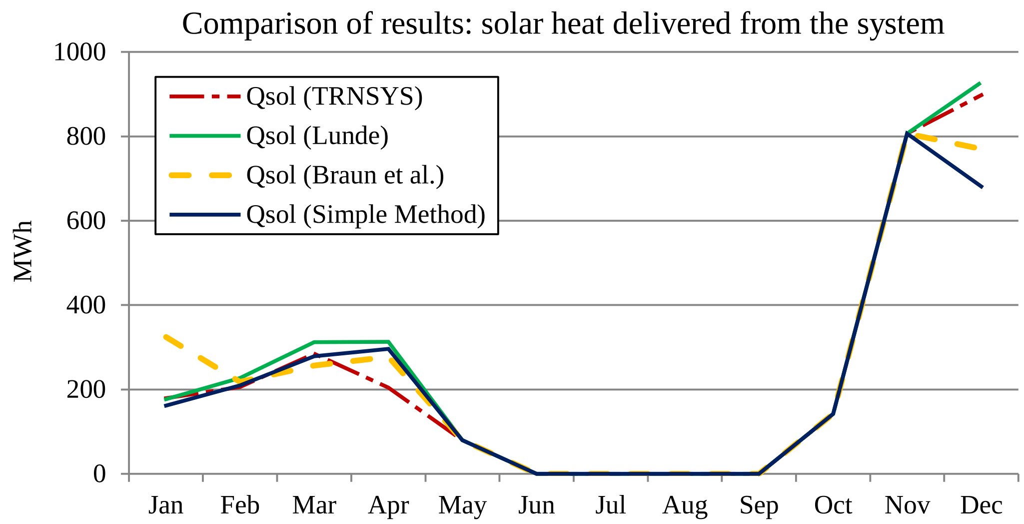

Figure 4.8: Comparison of results with different calculation methods

For the other methods considered in this chapter these are the conclusions reached:

- The design method of Drew and Selvage only allows sizing the main components for a specific case, 100% solar fraction with ideal behavior, which limits very much its application.
- The f-Easy design tool estimates the solar field annual production to be proportional to the solar radiation received. The solar field efficiency estimated, by this method, is 40%, much lower than the efficiency estimated by other methods for the comparison case ~60%.
- The SDH Online tool estimates the results with an empirical correlation obtained from a large number of TRNSYS simulations. Since the closest climatic zone available is Barcelona where the climate is warmer and the specific space heating demand is lower the design obtained is quite different and not appropriate for comparison. This design tool can be very useful for preliminary studies but locations selected and design parameters do not properly fit to different climates.

The design methods presented do not substitute dynamic simulations for the calculation and final design of CSHPSS but are valid tools to predesign and evaluate design alternatives. The results of the design methods need to be compared with real operating plants for a wide variety of cases to judge their reliability. The use of simple and validated tools to design CSHPSS can be as useful as the f-Chart method to design domestic hot water systems and might foster the development of clean and renewable solar energy systems.

Chapter 5:
Economic Analysis

5 Economic analysis

The European Union and its Member States have committed to achieve a 20% share of renewable energy by 2020. It is important not only to achieve this and other strategic energy targets, but also to maintain a low energy price for the long term. Energy is a basic commodity and the substitution from traditional energy sources to renewable ones should not increase its final price. Therefore, it is essential to find solutions for the future that displace the consumption of non-renewable energy at a minimum cost.

Solar thermal systems have already proved to be an economically profitable solution for domestic hot water production in many locations worldwide (IEA, 2011). In China, very low cost solar water heaters are present everywhere (see Fig. 5.1) and are already an economic alternative for less than 200 € per household for the production of domestic hot water. These solar water heaters are also available in Europe at higher price. Single family houses and community buildings use solar thermal systems to produce domestic hot water but other heating and even cooling demands can be supplied with solar thermal energy increasing the potential of this energy source and reducing the consumption of non-renewable energy sources.

Figure 5.1: Solar water heaters installed in Kunming China

District heating systems deliver heat produced by large centralized production plants to many consumers, which use the heat to produce hot water, space heating and other services. Large scale solar thermal plants can produce a share of the DH needs with low cost and have many advantages compared to individual systems: considerable economies of scale, flexibility of operation and better management conditions.

The production of thermal energy by a solar thermal system depends on the availability of the solar resource, which is higher in summer. On the other hand, the demand is higher in winter; therefore, only a small solar fraction can be produced without having long overproduction periods in summer.

A small fraction of the district heating needs can be produced with solar thermal energy with low environmental impact and low cost compared to alternative energy sources. In order to further reduce the consumption of conventional fuels it might be convenient to reach higher solar fraction levels.

To achieve a high solar fraction (higher than 50%) is necessary to accumulate the thermal energy overproduced in summer for its later consumption. Large thermal energy storages can be used as seasonal storages to accumulate thermal energy from summer to winter, but the accumulation of thermal energy implies a quite high extra cost.

Seasonal thermal energy storage systems have been tested in different locations for the last 40 years in Europe and Canada and important cost reductions have been achieved reaching economically viable solutions that can accumulate heat from summer to winter.

The cost of the seasonal storage has considerable economies of scale because the cost of the storage is dependent on the surface area instead of the volume. Besides, the storage efficiency is higher for larger applications, decreasing insulation needs and improving its efficiency.

In this chapter a model will be presented to estimate the economic investment required for a CSHPSS as well as a method to evaluate the cost of the solar heat produced by such installation. This economic model is used in combination with the simple calculation method in order to design CSHPSS based on economic results.

5.1 Economic model

5.1.1 Solar collector field

Large solar collector fields produce thermal energy from solar radiation for district heating systems. Solar fields use large size flat plate collectors specifically designed for this application. According to Ellehauge and Pedersen (2007) for new solar fields in Denmark, using large size solar collectors, the indicative cost including mounting, foundation and piping, is 280 €/m^2 for systems with a collector area of 1000 m^2, but lower cost is achieved for larger fields, as shown in Fig. 5.2.

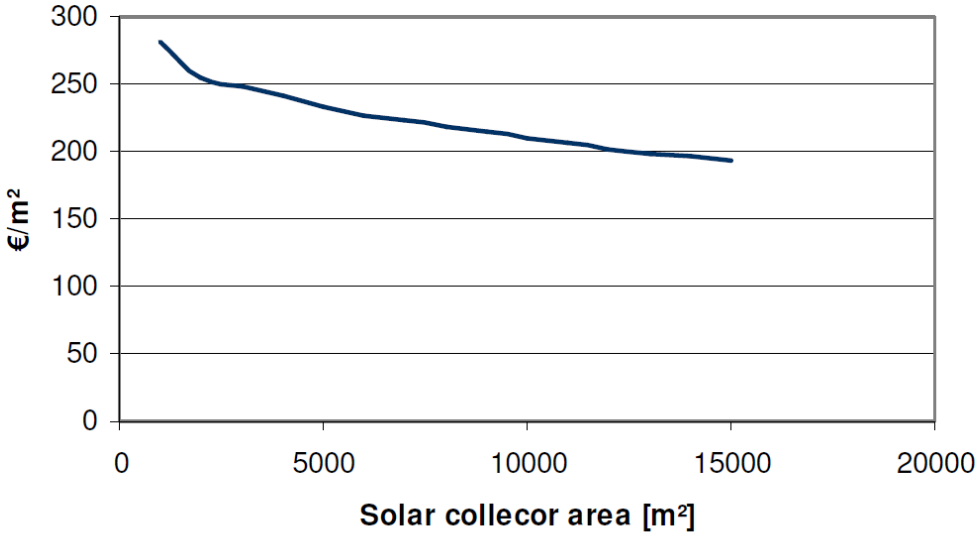

Figure 5.2: Indicative cost of collector field (Ellehauge and Pedersen, 2007)

From the graph of Ellehauge and Pedersen (2007) the following function is proposed to calculate the investment required for a large solar field.

$$Inv_{coll} = 740 \cdot A^{0.860} \qquad (1)$$

Since 2007, in Denmark, many large solar field systems have been installed. The database of Solvarmedata (2013) shows the performance of these systems and also characteristics of the projects and the investment required, which includes the cost of the solar field, the cost of the auxiliary energy system and the cost of the thermal energy storage.

The correlation proposed in Eq. 1 is presented in Fig. 5.3 as well as six dots extracted from the graph of Ellehauge and Pedersen to check the similarity among the correlation proposed and the data given by the authors. The correlation proposed is validated with the investment required per area of solar collector of the projects in Denmark with low solar fraction (< 20%). The investment required, for these real systems, is presented in Fig. 5.3, with green triangles.

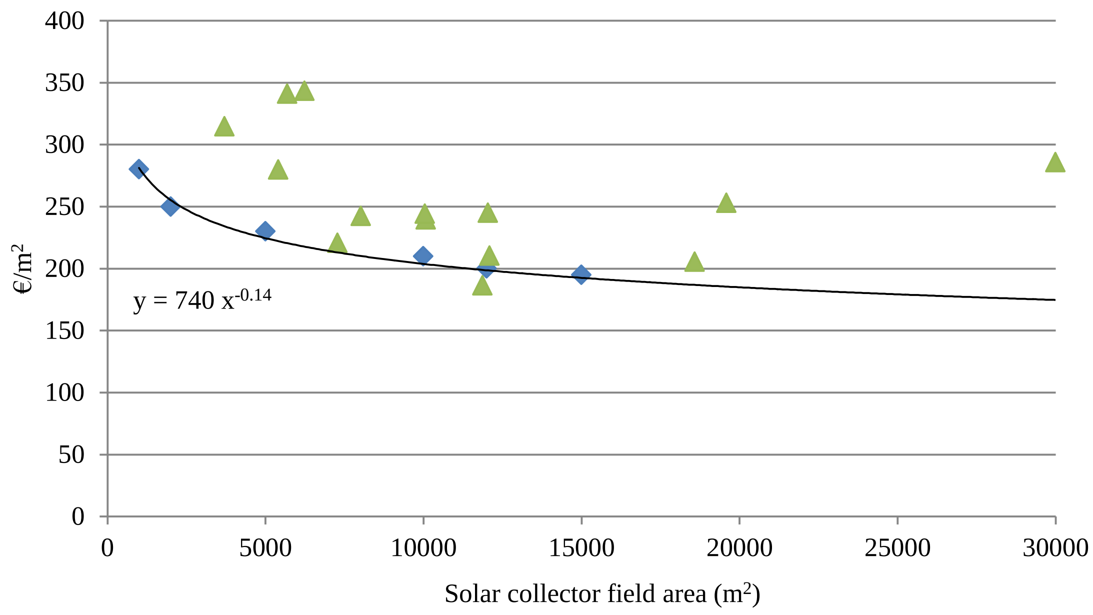

Figure 5.3: Indicative cost of collector field and indicative cost of real plants (Solvarmedata, 2013)

Compared to the correlation proposed, the investment required per area of solar collector in real plants in Denmark is higher. The cost of the real plants includes not only the investment for the solar field installation, but also the cost of auxiliary equipment and other indirect costs of the project, which might represent an extra 15-20%. Plants with a solar fraction higher than 20% have not been considered as they require a seasonal storage which considerably increases the cost of the system.

The solar thermal plants considered for this validation are presented in Table 5.1. The solar fraction of the systems is quite low as the most economically viable solution in Denmark is to produce a small fraction of the thermal needs. The plants with a solar fraction equal to 20% or higher are also included in this table but not in the collector field validation graph (Fig. 5.3).

There is a certain level of disagreement among different data sources about the characteristics of the Danish plants especially about the characteristics of Marstal and Braedstrup, as they have been upgraded several times. The data available in Solvarmedata, and presented in Table 5.1, do not refer to the last remodeling but to the state of the plant in 2012.

Table 5.1: Characteristics of solar thermal systems in Denmark (Solvarmedata, 2013)

Location	Year of construction	Collector surface (m^2)	Angle (º)	Production (MWh/yr)	Solar fraction	Alternative fuel	Investment (€)
Dionninglung	2014	37573	35	18000	50%	Natural gas	11,658,000
Ringkjobing	2014	30000	30	14250	14%	Natural gas	8,576,000
Vildbjerg	2014	21235	38	9500	22.6%	Natural gas	5,092,000
Nykobing		20084	38	9566	19%		
Helsinge	2014	19588	40	9400	20%	Natural Gas	4,958,000
Grasten	2012	19024	38	9700	28%	Natural gas	5,494,000
Braedstrup	2012	18612	33	8900	20%	Natural gas	7,008,200
Tarm	2013	18585	30	9000	17%	Wood chips	3,819,000
Marstal	2001	17943	40	8500	30%	Biofuel	6,834,000
Vojens	2012	17500	38	10000			
Oksbol	2013	14745	40	7777	25.5%	Natural gas	3,015,000
Sydlangeland	2013	12500	38	7500	22%	Straw	3,350,000
Grenaa	2014	12096	38	5875			
Sydfalster	2011	12094	38	6050	19%	Straw	2,546,000
Hvidebaek	2013	12038	38	5700	20%	Straw/oil	2,948,000
Saeby	2011	11866	30	6300	7%	Natural gas	2,211,000
Toftlund	2013	11000	40	5437	19%		
Gram	2009	10073	38	4857	17%	Natural gas	2,412,000
Jaegerspris	2010	10044	40	5200	16%		2,452,200
Svebolle-Vi.	2014	10000	38	5000	30%	Biofuel	1,447,200
Broager	2009	9988	40	5100	21.2%	Natural gas	2,385,200
Christiansfeld	2013	9545	38	4700	17.5%	Natural gas	
Frederiks	2013	8438	35				
Karup	2013	8063	35	3700	17.5%		
Strandby	2008	8019	35	3759	18%	Natural gas	1,943,000
Vejby	2012	8000	38	3720	22%	Natural gas	2,479,000
Sonderborg	2009	7576	45	3400	20%	Biofuel	
Gording	2012	7424	38	3400	17%	Wood flakes	
Torring	2009	7284	45	3431	12%	Natural gas	1,608,000
Aeroskobing	2010	7050	38	3000	22%	Wood pellets	1,474,000
Ejstrupholm	2011	6243	45	3000	18%	Natural gas	2,144,000
Skovlund	2013	5767	40	2300	25%	Natural gas	
Asaa	2014	5695	35	2690	19%	Natural gas	1,943,000
Tistrup	2010	5409	40	2141.5	18%	Natural gas	1,514,200
Ornhoj-Gron.	2012	5083	40	2390	22%	Natural gas	1,340,000
Ulsted	2006	5012	33	2202	23%	Wood pellets	1,152,400
Mou	2013	4775	38	2400	19%	Natural gas	
Tim	2013	4235	38				
Haderup	2014	4233		2279	24%		1,273,000
Feldborg	2012	4000	38	1937			
Hejnsvig	2011	3704	40	1770	20%	Natural gas	1,165,800
Sig	2013	3479	38	1727	23.3%	Natural gas	1,273,000
Rye	2014		37	1100	12%	Natural gas	

5.1.2 Seasonal storage

The achievement of a high solar fraction requires a seasonal storage, which typically raises the investment costs. Seasonal storages have been tested in different locations for the last 40 years in Europe and Canada and important cost reduction has been achieved in recent years reaching economically viable solutions. Besides, these plants are still in an experimental-demonstration stage and it is supposed that their cost will be reduced once in a commercial stage, in which a broader application will reduce the engineering and construction costs.

The investment cost of the seasonal storage is quite high, and should be calculated according to its size and the technology applied. From Solar District Heating guidelines (SDH, 2012b) a comparison of seasonal storage technologies performed by Solites (2014a) has been extracted. The graph in Fig 5.4 shows the investment per cubic meter of seasonal storage in district heating systems in a plot in which the horizontal axis is the volume of the storage. Note the strong economies of scale.

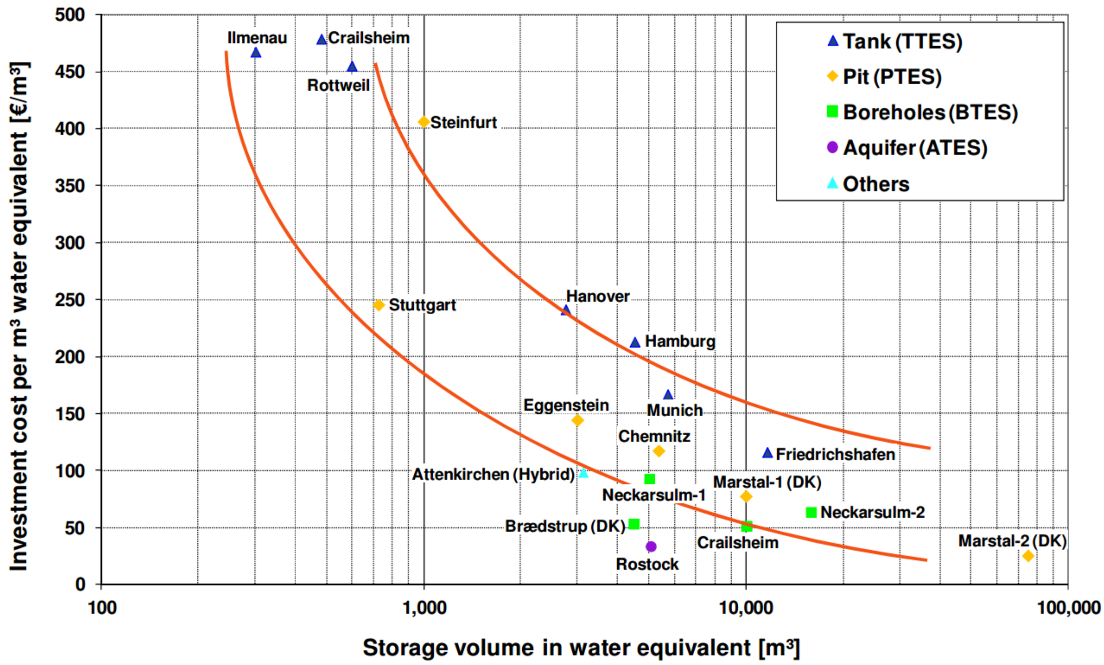

Figure 5.4: Specific storage cost of demonstration projects (Solites, 2014a)

Tank thermal energy storage cases are presented as blue triangles in the graph. This technology can be applied to any location; in comparison, PTES, BTES or ATES require special underground conditions. From TTES cases a correlation to estimate the cost as a function of the volume has been defined: see Eq. 2 and Fig. 5.5.

$$Inv_{acu} = \alpha \cdot 4660 \cdot V^{0.615} \qquad (2)$$

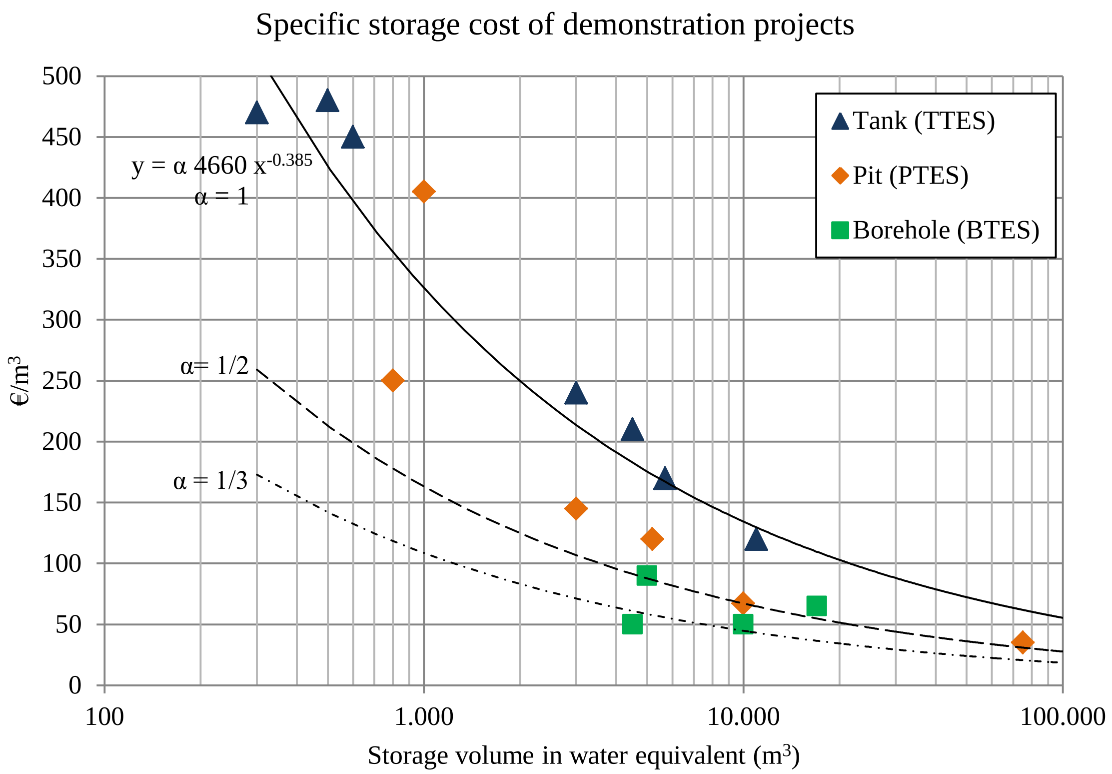

Figure 5.5: Seasonal storage cost of demonstration projects

The parameter α included in Eq. 2 is a correction factor that considers the economic behavior of different technologies of thermal energy storage (e.g. water tank, pit or borehole) or the expected future price reduction associated with the technology development. The value α = 1 corresponds to the experience gained in the demonstration projects of the last two decades using TTES.

Empirical evidences indicate that the investment cost for hot water tanks as seasonal storage is still very high but other technologies such as PTES or BTES can accumulate an equivalent amount of thermal energy with significant cost reduction of α = 1/2 or even 1/3 compared to TTES. It has been estimated that 10,000 m^3 pit storages can be built with a cost of 67 €/m^3 and for larger applications (~100,000 m^3) with a cost of 35 €/m^3 (Ellehauge and Pedersen, 2007).

The exponents in previous equations (Eq. 1 and Eq. 2) explain the scale economies of the solar collector field and the seasonal storage tank. The accumulator cost per unit of volume decreases significantly with the size, which has been verified by several authors (Baylin et al., 1981; Boysen and Chant, 1986; De Wit, 2007; Ellehauge and Pedersen, 2007; Hadorn and Chuard, 1983; Schmidt and Mangold, 2009; Task 45, 2014b and 2014c). The cost of the thermal energy storage for TTES and PTES depends on the cost of the envelope and therefore the economies of scale are very strong as the envelope area per cubic meter decreases with the size.

5.1.3 Capital investment for CSHPSS

The capital investment required for a new CSHPSS is the sum of the investment required for the solar field, the seasonal storage, the auxiliary equipment and the indirect costs (e.g. engineering cost). The investment required for the auxiliary equipment can be estimated to be proportional to the investment required for the solar field and the seasonal storage. Based on the results obtained in previous experiences an increasing factor of 25% (f_{aux} = 0.25) has been considered for the auxiliary equipment (i.e. pumps, heat exchangers, and auxiliary boilers). Indirect costs for the construction has been estimated at about 12% of the total investment (f_{ind} = 0.12). The final investment required for the installation is estimated as follows:

$$Inv = (1+ f_{ind}) \cdot (1+f_{aux}) \cdot (Inv_{coll}+Inv_{acu}) = 1036 \cdot A^{0.860} + \alpha \cdot 6524 \cdot V^{0.615} \quad (3)$$

The estimation of the auxiliary equipment has been obtained from the studies developed by Anastasia (2010), Frago (2011) and Lozano et al. (2010b and 2010c). They analyzed the detailed investment cost for CSHPSS calculating the cost of solar collectors, seasonal storage, pumps, heat exchangers and auxiliary boilers using design books for thermal systems (Ulrich and Vasudevan 2004; Walas, 1990) and commercial catalogues (Thermital, 2008). The investment cost for the plant designed by Anastasia (2010) are presented in Table 5.2.

Table 5.2: Investments costs for a CSHPSS (Anastasia, 2010)

Component	Capacity*	a*	b*	Cost (€)*	FBM†	CBM‡
Solar Field, SF	2760 m^2	740	0.86	673,600	1.0	673,600
Seasonal Storage	15,180 m^3	4660	0.615	1,737,200	1.0	1,737,200
DHW storage	47.5 m^3	3000	0.63	34,050	2.1	71,500
DH boiler	1800 kW	155	0.69	27,320	1.5	41,000
DHW boiler	208 kW	155	0.69	6160	1.5	9200
Heat exchanger 1	282 m^2	1350	0.7	70,660	1.7	120,100
Heat exchanger 2	282 m^2	1350	0.7	70,660	1.7	120,100
Heat exchanger 3	580 m^2	1350	0.7	116,100	1.7	197,400
Pump solar	15 kW	2200	0.35	5680	2.8	15,900
Pump 1	1.42 kW	2200	0.35	2490	2.8	7000
Pump 2	1.42 kW	2200	0.35	2490	2.8	7000
Pump 3	3.70 kW	2200	0.35	3480	2.8	9800
Total BMC						3,009,600
Contingencies and fees (15%)						451,400
Total Capital						3,461,000

* Cost = a · Capacity ^{b}. †FBM = Bare Module Factor. ‡ CBM = Bare Module Cost (CBM = Cost · FBM)

For this case, the auxiliary equipment of the plant (boilers, heat exchanger and pumps) represents an extra cost of 25% to the investment required for the seasonal storage and the solar field. For plants with heat pump or other special devices, the auxiliary equipment might represent a higher share. Table 5.2 also includes a budget for indirect costs which is calculated as an extra share of 15%.

The capital investment function for CSHPSS proposed in this Thesis (Eq. 3) has been compared with the results obtained by real plants installed in Europe and Canada. Design parameters and investment required has been obtained from several data sources (Arcon, 2014; Dalenbäck, 2014; SAIC, 2012; Schmidt and Mangold, 2009; Schmidt and Miedaner, 2012; SDH, 2015; Solarge, 2013; Solvarmedata, 2013; Task 45, 2014d). Large differences in the investment required even for installations of similar dimension have been found, which justify the general uncertainty about the economic result of such systems (Table 5.3 has been also presented in Chapter 2, see Table 2.5).

Table 5.3: Description of Central Solar Heating Plants with Seasonal Storage in operation

Name*	Year Built	Collector Area (m^2) †	Seasonal Storage Volume (m^3) ‡	Solar Fraction	Investment (€)
Friedrichshafen	1996	FPC 4050	TTES 12,000	47%	3,200,000
München	2007	FPC 2900	TTES 5700	47%	2,900,000
Mongolia	2012	CPC 5000	TTES 5000		
Hamburg	1996	CPC 3000	TTES 4500	49%	2,200,000
Rise Fjernvarme	1998	FPC 3582	TTES 4000	80%	697,200
Hannover Kronsberg	2000	FPC 1350	TTES 2750	39%	1,200,000
AEroeskoebing	1998	FPC 4875	TTES 1400	20%	1,200,000
Neuchatel	1997	UG 1120	TTES 1000		
Tubberupvaenge	1991	FPC 1030	TTES 1000		1,270,000
Marstal Fjernvarme	1996	FPC 33,000	PTES 75,000 PTES 10,340 TTES 2000	55%	9,440,000
Ottrupgaard	1995	FPC 565	PTES 1500		
Chemnitz	2000	ETC 540	WGTES 8000	30%	1,400,000
Augsburg	1998	FPC 2000	WGTES 6000		5,100,000
Eggenstein	2008	FPC 1600	WGTES 4500	37%	1,100,000
Sonderborg Vollerup	2008	FPC 7681	WGTES 4000	20%	
Steinfurt Borghorst	1999	FPC 510	WGTES 1500	34%	500,000
Neckarsulm Amorbach	1997	FPC 5670	BTES 63,000	50%	3,500,000
Anneberg	2002	FPC 2400	BTES 60,000		
Crailsheim	2003	FPC 7464	BTES 37,500	50%	4,500,000
Drake Landing, DLSC	2007	FPC 2164	BTES 34,000	96%	2,600,000
Braedstrup	2011	FPC 18,600	BTES 19,000 BTES 7500	30%	12,300,000
Attenkirchen	2002	FPC 800	BTES 9350	55%	760,000
Rostock Brinckmanshöhe	2000	FPC 980	ATES 20,000	62%	700,000

* Data obtained from different sources: Arcon, 2014; Dalenbäck, 2014; SAIC, 2012; Schmidt and Mangold, 2009; Schmidt and Miedaner, 2012; SDH, 2015; Solarge, 2013; Solvarmedata, 2013; Task 45, 2014d.

† FPC: Flat Plate Solar Collector, UG: Unglazed Solar Collector, ETC: Evacuated solar collector, CPC: Compound parabolic collector.

‡ TTES: Tank Thermal Energy Storage, PTES: Pit Thermal Energy Storage, WGTES: Water Gravel Thermal Energy Storage, BTES: Borehole Thermal Energy Storage, ATES: Aquifer Thermal Energy Storage.

The correlation proposed to estimate the cost of a CSHPSS has been validated with the collected data, presented in Table 5.3. The factor α in Eq. 2 and Eq. 3 represents the cost reduction for different technologies of seasonal storage. For PTES and WGTES α = 1/2 has been considered, such cost reduction compared to TTES has been obtained in Marstal. For BTES α = 1/3 and for ATES α = 1/4. For all the cases the auxiliary cost factor and the indirect costs factor have been maintained (f_{aux} = 0.25; f_{ind} = 0.12).

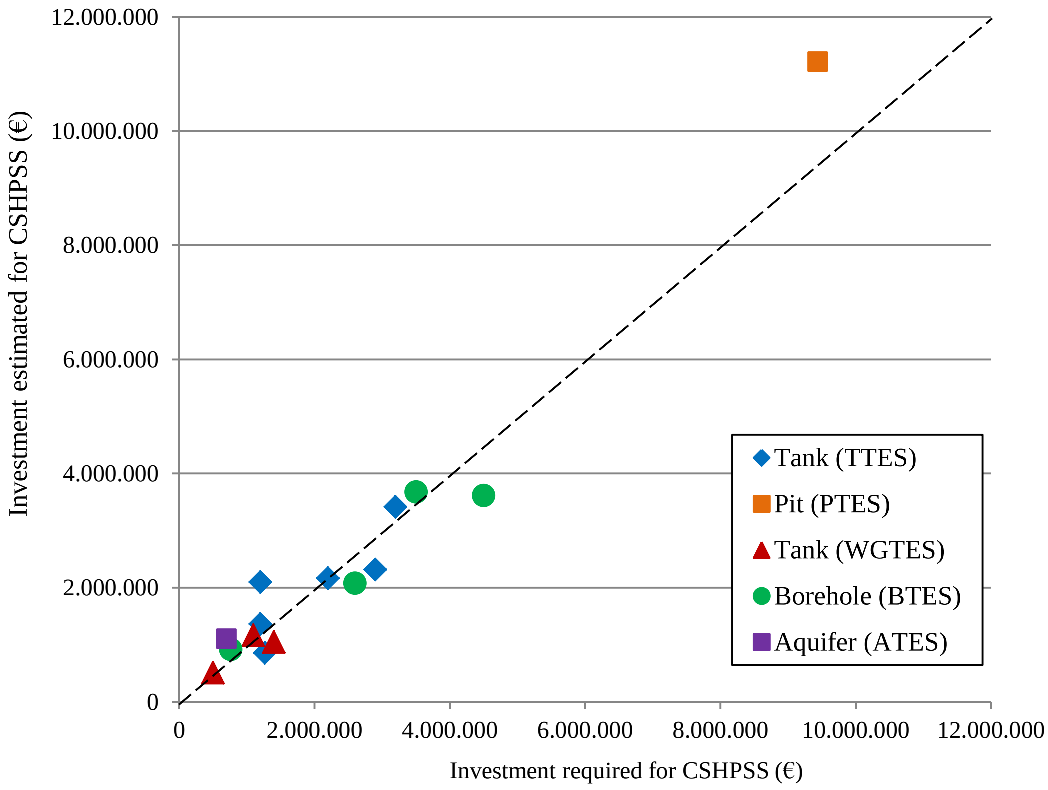

Figure 5.6: Validation of the economic model proposed for the investment

The investment estimated following the correlation in Eq. 3 is presented versus the real investment required in Fig 5.6. The correlation proposed, in average overestimates the cost of the CSHPSS by 7%. From the data available of investment costs for CSHPSS only the plant of Rise Fjernvarme has been eliminated from the correlation due to very big divergences compared to the other cases.

From the results obtained, we can conclude that the correlation proposed, while quite simple, estimates the investment cost for a wide range of cases and of different seasonal storage technologies. The correlation proposed tends to overestimate the investment costs required, except for the BTES systems, for which the correlation tends to underestimate the costs. Other key devices such as heat pumps should be considered to estimate the cost of plants with low temperature thermal energy storages, as BTES or ATES.

5.1.4 Solar heat cost

When the investment for a CSHPSS is estimated, the comparison with other heating technologies requires the cost of the solar heat produced. The solar heat cost depends on the annual amortization of the plant, the operation and maintenance costs and the annual production of thermal energy. The investment required for the project should be annually recovered. The Capital Recovery Factor CRF (yr^{-1}) converts a present value into a stream of equal annual payments over a time (n), at a specified discount rate (i).

$$CRF = i \cdot (1+i)^n/((1+i)^n - 1) \qquad (4)$$

The annual cost of the equipment, Z (€/yr), is calculated according to the CRF and the operation and maintenance cost. The CRF is calculated with an annual interest rate of 3%, ($i = 0.03$ $year^{-1}$), which is currently a common interest rate in countries where CSHPSS are installed, e.g. Denmark (Nielsen, 2014).

The amortization costs are distributed along the equipment's lifetime. Solar collectors have an estimated lifetime of 25 years (na = 25 years) and seasonal storages have an estimated life of 50 years (nv = 50 years). The annual operation and maintenance costs are estimated at about 1.5% ($f_{ope} = 0.015$ $year^{-1}$) of the investment cost according to the criteria proposed by the IEA (2012). Therefore, the annual costs are calculated with the following equations:

$$Z_{coll} = Inv_{coll} \cdot (f_{ope} + i \cdot (1+i)^{na}/((1+i)^{na} - 1)) = 54 \cdot A^{0.860} \qquad (5)$$

$$Z_{acu} = Inv_{acu} \cdot (f_{ope} + i \cdot (1+i)^{nv}/((1+i)^{nv} - 1)) = \alpha \cdot 251 \cdot V^{0.615} \qquad (6)$$

$$Z = (1+f_{ind}) \cdot (1+f_{aux}) \cdot (Z_{coll}+Z_{acu}) = 75 \cdot A^{0.860} + \alpha \cdot 352 \cdot V^{0.615} \qquad (7)$$

The unit cost of the solar heat (€/MWh) can be obtained as the quotient between the annual cost of the solar plant and the solar heat produced (Q_{sol}).

$$c_{sol} = Z/Q_{sol} \qquad (8)$$

Example of application

A base case of a CSHPSS that supplies heat, for space heating and domestic hot water, for a community of 1000 dwellings has been presented in Chapter 4. The system has a solar collector field area of 3210 m^2 and a seasonal storage volume of 19,260 m^3.

Following Equations 1, 2 and 3 the investment required for this system is estimated at about 3.9 million €. From the investment required the annual cost (including amortization, operation and maintenance costs) is estimated to be Z = 229,000 €/yr.

From this result the average cost of the solar heat produced can be obtained. The amount of heat produced by this installation is Q_{sol} = 2979 MWh/yr (determined in Chapter 4, Table 4.6) and therefore the solar heat cost is c_{sol} = 77 €/MWh.

The solar heat cost is based on the assumption of achieving an interest for the investment of 3% and op&m cost that represents 1.5% of the initial investment; but other scenarios are analyzed in Table 5.4.

Table 5.4: Sensitivity analysis of solar heat cost

	Solar heat cost under several scenarios (€/MWh)			
f_{ope} \ i	0%	*3%*	5%	10%
0.0%	33.3	*57.4*	77.4	135.1
0.5%	39.8	*63.9*	83.9	141.6
1.0%	46.4	*70.5*	90.4	148.1
1.5%	52.9	**77.0**	97.0	**154.7**
2.0%	59.4	83.6	103.5	161.2
2.5%	66.0	**90.1**	110.0	167.7

The financial, operation and maintenance cost of a central solar heating plant affect the economic viability. In the last few years, in Spain, loans for investment have been reduced and the interest rate has increased till 10%. For a central solar heating plant in which the return period is so long, a loan at 10% will double the solar heat cost c_{sol} = 154.7 €/MWh, making it completely ruinous.

According to the ratios proposed by the IEA-SHC operation and maintenance cost has been estimated. If this factor is decreased or increased by 0.5% (i.e. f_{ope} = 1% or 2%) then the price might be reduced or increased respectively by 13.5 €/MWh.

To achieve a low operation and maintenance cost as well as to get capital at a low rate, it is crucial to attain a good economic result. Profitable CSHPSS operate in countries with low interest applied, in locations where large solar collectors can be installed on ground with few and simple connections reducing operation and maintenance costs.

The economic analysis proposed estimates the cost of the production of thermal energy from the solar systems but the final price of the energy delivered to the consumers depends also on the distribution costs, i.e. the costs of using the district heating network. Distribution costs should include the amortization cost of the district heating network, operation and maintenance cost for distribution and thermal losses in transport.

5.1.5 Auxiliary heat cost

An auxiliary system is considered for the CSHPSS. A boiler with an efficiency of 93% (η_{BH} = 0.93) will supply the extra heat required to cover the heating demand. The gas required Q_{gas} can be calculated from the auxiliary energy required Q_{aux}.

$$Q_{gas} = Q_{aux} / \eta_{BH} \quad (9)$$

Large consumers of natural gas can apply for lower costs than domestic customers. In Spain the price of natural gas is set periodically by the Official Bulletin of the State (known in Spanish as BOE). Price of natural gas in Spain published in December of 2014 (BOE, 2014), is shown in Table 5.5 and has been used for the economic analysis.

Table 5.5: Price of natural gas in Spain for different size consumers (BOE, 2014)

Tariff applied	c_{fixed} (€/month)	$c_{variable}$ (€/MWh)
T.1 Consumption lower than 5 MWh/yr	4.36	55.33
T.2 Consumption lower than 50 MWh/yr and bigger than 5 MWh/yr	8.84	48.46
T.3 Consumption lower than 100 MWh/yr and bigger than 50 MWh/yr	60.38	42.27
T.4 Consumption bigger than 100 MWh/yr	181.72	39.15

The unit cost of the thermal energy produced along the year by the auxiliary system (Q_{aux}) depends on the fixed costs and on the consumption of gas times the variable price of the natural gas.

$$c_{aux} = (c_{variable} \cdot Q_{gas} + 12 \cdot c_{fixed}) / Q_{aux} \quad (10)$$

The cost of the boiler has not been included as it is considered negligible compared to the consumption of gas. The unit cost of the total thermal energy produced by the CSHPSS plant is:

$$c_{sys} = (Z + c_{aux} \cdot Q_{aux}) / Q_d \quad (11)$$

Example of application

For the base case proposed in Chapter 4 (see Table 4.6, case used in the previous example for solar heat cost) the system will consume Q_{gas} = 2550 MWh of natural gas with an annual cost of 102,026 €, tarification T.4 (BOE, 2014). The cost of the auxiliary heat (Q_{aux} = 2371 MWh) is c_{aux} = 43 €/MWh, lower than the cost of the heat produced by the solar system and lower than the cost of the heat produced by an individual boiler. The whole system, having a solar fraction of 56%, will have a cost of c_{sys} = 62 €/MWh.

In Europe the final district heating price for consumers strongly depends on the location, with a value between 40 and 100 €/MWh (Euroheat & Power, 2013b; see also Table 2.3 in Chapter 2). Special case is Iceland where the price is 11 €/MWh since the fuel used is the high temperature geothermal resource. The price of the heat produced for district heating systems can be partially compared with the heat produced by individual gas boilers, which is a typical solution in Spain for space heating and domestic hot water in locations with high demand. These boilers consume natural gas delivered to the houses by a piping system. A single family house with an annual consumption of 8

MWh/yr and a gas boiler with an annual average efficiency of 80% will produce heat at a final cost of ≈ 80 €/MWh (tarification T.2 BOE, 2014).

