Implementation of Solar Energy in Eco-Cities

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Abstract

The purpose of this study is to investigate the potential of implementing solar energy and solar technology systems in the energy systems of two conceptual Eco-Cities, as a possible way of tackling the inherent problems in global urbanization and contributing to a sustainable future. The cities are formed as one suburb to Sydney in Australia, and one suburb to Stockholm in Sweden. Studying the implementation of solar energy in a small-scale suburb is seen as a step towards integration in a large-scale city. The two areas were chosen in order to investigate the influence of different climates and other regional conditions on the possibility of integrating solar energy in an Eco-City.

The thesis examines the Eco-City concept and different solar technologies, and the method used comprises environmental, technical and economic analyses. The study investigates the energy demands of different types of buildings, and their possibility to be self sufficient in electricity and hot water supply through installing photovoltaic panels and solar thermal collectors at the building envelope. The demand coverage and costs of the solar technology systems are then compared, in economic terms, with the case of only purchasing energy to provide hot water and electricity.

The analysis shows that solar energy has a good chance of constituting an important part of an Eco-City’s energy system and contributing to a sustainable future. But the benefits are dependent on the environment in which the city is planned to be developed. In Sydney, both electricity from photovoltaic panels, and hot water from solar thermal collectors, have the possibility to lead to large cost savings and a healthier urban environment. In Stockholm, where the irradiation and energy prices are lower, and the current energy supply is more environmentally friendly, it is harder for solar energy to constitute a large part of the energy system.
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<th>Designation</th>
<th>Unit</th>
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<tr>
<td>Amount Used Hot Water</td>
<td>$V_{HW}$</td>
<td>m$^3$</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>$CO_2$</td>
<td></td>
</tr>
<tr>
<td>Conversion Constant for Hot Water</td>
<td>$C_{HW}$</td>
<td>kWh/m$^3$</td>
</tr>
<tr>
<td>Discount rate</td>
<td>$r$</td>
<td>%</td>
</tr>
<tr>
<td>Elevation Angle</td>
<td>$\gamma$</td>
<td>°</td>
</tr>
<tr>
<td>Energy</td>
<td>$E$</td>
<td>kWh</td>
</tr>
<tr>
<td>Energy for Hot Water</td>
<td>$E_{HW}$</td>
<td>kWh</td>
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<tr>
<td>Equivalent Annual System Cost</td>
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<td>SEK</td>
</tr>
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<td>Heat loss coefficient first order</td>
<td>$a_1$</td>
<td>W/m$^2$K</td>
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<tr>
<td>Heat loss coefficient second order</td>
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<td>year</td>
</tr>
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<td>m</td>
</tr>
<tr>
<td>Module Width</td>
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<tr>
<td>Photovoltaic</td>
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<td></td>
</tr>
<tr>
<td>Power</td>
<td>$P$</td>
<td>W</td>
</tr>
<tr>
<td>Roof Space Required</td>
<td>$S$</td>
<td>m$^2$</td>
</tr>
<tr>
<td>Simple One-Direction constant</td>
<td>$b_0$</td>
<td>-</td>
</tr>
<tr>
<td>Tilt Angle</td>
<td>$\beta$</td>
<td>°</td>
</tr>
<tr>
<td>Total Initial Investment Cost</td>
<td>$I$</td>
<td>SEK</td>
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<tr>
<td>User defined IAM, Longitudinal</td>
<td>$K_{\theta_{LW}}$</td>
<td>-</td>
</tr>
<tr>
<td>User defined IAM, Transversal</td>
<td>$K_{\theta_{NS}}$</td>
<td>-</td>
</tr>
<tr>
<td>Zero-loss efficiency</td>
<td>$\eta(0)$</td>
<td>%</td>
</tr>
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1 Introduction

The world is experiencing large-scale and rapid urbanization at the same time as global and local urban environmental challenges are increasing. Cities are hosting more than half of the world’s population and consume a large amount of energy. Their total energy demand covers more than 75 per cent of the world’s energy production and 80 per cent of greenhouse gas emissions come from the cities. In the most developed countries more than 80 per cent of the inhabitants live in cities, and due to the urbanization it is expected that 70 per cent of the world’s population will be living in cities by 2030 (Lazaroiu and Roscia, 2012).

As a way to handle these increasing challenges and minimise the energy consumption in urban environments governments and companies are developing and implementing new technologies and strategies with the objectives to create a sustainable future. One of these strategies is the development of Eco-Cities, which are communities in balance with nature representing a new way of considering cities. The Eco-City concept implies an optimization of available and new resources and aims to create a whole system solution. The solution considers many aspects such as lasting energy supply, public safety, well-being, heating and cooling systems, water supply, wastes management and mobility. Having this system approach is crucial for tackling the climate change and to improve the energy security, and succeeding to incorporate sustainable urban planning is a vital step in the right direction. Cities are large and complex systems with many possibilities for improvements. It is when discrete technologies are brought together and integrated in new ways and new systems that some of the largest sustainability advantages become a reality, with cost efficiency and major environmental benefits as a result.

One approach to handle the increasing urbanization and associated energy need is to maximize the utilization of ambient solar energy; either through active conversion using solar thermal and photovoltaic collectors (PV), or by passive design that displays demands for lightning and heating. In this thesis the potential of implementing solar energy for meeting the different objectives an Eco-City brings about will be examined and evaluated for two fictional Eco-City suburbs in Stockholm, Sweden and Sydney, Australia. Investigating two different areas with various preconditions presents different ways and possibilities for the implementation of solar energy, and gives a more global view of the solar energy potential.

