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Design of an active solar systems software component for a Performance-Based Optimization Environment

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CONTENTS

Abstract

Transition to Zero Energy Buildings requires on-site energy generation from renewable energy sources in order to offset the energy usage for building operation. Solar thermal collectors and photovoltaic panels are the most common building integrated renewable technologies and are used in order to reduce CO_2 emissions and dependence on imported energy. A combined use of the later, designed according to the building energy demand can potentially maximize the benefits of solar energy and enhance the environmental and financial building performance.

SEMERGY is an innovative performance-based optimization environment for building design and currently lacks of a tool for modeling of photovoltaic and solar thermal systems. Therefore the system is restricted to supporting decisions on energy efficiency measures, while energy generation solutions are not considered. The scope of this work is to address this problematic by defining the design problem of a solar system component and further by providing a description of what is to be built and how it is expected to be built in order to allow for software development to proceed with the implementation.

Two main issues are addressed, design optimization and seamless integration into a building design system (SEMERGY). This research determines the exact problem and its parameters, and investigates existing tools for active solar design in order to explore whether and how they answer the specific design problem. Further, it develops the design specifications in accordance with user requirements, defines the system architecture and the detailed computer system models, and executes test cases in order to test how the tool responds to the design specifications. Finally, the interaction with SEMERGY environment is analyzed and the necessary extensions to SEMERGY Building Model (SBM) are reported.

The design tool points to design solutions that achieve an optimum exploitation of the available area of the building envelope. Optimization is evaluated against preset design criteria for maximizing CO_2 reduction gains and financial performance.

As a result, the implementation of the solar system component enhances the optimization function of SEMERGY, since it allows the user to be able to design buildings with more specific requirements.

Keywords

Active solar systems, solar thermal collectors, photovoltaics, SEMERGY, software design, software component, performance optimization

Kurzfassung

Der Übergang zum Null-Energie-Gebäude erfordert die Vor-Ort-Energieerzeugung durch erneuerbare Energiequellen, um den Energiebedarf für den Gebäudebetrieb auszugleichen. Solarthermische Kollektoren und Photovoltaik-Module sind die häufigsten gebäudeintergrierten erneuerbaren Technologien und werden aufgebracht für die Reduzierung der CO_2-Emissionen und der Abhängigkeit von Energieimporten. Eine kombinierte Anwendung der Solartechnologien, ausgelegt nach dem Gebäudeenergiebedarf, könnte die Solarenergiegewinne maximieren und zu einer Steigerung der Umwelt-und Finanzleistung beitragen.

SEMERGY ist ein innovatives leistungsorientiertes Optimierungsystem für Bauplanung und verzichtet derzeit auf ein Tool für die Modellierung von Photovoltaik-und Solarthermieanlagen. Daher ist momentan das System auf die Unterstützung von Entscheidungen über Energieeffizienzmaßnahmen beschränkt, während Lösungen für die Energieerzeugung nicht berücksichtigt werden. Diese Arbeit adressiert diese Problematik an die Problemstellung des Entwurfs der Solarkomponenten, indem sie eine Beschreibung dessen gibt, was gebaut und wie es erwartungsgemäß gebaut werden soll, um die Software-Weitrentwicklung zu ermöglichen.

Zwei Hauptthemen werden angesprochen: die Designoptimierung und die nahtlose Integration in einem integrierten Gebäude-Design-System (SEMERGY). Die Arbeit legt das genaue Problem und seine Parameter fest, untersucht vorhandenene Werkzeuge für aktive Solarsysteme, um zu kontrollieren, ob und wie sie das spezifische Designproblem beantworten. Weiter entwickelt sie die Designvorgaben gemäß *den Benutzeranforderungen*, definiert die Systemarchitektur und die detaillierten Computersystemmodelle, und führt Testfälle an, um zu überprüfen, wie das Tool den Designvorgaben entspricht. Schließlich wird die Interaktion mit SEMERGY analysiert und über die notwendigen Erweiterungen des SEMERGY Informationsmodells (SBM) berichtet.

Das entwickelte Tool zeigt Lösungen auf, die eine optimale Nutzung der verfügbaren Fläche der Gebäudehülle erreichen. Die Optimierung wird gegenüber voreingestellten Designkriterien für die ökologische und finanzielle Leistung bewertet.

Die Umsetzung der Solaranlagenkomponente verbessert die Optimierungsfunktion von SEMERGY, da sie dem Benutzer erlaubt, Gebäude mit besonderen Anforderungen planen zu können.

Stichworte

Solaranlagen, thermische Solarkollektoren, Photovoltaik, SEMERGY, Software- Design, Softwarekomponente, Leistungsoptimierung

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1 INTRODUCTION

Current energy paths lead to an unsustainable model of development with implications on environment and energy security. During the last four decades the world total final energy consumption has grown by over 50% with an equally important increase in carbon dioxide emissions (Figure 1). The need for ecological and energy efficiency strategies is underlined by analysts and international organizations, whereas the benefits of such development models are extended to the economic, social and environmental sectors (UNDESA 2011). In this context, energy efficient and low-gas emission technologies play a key role in the transition towards sustainable energy paths.

The building sector is the major end-energy user, accounting for over one-third of total energy consumption and carbon dioxide emissions (IEA 2012). Growth in population, enhancement of building services and comfort standards, along with the increase in time spent inside buildings have raised building energy consumption to levels higher of transport and industry (Perez-Lombard et al. 2008). Figure 1 illustrates the share of end-energy use by sector. Between 1971 and 2011, the total energy consumption in the buildings sector grew by an average rate of 1.8% per year. Current predictions indicate an increasing trend, unless low-carbon and energy-efficient technologies are adopted by the sector.

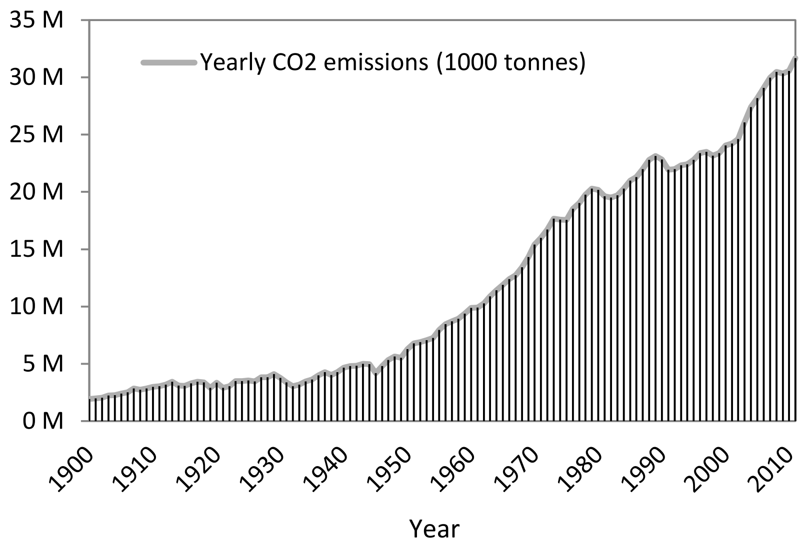

Figure 1: Yearly global CO_2 emissions since 1900 (CDIAC 2014)

The good news is that buildings have been identified by various studies as a sector with considerable energy use and greenhouse gas emissions mitigation potential. In the Energy Efficiency Plan 2011, the European Commission underscores that the greatest energy saving potential lies in buildings. The International Energy Agency defines the building sector as the one with the lowest realized energy efficiency potential, compared to transport and power generation, and on the same time as the one with the largest potential for cost-effective reduction of greenhouse gas emissions (IEA 2012).

A reduction in energy demand of the building sector will have positive benefits for other sectors as well, more significantly for the power generation sector, given that buildings account for 50% of total final electricity consumption (IEA 2013). Simultaneously, for the countries that encourage such models, the potential energy savings will help to reduce financial dependence on fuel and energy imports. Last but not least, for the building users, sustainable building solutions have a positive effect in reducing the energy costs, while adding comfort and contributing to life quality.

According to scenarios which take into account the sector growth trends, the total energy demand of the sector could be limited to a 10% increase until 2050 in contrast to

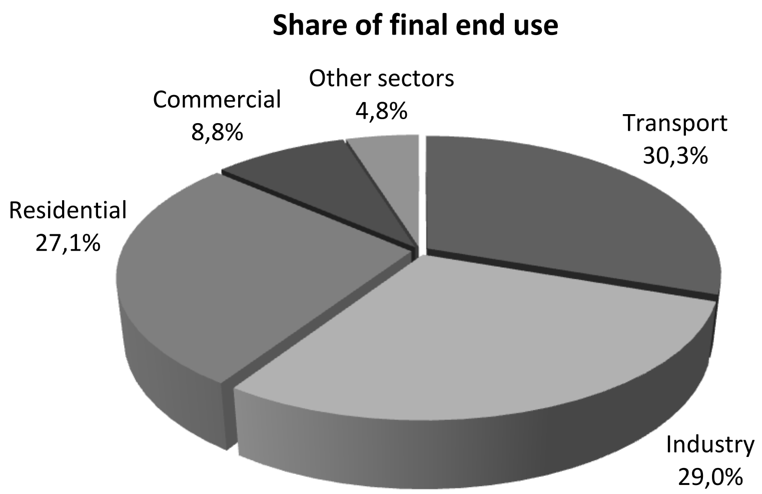

Figure 2: Energy consumption in different sectors (Laustsen 2008)

a 50% rise, which is estimated if no action is taken to reverse current trends (IEA 2013). For developing countries, a focus should be given on the new buildings which should be constructed according to the highest possible standards, whereas for the industrialized world deep renovations of the existing building stock and use of innovative technologies should form the basis of transformation of the sector (Laustsen 2008).

Buildings have a large potential in reducing energy use and green house gas emissions. This potential lies in minimization of building energy demand and maximization of energy share supplied from locally available, non-polluting renewable sources. In this framework, low energy buildings are constantly gaining importance and popularity. This trend is also supported by existing guidelines and regulations, such as the European Directive on energy performance of buildings that stipulate strict energy performance requirements for both existing and new buildings (European Comission 2003). As a result, the importance of building performance assessment has increased over the past years. Different definitions have been proposed for classification of energy saving buildings depending on the energy balance that the later achieve with most common terms are Low Energy, Zero Energy and Energy Plus buildings.

Decentralized on-site energy generation from renewable energy sources is essential in order to offset the energy demand for building operation. Table 1 summarizes the supply option hierarchy from renewable resources in Zero Energy Buildings. Rooftop photovoltaics and solar water heating are the most applicable supply-side technologies for on-site renewable energy generation within the building footprint. The abundance of solar radiation, the modularity and quick integration of the collectors on the building envelope along with the decreasing cost trends, strengthen the dynamics of deployment of solar systems.

Solar energy systems, compared to other renewable technologies, have technological advantages which make them compatible with building applications. First, a basic characteristic of solar systems is their scalability. Whereas wind, hydro and geothermal energy require high investment costs to reach full technological efficiency, solar PV and solar hot water heating are approximately as efficient independent of the system's scale. Another advantage is that their operation does not necessarily require moving parts. Fixed systems are more reliable and need little maintenance. In contrast, wind

Table 1: ZEB Renewable Energy Supply Option Hierarchy (Torcellini et al. 2006)

Option Number	ZEB Supply-Side Options	Examples
0	Reduce site energy use through low-energy building technologies	Daylighting, high-efficiency HVAC equipment, natural ventilation, evaporative cooling, etc.
	On-Site Supply Options	
1	Use renewable energy sources available within the building's footprint	PV, solar hot water, and wind located on the building.
2	Use renewable energy sources available at the site	PV, solar hot water, low-impact hydro, and wind located on-site, but not on the building.
	Off-Site Supply Options	
3	Use renewable energy sources available off site to generate energy on site	Biomass, wood pellets, ethanol, or biodiesel that can be imported from off site, or waste streams from on-site processes that can be used on-site to generate electricity and heat.
4	Purchase off-site renewable energy sources	Utility-based wind, PV, emissions credits, or other "green" purchasing options. Hydroelectric is sometimes considered.

resource is an example with constrained applications because of structural, noise and wind pattern considerations (Rasovsky 2012).

1.1 SEMERGY environment

SEMERGY is a decision support system developed to support the design of high performance and cost efficient buildings. The software combines simulation and optimization methods and includes routines for performing normative calculations and accreditation. As a result, all the required functions for the building design process are combined in one tool.

The SEMERGY system is being developed in the framework of the SEMERGY research project with the participation of the Department of Building Physics and Building Ecology and the Institute of Software Technology and Interactive Systems of Vienna University of Technology. It is web-based and is currently available for testing in Beta Version under the web-address *www.semergy.net.*

SEMERGY addresses two main issues in the building design process. The first issue is the automated design optimization, which supports design by pointing to efficient solutions in view of preset design goals. The second issue is the use of design-relevant information available on the web. Examples of such information are cost, technical and ecological data of construction materials, applicable codes and standards, as well as financing and subsidy opportunities. This information is critical in design optimization, however its manual collection requires a lot of time, effort and is prone to errors (Mahdavi et al. 2012a). A major feature of SEMERGY, is that it uses semantic web technologies for restructuring this web-based information into information models (ontologies) that can be further used as inputs in computer simulation (Shayeganfar et al. 2013).

For the optimization function, the system identifies alternative building configurations based on initial user data input. The optimization algorithm detects Pareto-dominant solutions in view of energy, ecological and financial performance according to the various filters that the user sets (e.g. maximum costs). This allows the user to evaluate the trade-offs between the objectives and select one of the solutions that best fulfills the design goals.

Target users of SEMERGY are individuals, expert designers as well as novice users, and policy makers such as local authorities. Thus, SEMERGY is designed to accommodate use cases of different expertise background and design scale. Building geometry can either be created using the GUI or more complex models can be imported from other modeling software. Simplified data entry is achieved using templates for operational data and predefined building components or more detailed information can be specified by advanced users. For policy making and evaluation in local scale, GIS data acquisition is integrated.

SEMERGY software is structured in three layers: the reasoning layer, the semantic layer and a graphical user interface. The reasoning layer includes calculation tools for dynamic performance assessment, steady-state normative calculations, cost estimation, environmental impact evaluation, life cycle analysis etc. The semantic layer contains the information models for building materials, climatic data, GIS data, financial data, codes etc. These models supply input data for the calculations in the reasoning interface. Finally, the graphical user interface (GUI) enables interaction with user for input of data that are not provided by the semantic interface (e.g. building geometry, location etc.).

This way the design problem is tailored to the specific needs of the user. Output results are communicated to the user though the GUI.

As far as the communication between the three layers is concerned, this is achieved though a common data model, the Semergy Building Model (SBM) (Ghiassi 2013). The input acquired from the graphical user interface and the semantic interface is post-processed and organized in SBM. This information is then supplied to the reasoning layer for execution of the computational routines. SEMERGY performs both dynamic calculations as well as simplified normative calculations, thus the model contains necessary information for both methods. The information contained in SBM can be classified into 3 categories: physical data, operational data and calculation parameters. More in detail, a schematic diagram of SBM is illustrated in Figure 3.

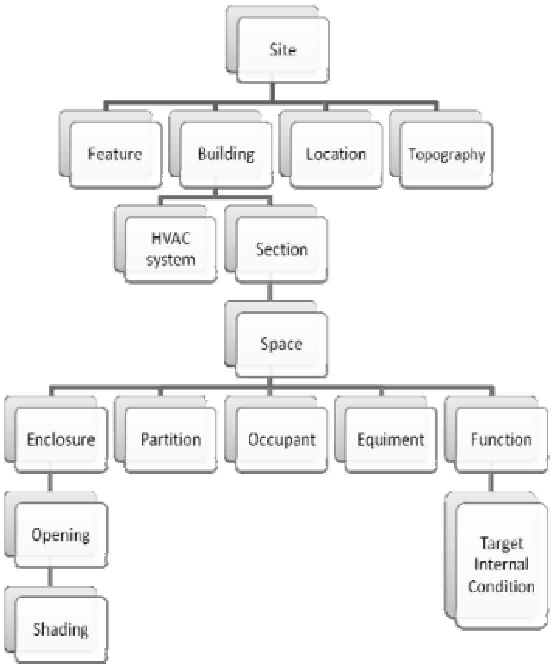

Figure 3: SEMERGY Building Model – Architecture (Mahdavi et al. 2012b)

1.2 Motivation

The design of buildings that comply with high performance standards requires consideration of on-site energy production from renewable resources. Solar technologies are constantly gaining attention due to the availability of solar radiation and their applicability for installation on the building envelope. Apart from the environmental benefits the development of solar technologies is also driven by financial benefits. Cost reduction trends of solar equipment achieved due to economies of scale and subsidy policies make often the solar technologies promising investment option. An effective design taking into account the building characteristics can maximize the potential financial and environmental benefits of solar energy.

The problematic is that SEMERGY optimization environment is currently under development and lacks of a tool for modeling of photovoltaic and solar thermal systems. Therefore the system is currently restricted to supporting decisions on energy efficiency measures, while energy generation solutions are not considered. Thus this work will address the design problem of a software component for active solar technologies in SEMERGY environment. How this component is integrated into the current system architecture is illustrated in Figure 4.

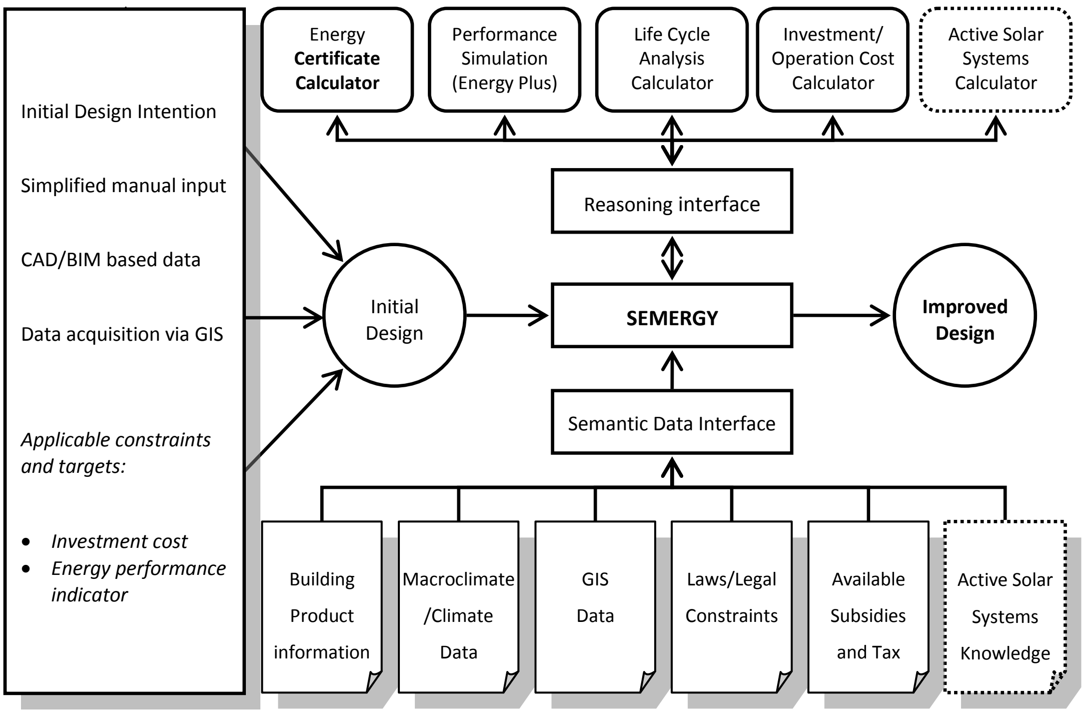

Figure 4: SEMERGY environment – Overview

(Adapted from Mahdavi et al. 2012a)

The designed tool will be used in conjunction with the pre-existing SEMERGY system and more specifically it will be integrated into the calculation system layer in order to model decision process, different design variants need to be created based on the user preferences and the design constraints. The different solutions will be evaluated and those that maximize design goals will be pointed out by the tool.

In order to address the above problematic, this work should define the design problem and further it should provide a description of what is to be built and how it is expected to be built in order to allow for software development to proceed with the implementation. More in detail, the design process should handle the following issues:

1. Determine the exact problem that the tool should solve and its parameters
2. Investigate existing tools for active solar design in order to explore whether and how they answer the specific design problem
3. Develop design specifications in accordance with user requirements
4. Define the system architecture in accordance with system restrictions
5. Define the computer models that will be used to resolve the problem
6. Execute test cases in order to test how the tool responds to the design specifications
7. Define the necessary extensions to the information model of SEMERGY system

This work will contribute to the design support of building-integrated active solar systems. The design process is speeded-up because the tool creates design alternatives and automatically runs a number of simulations to identify the optimal solution in view of preset goals. Moreover the effort required from the side of the user is reduced due to the automated acquisition of building information that is achieved through the information exchange in SEMERGY environment.