This evaluation for individual boilers does not include the distribution and installation cost for the gas distribution system, but the distribution costs were also not considered for the district heating system. Therefore, the real final heat cost will be slightly higher for both systems.

5.1.6 Conclusions

According to these results the solar system produces heat at a lower cost than an individual natural gas boiler when distribution cost is not considered for both technologies. This conclusion has been achieved considering a low interest rate (3%).

CSHPSS displaces the consumption of non-renewable fuels making the price of heat more stable but requiring a higher investment. Besides, a centralized district heating system has other advantages as better pull position for fuel purchase and an easier exchange of fuel compared to individual boilers. Furthermore, solar district heating systems are less sensible to variations of prices in the international market of fuels.

One of the biggest barriers for the development of CSHPSS is the uncertainty about the economic viability of these systems. In this section a methodology to estimate the investment cost and the price for the solar heat has been presented. The correlations have been compared with the results of the plants operating in Europe showing a great consistency for the capital investment cost of the main equipment (solar collector field and seasonal storage) and the whole plant.

5.2 Economies of scale

Important economies of scale can be achieved for CSHPSS. As justified in the economic model the cost of the seasonal storage is very dependent on the size. Thus, the economic viability of systems with seasonal storage requires large communities. The base case analyzed is an installation designed to attend the demand of 1000 dwellings in Zaragoza. When the number of dwellings is modified, the annual demand changes accordingly. Keeping the design ratios, RAD = 0.6 m^2/(MWh/yr) and RVA = 6 m^3/m^2, constant, the results obtained for different number of dwellings are shown in Table 5.6 and Fig. 5.7.

Table 5.6: Parametric analysis varying the number of dwellings (Zaragoza, RAD = 0.6, RVA = 6)

Number of dwellings	A (m^2)	V (m^3)	Q_{sol} (MWh/yr)	SF (%)	η_{coll} (%)	η_{acu} (%)	η_{sys} (%)	Inv/Dwe (€/Dwe)	Z (€/yr)	c_{sol} (€/MWh)
100	321	1926	288	53.9	58.3	75.9	52.9	8,315	48,000	165
500	1605	9630	1478	55.3	57.5	85.1	54.2	4,860	142,000	96
1000	*3210*	*19,260*	*2978*	*55.7*	*57.2*	*88.0*	*54.6*	*3,890*	*229,000*	*77*
5000	16,050	96,300	15,075	56.4	56.8	92.8	55.2	2,372	719,000	48

The most significant result is the considerably reduction of the solar heat cost with the increasing demand; for a community of 5000 dwellings the solar heat cost is reduced to 48 €/MWh. Part of this cost reduction is due to the slight increase of the system efficiency when increasing the size of the system but the dominant factor is the effect of the economies of scale on the investment cost per dwelling, Inv/Dwe, which is reduced by 40% when increasing from 1000 dwellings to 5000 dwellings.

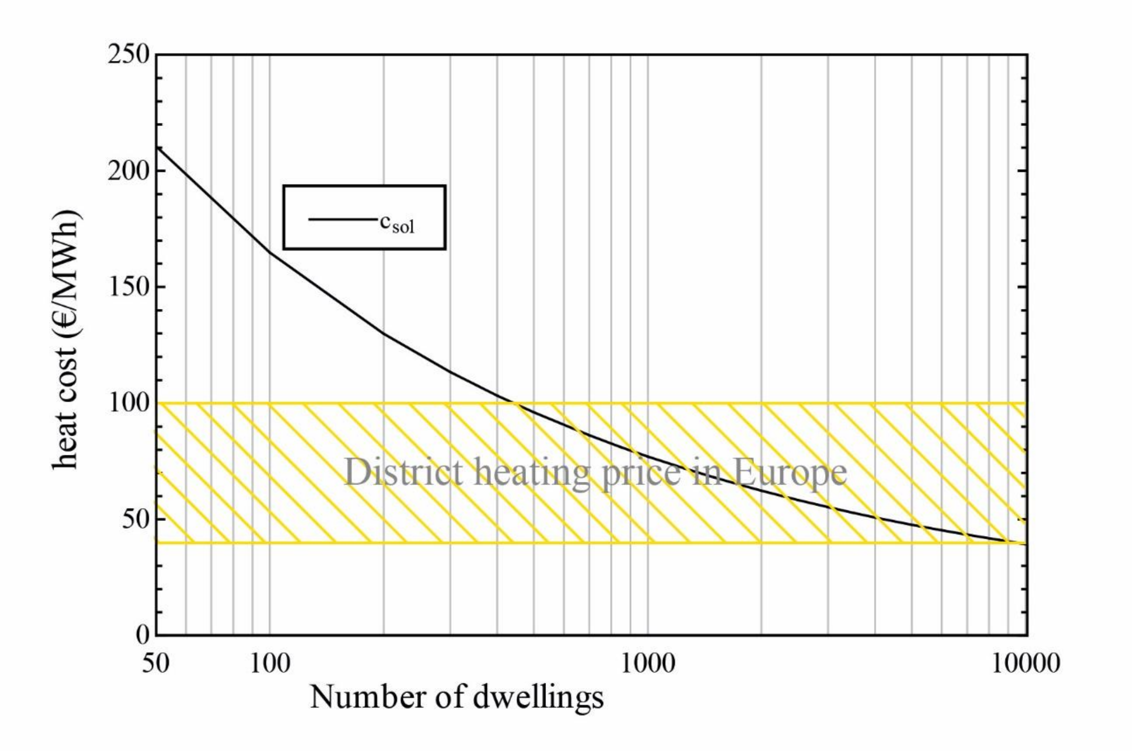

Figure 5.7: Economies of scale for solar heat cost

5.3 Critical volume

The maximum allowed temperature for the seasonal storage tank in the base case is 90ºC. Table 4.6 shows that the maximum temperature reached in the seasonal storage is 80.3ºC, i.e. the tank is not fully charged along the year. A reasonable design criterion for tank sizing would be based on the following premises:

1) Do not reject any fraction of the solar heat collected ($Q_x = 0$), which means that a thermal energy storage is required.
2) Maximum usage of the installed accumulation capacity, which means that the tank should be fully charged, i.e. the maximum allowed temperature in the tank should be reached only at the end of the charging period and the beginning of the discharge period.

Therefore, it is interesting to study the effect of varying the volume of the seasonal storage tank from the base case (RVA = 6 m^3/m^2) (see Fig. 5.8).

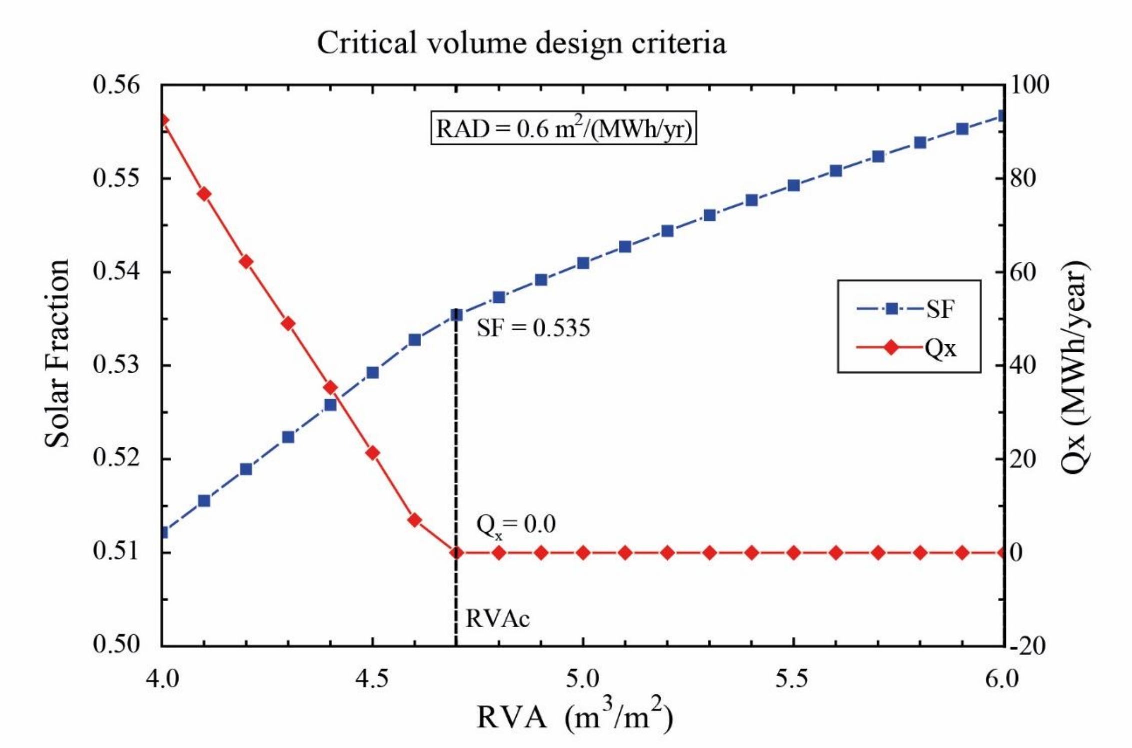

Figure 5.8: Effect of the accumulation volume on the solar fraction (SF) and the rejected heat (Q_x)

If the ratio RVA is reduced while maintaining the collector area constant, the maximum temperature reached in the seasonal storage rises and the solar fraction decreases. For a value of the ratio RVA lower than 4.7 m^3/m^2 the solar fraction decreases with a steeper slope, because the seasonal storage volume does not store all the heat collected and as a consequence part of this heat is rejected ($Q_x > 0$). The critical value of volume without heat rejection is defined here as *critical volume* V_c and the ratio RVA with critical volume is denoted RVA_C. In Table 5.7 it is shown the variation of the solar heat cost when the seasonal storage volume is modified to lower ratios of RVA.

Table 5.7: Variation of the ratio RVA for Zaragoza base case (RAD = 0.6)

RVA (m^3/m^2)	V (m^3)	$T_{acu,max}$ (°C)	Q_x (MWh/yr)	SF (%)	η_{sys} (%)	Inv (10^6 €)	Z (10^3 €/yr)	c_{sol} (€/MWh)
6.0	*19,260*	*80.3*	*0.0*	*55.7*	*54.6*	*3.89*	*229*	*77.0*
5.0	16,050	87.2	0.0	54.1	53.0	3.59	213	73.7
4.0	12,840	90.0	92	51.2	50.2	3.27	196	71.5
3.0	9630	90.0	233	47.9	47.0	2.91	177	68.9
2.0	6420	90.0	373	44.2	43.3	2.51	155	65.5
1.0	3210	90.0	532	40.4	40.3	2.01	128	58.2

Starting with the base case (RVA = 6 m^3/m^2) then the ratio RVA is reduced to 1 m^3/m^2. From the obtained results, the positive effects of increasing the volume of the seasonal storage (higher solar fraction and system efficiency) do not compensate the investment cost of increasing the seasonal storage and the solar heat cost is increased.

This effect occurs even when the installed volume is not big enough for storing all the heat produced and some solar heat is rejected. It can be concluded from this assessment that with the present investment costs of the water tank thermal energy storages the critical volume is not the optimum economic design but a logical design from a thermal efficiency point of view.

When the design criterion considers the critical volume ratio, RVA_c, then the number of free design variables can be reduced to one, the solar field area. The RVA_c has been obtained for different ratios RAD and the solar fraction calculated for the community of 1000 dwellings located in Zaragoza. The relationship between solar fraction and the design variables under such circumstances is shown in Fig 5.9.

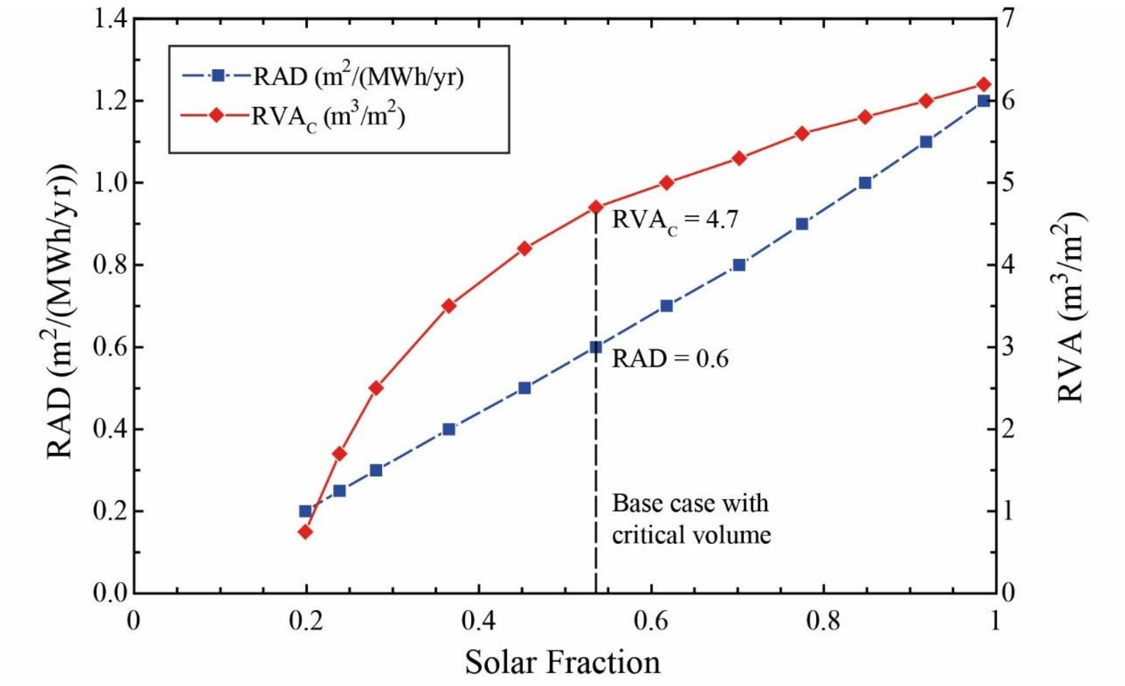

Figure 5.9: Design ratios RAD and RVA vs solar fraction with critical volume design criterion

To increase the solar fraction, it is necessary to enlarge linearly the solar collector field area. This relation is almost proportional because the efficiency of the solar collector will only change from 59% to 51%. However, the accumulation volume does not rise up linearly with solar fraction.

For low solar fraction values (SF < 20%) it is almost not necessary to accumulate heat in summer (RVA_c < 0.7 m^3/m^2) because with a small solar collector field area the summer solar production almost does not overpass the demand of domestic hot water. The need of thermal energy storage relative to solar field area increases quickly for low values of solar fraction (SF), and increases in a smooth way for high values of SF. For example, the accumulation needed to obtain a solar fraction close to 50% is RVA_c = 4.5 m^3/m^2 and for a solar fraction close to 100% is RVA_c = 6.1 m^3/m^2. Detailed results are presented in Table 5.8.

Table 5.8: Parametric analysis varying the solar fraction with critical volume design criterion

RAD (m^2/MWh·yr)	A (m^2)	RVA (m^3/m^2)	V (m^3)	Q_{sol} (MWh/yr)	SF (%)	η_{coll} (%)	η_{sys} (%)	Inv (10^6 €)	c_{sol} (€/MWh)
0.2	1070	0.75	803	1062	19.8	59.2	58.3	0.82	48.7
0.3	1605	2.5	4013	1501	28.1	56.9	55.0	1.66	67.0
0.4	2140	3.5	7490	1953	36.5	55.9	53.7	2.33	71.5
0.5	2675	4.2	11,235	2422	45.3	55.6	53.2	2.94	72.4
0.6	*3210*	*4.7*	*15,087*	*2865*	*53.5*	*55.0*	*52.5*	*3.50*	*72.7*
0.7	3745	5.0	18,725	3305	61.8	54.4	51.9	3.99	72.0
0.8	4280	5.3	22,684	3755	70.2	54.2	51.6	4.49	71.2
0.9	4815	5.6	26,964	4145	77.5	53.3	50.6	4.98	71.6
1.0	5350	5.8	31,030	4535	84.8	52.6	49.8	5.44	71.5
1.1	5885	6.0	35,310	4915	91.9	51.9	49.1	5.90	71.5
1.2	6420	6.2	39,804	5272	98.6	51.1	48.3	6.35	71.7

The economic results for the variation of the solar fraction from 20% to 100% with the design criterion of critical volume are the following ones:

1) The investment required rises with the solar fraction from 0.8 million € to almost 6.3 million € for a 98% solar fraction.

2) The solar heat cost for low solar fraction (20%) is only 49 €/MWh. If the solar fraction is increased to 40%, then the solar heat cost rises to 72 €/MWh and remains constant, i.e. it is not affected by further increase in the solar fraction.

5.4 Systems with minimum volume

Medium and large solar collector fields without seasonal storage can produce heat to partially cover the needs of domestic hot water and space heating for communities and district heating systems. In winter the solar production will cover part of the domestic hot water and space heating needs. In summer the solar production will cover domestic hot water demand and probably overproduction periods will happen.

Along the overproduction periods it will be required to disconnect the solar field to avoid damage to the pumps due to overheating and a too high temperature in the solar circuit (Task 49, 2014b). Another solution not considered in this thesis could be to use the overproduction heat to produce cooling with an absorption machine, as proposed by Qu et al. (2010). Cooling demands in summer might use the solar overproduction to produce a valuable resource, expanding the market opportunities for solar thermal energy (ESTTP, 2009).

Along the stagnation hours (a period without operation) the temperature of the solar collector might rise significantly and reduce the expected life of the solar collector. To avoid this problem, the solar collector field might also be connected to an auxiliary cooling system to reduce the temperature but consuming electricity.

For low solar fraction systems (<20%) overproduction may not occur but if higher solar fraction is obtained by increasing the size of the solar field then a considerable part of the heat produced in summer will be rejected. If a solar field is big enough, it can cover a big share of the space heating needs in locations with significant radiation in winter but the system, with a small thermal storage (RVA = 1 m^3/m^2), will have very poor efficiency and it will suffer long overheating periods. Obtained results showing these trends are shown in Fig. 5.10.

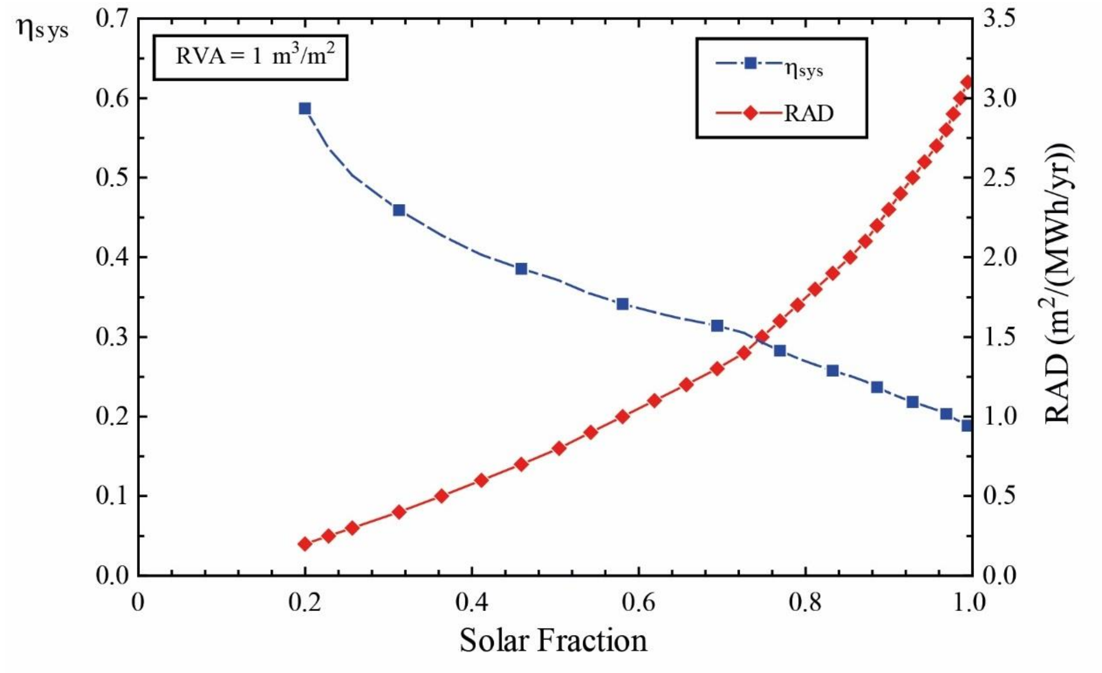

Figure 5.10: System efficiency and collector area requirements vs solar fraction for minimum storage

5.5 Trade-off between collector area and storage volume

In order to obtain a specific solar fraction with a CSHPSS, it is possible to design the plant either with the critical volume or with the minimum volume design criteria. That is, a specific solar fraction can be obtained with multiple combinations solar collector field area – seasonal storage volume (Sillman, 1981). For almost 700 different combinations of RAD and RVA design parameters the solar fraction has been calculated for the base case, a community of 1000 dwellings in Zaragoza, creating the design space. Applying data interpolation, lines with the same solar fraction values have been depicted in Fig. 5.11. Following whatever isoquant line several combinations area of the solar field – volume of the seasonal storage produce the same solar fraction i.e. trade-off between collector area and storage volume.

In the trade off diagram of Fig. 5.11 the systems previously designed, base case and critical volume case, are depicted in green and the designs with critical volume are depicted as blue squares, connected by a blue line. The design space located below the critical volume line, Space A, corresponds to combinations with storage smaller than the critical volume; part of the thermal energy produced along the year is rejected. The design area located over the critical volume line, Space B, corresponds to combinations with storage larger than the critical volume, and therefore, the maximum temperature is not reached. If the volume of the thermal energy storage is too big with respect to the solar collector field area, as in Space C, then storage thermal losses increase significantly losing the benefit of storing thermal energy; as a consequence, the solar fraction decreases with volume.

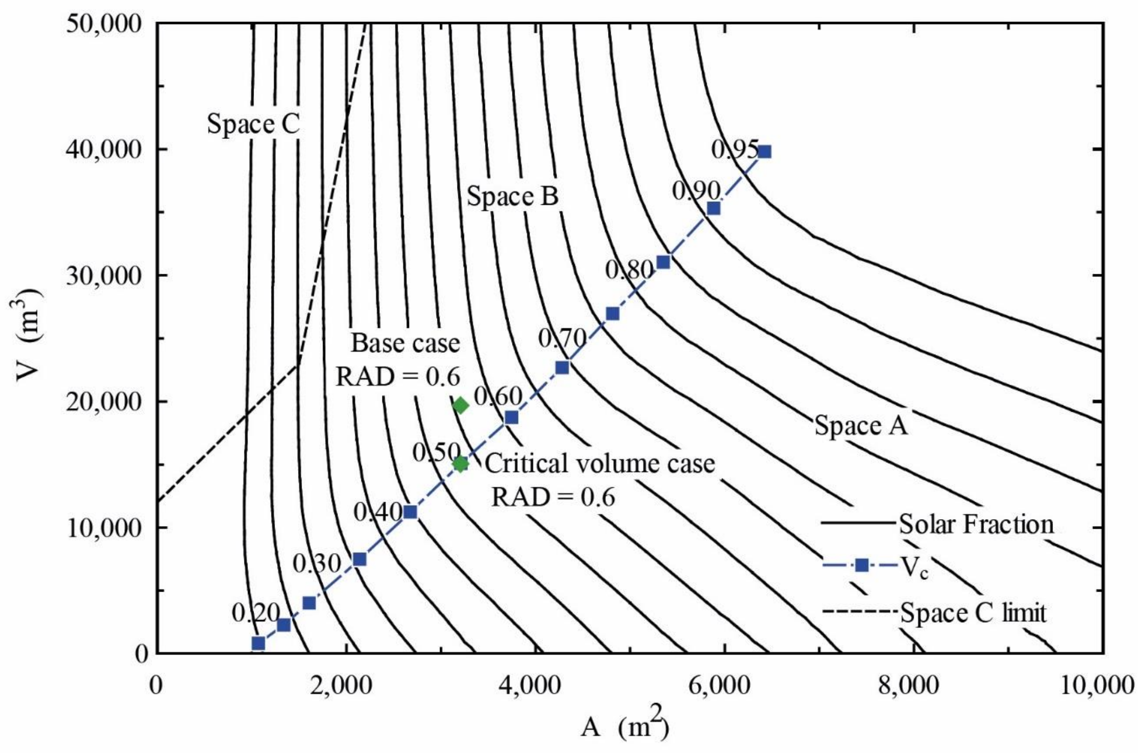

Figure 5.11: Trade-off diagram, solar field area vs seasonal storage volume

5.6 Economic opportunities for CSHPSS

The average unit heat cost of district heating systems in Europe is between 40 €/MWh and 100 €/MWh, depending on the location (Euroheat & Power, 2013b). From the analysis presented (economies of scale, critical volume and minimum volume) it has been concluded that: 1) systems with seasonal storage and high solar fraction can be competitive when the number of dwellings is very large, and 2) systems with low solar fraction can be competitive for a larger number of cases.

The most important factors for the economic viability of a CSHPSS are i) the selection of the desired solar fraction, and ii) the design criterion for the storage. To take these decisions from an economic point of view, a parametric analysis can be performed and the solar heat cost can be presented as a function of the solar fraction and the ratio RVA.

For the base case demand (location Zaragoza, demand of SH and DHW for a 1000 dwellings community), the solar heat cost of hundreds of cases with different couple of design ratios RAD and RVA has been calculated. Each case is presented in a graph XY, see Fig. 5.12, being X the solar fraction achieved and Y the design ratio RVA. A ratio RVA = 1 means that minimum storage criterion is being used.

For each case the solar heat cost has been calculated and isoquant lines of solar heat cost are traced by interpolation. Following each line designs that produce heat at the same cost are obtained. Designs of CSHPSS that fulfill the design criterion of critical volume are presented in red.

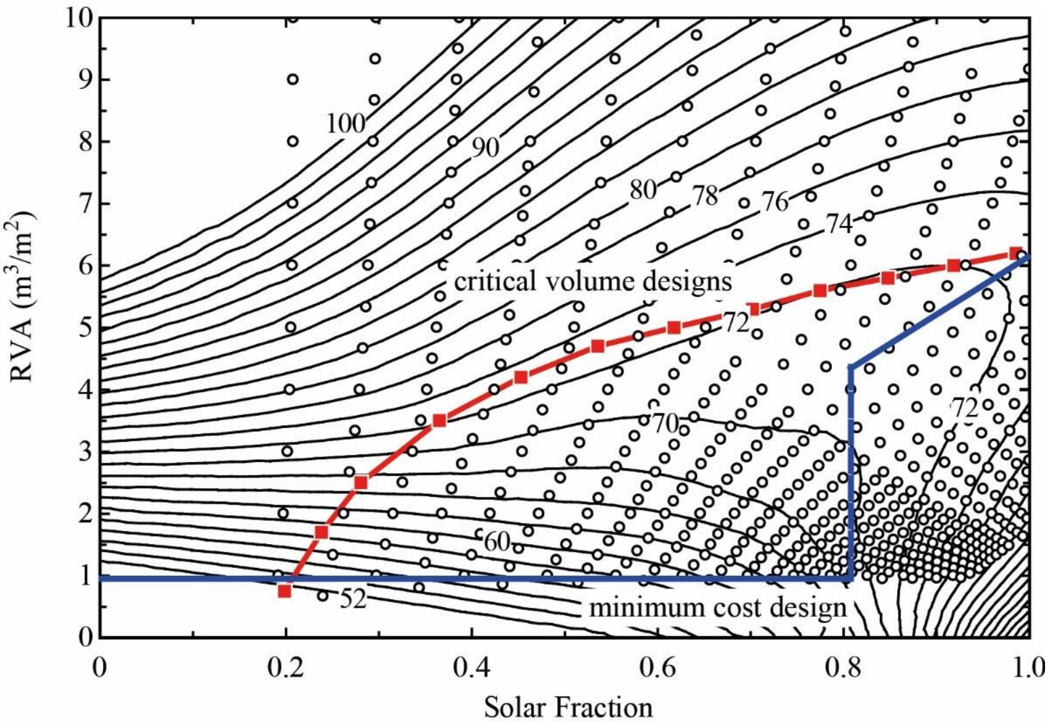

Figure 5.12: Minimum solar heat cost design diagram

The lowest solar heat cost is achieved at low solar fraction with small RVA ratio. For each solar fraction the ratio RVA with the lowest solar heat cost has been obtained, the blue line represents the designs with minimum solar heat cost. For solar fractions lower than 80% the designs with minimum solar heat cost are those without seasonal storage (RVA = 1) and only for systems with solar fractions higher than 80% the minimum solar heat cost RVA is close to the critical design ratio RVAc. These results have been achieved for Zaragoza (Spain) where the solar radiation in winter is still high and part of the space heating could be produced without seasonal storage.

All the cases previously presented are referred to thermal energy storage in a hot water tank "Water Tank Thermal Energy Storage", which is more expensive per unit of volume than other solutions but it is suitable for any universal application. The economic model presented shows an important cost reduction of the investment when the hot water tank is substituted by other technologies: PTES, BTES, ATES.

The parameter α used in Eqs. 2, 3, 6 and 7 considers the economic behavior of different technologies. The value α = 1 corresponds with the experience gained in the demonstration projects of the two last decades using a hot water tank for thermal energy storage. A value of α = ½ can be considered for a PTES with a size larger than 10,000 m^3 (Marstal) and a factor of α = ⅓ has been obtained in BTES of 34,000 m^3 (Drake Landing). It has been performed the same parametric analysis of minimum solar heat cost as for the base case with α = 1 for α = 1/2, 1/3 and 1/4. The designs with minimum solar heat cost are presented in Fig. 5.13.

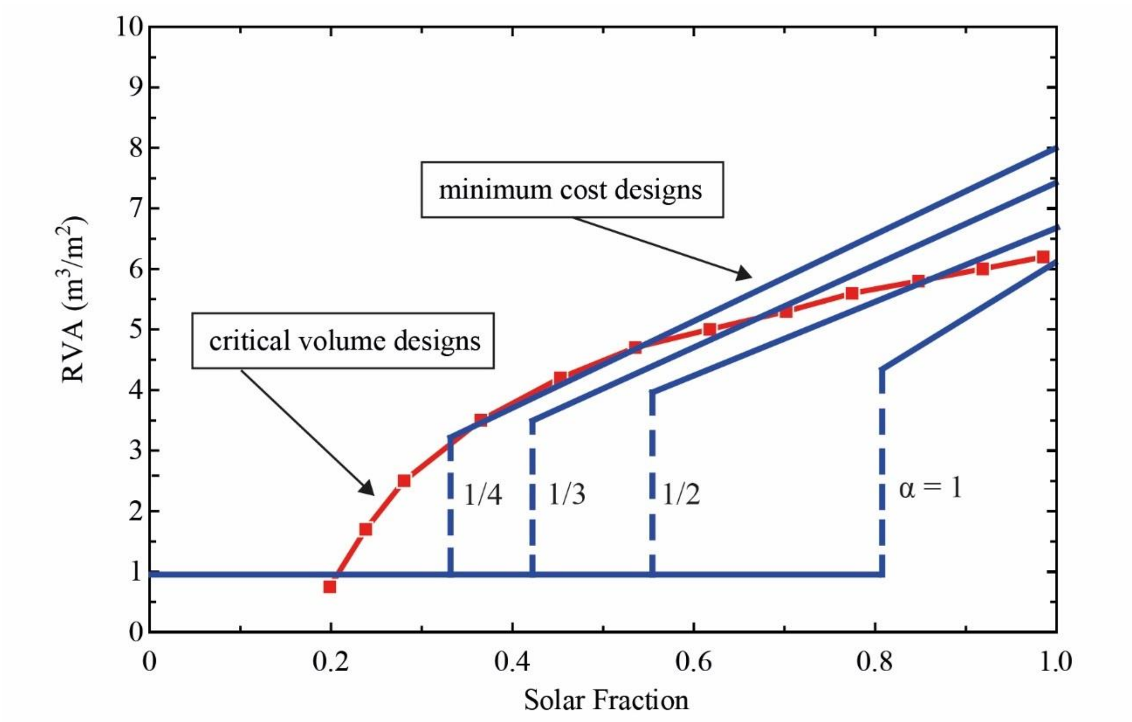

Figure 5.13: Designs with minimum solar heat cost vs solar fraction (α =1, 1/2, 1/3, 1/4)

For each alpha value analyzed, there is a critical solar fraction (see Fig. 5.13). Over that value the design with minimum solar heat cost corresponds to a seasonal storage close to critical volume design criterion and below that value, minimum volume is the optimum solution. For this solar fraction range a discontinuity in the most appropriate design criteria is generated from minimum to critical volume.

Table 5.9: Designs with minimum solar heat cost versus solar fraction

α	Solar fraction	40%	60%	80%	90%	95%
1	RVA (m^3/m^2)	1.0	1.0	1.0	5.3	6.0
	c_{sol} (€/MWh)	57	61	68	71	72
	Q_x/Q_c (%)	18%	29%	38%	4%	0%
	EA/EA_{Max} (%)	100%	100%	100%	100%	100%
$^1/_2$	RVA (m^3/m^2)	1.0	4.0	5.6	6.5	6.8
	c_{sol} (€/MWh)	46	50	49	49	50
	Q_x/Q_c (%)	18%	6%	0%	0%	0%
	EA/EA_{Max} (%)	100%	100%	100%	94%	92%
$^1/_3$	RVA (m^3/m^2)	1.0	5.0	6.3	7.2	7.5
	c_{sol} (€/MWh)	42	42	42	42	42
	Q_x/Q_c (%)	18%	0%	0%	0%	0%
	EA/EA_{Max} (%)	100%	99%	93%	87%	85
$^1/_4$	RVA (m^3/m^2)	4.2	5.4	6.7	7.4	7.8
	c_{sol} (€/MWh)	39	38	38	38	38
	Q_x/Q_c (%)	0%	0%	0%	0%	0%
	EA/EA_{Max} (%)	93%	94%	88%	84%	83%

Table 5.9 summarizes the results from the minimum solar heat cost analysis showing three meaningful facts:

1) The solar heat cost does not have a significant change with the solar fraction, so systems with high solar fraction result in an economically acceptable design.
2) When the investment cost of the seasonal storage is reduced by half or more then solar heat cost gets below 50 €/MWh for any solar fraction.
3) With storage cost reduction, designs with minimum solar heat cost are similar to designs obtained with the critical design criterion, i.e. the critical volume design is an acceptable criterion from an economic and thermal efficiency point of view.
4) When the cost of the seasonal storage is drastically reduced then it can be even justified to oversize the seasonal storage to reduce the system temperature increasing the average efficiency ($\alpha = \frac{1}{4}$; SF = 95%; RVA = 7.8; $T_{acu,Max} = 79.6$ ºC).

Parametric analyses can be performed with the *Simple Method* proposed in Chapter 4 obtaining predesigns based on minimum solar heat cost for specific climatic and demand data. The economic evaluation proposed in this chapter justifies the evaluation of CSHPSS in Spain as an economically viable solution for large communities with DH systems and can be used as a reference for preliminary studies.

Chapter 6: Environmental analysis

6 Environmental analysis

In the previous chapters CSHPSS that can supply heat to the residential sector have been analyzed. In Chapter 2 the state of the art of large scale solar thermal systems has been presented. Simulation and evaluation tools were presented in Chapter 3. In the second part, simplified tools for pre-design and analysis of CSHPSS have been developed. In Chapter 4 an original calculation method has been defined based on physical equations, using simple climatic data. In the search for a simplification of the design process a method to estimate the cost of these installations has been described and validated in Chapter 5. Chapter 6, focuses on the environmental assessment of CSHPSS, evaluating the environmental burdens generated or avoided. The main aim is to determine the environmental impact of these systems and develop a simplified model that could help estimate the environmental performance of CSHPSS. In this way a quite comprehensive physical, economic and environmental analysis of CSHPSS could be developed with a unified tool.

Two paramount objectives to be reached at European and World level are: 1) to reduce the emission of greenhouse gases (GHG) and 2) to reduce the consumption of non-renewable energy sources.

1) Several airborne emissions produce the so called greenhouse effect on the Earth. A common unit is used to measure the effect of all the pollutants emitted translating the effect of global warming into the equivalent effect of CO_2 emissions expressed in kg of $CO_{2\text{-eq}}$. The intergovernmental panel on climate change (IPCC) is an independent scientific international organism that establishes the global warming factor for each different GHG emission for a specific period of time. The Kyoto protocol and the following agreements about GHG emissions did not reach the expected effect because many countries had refused to accomplish them. Other strategies based on consumer’s choice are also contributing to the reduction of GHG emissions, e.g. carbon footprint labelling in some products as vehicles or white-goods.

2) The second objective to be achieved is the reduction of the consumption of non-renewable primary energy. The EU and its member states have committed to achieve in 2020 an important reduction in the consumption of non-renewable energy and to take future commitments in the next coming years to reach a reduction of the fossil fuel dependency by increasing the energy efficiency as well as the renewable production ratio for all the energy demands.

Systems driven by solar energy fulfill these two objectives. By displacing the consumption of fossil fuels the emission of GHG is reduced and increased the renewable energy ratio. High solar fraction systems can far-reach these objectives while systems with low solar fraction can only make a minor impact. CSHPSS can reach high solar fraction combining solar thermal collectors with seasonal thermal energy storage technology. These systems match the largest supply of solar radiation during summer, with the higher energy demand for space heating in winter, being feasible to reach high solar fractions of the combined demand for SH and DHW.

Centralized solar systems can play an important role in the future, due to the special characteristics of the solar thermal energy, free and available at the consumption place and at low cost for low temperature demand. In order to have a complete vision of the interest and advantages of these systems, not only their technical and economic viability should be determined but it is also necessary to gain a better understanding and knowledge of the potential environmental impacts caused or avoided.

Most environmental analyses of energy systems only consider the consumption of fuels and electricity to estimate the emission of GHG and other impacts. This method, while appropriate for non-renewable energy systems, is not appropriate for renewable energy systems and particularly for solar thermal energy since it neglects the environmental impact of the equipment, which is not negligible. To this end, the Life Cycle Assessment (LCA) procedure can be utilized to analyze the entire range of environmental damages associated with large scale solar thermal plants with or without seasonal storage.

LCA is an established and internationally standardized method for the analysis and quantification of environmental loads and impacts through the life cycle of products and services (Guinée Ed., 2002). It evaluates the consumption of natural resources and the emissions generated taking into account all stages in the life cycle process i.e: raw material extraction, intermediate and final manufacturing processes, packaging, transport, use and final disposal.

There are a limited number of LCA studies which focus on solar thermal systems. Most of these studies analyze the life cycle of solar systems for domestic hot water of single residential houses and multifamily buildings in different locations of European countries and North America (Albizzaty and Arese, 2011; Kalogirou, 2004; Kalogirou, 2009; Rey-Martínez et al., 2008; Simons and Firth, 2011). This implies that the solar collector field area and storage systems are small; in any case they do not reach the category of large size solar systems, greater than 500 m^2 collector area.

Hang et al. (2012) carried out a comparative LCA of solar thermal collectors focused exclusively on the analysis of flat plate collectors and vacuum tubes. Kalogirou (2004) presented the advantages of a solar assisted system for single family houses for DHW and space heating and in a more recent paper explained the advantages of thermosiphon solar water heaters (Kalogirou, 2009). Albizzati and Arese (2011) studied the environmental impact of solar assisted systems compared with conventional electric or gas systems. Oró et al. (2012) focused on alternative DHW storage systems (molten salt and solid medium). After a detailed bibliographic revision, no other studies that analyze the LCA of centralized solar thermal systems with seasonal thermal energy storage (CSHPSS) to cover the thermal energy demand in residential buildings have been found, but the documents elaborated in the development of this work (Raluy et al., 2013 and 2014).