A large-scale implementation of the different solar technologies and the strategies that characterize an Eco-City is needed to achieve meaningful progress globally. The economic part in developing Eco-Cities is essential, since only if the process is economically affordable will enough communities implement the necessary systems and technologies, and this report will therefore also present a cost analysis of different solar technologies systems.
1.1 Problem Definition and Objectives

An Eco-City has many different aspects, ranging from well-being to energy efficiency and healthy environment, which all must be concerned when planning and developing a city. To contribute to sustainability the three different dimensions: economical, ecological and socio-cultural must all be satisfied within an Eco-City project, which makes the process very complex. Individual conditions for different cities, such as weather, culture and financing, are also factors contributing to the difficulties of planning and building an Eco-City, and it is not possible to have a pre-written prescription for the urban structure.

If the conclusion is that solar energy has the potential to be a part of an Eco-City’s energy system, the objective of this thesis is to find the most prosperous way to implement solar energy systems in two Eco-Cities situated in Sweden and Australia, while simultaneously concerning all the aspects the concept of an Eco-City brings about.

1.1.1 Sub Questions

In order to reach the major objective of the thesis, and develop two conceptual Eco-Cities in Australia and Sweden, the following questions are considered:

- What aspects have to be considered when integrating solar energy in an Eco-City and how are these aspects limiting the maximal potential of solar energy performance?
- What are the preconditions in Sweden and Australia, and how do the energy systems look today and in the future?
- Which solar energy systems are most feasible in urban areas, given the energy demand in Sweden and Australia, respectively?

After this introduction and problem definition, the method used will be described in the next chapter. The Eco-City concept will be introduced and discussed in Chapter 3, followed by three chapters covering technical and economic factors related to solar energy. In Chapter 9 methods for numerical calculations and estimations are presented followed by chapters with calculations covering urban area, energy demand, cost calculations and energy production. The thesis ends with a sensitivity analysis and conclusions based on achievements and suggestions of future work.

2 Method

The method used to answer the sub questions presented in Chapter 1, and eventually to form the final conclusion, is divided in five main themes that are presented in Table 1. How the contents of these themes are connected to get the desired outcome is seen in the conceptual method outlined in Figure 2.1, and described below.

<table>
<thead>
<tr>
<th>Method Themes</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eco-City Planning</td>
<td>The first part of the method forms the basis for the whole process, as well as the framework in which the work is done. It covers the Eco-City concept, the design and construction of an Eco-City and its parts, and the potential for integrating solar energy in an Eco-City.</td>
</tr>
<tr>
<td>Solar Technologies</td>
<td>Solar energy and different solar technologies are investigated in order find the ones to be implemented in the two cities. Interview with Professor Alistair Sproul gives advice on which technologies to examine.</td>
</tr>
</tbody>
</table>
Today's Energy Systems

A small but important part of the method involves an investigation of the energy systems in Sweden and Australia today. This provides knowledge about the situation the countries are in today and their energy supply and consumption.

Energy – Demand, Prices and Production

After knowing which elements to include in the cities, the different buildings’ energy demand must be estimated through calculations in order to know how much energy the solar appliances should provide. To evaluate the costs and savings that implementing solar technologies may result in, investment costs and energy prices are investigated. A mail interview with Professor Jan-Olof Dalenbäck provides information about price and ongoing product development. The energy production from the chosen solar technologies is calculated through two different programs: PVWATTs and ScenoCalc.

Sensitivity Analysis

To examine the method used so far and find uncertain parameters affecting the output, the last part of the method includes a sensitivity analysis, in which the outputs of different chosen technologies’ are investigated in different input scenarios.

The methods used for numerical calculations and estimations of the total urban area, the area available for solar appliances, the total energy demand, the total energy production, the area coverage, and the economical analysis will be described in detail in Chapter 9.

<table>
<thead>
<tr>
<th>ECO-CITY DIMENSIONS</th>
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<tbody>
<tr>
<td>Residential, Offices, Schools</td>
</tr>
<tr>
<td>Solar Collectors</td>
</tr>
<tr>
<td>PV</td>
</tr>
<tr>
<td>Discount Rate</td>
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<tr>
<td>Energy Prices</td>
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<tr>
<td>AVAILABLE AREA</td>
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<tr>
<td>ENERGY DEMAND</td>
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<td>ENERGY PRODUCTION</td>
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<td>Losses</td>
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<td>ENERGY ANALYSIS</td>
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<td>EQUIVALENT ANNUAL COST</td>
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<td>RESULTS</td>
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<tr>
<td>EVALUATION</td>
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Figure 2.1: A Map of the Conceptual Method

In the centre of the method are the energy analysis and the economic analysis, which in turn are dependent on different factors. The energy analysis is based on the total energy demand and energy production in the Eco-City, where the different buildings need energy for different purposes and the energy production occurs in solar collectors and PVs.
The three Eco-City dimensions with social, economic and ecologic perspectives, influence the energy demand of buildings, since the buildings are assumed to be energy efficient buildings, to fulfil the goals of the three dimensions. The different buildings considered in the method are residential buildings, offices and schools, and monthly energy demand during one year will be examined. The box for energy demand is tilted to indicate that the energy demand may vary due to extreme weather and thus will be investigated further in the sensitive analysis. Thermal solar collectors and photovoltaics are placed at the roofs and facades of buildings, with the objective to cover every building’s energy demand. The programs PVWATTS and ScenoCalc are used to calculate the energy production from the collector and PV systems, and one large part of the production process is to find all required input data, such as weather data and solar appliances information. The calculations are based on average data and do not cover all possible losses and therefore system losses are found in a tilted box. The losses may influence the production output and is included as a variable input parameter in the sensitivity analysis. The energy analysis is done on a monthly basis in order to see how well the examined solar energy application’s production covers that month’s energy demand.

In order to estimate how economically justifiable the different solar energy systems are, a cost analysis will be made for the different systems. The economic analysis plays a central role in the working process, and it is based on a method called “equivalent annual cost”. It is used as a decision making tool when considering different investment during a selected lifespan. The chosen discount rate and the different energy prices are critical factors when evaluating an investment, and their influence will therefore be examined in the sensitivity analysis.