1.3 Background

In the current section computer methods for building systems' simulation and performance optimization are analyzed, in order to further proceed with the design of the software component. Methods for modeling of building systems can be classified in two main categories: simplified calculation methods and detailed simulation methods. Simulation based optimization uses the above methods to evaluate system performance and to detect optimum design solutions. However, most of optimization programs are stand-alone and thus they are difficult to integrate in the design practice. SEMERGY addresses the above issue, as it combines simulation and optimization functionalities in one system for building design and is analyzed in the current chapter.

1.3.1 Computer methods for building systems simulation

Simplified methods are based on simplified physical relations, rules of thumb and empirical calibration methods. Such methods are generally used by sizing tools for building systems and tools for normative calculations. Sizing tools base their calculations on the worst case scenario for the sizing of the HVAC equipment. Tools that perform calculations according to codes or standards, for example according to the EN ISO 13790, estimate annual energy tradeoffs using a steady-state approach which assumes mean monthly outdoor climate.

The basic advantage of steady state calculations is that they require a reduced number of inputs and they are computationally simple. However, steady state methods are unable to describe adequately transient phenomena, such as heat storage and internal peak loads, where a detailed analysis of the thermal processes needs to be carried out.

On the other hand, applications of computer simulation have seen an increased popularity during the last decades for handling complex engineering systems. This trend is supported by increased efficiency goals in buildings which are raising the performance requirements of the tools used in the design process. The detailed information provided by dynamic simulation is necessary for making informed decisions on the best design options.

The main advantages of dynamic simulation include the high temporal and spatial resolution and the accuracy of the algorithms to the underlying physical phenomena. Constraints generally include the large number of input data required for the simulations and the increased computational complexity. The simulation results can though only be as accurate as the input data for the simulation (Maile et al. 2007).

In solar system design, simulation tools are often used to test the progress during the design phase. The designer aims to identify the design solutions between a set of alternatives that best fulfill the design objectives. A trial-and-error process is usually iterated to produce alternative solutions and the best solution is selected for further development. The drawback of this process is that it is time-consuming while it relies mainly on the intuition of the designer. More in detail, tools for solar system design are analyzed and compared in the next section.

1.3.2 Current methods in building design optimization

Stringent performance requirements currently involved in the building design raise the importance of detecting efficient design solutions. Simulation-based optimization seems to be a promising solution to the increased design challenges. The process of performance optimization aims at the identification of the optimal solutions from a set of available alternatives for a given design problem, in view of a set of fixed performance criteria.

Despite the fact that numerical optimization methods have been already developed since 1980's, the idea of automated optimization in building design started to gain attention in the scientific community in the late 2000's (Nguyen et al. 2014). Most optimization studies are based on the coupling of a building simulation tool with a generic optimization platform. Optimization platforms generally include a library of optimization algorithms (direct search, gradient-based, meta-heuristic etc.) and algorithms for doing parametric runs. The user defines the objective function, the design parameters and eventual constraints using the interface of the optimization platform. The platform generates input files for the simulation program and launches the program. It then reads the value of the function being minimized and generates a new set of input parameters for the next run. This loop is iterated until the minimum of the function is found (Figure 5). Examples of common optimization platforms used in building performance optimization are MATLAB and GenOpt.

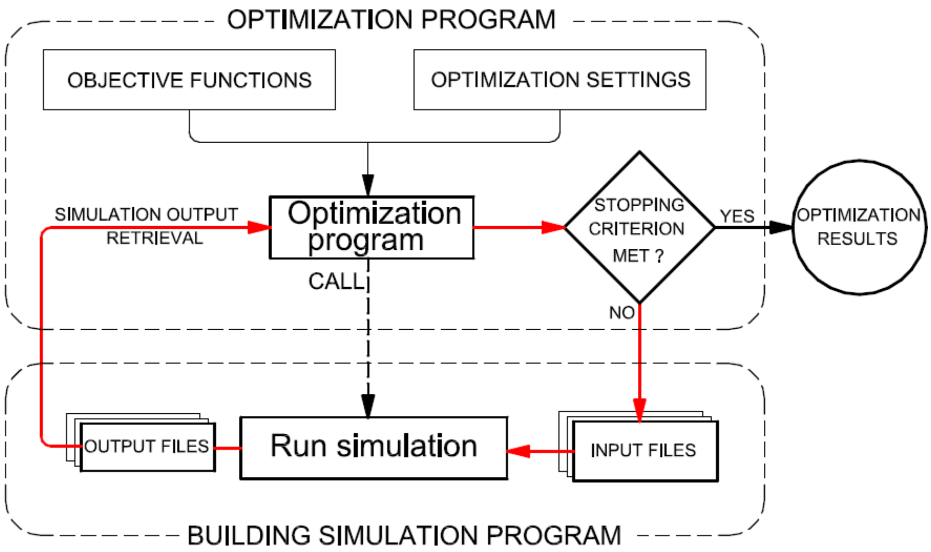

Figure 5: Activity diagram of simulation-based optimization in building performance studies (Nguyen et al. 2014)

In praxis, the coupling between simulation tools and optimization packages is a cumbersome task and requires time and expertise. From this point of view generic optimization tools are difficult to integrate into the design practice. This barrier can be overcome by the development of stand-alone tools that combine simulation and optimization algorithms and offer to the user full-functionality of automated design optimization. BeOpt for residential buildings and Opt-E-Plus for commercial buildings are two examples of standalone modeling and optimization programs. They are developed by the US Renewable Energy Laboratory (NREL) and use the simulation engines of EnergyPlus and DOE-2.2 (NREL 2010, Christensen et al. 2005).

2 DESIGN APPROACH

2.1 Overview

Solar energy technologies provide hot water, electricity and cooling, meeting the needs of buildings in various energy forms. Solar thermal systems have a significantly higher efficiency in capturing solar energy (70% peak efficiency) than photovoltaic (20% peak efficiency), as long as the heat is effectively used for the building needs in hot water. On the other hand, photovoltaic systems have the advantage of flexibility in the use of their production, either locally or by distant customers, so their energy output is fully absorbed. Low energy buildings, in order to efficiently offset their energy needs, will likely need to combine on their envelopes both solar thermal and photovoltaic systems (IEA 2011).

A successful integration of solar technologies in buildings plays a key role in the achievement of strict design goals. The objective in active solar design is to determine the system that efficiently achieves design goals. The problem lies in defining the values of design parameters that maximize the incident solar radiation and energy output of the system.

More specifically, incident solar radiation depends on the collector slope and orientation. The tilt angle can increase benefits of the sun altitude angles, while the orientation determines exposure to the solar path. For most common heating loads in northern latitudes the optimal orientation angle is true south, while small variations to the east or west of 30^{o} have little effect on the annual system performance (Figure 6). Roof profile and shading from neighbor buildings often set restrictions to the selection of optimal orientation.

	Osten					Azimut						Westen
	-90	**-75**	**-60**	**-45**	**-30**	**-15**	**0**	**15**	**30**	**45**	**60**	**75**	**90**
	1	2	3	4	5	6	7	8	9	10	11	12	13
Neigung **0**	85	85	85	85	85	85	85	85	85	85	85	85	85
15	85	85	85	95	95	95	95	95	95	95	85	85	85
30	85	85	85	95	95	95	100	95	95	95	85	85	85
45	75	85	85	85	95	95	95	95	95	85	85	85	75
60	75	75	75	85	85	85	85	85	85	85	75	75	75
75	65	65	75	75	75	75	75	75	75	75	75	65	65
90	55	55	65	65	65	65	65	65	65	65	65	55	55

Angaben in Prozent

Figure 6: Dependence of incident solar radiation on the tilt and orientation (Austrian Energy Agency 2014)

The energy output of a solar system depends on the system components and the system configuration. In solar thermal systems the design of the load must also be considered in the search for optimum design. Given a load that is some function of time through a year, a type of collector and a system configuration, the primary design variable is collector area. Storage capacity and other parameters are generally fixed in relationship to collector area (Duffie and Beckman 2006). For grid connected photovoltaic systems the performance is independent of the load and the system energy output is a linear function of the area of the collectors.

In practice, the problem of solar system design often resolves to a simpler one of determining the size of a solar energy system that achieves a specific energy or cost performance. However, when both technologies are examined as competent solutions under restrictions of available installation area, which is often the case in urban environments, the area allocation trade-off should be examined in order to detect optimal solutions. Optimal solutions are the solutions that maximize the system performance metrics and in this case should be detected automatically by the designed software component. The activity diagram that the solution process follows is illustrated in Figure 7 and the steps of the process are explained below.

Solution Space

In order to detect optimal design solutions the incident energy on the collectors and the energy production of the systems needs first to be determined. Initially, different design solutions are created. More specifically, the tilt angle scenarios are created by increasing the tilt angle with a step of 1 degree. The system size scenarios are created by dividing the maximum available area into a grid of 100 elements. The area can be either filled with solar thermal collectors or with photovoltaic collectors. For the production calculations the area of collectors is thus increasing with a step of 1% from 0% to 100% (Figure 8). All possible area scenarios for each system are examined. The production calculations are thus performed for 2x101 scenarios. For the optimization problem all resulting combinations of collector areas are considered, with the restriction that the resulting total area is equal or smaller than the available area. Thus all combinations of the 101 different system sizes are examined. The problem described is a combinatorial problem with a set of 101 elements (n=101) and distinct 2-element subsets and can be estimated using the binomial coefficient $\binom{n}{k}$ and the total number should be increased to include the cases of 1-element subsets (only photovoltaic or only solar). The increase should be 2x101. The total number of different system configurations is 5.252. Due to the fairly small number of resulting configurations, the optimal solution can be identified with the use of an exhaustive search.

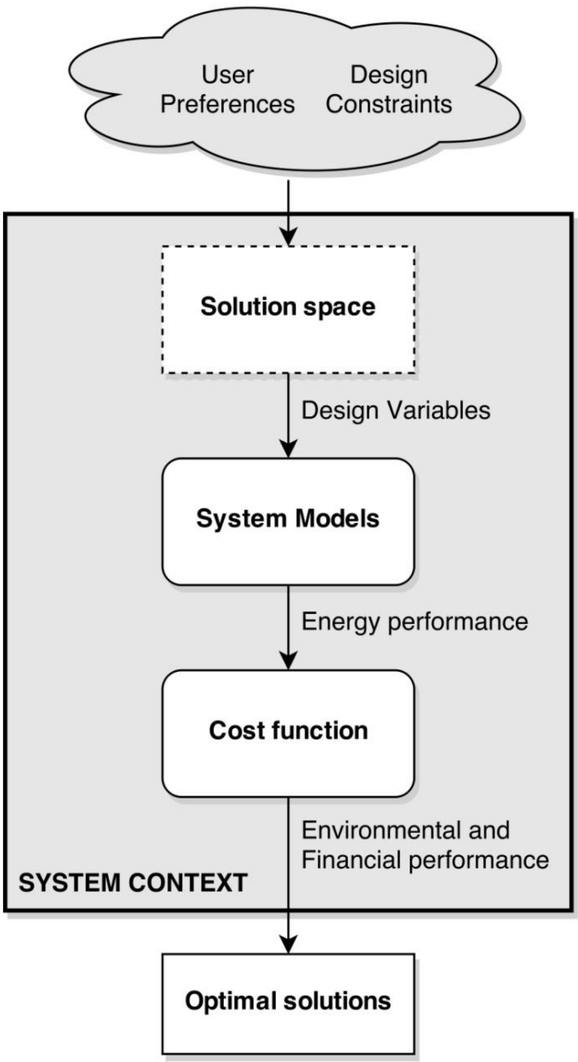

Figure 7: Design approach – Solution steps

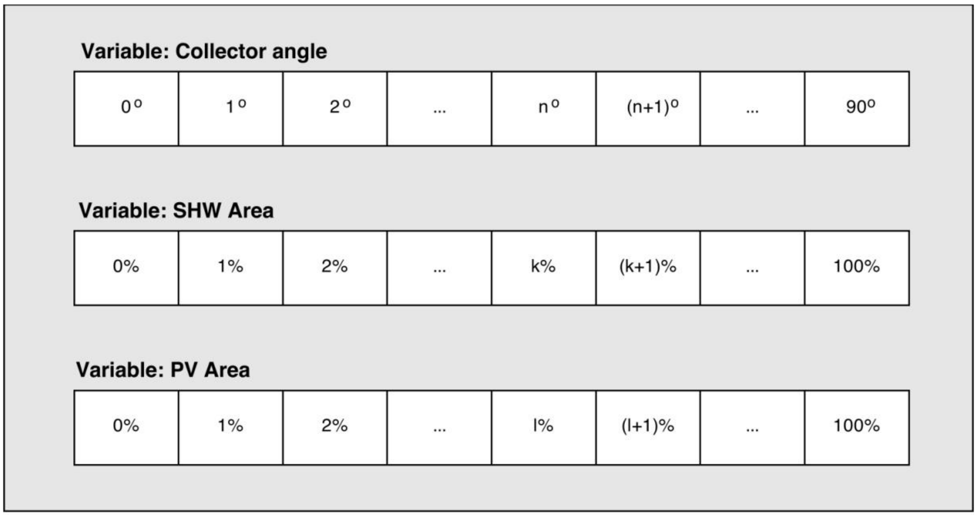

Figure 8: Design Variables – Generation of alternative design solutions

System Models

The solar system model includes the photovoltaic and solar thermal models. To compare the performance of the two systems, the energy produced by the systems during the year is estimated; this is the sum of the hourly simulated values. The arrays containing information on the area values of each system are given as input and the system models calculate the hourly performance of the system for each input. Output of the performance model are two arrays of the same dimension as the input (101 elements) containing annual estimated energy production values.

Regarding the thermal solar system, the hot water temperature in the tank is furthermore used for calculating the amount of energy delivered to the building and the auxiliary energy required for the building needs. As solar energy generation and load profile are not generally coupled, the produced thermal energy is stored in a tank, with the energy cost of thermal losses. The ratio between delivered energy and generated energy depends on the tank volume and on the tank thermal properties and geometry (U-value and height to diameter ratio). For typical domestic applications however, tank volume over a specific minimum does not greatly affect the system performance and for this reason the tank volume in the current model is considered a constant design parameter calculated as a linear function of the thermal collectors' area. According to the ASHRAE specifications for storage sizes, for the case of a constant daytime load for 7 days/week the volume of an economic efficient tank can be estimated by considering a constant value of 20.4 l/m^2 of gross collector area. For the case of a 5 days/week constant daytime load, a value of 40.8 l/m^2 of gross collector area is recommended.

For grid connected photovoltaic systems, the energy delivered to the building is equal to the electrical energy output of the system. The system performance depends on the efficiency of photovoltaic panels and is reduced by the effectiveness of the system equipment (Balance of System). Photovoltaic panels have a lower efficiency in respect to thermal collectors in converting solar energy to usable energy (20% compared with 60%). This fact bounds the whole system performance. However their advantage is that the electrical energy of the photovoltaic system is consumed on the grid, therefore there are no losses from the unused energy.

Cost Function

In order to evaluate the performance of the system against specific criteria a cost function is used. Optimal solutions maximize the cost function of the problem. Given that the number of design variants is fairly low, it is possible to estimate the cost function for all the feasible solutions of the problem and then to perform an exhaustive search in order to detect the global optimum. More in detail, the parameters of the cost function are analyzed in detail in the next section.

2.2 Problem Formulation

Determination of the optimization problem involves the definition of the problem parameters. The parameters of the problem are summarized in Figure 9 and are analyzed below.

Optimization variables

Decision or design variables are the aspects of the system that the designer has control over. The selection of the design variables is thus important as it determines the complexity and the computation time of the optimization problem. In theory, all of the physical parameters of collectors, storage, and other system components influence the performance of the solar system. This number increases considerably the complexity of the calculations required by the goal function. However, after a sensitivity analysis (Duffie and Beckman 2006), we can filter out the parameters that have low sensitivity in regard to the long term energy and financial performance. With this technique, it is possible to simplify the complexity of the calculations. There two optimization variables considered in the problem formulation:

1. *The tilt of the solar collectors*

   The angle of solar collectors in respect to the horizontal plane determines the amount of solar radiation collected by the system. The tilt angle is based on setting the horizontal angle of the solar collectors' plane so that it achieves maximum collection of solar radiation. This is dependent on latitude and time of year.

2. *The allocation of collector area for solar thermal and photovoltaic technologies*

   The area allocated to photovoltaic and thermal solar collectors, determines the energy mix produced by the system to offset the building energy demand.

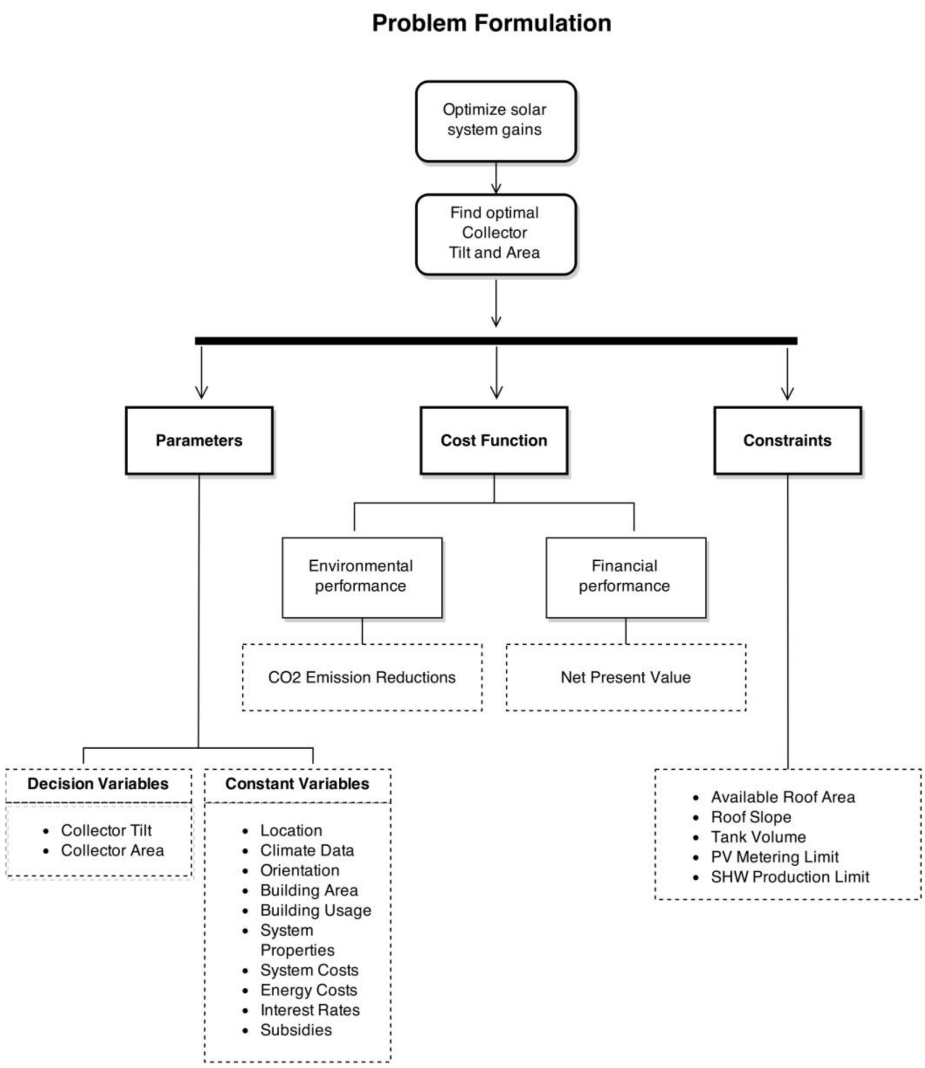

Figure 9: Problem formulation - Parameters of the design problem

Constant parameters

Constant parameters or circumstances are the aspects that the designer has no control over, or does not wish to control. In order to narrow down the complexity of optimization problem, parameters already determined at the preliminary design stage of the building are considered also to be constant. These parameters are: the building location (which determines the environmental parameters), the building orientation (which influences the orientation of the roof) and the building area and usage (which determine the building load and load profile). These parameters can be classified according to the following sets:

1. Environmental parameters: solar radiation, ambient temperature, albedo factor
2. Building parameters: location, orientation, building area, building usage, roof area
3. Economic parameters: energy costs, interest rates, system costs, subsidies

The parameters of the optimization problem are summarized in Figure 9.