This chapter has the following structure. In Section 6.1 the LCA methodology is introduced to evaluate the environmental impact of products along the life cycle. The LCA methodology has been used to analyze a case study in Section 6.2. The case study is a CSHPSS model available in literature (Lozano et al., 2010c) that generates heat for a community of 500 dwellings in Zaragoza. A detailed LCA of the case study analyzes the emission of greenhouse gases (GHG), the cumulative energy demand (CED) and the environmental impact based on the IMPACT 2002+ method. The environmental impact of all the components is evaluated with special consideration for the solar collector field and the seasonal storage. The environmental impact of the heat produced during the operation is also analyzed including the effect of the electricity required and the auxiliary energy, natural gas, consumed. The final result from this analysis is the environmental characterization of a CSHPSS and the environmental impact of the system per unit of heat produced considering the operation along its expected life.

From the results of this detailed LCA, a simplified environmental assessment for CSHPSS is proposed in Section 6.3. This simplified analysis can be used to determine the environmental impact of other installations but can only be applied for systems with hot water tanks and flat plate collectors.

6.1 Life Cycle Assessment Methodology

A life cycle assessment (LCA) is a standardized method for the analysis and quantification of environmental loads and impacts through the life cycle of products and services. In this research, the life cycle environmental burdens of the system will be estimated based on relevant emissions to the atmosphere, e.g. greenhouse gases, cumulative energy demand and a comprehensive environmental indicator, the IMPACT 2002+, which considers several environmental burdens of very diverse nature. To this end, the Life Cycle Assessment (LCA) procedure can be utilized to analyze the entire range of environmental damages associated with products and services.

The international standard (ISO 14040, 2006) declares that four stages compose the process of life cycle assessment, see Fig. 6.1: determination of goal and scope; life cycle inventory; evaluation of the environmental impact; and interpretation of results.

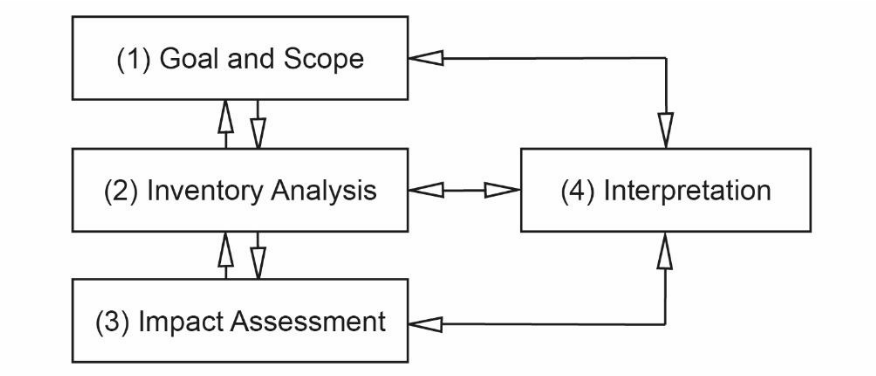

Figure 6.1: Life cycle assessment process

6.1.1 Goal and scope

The LCA starts with an explicit declaration of the goal and scope of the analysis as well as its limits, i.e. the aspects and premises that will be considered in the analysis are established in this phase. It is a key step and the standard ISO requires that clear objectives and limits of the LCA should be properly defined for the application proposed.

An important part of the goal and scope is the declaration and definition of the functional unit. The functional unit is the reference performance feature to standardize input and output data with respect to the environmental impact that will be determined. The functional unit can be of different nature, e.g. it can be 1 kg of iron produced for a steel factory or the generation of 1 MWh of electricity for an energy system.

The definition of objectives and limits includes the technical details that orientate the following work and should clearly describe the functional unit that will be used to evaluate the system.

6.1.2 Life cycle inventory

The life cycle inventory (LCI) implies the creation of an inventory of all the flows from and to the environment including water, energy, raw materials and emissions to the air, water and soil. It is an accounting of all the materials, resources and energy required by the system as well as the emissions generated throughout its life cycle, i.e. “from the cradle to the grave”.

A model for the system represented with a flow-chart diagram, that includes the activities that will be evaluated in the reference supply chain, defines components, materials and energy flows. The flow chart diagram clearly defines the system boundaries, the main streams and resources consumed along the process and the burdens generated.

For each activity, process and parts that are involved in the model as well as the input and output flows along the whole life cycle are analyzed. The data from each activity or process are collected and referred to the functional unit defined in the goal and scope stage.

6.1.3 Impact assessment

From the inventory obtained in the previous stage the impact assessment of each material, process or component listed is calculated. The accuracy of the impact assessment is related to the efforts applied in the elaboration of the inventory. On the other hand, the uncertainty of the impact assessment is determined according to the uncertainty of the inventory data and the uncertainty of the characterization factors. The impact assessment is composed of the following steps:

1) Selection of impact categories and characterization models.
2) Determination of the quantitative environmental impact using indicators.
3) Calculation of the environmental impact of the flows and products defined in the LCI using one of the different evaluation methodologies for LCA.

Common impact categories for energy systems are used in this LCA: emission of greenhouse gases and consumption of primary energy (using the cumulative energy demand method). In order to get a broader outlook about the environmental impacts, a third methodology has been used, the evaluation method IMPACT 2002+ based on 4 damage categories and 14 midpoint impact categories.

To handle a large inventory simplifying the calculation process of the impact assessment, the software Simapro 8.0.1 (2014) and the database of Ecoinvent V2.0 (2007) have been used.

6.1.3.1 Emission of greenhouse gases

The emission of GHG has been obtained following the IPCC methodology. The method evaluates the contribution to global warming of different emissions, due to anthropogenic activities, during the life cycle of the analyzed product or service. The characterization of different emissions according to their global warming potential and their aggregation in the impact category climate change is one of the most widely used methods in life cycle assessment. Characterization values for greenhouse gas emissions are based on Global Warming Potentials (GWP) published by the intergovernmental panel on climate change (IPCC, 2007). The environmental impact due to the emission of GHG for a component ($EI_{GHG,}$ kg $CO_{2\text{-eq}}$) consisting of a sort of items listed in the inventory LCI_k is obtained by multiplying each item in the inventory by the corresponding global warming potential GWP_k:

$$EI_{GHG} = \sum_k (LCI_k \cdot GWP_k) \quad (1)$$

GWP is an index to estimate the relative global warming contribution due to the emission of 1 kg of a particular greenhouse gas compared to the emission of 1 kg of CO_2 (final contribution measured in kg $CO_{2\text{-eq}}$). Three time horizons are used to evaluate the temporal effect of different gases: 20, 100 and 500 years. CO_2 has a global warming potential index of 1 for the three lifetimes. Methane has a lifetime of 72 for the shorter scenario, 20 years, 25 for 100 years and 7.6 for 500 years. In this thesis the scenario for 100 years has been used.

6.1.3.2 Cumulative energy demand

The consumption of primary energy has been obtained according to the cumulative energy demand method (CED). The CED method provides a comprehensive evaluation of the energy related environmental impacts along the life cycle including the consumption of energy required for the extraction of raw materials and the transformations required for the product or service. For a product or a process, the amount of resources consumed (EI_{CED}, MJ or MWh) from renewable and non-renewable energy sources can be obtained as a sum of the items listed in the inventory (LCI_k) multiplied by the corresponding consumption of energy (CED_k).

$$EI_{CED} = \sum_k (LCI_k \cdot CED_k) \quad (2)$$

For energy production systems the primary energy factor (PEF) can be obtained. The PEF (also known as energy yield ratio, EYR) is the ratio between the energy produced (E) and the cumulative energy resources consumed (EI_{CED}). The cumulative energy demand of a product and the PEF can be seen as indicators of the environmental impact for the depletion of energy resources considering the whole lifecycle (Wagner and Pick, 2004).

This methodology is very appropriate to compare renewable energy technologies (Gürzenich et al., 1999) and is also useful as environmental indicator of products and goods (Hujibregts et al., 2006 and 2010).

But CED and emission of GHG do not give a full picture of all the environmental impacts. The environmental impact of energy resources varies among different fuels (e.g. the impacts of coal use in relation to the energy content are usually more severe than those related to the use of natural gas) and technologies (e.g. clean coal process and exhaust treatment, among others). Thus, CED and emission of GHG should not be the only methods to evaluate the environmental impacts. To obtain a more comprehensive assessment the IMPACT 2002+ method, which encompasses 14 different midpoint impact categories and 4 damage categories, has been used, providing a more complete and richer assessment of the environmental loads.

6.1.3.3 IMPACT 2002+

IMPACT 2002+ (IMPact Assessment of Chemical Toxics) is an impact assessment methodology originally developed at the Swiss Federal Institute of Technology - Lausanne (Jolliet et al., 2003). The method has already been evaluated by different authors with respect to its suitability use for topics related to LCA (Meyer et al., 2009). It is a combination of four methods (IMPACT 2002, Eco-indicator 99, CML and IPCC), being largely based on Eco-Indicator 99 (Goedkoop and Sprinsma, 2001).

It proposes a feasible implementation of a combined midpoint/damage approach, linking all types of life cycle inventory results (elementary flows and other interventions) via 14 midpoint impact categories of different nature (human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nitrification, aquatic acidification, aquatic eutrophication, land occupation, global warming, non-renewable energy, and mineral extraction) to four damage categories (human health, ecosystem quality, climate change, and natural resources). More details are shown in Table 6.1 and Fig. 6.2.

Midpoint impact categories are commonly accepted environmental burden groups located somewhere on an intermediate position between the LCI and the damage categories (also called endpoint) on the impact pathway. As a consequence, a further step may allocate the midpoint impact categories to one or more damage categories, which try to express and quantify the case-effect chain of the usage of natural resources and the emissions up to the end-point or damage. In practice a damage indicator result is always a simplified model of a very complex reality, giving only a coarse approximation of the quality status of the item (Jolliet et al., 2003). In order to calculate the IMPACT 2002+ score (EI_{IMP}) the following steps are required.

Step 1: Evaluation of the resource extraction inventory, land use and all relevant emissions *k* in all processes that form the life cycle of the equipment or utility yielding the Life Cycle Inventory LCI_k.

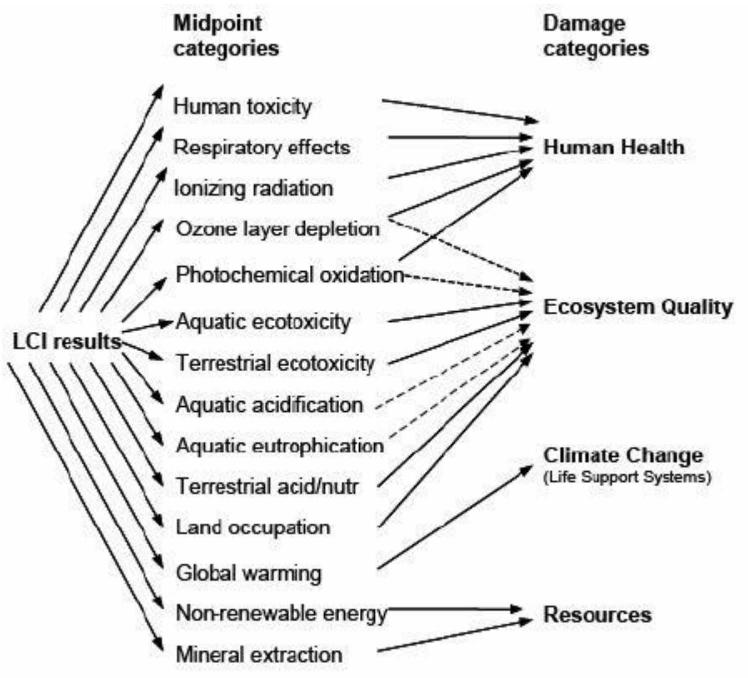

Figure 6.2: Overall scheme of the IMPACT 2002+ framework (Jolliet et al., 2003)

Step 2: The environmental impact of each midpoint impact categories (EI_{mic}) is obtained by multiplying each item of the inventory by the corresponding midpoint conversion factor ($cf_{mic,k}$).

$$EI_{mic} = \sum_k (LCI_k \cdot cf_{mic,k}) \qquad (3)$$

Midpoint characterization factors are based on equivalency principles, i.e. midpoint characterization scores are expressed in kg-equivalents of a reference substance. This process is similar to the evaluation of the global warming, in which the reference substance is 1 kg of $CO_{2\text{-eq}}$. Reference substances for midpoint impact categories are shown in Table 6.1.

Step 3: The contribution of the midpoint impact categories to the damage categories (EI_{dam}) is evaluated in two steps. First the environmental impact of each midpoint impact category is multiplied by the damage characterization factors (df_{mic}) that relate the contribution of each midpoint impact category to the corresponding damage category, and second all the contributions to each damage category are summed up. Note that each damage category encompasses several midpoint categories.

$$EI_{dam} = \sum_{mic \in mic(dam)} (EI_{mic} \cdot df_{mic}) \qquad (4)$$

Where mic(dam) denotes the set of midpoint impact categories (mic) that contribute to the damage category (dam). The midpoint impact categories that contribute to each damage category are presented in Table 6.1.

Table 6.1: Midpoint categories, reference substances, characterization factors, damage categories and damage units for IMPACT 2002+

Midpoint Category	Midpoint reference substance	Damage category	Damage unit	Normalized damage unit
Human toxicity (carcinogens + non-carcin)	kg Chloroethylene$_{eq}$ into air	Human Health	DALY	Point
Respiratory (inorganics)	kg $PM_{2,5eq}$ into air			
Ionizing radiations	Bq carbon-14$_{eq}$ into air			
Ozone layer depletion	kg CFC-11$_{eq}$ into air			
Photochemical oxidation (respiratory organics for human health)	kg Ethylene$_{eq}$ into air			
	kg Ethylene$_{eq}$ into air	Ecosystem quality	PDF·m^2·yr	Point
Aquatic ecotoxicity	kg Triethylene glycol$_{eq}$ into water			
Terrestrial ecotoxicity	kg Triethylene glycol$_{eq}$ into soil			
Terrestrial acidification / nitrification	kg SO_{2eq} into air			
Aquatic acidification	kg SO_{2eq} into air			
Aquatic eutrophication	kg $PO_4{}^{-3}{}_{eq}$ into water			
Land occupation	m^2 Organic arable land$_{eq}$ · yr			
Turbined water	Inventory in m^3			
Global warming	kg CO_{2eq} into air	Climate change	kg CO_{2eq}	Point
Non-renewable energy	MJ or kg Crude oil	Resources	MJ	Point
Mineral extraction	MJ or kg Iron$_{eq}$ in ore			
Water withdrawal	Inventory in m^3	n/a		n/a
Water consumption	Inventory in m^3	Human health	DALY	Point
		Ecosystem quality	PDF·m^2·yr	Point
		Resources	MJ	Point

Human health damage category is obtained by multiplying the midpoint characterization potentials (human toxicity, respiratory effects, ionizing radiation, ozone layer depletion and photochemical oxidation) with the damage characterization factors for human health. Human health damage is measured in DALY (Disability Adjusted Life Year) which is a measure of the overall disease burden expressed as the cumulative number of years lost due to ill health, disability or early death.

Ecosystem quality damage category is obtained by combining the midpoint categories of human toxicity, respiratory effect, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity, aquatic acidification, aquatic eutrophication, terrestrial acidification/nutrification and land occupation to the final damage evaluation measured in Potentially Disappeared Fraction of species, PDF.

Climate change damage category is equivalent to the midpoint category global warming, expressed in kg $CO_{2\text{-}eq}$. The midpoint category factors are taken from the IPCC list of global warming potentials (IPCC, 2007) for a 500-year time horizon with some additional considerations defined at Humbert et al. (2012).

Resources damage category is the sum of the midpoint categories non-renewable energy consumption and mineral extraction. This category is expressed in MWh or MJ with the concept of surplus energy. This is based on the assumption that a certain extraction leads to an additional energy requirement for further mining of this resource in the future, caused by lower resource concentrations or other unfavorable characteristics of the remaining reserves (Goedkoop and Spriensma, 2000).

Step 4: Normalized midpoint/damage factors are expressed in points (Jolliet et al., 2003). One point represents the average impact in a specific category 'caused' by one person during one year in Europe (Humbert et al., 2012). The normalization factor (σ_{dam}) is obtained by dividing the impact per unit of emission with the total impact of all substances of the specific category per person per year in Europe. The IMPACT 2002+ score (EI_{IMP}) is obtained by a final aggregation of the four damage categories with weighting factors (ζ_{dam}). In this thesis a weighting 1:1:1:1 has been used, giving the same relevance to each damage category.

$$EI_{IMP} = \sum_{dam} (EI_{dam} \cdot \sigma_{dam} \cdot \zeta_{dam}) \qquad (5)$$

This method takes advantage of both midpoint based indicators (CML) and damage based methodologies (Eco-indicator 99).

6.1.4 Interpretation of results

The interpretation of results encompasses the conclusions and recommendations obtained from the analysis. In an intermediate stage of the LCA process (remember that it is an iterative process) the results obtained from the impact assessment can be used to modify the boundaries of the system including new components in the system or analyzing in more detail some inventories in the light of the outcomes.

In the final iteration of the LCA process the obtained results from the assessment are the final evaluation for the functional units defined in the goal and scope and recommendations to reduce the environmental impact of the system.

6.2 Case study

A case study, completely described and referenced in literature has been used to characterize a CSHPSS from the environmental point of view. The CSHPSS produced SH and DHW for a community of 500 dwellings of 100 m^2 each in the residential area called “Parque Goya”, located in Zaragoza. The system reaches a 69% solar fraction for SH and DHW needs. This system has been designed by Lozano et al. (2010b, 2010c), Anastasia (2010) and Frago (2011) and was modeled in the software TRNSYS (Lozano et al. 2010c).

The system has three main parts (see Fig. 6.3): solar field loop, SH circuit and DHW circuit. The heat exchangers (HE_1 and HE_2) connect the solar field (primary circuit) to the SH and DHW circuits (secondary circuits), since the solar field circuit uses a water-glycol mixture (67/33 weight) as heat transfer fluid and the other circuits use hot water. The energy harvested by the solar collector field is transferred either to the seasonal energy storage or to the DHW storage, preferably to this one.

The seasonal storage is a cylindrical hot water tank built with reinforced concrete. It is connected to the distribution system through a third heat exchanger (ex3) which preheats the return water from the district heating network. Due to its large size, the processes of loading and unloading the seasonal storage is significantly slow, which facilitates its function of covering part of the SH demand during the winter season with the solar thermal energy that has been stored along the summer period. The DHW storage is an independent tank much smaller than the seasonal storage, which allows reaching in a few hours of solar heating the temperature required (60ºC) for the DHW daily service. This design approach together with the priority of loading the DHW tank with respect to the seasonal storage tank, allows reaching high solar fraction for DHW. The space heating system produces hot water at 50°C for a low temperature district heating network.

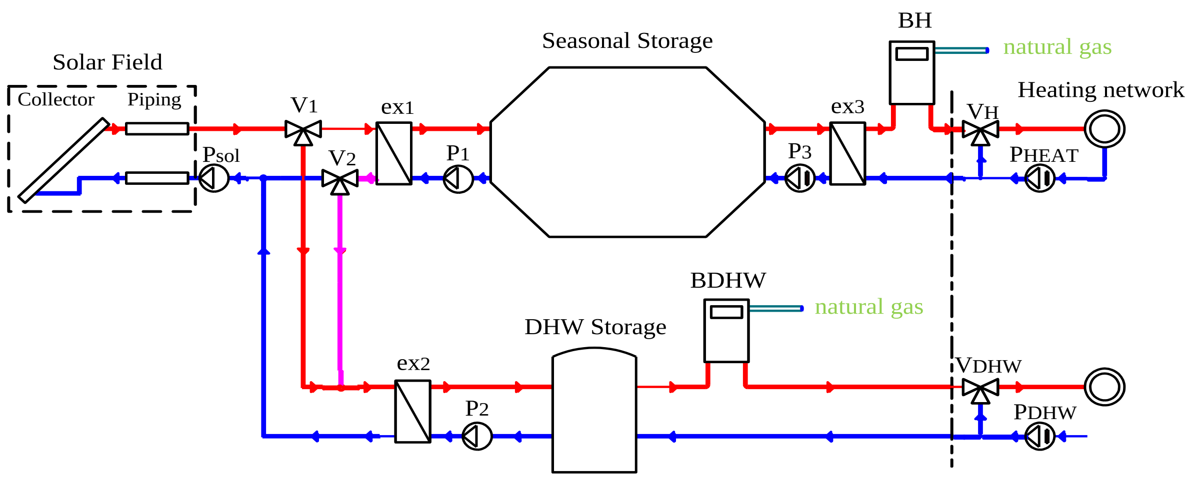

Figure 6.3: Diagram of the analyzed CSHPSS (Lozano et al., 2010b)

The system is completed with two auxiliary boilers, which support and guarantee the thermal energy demands when the water temperature from the storage is insufficient. Several circulation pumps and other auxiliary equipment are required to deliver the hot water at the appropriate temperature. The annual energy balance of the CSHPSS is shown in Fig. 6.4 including the most representative energy flows of the system (Lozano et al., 2010c).

The annual demand of thermal energy (Q_d) is 2905 MWh/yr, being 507.5 MWh/yr for DHW and 2397.5 MWh/yr for space heating. The pumps consume electricity to cover these demands ($E_P = E_{PS} + E_{P1} + E_{P2} + E_{P3}$) 59.4 MWh/yr.

The auxiliary system consumes natural gas in the auxiliary boilers G = 953.1 MWh/yr, being the natural gas consumed for space heating G_1 = 861.7 MWh/yr with an efficiency of 93% and the natural gas consumed for DHW G_2 = 91.4 MWh/yr with an efficiency of 96%.

Given the features of the energy services of the CSHPSS system, flat plate collectors have been chosen to harvest the solar radiation. The aperture area of the solar collector field installed on the ground is A = 2760 m^2, which means a ratio to the annual heat demand of A/Q_d = 0.95 m^2/(MWh/yr).

The DHW tank has been sized based on the daily average consumption of hot water to ensure the solar hot water demand for two days V = 47 m^3. The volume of the seasonal storage is V = 15,180 m^3, which means a ratio to solar collector field area of V/A = 5.5 m^3/m^2. It has been designed to be fully charged (the temperature of the water in its upper layer is about 100°C) just before the beginning of the heating season.

The system has auxiliary boilers with a thermal capacity of 208 kW for the DHW system and 1800 kW for the SH system. They have been sized to cover by themselves 100% of their respective demands.

The heat exchanger has been sized to guarantee an effectiveness of 95% even in the most demanding operating conditions. Finally, the sizing of the pumps has been obtained considering the current maximum flow rate and the pressure drop in the different parts of the hydraulic circuit. The pump of the solar field (P_{sol}) is the biggest with a rated power of 15 kW; and the power of the pumps P1, P2 and P3 is 1.4 kW, 1.4 kW and 3.7 kW respectively. A summary of the components and their main characteristics are presented in Table 6.2.

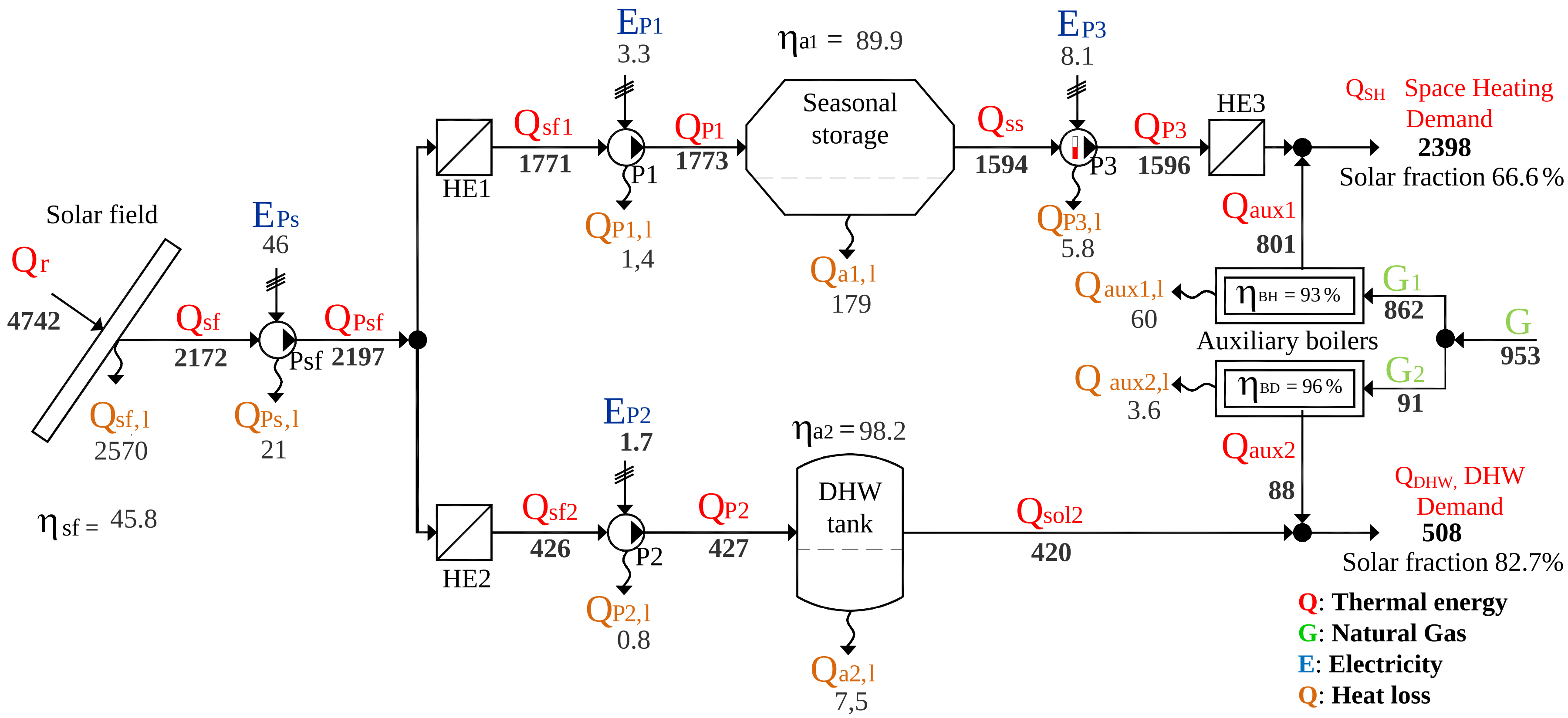

Figure 6.4: Energy flows of the analyzed system MWh/yr (Lozano et al., 2010b)

Table 6.2: Components of the CSHPSS (Lozano et al., 2010c)

Components	Characteristics	
Solar collector	Collector area: 13.575 m^2	Number of units: 204
	Total area: 2760 m^2	Slope: 50º
	Azimuth: 0º	η_0, optic efficiency: 0.738
	k_1, heat loss coef.: 1.63 W/(m^2·K)	k_2, heat loss coef.: 0.0299 W/(m^2·K^2)
	Specific flow rate: 20 kg/(h·m^2)	
Pipes	Total length: 1000 m	Diameter: 27 mm
	Insulation layer: 31 mm	Insulation conductivity: 0.144 kJ/(h·m·K)
Seasonal Storage	Volume: 15180 m^3	Height/Diameter: 0.6 m/m
	Diameter: 32.8 m	Height: 19.1 m
	Content: hot water	Heat conductivity: 0.45 kJ/(h·m^2·K)
	Maximum temperature: 100ºC	
Domestic hot water tank	Volume: 47 m^3	Height/Diameter: 1.5 m/m
	Diameter: 3.42 m	Height: 5.14 m
	Content: hot water	Heat conductivity: 1.6 kJ/(h·m^2·K)
	Maximum temperature: 100ºC	
Boiler 1	Nominal power: 1800 kW	Efficiency: 93%
Boiler 2	Nominal power: 208 kW	Efficiency: 96%
Heat Exchanger 1	Area: 282 m^2	Overall U: 3942 W/(m^2·K)
Heat Exchanger 2	Area: 282 m^2	Overall U: 3942 W/(m^2·K)
Heat Exchanger 3	Area: 580 m^2	Overall U: 3931 W/(m^2·K)
Pump solar field	Nominal flow: 54 m^3/h	Nominal power: 15 kW
Pump 1	Nominal flow: 51 m^3/h	Nominal power: 1.4 kW
Pump 2	Nominal flow: 51 m^3/h	Nominal power: 1.4 kW
Pump 3	Nominal flow: 104 m^3/h	Nominal power: 3.7 kW
District Heating	Supply temperature: 50ºC	Return temperature: 30ºC

The system described is used as case study to perform a LCA of a CSHPSS following the four stages declared in the international standard (ISO 14040, 2006): 1) goal and scope, 2) life cycle inventory, 3) impact assessment and 4) interpretation of results.

6.2.1 Goal and Scope

The main goal of this LCA is to determine and characterize the environmental impact of a CSHPSS determining critical issues and environmental benefits. The second objective is to obtain environmental results that could be applied to any location. This is made through the environmental assessment of the pieces of equipment of a CSHPSS separately. The third objective of this LCA is to obtain the environmental impact of the thermal energy produced by the system at different levels: internal flows and final thermal energy produced.

The life cycle inventory has been elaborated for the main materials and processes of the components considered. Materials and resources for maintenance have been neglected from the analysis as their contribution has been considered negligible. For the plant defined the impact for transportation of 600 km is considered. The plant will operate for 50 years, being the lifetime of the equipment 25 years, except in the case of the seasonal storage and the hot water tank, whose operation lifetime is 50 years. In the final disposal scenario part of the materials will be recycled: aluminium 32%, steel 37%, copper 18% and cast iron 35%.

In order to achieve the first objective, the environmental impact of the system along the plant lifetime will be evaluated. The impacts of the system will be generated by the installation required (considering the construction of the pieces of equipment and the whole CSHPSS as well as the final disposal) and by the consumption of auxiliary energy for the plant operation: electricity and natural gas. The result from the analysis is the environmental impact of the CSHPSS along the operation period and the identification of the critical issues that generate the biggest impacts on the environment.

From these results the environmental impact of the installation and the environmental impact of each piece of equipment can be obtained, accomplishing the second objective. Some equipment can be characterized per functional unit of design i.e. aperture area for solar collectors, envelope area for the seasonal storage. The rest of the equipment is characterized according to the materials consumed.

To achieve the third objective, the environmental impact of the equipment will be distributed along the expected life to obtain the environmental impact of the equipment per year. The environmental impact of the thermal energy produced considers the annual auxiliary energy required and the annual environmental impact of the equipment. Following a methodology proposed by Carvalho et al. (2012) the environmental impact of internal energy flows per unit of heat transferred, MWh, will be determined.

The Life Cycle Impact Assessment (LCIA) will be evaluated by applying three different methodologies: emission of GHG (IPCC, 2007), cumulative energy demand (CED) methodology (Hujibregts et al., 2006 and 2010), and the IMPACT 2002+ methodology (Jolliet et al., 2003), to have a broad outlook of the environmental impacts.

6.2.2 Life cycle inventory

The LCI of the analyzed system has been divided into assembly and operational phases. The assembly phase is subdivided into the most important components: solar collector and seasonal storage, and the auxiliary equipment required. Consumption of materials, manufacturing processes, transportation and land occupation are considered for each component. In the operational phase the annual consumption of electricity and natural gas has been considered.

6.2.2.1 Solar collector inventory

The solar collector is a large size flat plate collector ARCON HT-SA 28/10 (Arcon, 2013), which is depicted in Fig. 6.5. The materials consumed by this solar collector have been obtained from the datasheet of the solar collector. The inventory of the solar collector includes the consumption of materials and several operations and processes taken from Ecoinvent V2.0 (2007) database, see Table 6.3. This table also includes, for comparison purposes, the materials required and the processes considered by different authors (Albizzati and Arese, 2011; Kalogirou, 2009; Simons and Firth, 2011) as well as the suggested inventory considered in Ecoinvent V2.0 (2007) for flat plate collectors.

Figure 6.5: Solar collector description (Arcon, 2013)

Differences among inventories are: solar collector materials (copper, stainless steel or aluminium for the absorber, pipes or frame), different geometry (big solar collector versus small solar collectors requires less material per square meter), and different level of degree in the inventory or the processes required.

Table 6.3: Comparison of solar collector inventory per square meter (aperture area): process considered from Ecoinvent V2.0

	Case study	Ecoinvent	Simons and Firth	Kalogirou	Albizzati and Aresse
Electricity, production mix ES penin 2012 (kWh/m^2)	*1.16*	1.16	2.03	---	---
Tap water, at user /RER U (kg/m^2)	*9.4*	9.4	9.4	---	---
Water, completely softened, at plant RER U (kg/m^2)	*1.38*	1.38	---	---	---
Land occupation (Ha/m^2)	*2.0 E-7*	2.0 E-7	---	---	---
Aluminium, production mix, at plant RER U (kg/m^2)	*7.05*	4.374	0.324	---	---
Copper, at regional storage/RER U (kg/m^2)	*0.614*	1.317	3.88	11.11	---
Chromium steel 18/8, at plant/RER U (kg/m^2)	---	---	---	6.07	15.7
Solar glass, low-iron, at regional storage/RER U (kg/m^2)	*7.407*	7.407	9.75	7.03	10.1
Rock Wool, packed, at plant/RER U (kg/m^2)	*3.345*	5.32	1.28	3.19	0.6
Sheet rolling, aluminium/RER U (kg/m^2)	*7.050*	4.374	9.75	---	---
Selective coating, aluminium sheet, nickel pigmented aluminium oxide/SK U (m^2/m^2)	*0.921*	1	---	---	---
Anti-reflex-coating, etching solar glass/DK U (m^2/m^2)	*1.0*	1	1	---	---
Propylene glycol, liquid, at plant/RER U (kg/m^2)	*1.01*	1.01	1.03	---	---
Transport, lorry 20-28t, fleet average/CH U (ton·km/m^2)	*11*	90	124	---	---
Synthetic rubber (kg/m^2)	---	0.732	0.413	0.500	---
Soft solder (kg/m^2)	---	0.0588	0.0588	---	---
Brazing solder (kg/m^2)	---	0.00368	0.00368	---	---

The inventories presented by Albizzati and Aresse (2012) and Kalogirou (2009) for flat plate solar collectors are considerably much simpler than the inventories of the case study or the inventory of Simons and Firth (2011). While Albizzati and Aresse, and Kalogirou elaborated their inventories based only on their personal evaluation, Simons and Firth, and the case study use the reference case available in Ecoinvent V2.0 (2007) with modifications to some of the materials consumed by the solar collector applied. Remarkable differences can be found between the consumption of aluminium, copper, chromium steel, solar glass and rock wool. The solar collector described is a large size solar collector designed for large applications consuming less material per square meter than conventional solar collectors.

6.2.2.2 Seasonal storage inventory

The design and the components of the seasonal storage are based on the proportions and constructive information of the seasonal storage built in Friedrichshafen (Schmidt et al., 2003; High-combi, 2008). The volume of the seasonal storage is 15,180 m^3 with a height of 19.1 m and a diameter of 32.8 m.

The storage has reinforced concrete walls, built with concrete and reinforcing steel having a thickness of 30 cm. It is insulated on the outside of the concrete walls with 20 cm of XPS (Extruded Polystyrene). To avoid vapor diffusion, it has a layer of 1.2 mm of stainless steel in the inner side of the storage and the insulation material has a PVC layer to protect the insulation layer from the soil humidity. See Fig. 6.6 based on a drawing from Schmidt et al. (2003).

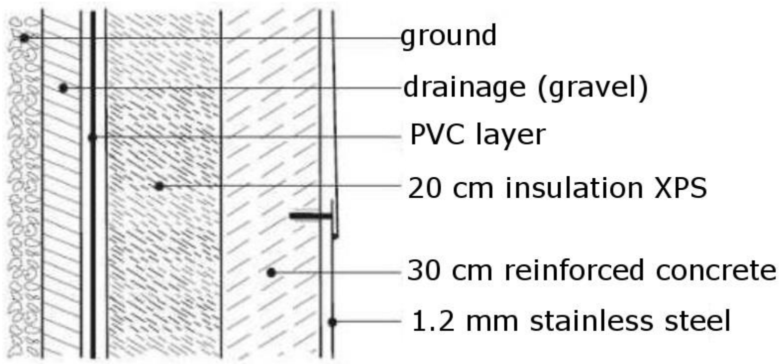

Figure 6.6: Layers of the seasonal storage built based on Friedrichshafen storage

The consumption of materials estimated for the seasonal storage is presented in Table 6.4 as well as several processes taken from the database of Ecoinvent V2.0 using the nomenclature applied in this database and also a simplified nomenclature that will be used in other tables.

Table 6.4: Seasonal storage inventory: considered materials and processes taken from Ecoinvent V2.0

Inventory	Ecoinvent V2.0 reference	Amount
Concrete	Concrete, exacting, at plant/CH U	944.6 m^3
Reinforcing steel	Reinforcing steel, at plant/RER U	818.6 ton
PVC layer	Polyvinylchloride, at regional storage/RER U	5.6 ton
Insulation (XPS)	Polystyrene, extruded (XPS), at plant/RER U	104.95 ton
Steel vapor barrier	Chromium steel 18/8, at plant/RER U	32.7 ton
Factory	Hot water tank factory/CH/I U	0.00002 p*
Transportation	Transport, lorry 20-28t, fleet average/CH U	1970 kton·km†
Heat waste	Heat, waste (50 years life)	8950 MWh
Disposal insulation	Disposal, building mineral wool, to sorting plant/CH U	104.95 ton
Disposal plastics	Disposal, plastics, 15,3% water, to municipal incineration/CH U	5.6 ton

* p: impact of a factory for hot water tanks with an annual capacity of 1000 tanks operating for 50 years
† kton·km: transportation of 1000 tons of material for 1 km

In this project a TTES seasonal storage with a design equivalent to the design applied in the plant of Friedrichshafen has been considered but other designs might be applied. In Table 6.5 the materials consumed by several seasonal storages described in literature (High-combi, 2008) are compared. The materials are classified as: structural materials, insulation materials, and vapor barrier materials. The materials selected for the construction of the storage affect cost, efficiency and expected life of the storage. The geometric dimensions of the seasonal storage as well as the materials used are presented in Table 6.5.

Table 6.5: Constructive characteristics of different seasonal storage

	Volume (m^3)	H/D (m/m)	A/V (m^2/m^3)	Structural material	Insulation material	Liner, vapor barrier
Ilmenau	300	1.11	1.14	reinforced glass fibre	PUR foam	---
Crailsheim	480	2.3	0.75	concrete	glass wool foam glass	1.25 mm stainless steel
Rottweil	600	0.38	0.48	concrete	mineral wool	0.5 mm stainless steel
Studsvik	800	0.48	0.69	concrete	PUR foam	2 mm synthetic rubber
Hannover	2750	0.58	0.41	concrete	glass wool	---
Hamburg	4500	0.43	0.37	concrete	mineral wool	1.25 mm stainless steel
Munich	6000	0.67	0.30	concrete	glass wool	1.25 mm stainless steel
Lombohov	10,000	0.37	0.18	concrete	PUR	2 mm synthetic rubber
Friedrichshafen	12,000	0.61	0.23	reinforced concrete	XPS	1.25 mm stainless steel
Case study	*15,180*	*0.60*	*0.23*	*reinforced concrete*	*XPS*	*1.25 mm stainless steel*

As structural material a concrete structure is the most common solution but some other options use reinforcing steel or glass fibre reinforced structure.

For the insulation materials there are several options. In the analyzed case study, the XPS is the insulation material as it has very good properties for a long time operation. The XPS is the only insulation material that can be wet without losing its insulation properties. On the other hand, this material generates a big impact on the environment as it will be shown in the following section.

As vapor diffusion barrier the stainless steel is the best material but has a high economic cost and also a high environmental impact (see Section 6.2.3.2). Other materials can be used, e.g. synthetic rubber. According to the dimension of the storage the consumption of materials required to build the storages has been estimated. Inventories and processes have been taken from Ecoinvent V2.0 (2007) and are presented in Table 6.6.