Another aspect that is very important to consider before calculating the results is the available area, which is highly influenced by the Eco-City dimensions. A high density of buildings in a city leads to increased energy efficiency, and large green spaces lead to an increase in is the social and ecological well-being, which are two factors that, even though they are desirable, limit the roof area available for solar thermal collectors and PVs. The method will therefore include two different area cases to investigate how the available roof area affects the results.

The energy analysis, the economic analysis and the two area cases form the results of how large energy demand coverage, area coverage and costs the implementation of solar thermal collectors and PVs entails in the two different Eco-Cities in Stockholm and Sydney. This part involves a combination of the energy production from solar technologies and purchasing of energy from the surrounding city’s grids. The results will be varied through changing some selected input parameters that are examined in the sensitivity analysis to find especially critical factors that influence the process of implementing solar technologies in an Eco-City.

The final step in the method consists of an evaluation, which means that the results of the different cases of solar technology implementations are discussed, and an overall conclusion about the potential for solar energy to form a part of an Eco-City’s energy system in Stockholm and Sydney will be drawn.
3 Definition of the Eco-City Concept

The ambition to minimise the resource demand that are due to urbanization have resulted in many ideas regarding the way a city could be planned or developed. There are many different definitions of Eco-Cities and these have changed since the term was first coined.

The first one to discuss the idea of an Eco-City was Richard Register in 1987. His focus was on minimizing inputs of resources and energy and outputs of waste (Huang, Yeh & Chang, 2010). In early 1993 leaders of Urban Ecology Australia established different design principles for an Eco-City with main points in restoring and enriching the landscape, curbing the urban sprawl, healing and fitting the bioregion and contributing to the economy. They also pointed out the importance of optimizing energy performance, something that is even more discussed and sought today (Register, 2006).

In Register’s later book in 2006 the Eco-City is presented as one of the most important effort made towards sustainable urban development, defined as an ecologically healthy city designed to minimise its ecological footprint. Register’s three environmental maxims for construction of Eco-Cities are: conserve, recycle and preserve biodiversity. Towns and villages will be based on both history and solutions to a troubled future and become centres for a new type of building and living with public and natural open spaces, attractive design and smart transit solutions. His most important principles for an Eco-City are (Register, 2006):

1. A city is a living system and should be formed for people rather than for non-living things such as cars.
2. The city should be sustainable but also fit the evolution expressing compassion and creativity.
3. From the very beginning of building a new city, or remodelling an old, the infrastructure has to be ecologically tuned.
4. The transportation hierarchy should be reversed from today’s hierarchy: pedestrians first, then bicycles, rail transit, busses and finally trucks and cars.
5. Biodiversity should be improved.
6. It is not possible to create impeccable Eco-Cities. While solving today’s problems the development of Eco-Cities will define a range of new problems, but overall the cities will reduce the collateral damage today’s cities are causing and contribute to healthier nature and society.

One definition, presented 2009, of the main goal of an Eco-City is: to switch to a sustainable development. All over the world radical changes in how cities are planned are being made to design them to be ecologically friendly. The planning is guided by concepts like carbon neutrality and self-sufficiency (Cheng & Hu, 2009). A sustainable development contributes to fulfilling the sustainability criteria. As stated in the Brundtland Report in 1987, this means that it is possible for the current generation to meet its needs without compromising the ability of future generations to meet their needs (WCED, 1987).

The EU-funded ECO CITY project was created to contribute to the implementation of sustainability objectives in several communities in Europe, either in new urban quarters or by adapting existing ones. Minimising use of land, energy consumption, materials and the impairment of the natural environment are the presented main objectives for sustainability in the urban development. The term sustainability is general and the three more specified primary
aspects of the term are the ecological, economic and socio-cultural dimensions. Each of these three dimensions has sector-focused goals shown in Figure 3.1 (Gaffron, 2005a).

<table>
<thead>
<tr>
<th>Ecological Dimensions</th>
<th>Economic Dimensions</th>
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<tbody>
<tr>
<td>* Minimise: demand for land and transport</td>
<td>* Minimise total life cycle costs</td>
</tr>
<tr>
<td>* material and energy consumption</td>
<td>* Maximise productivity</td>
</tr>
<tr>
<td>* impairment of natural environment</td>
<td>* Realise a diversified, crisis-resistant,</td>
</tr>
<tr>
<td></td>
<td>innovative local economy</td>
</tr>
<tr>
<td>* Maximise respect for natural context</td>
<td></td>
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**SUSTAINABLE DEVELOPMENT**

<table>
<thead>
<tr>
<th>Socio-Cultural Dimensions</th>
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<tbody>
<tr>
<td>* Minimise impairment of human health and realise structures for human care</td>
</tr>
<tr>
<td>* Maximise: mental wellbeing, community feeling and awareness of sustainable development</td>
</tr>
<tr>
<td>* Satisfy basic needs and create a framework for good governance</td>
</tr>
</tbody>
</table>

Figure 3.1: The Dimensions of Sustainable Development and their Sector-Focused Goals

The endeavour of reaching these sector-focused goals helps fulfilling the ECOCITY vision, which consists of different features that together contribute to form a sustainable development. Some of these features could be a city with public space, in balance with nature, for pedestrians, cyclists and public transport, of reduction, re-use and recycling of waste, as a power station of renewable energies, of well-being and safety, of strong local economy, of minimized energy consumption, of cultural identity and social diversity (Gaffron, 2005b).