Domain constraints

Restrictions that hold for the different decision variables are expressed by domain constraints. The constraints that apply to the current optimization problem are the following:

- The collector slope from the horizontal is between roof angle and 90 degrees
- The total area of solar collectors is smaller or equal to the available area and larger than or equal to zero
- The area of photovoltaic panels is smaller or equal to the area of all the solar collectors
- The area of thermal collectors is smaller or equal to the area of all the solar collectors
- The volume of the storage tank does not exceed the upper value specified by the user
- The energy production of the solar thermal system does not exceed 80% of the hot water energy load
- The capacity of the photovoltaic system is smaller or equal to the policy net metering limit
-

Optimization objective

Performance metrics are used to express design goals and evaluate design variants. In building optimization studies the most common criteria for optimization are energy, cost, comfort and carbon emissions (Figure 10). Since comfort is a complex function of building properties and building systems is not used as a performance criterion in the current study.

The use of renewable technologies may be either imposed by legislation, or rewarded by subsidies or simply required by the owner for individual reasons. On the other hand, the viability of an investment is tightly connected to its economical performance. For this reason an economical parameter should be considered.

For this reason both environmental and economical performance are considered in the optimization problem. Environmental and financial gains depend on the system energy output, thus the energy performance of the system should be also estimated in order to resolve the optimization problem.

Based on the above, the performance metrics used to evaluate the design solutions are:

- the environmental performance (achieved CO_2 emission reductions)
- economy (installation costs, operational costs and financial gains)

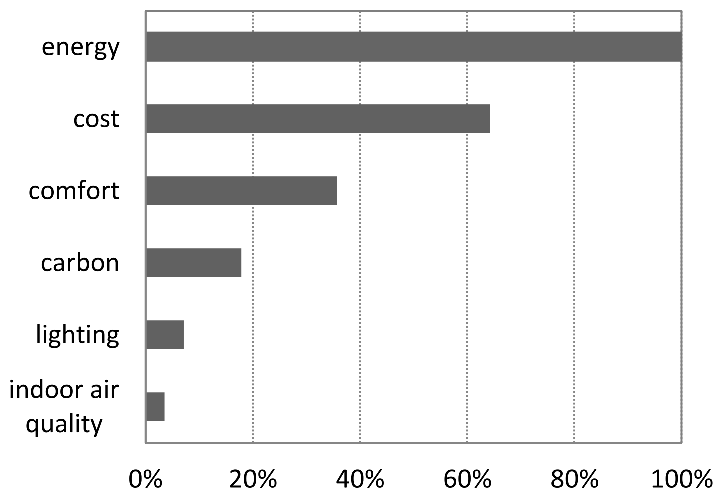

Figure 10: Optimization objective functions in building design: user choices according to the research (Attia et al. 2013)

The objective function that the system performance should maximize can be written as:

$$\text{optimize}\{\textit{environmental gains}, \textit{economic performance}\} \quad (2.1)$$

Equation (2.1) describes a multi-objective optimization problem as it involves simultaneous optimization of more than one function.

To evaluate the performance of the systems, it is necessary to calculate the annual energy produced by the systems during the year; this is the sum of the hourly simulated values. Based on energy production calculations, the environmental and financial benefits can further be estimated. The performance metrics included in the cost function are analyzed below.

Performance metrics

The functions used to describe each objective are analyzed in the following:

a) Environmental performance

The evaluation of environmental performance is performed by the calculation of the primary energy CO_2 emission reductions between the simulated systems.

The amount of reductions is estimated as a sum of the achieved energy gains multiplied by the corresponding CO_2 conversion factor

$$CO_2 \text{ Emissions reduction} = f_{CO2,elec}E_{PV} + f_{CO2,DHW}E_{SHW} \quad (2.2)$$

where E_{PV} is the energy provided by the photovoltaic system, E_{SHW} is the energy provided by the solar water system and f_{CO2} is the CO_2 conversion factor corresponding to the energy carrier of the auxiliary system. In the case of PV systems CO_2 reduction is due to electrical energy gains. The achieved environmental gains for SHW systems depend on the auxiliary system that is used to supply thermal energy to the building (e.g. gas boiler, electrical heater etc.).

Annual environmental benefits account for all CO_2 emission reductions achieved during the year due to solar system operation and are calculated from the sum of the hourly simulated values.

Exemplary CO_2 conversion factors, are shown in Table 2, and are based on the values estimated by the International Energy Association for the subtask 37 (Hastings 2010).

Table 2: Primary Energy and CO_2 conversion factors (Hastings 2010)

Primary Energy and CO_2 conversion factors	PEF	CO_2 eq
	(kWh_{pe}/kWh_{end})	(g/kWh)
Oil-liter	1.13	311
Natural gas	1.14	247
Hard coal	1.08	439
Lignite	1.21	452
Wood logs	0.01	6
Wood chips	0.06	35
Wood pellets	0.14	43
EU-17 Electricity, grid	2.35	430
District heating CHP-coal cond. 70%, oil 30%	0.77	241
District heating CHP-coal cond. 35%, oil 65%	1.12	323
District heating plant; oil 100%	1.48	406
LDH CHP-coal cond. 35%, oil 65%	1.10	127
LDH Heating plant, oil 100%	1.47	323
Local solar	0.00	0
Solar heat (flat) central	0.16	51
PV (multi)	0.40	130
Wind electricity	0.04	20

b) Economy

The second objective function that is considered for optimization is the economic performance of the system. In this case, the criterion used to evaluate the design variants from an economic point of view is the net present value (NPV). Net present value includes all benefits (R) and expected costs (E) of the investment as well as the investment capital (C) throughout the life of the system of n years discounted to present value (discount rate r). Between various possible investments, the solution with the highest NPV exhibits the best economic performance (Parys 2013):

$$NPV = \ -I_o + \sum_{i=1}^{n} \frac{R_i - E_i}{\left(1+r\right)^i} \tag{2.3}$$

Initial investment cost for solar systems consists of the equipment cost and the installation cost of the solar system. Benefits include financial gains from the system operation, such as subsidies and income by electricity sold on the grid. The expected costs throughout the lifecycle of the system include maintenance and energy operation costs. In the expected costs are also included the energy costs for operation of the auxiliary system.

Based on the above, the net present value can be formulated to include the financial parameters of the system. In (2.3) I_o is the initial investment capital, S_o is the initial investment subsidy, $E_{elc,}$ is the annual electricity cost for the system operation, E_{aux} is the annual energy cost for the operation of the auxiliary energy system, $E_{,main}$ is the annual maintenance cost, E_{enerPV} is the annual energy gains from the photovoltaic system operation and $E_{enerSHW}$ is the annual energy gains saved due to the solar thermal system operation, r_{real} is the annual price increase above inflation and α_{real} represents the discount rate in real terms

$$\begin{aligned} NPV = -I_o + S_o &- \sum_{i=1}^{n} E_{elec,i} \frac{\left(1+r_{elec,real}\right)^i}{\left(1+a_{real}\right)^i} - \sum_{i=1}^{n} E_{aux,i} \frac{\left(1+r_{aux,real}\right)^i}{\left(1+a_{real}\right)^i} \\ &- \sum_{i=1}^{n} E_{maint,i} \frac{\left(1+r_{maint,real}\right)^i}{\left(1+a_{real}\right)^i} + \sum_{i=1}^{n} E_{enerPV,i} \frac{\left(1+r_{enerPV,real}\right)^i}{\left(1+a_{real}\right)^i} \\ &+ \sum_{i=1}^{n} E_{enerSHW,i} \frac{\left(1+r_{enerSHW,real}\right)^i}{\left(1+a_{real}\right)^i} \end{aligned} \tag{2.4}$$

For the annual solar system savings estimation, the above values are calculated in annual basis. The time value of money is taken into account considering the discount rate parameter. The discount rate represents the rate of return of the best known alternative investment and is used to determine what the expected investment stream is worth in the present.

To be able to calculate the exact solar system savings the following information is required:

- Exact price of the fuel cost at any given time in the future during the life cycle of the system

- Exact annual maintenance cost in the future, during the life cycle of the system
- The life span of the system

Fuel costs play a major role in the determination of the net present value of a system (2.4). These values can be influenced by geopolitical issues. In order to reduce the impact that extreme variance in gas and oil prices in a specific period of time could have in the sizing of the system, a control loop is used in the software component to ensure that the produced hot water corresponds to a maximum of 80% of the total hot water load.

2.3 Use Case Scenario

Once the problem has been formulated, it is necessary to define the scope and the specifications of the component in order to further proceed with the definition of the software architecture. As starting point, a use case scenario is developed in order to enable identification of system requirements and tasks that the system should be able to accomplish in its environment and context.

Use case scenarios are generally used to capture interactions with the user that the software should be able to respond. A typical use case scenario related to the solar system component has the following structure:

The SEMERGY user decides to invest on active solar systems in order to achieve a better building performance. He is interested to explore how he can increase system gains given existing design restrictions. Initially, he provides information on building and systems, and design preferences. Data entries relevant to the solar system design include building information (location, usage, area, total area available for solar collectors and orientation) and system information (type of collectors and auxiliary energy systems). The amount of data entries can vary upon the expertise of the user. Constraints refer to investment costs and minimum levels of environmental performance.

User entries are transferred to the building model along with relevant information from the semantic layer (product costs, technical data and subsidies). Based on the information contained in SBM the program generates design alternatives and calculates performance for each solution. The output results are the input to the optimization algorithm. The algorithm identifies the optimal solutions against criteria of

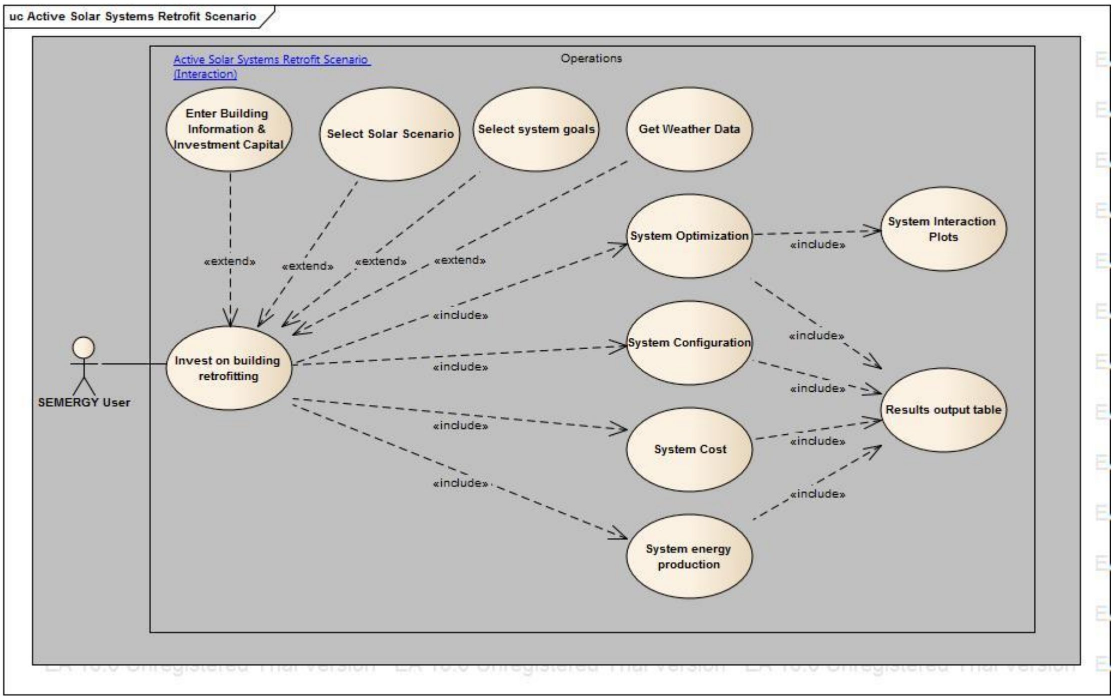

Figure 11: Use case scenario of solar component

environmental and cost performance. Upon completion of this task the results are presented to the user through the graphical user interface of SEMERGY.

The component needs to interact with a number of entities and systems, including:

- User accessing the component over the SEMERGY
- Building information database contained in building data model
- Product, weather and subsidies databases available on the semantic layer
- Calculation engines of the calculation layer for data exchange

The above information needs to be considered for the definition of the system specifications which should be specified before proceeding with the definition of the system architecture.

2.4 Requirements specification

In order the system to be able to respond to the user requirements, it should exhibit certain specifications. Requirements describe the tasks that software should be able to perform (functionalities) and certain properties that the software should exhibit while performing these tasks (qualities). Based on this distinction, requirements are typically classified into functional requirements and perspectives (Rozanski and Woods 2005). The requirements of the software component are identified and presented below:

Functional Requirements

In order to optimize design, the system should model the performance of photovoltaic and solar thermal systems. Acquisition of load profiles is also required, since the performance of thermal solar systems is dependent upon the demand and operation. For the optimization function, the software should generate alternative design solutions and evaluate them in terms of cost and energy related indices.

The functionalities that the software should have are summarized below:

1. Include computer models for the following systems:
    - Photovoltaic systems
    - Solar water heating for residential or commercial buildings
2. Generate alternative design variants based on the initial design
3. Simulate the systems' performance over a single year
4. Perform financial calculations
5. Detect optimal values of the design parameters against environmental and financial performance criteria

Architectural perspectives

The SEMERGY system is addressed to users with different level of experience. The designed software should thus allow for data inputs of different level of detail. Where possible the software should perform automated data acquisition from the system environment (e.g. building information) in order to reduce set-up time and minimize errors. It should also perform data input validation and show error messages to the user. Finally the software must be able to operate in the SEMERGY platform.

The qualities that the software must exhibit refer to usability, reliability and interoperability properties and are summarized below:

1. Usability:

– Minimize data entry with the use of default data values
– Allow users to modify default values for fine tuning
– Reduce set-up time through automated data acquisition from Semergy Building Model
– Include component libraries to allow selection between market products

2. Reliability:

Perform data input validation before running the simulation

3. Interoperability:

– Provide compatibility with SEMERGY system and the Semergy Building Model (SBM)

2.5 Prior development effort

After the problem formulation and definition of system specifications, existing tools for solar system design are studied in order to explore how and in which extend the address the design problem. Computer tools for solar system design can be divided into two categories based on their functionality: performance evaluation tools and optimization tools (Figure 12). Table 3 provides an overview of the features and capabilities of some common used software tools for solar system design listed in the "Building Energy Software Tools Directory" of the U.S. Department of Energy (DOE 2014).

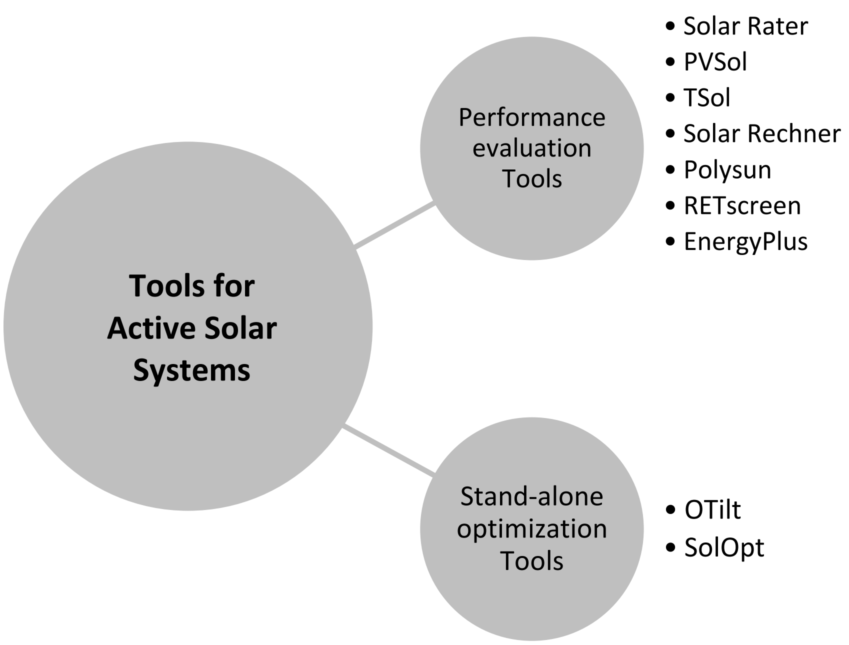

Figure 12: Computer tools for active solar systems design

Solar rater is an Android application for photovoltaic solar systems. It performs solar energy potential estimation and photovoltaic system sizing. The location is automatically detected with GPS or Wi-Fi. User inputs refer to panel location and orientation, energy load, energy costs and system efficiency. Output is the size of the photovoltaic system, and the achieved greenhouse gas reductions and other environmental benefits. The programming language is Android Java. The tool is addressed to energy professionals and facility managers. The basic strength is that it performs quickly on site evaluations by automatically detecting the geocode information; however it models only photovoltaic systems and currently has no specific solar components' libraries, so the user should provide an estimation of the system performance.

PVSol is a dynamic simulation program for the design of grid-connected and off-grid photovoltaic systems. The tool is sizing the photovoltaic system based on the input information and performs production calculations, and performance and financial analysis calculations. Input information consists of array area, shading objects, electricity costs, load profiles and type of panels. Output includes among others annual system yield, solar fraction, system efficiency and economic efficiency. The program is developed in C sharp and Turbo Delphi. Target users of the program are engineers and planners, system installers, and energy consultants, as well as research institutes. The program contains an extensive database of system components and has a user friendly graphical interface. However, the tool simulates only photovoltaic systems so an integrated solar system design is not possible.

TSol is a dynamic simulation tool for design of thermal solar systems. The tool includes system configurations among which the user can select and sizes the collector and storage tank systems. It performs automatic variant calculation and allows the user to select the preferred system configuration. Inputs for the simulation include location, collector type, regulating temperatures, costs, consumption profile. Outputs are figures and table summaries of energy balance, efficiency, solar fraction and CO_2 emission gains. Target users of TSol are engineers and planners, soar professionals and energy consultants as well as research institutes. The program is developed in Turbo Delphi. Its main strength is the user friendly interface which includes a design assistant and the reduced number of required inputs due the possibility of selection of existing system configurations. Its main weakness is that it simulates only thermal solar systems and therefore an integrated solar system design is not possible.

Solar Rechner is an online tool for planning of solar thermal systems. It is available online on the site of the company Sonnenkraft. The tool is based on the computational kernel of Polysun, which is analyzed below. Required data input is building information regarding location, net area, building energy load, roof geometry, and user preferences concerning the auxiliary system. Output of the tool is a PDF report on system dimensioning, economic, and environmental and energy due to system operation. Target users are home owners, planners and solar energy professionals. Basic strength of the tool is the ease of use thanks to a user friendly graphical user interface and the required number of inputs. Weaknesses include that only residential buildings are considered in the calculations, while product libraries include only components from the company Sonnenkraft and are not extensible.

Polysun is a simulation software for solar systems and heat pumps design. The tool includes detailed system models and integrated meteorological data and provides production forecasts which can serve as a basis for optimization of existing and new systems. Required input is the geographic location, component characteristics, horizon characteristics, energy load profile and costs for economic evaluation. Output data include solar fraction, hourly energy system usage, and economic analysis and are provided in form of output tables and customizable graphs. Target users are engineers and designers. Programming language is Java. Basic strengths of the tools are the large component catalog and the detailed simulation models for solar thermal systems and heat pump simulation. Currently the tool is limited to simulating of on-grid photovoltaic systems.

Retscreen is an Excel-based tool for evaluation of renewable energy and energy efficient projects. Outputs of the analysis include information on energy production and savings, costs, emission reductions, financial viability and risk assessment. Target users of Retscreen are engineers, architects and planners, and facility managers. The tool includes a database of climate and product data libraries, project database included, default and suggested values. Programming language is Visual Basic and C#. The program provides an extensive documentation and a large number of project databases which support the user in the completion of feasibility studies for renewable energy and energy efficiency technologies. Weaknesses include the lack of detailed system models, as steady state analysis is performed, and the generally large amount input data that is required for the analyses.

EnergyPlus is a widely used simulation program for integrated building energy performance analysis including on-site energy generation and renewable technologies. The program has been developed by the US Department of Energy. It is based on two earlier programs, DOE-2 and BLAST and integrates powerful capabilities such as modular systems and time steps of less than one hour. Input to the program is an ASCII file containing the complete object-based description of the building and its systems. Output results are reported in an ASCII file that can be accessed by output agents for further processing of the results. Target users of EnergyPlus are engineers and architects, researchers and federal agencies. The software is written in FORTRAN programming language. Strengths of EnergyPlus related to solar systems include detailed solar and shading calculations, integrated simulation, heat balance based solution for panel temperatures, anisotropic sky model for improved calculation of diffuse solar on tilted surfaces, sub-hourly time steps and extensive weather files databases. Main weakness is that the program is stand-alone simulation program and lacks of a user friendly graphical user interface. External graphical user interfaces that integrate the program are however available. Also, the strong modeling capabilities of the program require detailed input data values and a technical background.

Two programs performing design optimization of solar systems, oTilt and SolOpt are presented in the rest of this section. These programs will be used as a basis for the design of the solar component in SEMERGY.