Table 6.6: Comparison of seasonal storage inventories: considered materials and processes taken from Ecoinvent V2.0

		Ilmenau	Crailsheim	Rottweil	Studsvik	Hannover	Hamburg	Munich	Lombohov	Friedrichshafen	Case study
Inventory	Volume of the seasonal storage analyzed (m^3)	300	480	600	800	2750	4500	6000	10,000	12,000	15,180
Concrete*	Concrete, exacting, at plant/CH U		266.6	212.9	405.1	836	1215	1326	1289	1853	2139
Steel	Reinforcing steel, at plant/RER U		84.71	67.63	128.7	265.6	386.1	421.2	409.5	654.3	818.6
UP, reinforced plastic	Glass fiber reinforced plastic, polyester resin hand lay-up at plant/RER	49.5									
Glass foam	Foam glass, at plant/RER		0.37					8.1			
Glass wool	Glass wool mat, at plant/CH		5.09			22.7		36.9			
PUR	Polyurethane, rigid foam, at plant/RER U	2.1			1.62				10.7		
XPS	Polystyrene, extruded (XPS), at plant/RER U									83.9	104.9
Rockwool	Rock wool, at plant/CH			6.81			22.3				
EPS	Polystyrene, expandable, at plant/RER			0.8							
Lightweight concrete	Lightweight concrete block, expanded clay, at plant/CH								327.4		
Stainless steel	Chromium steel 18/8, at plant/RER U		4.23	1.13		265.6	16.1	17.6		27.26	32.74
PVC	Polyvinylchloride, at regional storage/RER U									4.47	5.6
Synthetic rubber	Synthetic rubber, at plant/RER				1.32				4.2		
HDPE	Polyethylene, HDPE, granulate at plant/RER U				1.16						

* Concrete density 2440 kg/m^3

6.2.2.3 Auxiliary equipment inventory

As described in the introduction, besides the solar collector and the seasonal storage other pieces of equipment have been considered: insulated pipes in the solar field, pumps, heat exchangers and boilers.

The solar collector field requires, for connections, 1000 m of pre-insulated pipes, as shown in Fig. 6.7. The pipes are made of stainless steel (diameter 27 mm; thickness 3 mm). They are insulated by 31 mm of PUR foam around the steel pipe and are covered by a hard cover of HDPE of 3 mm thickness, description from Logstor (2015).

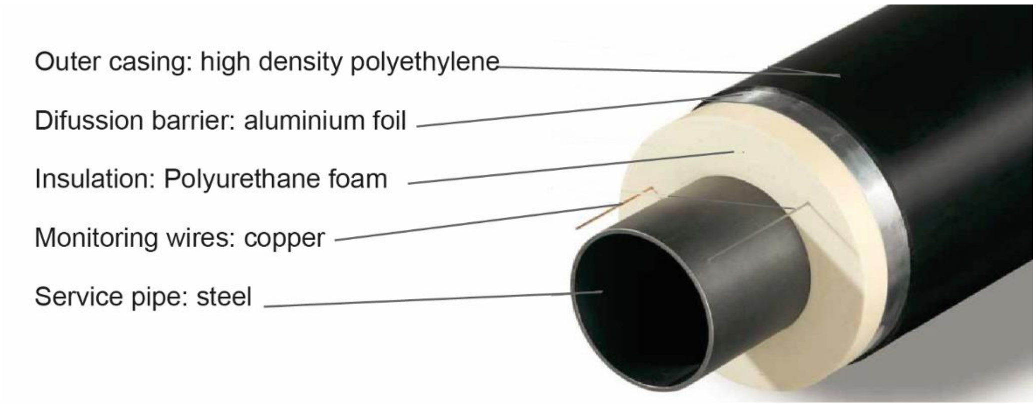

Figure 6.7: Description of pre-insulated pipes (Logstor, 2015)

Based on this description of the pipes, the consumption of materials and the processes required per meter of pipe have been determined.

Table 6.7: Insulated pipes inventory: considered materials and processes taken from Ecoinvent V2.0

Inventory	Ecoinvent V2.0 reference	Amount
Stainless steel	Chromium steel 18/8, at plant/RER U	1.558 kg/m
Insulation	Polyurethane, rigid foam, at plant/RER U	0.336 kg/m
Cover HDPE	Polyethylene, HDPE, granulate at plant/RER U	0.738 kg/m
Transportation	Transport Lorry >28t, fleet average/CH U	1.578 ton·km/m

The plant described has a domestic hot water tank with a volume of 47 m^3 with a height of 5.14 m and a diameter of 3.42 m. The storage has reinforced concrete walls with a thickness of 30 cm, insulated with 20 cm of XPS (Extruded Polystyrene). The storage has a vapor diffusion barrier of 1.2 mm of stainless steel in the inside of the storage and a PVC layer to protect the insulation layer from humidity.

The inventory includes the consumption of materials and the disposal of elements by the end of the storage life. The amount of heat emitted to the environment, waste heat (see Table 6.8) is also presented. Transportation of materials for a distance of 600 km has been considered but the consumption of water has not been included as part of the resources consumed.

Table 6.8: Hot water tank inventory: considered materials and processes taken from Ecoinvent V2.0

Inventory	Ecoinvent V2.0 reference	Amount
Concrete	Concrete, exacting, at plant/CH U	19.88 m^3
Reinforcing steel	Reinforcing steel, at plant/RER U	17.23 ton
PVC layer	Polyvinylchloride, at regional storage/RER U	117.79 kg
Insulation (XPS)	Polystyrene, extruded (XPS), at plant/RER U	2.21 ton
Steel vapor barrier	Chromium steel 18/8, at plant/RER U	689 kg
Factory	Hot water tank factory/CH/I U	0.00002 p
Transportation	Transport, lorry 20-28t, fleet average/CH U	41,400 ton·km
Heat waste	Heat, waste	375 MWh
Disposal insulation	Disposal, building mineral wool, to sorting plant/CH U	2.21 ton
Disposal plastics	Disposal, plastics, 15,3% water, to municipal incineration/CH U	69 kg

The pump of the solar field P_{sf} and the other auxiliary pumps P_1, P_2 and P_3 are built from cast iron. The amount of material required for these pieces of equipment has been obtained from the original datasheet of the components sized, see Fig. 6.8.

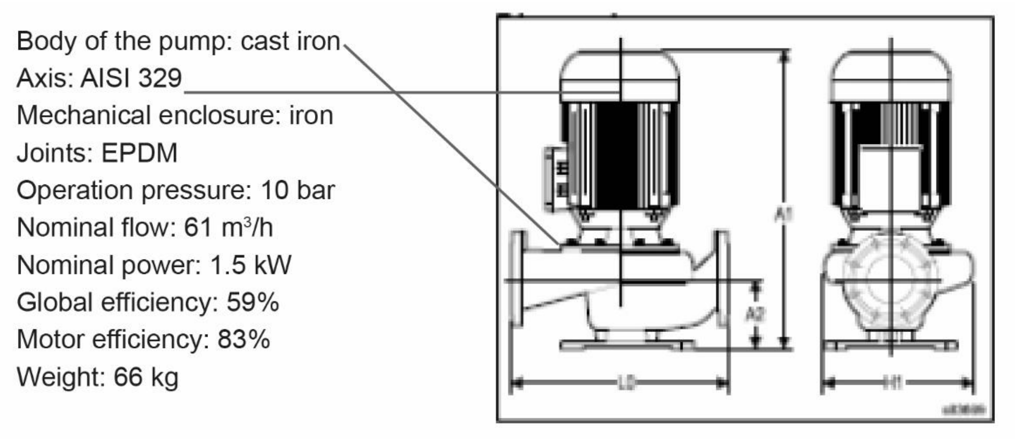

Figure 6.8: Description of pump, P3 (Sedical, 2007)

The consumption of materials for each pump has been obtained from the works by Frago (2011) and Anastasia (2010) that sized the pumps from the Sedical catalogue (Sedical, 2007). Life cycle inventory of the four pumps is presented in Table 6.9.

Table 6.9: Pumps inventory: considered materials and processes taken from Ecoinvent V2.0

Reference	Ecoinvent V2.0 reference	Amount
Cast iron P_{sf}	Cast iron, at plant/RER U	109 kg
Transport P_{sf}	Transport, van <3.5t/RER U	65.4 ton·km
Cast iron P_1	Cast iron, at plant/RER U	66 kg
Transport P_1	Transport, van <3.5t/RER U	39.6 ton·km
Cast iron P_2	Cast iron, at plant/RER U	66 kg
Transport P_2	Transport, van <3.5t/RER U	39.6 ton·km
Cast iron P_3	Cast iron, at plant/RER U	76 kg
Transport P_3	Transport, van <3.5t/RER U	45.6 ton·km

The heat exchangers (HE_1, HE_2 and HE_3) are plate heat exchangers made of stainless steel and the design information, shown in Fig. 6.9 has been obtained from Frago (2011) and Anastasia (2010) works.

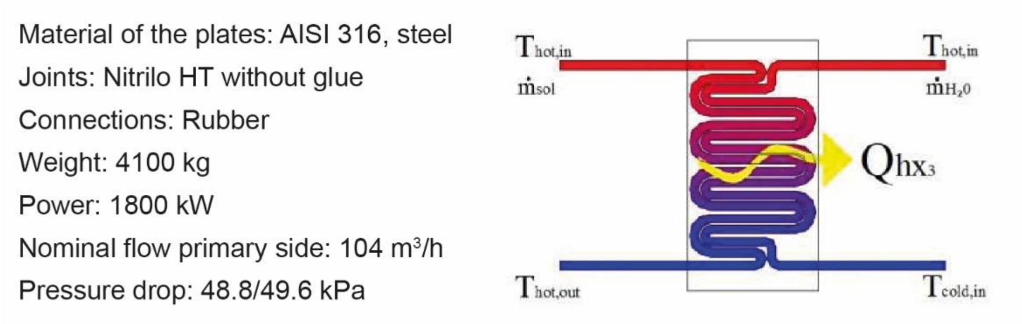

Figure 6.9: Description of the heat exchanger HE_3 (Sedical, 2007)

The system uses an auxiliary boiler to reach the supply temperature (see Fig. 6.10). The boiler for the district heating system has a power of 1800 kW and an efficiency of 93%, selected from Thermital (2008) catalog. The hot water system uses a 208 kW boiler with an efficiency of 96%. Both boilers are made of steel. Inventory for the pumps and boilers is presented in Table 6.10.

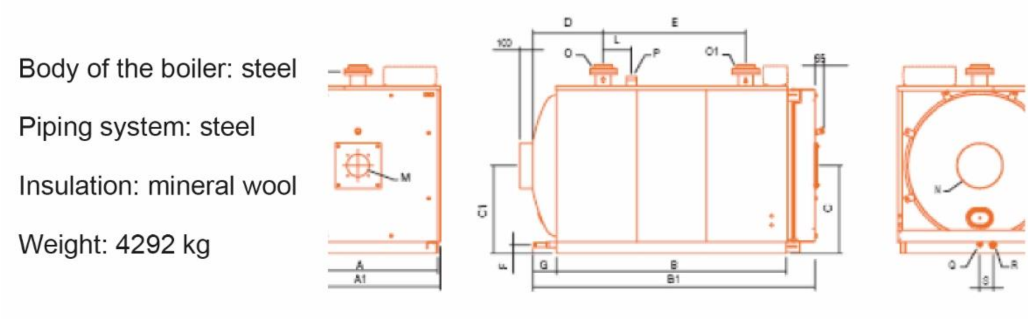

Figure 6.10: Description of the boiler for the district heating system (Sedical, 2007)

Table 6.10: Heat exchangers and boilers inventory: considered materials and processes taken from Ecoinvent V2.0

Inventory	Ecoinvent V2.0 reference	Amount
Steel HE_1	Chromium steel, 18/8, at plant/RER U	2626 kg
Transport HE_1	Transport, lorry >28t, fleet average/CH U	1575.6 ton·km
Steel HE_2	Chromium steel, 18/8, at plant/RER U	2626 kg
Transport HE_2	Transport, lorry >28t, fleet average/CH U	1575.6 ton·km
Steel HE_3	Chromium steel, 18/8, at plant/RER U	4100 kg
Transport HE_3	Transport, lorry >28t, fleet average/CH U	2460 ton·km
Steel Boiler B1	Reinforcing steel, at plant/RER U	455 kg
Transport B_1	Transport, van <3.5t/RER U	273 ton·km
Steel Boiler B2	Reinforcing steel, at plant/RER U	4292 kg
Transport B_2	Transport, van <3.5t/RER U	2575 ton·km

A summary of the main materials consumed for the construction of the CSHPSS is presented in Table 6.11. To carry out the LCA it is important to notice that all the pieces of equipment except the seasonal thermal energy storage will be installed two times along the life period, 50 years. Therefore, along the life cycle the inventory of some components should be applied twice. Complete inventories for each component have been presented separately in this section.

Table 6.11: Main materials consumed for the construction of the CSHPSS

Consumption of materials (ton)	Glycol	Glass	Aluminum	Mineral wool	Copper	XPS	Concrete	PVC	Steel	Stainless steel	HDPE	PUR	Cast iron
Collectors	2.79	20.51	19.52	9.26	1.7								
Seasonal Sto.						105	2139	5.6	818.6	32.7			
Water tank						2.2	47.8	0.12	17.2	0.7			
Boiler 1									4.29				
Boiler 2									0.45				
Heat Ex. 1										2.63			
Heat Ex. 2										2.63			
Heat Ex. 3										4.10			
Pipes										1.56	0.74	0.34	
Pump Solar													0.110
Pump 1													0.066
Pump 2													0.066
Pump 3													0.076
Total	2.79	20.51	19.52	9.26	1.7	107.2	2187	5.72	840.5	44.32	0.74	0.34	0.318

6.2.2.4 Energy consumed in operation

Electricity and natural gas are required for the operation of the plant; see the energy flow diagram in Fig. 6.4. While the inventory for the equipment can be considered equivalent for each location in Europe the inventory of the electricity depends on the electricity mix of the location. The electricity production mix in Spain (2012) has been used as scenario for the electricity inventory. Further details are presented in Section 6.2.3.4. The annual consumption electricity for pumping is E_P = 59.1 MWh/yr.

The inventory for natural gas considers the gas extraction, processing, transport, distribution and combustion of the natural gas consumed in Spain. This resource is composed of the processes *Energy gas I* (Idemat database; Pré Consultants, 2013) and *Heat, natural gas, industrial furnace at >100kW* (Ecoinvent V2.0). The natural gas consumed by the system is G = 953 MWh/yr.

6.2.3 Impact assessment

The objective of this analysis is to determine the impact assessment of a CSHPSS. The environmental impact corresponding to the construction of the equipment and the energy required for its operation has been considered separately.

The environmental impact corresponding to the solar collector field, and per area of solar collector have been obtained. The seasonal storage impact has been characterized per area of envelope and has also been obtained for the case study. The impact of the auxiliary equipment has been determined only for the case study and contributes less than 5% to the impacts generated. The electricity and the natural gas consumed have been characterized apart from the installation per unit of energy, MWh. Finally, the impact of the whole system has been determined as the sum of the parts and the environmental impact of the heat produced by the system, the solar plant and the auxiliary system.

It is vital to have specific inventories to properly compare different design alternatives. The use of different technologies and materials affect the environmental impact. For solar collectors, different materials e.g. copper, steel or aluminium can be used generating big differences in the environmental impact of the equipment. For the seasonal storage the differences obtained are bigger, depending on the construction materials employed. Hot water tanks built with reinforced concrete have been analyzed but the impact per area of envelope has been compared with other designs, besides other technologies that consume fewer resources (as PTES, BTES or ATES) could be used reducing further the environmental impact.

The software Simapro 8.0.1 (2014) and the database of Ecoinvent V2.0 have been used to transform the listed components into environmental burdens: emission of greenhouse gases, CED and points of IMPACT 2002+.

6.2.3.1 Solar collector impact assessment

The obtained LCA results of the analysed solar collector per area of solar collector (aperture area considered) are presented in Table 6.12. For the emission of GHG the impact is measured in kg of $CO_{2\text{-eq}}$ per aperture area (kg $CO_{2\text{-eq}}/m^2$) and the CED is measured in MWh/m^2. IMPACT 2002+ (IMP) results are presented in mpoints per square meter (10^{-3}points/m^2). Electricity consumption for the operation of the solar field has not been included in this analysis in order to consider separately the environmental impact corresponding to the construction of the equipment and the energy required for its operation.

Table 6.12: Environmental impact of the solar collector

Inventory	GHG/A (kg $CO_{2\text{-eq}}/m^2$)	CED/A (MWh/m^2)	IMP/A ($mpoints/m^2$)
Aluminium	60.29	0.23448	18.834
Solar glass, low iron	8.10	0.01771	2.390
Selective coating	5.20	0.02090	1.747
Sheet rolling aluminium	4.26	0.01530	1.092
Propylene glycol	4.10	0.02145	1.237
Rock wool, packed	3.79	0.01446	1.491
Treatment heat carrier	2.12	0.00123	0.262
Transport	2.13	0.00926	0.817
Anti-reflex coating	1.49	0.00359	0.342
Copper	1.156	0.00468	3.095
Electricity	0.45	0.00219	0.138
Solar collector factory	0.337	0.00131	0.155
Disposal mineral wool	0.086	0.00044	0.044
Disposal glass sheet	0.074	0.00046	0.033
Total	93.59	0.3475	31.69

The environmental impact calculated for the solar collector has been compared with the results obtained by different authors and with the value obtained from the Simapro component *solar collector* (see Table 6.13).

Table 6.13: Comparison of solar collector impact assessment by different authors (Albizzati and Arese, 2011; Kalogirou, 2004; Simapro, 2014; Simons and Firth, 2011)

Author	GHG/A (kg $CO_{2\text{-eq}}/m^2$)	CED/A (MWh/m^2)	IMP/A ($mpoints/m^2$)
Case study	*93.6*	*0.347*	*31.7*
Simapro, 2014; solar collector	89.4	0.336	---
Kalogirou, 2004	509	0.518	---
Simons and Firth, 2011	97.1	0.877	---
Albizzati and Arese, 2011	85.7	0.246	---

The inventory for each author has already been presented in Section 6.2.2.1, the consumption of copper and stainless steel produces the big difference between Kalogirou and the other authors. Nevertheless, it can be seen that excluding that source (Kalogirou, 2004), the emission of GHG for a solar collector is 90 ± 5 kg $CO_{2\text{-eq}}/m^2$.

For the primary energy embodied in the solar collector a bigger divergence can be observed from 0.25 to 0.85 MWh/m^2. For the IMPACT 2002+ the case study is the first evaluation for a flat plate solar collector.

6.2.3.2 Seasonal storage impact assessment

The environmental impact of the seasonal storage (volume 15,180 m^3) has been calculated and the obtained results are presented in Table 6.14.

Table 6.14: Environmental impact of the seasonal storage

Inventory	GHG (ton $CO_{2\text{-eq}}$)	CED (MWh)	IMP (points)
Reinforcing steel, at plant /RER U	1184.1	4387.3	422.3
Polystyrene, extruded (XPS)/RER U	1166.2	1880.2	135.6
Transport, lorry	381.9	1659.4	146.3
Concrete, exacting at plant/CH U	306.6	434.3	54.1
Chromium steel 18/8, at plant/RER U	147.4	531.5	85.4
Disposal plastics, mixture 15.3% water/CH U	13.1	0.79	1.63
Polyvinylchloride, at regional storage/RER U	11.2	61.1	3.05
Disposal, building, mineral wool/CH U	2.68	13.7	1.39
Total	3213	8968	850

Reinforcing steel and the insulation material XPS produce most of the environmental burdens. The usage of other insulation materials reduces the environmental impact of the seasonal storage but the most important characteristic of the XPS is the long life as insulation material. Conventional insulation materials might lose insulation capacity with time, although this is not a well-known aspect. Besides the case defined for this chapter, the impact assessment for other seasonal storage descriptions has been calculated.

Table 6.15: Environmental impact of different seasonal storage

Seasonal storage plant	Volume (m^3)	GHG (ton $CO_{2\text{-eq}}$)	CED (MWh)	IMP (points)
Ilmenau	300	618	745	111.0
Crailsheim	480	201.6	713	66.7
Rottweil	600	170.4	592	58.1
Studsvik	800	311.2	1080	101.6
Hannover	2750	638	2284	211.8
Hamburg	4500	981	3388	345.2
Munich	6000	1116	3967	387.0
Lombohov	10,000	1170	4111	380.0
Friedrichshafen	12,000	2652	7500	711.6
Case study	15,180	3213	8968	850

The environmental impact of a seasonal storage is mainly produced by the construction of the shell; therefore, it is appropriate to compare the environmental impact of storages presented per envelope area (Fig 6.11). Ilmenau's case has been removed from the graph due to the very high environmental impact (1800 tons of $CO_{2\text{-eq}}$ per m^2) and to the consumption of UP with reinforcing glass fiber in the structure.

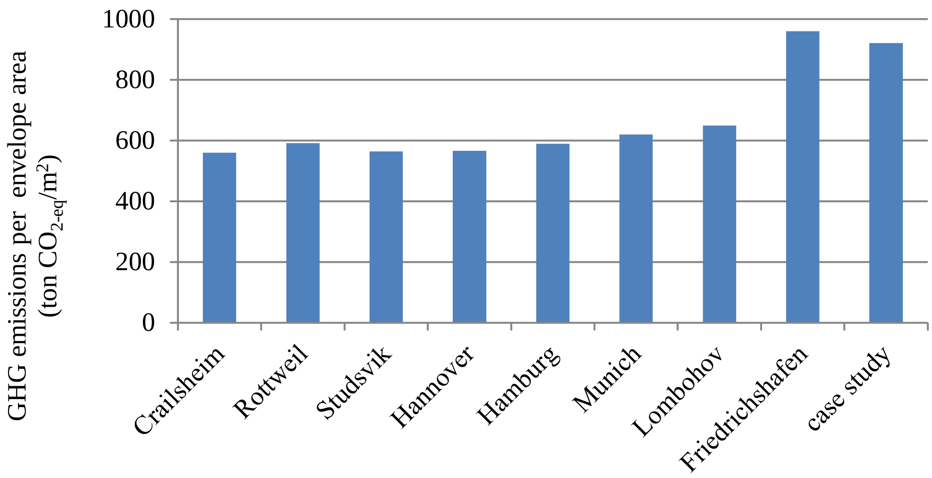

Figure 6.11: Emission of GHG per envelope area for different seasonal storages built in Europe

The environmental impact per envelope area is very similar for all the cases. Similar consumption of concrete and reinforcing steel per envelope area has been considered (same wall thickness). But differences in the liner used or in the insulation material generate the divergences among the cases. Friedrichshafen and the case study present a higher environmental impact, due to the consumption of XPS. Differences between these two cases are due to different insulation thickness. Characteristics of the analyzed seasonal storages were obtained from High-combi (2008).

6.2.3.3 Auxiliary equipment

The environmental impact of the auxiliary equipment has also been evaluated. As it has a minor environmental effect compared to the main components already described (solar collectors and seasonal storage) the impacts for each auxiliary device are presented in one table, Table 6.16.

Table 6.16: Environmental impact of the CSHPSS

	GHG (ton $CO_{2\text{-eq}}$)		CED (MWh)		IMP (points)	
Seasonal storage	3213.3	89.1%	8968.3	86.5%	849.86	85.9%
Solar collector	258.3	7.2%	959.1	9.3%	87.45	8.8%
Hot water tank	67.14	1.9%	187.7	1.8%	17.77	1.8%
Heat exchanger 3	18.79	0.52%	68.0	0.66%	10.82	1.09%
Heat exchanger 1	12.04	0.33%	43.6	0.42%	6.932	0.70%
Heat exchanger 2	12.04	0.33%	43.6	0.42%	6.932	0.70%
Boiler 1	11.09	0.31%	44.7	0.43%	3.842	0.39%
Pipes	10.10	0.28%	42.0	0.41%	5.061	0.51%
Boiler 2	1.175	0.03%	4.7	0.05%	0.407	0.04%
Pump solar field	0.285	0.01%	1.22	0.01%	0.113	0.01%
Pump 3	0.199	0.01%	0.85	0.01%	0.079	0.01%
Pump 1	0.173	0.00%	0.74	0.01%	0.069	0.01%
Pump 2	0.173	0.00%	0.74	0.01%	0.069	0.01%
Total	3605	100%	10,365	100%	989.4	100%

For the three methodologies applied to determine the environmental impact (emission of GHG, CED and IMPACT 2002+) the seasonal storage generates between 85 and 90% of the impacts and the solar collectors between 7 and 9% extra; therefore, by analyzing only both components, it would be possible to estimate 95% of the impacts of the plant, corresponding to the construction phase.

6.2.3.4 Auxiliary energy

The emission of GHG and the CED for the electricity consumed has been obtained by weighting, according to the Spanish mix of 2012 (REE, 2012), the impact of different energy sources, with the Spanish conversion factors (IDAE, 2012). The emissions of GHG and the CED for natural gas have been obtained from the conversion factors of IDAE (2012). The environmental impact measured in points of IMPACT 2002+ has been determined with Simapro and the Ecoinvent V2.0 databases. The obtained results are shown in Table 6.17.

Table 6.17: Environmental impact of the electricity mix in Spain (IDAE, 2012; Ecoinvent V2.0, 2007)

Ecoinvent V2.0 reference	Share (2012)	GHG (kg $CO_{2\text{-eq}}$/MWh)	CED (MWh/MWh)	IMP (mpoints/MWh)
Electricity, hard coal, at power plant/ ES U	20.67%	1090	3.04	---
Electricity, natural gas, at combined cycle plant, best technology/RER U	14.48%	410	2.15	---
Electricity, hydropower, at power plant/ES U	7.07%	0	1.09	---
Electricity, hydropower, at pumped storage power plant/ES U	1.66%	0	1.09	---
Electricity, nuclear, at power plant/UCTE U	22.75%	0	3.31	---
Electricity, production mix photovoltaic, at plant/ES U	2.94%	0	1.09	---
Electricity, at wind power plant/RER U	17.88%	0	1.09	---
Electricity, at cogen 500 kWe lean burn, allocation exergy/CH U	12.38%	420	1.95	---
Electricity at cogen, with biogas engine, allocation exergy/CH U	1.82%	0	3.04	---
Electricity, production mix ES penin 2012	1 MWh	337	2.31	119
Natural gas for boilers	1 MWh	201	1.07	57

6.2.3.5 System impact assessment

The environmental assessment of the whole CSHPSS can be evaluated after the environmental assessment of each piece of equipment and the energy consumed by the system have been evaluated. The case study operates for 50 years and is dismantled at the end of the period. All the pieces of equipment except the seasonal storage and the hot water tank have a lifetime of 25 years and have to be replaced. This aspect has been considered in the system impact assessment. The annual consumption of electricity and natural gas generates an impact that has been estimated to be uniform along the operation period. System results of the impact assessment for the expected life are presented as tree diagrams in Figs. 6.12, 6.13 and 6.14, showing the most significant contributions to the analyzed indicators. Results are discussed by indicators in the following titles.

Emission of greenhouse gases

The obtained results show that the plant generates 14,480 tons of $CO_{2\text{-}eq}$ along the 50 years of operation. In comparison, for the same demand and period, a centralized system that only consumes natural gas generates 31,400 tons of $CO_{2\text{-}eq}$. The auxiliary system that covers 31% of the heating needs generates 66% of the GHG emissions, 9577 tons of $CO_{2\text{-}eq}$. The construction of the plant produces 3605 tons of $CO_{2\text{-}eq}$, renovation of components by the year 25 will emit an extra of 325 tons of $CO_{2\text{-}eq}$ and the consumption of electricity generates 996 tons of $CO_{2\text{-}eq}$.

It is remarkable that the seasonal storage produces most of the emissions in the solar system, 3213 tons of $CO_{2\text{-}eq}$. The auxiliary equipment represents such a small share that they are not depicted in the tree diagrams but detailed results can be found in Table 6.18.

Cumulative energy demand

For the CED analysis similar conclusions are obtained. The consumption of natural gas is the major responsible for the consumption of energy resources, 50,985 MWh. The installation of the solar plant requires 10,365 MWh of CED (EI_{plant}).

Annually the plant produces solar heat (Q_{sol} = 2016 MWh/yr) that displaces the consumption of natural gas, $CED_{displaced}$. A natural gas boiler produces heat with an efficiency η_{boiler} = 0.93. The natural gas consumed in Spain has a conversion factor of CED_{gas} = 1.07. Therefore, the annual amount of primary energy displaced by the solar system is $CED_{displaced}$ = 2319.5 MWh/yr. The annual operation of the plant consumes 59.1 MWh of electricity, with a $CED_{operation}$ = 136.5 MWh/yr. The energy payback is defined as the period of time required to save the amount of primary energy consumed in the installation of the plant (Streicher et al., 2004).

$$Payback = EI_{plant} / (CED_{displaced} - CED_{operation}) \qquad (6)$$

For the case study, the payback period is 4.75 years. So the plant needs to operate for 5 years to cover the energy consumed in its construction. In fact, the plant will operate for 50 years, reducing considerably the environmental impact of the community.

IMPACT 2002+

In order to have a wider outlook of the environmental impacts, the points of IMPACT 2002+ are calculated. The evaluation method IMPACT 2002+ considers damages to human health, ecosystem quality, climate change and consumption of resources. Results have been obtained by the normalization of the four damage categories in equivalent proportions, results are presented in Fig. 6.14.

For this analysis, natural gas generates 2720 points of IMPACT 2002+, seasonal storage produces 850 points, electricity generates an impact of 352 points, and solar collectors generate 175 points along the 50 years period.

The results from the LCIA have been summarized in Table 6.18. Environmental impact corresponding to: i) the installation, considering the materials, process, etc. required for the construction of the pieces of equipment and the CSHPSS as well as the final disposal at the end of their lifetime; ii) the annual environmental impact of the system considering the construction, final disposal and operation of the analyzed system and iii) the environmental impact of the system considering the construction, final disposal and operation during the plant lifetime (50 years).

The analysis of the CSHPSS considers constant conditions along the expected life: the same impact for replacement equipment and the same environmental impact for electricity and natural gas along the operation period. These assumptions might be quite conservative; the progressive switch to less pollutant energy sources in the electricity mix and the increasing share of biofuels in conventional fuels will reduce annually the environmental impact. It could be more appropriate to present the results of these installations for the year in operation and to calculate the environmental impact per unit of heat produced according to the current conditions.

In the following section (Section 6.2.4) the analysis of the internal energy flows during one year is presented, determining the environmental impact of the thermal energy produced following the productive process and using this information to analyze and assess the formation of the environmental burden.

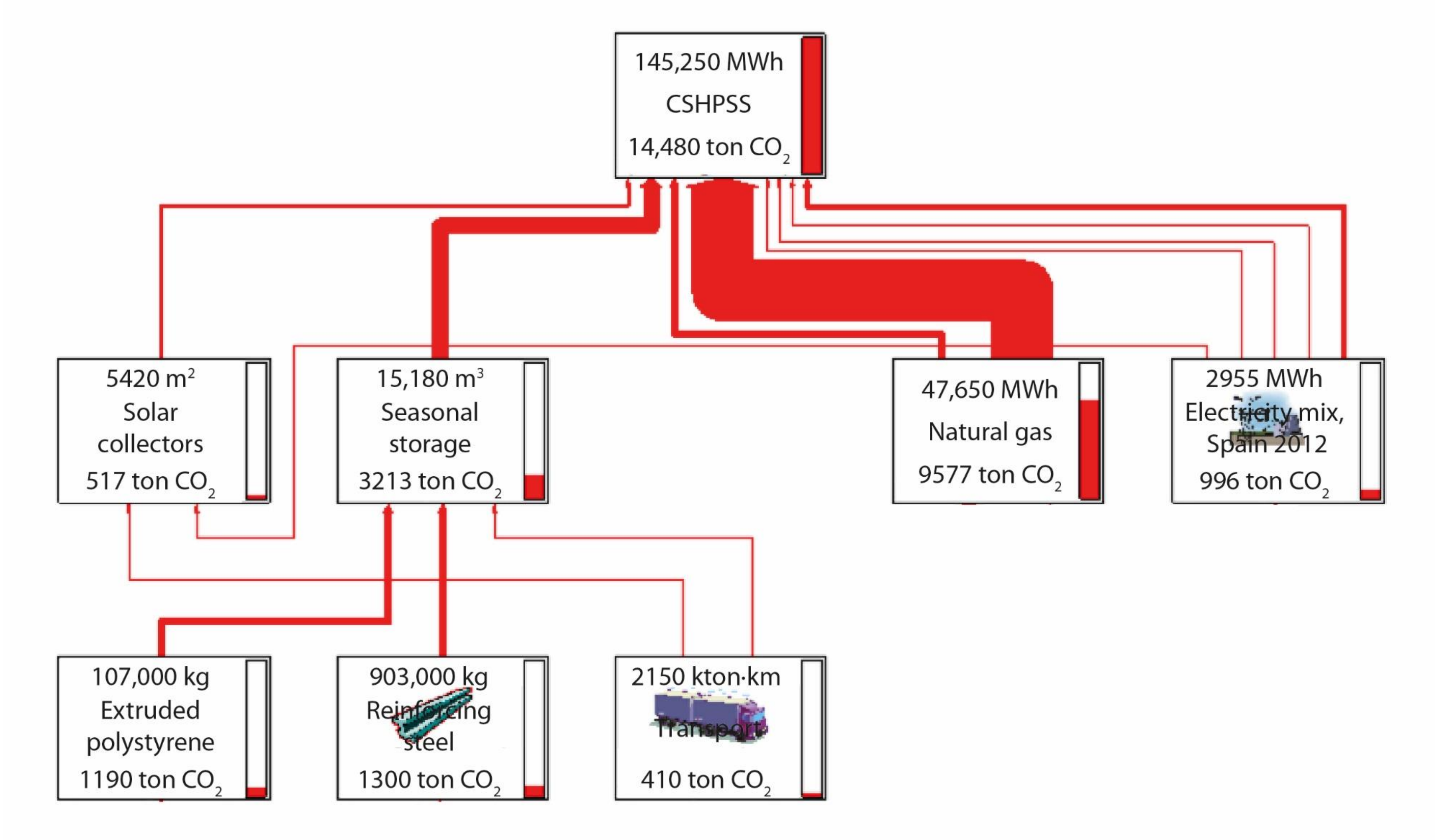

Figure 6.12: Emission of GHG along 50 years of life for the case study

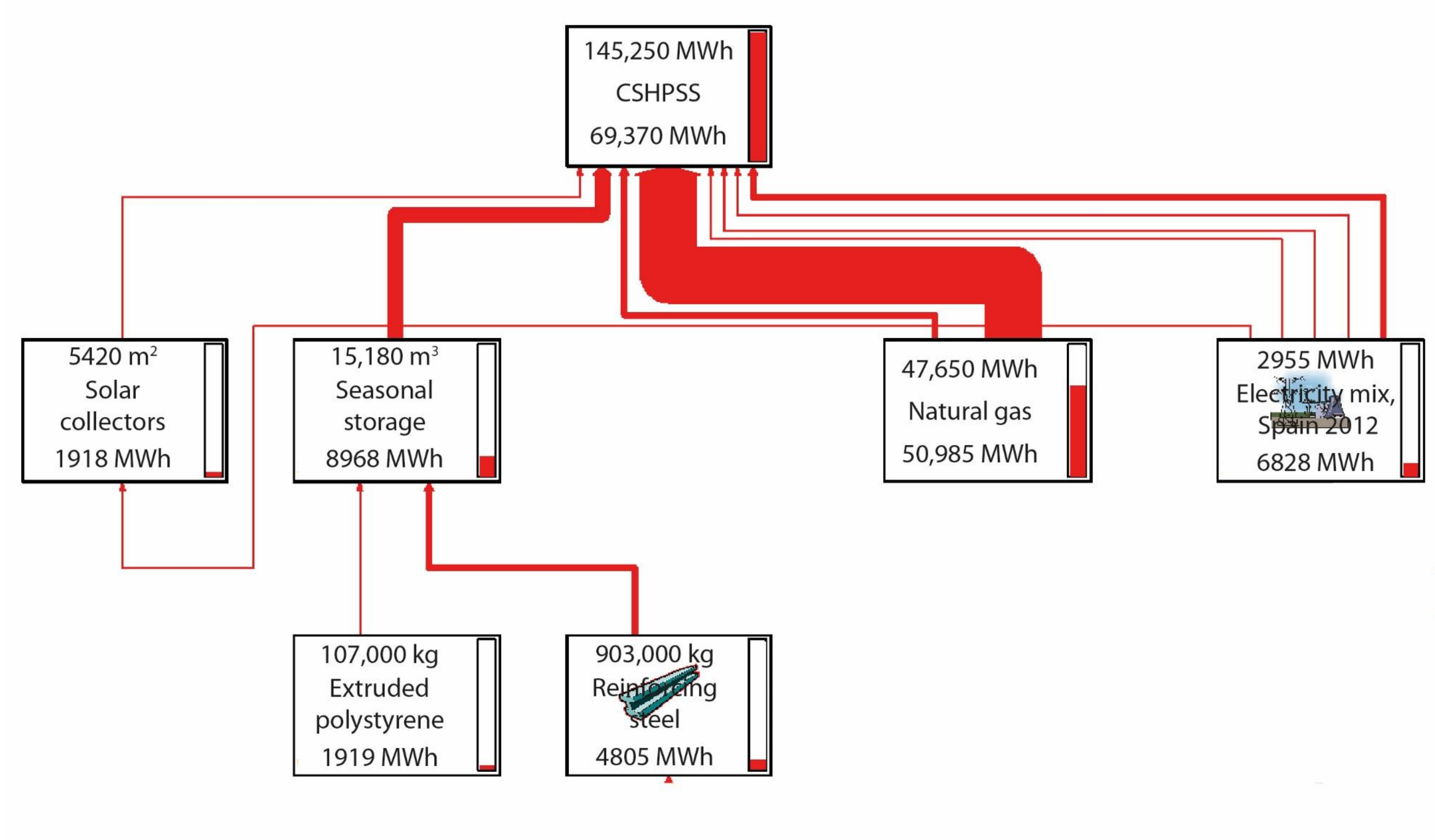

Figure 6.13: CED along 50 years of life for the case study

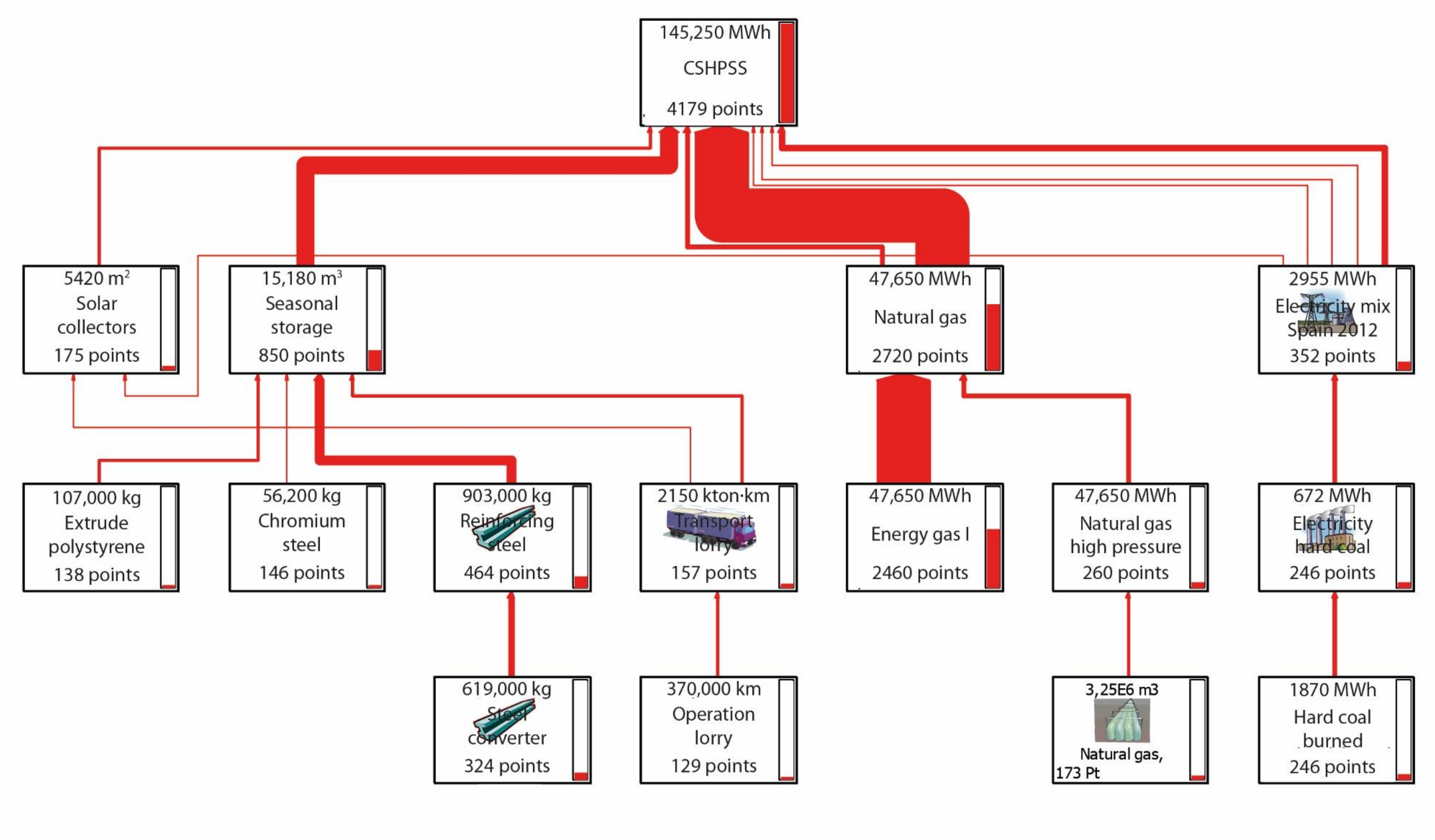

Figure 6.14: Points of IMPACT 2002+ generated along 50 years of life for the case study

Environmental Impact (EI) of the installation (construction and final disposal), Annual Environmental Impact (AEI) of the system (construction, final disposal and operation) and Environmental Impact of the system (construction, final disposal and operation) during 50 years.