In some contexts Key Performance Indicators (KPIs) are used for describing and measuring the performance of different objectives of an Eco-City, covering its social, ecological and economic development – the same areas as the three sustainability dimensions mentioned above. For Tianjin, an Eco-City project between Singapore and China, the KPIs are guiding the planning and the development of the city. KPIs can be defined either as quantitative or qualitative measurements, and examples of different components are presented in Figures 3.2 and 3.3, (Government of Singapore, 2012).
One distinction that can be noticed regarding the development of the Eco-City concept is that in 1993, halting the urban sprawl was one of the main goals with the Eco-City. Now it is realized that the urbanization cannot be stopped and it is also contributing to economic value. There is a correlation between urbanization and an increasing gross domestic product (GDP). Studies show that for every time the proportion of people living in cities in a country increases with 10 per cent, its GDP increases by 30 per cent (Storm et al., 2011). Thus urbanization can create wealth and is an important platform for innovation. Focus is shifted from halting the urban sprawl to maximizing energy and resource efficiency and the use of renewable energies to minimize carbon emissions. A reason for now focusing on energy efficiency and renewable energy technologies when developing Eco-Cities might be the increasingly focus of managing the climate change.

To define Eco-Cities it would be desirable to express the different criteria with numbers, but by studying several scientific texts and case studies it is realized the task is complex. There are no collective main goals such as specified per cent reduction of energy demand and production, amount of reduced CO₂ emissions, amount of square meters green area per citizen, etc. The reason is probably that every community, city and country has different preconditions and also that some factors, such as human well-being, are complicated to measure and compare.
When developing an Eco-City, one of the most essential parts is to have a goal. The Swedish scientists Karl-Henrik Robért, Göran Broman and John Holmberg describe a planning called “the compass”, relating an individual’s decisions to their eventual outcome, even in a distant future. They indicate that when planning a city, you should be “thinking upstream” to a problem’s source and not just manage its symptoms. The human uses a compass to know which direction to move in and therefore planning starts with the most radical goals to be achieved in the long run. Goals should be designed for being long term, inspirational and challenging. The non-profit organization The Natural Step, created by Robért and Holmberg for training practitioners in environmental planning, has set principles that are leading to these five goals:

- Zero climate damage
- Zero extinction
- Zero pollution
- Zero soil degradation
- Zero waste

Long term goals, as these zero goals mentioned, must be coupled with quantified targets and indicators, and strategies to achieve them. Setting intermediate targets to be achieved within a specified period is the subsequent step after setting the radical goals. It is a very important part knowing when the targets have been reached, or how long it is left reaching them. The question to be asked is: “What can practically be changed that will make a difference in terms of the compass of sustainability?” (Low et al., 2005). This is a question that might have different answer in different regions. As each city is different, there is a need to find individual ways towards sustainability. There are many different examples of Eco-City project around the world that are developed to contribute to a sustainable urban future. A large project happening right now is the construction and development of Masdar City, a carbon-neutral city in the United Arab Emirates. The goal is to transform the carbon-based economy and promote the utilization of renewable energy through creating an environment that foster innovation and entrepreneurship. There is a particular focus on solar energy, and solar appliances are integrated both in buildings and large-scale plants, in forms of PV panels and solar thermal collectors (Masdar City, 2011). Many Eco-City projects of smaller scale can be found in Europe, such as the Kronsberg district in Hannover, Hammarby Sjöstad in Stockholm and Eco-Viikki in Helsinki. These areas work as ecological suburbs with integrated renewable energy, passive solar designs and low-energy housing, and have demonstrated success in several areas (von Haaren & Reich, 2004, Hakaste et al., 2005 and Hammarby Sjöstad, 2008).

A very important approach while developing Eco-Cities is that sustainable development is a process rather than a final destination. Many unsustainable structures have evolved over several decades and it is not possible to turn them into sustainable structures in just a few years. Urban areas with long-lasting infrastructure and systems that are tightly interconnected are particularly hard to transform (Gaffrón, 2005). This report focuses on newly built urban areas, and in the following subchapter different Eco-City aspects to be considered while designing the two cities are presented.
3.1 Eco-City Designing Factors

There are several aspects in an Eco-City that may influence the potential utilization of solar energy. When integrating solar active applications in a city, the available area for installation of solar panels is the key factor. Three main aspects that will be taken in consideration when discussing how solar energy applications can be integrated in an Eco-City have been identified. These aspects are the density of the city, requirements of public green spaces, green roofs and walls, and mixed-used neighbourhoods.

3.1.1 High Urban Density is a Key to Sustainable Housing

There is a clear correlation between housing density and energy use; the more compact housing, the greater energy efficiency. The increased efficiency is a result from different sources: high-density housing results in less transport and use of private cars needed, less domestic heating and synergy benefits from communal energy initiatives. However there are constraints on high-density cities and the main constrains are the access to daylight and sunlight, as well as the social acceptance. High density-cities reduce the advantage of passive solar gain, and reduce the potential for covering a city’s energy demand with active solar energy systems. However, it is argued that density is the key to sustainable housing and only by achieving housing above 200 persons per hectare, development readily supports local schools, shops, employment etc., and encourages walking and riding bikes (Edwards, 2010). Compact cities are also good for the natural world, thus it is a source to protect the undeveloped and sensitive land. Compactness also decreases the paved area per person, further improving the quality of the water (Farr, 2008).

The same density can be obtained through a variety of urban forms. As shown in Figure 3.4 a high rise buildings implies a low area coverage, medium rise buildings implies in medium ground coverage and low rise buildings as implies in a high ground coverage (Ng, 2010). This will be considered when developing the two Eco-Cities through investigating two different area cases.
3.1.2 Public Green Spaces

Urban green spaces include public parks, gardens, recreation venues and informal green spaces such as river or sea fronts (Gupta et al., 2012). Green areas are acting as urban lungs and contribute to the urban development in many positive ways. Biodiversity, the lived-in urban environment, economic attractiveness, health, urban climate, education and community pride are all benefitting from including public green spaces in the design of the Eco-City (Jabareen, 2012). In an Eco-City the human’s wellbeing is important, and green areas contribute to this. Many research studies have shown that green spaces help individuals to recuperate from mental and psychical stress, enhances feeling of social safety, increases social interaction and are also acting as noise barriers (Gupta et al., 2012).