OTilt is an online tool for the determination of optimal tilt angle for solar collectors. The tool estimates the slope which maximizes the collection of solar energy for a given span of the year. An isotropic sky model is assumed for the estimation of the incident solar radiation. Input to the program is the site location. Shading phenomena are not taken into account. The user can determine the site location either directly entering the geocode information or through an interface with an interactive map for selection of the site. Output is a table with optimal monthly, seasonal, half-year and fixed and the respective energy collection during these time frames.

SolOpt is a tool for the evaluation of design of rooftop solar technologies, developed by the National Renewable Energy Laboratory of the United States (NREL). The tool determines the optimal use of available roof space for installation of solar photovoltaic and solar thermal systems. SolOpt is currently in beta version and runs on an excel-based interface. Production calculations in SolOpt are run with hourly step and the optimal mixture of technologies is identified. Inputs for the simulation are building information, weather data files, electrical usage, domestic hot water system, and fuel and electricity costs. The tool is designed for users with different technical background. Default and auto-sized data allow for simulations with a reduced number of inputs. An advanced input option is available for experienced users (Lisell et al. 2011). The tool determines the optimal solar system configuration for five optimization criteria options. These options are maximum net present value, carbon footprint reduction, energy savings, payback period and levelized cost of energy.

Most of the above design tools are stand-alone, in the sense that they operate independently of building design programs. In building integrated solar systems however, provision of building related information is required for accurate performance evaluation calculations. In order to increase the ease of use of solar computer tools, their seamless integration into the building design software is thus necessary.

Table 3: Software for solar system design – Comparison table

	PV - system modeling	**SHW - system modeling**	**Energy production calculations**	**Integrated building energy analysis**	**Financial analysis**	**Hourly time step**	**Detailed shading calculations**	**Tilt optimization**	**PV-SHW mix optimization**	**Customizable libraries**	**Free availability**
Solar Rater	x		x								*
PV*SOL	x		x		x		x			x	
T*SOL		X	x		x		x			x	
Solar Rechner		x	x			x					x
Polysun	x	x	x		x	x	x			x	*
RETscreen	x	x	x	x	x					x	x
EnergyPlus	x	x	x	x	x	x	x			x	x
oTilt								x			x
SolOpt	x	x	x		x	x			x		x

* Advanced versions require a license fee

2.6 System architecture

In a typical systems engineering process, requirements analysis focuses on the problem space and works within a set of constraints, the system's required scope. Software design on the other hand, is focusing on the solution space and is targeted primarily at the developers. It works within a set of constraints, the system's requirements. The definition of system architecture includes elements of design and also of requirements analysis and is bridging the gap between the problem and solution space. More specifically, the system architecture takes into account the system requirements and the existing constraints (e.g. technical, deployment environment, resources) and defines a pragmatic system that best meets these requirements.

In order to detect the optimal design variant as already discussed in section 2.1, the annual system performance needs to be calculated. In theory this requires an integrated solar radiation model coupled to the PV and SHW model for each of the combinations. Such an approach would however create a huge number of design variants and would therefore increase the computational time. Based on the discussion above, the energy production calculations and the detection of the optimal solution can be drastically simplified to a level that allows evaluation of the number of optimization variants. This can be achieved by decoupling the incident solar radiation and system production

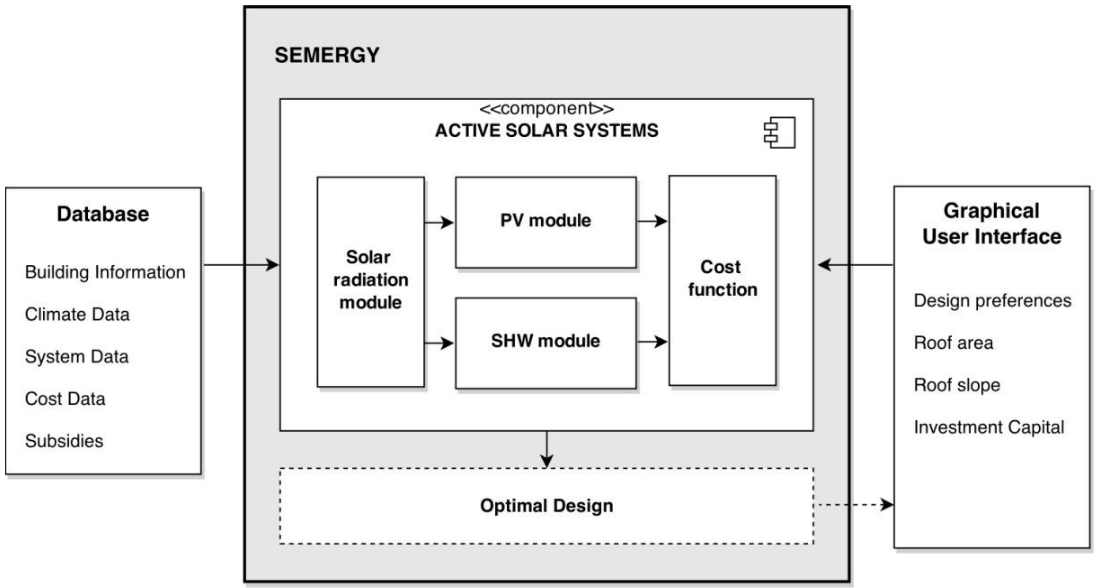

Figure 13: Active solar systems component - System Architecture

calculations. For this reason, the assumption that the angle which maximizes incident solar radiation on the collectors' plane also maximizes the energy output of the solar system can be made. Assuming that tilt angle and system size are independent variables, the detection of optimal tilt calculations can be performed prior to the system energy production calculations. Once the optimal tilt value is detected it can be further used as a constant by the system models for the production calculations.

Based on the discussion above, the software component in order to deliver the required functionalities should contain a solar radiation module which process climate data and detects the optimal tilt that maximizes incident solar radiation on the collectors' plane. This output is the input to the PV modules and SHW modules for the calculations of the system energy performance for each of the design variants. In the next step, the output of the system modules is given as an input to the cost function calculator, for the estimation of the system performance in view of the environmental and economical criteria. The system architecture is illustrated in Figure 13.

2.7 Activity diagrams

In order to detect solutions that optimize system performance in view of the design objectives, the optimization algorithm is developed. The algorithm consists of a sequence of numbered steps (Figure 14):

1. The optimal tilt is detected given the building location
2. Design alternatives are generated by assigning different collector areas to the systems and the energy output for each alternative solution is calculated
3. Performance evaluation for each design alternative is performed using the cost function
4. Exhaustive search is performed to define solutions that maximize performance and output results are displayed

These steps are described below:

Step 1: Optimal tilt detection

Fixed tilt angle systems are quite common in building applications because of the easy installation on the building envelope and the low maintenance costs. In this step the tilt angle of collectors that maximizes the incident solar radiation on the tilted plane over the year is determined. This angle depends upon the solar radiation components (global, beam and diffuse) and the location (latitude).

The algorithm estimates the optimum tilt angle for a specific location (latitude) using solar radiation data. Solar radiation data are generally measured in the form of global radiation on a horizontal plane. Thus, the problem of calculating solar radiation on a tilted surface lies in determining the relative amount of beam and diffuses components contained in the measured horizontal global radiation I_{solar} (Ahmad and Tiwari 2009).

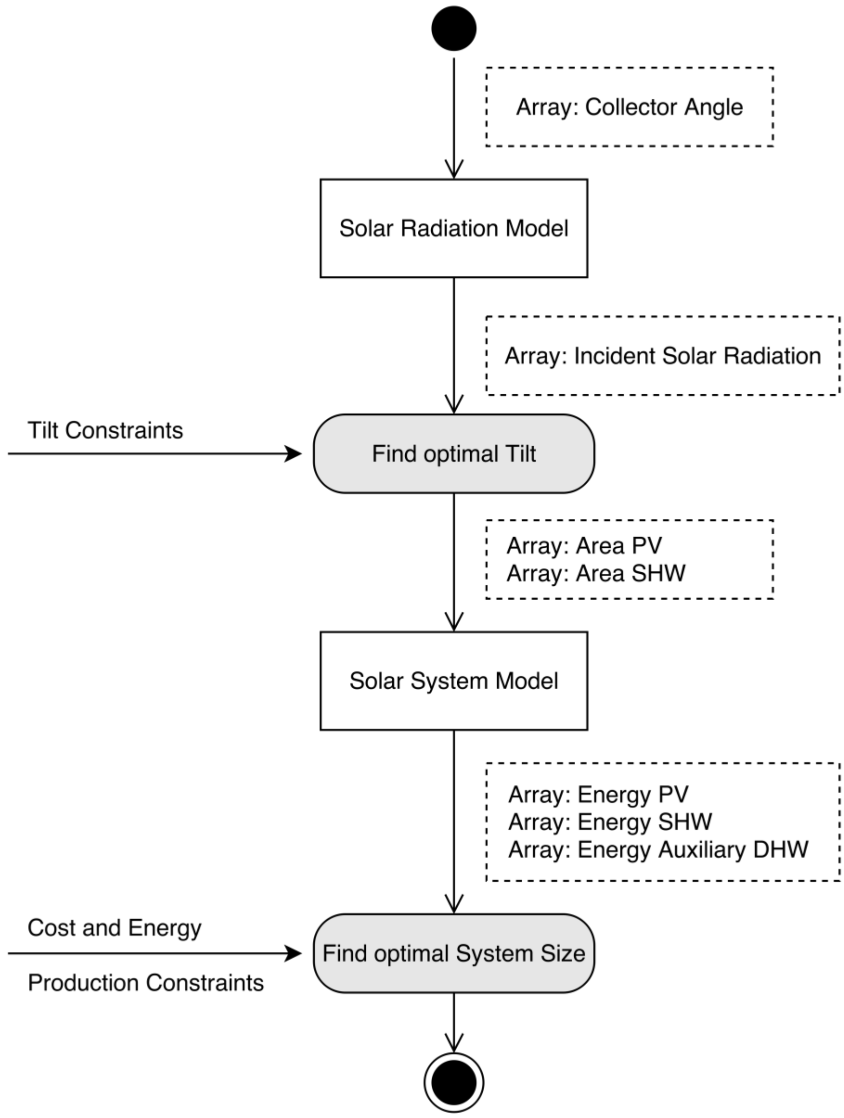

Figure 14: Solar systems component - Activity diagram

Many models have been developed to decompose the global radiation into its components. These models generally establish correlations between the diffuse fraction and various predictors (Lanini 2010).

The presented algorithm uses the polynomial model developed by NASA in the Surface meteorology and Solar Energy SSE methodology to estimate the diffuse radiation component. The ratio of diffuse radiation to the global radiation is related to the clearness index K_T, sunset hour angle ω_s and noon solar angle ω using the following relations (Ahmad and Tiwari 2009):

For latitudes $0^o \le \varphi < 45^o$

$$\frac{I_{solar,Diff}}{I_{solar}} = 0.96268 - 1.45200K_T + 0.27365{K_T}^2 + 0.04279{K_T}^3 + 0.000246\omega_s + 0.0011$$

For latitudes $45^o \le \varphi < 90^o$

If $0^o \le \omega_s < 81.4^o$

$$\frac{I_{solar,Diff}}{I_{solar}} = 1.441 - 3.6839K_T + 6.4927{K_T}^2 - 4.147{K_T}^3 + 0.0008\omega_s - 0.008175\omega$$

If $81.4^o \le \omega_s < 100^o$

$$\frac{I_{solar,Diff}}{I_{solar}} = 1.6821 - 2.5866K_T + 2.373{K_T}^2 - 0.5294{K_T}^3 - 0.00277\omega_s - 0.004233\omega$$

If $100^o \le \omega_s < 125^o$

$$\frac{I_{solar,Diff}}{I_{solar}} = 0.3498 + 3.8035K_T - 11.765{K_T}^2 + 9.1748{K_T}^3 + 0.001575\omega_s - 0.002837\omega$$

If $125^o \le \omega_s < 150^o$

$$\frac{I_{solar,Diff}}{I_{solar}} = 1.6586 - 4.412K_T + 5.8{K_T}^2 - 3.1223{K_T}^3 + 0.000144\omega_s - 0.000829\omega$$

If $150^o \le \omega_s < 180^o$

$$\frac{I_{solar,Diff}}{I_{solar}} = 0.6563 - 2.893K_T + 4.594{K_T}^2 - 3.23{K_T}^3 + 0.004\omega_s - 0.0023\omega \qquad (2.5)$$

The clearness index is the ratio of the solar radiation on the horizontal plane to the extraterrestrial solar radiation and is written as

$$K_T = \frac{I_{solar}}{I_{solar,o}} \quad (2.6)$$

where I_{solar} is the global radiation incident on a horizontal plane and $I_{solar,o}$ is the extraterrestrial solar radiation.

The noon solar angle ω is estimated by

$$\omega = \begin{cases} 90 - abs(\phi - \delta), \text{ for nothern hemisphere} \\ 90 - abs(\delta - \phi), \text{ for southern hemisphere} \end{cases} \quad (2.7)$$

Once the diffuse solar component is known, the total radiation on a tilted plane can be calculated by

$$I_{solar}^{T} = I_{solar,B} R_B + \frac{I_{solar,Diff}}{2}\left(1+\cos\beta\right) + \frac{I_{solar}\rho}{2}\left(1-\cos\beta\right) \quad (2.8)$$

The activity diagram of the method used to determine the optimal tilt angle of the collectors for a given location is illustrated in Figure 15. The monthly average diffuse and direct normal solar radiation components on the horizontal plane are initially estimated in basis of the global radiation data using (2.5). Next, the solar components on the tilted surface are estimated according to (2.8). An exhaustive search is finally performed to determine the tilt angle that maximizes solar collection over the year.

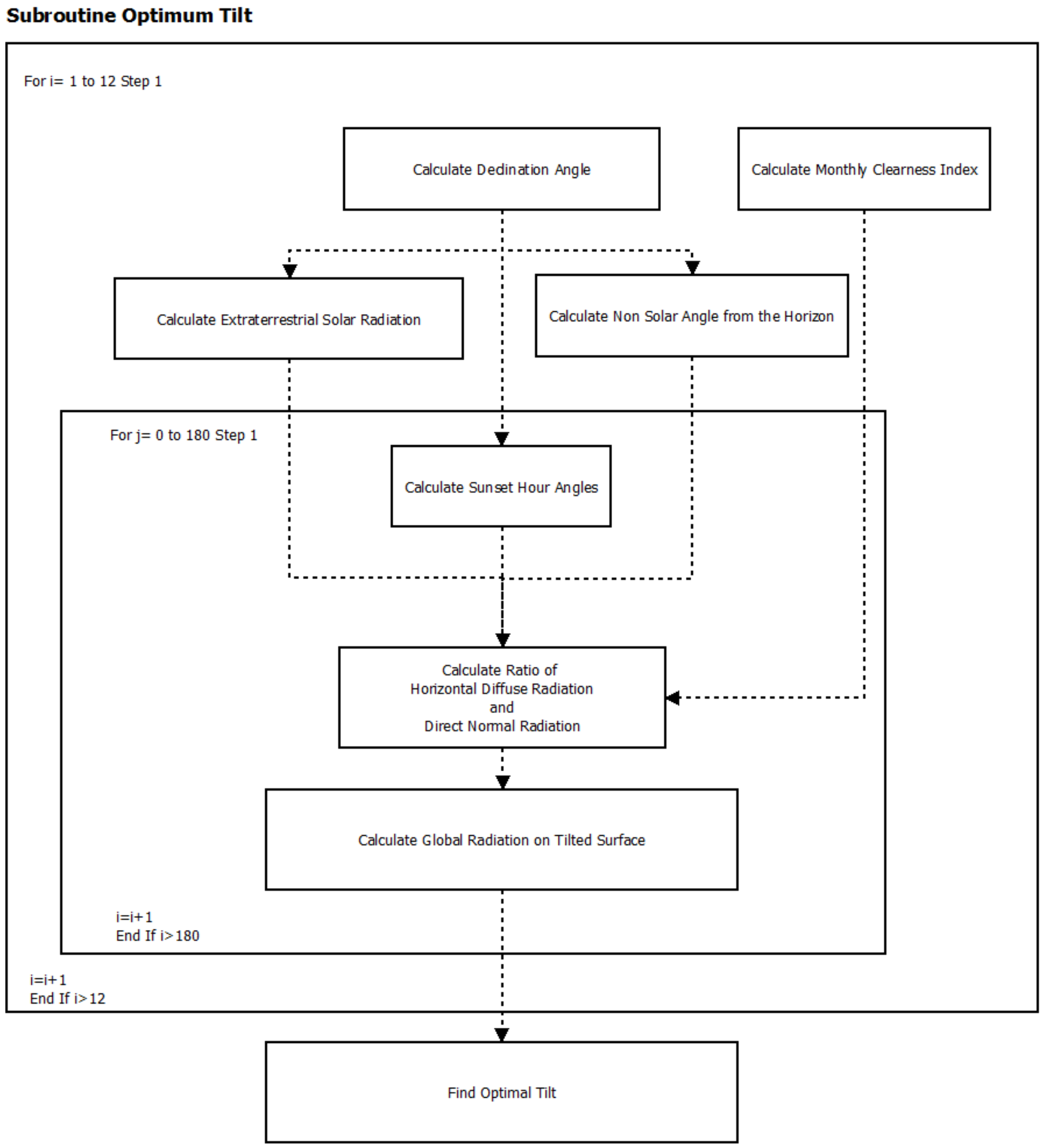

Figure 15: Optimal tilt detection (Step 1) - Activity diagram

Step 2: Generation of alternative design solutions and production calculations

In order to determine the optimal area allocation for solar technologies alternative design solutions are generated based on the initial user intention. Each solution represents different area values of photovoltaic and solar thermal collectors. The solutions are generated by increasing the collectors' area with a step of 1%. The computer models of the systems calculate the system performance for each alternative. The method followed is described below:

The subroutine Production Calculation generates multiple design alternatives by assigning different areas to photovoltaic and solar thermal collectors (Figure 16). For each alternative it calls the functions SHW Energy Production and PV Energy (Figure 17) which calculate the system maximum production. For the PV system the routine

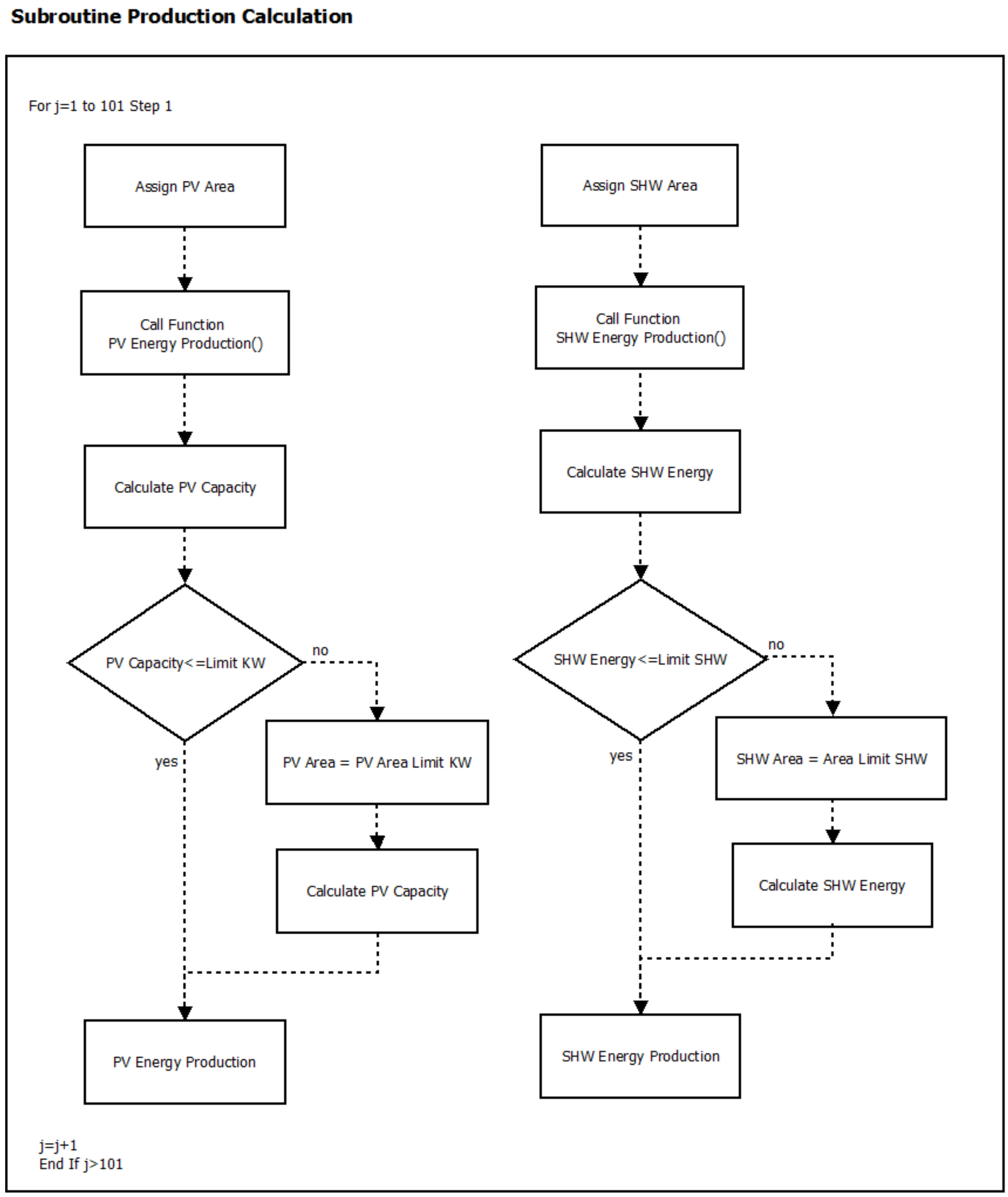

Figure 16: Generation of alternative design solutions and production calculations (Step 2) - Activity diagram

controls if the output exceeds production constraints imposed by the grid. If the production constraints are exceeded the area of the PV system is recalculated to follow the constraints.