Table 6.18: EI and AEI for the pieces of equipment and for the consumption of electricity and natural gas

	Environmental impact (EI)				Annual environmental impact (AEI) †			Environmental impact for 50 years		
	GHG (kg CO_{2-eq})	CED (MWh)	IMP (point)	Life	GHG (kg CO_{2-eq}/yr)	CED (MWh/yr)	IMP (mpoints/yr)	GHG (ton CO_{2eq})	CED (MWh)	IMP (points)
Seasonal storage	3213.3	8968.3	849.86	50	64,266	179.37	16,997.2	3213.3 (82%)	8968.3 (77%)	849.86 (76%)
Collectors	258.3	959.1	87.45	25	10,332	38.36	3498.0	516.6 (13%)	1918.2 (17%)	174.9 (16%)
Water tank	67.14	187.7	17.77	50	1342.8	3.75	355.4	67.14 (1.7%)	187.7 (1.6%)	17.77 (1.6%)
HE 3	18.79	68.0	10.82	25	751.6	2.72	432.9	37.58 (1.0%)	136 (1.2%)	21.64 (1.9%)
HE 1	12.04	43.6	6.932	25	481.6	1.744	277.3	24.08 (0.6%)	87.2 (0.8%)	13.86 (1.2%)
HE 2	12.04	43.6	6.932	25	481.6	1.744	277.3	24.08 (0.6%)	87.2 (0.8%)	13.86 (1.2%)
Boiler 1	11.09	44.7	3.842	25	443.6	1.788	153.7	22.18 (0.6%)	89.4 (0.8%)	7.684 (0.7%)
Pipes	10.10	42.0	5.061	25	404.0	1.680	202.4	20.20 (0.5%)	84.0 (0.7%)	10.12 (0.9%)
Boiler 2	1.175	4.7	0.407	25	47.0	0.188	16.28	2.350 (0.06%)	9.4 (0.08%)	0.814 (0.07%)
Pump solar	0.285	1.22	0.113	25	11.4	0.0488	4.52	0.570 (0.01%)	2.44 (0.02%)	0.226 (0.02%)
Pump 3	0.199	0.85	0.079	25	7.96	0.0340	3.16	0.398 (0.01%)	1.70 (0.01%)	0.158 (0.01%)
Pump 1	0.173	0.74	0.069	25	6.92	0.0296	2.76	0.346 (0.01%)	1.48 (0.01%)	0.138 (0.01%)
Pump 2	0.173	0.74	0.069	25	6.92	0.0296	2.76	0.346 (0.01%)	1.48 (0.01%)	0.138 (0.01%)
Plant*	3605	10,365	989.4		78,583	231.5	22,224	3929 (27%)	11,575 (17%)	1111.2 (27%)
G_1 862 MWh/yr					173,262	922.3	49,130	8663.1 (90%)	46,115 (90%)	2456.50 (90%)
G_2 91 MWh/yr					18,291	97.4	5187	914.55 (10%)	4870 (10%)	259.35 (10%)
Natural gas‡					191,553	1019.7	54,321	9577 (66%)	50,985 (73%)	2715.8 (65%)
E_{Ps} 46 MWh/yr					15,502.0	106.3	5474.0	775.1 (78%)	5315.0 (78%)	273.7 (78%)
E_{P3} 8.1 MWh/yr					2729.7	18.71	963.9	136.49 (14%)	911.5 (14%)	48.20 (14%)
E_{P1}3.3 MWh/yr					1112.1	7.623	392.7	55.61 (5.6%)	371.5 (5.6%)	19.64 (5.6%)
E_{P2} 1.7 MWh/yr					572.9	3.927	202.3	28.64 (2.9%)	191.0 (2.9%)	10.10 (2.9%)
Electricity‡					19,917	136.5	7033	995.8 (7%)	6,828 (10%)	351.6 (8%)
System					***290,053***	***1387***	***83,570***	***14,480 (100%)***	***69,400 (100%)***	4179 ***(100%)***

* Plant: environmental impact calculated for the plant installed the first year, per year and for the 50 years period.

† Annual environmental impact considers distribution of the equipment along the expected life of each device.

‡ Natural gas and electricity: environmental impact of the auxiliary energy required each year and along the expected life of 50years.

6.2.4 Analysis of internal flows

A thermoeconomic analysis for a CSHPSS was performed by Lozano et al. (2010c) for the case study presented in this chapter. In this section the thermoeconomic analysis is combined with the environmental assessment of the plant, obtaining the environmental impact corresponding to the internal energy flows (Carvalho et al., 2012).

From the initial energy source, solar radiation, it is obtained the environmental cost, i.e. environmental impact, of the internal energy flows that lead to the final products accounting component by component the environmental burden assessed to the different pieces of equipment and the auxiliary energy required.

The environmental impact of the outlet energy flows from a component, process or subsystem $Ec_{out,i}$ is calculated from the environmental impact of the inlet flows, $Ec_{in,i}$ and the annualized environmental impact of the equipment AEI_i.

$$\sum(Q_{out,i} \cdot Ec_{out,i}) = AEI_i + \sum(Q_{in,i} \cdot Ec_{in,i}) \qquad (7)$$

If several products are obtained from a component or a process the distribution of the environmental impact among the streams is a delicate question, but for this system it is an easy issue. The solar field produces a stream of hot water for DHW and another stream for space heating. As both streams are equivalent (same product and same temperature) the same environmental cost has been considered for each stream and the environmental impact is divided according to the energy transferred. Results obtained by applying the emission of GHG, CED and IMPACT 2002+ methodologies are presented in Figs. 6.15, 6.16 and 6.17, respectively.

Emission of greenhouse gases

The environmental impact of the heat produced by the solar field is Ec_{sf} = 4.94 kg $CO_{2\text{-eq}}$/MWh. Considering also heat exchangers and electricity consumption the heat produced before being stored in the seasonal storage has an environmental impact of Ec_{P1} = 12.84 kg $CO_{2\text{-eq}}$/MWh. The seasonal storage, even when a long lifetime of 50 years is considered, raises the environmental cost to Ec_{sol1} = 56.72 kg $CO_{2\text{-eq}}$/MWh. For the SH needs, 33% comes from an auxiliary source obtaining a final environmental cost of Ec_{SH} = 110.19 kg $CO_{2\text{-eq}}$/MWh. For the production of DHW the emissions are lower, Ec_{sol2} = 17.83 kg $CO_{2\text{-eq}}$/MWh due to the lack of the seasonal storage. The environmental impact of the DHW is Ec_{DHW} = 50.84 kg $CO_{2\text{-eq}}$/MWh.

It is remarkable that the auxiliary system generates half of the emissions for the SH demand while it only represents 33% of the heat produced. A higher share of solar thermal energy will reduce the emission of GHG. Compared with a system fed only by natural gas the centralized system saves 91 kg $CO_{2\text{-eq}}$/MWh for SH and 150 kg $CO_{2\text{-eq}}$/MWh for DHW. As a reference, the emission of GHG for the most common energy sources is: 201 kg $CO_{2\text{-eq}}$/MWh for natural gas, 235 kg $CO_{2\text{-eq}}$/MWh for diesel oil and 337 kg $CO_{2\text{-eq}}$/MWh for the electricity (IDAE, 2012).

Cumulative energy demand

Another objective of the European Union is to reduce the consumption of non-renewable energy sources. The primary energy factor (PEF = CED/E, see Section 6.1.3.2) of internal energy flow considering the embodied energy of the pieces of equipment is presented in Fig. 6.16.

The heat produced by the solar field has a PEF of Ec_{sf} = 0.0184 MWh/MWh; including the heat exchanger and the consumption of electricity this factor reaches Ec_{P1} = 0.0718 MWh/MWh; if the seasonal storage is required to cover SH needs this factor significantly increases till Ec_{sol1} = 0.2056 MWh/MWh; but for DHW the factor only increases to Ec_{sol2} = 0.0900 MWh/MWh.

The factors obtained using the LCA methodology, (0.2056 MWh/MWh for SH and 0.0900 MWh/MWh for DHW) are quite far from the factor 0 MWh/MWh proposed by most standards in the literature about consumption of primary energy by solar thermal systems. The subsystem for SH with 67% of solar energy will get a PEF = 0.52 MWh/MWh and the subsystem for DHW with 83% solar fraction a PEF = 0.27 MWh/MWh.

IMPACT 2002+

The methodology IMPACT 2002+ evaluates the environmental impact of an activity process or a product compared to the average environmental impact of one person for one year in Europe (1 point). The final evaluation presented in Fig 6.17 has been obtained from the normalized evaluation of each damage category with uniform weighting. Results are presented in mpoints (10^{-3} points) per MWh.

As presented in Table 6.17, 1 MWh of electricity generates an estimated impact of Ec_{ele}=119 mpoints/MWh and 1 MWh of gas generates an impact of Ec_{gas}=57 mpoints The heat produced by the solar collector has a very low impact, only Ec_{sf}=1.70 mpoints/MWh. Including the effect of the seasonal storage the environmental cost rises to Ec_{sol1}=16.58 mpoints/MWh. For the production of DHW the IMPACT 2002+ value is Ec_{sol2}=6.23 mpoints/MWh.

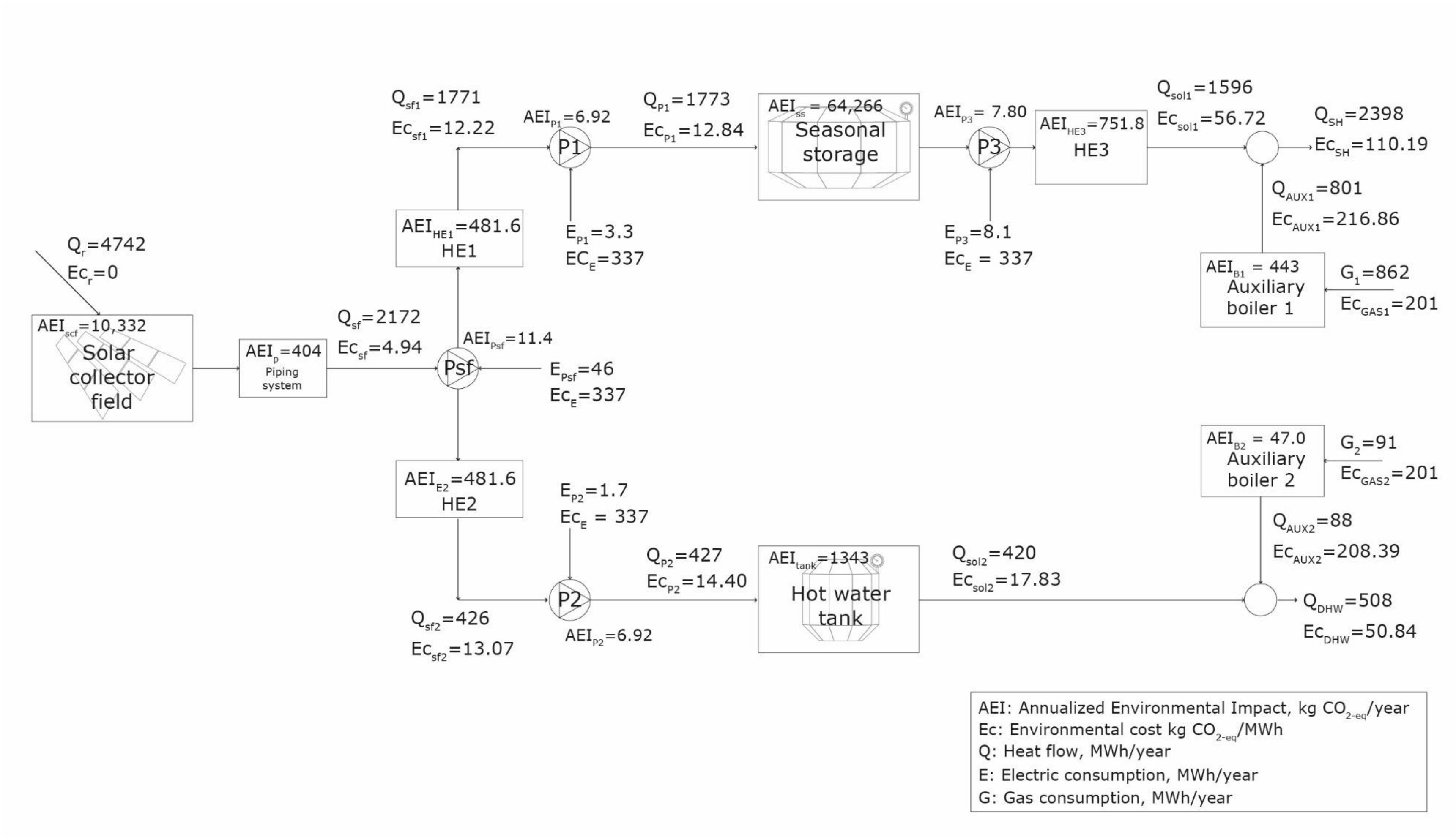

Figure 6.15: Emission of greenhouse gases for the internal energy flows

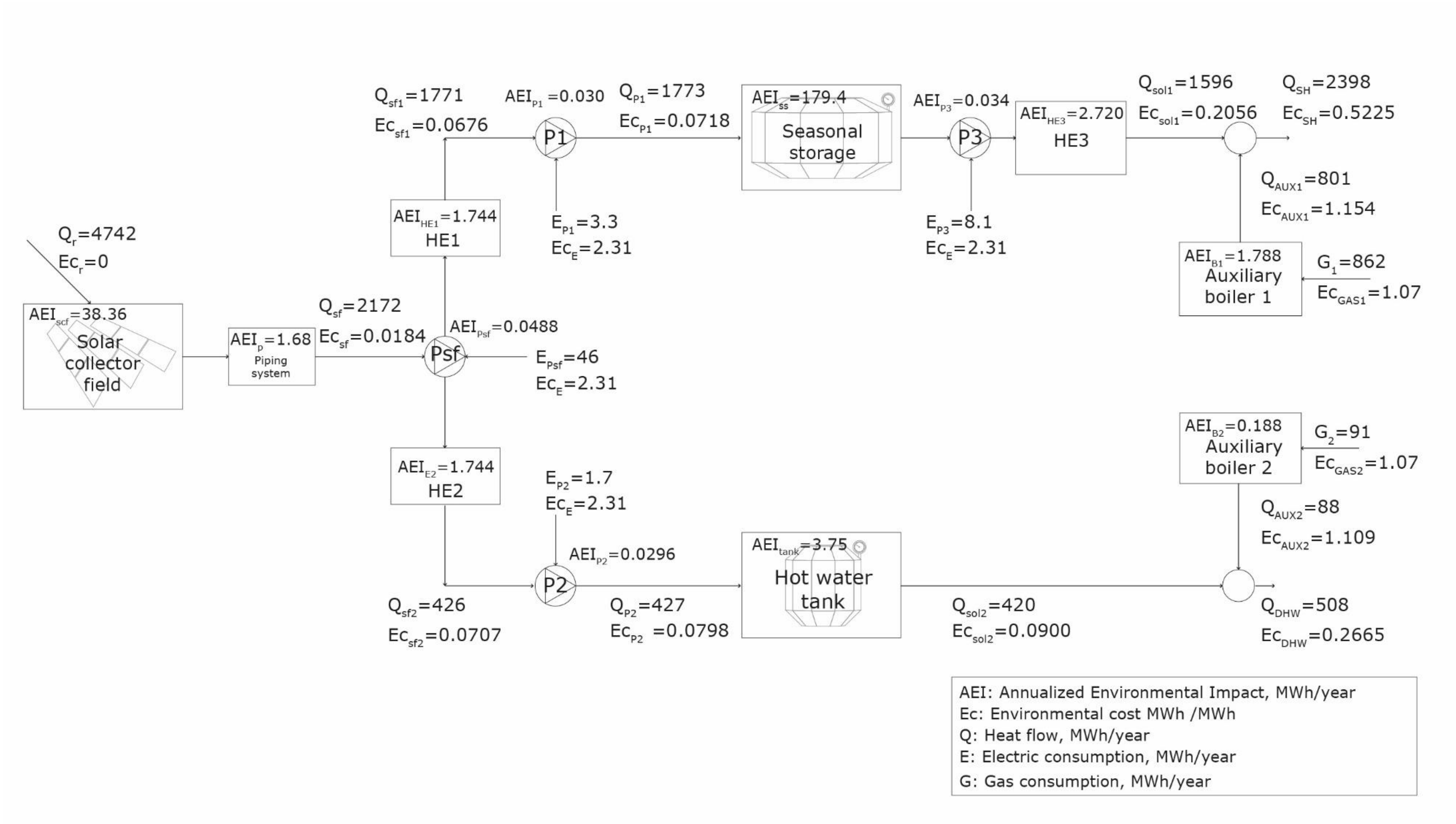

Figure 6.16: CED for the internal energy flows

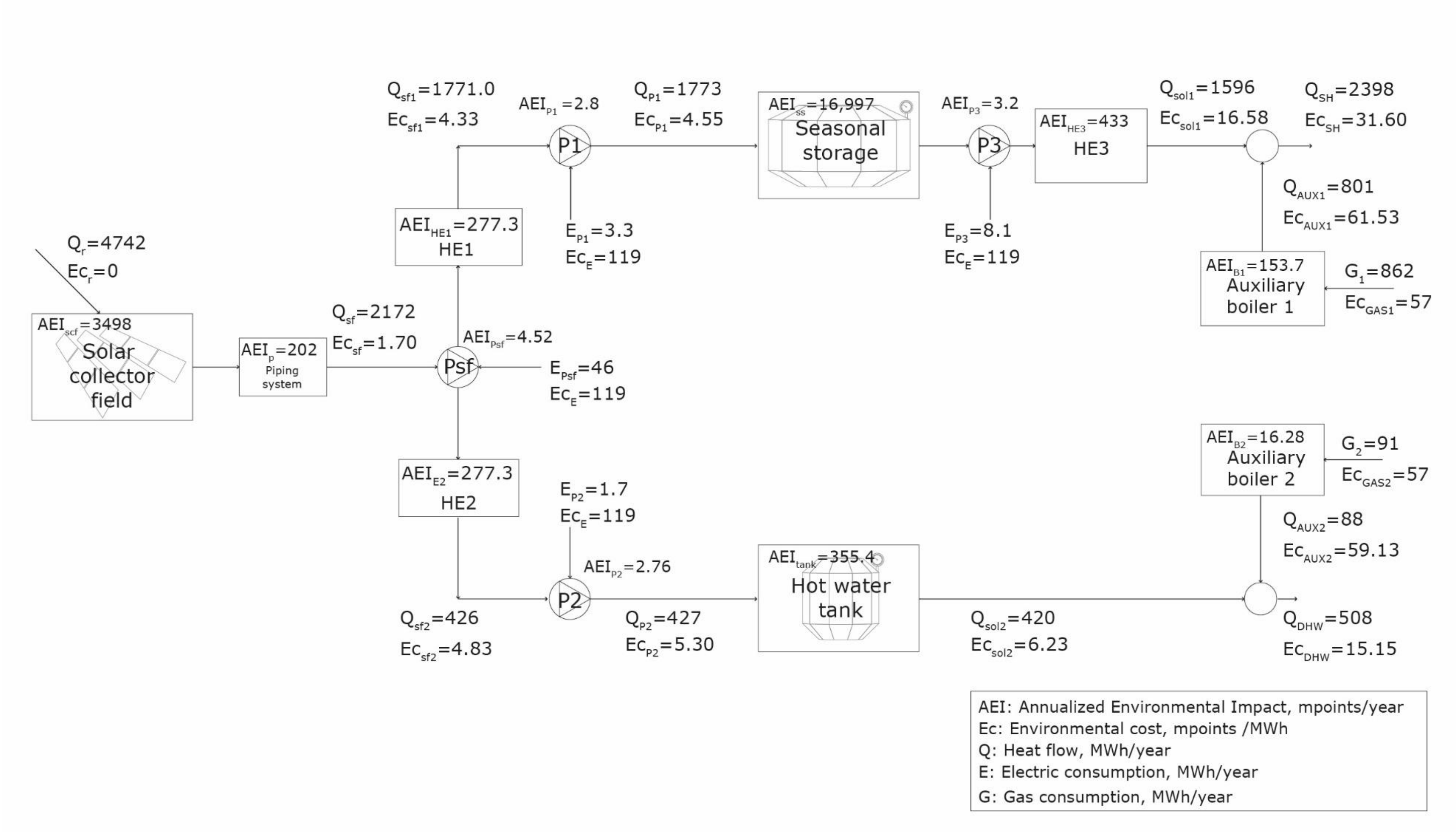

Figure 6.17: Evaluation IMPACT 2002+ for the internal energy flows

6.2.5 Interpretation of results

The environmental impact of a CSHPSS has been analyzed with the LCA methodology obtaining the emission of GHG, CED and IMPACT 2002+ points. The plant produces DHW and SH for a community of 500 dwellings with 69% solar fraction.

1) The solar plant produces heat with lower environmental impact than conventional energy systems, i.e. natural gas or electricity.
2) The natural gas consumed in the auxiliary system that covers only 31% of the heating needs is responsible for most of the impacts.
3) The emission of GHG per MWh of heat in the solar field is more than 15 times smaller than the emission of GHG per MWh of natural gas.
4) The production of SH with high solar fraction requires a seasonal storage, but the seasonal storage raises the environmental impact by a factor of 3 to 4.
5) The environmental impact of the solar heat compared to the auxiliary system is 4 to 5 times smaller for the production of SH and 10 to 12 times smaller for the production of DHW.
6) The environmental impact generated by the boiler can be neglected in comparison with the impact of the natural gas consumed.
7) Most of the solar system impacts are generated by the construction of the plant.
8) Increasing the solar fraction reduces significantly the environmental impact of the system, as the major responsible for the impact is the consumption of natural gas.
9) The consumption of electricity is also one of the major responsible for the environmental impact of the solar system. Reducing its consumption or increasing the share of renewable energies in the electricity mix might reduce significantly the environmental impact of the solar system.

Results obtained for this case cannot be translated to every plant with seasonal storage as the characteristics of each plant are unique and big differences can be found among different plants. But some of the results can be extrapolated to estimate the impact of other plants.

The environmental impact of the district heating system has not been considered. Very little information can be found in literature that estimates the impact of the insulated pipes or the electricity consumed for pumping.

Most renewable energy systems do not consider the impact of the equipment required, with this simplification very appealing scenarios are obtained in which zero emissions of CO_2 are generated and only the consumption of fuels and electricity generates an environmental impact (Frederiksen and Werner, 2013). If we consider all the emissions associated with the production of energy, more realistic scenarios would be obtained. The following section will present a methodology to estimate the emission of GHG, the CED and the points of IMPACT 2002+ for solar district heating systems based on the results obtained from the LCA.

6.3 Definition of a simplified impact assessment for CSHPSS

In the previous section the environmental impact of a CSHPSS has been analyzed considering all the pieces of equipment and the consumption of energy. From this analysis, the factors that have the greatest impacts have been defined: consumption of natural gas, consumption of electricity, construction of the seasonal storage, and construction of the solar collector field. Other pieces of equipment represent less than 2% of the annual impacts.

This section presents a methodology to estimate the environmental impact of a CSHPSS as a function of the main design parameters (solar field area and seasonal storage volume) and the consumption of electricity and natural gas. This method can be implemented in the *Simple Method*, through the system flow diagram presented in Fig. 6.18.

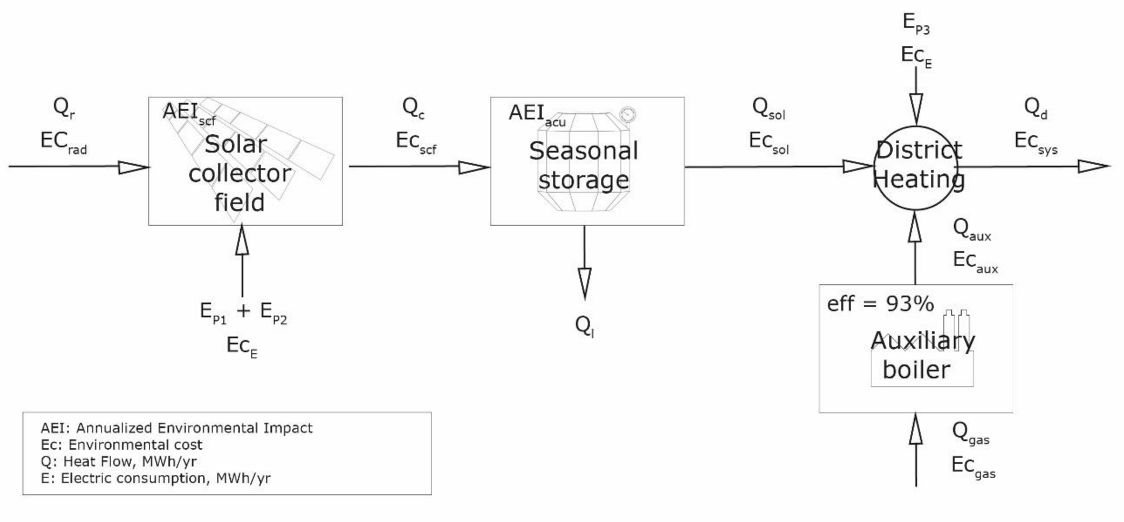

Figure 6.18: Flow diagram of the simplified impact assessment

6.3.1 Solar collector field

The annual environmental impact of the solar field (AEI_{scf}) is estimated from the annual environmental impact of the components: solar collector (AEI_{coll}), pipes (AEI_{pipes}), heat exchanger (AEI_{HE1}), primary circuit pump (AEI_{Psf}) and secondary circuit pump (AEI_{P1}).

$$AEI_{scf} = AEI_{coll} + AEI_{pipes} + AEI_{HE1} + AEI_{Psf} + AEI_{P1} \quad (8)$$

The sizing of the pipes and heat exchanger and the annualized environmental impact can be considered approximately proportional to the solar collector field area. From the results obtained in the previous section with a solar collector field area A = 2760 m^2 the following correlation has been obtained for the emission of GHG.

$$AEI_{scf} = 10{,}332 + 404.4 + 481.6 + 11.4 + 6.9 = 11{,}236 \text{ kg } CO_{2\text{-}eq}/yr \quad (9)$$

$$AEI_{scf} / A = 4.07 \text{ kg } CO_{2\text{-}eq} / (m^2 \cdot yr) \quad (10)$$

Eqs. 11 and 12 show the proportional factors for CED and IMPACT 2002+ points, applying a similar procedure.

$$AEI_{scf} / A = 0.0152 \text{ MWh} / (m^2 \cdot yr) \quad (11)$$

$$AEI_{scf} / A = 1.44 \text{ mpoints} / (m^2 \cdot yr) \quad (12)$$

6.3.2 Seasonal storage

The seasonal storage has the ability to accumulate thermal energy for long periods of time. The amount of energy that can be stored is proportional to the volume of water but the resources consumed in the construction are proportional to the envelope area. Charge and discharge of heat from the seasonal storage also require auxiliary equipment (heat exchanger and pump).

$$AEI_{acu} = AEI_{ss} + AEI_{HE3} + AEI_{P3} \quad (13)$$

$$AEI_{acu} = 64{,}260 + 752 + 8 = 65{,}020 \text{ kg } CO_{2\text{-}eq}/yr \quad (14)$$

The seasonal storage of the case study has an envelope area of 3498 m^2 and the following proportionality factors have been obtained for the emission of GHG (Eq. 15), CED (Eq. 16) and points of IMPACT 2002+ (Eq. 17).

$$AEI_{acu} / A_{acu} = 18.59 \text{ kg } CO_{2\text{-}eq} / (m^2 \cdot yr) \quad (15)$$

$$AEI_{acu} / A_{acu} = 0.0521 \text{ MWh} / (m^2 \cdot yr) \quad (16)$$

$$AEI_{acu} / A_{acu} = 4.98 \text{ mpoints} / (m^2 \cdot yr) \quad (17)$$

6.3.3 Consumption of electricity

The simplified impact assessment requires knowing the electricity consumed. The consumption of electricity is estimated from the pumping requirements for the three pumps: primary pump of the solar field P_1, secondary pump of the solar field P_2 and discharging pump from the seasonal storage P_3. To estimate the electricity consumption for the solar collector field, it is required to know the nominal fluid flows in primary V_{P1} (m^3/s) and secondary V_{P2} (m^3/s) circuits.

$$V_{P1} = A \cdot m_s / (\rho_{sf} \cdot 3600) \quad (18)$$

where m_s (kg/(h·m^2)) is the specific mass flow rate of the primary, ρ_{sf} (kg/m^3) is the density of the working fluid and $c_{p,sf}$ (J/(kg·K)) is the specific heat of the working fluid in the solar field.

For the secondary circuit the volumetric flow rate V_{P2} is calculated as,

$$V_{P2}/V_{P1} = (\rho_{sf} \cdot c_{p,sf}) / (\rho_w \cdot c_{p,w}) \tag{19}$$

being ρ_w (kg/m^3) and $c_{p,w}$ (J/(kg·K)) the density and specific heat of the water. Solar collectors (ΔP_{coll} = 3.8 kPa), pipes (ΔP_{pipes} = 400 kPa) and heat exchanger (ΔP_{HE1} = 50 kPa) generate a pressure drop (ΔP_{P1}) on the primary circuit. Reference values have been obtained from the works of Frago (2011) and Anastasia (2010).

$$\Delta P_{P1} = \Delta P_{coll} + \Delta P_{pipes} + \Delta P_{HE1} = 454\ kPa \tag{20}$$

Pressure drop on the secondary circuit ΔP_{P2} is only caused by the heat exchanger.

$$\Delta P_{P2} = \Delta P_{HE1} = 50\ kPa \tag{21}$$

The power of the pumps P_{Pi} (kW) is calculated according to the pressure drop in the circuit (ΔP_{Pi}), pump flow rate (V_i) and mechanical efficiency (η_p = 0.54).

$$P_{Pi} = \Delta P_{Pi} \cdot V_i / \eta_p \tag{22}$$

The consumption of energy E_{Pi} (MWh/yr) from these pumps is the result of multiplying the power by the number of hours operating per year H_f (hours/yr).

$$E_{Pi} = P_{Pi} \cdot H_f / 1000 \tag{23}$$

The number of operating hours is obtained from the hourly performance of a typical day in the *Simple Method* for each month. For the third pump, P_3, the process applied is slightly different. Annually the pump of the seasonal storage will move a volume of water VH_{P3} (m^3/yr) with a difference of temperature between supply and return $T_{sup} - T_{ret}$ = 20 K to cover the thermal needs.

$$VH_{P3} = Q_d \cdot 3.6 \cdot 10^9 / (\rho_w \cdot c_{p,w} \cdot (T_{sup} - T_{ret})) \tag{24}$$

Pressure drop in this circuit is generated by the heat exchanger on the discharging side, ΔP_{HE2}.

$$\Delta P_3 = \Delta P_{HE2} = 50\ kPa \tag{25}$$

The consumption of energy for this pump is obtained as follows:

$$E_{P3} = VH_{P3} \cdot \Delta P_3 / (\eta_p \cdot 3.6 \cdot 10^6) \quad (26)$$

6.3.4 Example of application

The environmental impact of the base case presented in Chapter 4 is calculated. The system produces space heating and domestic hot water for a community of 1000 dwellings in Zaragoza. The CSHPSS has a solar collector field area A = 3210 m^2 which produces Q_c = 3124 MWh/yr. Part of this production is accumulated in the seasonal storage with volume V = 19,260 m^3 and thermal losses to the ambient Q_l = 146 MWh/yr. The demand Q_d = 5350 MWh/yr is supplied by the solar system Q_{sol} = 2997 MWh/yr and by an auxiliary natural gas boiler Q_{aux} = 2372 MWh/yr.

The process to determine the environmental cost of the internal flows has been described in Section 6.2.4. For the *Simple Method* a reduced number of parameters summarized in Table 6.19 will be required.

Table 6.19: Summary of environmental assessment characterization factors for the *Simple Method*

	Emission GHG	Primary energy CED	IMPACT 2002+
AEI_{scf} /A	4.07 kg $CO_{2\text{-}eq}$/yr/m^2	0.0152 MWh/yr/m^2	1.44 mpoints/yr/m^2
AEI_{acu}/A_{acu}	18.59 kg $CO_{2\text{-}eq}$/yr/m^2	0.0521 MWh/yr/m^2	4.98 mpoints/yr/m^2
AEI_{scf}	13,065 kg $CO_{2\text{-}eq}$/yr	48.8 MWh/yr	4622 mpoints/yr
AEI_{acu}	76,238 kg $CO_{2\text{-}eq}$/yr	213.7 MWh/yr	20,423 mpoints/yr
Ec_E (IDAE, 2012)	337 kg $CO_{2\text{-}eq}$/MWh	2.31 MWh/MWh	119 mpoints/MWh
Ec_{gas} (IDAE, 2012)	201 kg $CO_{2\text{-}eq}$/MWh	1.07 MWh	57 mpoints/MWh

The environmental impact of the heat produced in the solar field (Ec_{scf}) is calculated according to the consumption of electricity (E_{P1} + E_{P2}) and the annual environmental impact of the solar field (AEI_{scf}).

$$Ec_{scf} = (AEI_{scf} + (E_{P1} + E_{P2}) \cdot Ec_E) / Q_c \quad (27)$$

$$Ec_{scf} = 10.8 \text{ kg } CO_{2\text{-}eq}/MWh \quad (28)$$

$$Ec_{scf} = 0.0609 MWh/MWh \quad (29)$$

$$Ec_{scf} = 3.81 \text{ mpoints}/MWh \quad (30)$$

The heat collected is charged into the seasonal storage and discharged for its later consumption increasing the environmental cost. The annual environmental impact of the seasonal storage AEI_{acu} is proportional to the envelope area A_{acu} = 4101 m^2.

The environmental impact of the heat produced by the solar system is obtained from the impact of the solar field and the seasonal storage.

$$Ec_{sol} = (AEI_{acu} + Q_c \cdot Ec_{scf}) / Q_{sol} \qquad (31)$$

The environmental impact for the emission of GHG, CED and points of IMPACT 2002+ per unit of heat produced by the solar system (Ec_{sol}) are obtained.

$$Ec_{sol} = 30.0\ kg\ CO_{2\text{-}eq}/MWh \qquad (32)$$

$$Ec_{sol} = 0.14\ MWh/MWh \qquad (33)$$

$$Ec_{sol} = 8.43\ mpoints/MWh \qquad (34)$$

After the seasonal storage, the primary energy factor rises until 0.14 MWh/MWh. This value is lower than the value obtained by the detailed method for the stream of SH but higher than the stream for DHW.

The consumption of gas or auxiliary energy is estimated by the *Simple Method* described in Chapter 4. The system consumes natural gas (Q_{gas}) to cover the needs of auxiliary energy (Q_{aux}). A boiler with an efficiency of η_{BH} = 93% has been considered and the annual environmental impact of the boiler has been neglected from the analysis according to the results obtained in the previous section.

$$Ec_{aux} = Q_{gas} \cdot Ec_{gas} / Q_{aux} = Ec_{gas} / \eta_{BH} \qquad (35)$$

The environmental impact of the auxiliary heat is presented in the following equations.

$$Ec_{aux} = 216\ kg\ CO_{2\text{-}eq}/MWh \qquad (36)$$

$$Ec_{aux} = 1.15\ MWh/MWh \qquad (37)$$

$$Ec_{aux} = 61.3\ mpoints/MWh \qquad (38)$$

The environmental cost (i.e. environmental impact per unit of heat produced by the system) depends on the solar fraction (SF), the impact of the solar system, impact of the auxiliary system and electricity consumed by the discharging pump E_{P3} = 54 MWh.

$$Ec_{sys} = SF \cdot Ec_{sol} + (1 - SF) \cdot Ec_{aux} + E_{P3} \cdot Ec_E \qquad (39)$$

$$Ec_{sys} = 120\ kg\ CO_{2\text{-}eq}/MWh \qquad (40)$$

$$Ec_{sys} = 0.61\ MWh/MWh \quad (41)$$

$$Ec_{sys} = 34.4\ mpoints/MWh \quad (42)$$

The primary energy factor of the heat produced by the system is 0.61 MWh/MWh, as shown in Fig. 6.19. If it had been considered only the environmental cost of the auxiliary energy the primary energy factor obtained would have been 0.51 MWh/MWh. It can be concluded that conventional evaluation methods underestimate the consumption of primary energy.

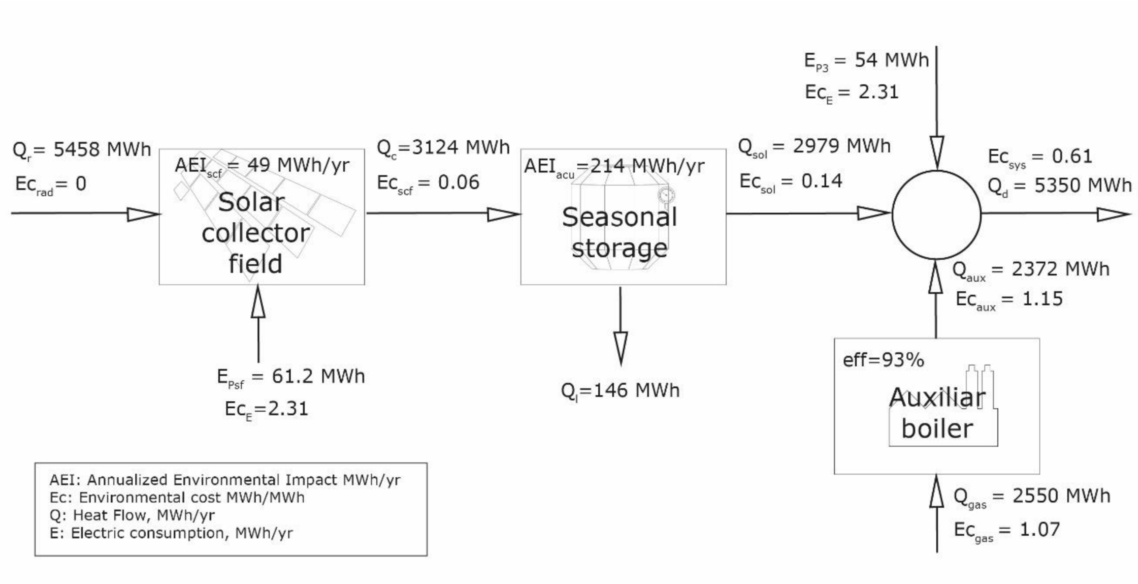

Figure 6.19: Environmental analysis (primary energy factor) of the *Simple Method*

Results from this chapter show the importance of analyzing renewable energy systems with the LCA methodology to do a proper evaluation of the environmental impact deriving from the energy produced with renewable systems.