The green area coverage differs a lot between cities all over the world, from just a couple of square metres per person up to a couple of hundreds. The World Health Organization recommends a minimum availability of 9 square metres of green space per citizen, a number also adopted by the publications of FAO, United Nations Food and Agriculture Organization. There are some discernible trends that emerge from cities that are renown for their urban green spaces. They have approximately 15 to 25 square metres urban green spaces per capita, and green area coverage of the cities total area of 20 to 30 per cent (Singh, Pandey & Chaudhry, 2010).
3.1.3 Green Roofs and Walls

There are several benefits connected to green roofs and other surfaces covered by vegetation, such as green walls. Green roofs can help prevent local flooding thus a big part of the water kept on the roof returns to the natural water cycle by evaporation and transpiration processes that are constantly taking place on a green roof. The green roofs are also causing a run-off delay, which reduces the stress during peak flows, and they are preventing the urban heat island effect, which refers to the higher air temperatures in densely urbanized areas as opposed to the lower temperature in more rural areas. Dark-coloured areas, excess heat from buildings, traffic and lack of vegetation in densely urban areas are causing this effect. By introducing green roofs and green walls the light that otherwise would be converted into energy and heat is instead absorbed by the vegetation. Therefore green roofs contribute in reducing the need of air conditioning and provide healthier and more comfortable outdoor environment. Vegetated surfaces are also reducing dust and air pollution, because the different harmful substances are deposited in the growing plants. (Scandinavian Green Roof Institute, n.d.). Green Roofs are also an opportunity for local food production and offer the potential to enhance biodiversity in urban areas. (Green Roofs – for healthy cities, 2013) Green roofs and walls may compete with solar appliances about roof area, and this compromise is discussed further in the results chapter.

3.1.4 Mixed-Use Residential Neighbourhoods

Mixed-use areas are places where different activities take place in the same neighbourhood, street or building (Ng, 2010). Mixed-use places, especially in cities with a high density, are proved positive in several aspects. They are more likely to offer local employment, improve personal security and, by mixing housing with shops, offices etc., the energy efficiency can be increased. Thus heat losses during the day from offices and shops can contribute to the heating of the neighbouring housing during evening and night (Edwards, 2010). Further, the viability of local shops and facilities encourages walking and reduces the need of transport and brings health benefits (Ng, 2010). Hence, a dense mixed-use neighbourhood is most sustainable in environmental, social and economical point of view (Ng, 2010 & Edwards, 2010).

The two Eco-Cities developed in this report are based on the concept of mixed-use residential neighbourhoods, through offices that are located on the ground floor of the residential buildings, and, even though the energy demand for local shops, sports halls and other activities will not be investigated, they are integrated in the mixed-use urban areas in the Eco-Cities as well. One common problem with solar appliances integrated in residential buildings is that the energy supply is largest during the day when people are in the city centre working. Placing offices at the ground floor of the residential buildings offers local employment and evens out the differences in energy supply and energy demand, which maximizes the utilization of the solar technologies.
4 The Role of Solar Energy in an Eco-City System

To obtain an overview of a whole Eco-City system and all parts that have to be considered when planning the city, a conceptual summary map is illustrated in Figure 4.1. This map highlights the quantity of components involved, and the complexity of integrating them all in a city system. The boxes with dashed lines are those outside the system boundaries, i.e., factors that affect the system but cannot be changed. This report concerns the energy and water parts, and focuses on the potential of solar energy to satisfy the electricity, space heating and cooling and hot water demands.

![Figure 4.1: An Example of an Eco-City System](image)

4.1 The Potential for Solar Energy Technologies to Fulfil the Eco-City Requirements

In order to build an Eco-City, the different requirements involved in the concept must be met. It must be investigated how an energy system including solar energy may contribute to fulfil the different Eco-City objectives covering social, economical and ecological dimensions.

Through analysing the three Eco-City and sustainability dimensions it is shown that solar energy, through photovoltaic and solar collectors, may help reaching several of the dimensions’ sector focused goals. Photovoltaic and solar collectors help minimizing the demand for land and transmission of energy, since the energy production takes place at buildings’ unexploited area and requires no land resources or transmission. The energy consumption may also be reduced, since
the minimising of transport leads to minimised amount of energy losses. The people living in the buildings may develop a more energy efficient behaviour from knowing that the energy is produced at your own roof, which also leads to a reduction of energy consumption. Photovoltaic and solar collectors are also minimising the impairment of the natural environment, producing energy in a CO₂ neutral way and uses no, or damage any, resources from the surrounding nature (Gaiddon, Kaan & Munro, 2009). These solar energy technologies are also presenting few, if any, health risks for the end user (The Energy Solar, 2012). The energy production from PV and solar collectors will contribute to satisfy basic needs as electricity, heat and cooling, and hot water. The two solar technologies will also contribute to a more diversified, crisis-resistant and innovative local economy. Every house has its own energy production and will therefore not be very affected by some, for example, global fuel-crisis, and the city will encourage innovative thinking through an innovation centre located in the middle of the city.

PVs and solar collectors are also helping to reach high quantitative and qualitative Key Performance Indicators, which were presented in Chapter 3. The technologies are leading to high usage of renewable energy, better air quality, no carbon emissions, green buildings, a healthy ecology and regional collaboration.

This analysis clearly indicates that solar energy may have a significant chance to constitute a key factor in an Eco-City’s energy system, contributing to the achievement of ecological and socio-cultural goals. The report will therefore present an evaluation of the two technologies’ chances to be sustainably implemented. The evaluation is carried out through different calculations built on opportunities and constraints that are involved in the Eco-City concept. The calculations will investigate the possibilities of PVs and solar collectors to fulfil two of the economic dimensions, viz., minimising total costs and maximising productivity. The next chapter will present the first step in the process: the features of solar energy and its appliances.