The production calculations as a function of the area of collectors are performed by the functions SHW Energy Production and PV Energy. The activity diagram of these functions is shown in Figure 17. Input to the function SHW Energy Production is the SHW load. Output of the functions is the system production, energy losses for equipment operation and the auxiliary energy needed to offset the building load.

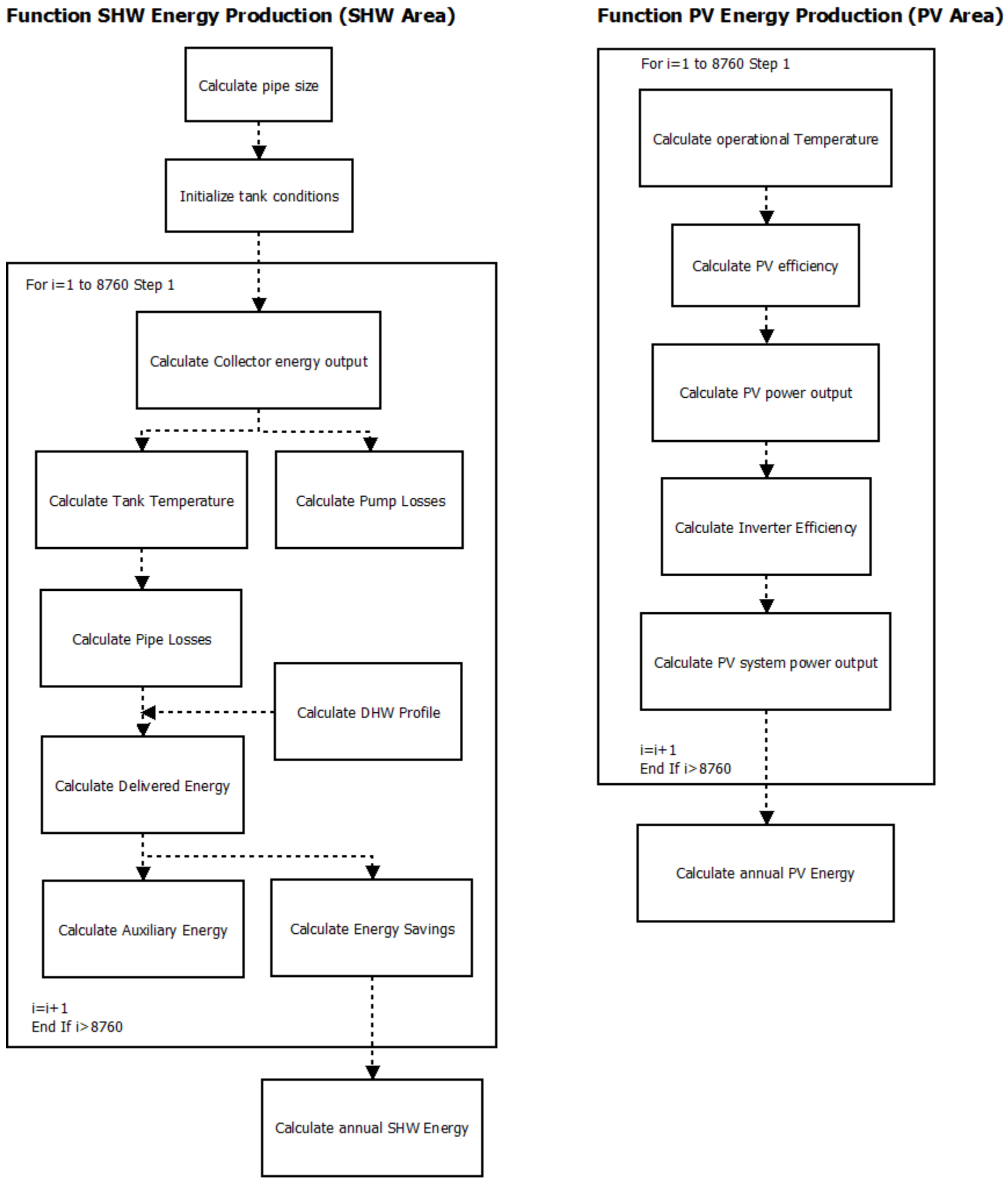

Figure 17: Functions SHW and PV system energy production - Activity diagram

Step 3: Performance evaluation

Performance assessment of the design solutions of the previous step is done in this step by the subroutine Evaluate Performance. Energy production, energy losses and auxiliary energy values are the input information to the subroutine. The subroutine calculates the performance metrics for every combination of sizes of the two systems, according to the activity diagram in Figure 18. Calculations are performed based on the equations (2.2) and (2.4). The output of this algorithm is an array with is 5.252 elements as already discussed in section 2.1.

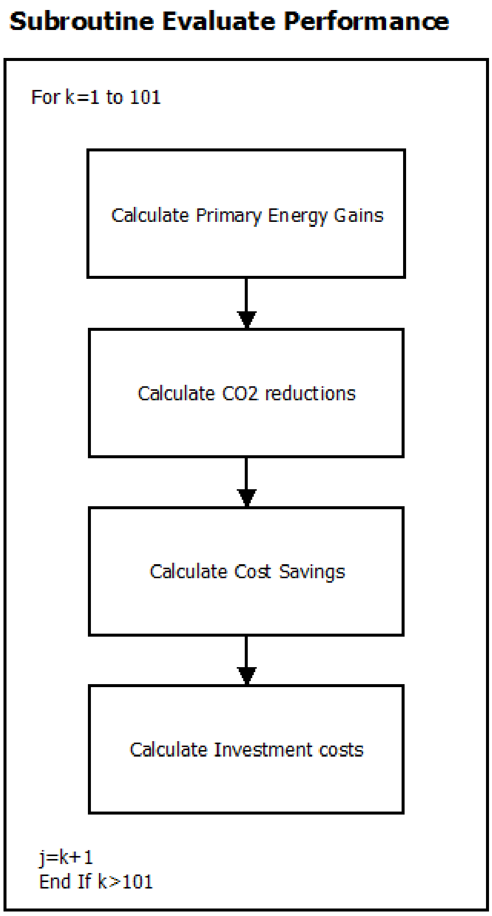

Figure 18: Performance evaluation (Step 3) - Activity diagram

Step 4: Detection of optimal solutions and output of results

At the final step, an exhaustive search is performed in order to detect the values that maximize performance. Optimal values of design variables and the corresponding system performance are the output of the optimization algorithm. The output of this algorithm can be used as an input by other calculation tools in SEMERGY in order to evaluate the whole building performance. For example, achieved carbon dioxide emission reductions can be subtracted from the emissions due to the building operation in order to estimate the overall building environmental performance.

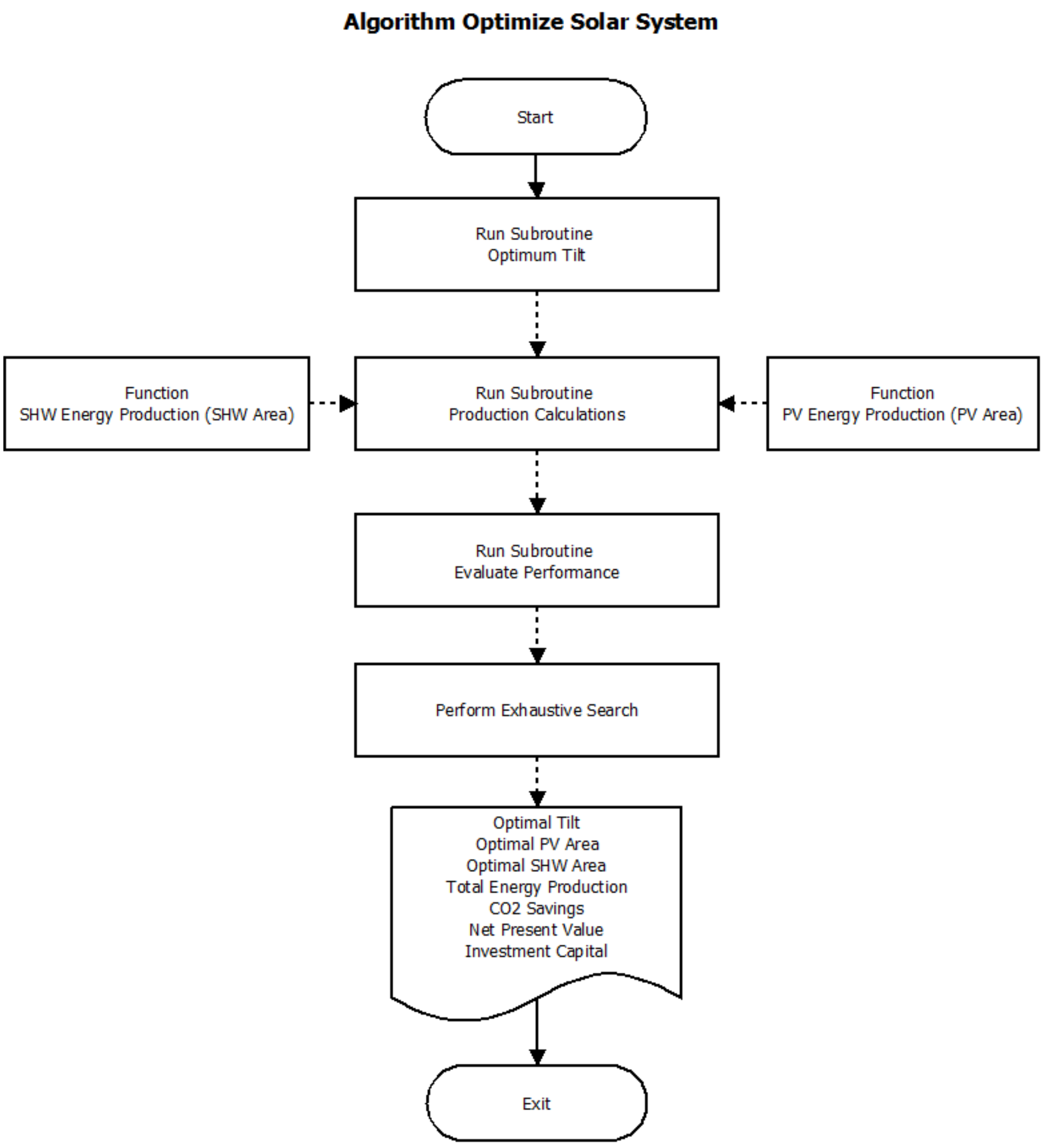

Figure 19: Detection of optimal solutions - Activity diagram

3 SYSTEM MODELS

In order to proceed to the optimization phase the computer models of the systems need first to be determined. As already discussed in the design approach, the system model to be optimized should be simplified, in order to reduce complexity and time delay of optimization, but should not be too simple to prevent the risk of inaccurate modeling of various interactions and system phenomena.

3.1 Thermal solar system model

Active thermal solar energy systems collect incident solar radiation and store it as useful thermal energy in the form of elevated temperature heat transport fluid or storage medium, to eliminate the need for non-renewable fuel consumption. The solar thermal system can be divided into four subsystems based on the function they perform: the collector subsystem, the transport subsystem, the storage subsystem and the control subsystem (UFC 2007).

The **collector subsystem** collects solar radiation and converts it into thermal energy by raising the temperature of a circulating heat transfer fluid. It comprises the solar collectors, the interconnecting piping and the necessary supporting structural equipment on the building envelope.

The **transport subsystem** transfers the converted energy from the collectors to the storage subsystem. It consists of the piping, the heat transfer fluid, the pumps, the expansion tank and the heat exchanger, in the case that the heat transfer fluid is other than water.

The **storage subsystem** stores the converted thermal energy in the form of elevated temperature fluid, so that the system acts as a relatively steady source of thermal energy, limiting the effects of the relatively variable incident solar radiation. It comprises the storage tank, the stored water as well as the necessary support equipment.

The **control subsystem** regulates the operation of the solar system. It activates the system to collect the solar radiation when there is enough energy for collection and deactivates the system when this energy is not enough to deliver net energy gains. It includes the temperature sensors and the control unit that processes the data from the sensors and controls the system operation.

Additional to the solar thermal collector system, an **auxiliary energy conversion subsystem** is used when the supply of solar energy is inadequate to meet the thermal energy demand, compensating for the intermittent and variable amounts of solar radiation. The function of this subsystem is to combine the energy available from the solar system with auxiliary energy produced by conventional energy sources. The subsystem utilizes conventional HVAC equipment such as electrical heaters, fuel fired boilers, as well as their associated heat exchangers, pumps, piping and control equipment.

The computer model used to describe the solar thermal system with flat plate collector is presented below. This model is based on the equations from Duffie and Beckman (2006).

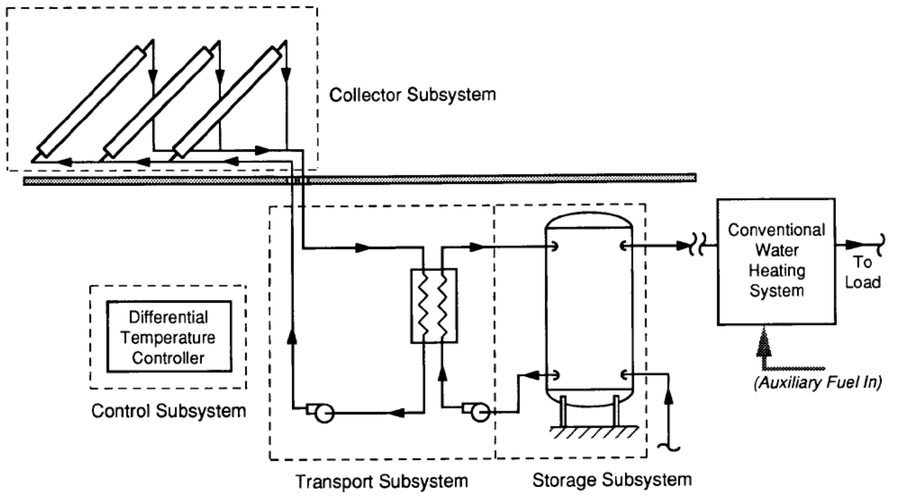

Figure 20: Model Diagram of a typical Solar Thermal System (UFC 2007)

3.1.1 Collector subsystem

<u>Thermal performance</u>

Solar collectors convert the incident solar energy into thermal energy by raising the temperature of a working fluid that comes in thermal contact with the absorption surface. In steady state the solar radiation collected by a collector per unit area is equal to the difference between the absorbed solar radiation and the thermal energy losses.

A heat transfer coefficient U_L is used to represent thermal energy losses from the collector to the surroundings by conduction, convection and radiation. The collected energy can be written as a function of the temperature difference between the inlet temperature of the heat transfer fluid and the ambient temperature (Duffie and Beckmann 2006)

$$\frac{q}{A} = F_R\left(I_{solar}\left(\tau\alpha\right) - U_L \Delta T\right) \tag{3.1}$$

where q are the heat gains, A is the aperture area of the collector, F_R is the collector heat removal factor, an empirically determined correction factor describing the ratio of actual energy gained by the collector to the maximum possible heat gain, I_{solar} is the total incident solar radiation, τα is the product of all transmittance and absorbance terms, U_L is the overall heat loss coefficient combining conduction, convection, and infrared radiation losses, and ΔT is the temperature difference between the inlet fluid T_{in} temperature and the ambient temperature T_{air}.

The thermal efficiency of a collector is defined as the fraction of solar energy incident upon the gross surface area of the collector that is removed by the fluid circulating through the collector

$$n = \frac{q/A}{I_{solar}} \tag{3.2}$$

Substituting (3.1) into (3.2) yields

$$n = F_R\left(\tau\alpha\right) - F_R U_L \frac{\Delta T}{I_{solar}} \tag{3.3}$$

Assuming that FR(τα) and $-F_R U_L$ are constants for a given collector and flow rate, then the efficiency given by (3.3) is a linear function of the three parameters I_{solar}, T_{in}, and T_{air} defining the operating condition. A linear fit can be formulated to approximate the collector efficiency

$$n = n_o + a_1 \frac{\Delta T}{I_{solar}} \tag{3.4}$$

Similarly, a second order fit can be constructed using the form

$$n = n_o + a_1 \frac{\Delta T}{I_{solar}} + a_2 \frac{(\Delta T)^2}{I_{solar}} \tag{3.5}$$

where n_0, a_1 and a_2 are the performance parameters of the collector (ESTIF 2014):

n_o: Optical efficiency

Combined efficiency of the transparent cover and the absorber (-)

a_1: first order heat loss coefficient

Heat loss coefficient at collector fluid temperature equal to ambient temperature (W/m^2K)

a_2: second order heat loss coefficient

Temperature dependent term of heat loss coefficient (W/m^2K^2)

The collector performance parameters are provided by collector manufacturers and are estimated by performance rating tests under specific operating conditions.

<u>Incident Angle Modifier</u>

The transmittance and absorbance of the collector glazing varies with the incidence angle of radiation. Test conditions determine the performance parameters for normal incidence. An incident angle modifier $K_{\tau\alpha}$ can be introduced in order to account for the effects of off-normal incidence angles on the collector's plane. $K_{\tau\alpha}$ is written as (Duffie and Beckmann 2006)

$$K_{\tau\alpha} = \frac{\tau\alpha}{(\tau\alpha)_n} \tag{3.6}$$

The incident angle modifier varies from one collector to the other and is estimated experimentally as a function of incident angle. For flat plate collectors this relationship can be approximated by a linear fit

$$K_{\tau\alpha} = 1 + b_o \left(\frac{1}{\cos\vartheta} - 1 \right) \tag{3.7}$$

where b_o is the incidence angle modifier coefficient and θ is the incidence angle of the solar radiation on the collector plane.

Incident angle modifiers are estimated separately for direct, diffuse and reflected radiation. The global incident angle modifier is calculated by averaging the weighted values of each component

$$K_{\tau\alpha,n} = \frac{K_{\tau\alpha,B} I_B + K_{\tau\alpha,Diff} I_{Diff} + K_{\tau\alpha,R} I_R}{I_B + I_{Diff} + I_R} \tag{3.8}$$

The incident angle modifier of each solar component is calculated from (3.7). The incidence angles of diffuse and reflected radiation on a surface are given by

$$\theta_{diffuse} = 59.70 - 0.1388\beta + 0.001497\beta^2 \tag{3.9}$$

$$\theta_{reflected} = 90.00 - 0.5788\beta + 0.002693\beta^2 \tag{3.10}$$

where β is the collector tilt in degrees.

Inserting (3.8) into (3.1) and (3.3) heat gains and collector efficiency are written accordingly

$$\frac{q}{A} = F_R \left[I_{solar} K_{\tau\alpha,n} \left(\tau\alpha\right)_n - U_L \Delta T \right] \tag{3.11}$$

$$n = F_R K_{\tau\alpha,n} \left(\tau\alpha\right)_n - F_R U_L \frac{\Delta T}{I_{solar}} \tag{3.12}$$

Outline Temperature

The rate of gains per unit area calculated using (3.11) can be written as a function of the inlet and outlet temperature of the heat transfer fluid through the collector

$$\frac{q}{A} = \dot{m} C_p (T_o - T_i) \tag{3.13}$$

where

$\dot{m}$ = mass flow rate of the heat transfer fluid through the collector

C_p = specific heat of the heat transfer fluid

T_o = outlet temperature of the heat transfer fluid at the exit of the collector

T_i = inlet temperature of the heat transfer fluid at the exit of the collector

Equation (3.13) yields the outlet temperature of the heat transfer fluid

$$T_o = T_i + \frac{q}{\dot{m} C_p A} \tag{3.14}$$

3.1.2 Transport subsystem

The fluid transport subsystem is required to maintain efficient transport of thermal energy from the collectors to the storage tank. Water - propylene or ethylene glycol solutions are often used as heat transfer fluid due to the antifreeze and non-corrosion properties. In order to allow the use of antifreeze solutions in the collector loop a heat exchanger between collector and storage is used in combination with the collectors. The use of a heat exchanger degrades the overall performance of the solar energy system. The amount of degradation depends on the heat exchanger characteristics.