However, the standards for district heating systems (AGFW, 2010) calculate the primary energy factor according to the fuel consumed, i.e. zero emissions for a solar system. Considering all the impacts along the life cycle the primary energy factor of a CSHPSS is 0.14 MWh/MWh.

The application of the LCA to district heating systems will improve the development of technologies that generate a lower environmental impact, e.g. seasonal storages with lower consumption of materials and solar fields operating with lower consumption of electricity.

The simplified impact assessment presented can be used to perform preliminary analysis of CSHPSS in order to design systems with minimum impact. In the following chapter the methodology proposed is used in combination with the *Simple Method*. Designs based on minimum cost and environmental impact will be created as well as a software application to perform feasibility analysis of CSHPSS from a thermal, economic and environmental point of view.

Chapter 7: Applications of the Simple Method, environmental and geographic analysis

7 Applications of the Simple Method: environmental and geographic analysis

Further results of the thesis that have been obtained from the tools developed in previous chapters, are presented in this chapter divided into 4 Sections.

Section 7.1 analyzes the effect of design criteria on the environmental impact of a CSHPSS. Economies of scale on the environmental impact have been evaluated. The environmental impact of the heat produced for different solar fractions have been determined for minimum and critical volume, comparing these two design criteria. Finally, a multiobjective optimization balancing designs with minimum cost and minimum environmental impact have been performed.

To expand the application of the *Simple Method*, correlations to estimate some demand and climatic data required are presented in Section 7.2. These correlations estimate: monthly degree-days using ambient temperature, European Heating Index (EHI) using monthly degree-days, and cold water temperature (to determine the DHW consumption) based on the ambient temperature.

A software application using the Engineering Equation Software (EES, 2013) has been developed based on: i) the *Simple Method*, ii) the economic model, iii) the simplified environmental assessment, and iv) the extension of climatic and demand data. User manual of the application is presented in Section 7.3. The software application can be used in any personnel computer to predesign CSHPSS, obtaining the thermal performance, the cost and the environmental impact. This software is available online at Task 45 website (Task 45, 2015).

The effect of location and climate are very influential when designing a CSHPSS. In Section 7.4 the software application has been used to design equivalent installations in different locations of Europe (i.e. same size community and same solar fraction). The geographic analysis shows the significant design differences between north and south European climates and the economic and environmental impact of installations designed for different locations.

7.1 Environmental analysis of CSHPSS

The *Simple Method* for CSHPSS (Chapter 4), the economic model (Section 5.1) and the simplified impact assessment for CSHPSS (Section 6.3) have been joined in this section. With low calculation effort the physical, economic and the environmental impact of different designs can be calculated. In this subsection the effect of design parameters over the final economic and environmental cost of the system is analyzed. The effect of economies of scale and solar fraction with the criterion of critical volume are presented.

Environmental analyses are performed for the emission of GHG and for the consumption of primary energy (CED). The emission of GHG per unit of heat produced and the primary energy factor (PEF) are obtained, considering the consumption of fuels and the embodied energy.

7.1.1 Economies of scale

As presented in Section 5.2, CSHPSS for big communities reduces the economic cost of the solar heat and increases the efficiency of the plant. As the environmental cost of the seasonal storage is proportional to the storage envelope area, increasing the storage volume reduces the environmental cost of the solar heat. On the other hand, the embodied energy in the solar collector field and the consumption of electricity is not decreased by a size increase. For the base case presented in the economic analysis, located in Zaragoza, with the same design ratios RAD = 0.6 m^2/(MWh/yr) and RVA = 6 m^3/m^2, the unit environmental cost of the solar heat (environmental impact per unit of heat produced) has been calculated for different community sizes. The results are presented in Fig. 7.1.

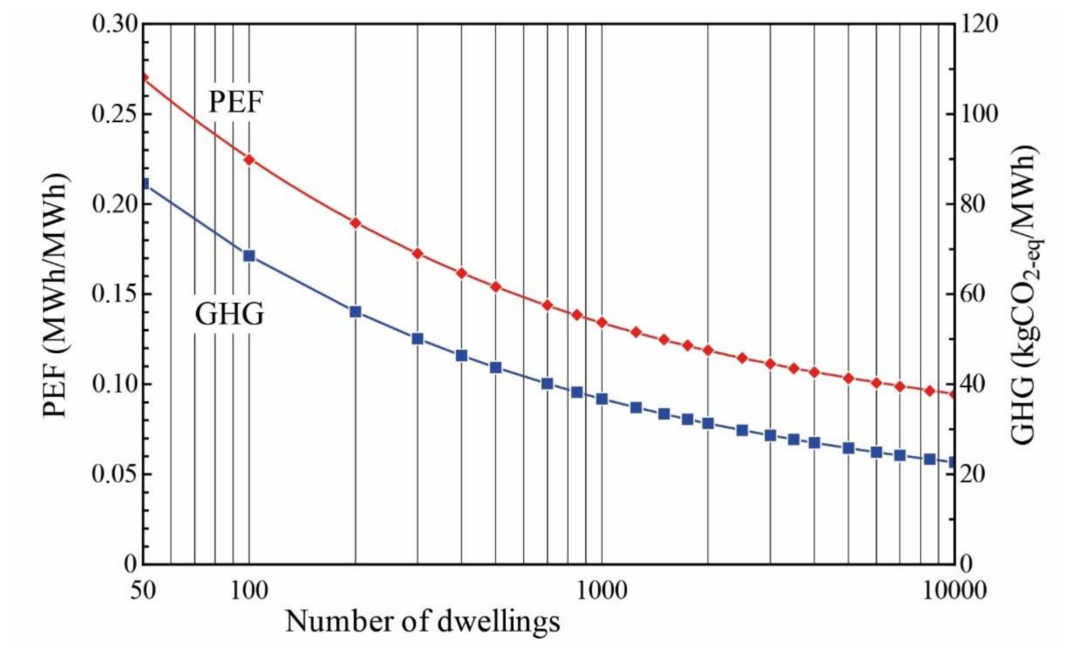

Figure 7.1: Environmental cost of solar heat for communities of different size

The environmental cost of the solar heat is reduced when the community size is increased. From a small community of 50 dwellings to a big community of over 1000 dwellings the environmental cost of the solar energy can be reduced by half. Similar conclusions were obtained with the economic analysis; therefore, designing systems for a large community is appropriate from an economic and environmental point of view.

7.1.2 Effect of solar fraction

CSHPSS with critical volume (design criterion described in Section 5.3) do not reject heat in summer, accumulate all the summer overproduction and reach the maximum storage temperature at the end of the charging season. Such systems make the best use of the equipment from a thermal point of view. Considering this design criterion, the solar fraction and the environmental impact have been calculated for systems with different solar collector field areas delivering heat to a community of 1000 dwellings. The results are presented in Fig. 7.2.

The PEF of the thermal energy produced by the solar system (Ec_{sol}, red line) is higher for high solar fraction due to the higher requirements of accumulation, but is still quite low for the whole range in comparison to thermal energy produced by the auxiliary system (Ec_{aux}, black line). The PEF of the energy produced by the system (Ec_{sys}, blue line) follows a linear function with the solar fraction, reaching a minimum value of 1.5 MWh/MWh for a solar fraction of almost 100%. Equivalent results are obtained for the GHG emissions.

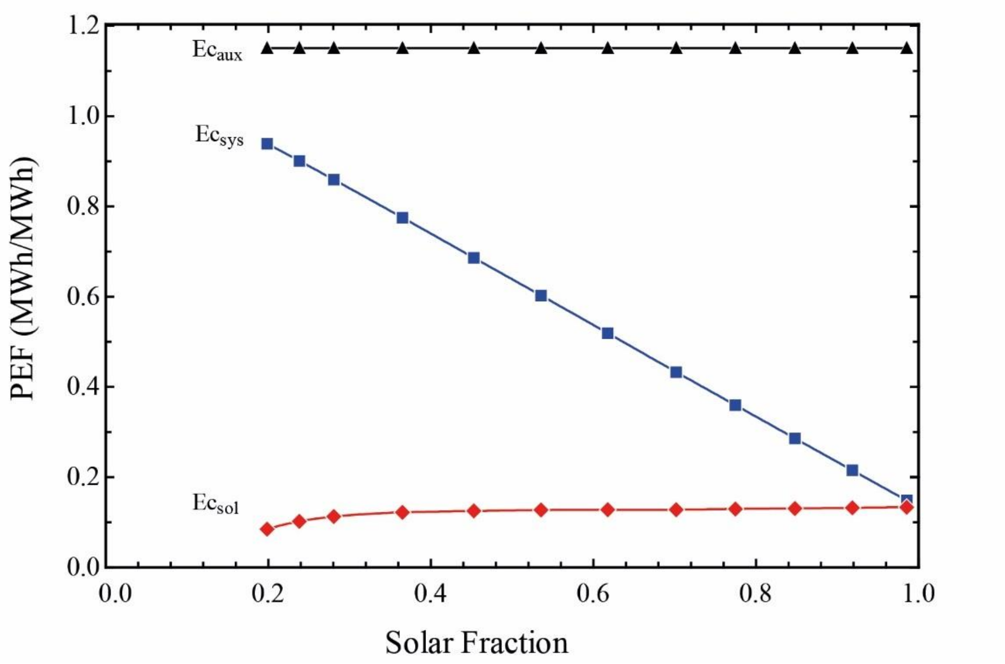

Figure 7.2: Environmental cost of energy flows vs solar fraction; design criterion critical volume

7.1.3 Critical volume and minimum volume criteria

Low solar fraction can be obtained with a large solar collector field and without seasonal storage. The summer production will be used to cover the domestic hot water demand and in winter it will cover the domestic hot water demand. If the solar field is big enough it might be even possible to cover some share of the space heating needs in locations with high solar radiation in winter.

High solar fraction systems without seasonal storage need to reject big amounts of heat in summer. For this purpose, active systems are required to avoid overheating in the solar field, which harms the equipment. This cooling equipment might consume a considerable amount of electrical energy but also passive strategies can be followed as disconnecting part of the solar field along the summer season and/or shadowing the solar collectors. The economic and environmental impact of this auxiliary equipment has not been considered.

The solar fraction and the PEF for a set of cases with minimum volume (RVA_{min} = 1 m^3/m^2) have been calculated and compared with the results obtained with critical volume. The results are presented in Fig. 7.3. For low solar fraction, designs with minimum volume (red line, RVA_{min}) have a PEF lower than systems with seasonal storage (blue line, RVA_c). Over a solar fraction of 0.6 systems with critical volume have a lower PEF.

For low solar fraction, systems with small storage might be more convenient from an economic and environmental point of view rather than systems with seasonal storage. Nevertheless, preventing harm to devices has not been considered. Similar conclusions were obtained from the analysis of GHG emissions.

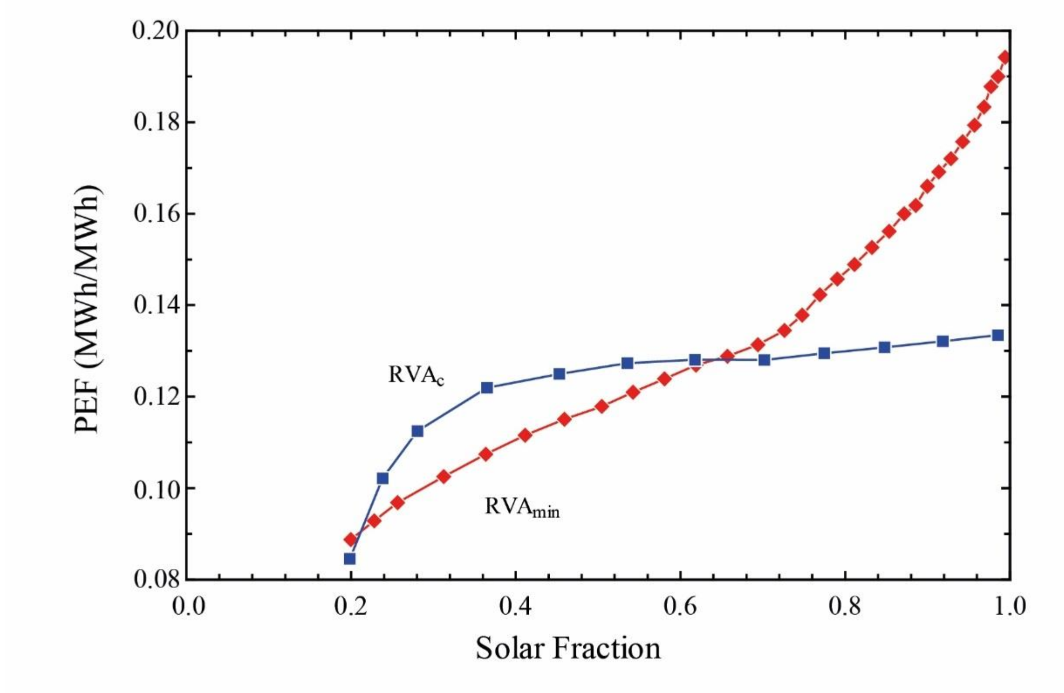

Figure 7.3: Environmental cost of solar energy for critical volume and minimum volume criteria

7.1.4 Multiobjective optimization

When dealing with economic and environmental analyses a multiobjective optimization problem is faced, in which the economic cost and the environmental impact should be minimized. This problem usually does not have a single solution but a range of solutions with minimum economic cost for a certain environmental impact.

The solar fraction, the environmental cost of the system and the economic cost of the final energy produced have been obtained from a large number of cases with different design parameters of storage volume and solar collector field area. Each calculated case has been presented as a dot in a XY graph in which the value of X and Y are, respectively, the economic and the environmental results. The PEF of the heat produced by the system vs the economic cost is presented in Fig. 7.4. The Pareto front, group of solutions that are the local minimum results, is generated by the union of the designs with minimum volume (blue line) for low cost designs, and for very low environmental impact systems with critical volume (red line).

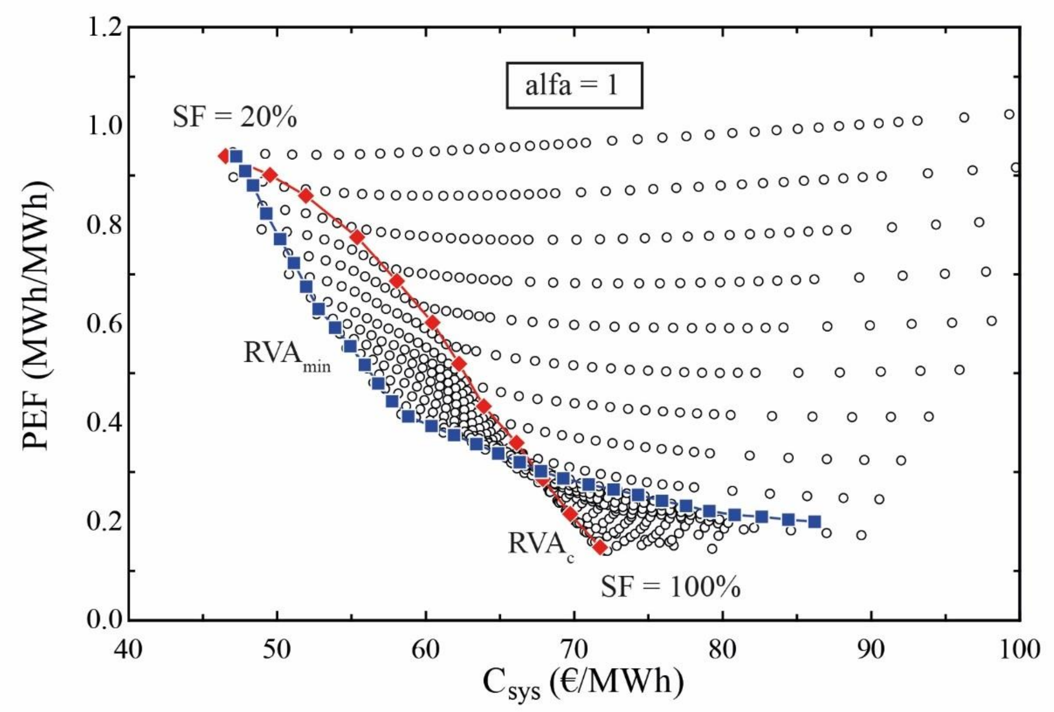

Figure 7.4: Multiobjective optimization: final heat cost vs primary energy factor

By comparing the GHG emissions against the economic cost a similar Pareto curve can be obtained (Fig. 7.5). According to the results, the cheapest result is a system with a heat cost of 50 €/MWh but with GHG emissions of 180 kg $CO_{2\text{-eq}}$/MWh. Systems with a solar fraction lower than 20% have not been considered. A system consuming only natural gas produces GHG emissions of 201 kg $CO_{2\text{-eq}}$/MWh (data from Chapter 6, Table 6.17). On the other hand, the most environmentally friendly option would be a 100% solar system with critical volume; GHG emissions of only 35 kg $CO_{2\text{-eq}}$/MWh with a heat cost of 72 €/MWh.

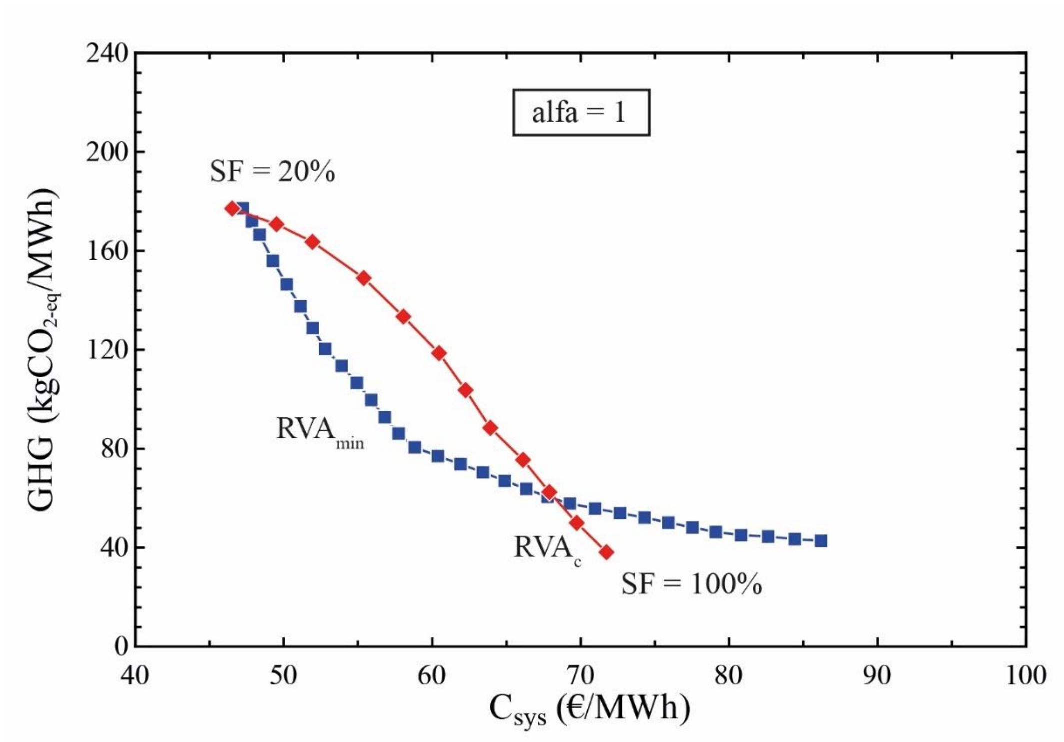

Figure 7.5: Multiobjective optimization: final heat cost vs GHG emissions

The annual cost and the annual emissions can be obtained by multiplying these results by the annual demand of thermal energy (5350 MWh/yr). Along the life cycle of 50 years a 100% solar system might reduce the GHG emissions by 44,405 tons of $CO_{2\text{-eq}}$ compared to a 100% natural gas system.

Several factors can change the intersection point in which critical volume designs become more cost effective than designs with minimum volume. If other technologies of seasonal storage are used, lower environmental impact and lower economic cost are achieved. For these scenarios, designs with critical volume will be cheaper than systems with minimum volume for a wider range of solutions. On the other hand, PTES, BTES and ATES require special underground conditions and cannot be applied anywhere. Currently pit thermal energy storage technologies have an investment cost half than hot water tanks ($\alpha = 1/2$). From TTES cases a correlation to estimate the cost as a function of the volume has been defined, see Eq. 2 and Fig. 5.5.

It is reasonable to consider that this reduction will also make the storage more environmentally friendly. Fig. 7.6 shows the multiobjective optimization results for a case in which environmental and economic cost of the storage have been reduced by half. In this scenario, systems with critical volume (red line) are more economic and environmentally friendly if a primary energy factor of 0.5 or lower can be applied.

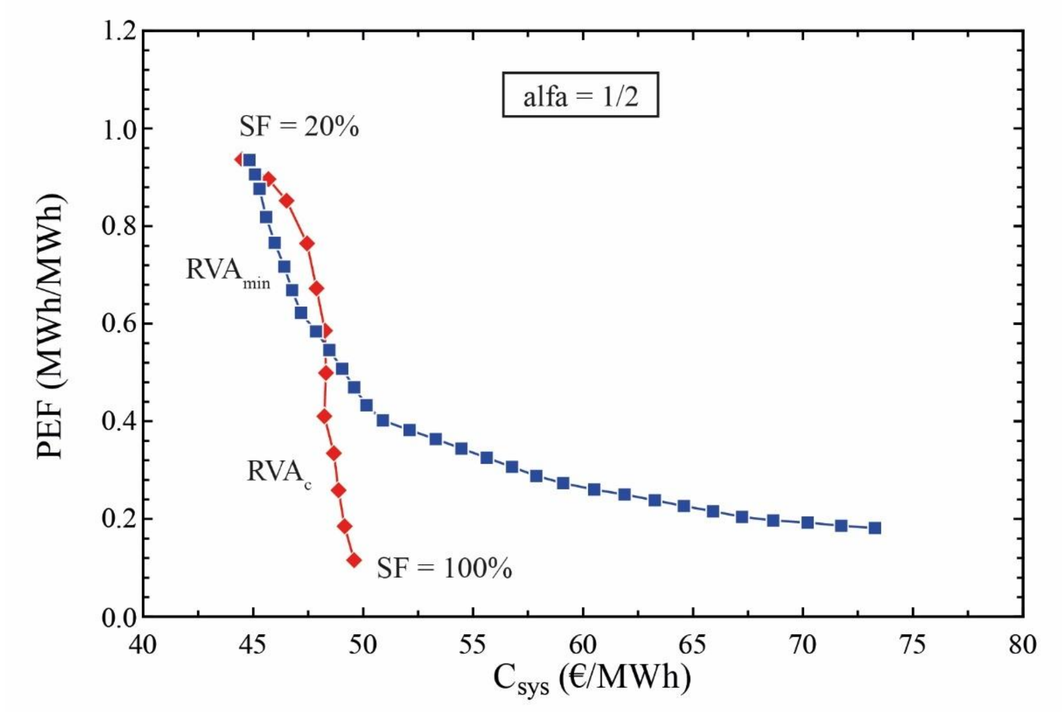

Figure 7.6: Multiobjective optimization: final heat cost vs primary energy factor when α = 0.5

CSHPSS for very large applications using pit thermal energy storage or other technologies that might reduce by half the economic and environmental cost of the storage might become an economic competitive solution compared to conventional energy source. Moreover, this technology produces fewer emissions to the atmosphere and requires only a small contribution from non-renewable energy sources. Considering a future scenario in which the price of fuels is rising this technology might become not only more environmentally friendly but also more economic than conventional technologies for long term application.

7.2 Extension of climatic and demand data

The *Simple Method* presented in Chapter 4 allows to predesign CSHPSS with simple climatic and demand data in Spain. To make this method extensible to any location, it is necessary to transform common climatic data into the input data required.

Key point is demand characterization. In Spain reference values of SH and DHW demand can be obtained for some specific cities but for other locations it has to be estimated using a method based on common climatic data.

7.2.1 Space heating

The annual demand of space heating for different locations in Europe depends not only on the climate but also on the characteristics of the buildings: geometry, average size and habits of consumption.

Werner proposed a method to estimate the SH demand for different locations in Europe according to the annual degree days to get a proper overview of the European heat market (Werner, 2006; Frederiksen and Werner, 2013). The European Heating Index (EHI) is the result of the analysis of the SH demand when thermal insulation has been applied properly.

Locations with more degree-days per year expend more resources to increase the efficiency of the buildings. Therefore, the EHI instead of being proportional to the degree-days is proportional to the square root of the degree days for a certain location based on the optimal thermal insulation. The EHI has been obtained by normalizing the square root of the degree-days to the European average degree days DD_{ave} = 2600 K·day.

$$EHI = 100 \cdot (DD / DD_{ave})^{1/2} \quad (1)$$

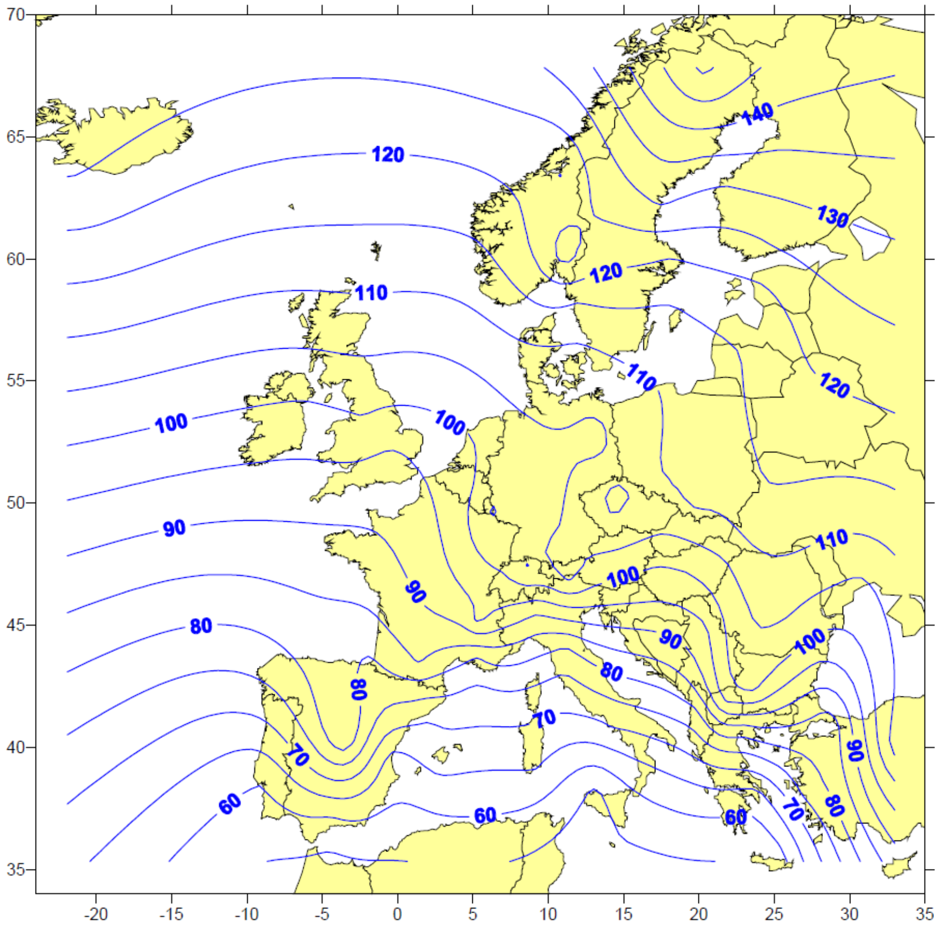

Figure 7.7: European heating index (EHI) contour map generated by 80 urban locations in Europe

The correlation between the actual residential heat demand and the EHI has been presented by Werner (2006). As can be seen in Fig. 7.8, the correlation presented is not perfect as it compares the consumption of electricity and heat with the EHI but it is an appropriate method to make a first estimation for space heating needs.

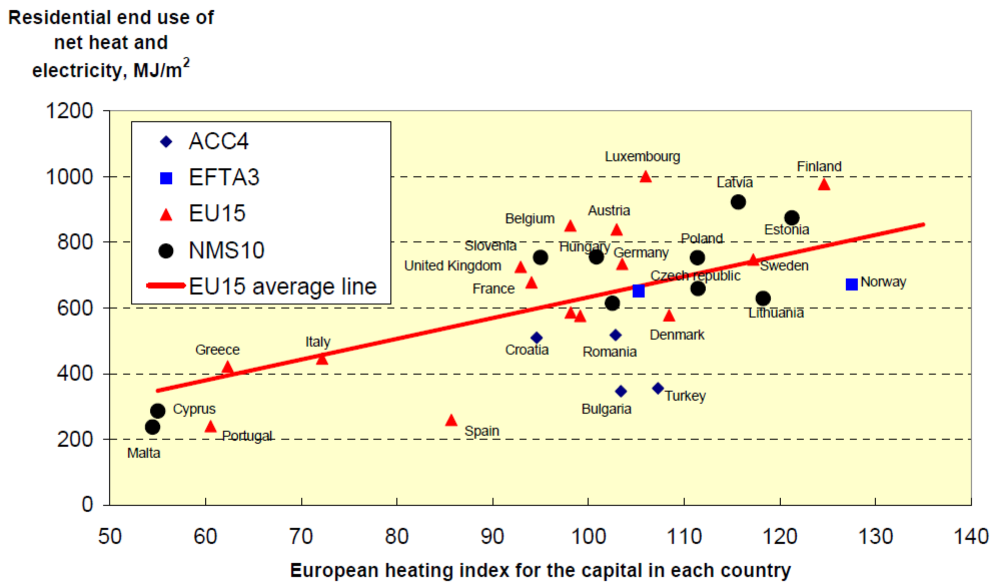

Figure 7.8: Residential net heat and electricity use during 2003 vs EHI (Werner, 2006)

Hereafter the EHI factor (Werner, 2006) is used. In Fig. 7.9 is shown (for eight locations in Europe) that the EHI can be calculated with degree-days obtained with the correlation of Erbs et al. (1983).

$$EHI_{calc} = 100 \cdot (DD_{18} /2600)^{0.5} \qquad (2)$$

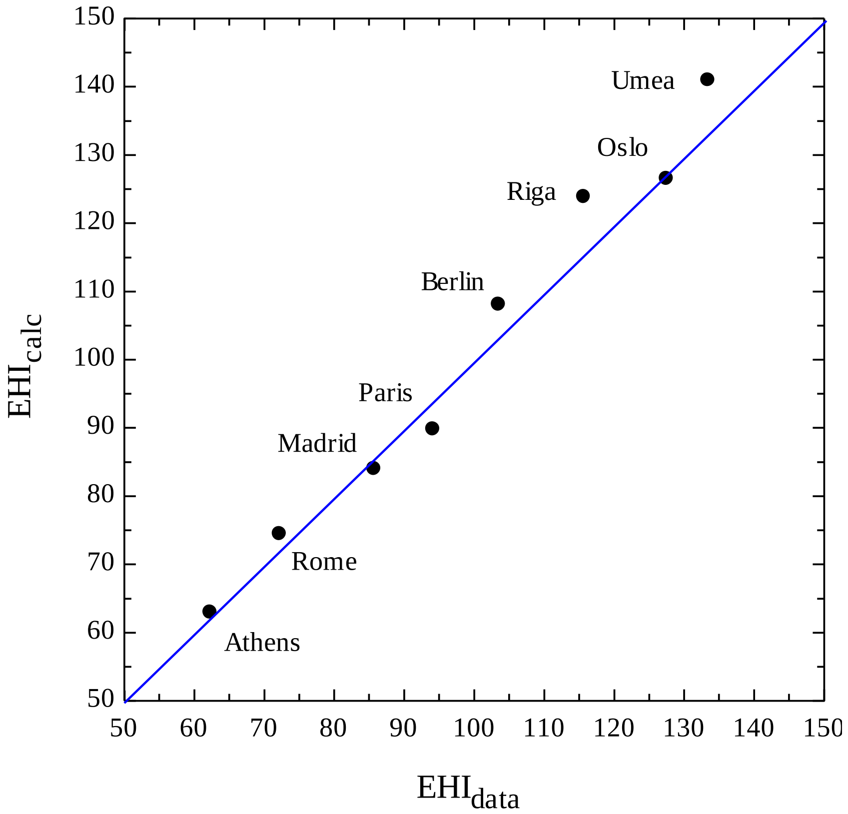

Figure 7.9: Validation of EHI correlation vs EHI from Werner (2006)

7.2.2 Domestic hot water

The demand of domestic hot water (DHW) in a house depends not only on the climate but also on the building occupation and habits of consumption. Estimations of the average demand of DHW can be done using reference values for different locations. The *Simple Method* presented in Chapter 4 uses the annual reference demand of DHW for multifamily buildings in Spain (IDAE, 2009). This factor depends on the location with a range from 12.0 to 14.0 kWh/m^2 but cannot be extended to other locations.

For a specific location, monthly DHW consumption can be estimated using the average daily consumption of hot water per person (DHW_{day}) multiplied by the average occupancy (o_{cc}), number of houses (N_{dwe}) and number of days (N). Correction factors based on the experience for monthly consumption can be included (CI_{DHW}). To calculate the energy required for DHW the hot water temperature (T_{DHW}) and the cold water temperature (T_{CW}) must be known.

$$Q_{DHW} = o_{cc} \cdot DHW_{day} \cdot N_{dwe} \cdot N \cdot CI_{DHW} \cdot (T_{DHW} - T_{CW}) \cdot \rho \cdot c_p \qquad (3)$$

Usually cold water supply temperature is not available in most data sources but based on the symmetry of ambient temperature and cold water supply temperature a correlation has been defined (see Fig. 7.10).

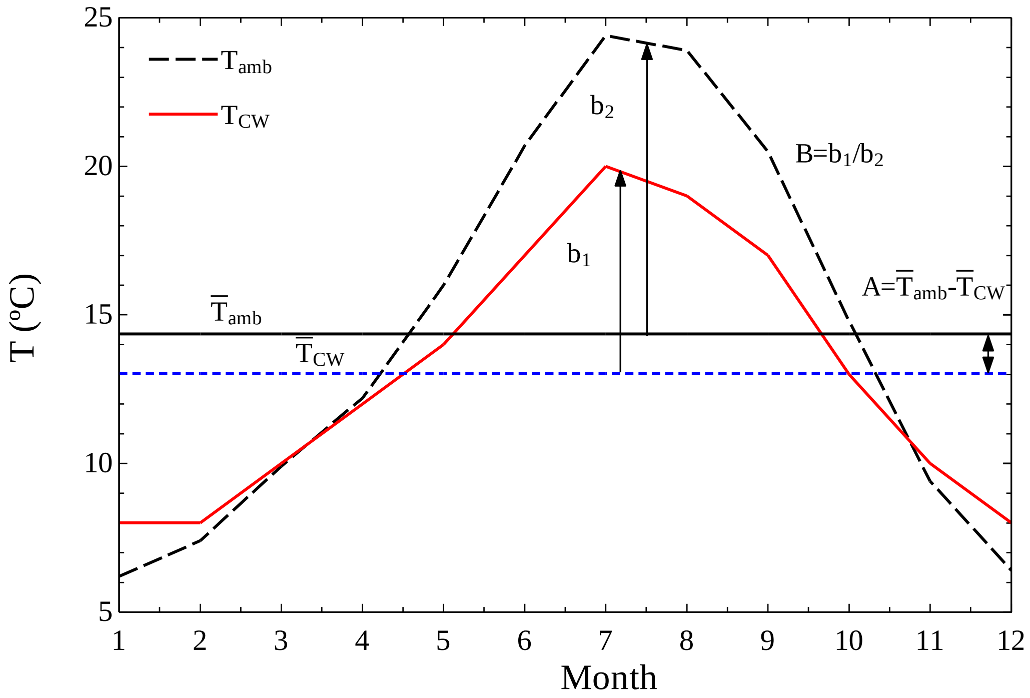

Figure 7.10: Cold water correlation developed based on the ambient temperature.

$$T_{CW} = Max\,(4;\, A + B \cdot T_a) \tag{4}$$

The coefficients of the correlation A and B have been adjusted with data from 12 cities in Spain. The limit of 4ºC has been included; when the ambient temperature is close to 0ºC and the water sources start to freeze, due to stratification effects water at 4ºC maximum density of liquid can be found at the bottom of lakes and rivers.

$$T_{CW} = Max\,(4;\, 10/3 + 2/3 \cdot T_a) \tag{5}$$

The cold water temperature obtained with Eq.5 is compared in Fig. 7.11 with the cold water temperature proposed by UNE 94.002 for 12 cities in Spain. The deviation observed is smaller than the accuracy of the data served by the climatic source (UNE 94.002, 2005).

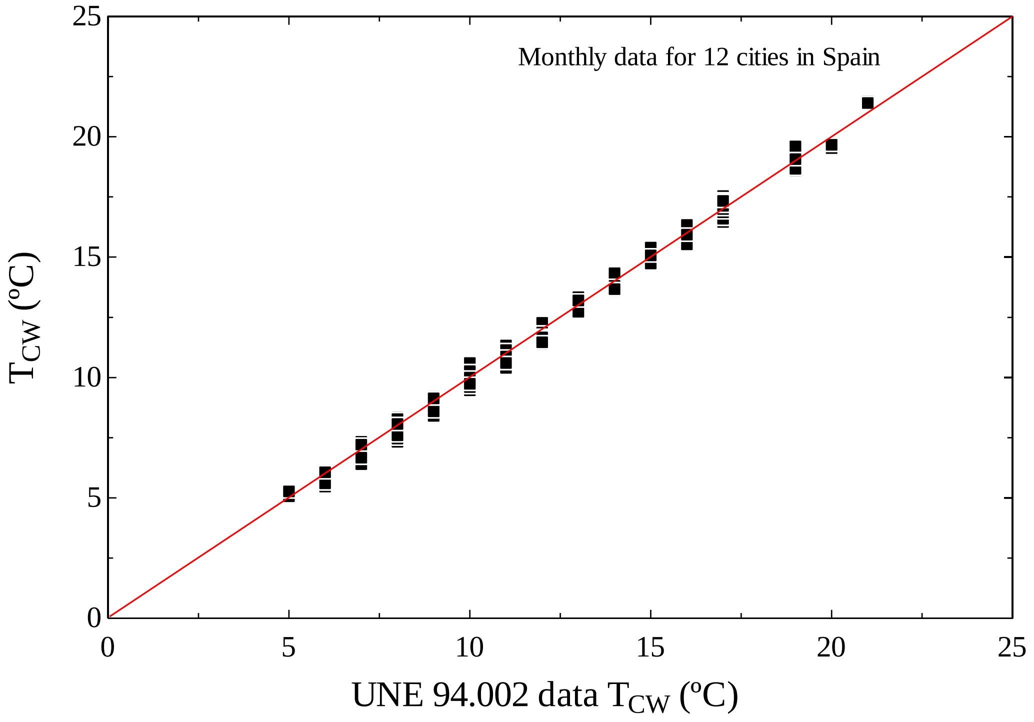

Figure 7.11: Validation of T_{CW} correlation with T_{CW} from UNE 94,002 (2005) for Spain

The consumption is not uniform along the year. Usually the consumption is lower in summer but in specific locations (summer houses) it can be much higher. The consumption index (CI_{DHW}) corrects the monthly consumption of DHW to the monthly habits. An example of the seasonal variation of the relative flow demand for domestic hot water in multi-dwelling buildings in Sweden is shown in Fig. 7.12. Monthly averages are compared to the annual average hot water flow demand (equal to 1 in the figure).