5 Solar Energy Features

In order to choose solar technologies and make calculations on energy production, the different technologies, solar radiation and different influencing factors must be investigated.

5.1 Solar Radiation

In terms of solar energy technology there are two main ways of measuring light: irradiance and insolation.

Irradiance is the total rate of energy that is falling on a horizontal plate at any given time, and is a way of measuring irradiation. It is usually measured in units of watts per square metre of surface (Irradiation = Power/Area) (Ross & Royer, 1999). The global irradiation that arrives at an array is defined as the sum of beam, diffuse and reflected radiation. Beam radiation arrives uninterrupted from the sun and is the richest form in energy. Diffuse radiation has been scattered in the atmosphere, and reflected radiation is reflected from e.g. the ground. The sum and the proportion of the different forms of radiation vary depending on the cloud cover and the clarity of the atmosphere. Solar panels function with all form of light, although direct radiation can be more efficiently used (Weller, Hemmerle et al., 2010).

Insolation is the total amount of energy that has been collected of any surface area within a specific time (Insolation=Power*Time/Area). The route of the sun and the varying weather condition results in a great variation of distribution of solar insolation (Weller, Hemmerle et al.,
The average of insolation energy in Stockholm is around 990 kWh/m$^2$ and year (SMHI, 2009). In Sydney the average of insolation energy is significantly higher and is measured to be around 1700 kWh/m$^2$ and year (BOM, 2013). The Australian continent has the highest average solar radiation per square metre of any continent (IEA, 2003).

### 5.2 Solar Energy Applications’ Possibility to Integrate in An Eco-City

In solar energy applications the energy from the sun is converted to other forms of energy, such as electrical energy or thermal energy. Each converting process and energy form has its own advantages. Thermal conversion has a relatively high efficiency of about 75-85 per cent while conversion to electrical energy has a lower efficiency of about 15-20 per cent. Solar energy can be used in both passive and active applications (S-Solar, 2010).

#### 5.2.1 Passive Applications

The basic definition of passive solar energy is that the sun’s energy primarily is used without mechanical equipment or distribution systems. Solar energy has been used in passive applications for a long time, and one example is garden greenhouses. The orangeries of the 19th century, similar to greenhouses, made a very efficient use of the sun by having a massive brick wall on the north side that is being heated up by the sun during the day and released from the wall during the night. The benefits of passive solar energy has the recent years been emphasized and more advanced applications of passive solar energy have been developed. An increasing number of houses are designed to effectively use the sunlight, collect the solar energy, store energy in the structure and internally distribute the energy (S-Solar, 2010). The buildings in the two Eco-Cities will be design for utilizing the passive applications of solar energy, resulting in more energy efficient buildings.

#### 5.2.2 Active Applications

Active applications of solar energy refer to various types of solar collectors for thermal solar energy production and solar cells (PVs) for electricity production. Thermal energy can be used to provide domestic hot water and space heating by charging a thermal energy storage tank. It can also provide cooling by thermally driven chillers, and at high temperatures the thermal energy can be converted into work and provide electricity (S-Solar, 2010). This report focuses only on PV systems for electricity production and thermal solar collector systems for hot water applications since these are the most common used solar systems.

An investment in solar energy appliances may be one step on the way to reduce both carbon emissions and future energy costs, since it is likely that increasing energy prices will make PV and solar thermal collectors profitable. Integrating PVs and solar thermal collectors also pushes the development of becoming self-sufficient in energy forward (Gaiddon, Kaan & Munro, 2009). The next subchapters describe the two technologies and their use more detailed.

#### 5.2.2.1 PV Systems for Electricity Production

Photovoltaic energy conversion is a direct conversion of light into electricity, and the process takes place in semiconductor materials in the solar cell. There are several solar cells available on the market and they differ in terms of the structure and the material used. The commercially used
solar cell types can be categorized into two principles groups: crystalline silicon cells and thin-film cells (Weller, 2010).

**Crystalline Silicon cells**

The traditional crystalline silicon cells are by far the most-used type accounting for about 85 percent of the solar cells used worldwide in 2010. There are two main types of crystalline silicon cells; Monocrystalline and Polycrystalline. The differences between the two types are a result of the different manufacturing processes. The Monocrystalline solar cell consists of one crystal, the structure is homogenous and the potential conversion is relatively high: 15-20 per cent. The Polycrystalline has a cheaper and simpler production process, which results in a slightly lower conversion efficiency compared to the Monocrystalline cells (Weller, 2010).

**Thin-film Cells**

Thin-film cell, usually called the second generation of solar cells, is made from various semiconductor materials. Thin-film cells are made through depositing one or more thin layers of thin-film silicon or compound semi-conductors on a substrate. The advantages of thin-film cells over crystalline solar cells are lower material and energy consumption during production. Semi-conductive material is saved thus the thin-film cells are about 100 times thinner. The thin-film also results in a greater design potential such as facade integrated PV (Weller, 2010). The Amorphous thin-film cell is the most common used thin-film cell and has a conversion efficiency of approximately 6-8 per cent (Solar Choice, 2009).

**Photovoltaics in Different Climates**

The two Eco-Cities in this report are placed in two different climates: cold climate in Stockholm, and temperate climate in Sydney, which entails several different aspects to take into account when designing the PV systems. The definition of old climate is in this context a climate in which freezing temperatures, snow, ice, dark winters, and long summer days are significant considerations in the design of a PV system. It is proved that PV systems work in both cold and warm climates, but the systems function differently in cold climates than in more tropical areas. Many components of PV systems in cold climates are affected by greater variation in sunshine amount because of seasonal changes, leading to a need of systems with larger storage systems and larger arrays, and snow and ice accretion might affect the design of the installation system. Some of the effects are positive, and most PV modules actually become more efficient by decreasing temperatures. But at the same time result lower temperatures in a decrease in the amount of energy that can be usefully stored in a PV system’s battery through hampered chemical reactions (Ross & Royer, 1999).