<u>Heat exchanger</u>

A common measure of heat exchanger performance is its effectiveness. Effectiveness is defined as the ratio of the actual heat transfer rate to the maximum possible rate. The heat exchanger performance is expressed in terms of effectiveness (Duffie and Beckmann 2006)

$$Q_{HX} = \varepsilon\left(\dot{m}C_p\right)_{\min}\left(T_o - T_{in}\right) \tag{3.15}$$

where $\left(\dot{m}C_p\right)_{\min}$ is the smaller of the fluid capacitance rate on the collector side and tank side of the heat exchanger, T_o is the outlet fluid temperature from the collector and T_{in} is the inlet water temperature to the heat exchanger.

The combination of a collector and a heat exchanger performs exactly like a collector alone, but with a reduced value of F_R' and is written as

$$\frac{q}{A} = F_R'\left[I_{solar}K_{\tau\alpha}\left(\tau\alpha\right)_n - U_L\Delta T\right] \tag{3.16}$$

where the modified heat removal factor F_R' is given by

$$\frac{F_R'}{F_R} = \left[1 + \frac{AF_RU_L}{\left(\dot{m}C_p\right)_c}\left(\frac{\left(\dot{m}C_p\right)_c}{\varepsilon\left(\dot{m}C_p\right)_{\min}} - 1\right)\right]^{-1} \tag{3.17}$$

<u>Pipe losses</u>

The energy losses from pipes leading to and returning from the collector to the ambient temperature T_a can be approximated by

$$L_{pipe} = U_p A_i \left(T_i - T_a\right) + U_p A_o (T_o - T_a) \tag{3.18}$$

where U_p is the heat loss coefficient of the pipes, A_i is the area for heat loss of the inlet pipe, A_o is the area for heat loss of the outlet pipe, T_i is the inlet fluid temperature at the point where it enters the pipe, T_o the outlet fluid temperature at the point where it leaves the pipe and T_a the ambient temperature.

Equation (3.16) can be modified to incorporate the pipe losses to the ambient

$$\frac{q}{A} = F_R' \left[I_{solar} K_{\tau\alpha,n} \left(\tau\alpha\right)_n - U_L \Delta T \right] - L_{pipe} \tag{3.19}$$

Equation (3.19) can be formulated to look like the usual collector equation if new modified values (τα)’ and U'_L are defined. The energy gain of the collector-pipe-heat exchanger system is given by

$$\frac{q}{A} = F_R' \left[I_{solar} K_{\tau\alpha,n} \left(\tau\alpha\right)_n' - U_L' \Delta T \right] \tag{3.20}$$

where (τα)’ is given by

$$\left(\tau\alpha\right)' = \frac{1}{1 + \dfrac{U_p A_o}{\dot{m} C_p}} \left(\tau\alpha\right) \tag{3.21}$$

and U'_L is written as

$$U_L' = \frac{1 - \dfrac{U_p A_i}{\dot{m} C_p} + \dfrac{U_p \left(A_i + A_o\right)}{A F_R U_L}}{1 + \dfrac{U_p A_o}{\dot{m} C_p}} U_L \tag{3.22}$$

3.1.3 Storage subsystem

The intermittent nature of solar energy establishes a need for storage of the thermal energy collected by the collector subsystem in order to increase the system’s reliability to meet a particular load. The most common storage method for a thermal solar system is through the use of a water-filled tank that obtains thermal energy from the collector subsystem either directly or through a heat exchanger. The preheated water from the storage tank then functions as a source to an auxiliary heater or boiler that adds the necessary energy to raise it to the required temperature. The storage medium may be heated above the required temperature and a mixing valve is used to reduce the storage fluid to the desired temperature mixing it with mains water before it reaches the load.

The energy balance equation at the storage tank can be written as

$$\dot{m}C_p \frac{dT_s}{dT} = Q - L - U_s A_s \left(T_s - T_a\right) \tag{3.23}$$

where Q is the rate of addition of energy to the tank, L the rate of removal of energy to the load, U_s is the heat loss coefficient of the tank, A_s is the external surface of the tank, T_s is the tank temperature and T_a is the ambient temperature for the tank.

Using the simple Euler integration the tank temperature at the time point T_s^+ is calculated by

$$T_s^+ = T_s + \frac{\Delta t}{\left(\dot{m}C_p\right)_s}\left[Q - L - U_s A_s \left(T_s - T_a\right)\right] \tag{3.24}$$

In this case a mixed tank model is considered, an assumption which can be justified due to the relative small volume of the tank that is used in typical building applications. Simpler models are advantageous since they are computationally more efficient. This is not to say mixing phenomena are not important in a tank model, but other effects such as pipe losses, auxiliary heat, and internal heat exchangers would probably be rather difficult to incorporate into these models (Newton 1995, Zurigat et al. 1989).

3.1.4 Control subsystem

Control units are used in active solar systems to regulate the system operation and ensure that the system operates only under net energy gains conditions. The most common control scheme is the differential temperature control. Two temperature sensors are used, one at the exit of the collector and the second at the bottom of the storage tank. The control unit receives the data from the sensors and activates the circulating pump whenever the temperature difference between solar collector and storage tank exceeds a specified amount ΔT_{on}. Similarly, whenever the temperature difference falls below a limit value ΔT_{off} the pump is turned off.

In order to take into account the controlled system operation Equation can be modified to account for the control unit

$$\frac{q}{A} = F_R'\left[I_{solar}K_{\tau\alpha,n}\left(\tau\alpha\right)_n' - U_L'\Delta T\right]^+ \tag{3.25}$$

The superscript in this case denotes the system operation only when the energy output of the system is positive q>0 or equivalently under net gain conditions.

3.1.5 Solar thermal system efficiency

Substituting (3.25) to (3.20) the instantaneous efficiency of the solar system is given by

$$n_{SHW} = \frac{F_R'\left[I_{solar}K_{\tau\alpha,n}\left(\tau\alpha\right)_n' - U_L'\Delta T\right]^+}{I_{solar}} \tag{3.26}$$

The solution of the above equation requires taking transient phenomena into consideration, due to the variable nature of solar radiation and can be estimated using numerical methods as analytical solution approaches provide results with reduced accuracy (Duffie and Beckman 2006, Hassan 2003).

3.1.6 Solar thermal system energy output

The energy output of a thermal system can be calculated from (3.1) which yields

$$E_{out,SHW} = n_{SHW} I_{solar} A_{SHW} \tag{3.27}$$

where $E_{out,SHW}$ is the energy output of the solar system, n_{SHW} is the efficiency of the system calculated from (3.26), I_{solar} is the incident solar radiation in the collector plane and A_{SHW} is the area of the collectors.

Substituting (3.26) to the above equation yields

$$E_{out,SHW} = F_R'\left[I_{solar}K_{\tau\alpha}\left(\tau\alpha\right)_n' - U_L'\left(\mathrm{T}_i - T_a\right)\right]^+ A_{SHW} I_{solar} \tag{3.28}$$

Once the overall efficiency of the system is determined the solar thermal energy delivered to the building can be estimated. The data flow diagram for the estimation of the Solar Water Heating system performance based on the model described above is illustrated in Figure 21.

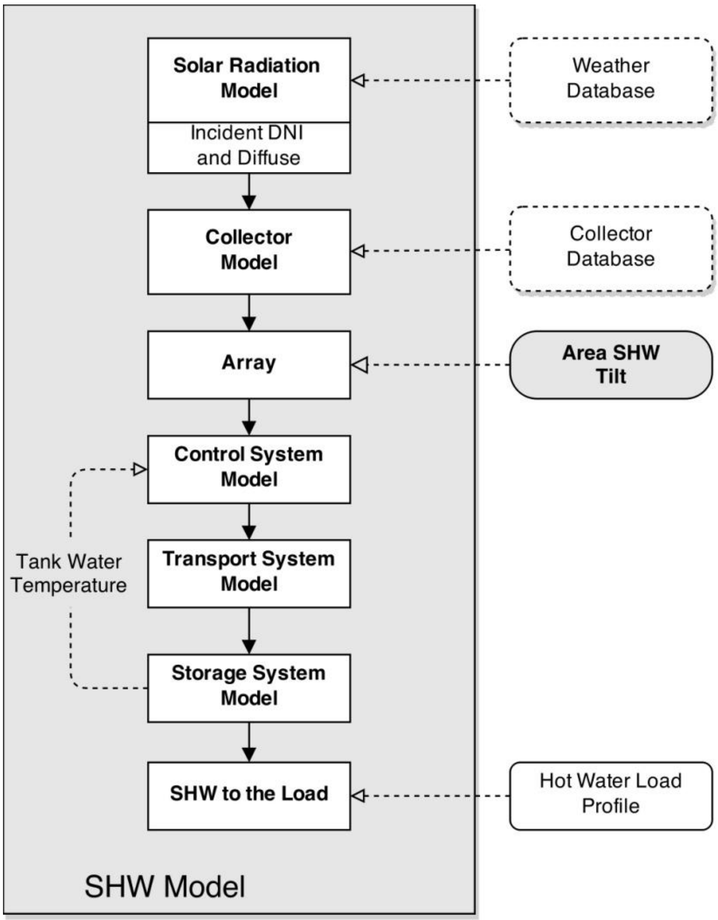

Figure 21: SHW system model – Data flow diagram

3.2 Photovoltaic system model

Photovoltaic solar energy systems capture incident solar radiation and convert it directly into electricity based on the photovoltaic effect. PV systems can operate as grid-connected systems, connected to an electrical utility grid, as stand alone, off the grid using storage batteries, or in some cases as direct use systems applications where the load matches the available radiation exactly.

Photovoltaic systems have relatively few components. The behavior of these components is generally non-linear and their interactions are complex. A photovoltaic energy system can be divided into two subsystems the solar array and the balance of system (BOS).

The **solar array subsystem** consists of the PV panels which are electrically and mechanically assembled into arrays. The number of modules in series determines the system voltage whereas the parallel connection of module strings determines the current of the plant. The output power of the array is the product of system voltage and current.

The **balance-of-systems** includes all the components added to the PV panels. Balance of system components are usually divided into four categories based on their basic functions: *inverters,* required to convert the DC power produced by the PV array into AC power, *energy storage batteries*, used in stand-alone systems to store electricity to provide energy on demand, *controllers,* necessary for the smooth operation of the system as they regulate energy storage to the battery as well as energy delivery to the load and finally the associated *mounting structure* used to install the PV modules and other components. The cables and protection devices necessary for safe current transfer are also included into the balance-of-systems.

The computer model used to describe the photovoltaic energy system for on-grid applications is presented below. This model is based on the NOCT model for predicting the cell temperature.

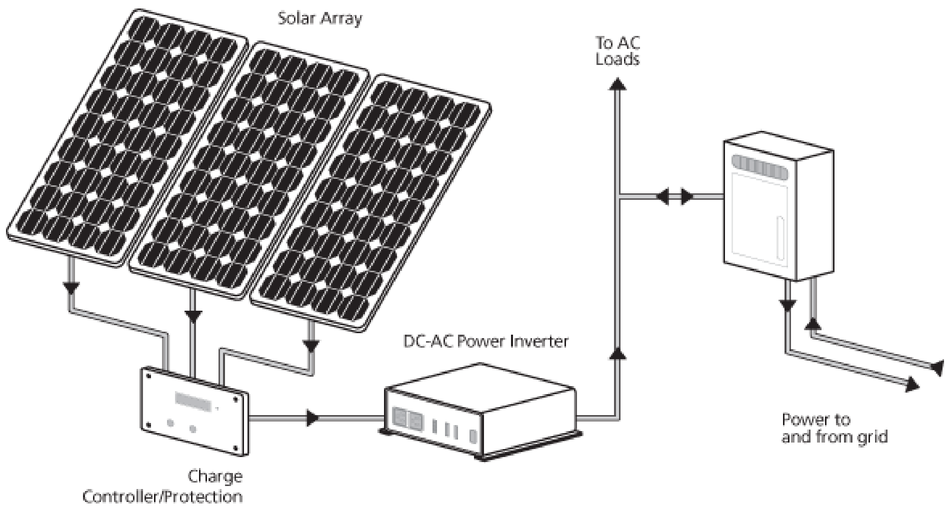

Figure 22: Model Diagram of a typical On-grid Photovoltaic System (SamlexSolar 2014)

3.2.1 Array subsystem

Photovoltaic collectors absorb the incident solar radiation and convert it directly into useful electrical energy.

In steady state the solar radiation absorbed by a panel per unit area is equal to the difference between the solar energy converted into electricity and the thermal energy losses.

A heat transfer coefficient U_L can be used to represent the thermal energy losses from the panel to the surroundings by conduction, convection and radiation as a function of the temperature difference between the cell temperature of the panel and the ambient temperature. The energy output described by the equation above can be represented as

$$\frac{p}{A} = I_{solar}\left(\tau\alpha\right) - U_L\left(T_c - T_a\right) \tag{3.29}$$

where p is electrical energy output of the panel, A is the aperture area of the panel, I_{solar} is the total incident solar radiation on the panel plane, τα is the transmittance-absorbance product, U_L is the heat transfer coefficient, T_c is the cell or panel temperature and T_a is the ambient temperature.
The solar energy collection efficiency of a photovoltaic panel is defined as the ratio of the power output of collector, to the usable incident solar radiation on the aperture area of the panel

$$n = \frac{p/A}{I_{solar}} \tag{3.30}$$

where p is the electrical energy output, A is the aperture area of the panel and I_{solar} is the total incident solar radiation on the panel plane. The above equation is similar to Equation (3.2) used to estimate the efficiency of a solar thermal system.

The ratio $\tau\alpha/U_L$ can be written as a function of the cell temperature, ambient temperature and solar radiation under reference operating conditions using

$$\frac{\tau\alpha}{U_L} = \frac{T_{c,r} - T_{a,r}}{I_{solar,r}} \tag{3.31}$$

where $T_{c,r}$ is the cell temperature at reference conditions, $T_{a,r}$ is the ambient temperature at reference conditions, $I_{solar,r}$ is the incident solar radiation at reference conditions. Usually the value of the cell reference temperature is measured at nominal operating conditions with solar radiation level of 800 W/m^2, ambient temperature of 20^{o}C and wind speed of 1m/s.

The cell temperature of the PV at any other condition, assuming that $\tau\alpha/U_L$ remains constant is estimated by (Duffie and Beckmann 2006)

$$T_c = T_a + \frac{K_{\tau\alpha,n} I_{solar}}{I_{solar,r}} \left(T_{c,r} - T_{a,r}\right)\left(1 - \frac{n_{c,r}}{\tau\alpha}\right) \tag{3.32}$$

where T_a *is the ambient temperature,* I_{solar} is the total solar radiation on the panel plane, $K_{\tau\alpha,n}$ is the global incident angle modifier calculated by Equation (3.8), $n_{c,r}$ is the efficiency of the panel in converting incident solar energy into electricity at reference conditions and $\tau\alpha$ is the transmittance-absorbance product of the panel. The values of reference cell temperature $T_{c,r}$ and reference panel efficiency $n_{c,r}$ are provide by the manufacturer.

The efficiency of a photovoltaic panel or array at any irradiance level and ambient temperature can be written as a function of the cell temperature T_c

$$n_c = n_{c,r}\left[1 - \beta\left(T_c - T_{c,r}\right)\right] \tag{3.33}$$

where β is the temperature efficiency coefficient of the panel provided also by the manufacturer.

3.2.2 Balance-of-systems

The array efficiency calculated by (3.33) has to be further reduced by a factor n_p in order to account for the losses introduced at the Balance-of-systems components. The factor n_p represents various losses at the inverter, the transformers and the wiring and can be written as

$$n_e = n_i n_{BOS} \tag{3.34}$$

Where n_i is the efficiency of the inverter and n_{BOS} is the efficiency of the rest of the BoS components.

3.2.3 Photovoltaic System Energy Output

The electrical energy output of the collector is calculated by (3.29) which by substituting by (3.33) and (3.34) can be written as

$$E_{out,PV} = n_c n_i n_{BOS} K_{\tau\alpha,n} I_{solar} A_{PV} \tag{3.35}$$

where $E_{out,PV}$ is the energy output of the solar system, n_c is the efficiency of the panels, by (3.34), I_{solar} is the incident solar radiation on the panel plane and A_{SHW} is the area of the panels.

Substituting (3.35) to the above equation yields

$$E_{out,PV} = n_{PV} K_{\tau\alpha,n} I_{solar} A_{PV} \tag{3.36}$$

Once the overall efficiency of the system is determined the energy output of the system can be estimated. The data flow diagram for the estimation of the Photovoltaic system performance based on the model described above is illustrated in Figure 23.

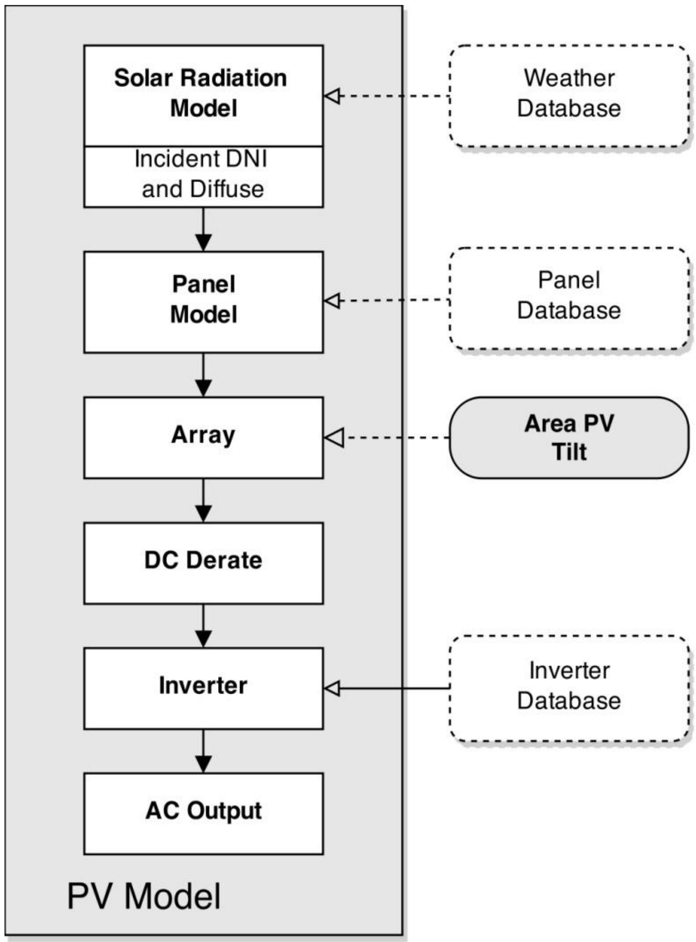

Figure 23: PV system model Flowchart

3.3 Solar Energy System Performance

The design of an effective solar system depends upon the annual system performance which is generally different from the collector efficiency. The performance of solar systems can be evaluated using performance indicators. Solar fraction *SF* and the capacity factor *f* are two common performance indicators for active solar systems. Solar fraction relates energy output of the system to the load demand, and is usually used for the performance evaluation of solar thermal systems, whereas capacity factor relates the system output to its maximum output and is often used for the evaluation of photovoltaic systems.

Solar fraction can be defined as the fraction of the energy supplied by the solar technology divided by the total energy required. For a particular system solar fraction is dependent on the load, the collection and storage sizes, the system efficiency and the climate. For solar thermal systems, a relatively small increase in collector area leads to a steep increase in the solar fraction in the region of small collector area. As the area of collectors' further increases, additions to the solar surface result into smaller increases of solar fraction (Figure 24).