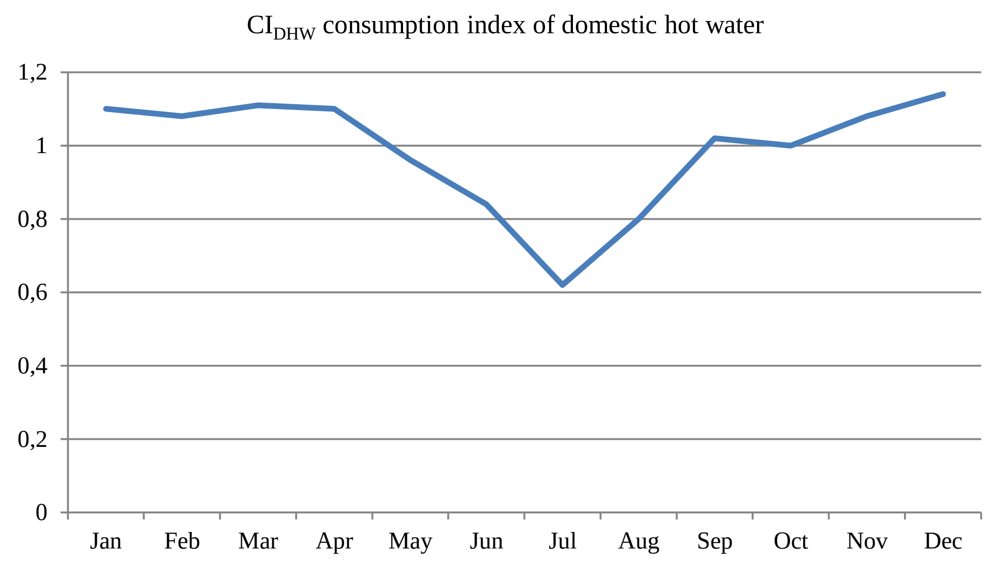

Figure 7.12: Monthly consumption index for domestic hot water (Frederiksen and Werner, 2013)

7.2.3 Example of application

For a community of 1000 dwellings in Madrid in this example the demand data required by the *Simple Method* will be determined using the climatic data of Table 7.1, extracted from Meteonorm (2014).

Table 7.1: Climatic data of Madrid (Meteonorm, 2014)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
$\bar{H}$ (MJ/m^2/day)	7.1	10.5	15.6	19.4	22.6	26.5	26.6	23.3	17.8	11.3	7.9	5.7	16.2
Ta_{min} (ºC)	2.4	3.5	6.4	8.1	12.4	17.6	20.0	19.6	15.4	11.4	5.7	2.8	10.5
Ta_{ave} (ºC)	5.9	7.7	11.0	13.3	17.8	24.2	26.4	25.8	21.3	15.6	9.5	6.2	15.4
Ta_{max} (ºC)	10.3	12.6	16.2	18.3	23.2	29.9	32.7	32.1	26.8	20.6	14	10.5	20.6

The space heating demand in Madrid for multifamily buildings is 43.2 kWh/(m^2 · yr) (IDAE, 2009). For a community of 1000 dwellings of 100 m^2, the annual demand of space heating is Q_{SH} = 4320 MWh/yr.

The demand of thermal energy for SH in Madrid is distributed monthly according to the degree-days method presented in the *Simple Method*. If degree-days data are not available, as in this case, Erbs correlation for degree-days can be used. In this example degree-days in base 18 have been obtained. Results are presented in Table 7.2.

To estimate the consumption of DHW, average EU-25 conditions have been considered: household of 100 m^2 and occupation of 2.5 people per household. With an average consumption of DHW_{ave} = 30 l/(person·day) of hot water at 60ºC (T_{DHW}), the daily consumption is DHW_{day} = 75 m^3/day. This daily consumption of DHW has been monthly adjusted following the consumption index presented in Fig. 7.12. Using the cold water correlation proposed (Eq. 5) the energy required per month has been calculated.

Table 7.2: Climatic and demand data generated for Madrid

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
DD_{18} (K·day)	376	290	223	152	54	3	1	1	13	99	259	367	1838
Q_{SH} (MWh)	894	688	529	361	128	0	0	0	0	235	613	872	4320
T_{CW} (ºC)	7.3	8.5	10.7	12.2	15.2	19.5	20.9	20.5	17.5	13.7	9.7	7.5	---
Q_{DHW} (MWh)	159	138	150	139	118	90	66	86	115	127	144	164	1495

The space heating demand obtained is used as reference to calculate the space heating demand in other locations, using the EHI as proportional factor. The EHI in Madrid is 85.7 and in Berlin 103.5 therefore, the annual demand for a same size community in Berlin is 5217 MWh/yr.

7.3 Software Application for CSHPSS

The simulation of CSHPSS during the year is a complex process requiring detailed climatic and demand data in order to properly design/size the plant components to reach the desired solar fraction. The utilization of simple methods for the calculation of these plants allows the sizing of the main components and provides an estimation of the system performance during the year, using easy to find climatic and demand data. In this section a software based on the *Simple Method* is presented to perform predesign analyses for different locations in Europe.

The software provides a pre-design of the CSHPSS main components and can be used to perform preliminary economic and environmental analyses. The software application is a distributable program elaborated with Engineering Equation Software. EES (2013) is a general equation solver that can numerically solve thousands of coupled non-linear algebraic and differential equations. The distributable program created solves the system of equations elaborated in Chapter 4, performs economic analysis based on Chapter 5 results and environmental analysis based on the simplified impact assessment presented in Chapter 6. This software can be used to pre-design a new CSHPSS, estimate the thermal performance and calculate the investment required or the environmental impact.

Data corresponding to several cities from Europe have been initially included in the application (Aberdeen, Amsterdam, Ankara, Athens, Barcelona, Belgrade, Berlin, Bordeaux, Bratislava, Brno, Brussels, Budapest, Cagliari, Chisinau, Copenhagen, Debrecen, Dublin, Firenze, Frankfurt, Grenoble, Göteborg, Hamburg, Helsinki, Innsbruck, Izmir, Kiev, Krakow, Lisbon, London, Lyon, Madrid, Manchester, Marseille, Milano, Minsk, Nantes, Napoli, Odessa, Oslo, Oulu, Palermo, Paris, Porto, Riga, Roma, San Sebastian, Skopje, Sofia, Stockholm, Strasburg, Tallinn, Tirana, Toulouse, Trondheim, Umea, Valencia, Varna, Warszawa, Wien, Zagreb, Zaragoza and Zürich) but more locations can be added by the user.

The application uses the simple method calculation process: 1) elaborates the climatic and demand data, 2) estimates the hourly performance of the solar collector field on a typical day each month, 3) determines system monthly performance, and 4) obtains the annual performance and the economic and environmental results.

The size of the community (number of dwellings) and the design ratios for the solar collector area (RAD) and for the thermal energy storage (RVA) are primary user defined parameters, but secondary coefficients can also be adjusted e.g. solar collector curve, heat exchanger effectiveness or seasonal storage heat transfer coefficient.

Furthermore, the application calculates the annual economic result of the system. Some economic parameters can be adjusted, as the interest rate applied or the price of the gas consumed. An environmental assessment is also carried out by the software. The environmental parameters that have a bigger variation among the European countries, environmental impact of electricity and natural gas, can be adjusted by the user.

In summary, the software developed can be used to pre-size the solar field and the volume of the seasonal thermal energy storage for a CSHPSS using specific climatic and demand data for each location. The software provides thermal performance results but also economic and environmental results of the system such as the solar heat cost or the environmental impact of the internal energy flows.

Results can be obtained using only the main interface window. This is useful for an initial evaluation in an early stage of a project, contributing also to establish optimization and design criteria from the initial moment. To obtain more detailed results and to adjust secondary parameters the software has five more interface windows.

7.3.1 Main window

The main window of the software, shown in Fig. 7.13, presents the primary design variables of a CSHPSS as well as the main results of the system in 6 blocks.

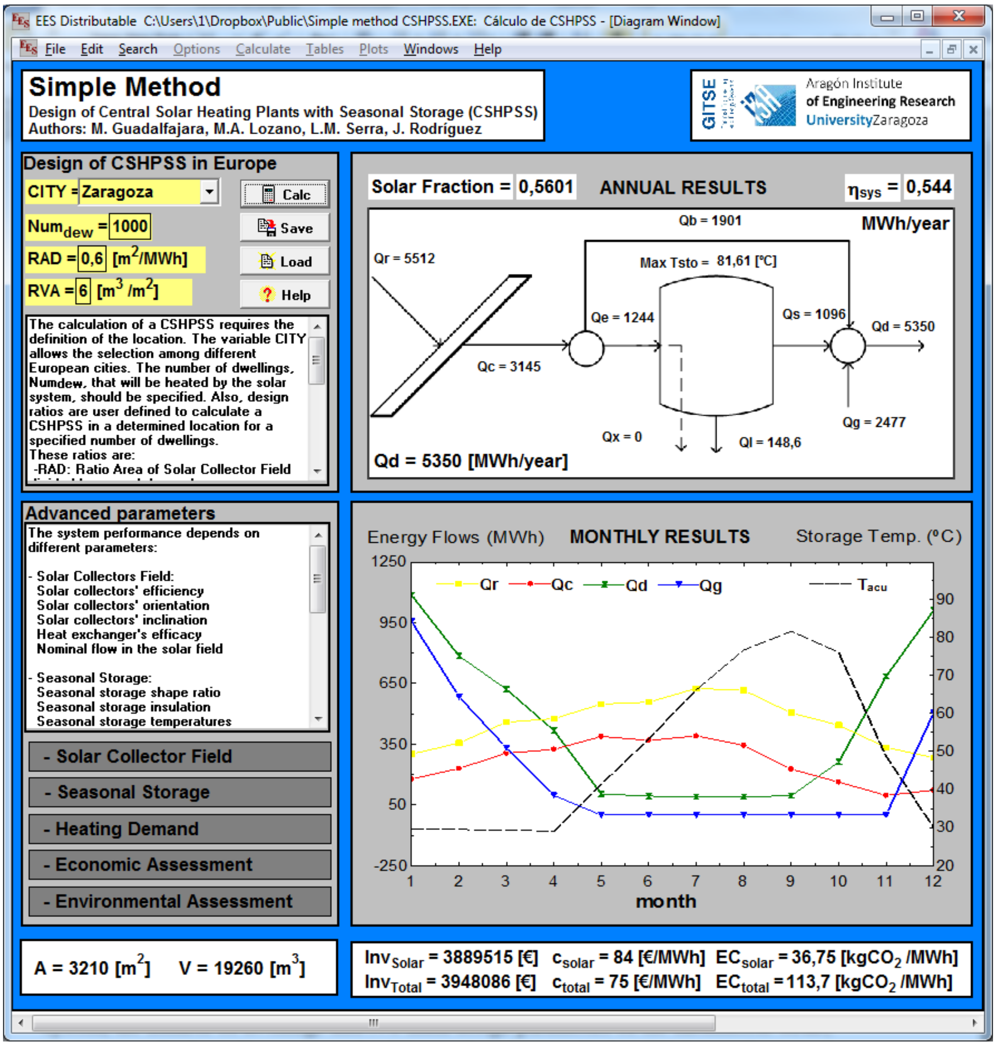

Figure 7.13: Main window of the developed software

In the block on the left and top, the user selects the system location, the number of dwellings and two main design parameters: RAD, Ratio Area of solar collector per unit of Demand, and RVA, Ratio of Volume of seasonal thermal energy storage per Area of solar collector. For each location the application uses the following climatic data: latitude; monthly daily average horizontal radiation; minimum, average and maximum temperatures of a typical day each month; and the European Heating Index. It is possible to add user defined locations, by selecting the option “New City” and introducing the corresponding climatic and demand data.

Some limitations should be taken into account when using the application. The number of dwellings should be limited between 100 and 10,000. Regarding the RAD, its value usually stays in a range between 0.2 and 5 m^2/(MWh/yr); and in the case of RVA, the recommended interval is 0.5 to 10 m^3/m^2. Each design generated can be calculated pressing the button “Calc”. Further it can be saved and loaded for future evaluations.

On the right side a diagram of the CSHPSS presents the annual results including the internal energy flows, the system efficiency, the solar fraction achieved and the maximum temperature reached at the seasonal storage. These results can be used to obtain a general idea of the system designed. Other windows of the software can be accessed from the main window: Solar Collector Field, Seasonal Storage, Heating Demand, Economics Assessment and Environmental Assessment.

The monthly results for the main energy flows are depicted bellow on the right side: incident solar radiation Q_r, solar heat collected Q_c, heating demand Q_d, auxiliary energy required Q_g; and seasonal storage temperature T_{acu}. The main sizing results are shown at the bottom, i.e. solar collector area A and seasonal storage volume V. Furthermore, at the bottom the investment required, cost of thermal energy and emission of GHG per unit of heat produced are presented.

Results obtained for a system located in Zaragoza (Spain) of 1000 dwellings with design ratios RAD = 0.6 m^2/(MWh/yr) and RVA = 6 m^3/m^2 are shown in Fig. 7.13. It can be noticed that the seasonal storage reaches a maximum temperature of 81.6ºC which is lower than the maximum temperature permitted, indicating that the seasonal storage is oversized.

Calculating with RVA = 4 the storage reaches the maximum temperature but the system has to reject part of the production in summer, Q_x = 122 MWh/yr. Following an iterative process, the ratio RVA that accumulates all the summer production without heat rejection and reaching the maximum temperature can be obtained.

7.3.2 Solar Collector Field

The features of the solar collector field can be adjusted by the user in a specific window. The performance coefficients of a commercial large flat plate solar collector (Arcon HT-SA 28/10) are implemented by default in the software and are shown in this window, but specific user defined values can be used. The solar collectors are considered by default oriented to the south (North hemisphere) and tilted with an inclination equal to the latitude, but deviations from this orientation and inclination can be used. The ground reflectance considered by default is 0.2.

The specific heat capacity and density of the solar field fluid and the solar field flow per area of solar collector can also be adjusted. It is considered a heat exchanger between the primary loop and the secondary loop feeding the seasonal storage tank, whose effectiveness can also be user defined. By default, water is considered as the working fluid in the solar field with a specific flow of 20 (kg/h)/m^2 and the heat exchanger effectiveness is 90%.

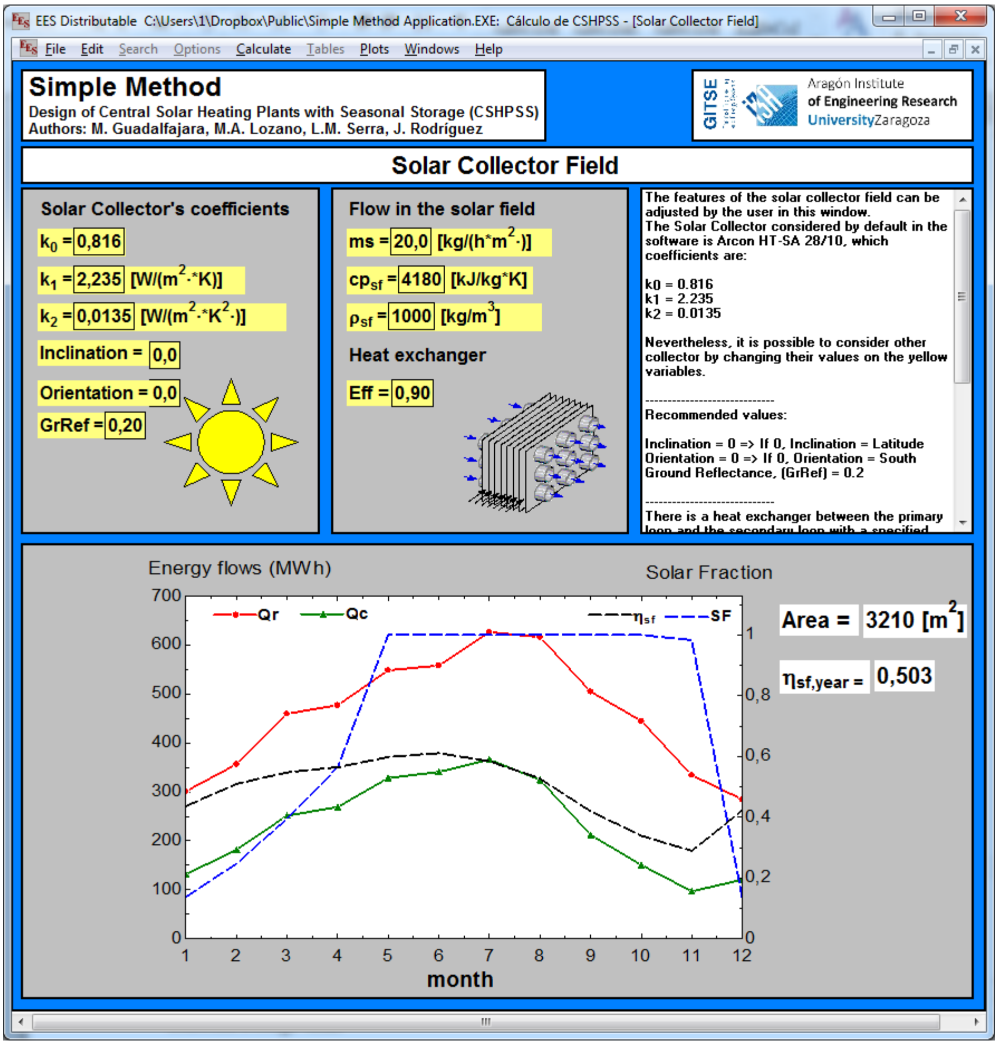

Figure 7.14: Solar collector field window

The monthly performance of the solar collector field is shown in a chart in which the incident solar radiation Q_r, solar heat collected Q_c, solar collector field efficiency η_{sf}, and solar fraction SF, are depicted. For the analyzed case, the solar collector field has a monthly efficiency between 30% and 60% (see Fig. 7.14). Note that the efficiency of the solar collectors is lower at the end of the charging season due to the high temperature in the seasonal storage tank.

7.3.3 Seasonal Storage

The seasonal thermal energy storage considered is a hot water tank. Its volume has already been determined with the design parameters RAD and RVA in the main window. More specific parameters of the thermal energy storage are set in this window.

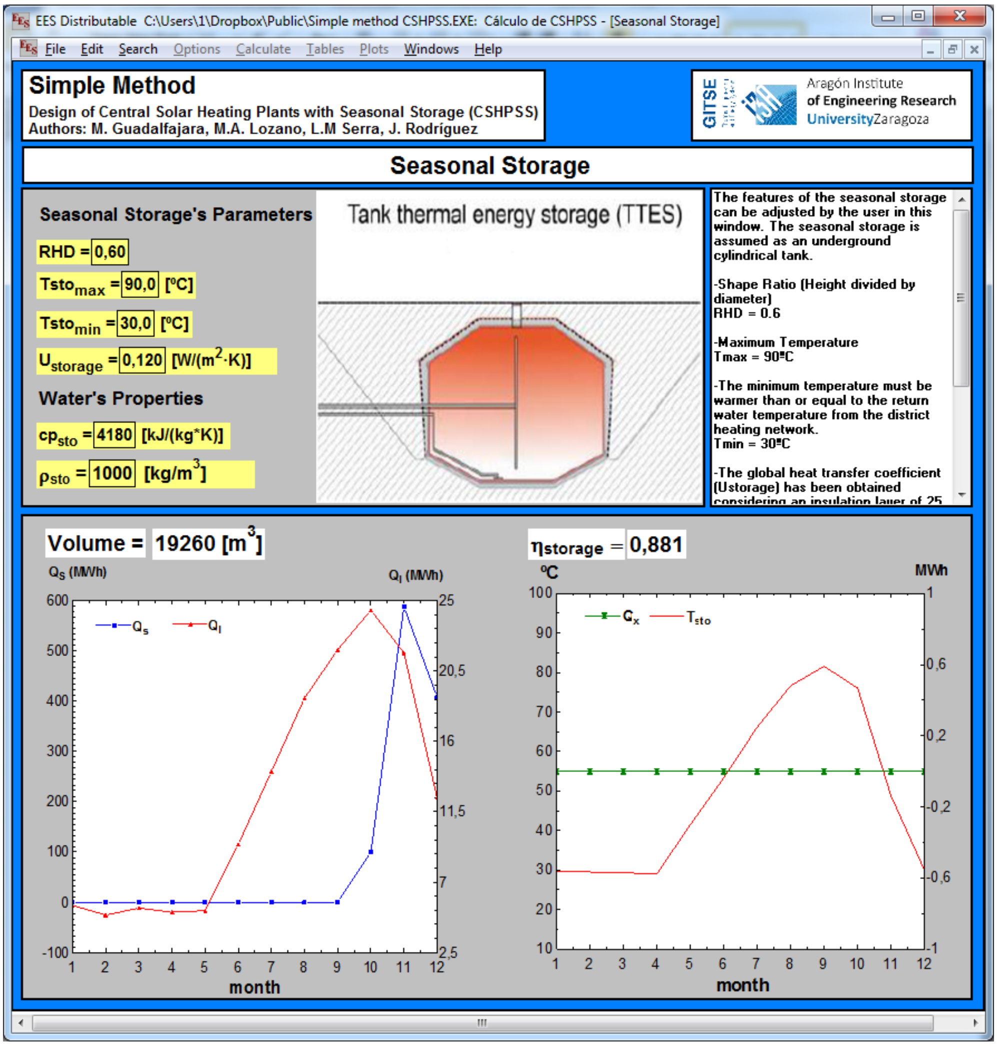

Figure 7.15: Seasonal storage window

The shape of the thermal energy storage affects the thermal energy transferred to the ambient. A cylindrical thermal energy storage tank is considered and the aspect of the tank (height divided by diameter) can be selected. By default, the minimum seasonal storage temperature is 30ºC, as it is considered a low temperature district heating system with return temperature 30ºC, but other minimum temperature values can be given if the designer considers different design restrictions. Similarly, the maximum default storage temperature considered is 90ºC but different maximum temperature values can be set.

The seasonal thermal energy storage tank has thermal losses to the environment through the storage envelope. The heat transfer coefficient considered is 0.12 W/(m^2·K) but other values can be selected by the user. Further, the substance considered by default for thermal energy storage is water. However, different substances, e.g. soil or gravel-water mixtures can be considered by implementing the corresponding heat capacity and density of the considered substance (Guadalfajara et al., 2014f). On the lower part of the window (see Fig. 7.15) the main energy flows of the seasonal thermal energy storage are presented: thermal losses Q_l, heat discharged Q_s, and heat rejected when the storage tank is fully charged Q_x. The seasonal storage tank temperature is also shown.

7.3.4 Heating Demand

The heating demand is calculated according to the number of dwellings, the dwelling size, and the average consumption of thermal energy per square meter. The size of the dwelling is 100 m^2 but it can be adjusted by the user as a design parameter, as shown in Fig. 7.16.

The annual space heating demand is 43.2 kWh/m^2 for Madrid (Spain). Space heating demand for other locations in Europe has been obtained applying the European Heating Index. The space heating demand is distributed monthly according to the degree-days method. Erbs et al. (1983) correlation for degree-days is used to calculate monthly degree-days, and the user can select the base temperature (more details about the method applied are given in Section 7.1). The user can modify the distribution of the thermal energy demand by changing the base temperature. Typical values used are 18ºC for regular buildings and 15ºC for efficient buildings, but other user defined values can be applied.

The consumption of thermal energy for the production of DHW depends on the size of the community, average consumption of hot water, occupation of the houses and temperature difference between supply water and hot water demand temperature, 60ºC. An average consumption of 30 l/(person·day) and an occupancy of 40 m^2 per person are considered, but they can be adjusted by the user.

In the lower part of the window the monthly distribution of the DHW demand $Q_{d,DHW}$, space heating demand $Q_{d,SH}$ and the total heating demand Q_d, as well as the average ambient temperature are shown.

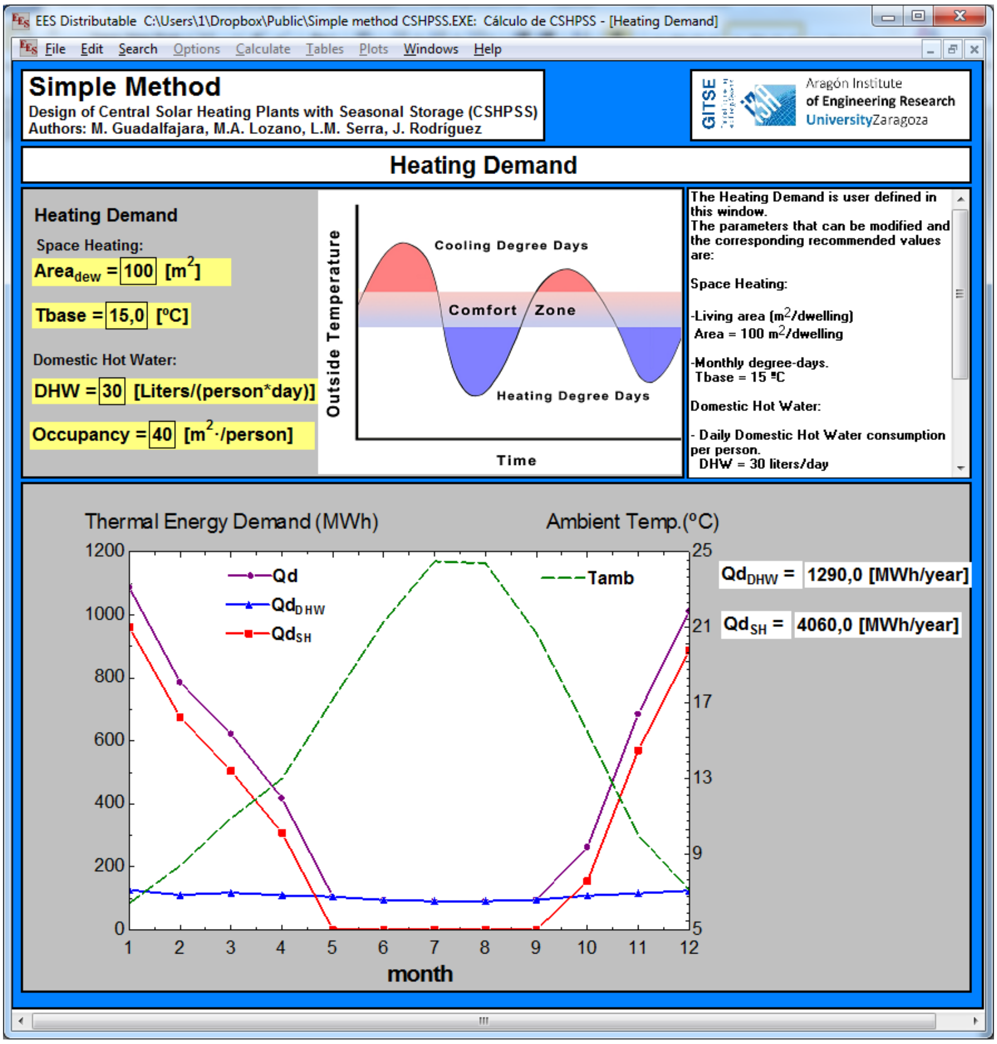

Figure 7.16: Heating demand window

7.3.5 Economic Assessment

The economic evaluation method presented in Chapter 5 has been implemented in the software. The price of the electricity and the auxiliary energy source for heating are input values through the user interface (see Fig. 7.17), as well as the efficiency of the auxiliary boilers that can be given by the user. The investment needed is calculated taking as base Eqs. 6 and 7.

$$Inv_{coll} = 740 \cdot A^{\,0.860} \qquad (6)$$

$$Inv_{acu} = \alpha \cdot 4660 \cdot V^{\,0.615} \qquad (7)$$

The parameter α included as input data in the user interface is proposed to consider the economic costs of different technologies of thermal energy storage or the expected future price reduction associated with the technology development, already explained in Chapter 5. The value α = 1 corresponds with the experience gained in the demonstration projects of the two last decades using a hot water tank for seasonal storage.

The amortization factor is calculated with 3% annual interest rate (i = 0.030 yr^{-1}), which is an input value for the software. The amortization costs are distributed along the equipment lifetime (25 years for the solar collector and 50 years for the seasonal storage). The annual operation and maintenance costs are estimated to be 1.5% (f_{ope} = 0.015 yr^{-1}) of the investment cost, where the electricity cost c_{ele} = 166.5 €/MWh with the electricity consumption estimated in Chapter 6 for the solar field E_{psf} and the discharging process E_{pdh}.

$$c_{sol} = (75 \cdot A^{0.860} + \alpha \cdot 352 \cdot V^{0.615} + c_{ele} \cdot (E_{psf} + E_{pdh})) / Q_{sol} \qquad (8)$$

In the example illustrating this section, Fig. 7.17, the auxiliary energy system consists of a gas boiler with an efficiency of 95%. Natural gas price is 58.3 €/MWh. The software estimates the CSHPSS investment required (with more detailed information for the main components –solar field and thermal energy storage), as well as the cost of the solar heat and the cost of the auxiliary heat. A sensitivity analysis is also presented in a chart considering different values of annual interest rate for the investment.

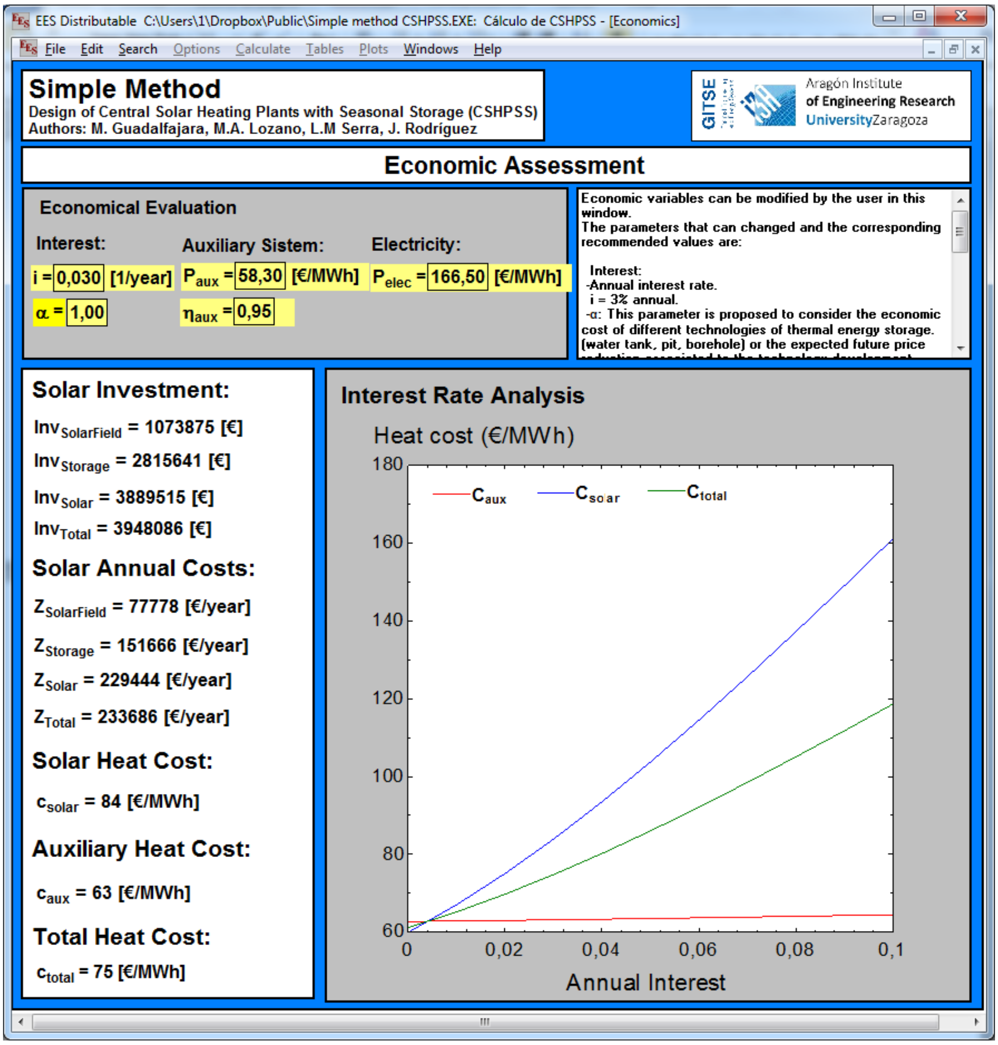

Figure 7.17: Economic assessment window

7.3.6 Environmental Assessment

There is also a specific window providing an environmental assessment of the analyzed CSHPSS system based on the Life Cycle Assessment (LCA) methodology presented in Chapter 6. The software provides the greenhouse gas emissions of the system expressed in kg of CO_2 equivalent per MWh of heat produced and the PEF expressed in MWh per MWh of heat produced. In both cases the software evaluates the greenhouse gas emissions and the primary energy consumption associated with equipment following the correlations proposed in Section 6.4

$$AEI_{scf} = A \cdot (4.07\ kg\ CO_{2eq}/yr;\ 0.0152\ MWh/yr) \quad (9)$$

$$AEI_{acu} = A_{acu} \cdot (18.59\ kg\ CO_{2eq}/yr;\ 0.0521\ MWh/yr) \quad (10)$$

Similar environmental impact can be considered for the installation of the equipment in different European locations.

The electricity consumption is estimated with the process described also in Chapter 6 and the environmental impact of the electricity can be adjusted by the user according to specific data. By default, the values implemented in the software are the Spanish conversion factors for the electricity and natural gas corresponding to the year 2011 (IDAE, 2012).

$$Ec_{sol} = (AEI_{acu} + AEI_{scf} + E_{Psf} \cdot Ec_E) / Q_{sol} \quad (11)$$

For a better understanding of the environmental results, at the bottom of the Environmental Assessment window (Fig. 7.18) two diagrams showing the emissions of GHG and the CED for the equipment and the internal energy flows are presented.

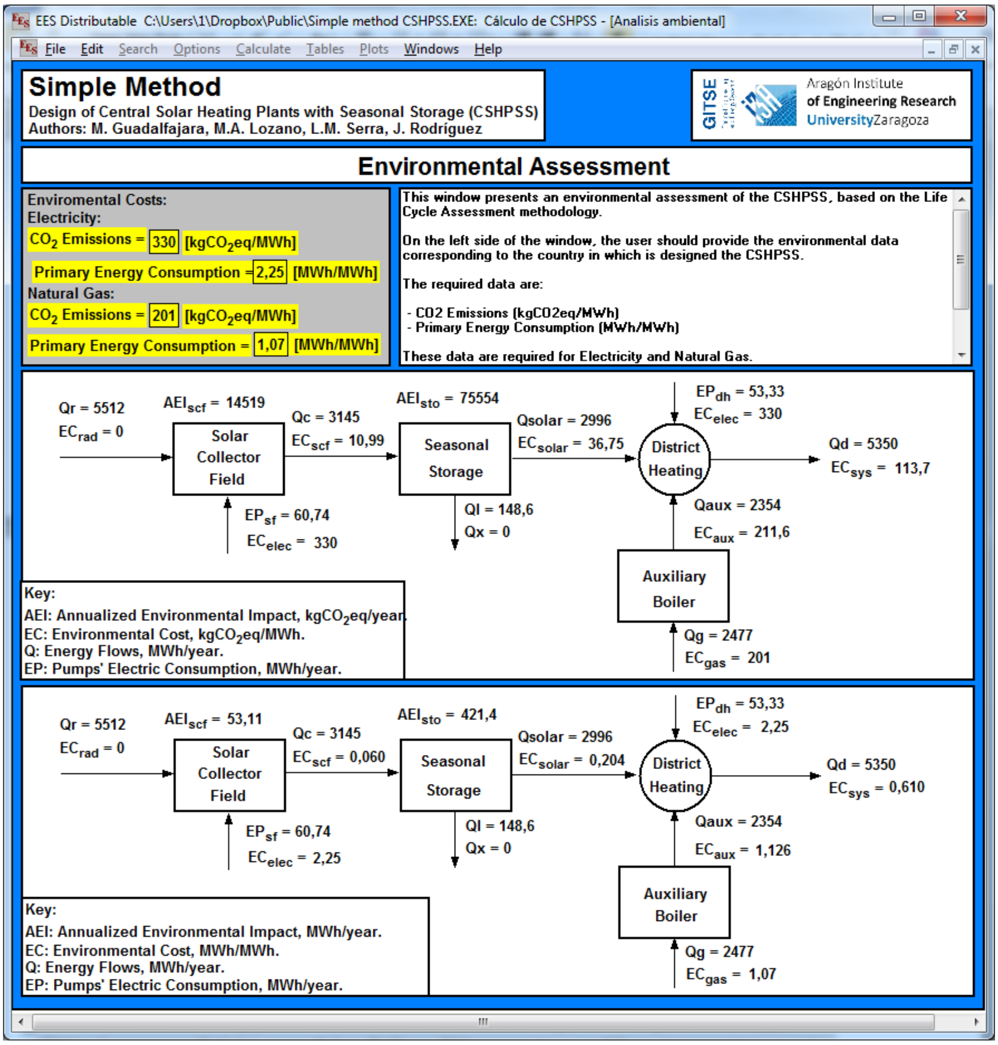

Figure 7.18: Environmental Assessment window

7.4 System design for different locations in Europe

The design of a CSHPSS is very much dependent on the geographic location. The annual radiation received determines the production of the solar collector field, and the severity and duration of the heating period determines the amount and distribution of the demand. With the software developed and presented in the previous section (Section 7.3), an equivalent case on different locations in Europe has been calculated.

7.4.1 Input data

The equivalent case is a community of 1000 dwellings which needs heat for SH and DHW from a CSHPSS with a solar fraction of 50%. The case is applied on eight locations in Europe (Athens, Rome, Madrid, Paris, Berlin, Riga, Oslo and Umea) that represent a wide range of climate conditions. Thus the design of the CSHPSS will be very different.

The climatic and demand data are obtained with the process presented in Section 7.2. The climatic data required ($\bar{H}$, Ta_{min}, Ta_{ave}, Ta_{max}) have been obtained from Meteonorm (2014) and the demand data has been generated according to the EHI and the degree-days method for its distribution. Climatic, demand and geographic input data are summarized in Table 7.3.

Table 7.3: Climatic and demand data estimated for eight locations in Europe

City	$\bar{H}$ MJ/(m²·day)	Lat. * º	T_a ºC	DD_{18} † K·day	EHI	Q_{DHW} MWh/yr	Q_{SH} ‡ MWh/yr	Q_d MWh/yr
Athens	17.7	38.0	18.7	1032	62.3	1424	3140	4564
Rome	15.7	41.9	16.7	1444	72.2	1466	3639	5106
Madrid	16.3	40.4	15.4	1838	85.7	1495	4320	5815
Paris	10.2	48.9	13.2	2099	94.1	1536	4743	6280
Berlin	10.3	52.5	1. 4	3039	103.5	1600	5217	6818
Riga	9.8	56.9	7.5	3993	115.7	1644	5832	7477
Oslo	8.7	59.9	6.9	4166	127.5	1657	6427	8084
Umea	8.8	63.8	4.0	5169	133.4	1688	6724	8413

* Lat.: Latitude of the location, degrees (º)

† DD_{18}: Degree-days generated in base 18 (Erbs et al., 1983) with monthly average ambient temperature (Meteonorm, 2014)

‡ Q_{SH}: Space heating demand proportional to the EHI and the reference value obtained for Madrid.

For each location solar collectors are tilted with latitude angle and monthly radiation on collectors is obtained with the isotropic sky model. The solar resource is abundant in south European locations (Athens, Madrid, Rome) along the whole year (see Fig. 7.19). High levels of radiation increase the production of thermal energy, locations with high radiation are very appropriate for solar thermal systems as their production is bigger along the year.