**Calculations on Photovoltaics**

When determining how a PV system would operate under a particular set of conditions, computerized simulation tools are often useful, and this is the reason the method used in this report contains a major part of computer calculations. When calculating on solar radiation, the radiation on a horizontal surface is the most important component, but since many PV arrays are tilted, this radiation is not enough. The higher latitude, the higher error it will be to only calculate on the horizontal component, since PV modules must have higher tilt angle to enhance winter output (Ross & Royer, 1999). The different angles that affect the energy production will be explained in following subchapters. Hourly measurement of solar radiations, with separate measurements of beam and diffuse radiation should be included to estimate the radiation on
tilted surfaces, and it is this type of data that is used in the calculation process described later in the report.

**Solar Angles**

It is not only the strength of the sunlight that decides the amount of sunshine falling on a photovoltaic array; it is also the orientation of the array and the array’s orientation in relation to the sun’s position. The orientation is described by the tilt angle and the surface azimuth angle, where the tilt angle is the angle formed by the array and the horizontal, and the surface azimuth angle describes where the array is facing: south is 0°, west is +90° and east is -90° (See Figure 5.1). The incidence angle shown in Figure 5.2 is describing how the radiation strikes the array, and the solar energy is maximized when the angle of incidence is 0°. Some arrays are able to physically track the sun to achieve an angle close to 0°, but they are more expensive and most of the arrays available at the market are fixed. The calculations in this report are based on the fixed types. The array’s location, tilt and orientation are normally the only factors that can be influenced to improve the array’s performance. Unlike solar thermal collectors, the output of a PV module is almost linearly dependent on the radiation incident, which means that even small incident radiation enhancements can make a difference (Ross & Royer, 1999).

![Figure 5.1: Azimuth Angle and Tilt Angle (NREL, 2012)](image1)

![Figure 5.2: Incidence Angle (Archived Ecotect Resources, n.d.)](image2)
The array should have an orientation that results in an incidence angle of 0° when the sun is strongest, which is achieved through the array facing the equator, and the tilt angle is optimized according to the location’s latitude. If it is a climate with snow, as for the Eco-City in Sweden, the snow must be able to slide off the array, which means that the tilt angle can not be too low. The critical angle for this is usually 45° or higher, and in the calculations for the Eco-City in Stockholm this is the base scenario tilt angle. At sites within 30° of the equator, an array tilt equal to the latitude maximizes the annual energy production. The latitude of Sydney is 34°, which is near 30°, and therefore the tilt angle of the arrays in the Australian Eco-City will start on 34° in the calculations. At higher latitudes a tilt angle lower than the latitude maximizes the energy production most. High tilt angles favour winter production and low tilt angles favour summer production at higher latitudes, which means that since much more energy is available during the summer the tilt angles should be low, favouring summer production in order to maximize the annual energy production. The optimum tilt angle for maximizing the energy production from the arrays in Stockholm is 43°, but 45° is needed to avoid snow accumulation (Ross & Royer, 1999).

Shading

Shading is an essential factor to consider when designing a PV system, since shading of the array decreases the output greatly. At high latitudes the shadows are longer due to a lower sun, which makes the shading problematic in cold climates. With the objective of minimizing the shadows, the PV array should be located as high above the ground and as far away from shading objects, such as trees and high buildings, as possible. If it is not possible to avoid shadow, the array can be enlarged for being able to produce the required amount of electricity (Ross & Royer, 1999).

Problem With Demand and Supply

Another difficulty with solar energy, and in particular PVs, is that the radiation is intense and the electricity production on dwelling houses is largest when the need is smallest. The demand is largest during mornings and evenings, but the radiation is largest during the days, and the problem for PV cells is that there is no efficient way for storing the energy in order to use it when the demand is largest (Sproul, 2013). By, as previously presented, placing the offices with the largest energy consumption during the days at the ground floors of the residential houses in the two Eco-Cities, the difference in demand and supply offsets. This thesis will not investigate the potential mismatch of electricity supply and demand during the days, but look at the total monthly production and demand.

5.2.2.2 Thermal Solar Energy Applications

Thermal solar energy applications have due to their high performance in energy conversion efficiency and energy storage density become a hot topic for researcher in the solar energy field. The major component in any thermal solar energy system is the solar collector. A solar collector is an energy exchanger that absorbs solar irradiation and converts it into heat through a photothermal conversion. The heat is then transferred to a working medium such as air, water or oil, and can be used in different applications for providing buildings with e.g. domestic hot water and space heating (Tian et al., 2012).
Different Types of Solar Thermal Collectors

Various types of solar thermal collectors are available on the market and one way to classify them is as either non-concentrating collectors for low temperature applications, or concentrating collectors for high temperature applications such as electricity production (Tian et al., 2012). Solar collectors can also be distinguished by their motion: stationary collectors, 1-axis tracking or 2-axis tracking collectors. Stationary collectors are permanently fixed in position and do not track the sun and therefore need to be oriented appropriately to maximize the energy production. The solar collectors implemented in the Eco-Cities are fixed, since the tracking collectors are very expensive and have short lifespan, and fixed collectors are more commonly used. Fixed collectors should, as the PV arrays, be oriented directly towards the equator, facing north in the southern hemisphere and south in the northern hemisphere. There are three main types of collectors within this category: Flat Plate Collectors, Compound Parabolic Collectors and Evacuated Tube Collectors. The Flat Plate Collectors and Evacuated Tube Collectors are the most common used and will therefore be the two collectors investigated in this report. The following subchapters present a more detailed explanation of these two collectors.