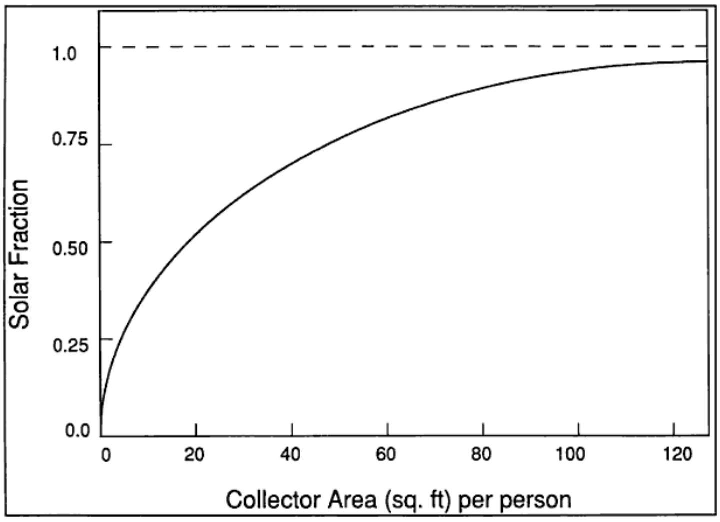

Figure 24: Fraction by solar as a function collector area (UFC 2007)

Capacity factor *f* refers to the difference between what the system can produce at continuous maximum output, the power rating, versus what it actually supplies under normal operating conditions. For example, if a solar collector has a capacity factor of 20% its average energy output will be 20% of what it was designed to achieve, e.g. a 100 W solar collector with a capacity factor of 20% has an average energy output of 20 W. The capacity factor of a power system is defined as the average power output of the system divided by its rated power output.

The solar collector power rating is an analytically-derived value representing the characteristic average energy output of the solar collectors under standard rating conditions, measured in Watts per square meter (W/m^2). Capacity factor *f* relates thus to the climate and the system efficiency.

For a photovoltaic system f_{PV} results from (3.36) and the definition of capacity factor and is written as

$$f_{PV} = \frac{n_{PV} I_{solar} A_{PV}}{E_{rated,PV} A_{PV}} = \frac{n_{PV} I_{solar}}{E_{rated,PV}} \qquad (3.37)$$

The efficiency of a photovoltaic system is independent of the area of collectors, as seen in (3.37). Therefore the performance is a linear function of the solar area and the value of *f* remains constant as the area increases.

The above conclusions are useful for interpreting the output results that are presented and discussed in the next chapter.

4 DEMONSTRATIVE RUNS

In the previous chapter the models for photovoltaic generation, thermal generation and thermal energy storage devices were determined in order to quantify the supplied energy from the system. In the current chapter the output results of demonstrative runs of the system models are presented in order to explore the trade-offs between design variables and system performance. First the input values for the simulation are discussed and determined and next, the results of three design scenarios are presented and compared.

4.1 General set-up

Before running the performance analyses against environmental and economical criteria, the input values need first to be determined.

CO_2 emission factor

As already discussed in chapter 2.1 this work concentrates on the use of the emission factor based method for the evaluation of the environmental performance. According to this method, the environmental performance can be assessed considering the carbon dioxide (CO_2) emissions gains achieved due to the solar system operation. For the calculations it is necessary to estimate the annual energy production and energy consumption of the system, and the carbon dioxide conversion factor. CO_2 emission factor is an index used to derive estimates of carbon dioxide emissions based on the amount of fuel combusted. The value is dependent upon the fuel that is used to produce the required energy.

Carbon dioxide emissions from fuel combustions are derived by multiplying fuel consumption total by the appropriate conversion factor; specifically for electric energy, the ranges of emissions factor vary significantly between countries, due to differences in the electricity mix.

For the base case scenario, a standard gas boiler is considered to deliver auxiliary thermal energy when the thermal solar system energy output is not sufficient to cover the load energy demand.

Cost analysis

Based on the discussion in Chapter 2, the cost benefit analysis takes into account the life cycle of the system. For this reason, the net present value of each design variant is determined according to Equation (2.2). For the estimation of the net present value the following parameters need to be determined:

- the initial investment cost of the system
- the maintenance costs
- energy costs
- the annual price increase above inflation
- the discount rate
- the amount of subsidies
- the life span of the system

Initial investment costs of the system correspond to the equipment costs and mounting costs. Costs of photovoltaic systems are usually provided as a function of the installed energy of the system (Euros/kWh), while for thermal solar systems these costs are given per area of installed collectors. For residential applications a fixed price per unit of installed energy / collectors' area can be considered as a realistic approach. Current costs of solar thermal systems in Austria are estimated to be 970 Euros/m^2 (Austria Solar 2014). Costs of photovoltaic systems are estimated to be 2.250 Euros/kWp (Austrian Energy Agency 2014). Maintenance costs are estimated in the current study to be 1% of the total initial cost of the system. Current energy costs in Austria are 0,178 Euros/kWh for electricity, 0,0728 Euros/kWh for natural gas and 0,9120 Euros/Liter for oil (IWO 2014). Retail electricity prices are influenced by fuel prices, and particularly by natural gas prices. Subsidies related to the initial investment costs are considered to be 30% of the initial capital cost for both solar thermal and photovoltaic systems, while the costs of photovoltaic electrical energy sold to the grid are currently 0,125 Euros/kWh (Austria Solar 2014, Bundesgesetzblatt 2013). Electricity subsidies are estimated to rise with a rate of 3% during the next 25 years (Austrian Energy Agency 2014). For electricity costs an increase rate of 3% is also adopted (Figure 25). The physical life expectancy of the system is estimated to be 25 years, which is a common assumption for solar systems. An annual system performance degradation of 0,5% is considered. The real discount rate adopted in the current study is assumed to be equal to the interest rate. Based on the interest rate values for the last 25 years (Figure 26) the mean value of 2,5% can be used to estimate the interest rate during the life cycle of the system.

The values of the financial analysis parameters are summarized in Table 4.

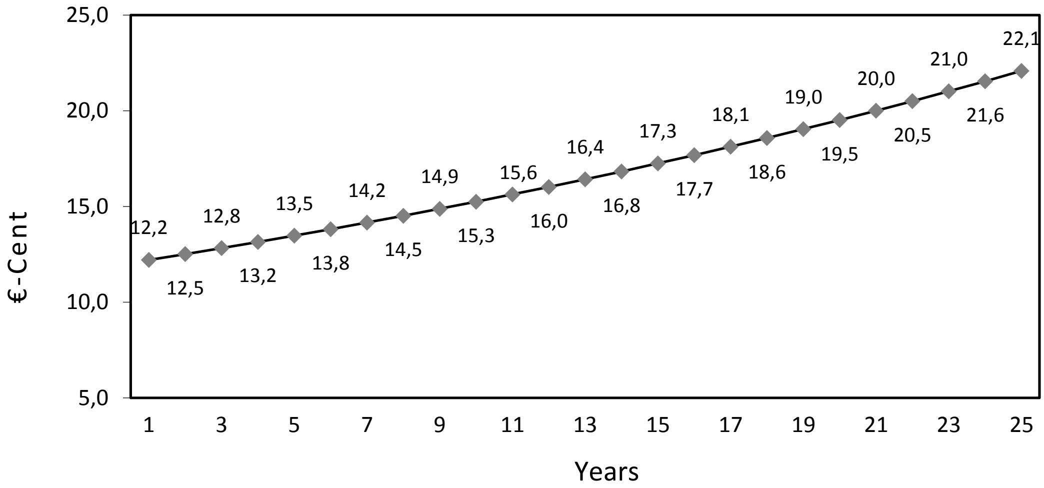

Figure 25: Forecast for electricity buy down rate during the system life span (Austrian Energy Agency 2014)

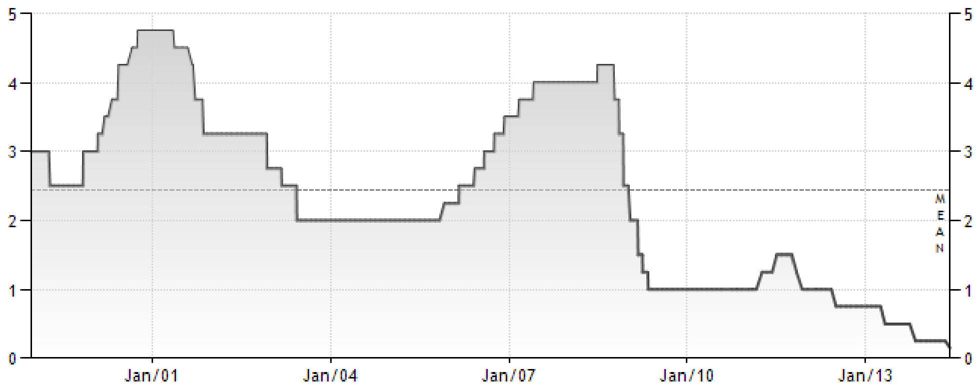

Figure 26: Austria Interest rate 1998 – 2014 (European Central Bank 2014 Trading Economics 2014)

Table 4: Set-up values for the economical analysis

Cost parameter	Value
Investment Cost SHW system	970 Euros/m^2
Investment Cost PV system	2.250 Euros/kWp
Annual maintenance costs	1 % of the total investment
Life span of the system	25 years
Annual system degradation	0,5 %
Electricity costs	0,178 Euros/ kWh
Natural gas costs	0,0728 Euros/kWh
Real annual electricity price increase	3 %
Discount rate	2,5 %
PV installation subsidy	30%
SHW installation subsidy	30%
PV production price	0,125 Euros/kWh

4.2 Results overview

Outputs of the computer models and the optimization method are presented and discussed below. A base case scenario is initially considered and next two alternative design scenarios are studied. The trade-off between the size of each system (photovoltaic and solar thermal) and the system performance is plotted and the results are discussed. The performance criteria used are the carbon dioxide emission reduction and the net present value of the solar system.

The maximum total area of the collectors remains constant. A run is performed for a residential building with an area of 1000m^2 and area of collectors equal to 300m^2. This building will be used as reference for the output results. Next the output is calculated for a higher total area of collectors equal to 400 m^2 and a transition of the optimum towards a larger area of photovoltaic systems is noticed, in comparison with the base-case scenario. Finally, a scenario with a lower total area of 100m^2 is studied. The optimal point in this case is moved towards a larger area of thermal collectors. The studied scenarios and the output results are analyzed below.

Base-case scenario

For the base-case scenario an area equal to 30% of the building net floor area is available for installation of solar systems. An auxiliary system of standard gas tank is used to deliver energy to the load when the energy supply of the solar thermal system is not enough. Output plots for the base case scenario are presented below. Figure 27 illustrates the CO_2 emission reduction trade-off and Figure 28 the net present value trade-off for different allocations of the available installation area.

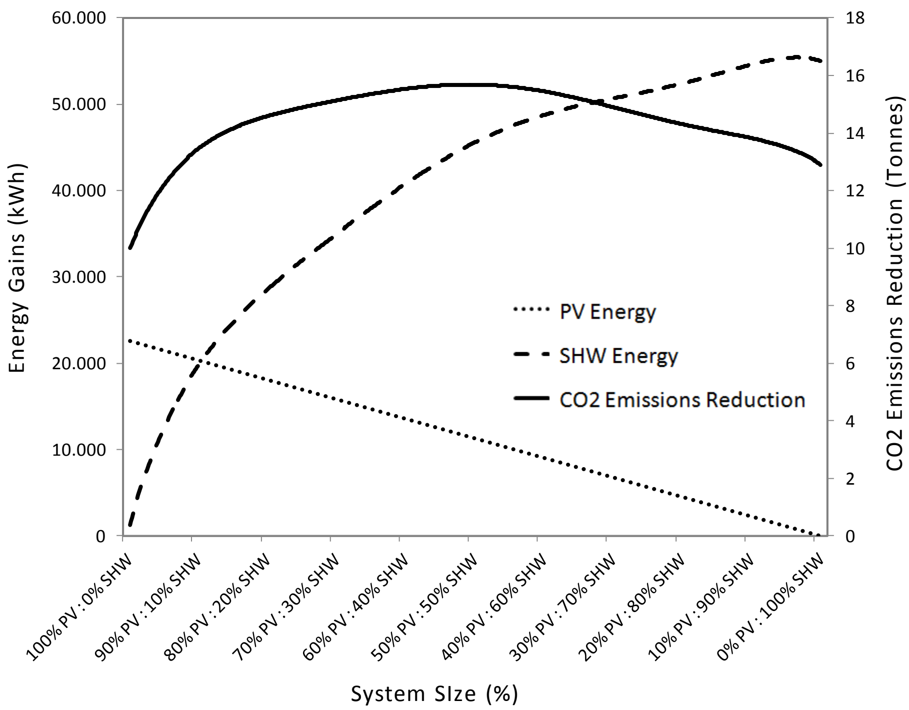

Figure 27: System CO_2 emission reductions trade-off as a function of area allocation

DHW Auxiliary system: Natural gas standard tank

(Collector area: 30% building area, optimal tilt =36^o)

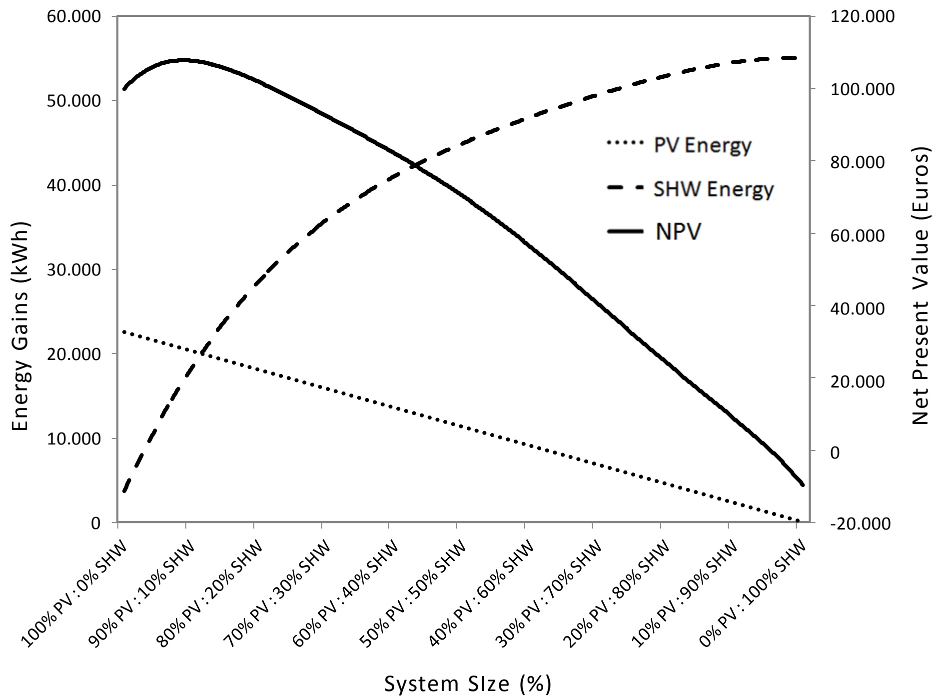

Figure 28: System Net Present Value trade-off as a function of area allocation

DHW Auxiliary system: Natural gas standard tank

(Collector area: 30% building area, optimal tilt =36^o)

Scenario 40% available area

A second scenario with a higher available area equal to 40% of the building net floor area is considered. From the output plots it is noticed that as the total collector area of the system increases, the optimal point is moving towards a lower percentage of solar collectors. This is because the increment of collector area results into increased losses due to unused energy and therefore system capacity factor decreases. For the same reason it is noticed that an increase in thermal collector area has a small impact on total thermal energy production. The optimal point is when the solar fraction of the thermal collectors' system is maximized. This is explained by the fact that the capacity of the photovoltaic system remains constant, as already discussed, because it is not dependent on the collector area. The CO_2 emission reduction trade-off for different allocations of the available installation area is illustrated in Figure 29 and the net present value trade-off is presented in Figure 30.

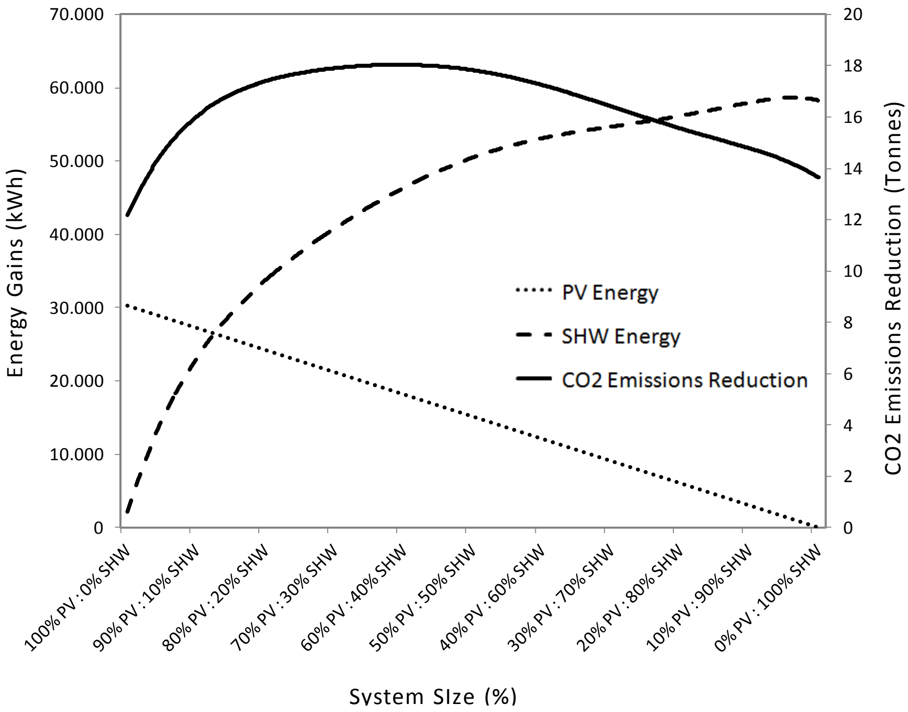

Figure 29: System CO_2 emission reductions trade-off as a function of area allocation

DHW Auxiliary system: Natural gas standard tank

(Collector area: 40% building area, optimal tilt =36^o)

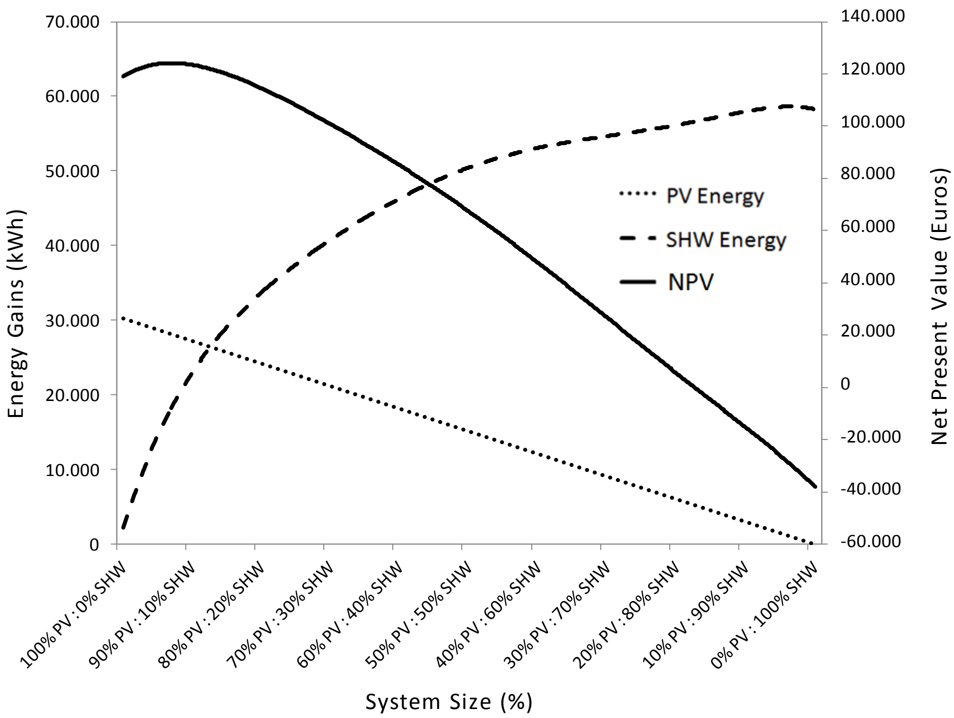

Figure 30: System Net Present Value trade-off as a function of area allocation

DHW Auxiliary system: Natural gas standard tank

(Collector area: 40% building area, optimal tilt =36^o)

<u>Scenario 10% available area</u>

A third scenario is with an available area equal to 10% of the building net floor area is studied. The energy gains of the solar system are in this case lower in comparison to the base-case scenario and the achievable CO_2 emission benefits of the optimal system are reduced by half, while the net present value is around reduced to one third. In this case, the variation in the financial performance of the optimal system is proportional to the total system area. Figure 29 illustrates the CO_2 emission reduction trade-off and Figure 30 the net present value trade-off for different allocations of the available installation area.