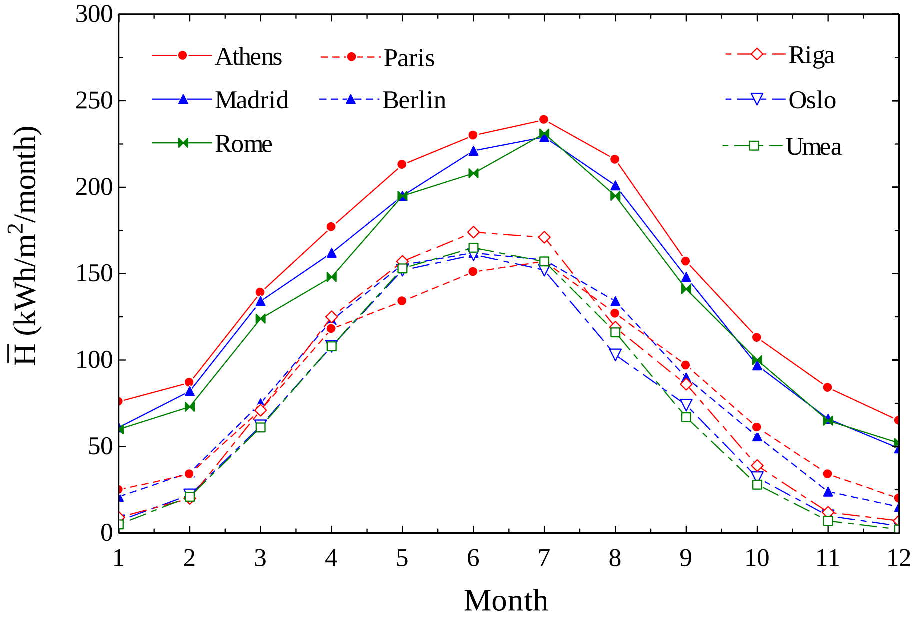

Figure 7.19: Daily horizontal radiation on different locations in Europe

Demand of thermal energy for SH and DHW is distributed monthly according to the method proposed. Distribution of SH demand depends on the monthly degree-days. Locations with cold climates have a long winter and in warm climates the winter might be shorter. Proximity to the sea also affects winter severity, being smoother close to seacoast.

The needs for DHW are quite similar for different climates. The monthly distribution and the consumption index applied in this analysis generate a lower demand of DHW in summer. The monthly demand of thermal energy required SH+DHW is presented in Table 7.4.

Table 7.4: Heating demand and its distribution

Q_d (MWh)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Athens	856	812	707	462	114	89	64	83	110	118	421	729	4564
Rome	997	816	664	428	115	91	67	86	114	258	565	906	5106
Madrid	1052	826	679	500	246	90	66	86	115	361	757	1036	5815
Paris	1023	868	806	545	314	97	73	94	243	464	741	1014	6280
Berlin	1084	916	873	577	310	184	74	96	306	561	792	1045	6818
Riga	1097	1009	950	623	382	233	124	176	377	634	833	1040	7477
Oslo	1125	1027	1008	706	455	264	170	221	416	701	880	1112	8084
Umea	1121	1046	1046	770	542	312	191	254	461	718	887	1066	8413

The inherent relation among locations with high radiation and low heating demand is presented in Fig. 7.20. Cities in the north of Europe present higher demand and lower radiation while in the south of Europe radiation is higher and demand much lower. Big blue marks represent the cities used in the analysis and the other dots presented in the graph correspond to the 63 cities included in the software application developed.

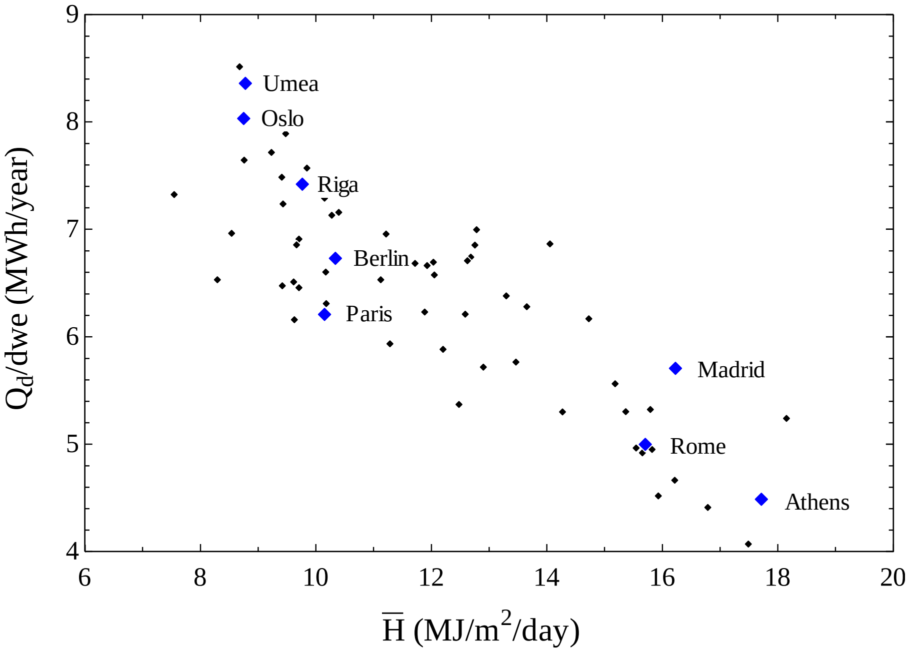

Figure 7.20: Annual demand of thermal energy vs annual radiation over horizontal surface

7.4.2 Design of CSHPSS for different locations

Designing and sizing the equipment of a CSHPSS system is very much dependent on its geographic location. For each of the eight locations selected a specific CSHPSS installation that reaches a solar fraction of 50% and has a seasonal storage with critical volume has been designed.

The critical volume is the volume of the storage that does not reject any fraction of the solar heat collected ($Q_x = 0$) and has a maximum usage of the installed accumulation capacity, which means that the tank should be fully charged at the end of the charging period (Section 5.3). The software application has been used to size the solar field and the volume of the seasonal storage with an iterative process. Designs obtained with solar fraction close to 50% (± 0.5% allowed) and critical volume criterion are presented in Table 7.5.

Table 7.5: Climatic conditions, design parameters and results for different locations in Europe

	RAD m^2/(MWh/yr)	RVA m^3/m^2	A m^2	V m^3	Q_x MWh/yr	SF	η_{coll}^*	η_{acu}^*	η_{sys}^*
Athens	0.45	5.08	2054	10,434	0	49.7%	58.3%	87.0%	55.8%
Rome	0.52	4.85	2655	12,877	0	50.4%	56.7%	87.7%	54.2%
Madrid	0.49	4.84	2849	13,791	0	49.7%	58.4%	88.7%	56.1%
Paris	1.02	2.41	6405	15,437	0	49.9%	46.0%	88.0%	44.1%
Berlin	0.97	2.58	6613	17,062	0	50.0%	46.1%	87.8%	44.1%
Riga	1.19	2.41	8897	21,443	0	50.1%	41.3%	87.3%	39.1%
Oslo	1.39	1.75	11,237	19,665	0	49.9%	37.8%	86.8%	36.1%
Umea	1.10	1.37	9254	12,678	0	49.7%	41.9%	85.4%	40.5%

* η_{coll}, η_{acu} and η_{sys}: Efficiency ratios defined in Chapter 4.

From the obtained results for the European cities, that are representative of a wide variety of climates, a RAD between 0.45 and 1.4 (m^2/(MWh/yr)) is necessary to obtain a solar fraction of 50%. This ratio is higher in locations with low radiation and especially low in Athens, Rome and Madrid. Furthermore, cities located in the south of Europe require a higher RVA around 5 m^3/m^2 compared to the low ratios required in Paris, Berlin or Riga 2.5 m^3/m^2 or the even lower values in Oslo or Umea 1.5 m^3/m^2. Thus, high RVA ratios are needed in places where the production of solar energy is high and where the heat demand is concentrated in few months.

The efficiency of the system mainly depends on the efficiency of the solar field, which is higher in locations with high radiation and lower in locations with low radiation. For south European locations the overall efficiency η_{sys} remains around 55% and for north and center European locations values between 35% and 45% have been obtained. The disparity among efficiency ratios emphasizes the need for specific climatic and demand data when designing, even in preliminary studies.

From the cities selected in the south of Europe, Madrid might be a very appropriate location for a CSHPSS due to its high solar radiation and high demand of thermal energy along the year. For the center of Europe, Berlin or Paris might represent locations with considerably lower radiation but higher demand. The cold city of Oslo represents a location with very high demand of thermal energy and quite low solar radiation. The cities of Oslo, Berlin and Madrid represent three different climates in Europe with different design characteristics.

A more detailed analysis for these three cities has been performed and the results are depicted in Fig. 7.21, which represents the area of solar collectors and the volume of seasonal storage required to obtain a specified solar fraction. The volume of the seasonal storage has been chosen with the critical volume design criterion and the value of solar fraction obtained is presented next to the calculation points.

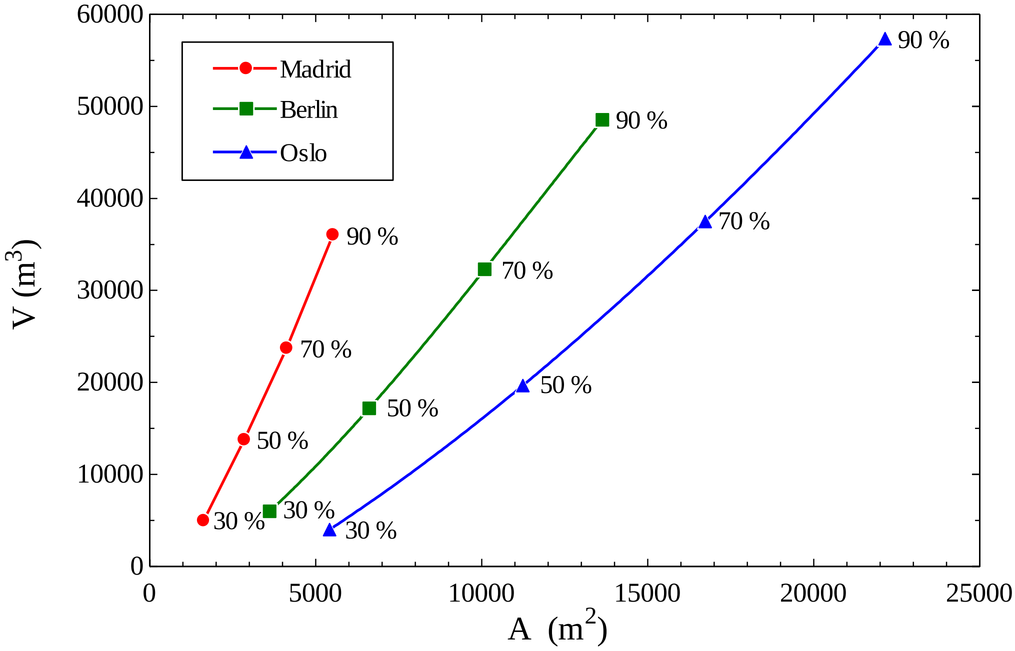

Figure 7.21: Design parameters for different solar fraction in different European climates

Relevant conclusions about the effect of the location on the design of these systems can be obtained from this graph. To obtain the same solar fraction a larger solar collector area is required in cold climates than in warm climates. In other words, with the same area of solar collectors per house in different climates very different solar fractions can be achieved. Moreover, the accumulation ratios RVA required are very different if we compare north, center and south European locations, being higher in southern European countries. Nevertheless, the required volume of the seasonal storage is bigger in center and north European locations.

7.4.3 Economic and environmental analysis

The economic and the environmental cost of the solar heat depend on the size of the main equipment (area of solar field and volume of the seasonal storage) and the production of thermal energy. For each location the design requirements to achieve a solar fraction of 50% are very different, therefore the cost of the solar heat and the environmental impact per unit of heat produced is very different.

The GHG emissions per unit of solar heat produced (kg $CO_{2\text{-eq}}$/MWh) versus solar heat cost (€/MWh) are shown in Fig. 7.22 for the eight locations. Madrid achieves the lowest economic and environmental cost due to its high radiation and demand. The other locations have higher cost and environmental impact; there is a proportional relation between environmental impact and cost.

Among the cities analyzed Umea is an interesting case as the solar heat cost is as low as south European locations, due to its uniform demand along the year and good production of thermal energy. Locations with favorable conditions for solar thermal energy can produce thermal energy with low cost and low environmental impact.

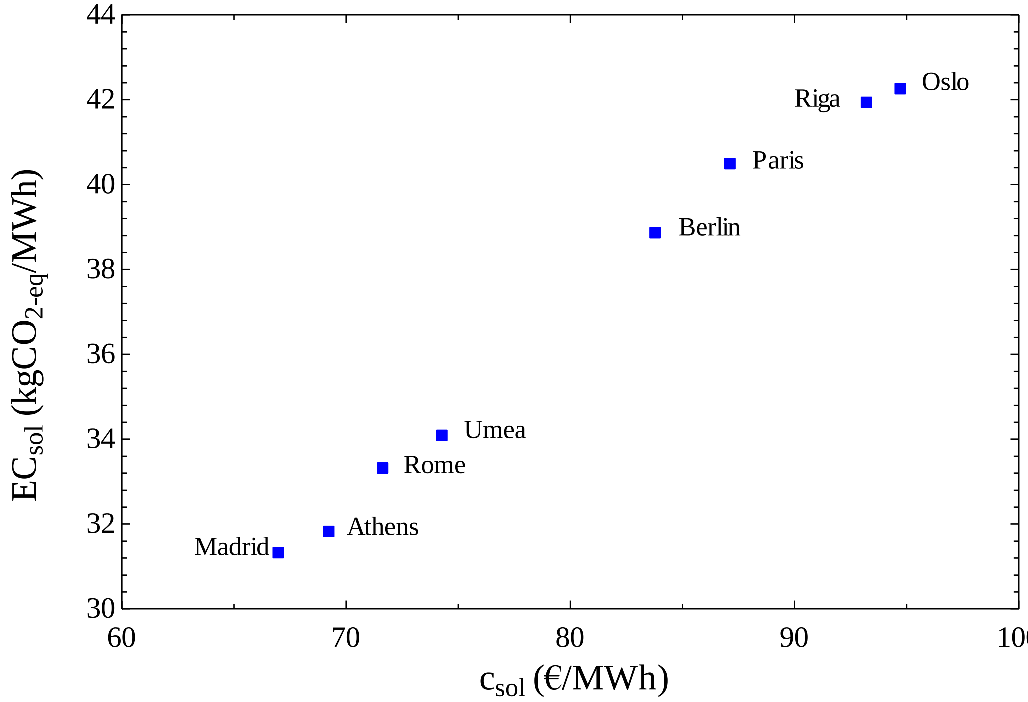

Figure 7.22: Economic and environmental cost of the solar heat produced in Europe

Chapter 8: Conclusions

8 Conclusions

8.1 Synthesis

Climate change, rising prices and scarcity of resources are triggering a switch to an energy model less dependent on non-renewable energy sources. In this scenario, buildings, which represent 40% of the European Union's final energy consumption, need to increase their efficiency and use of renewable energy sources. Thermal needs in buildings represent 70% of their energy consumption and solar thermal energy can play a very important role transforming solar radiation into heat for those demands.

Experiences in north and central European countries demonstrate that it is possible to supply an important share of the heating needs in buildings with solar thermal energy. Large solar collector fields are common in Denmark and other central European countries producing a small share of the district heating needs (less than 20%) with low cost and low environmental impact.

To achieve a higher solar fraction, the seasonal storage has been used to accumulate heat from the period of higher offer (summer) to the period of higher demand (winter). These systems are known as Central Solar Heating Plants with Seasonal Storage (CSHPSS). Demonstration projects of seasonal storage have been developed in Germany and Denmark since the 1980s but the economic viability of this technology has been questioned. Nevertheless, recently important cost reductions in thermal energy storages have been obtained.

The initial hypothesis of this thesis was that CSHPSS are appropriate in Spain from a technical, economic and environmental point of view. To prove this hypothesis, detailed analysis of the state of the art of the technology as well as simulation tools and design methods available, have been developed. This information is the base of the project and has been used to develop an original calculation method, *Simple Method*.

The economic viability of these plants has been determined by obtaining an economic characterization model based on the results from demonstration projects in Europe. The cost of the heat produced with a CSHPSS has been compared with the average price of other heat sources and the average price of district heating in Europe obtaining positive results. The environmental impact of CSHPSS has been analyzed with a well proved methodology, the Life Cycle Assessment (LCA) that considers the environmental burdens along the plant life cycle.

The results from this thesis prove that a CSHPSS might produce heat for big communities in Spain with an economic cost similar to conventional systems reducing considerably the environmental impact. To make the results from this thesis extensible, a software application has been developed. This tool can be used to pre-design CSHPSS systems evaluating its performance, economic cost and environmental impact for several locations in Spain and Europe.

8.1.1 Design of CSHPSS

The performance of a CSHPSS depends on the climatic and demand conditions. Compared to northern and central European countries, in Spain the availability of the solar resource is bigger and therefore the production of large solar fields will be also bigger. Moreover, the demand is different in intensity and duration. Many current design tools for CSHPSS do not consider different climatic and demand conditions and are not appropriate for south European climates.

An original calculation method for CSHPSS, called *Simple Method*, has been developed in this thesis to estimate the performance of such systems based on the physics of the equipment. The *Simple Method* reduces considerably the calculation effort compared to simulation tools and use simple and common climatic and demand data that can be easily obtained for any location. The method presented has been validated with simulation tools, as TRNSYS, and other simple design methods.

The new proposed *Simple Method* has been used to analyze the relation between the solar fraction and the CSHPSS design parameters: solar collector area and seasonal storage volume. Several combinations area-volume can produce the same solar fraction; therefore, a secondary design criterion should be applied.

The critical volume design criterion has been proposed in this thesis to optimise the size of the seasonal storage. This implies to follow the next premises: 1) do not reject any fraction of the solar heat collected, 2) maximize usage of the installed accumulation capacity. Applying critical volume design criterion, solar field area and solar fraction follow a nearly linear relationship. Accumulation requirements are low for low solar fractions but then rise strongly with the solar fraction. The functions that relate design parameters and solar fraction are different for each location and they cannot be extrapolated from northern to southern European climates. Detailed results of the critical volume design criterion have been presented in Section 5.3 and further results about the effect of climate on design parameters have been presented in Section 7.4.

8.1.2 Economic analysis

Based on the results from real plants operating in Europe, an economic model for CSHPSS has been presented in this thesis. The economic model estimates: 1) investment for a large solar collector field, 2) investment for a seasonal storage, 3) investment required for auxiliary equipment, 4) total investment for a CSHPSS, 5) annual amortization of the system and 6) cost of the heat produced by the system.

The capital investment function for large solar collector fields has been validated with several plants that are operating in Denmark. For the seasonal storage an original interpretation of the investment cost has been proposed that considers different seasonal storage technologies with equivalent economies of scale. The capital investment function obtained for CSHPSS has been validated with 15 real cases obtaining acceptable discrepancies.

The solar heat cost has been obtained from the annual amortization of the plant, the annual operation and maintenance costs and the annual production of thermal energy. For a community of 1000 dwellings in Zaragoza a CSHPSS with 50% solar fraction might produce heat at a cost of 72 €/MWh. The period of amortization and the interest rate applied for the investment are critical when determining the solar heat cost.

The seasonal storage and the solar field have important economies of scale, specially the seasonal storage because the storage cost depends on the envelope area. For small communities the cost of the seasonal storage becomes, proportionally, very high and only systems with small solar fraction, which do not require seasonal storage, are economically viable. For large communities (more than 1000 dwellings) systems with seasonal storage and high solar fraction become economically viable. Nevertheless, new technologies have been developed in recent years that reduce the cost of the seasonal storage by half or even further improving the economic result of the plant.

8.1.3 Environmental analysis

The standardized method LCA has been used in this thesis to evaluate the environmental impact of a CSHPSS. The plant analyzed is a case available in literature (Lozano et al., 2010c) that produces heat for a community of 500 dwellings in Zaragoza with 69% solar fraction. The environmental burdens have been determined for: 1) emission of greenhouse gases (GHG), 2) cumulative energy demand (CED), and 3) environmental indicator IMPACT 2002+.

A detailed inventory has been defined for the main components of the plant calculating the consumption of materials. The solar field and the seasonal storage consume most of the materials compared to the inventory of auxiliary equipment. The consumption of electricity for the operation of the plant is considered as well. The consumption of natural gas has been considered for the annual operation of the system.

The environmental impact of the plant has been determined for its operation period (50 years), considering the replacement of some equipment along the expected life and including the consumption of electricity and natural gas. Along this period the consumption of natural gas that will only cover 31% of the heating needs will produce most of the emissions. The main agent of the CSHPSS environmental impact is the seasonal storage. Further results are presented in tables and graphs in Chapter 6.

The environmental impact of the internal energy flows has been obtained. The solar field has quite low emissions of GHG 13 kg $CO_{2\text{-eq}}$/MWh. Nevertheless the seasonal storage increases considerably the impact to 57 kg $CO_{2\text{-eq}}$/MWh. These emissions are quite low compared to a natural gas boiler (210 kg $CO_{2\text{-eq}}$/MWh) but far from being negligible. Equivalent results have been obtained with the other evaluation methodologies (cumulative energy demand and environmental indicator IMPACT 2002+)

To make the analysis extensible to other plants a simplified impact assessment for CSHPSS has been defined. The function proposed considers the main design values to calculate the system impact assessment. This function has been used to design new systems with minimum environmental impact.

8.1.4 Software application

The design and performance evaluation of CSHPSS is a complex task and a challenge for urban planners, architects and engineers. A software tool has been developed as a final result of this thesis, and in the framework of the International Energy Agency Task 45 activities. The *Simple Method* software application is a user friendly feasibility tool oriented to perform preliminary analysis of CSHPSS, providing: 1) a quick analysis of the monthly and annual performance of a CSHPSS, 2) information to pre-design the size of the main plant components, and 3) economic feasibility and estimation of the environmental benefits, contributing also to establish optimization and design criteria of CSHPSS.

The tool has climatic and demand information for over 60 locations in Europe and a method has been presented in this thesis to introduce more locations. Detailed information of this tool has been presented in this thesis but user manuals and other documentation is available in Task 45 website (Task 45, 2015).

8.2 Contributions

The main contributions of this work are the following ones:

1) Revision of the state of the art of district heating systems, with emphasis to: i) solar district heating systems and CSHPSS, ii) design and calculation methods that could be used for new systems in Spain, iii) economic results from solar district heating systems and CSHPSS, and iv) environmental assessment methodologies and analysis performed for solar thermal components and systems.

2) Development of an original calculation method for CSHPSS, validation of the method proposed and identification of climatic and demand data sources for its application in Spain and, in addition, for European countries.

3) Economic and environmental characterization of CSHPSS for the whole life cycle using the LCA methodology for the environmental assessment. Development of evaluation methods based on the main design variables and validation of the evaluation methods proposed with results from real projects in north European countries. Analysis of the impacts generated and avoided by a CSHPSS under several evaluation methodologies: i) emission of greenhouse gases, ii) consumption of primary energy, and iii) environmental indicator IMPACT 2002+.

4) Definition of new design criteria for CSHPSS based on thermal, economic and environmental evaluations, considering local climatic and demand conditions and concluding that design ratios for north European countries can not be applied for south Europe. Analysis of the relation between solar fraction and the environmental and economic results under different design criteria for thermal energy storage.

5) Development of a software application to design CSHPSS in Europe that determines the thermal performance, economic cost and environmental impact with a friendly user interface. The sofware application is available online in IEA-SHC Task 45 website as reference design tool for CSHPSS and can be freely downloaded.

8.3 Future lines of research

Hereafter, four possible lines of research are proposed:

1) Construction of the first CSHPSS in Spain. With the results of this thesis new communities can evaluate the possibility of including a CSHPSS. The software tool developed can be used to predesign the installation, although further detailed design and engineering work should be done for the system construction. This plant will be used to adjust the design tool and to extract conclusiones about the real performance of these plants in south European climates.
2) Cost reduction for seasonal storage. Promising results have been obtained in Denmark and Canada in recent years but further improvements should be obtained in cost reduction. New seasonal storage designs should consume less material. A research in structural optimization and selection of materials might reduce the cost and the environmental impact of this key component.
3) Study of energy integration opportunities including: i) heat pumps to increase the potential of solar thermal energy and application of BTES and ATES, ii) cogeneration to produce heat and electricity, iii) absorption machines to produce cooling with solar thermal energy, iv) seasonal storage to accumulate thermal energy from other energy sources, and v) addition of other heating demands.
4) Evaluation of other renewable energy sources following the methodology proposed in this thesis for the economic and the environmental analysis.

Moreover, further research can be done in common problems for energy production systems in the residential sector. The lack of proper demand characterization methods always compromises the result of energy supply systems.

Demands of the residential sector should be properly defined, including average value, error and uncertainty. Data from buildings that are being monitored should be publicly available. In addition, characterization of district heating networks including consumption of electricity for operation and thermal losses to the environment can be improved.

CSHPSS can be an economically viable solution for new communities of 1000 dwellings or more in many Spanish locations. It is necessary to show this concept to urban planners, architects and investors to be considered as a design alternative in an early stage of a project. Nowadays, there is no other way to build a community with high solar fraction reducing the environmental impact and supplying heat at an affordable cost.

8 Conclusiones

8.1 Síntesis

El cambio climático, el aumento del precio de los combustibles y su próximo agotamiento está generando una evolución hacia un modelo energético menos dependiente de las fuentes de energía no renovables. En este marco, los edificios, cuyo consumo en la Unión Europea representa el 40% del consumo de energía final, necesitan mejorar su eficiencia y aumentar el uso que hacen de las fuentes de energía renovables. Las necesidades térmicas de los edificios representan el 70% de su consumo energético y la energía solar térmica podría jugar un rol muy importante transformando la radiación solar en calor para satisfacer estas demandas.

Experiencias en el norte y centro de Europa demuestran que es posible cubrir una parte importante de las necesidades térmicas en edificios con energía solar. Grandes campos de captadores solares térmicos son comunes en Dinamarca y en otros países centroeuropeos cubriendo una fracción de la demanda en sistemas de distrito (inferior al 20%) con bajo coste y poco impacto ambiental.

Para alcanzar una fracción solar mayor puede utilizarse el acumulador estacional capturando calor en los periodos de mayor oferta (verano) para emplearlo en los periodos de mayor demanda (invierno). Estos sistemas se denominan centrales solares térmicas con acumulación estacional (CSHPSS, por sus siglas en inglés). Proyectos de demostración de acumulación estacional se vienen desarrollando en Alemania, Dinamarca y otros países centroeuropeos desde los años 80, pero la viabilidad económica de esta tecnología ha sido cuestionada. Sin embargo, en los últimos años se han conseguido importantes reducciones en costes tanto en acumuladores como en el conjunto de la instalación.

La hipótesis inicial de esta tesis era que las CSHPSS son apropiadas para España desde un punto de vista técnico, económico y ambiental. Para probar estar hipótesis se ha estudiado el estado del arte de esta tecnología así como las herramientas de simulación y diseño disponibles. Esta información ha sido la base de este proyecto y se ha utilizado para desarrollar un método de cálculo original: *Método Simple*.

Para evaluar la viabilidad económica de estas plantas en España se ha generado un modelo económico a partir del resultado de plantas de demostración en Europa. El coste del calor producido por los sistemas diseñados se ha comparado con el precio de fuentes de calor alternativas y con el precio del calor en redes de calefacción de distrito en Europa, obteniéndose resultados positivos. El impacto ambiental de las instalaciones CSHPSS ha sido analizado con una metodología bien conocida, el Análisis de Ciclo de Vida (LCA por sus siglas en inglés) que considera los impactos a lo largo del ciclo de vida de la instalación.

Los resultados de esta tesis muestran que una CSHPSS podría producir calor para grandes comunidades en España con un coste económico similar a los sistemas convencionales y reduciendo considerablemente el impacto ambiental que generan. Para hacer extensibles los resultados de la tesis se ha desarrollado una aplicación de software. Esta aplicación de fácil uso puede ser empleada para pre-diseñar sistemas CSHPSS y evaluar su funcionamiento, coste económico e impacto ambiental.

8.1.1 Diseño de CSHPSS

El funcionamiento de una CSHPSS depende de las condiciones climáticas y de demanda. Comparado con las condiciones del norte y centro de Europa en España la disponibilidad del recurso solar es mucho mayor y por tanto la producción en los campos de captadores también lo es; además la demanda de energía térmica es diferente en su intensidad y distribución. Muchas herramientas de diseño actuales para CSHPSS no consideran el efecto de las diferentes condiciones climáticas y de demanda y, por tanto, no son apropiadas para la climatología del sur de Europa.

En esta tesis se ha desarrollado un método original de cálculo para CSHPSS, denominado *Método Simple*, para estimar el funcionamiento de estos sistemas en base a su comportamiento físico. El *Método Simple* reduce considerablemente el esfuerzo de cálculo en comparación con otras herramientas de simulación y usa datos climáticos y de demanda que pueden obtenerse fácilmente para cualquier localización. El método presentado se ha validado con herramientas como TRNSYS utilizadas para la simulación detallada de estos sistemas, así como con otros métodos de diseño.

El *Método Simple* se ha utilizado para analizar la relación entre la fracción solar y los principales parámetros de diseño de una CSHPSS: área de captadores solares y volumen del acumulador estacional. Varias combinaciones área-volumen pueden producir la misma fracción solar; por tanto, un segundo criterio de diseño debe ser aplicado.

Se ha propuesto en esta tesis el criterio de volumen crítico para definir el tamaño del acumulador estacional. Este criterio se basa en las siguientes premisas: 1) no rechazar ninguna fracción del calor captado, y 2) maximizar el uso de la capacidad instalada alcanzando la máxima temperatura del acumulador. Aplicando el criterio de volumen crítico, el área de captadores y la fracción solar siguen aproximadamente una relación lineal. Los requerimientos de acumulación son reducidos para una fracción solar baja pero aumentan considerablemente con la fracción solar. Las funciones que relacionan la fracción solar con los parámetros de diseño son diferentes para cada localización y no pueden ser extrapoladas del norte al sur de Europa. Resultados detallados del criterio de volumen crítico se han presentado en la sección 5.3 y más resultados sobre el efecto del clima en los parámetros de diseño se han mostrado en la sección 7.4.

8.1.2 Análisis económico

En base a resultados de plantas que están operando en Europa se ha definido un modelo económico para CSHPSS. El modelo económico estima: 1) la inversión necesaria para el campo solar, 2) inversión necesaria para el acumulador estacional, 3) inversión necesaria para el equipamiento auxiliar, 4) inversión total de la instalación, 5) coste anual del sistema, y 6) coste del calor producido por el sistema.

La función de costes para el campo de captadores se ha validado con datos de varias plantas operando en Dinamarca. Para estimar el coste de inversión del acumulador estacional se ha propuesto una correlación original que considera diferentes tecnologías de acumulación, bajo la hipótesis de idénticas economías de escala. La función final de costes obtenida se ha validado con datos de 15 casos reales obteniendo discrepancias aceptables.

También se ha determinado el coste del calor solar a partir del coste anual de amortización de la planta, los costes anuales de operación y mantenimiento, y la producción anual de energía térmica. Para una comunidad de 1000 viviendas en Zaragoza, una CSHPSS con una fracción solar del 50% podría producir calor a 72 €/MWh. El periodo de amortización aplicado y la ratio de interés utilizada son críticos al determinar el coste del calor solar.

La instalación tiene importantes economías de escala, especialmente el acumulador estacional puesto que su coste es proporcional al área de la envolvente. Para pequeñas comunidades el coste del acumulador es proporcionalmente muy elevado y solo los sistemas con baja fracción solar y sin acumulación estacional son económicamente viables. En grandes comunidades (superiores a 1000 viviendas) los sistemas con acumulador estacional y alta fracción solar resultan económicamente viables. En los últimos años se ha conseguido reducir a la mitad el coste de los acumuladores estacionales mejorando el resultado económico de estos sistemas. Más resultados sobre el coste económico se han presentado en el capítulo 5.

8.1.3 Análisis ambiental

El método estandarizado LCA se ha utilizado para evaluar el impacto ambiental de una CSHPSS. La planta analizada es un caso disponible en la literatura (Lozano et al., 2010c) que produce calor para una comunidad de 500 viviendas en Zaragoza con una fracción solar del 69%. El impacto ambiental se ha determinado para: 1) emisión de gases de efecto invernadero (GHG), 2) demanda de energía acumulada (CED), y 3) indicador ambiental IMPACT 2002+.

Para los principales equipos de la planta se ha definido un inventario detallado del consumo de materiales. El campo solar y el acumulador consumen la mayor parte de los materiales pero también se ha considerado el consumo de éstos en los equipos auxiliares. El consumo de gas natural, como energía auxiliar, se ha considerado en el análisis del funcionamiento anual del sistema. El consumo de electricidad para la operación de la planta, aunque reducido, también es importante.

El impacto ambiental de la planta se ha determinado para un periodo de operación de 50 años, considerando el reemplazo de algunos equipos a lo largo del periodo de vida e incluyendo el consumo anual de electricidad y gas natural. A lo largo de este periodo el consumo de gas natural que solo cubre el 31% de la demanda producirá la mayor parte de las emisiones siendo el acumulador estacional la parte del subsistema solar causante de la mayor parte de las emisiones. Resultados más detallados se presentan en tablas y gráficos del capítulo 6.

Así mismo, se ha obtenido el impacto ambiental de los flujos internos de energía. El campo solar tiene bajas emisiones, tan solo 13 kg $CO_{2\text{-eq}}$/MWh, sin embargo el acumulador estacional aumenta el impacto hasta 57 kg $CO_{2\text{-eq}}$/MWh de calor solar producido. Estas emisiones aunque bajas comparadas con una caldera de gas natural, que emite 210 kg $CO_{2\text{-eq}}$/MWh de calor producido, están lejos de ser despreciables. Resultados equivalentes han sido obtenidos con las otras metodologías de evaluación de impacto ambiental.

Para hacer el análisis extensible a otras plantas se ha formalizado un método simplificado de evaluación de impactos para instalaciones CSHPSS. La función propuesta considera las principales variables de diseño para calcular el impacto ambiental del sistema. Esta función se puede emplear para diseñar sistemas de mínimo impacto ambiental.

8.1.4 Aplicación de cálculo

El cálculo y diseño de CSHPSS es una tarea compleja y un reto para planificadores urbanos, arquitectos e ingenieros. Se ha desarrollado una aplicación informática como resultado final de esta tesis y en el marco de los trabajos realizados en la Task 45 de la Agencia Internacional de la Energía. La aplicación del *Método Simple* es una herramienta fácil de utilizar y que permite realizar estudios de viabilidad en una fase preliminar generando: 1) un análisis detallado del funcionamiento mensual y anual del sistema, 2) información para determinar el tamaño de los principales componentes, y 3) una estimación del coste económico y del impacto ambiental, facilitando todo ello el establecimiento de criterios de diseño y optimización.

La aplicación desarrollada contiene datos climáticos y de demanda para más de 60 localizaciones en Europa y en el capítulo 7 se ha presentado un método para incluir datos para más localizaciones. Información más detallada de esta herramienta se ha presentado en esta tesis, pero los manuales de usuario y otra documentación están disponible en la web de la Task 45 (Task 45, 2015).

8.2 Contribuciones

Las principales contribuciones de este trabajo son las siguientes:

1) Revisión del estado del arte de sistemas de calefacción de distrito con énfasis en: i) sistemas solares de distrito y CSHPSS, ii) métodos de diseño y cálculo que puedan ser usados para nuevos sistemas en España, iii) datos e información económica de sistemas solares de distrito y CSHPSS, y iv) metodologías de análisis de impacto ambiental y su aplicación en componentes solares térmicos y sistemas CSHPSS.

2) Desarrollo de un método original de cálculo para CSHPSS, validación del método propuesto e identificación de fuentes de datos climáticos y de demanda para el cálculo en España y en otros países de Europa.

3) Caracterización económica y ambiental de CSHPSS para el ciclo de vida de la instalación, usando la metodología LCA para el análisis ambiental. Desarrollo de métodos de evaluación económica basados en las principales variables de diseño y validación de los métodos propuestos con resultados de proyectos reales en países del norte y centro de Europa. Análisis de los impactos ambientales generados y evitados por una CSHPSS aplicando diferentes metodologías: i) emisión de gases de efecto de invernadero, ii) consumo de energía primaria, y iii) indicador ambiental IMPACT 2002+.

4) Definición de nuevos criterios de diseño para CSHPSS basados en evaluaciones térmicas, económicas y ambientales que consideran condiciones climáticas y de demanda locales concluyendo que los ratios de diseño para países del norte Europa no pueden ser aplicados para el sur de Europa. Análisis de la relación entre la fracción solar y el resultado económico y ambiental de las instalaciones bajo diferentes criterios de diseño y tecnologías de acumulación de energía térmica.

5) Desarrollo de una aplicación de software para diseñar CSHPSS en Europa que determina el funcionamiento térmico, el coste económico y el impacto ambiental con una interfaz fácil de utilizar. La aplicación está disponible en la página web de la IEA-SHC Task45 como herramienta de referencia para CSHPSS y puede ser descargada gratuitamente.

8.3 Futuras líneas de investigación

A continuación se proponen cuatro posibles líneas de investigación.

1) Construcción de la primera CSHPSS en España. Con los resultados de esta tesis se puede evaluar la posibilidad de incluir una CSHPSS en una comunidad de nueva construcción. La herramienta de cálculo puede ser usada para prediseñar la instalación, sin embargo falta conocimiento sobre ingeniería de detalle para la construcción del sistema. Esta planta podrá utilizarse para ajustar la herramienta de cálculo y obtener conclusiones sobre el funcionamiento real en el sur de Europa.
2) Reducción de costes en acumulación estacional. En los últimos años se han obtenido resultados prometedores en Dinamarca y en Canadá; sin embargo aún resulta posible una mayor reducción de costes en el futuro. Se requieren nuevos diseños de acumuladores estacionales para consumir menos materiales. La investigación en optimización estructural, el desarrollo de nuevas técnicas de construcción, y una selección de materiales acertada podría reducir el coste y el impacto ambiental de este componente clave.
3) Estudio de oportunidades de integración energética incluyendo: i) bombas de calor para aumentar el potencial de la energía solar térmica y la aplicación de los acumuladores tipo BTES y ATES, ii) cogeneración para producir calor y electricidad, iii) máquinas de absorción para producir frío a partir de energía solar térmica, iv) acumulador estacional para almacenar energía térmica de otras fuentes de energía, y v) incorporación de otras demandas de energía térmica.
4) Evaluación de otras fuentes de energía renovables siguiendo la metodología propuesta en esta tesis para el análisis económico y ambiental.

Además, es necesario desarrollar más investigación abordando problemas comunes a los diferentes sistemas de producción de energía para el sector residencial. La falta de métodos apropiados para la caracterización detallada de las demandas de servicios energéticos compromete el estudio de los sistemas de producción de energía.

Las demandas del sector residencial deben definirse apropiadamente, incluyendo valores medios, margen de error y nivel de incertidumbre. La información de edificios públicos que están siendo monitorizados debería ser pública. Además la caracterización de redes de calefacción de distrito incluyendo el consumo de electricidad en operación y las pérdidas térmicas al ambiente pueden ser mejoradas.

CSHPSS pueden ser una solución económicamente viable para nuevas comunidades de gran tamaño, 1000 viviendas o más, en muchas zonas de España. Es necesario que este tipo de sistemas se muestre a urbanistas, arquitectos y promotores para que puedan considerar esta alternativa en una fase inicial de un proyecto. En estos momentos no existe otra forma de construir una comunidad con alta fracción solar, reduciendo el impacto ambiental y suministrando calor a un precio asequible.

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