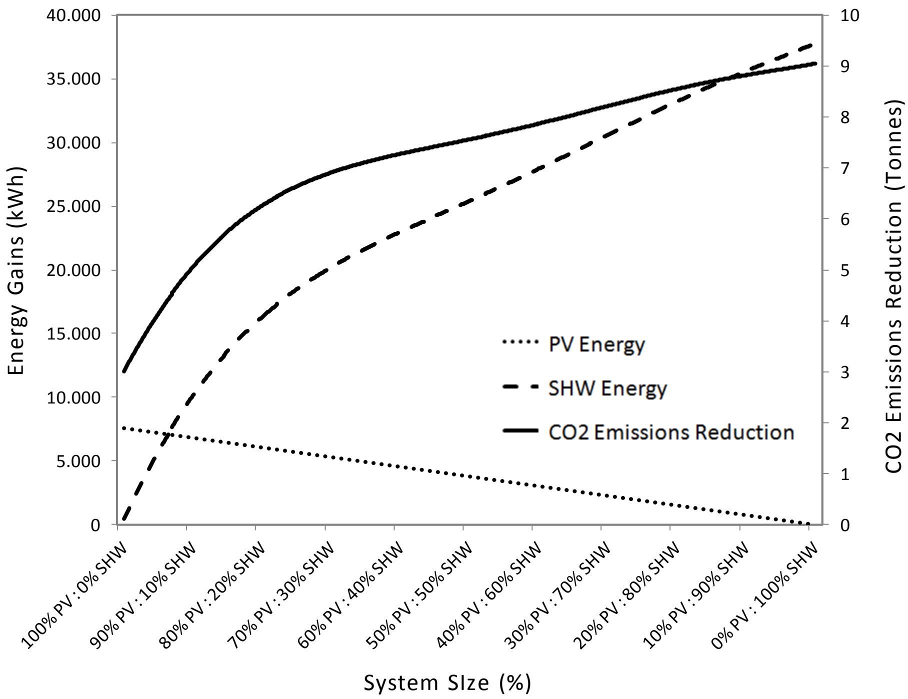

Figure 31: System CO_2 emission reductions trade-off as a function of area allocation
DHW Auxiliary system: Natural gas standard tank
(Collector area: 10% building area, optimal tilt =36^o)

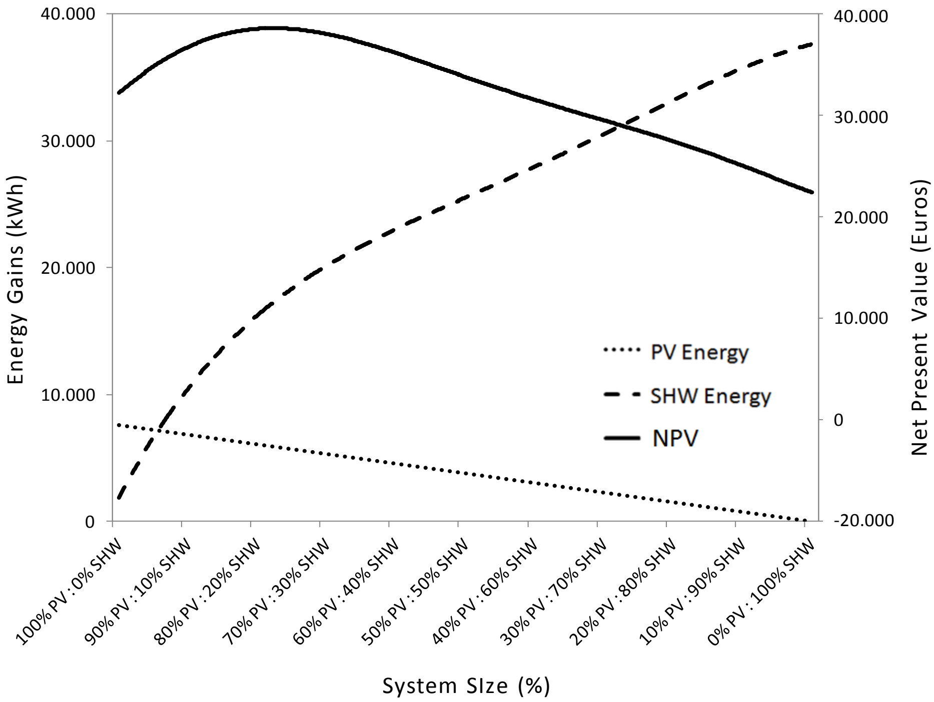

Figure 32: System Net Present Value trade-off as a function of area allocation

DHW Auxiliary system: Natural gas standard tank

(Collector area: 10% building area, optimal tilt =36^{o})

The output results reveal that the optimal combination of solar technologies for a specific building and available area depends on the performance criterion that is used for the evaluation of the system.

For an available area equal to 30% of the building area, the optimal mix is 50% SHW and 50% PV when the criterion is the benefits from CO_2 emission reduction, and 10% SHW and 90% PV when the criterion is the maximization of the net present value.

For a relatively higher available area, equal to 40% of the building area, the optimal mix is 40% SHW and 60% PV when the criterion is the CO_2 emission reduction benefits, and 5% SHW and 95% PV when the criterion is the maximization of the net present value.

For a relatively lower available area, equal to 10% of the building area, the optimal mix is 100% SHW and 0% PV when the criterion is the CO_2 emission reduction benefits, and 20% SHW and 80% PV when the criterion is the maximization of the net present value.

Based on the above we conclude that when the design objective is the economical performance, systems with larger photovoltaic area result compared to the systems that result when the criterion is the maximization of the environmental performance. This is due to the financial gains achieved by the photovoltaic energy production which is sold to the grid.

Generally, the solar thermal system exhibits higher energy performance, however the achieved energy gains are balanced by higher CO_2 reductions achieved by the photovoltaic system. This is due to the fact that CO_2 emission coefficient for electricity is higher than the equivalent coefficient for gas as seen in Table 2.

5 EXTENSIONS TO SEMERGY BUILDING MODEL

The addition of the solar component to the system will require the extension of Semergy Building Models to support the required inputs for the calculations. A main characteristic of SEMERGY Building Model is its modular structure (Figure 33). Each component in SEMERGY that performs a specific function accesses the SEMERGY data model to get the necessary input for this function. The solar system module requires several inputs that must be derived from the building description and the location properties.

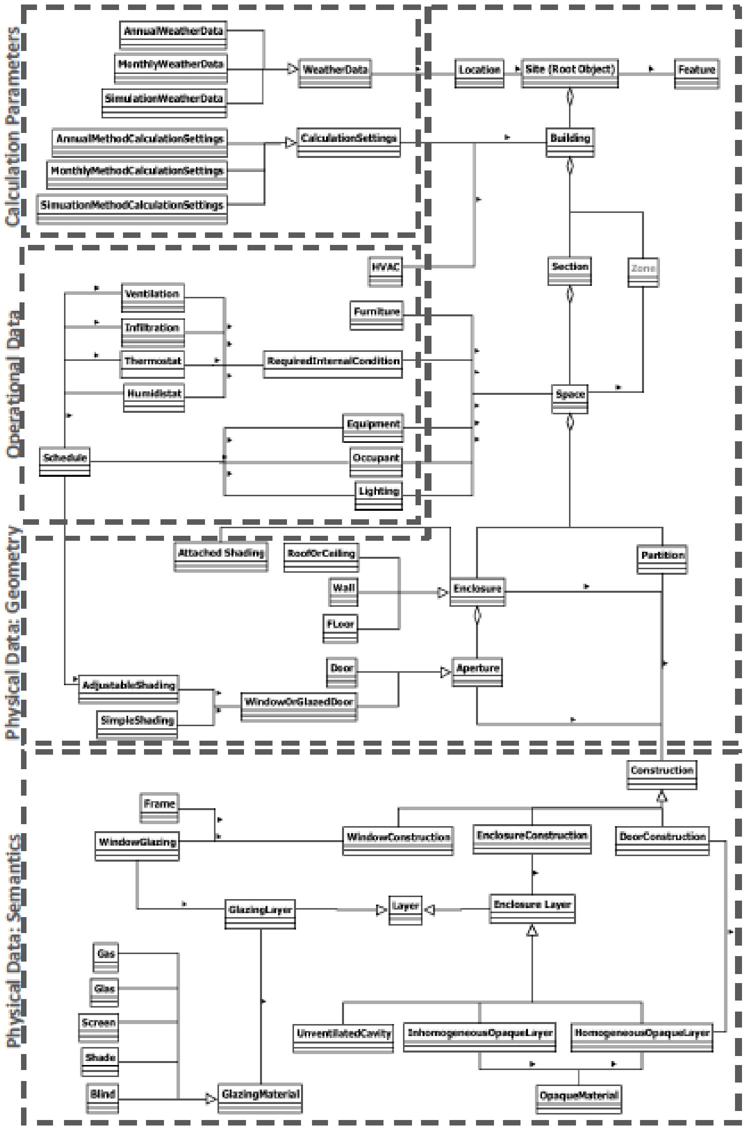

Figure 33: SEMERGY Building Model - Schematic Diagram (Ghiassi 2013)

Active solar system properties are classified under the operational data category of SBM. Their information is contained in the Active Solar Systems module which is object of the Building module.

The Active Solar System module is comprised of two sub modules. The first module includes information on the Photovoltaic system and the second of the thermal solar system.

Information contained in other modules is required for the calculations and is the following:

a) Weather data, contained in the Weather Data Class of the Location object
b) Building usage, contained in Building object. This input is required for the determination of the hot water load profile template from the predefined data repositories
c) Enclosure gross area (wall, roof), contained in the Enclosure object. This input is required for the determination of the maximum area for collectors' installation, if not else specified by the user

5.1 Solar system data model

Input parameters of the solar system are structured in the solar data module. The module contains information which is common for the solar system and more specifically on the surface available for the installation of the collectors. The input fields are analyzed below:

RelativeDirectionToNorth: double

This value refers to the orientation of the installation surface (degrees). The input is retrieved from the Enclosure object. The user can however overwrite this value if the user defined input is chosen in the field Installation surface.

RelativeAngleToHorizontal Plane: double

The relative angle in respect to horizontal plane refers to the slope of the installation surface (degrees). The value serves to estimate the relative position of collector rows

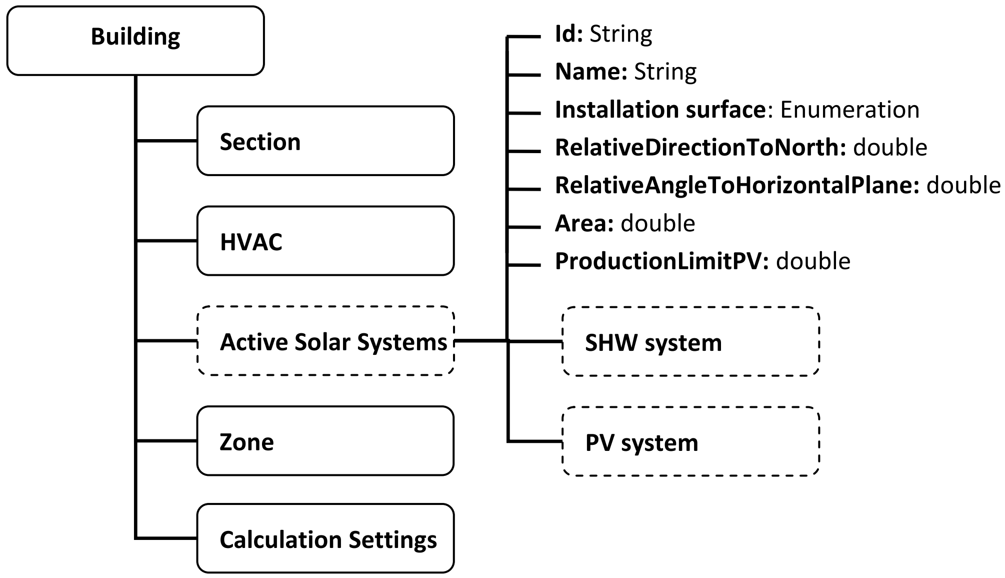

Figure 34: Extension of Building Object in SBM to include Class Active Solar Systems (Adapted from Ghiassi 2013)

for shading calculations. The input is retrieved from the Enclosure object; however the user can overwrite this value if the user defined input is chosen in the field Installation surface.

Area: double

This value refers to the total area available for installation of solar collectors (m^2). The input is retrieved from the Enclosure object. The user can however overwrite this value if the user defined input is chosen in the field Installation surface.

ProductionLimitPV: double

This value refers to the eventual net metering limits for on-grid photovoltaic system production (kWh).

5.2 Solar thermal collector data model

Input parameters of a thermal solar water system are structured in the SHW data module. The module contains information on the solar collectors, the pump, the heat tank and the heat exchanger. The input fields are analyzed below:

id: String

A unique ID number assigned to the SHW module

Name: String

A unique name assigned to the SHW module

SelectCollector: enum

The variable points to a specific element of a list of arrays named SelectPanelList. Each element of SelectPanelList corresponds to an array that contains the properties of a specific SHW collector. The list should be constantly updated according to the existing market products and the manufacturers' specifications. An input of zero enables the manual input of the properties of collector.

ApertureArea: double

The aperture area (m^2) of the thermal collector

CollectorLength: double

The length (m) of the thermal collector

CollectorHeight: double

The height (m) of the thermal collector

ZeroLossCollectorEfficiency no: double

Optical efficiency of the collector, (-)

HeatLossCoefficient: double

The first-order coefficient in collector efficiency equation, a_1 (W/m^2K)

TemperatureDependentHeatLossCoefficient: double

The second-order coefficient in collector efficiency equation, a_2 (W/m^2K)

The above 3 collector parameters are provided for collectors tested according to European Standards on solar collectors (CEN 2001).

PipeLength: double

The length of piping (m) of the SHW system

PipeInsulationConductivity: double

The conductivity (W/mK) of the piping insulation

PumpEfficiency: double

This value refers to the efficiency of the circulation pump (-)

FluidFlowRate: double

The flow rate of the transfer fluid per collector (kg/s)

HeatExchangerUValue: double

The U value (W/m^2K) of the of the insulation of the heat exchanger

TankUValue: double

The U value (W/m^2K) of the of the insulation of the storage tank

TemperatureMechanicalRoom: double

The temperature of mechanical room (^oC) for calculation of heat losses at storage tank

AuxiliarySystem: enum

This value refers to the type auxiliary heating system used to provide hot water when the solar production is not enough to offset the demand. The variable points to a specific element of the list of predefined building systems for hot water preparation. The option “user defined input” allows user to manually input information to the relevant fields.

AuxiliarySystemHeatingEfficiency: double

The efficiency of auxiliary heating system used to provide hot water when the solar production is not enough to offset the demand (-). The input is retrieved from a predefined list, however the user can overwrite this value if the user defined input is chosen in the field Installation surface.

AuxiliarySystemEnergyFactor: double

The value is used to calculate the energy conversion factor of auxiliary heating system used to provide hot water when the solar production is not enough to offset the demand (-). The input is retrieved from a predefined list, however the user can overwrite this value if the user defined input is chosen in the field Installation surface.

SHWSystemCostPerSquareMeter: double

System installation cost per square meter ($Euros/m^2$). The value is used for the estimation of investment costs.

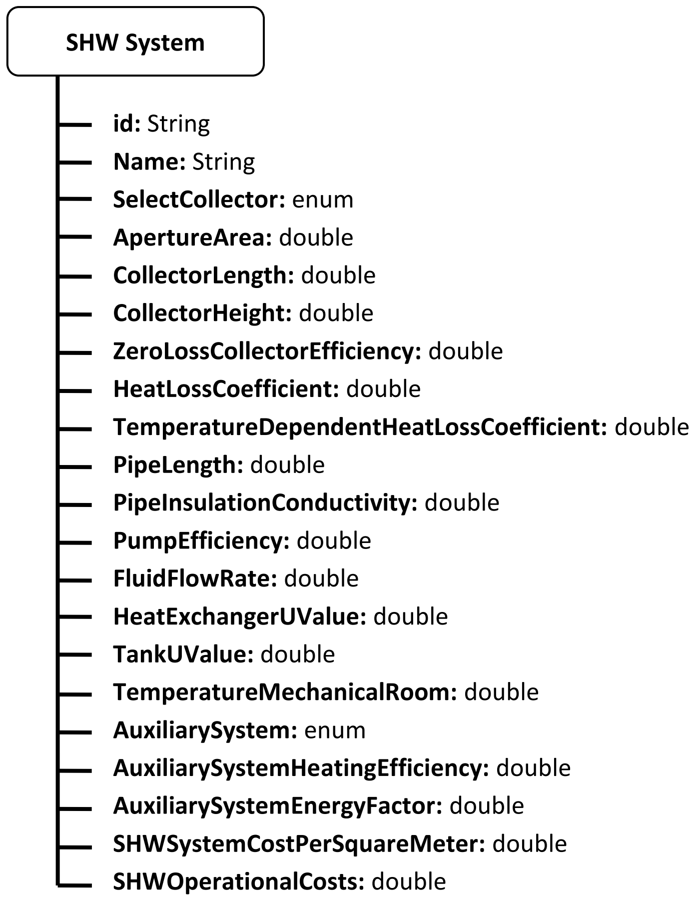

Figure 35: SHW System data model in SBM

SHWOperationalCostsPerSquareMeter: double

System operation and maintenance cost per square meter (Euros/m^2). The value is used for the estimation of investment costs.

5.3 Solar photovoltaic data model

Input parameters of the photovoltaic system are structured in the PV data module. The module contains information on the photovoltaic panels, the inverter and the balance of systems. The input fields are analyzed below:

id: String

A unique ID number assigned to the PV module

Name: String

A unique name assigned to the PV module

SelectPanel: enum

The variable points to a specific element of a list of arrays named PVSelectPanelList. Each element of PVSelectPanelList corresponds to an array that contains the properties of a specific PV collector. The list should be constantly updated according to the existing market products and the manufacturers' specifications. An input of zero enables the manual input of the properties of collector.

ApertureArea: double

The aperture area (m^2) of the photovoltaic panel

PanelLength: double

The length (m) of the photovoltaic panel

PanelHeight: double

The height (m) of the photovoltaic panel

PanelRatedPower: double

Rated power of the panel according to the manufacturer (kW)

TemperatureEfficiencyCoefficient: double

The temperature efficiency coefficient according to the manufacturer (K^{-1}). This value is used for estimation of the performance of the PV panel

NominalOperatingCellTemperature: double

The Nominal Operating Cell Temperature (NOCT) according to the manufacturer (K)

RadiationSTC: double

Solar radiation at Standard Test Conditions (STC) as provided from the manufacturer

CellTemperatureSTC: double

Panel cell temperature at Standard Test Conditions (STC) as provided from the manufacturer

EfficiencyBOS: double

Efficiency factor of the Balance of Systems

PV System

- **id:** String
- **Name:** String
- **SelectPanel:** enum
- **ApertureArea:** double
- **PanelLength:** double
- **PanelHeight:** double
- **PanelRatedPower:** double
- **TemperatureEfficiencyCoefficient:** double
- **NominalOperatingCellTemperature:** double
- **RadiationSTC:** double
- **CellTemperatureSTC:** double
- **EfficiencyBOS:** double
- **SystemCostPerSquareMeter:** double
- **PVOperationalCostsPerSquareMeter:** double
- **PVSystemCosts PerSquareMeter:** double

Figure 36: Photovoltaic system data model in SBM

PVSystemCostPerSquareMeter: double

System installation cost per square meter (Euros/m^2). The value is used for the estimation of investment costs.

PVOperationalCostsPerSquareMeter: double

System operation and maintenance cost per square meter (Euros/m^2). The value is used for the estimation of investment costs.

6 CONCLUSIONS AND FURTHER RESEARCH

A combined use of thermal collectors and photovoltaics, planned according to the building energy demand can maximize the potential energy gains and improve building performance. Design of building integrated active solar systems is nonetheless bounded by usability restrictions on the available software tools. Most of these tools make performance assessments and do not point to efficient design paths. Also current tools performing design optimization are stand-alone, a fact that increases design time and effort. Two issues need thus to be addressed: design optimization and seamless integration into a common building design system.

These topics are addressed in the current work with the development of a software component for solar systems design that runs on SEMERGY, a multi-objective optimization platform for buildings.

The modular design of SEMERGY provides the flexibility to develop various modules easily and independently with the rest modules; therefore it reduces the possibility of errors and minimizes development time.

The implementation of the solar system component enhances the optimization functions of SEMERGY, since it allows the user to be able to design buildings with more specific requirements.

The algorithm which the software component implements, detects the optimal solar system configuration and thus enhances the performance of the building where the system is integrated.

Based on the conclusions of this study, the further future research is recommended:

The thermal model currently considers only hot water load profile. It could be further extended to include energy for the heating demand of the building. This energy can be estimated by the heating load profile that is calculated in SEMERGY.

The thermal storage model considers a mixed storage tank model. A stratified tank model can be developed to deliver more detailed results.

The temperature of mechanical room is currently considered constant. A more accurate temperature profile can be estimated based on the zone temperature information calculated in SEMERGY.

The photovoltaic solar model can be further extended to include off the grid systems with battery storage.

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