Flat Plate Collectors

A typical Flat Plate Collector consists of many different components, such as glazing covers, absorber plates, insulation layers, recuperating tubes filled with the heat transfer fluids, and other auxiliaries. The collectors collect both direct and diffuse radiation, and the solar radiation passes through the transparent cover and a large part of this energy is absorbed by the plate and transferred to the transport medium. The underside of the absorber is insulated to reduce conduction losses. Flat Plate Collectors have been built with various materials and designs, and e.g. the glazing material is typically glass or other diathermanous (radiation-transmitting) material. Historically, the flat plate collector is the most commonly used collector for low temperature applications up to 100 °C. Overheating and freezing is one of the major issues with flat plate collectors, but the freezing can be prevented trough use of e.g. glycol (Kalogirou, 2004).

Evacuated Tube Collectors

Like the Flat Plate Collectors the Evacuated Tube Collectors collect both direct and diffuse radiation. Evacuated Tube Collectors consist of a heat pipe inside a vacuum-sealed tube, and in the heat pipe a small amount of a fluid (e.g. methanol) is undergoing an evaporating-condensing cycle. The solar heat evaporates the liquid and the vapour is transferred to the heat sink, the vapour condenses and its latent heat is released. The condensed fluid then goes back to the collector and the process start again. The vacuum reduces the convection and conduction losses, which makes it possible to operate at high temperatures. Since no condensation and evaporation above the phase-change temperature is possible, the evacuated heat pipe collector features a self-limiting temperature control, which protects the working medium to freeze or to be overheated (Kalogirou, 2004). Due to mechanical complexity and expensive component materials in the Evacuated Tube Collectors, these collectors are more expensive than Flat Plate Collectors, but they are also more efficient (Heliodyne, n.d.).

Incidence Angle and its Influence on Solar Thermal Efficiency

Depending on the design of the collector, the output changes as the angle between the collector and the sun changes. This influence is referred to as the Incidence Angle Modifier (IAM). The IAM is defined as the efficiency at the given incidence angle divided by the efficiency at normal incidence, and is thus equal to one for the direct radiation.
The IAM is divided in two different types presented in Figure 5.3:

- **Transversal IAM**, which measures the change of performance as the angle of the sun in relation to the collector changes through the **day**.
- **Longitudinal IAM**, which measures the change of performance as the angle of the sun in relation to the collector changes through the **year**.

![Figure 5.3 Transversal IAM and Longitudinal IAM (Apricus, 2012)](image)

As the IAM curves are different for different types of collectors it is important to consider this factor. In general all Flat Plate Collectors have the same IAM curves throughout the day, but Evacuated Tube Collectors and collectors with reflectors can have very different curves (Apricus, 2012). Figures 5.4 and 5.5 shows the different IAM curves.

For Flat Plate Collectors both the longitude and transversal curves follow the same, close to cosinus, path. For Evacuated Tube Collectors the longitudinal curve is typical similar to the one for flat plate collectors. But the transveral curve differs greatly and is dependent on the space between the evacuated tubes, weather there is a reflector plate or not and if they are installed horizon tally or vertically (Apricus, 2012).

![Figure 5.4: IAM for a Typical Flat Plate Collector (Apricus, 2012)](image)
Solar Thermal Hot Water Systems in Stockholm and Sydney

In Sweden where it is a high demand of space heating during long periods of the year, the so-called Combi-Systems providing heat both for domestic hot water and for space heating is appropriate to install. In warmer climates, with low space heating demand, installation of Solar Domestic Hot Water systems (SDHW) is dominating (ESTIF, 2013). It is assumed that the Eco-City in Stockholm uses a Combi-System, and district heating is used as auxiliary energy source. The Eco-City in Sydney is assumed to use a Domestic Hot Water System with gas boosters.

The solar thermal collectors in the two Eco-Cities should be installed at different angles to be most efficient. Sydney has good conditions to produce solar heat in winters and in order to achieve better performance during winters the preferable installation angle is between 40-50°, which is higher than the latitude equaling and maximizing angle used for PVs. A higher angle also minimises losses through the temperature and pressure valve and prevents overheating in the hot summer months (DCCEE, 2013). A 34° tilt angle in Sydney leads to an incidence angle close to zero in summers, and therefore very high temperatures. In the Eco-City in Sydney the Evacuated Tube Collector will be evaluated at a 34° tilt angle as well, since it is protected from overheating. In Sweden the general optimal installation angle is 45°, which maximises the sum of energy output over the year. But when over dimensioning the solar collector area in order to cover the demand longer periods over the year the preferred angle is 60-70°. The sum of energy over the year is less but more energy is produced when the demand is high during the colder periods, and less is produced during summers when demand is low (Sol & Energiteknik AB, 2013). The calculations will be based on dimensioning the solar energy systems to cover the energy demand of one month, and not having capacity that exceeds any month’s demand. This will probably lead to a chosen angle of 45° in Stockholm since the summer demand will be covered first, but higher angles are also investigated.

Figure 5.5: IAM for a Typical Evacuated Tube Collector (Apricus, 2012)
Boosters Enable Constant Hot Water Supply

It has been shown that solar thermal collectors have the ability to meet the most of Australian household’s hot water needs, but some factors may reduce the supply or increase the usage. Depending on location, direction of solar panels, weather, and the amount of water use, the solar thermal collectors provides in general between 50 to 90 per cent of Australian household’s hot water need. To provide the rest of the need, the solar thermal collectors often come with a gas or electric booster. The gas or electric boosting is only activated when the temperature of the stored water is below the settings of the thermostat, and is automatically turned off when the water reaches the required temperature. Boosting leads to solar hot water systems having no more likely than other hot water systems to run out of hot water (IPART, 2011). The conditions for gas booster use in Sydney are favourable, since the supply of gas is large. This report will only investigate the use of gas boosters in the Eco-City in Sydney, since the large-scale district heating available in Stockholm is assumed to be better suited to cover up for the very high demand that results from the hot water being used for both space heating and domestic hot water.

Using gas boosters for water heating systems reduces the electricity consumption significantly more than the use of electric boosted solar hot water systems. If the electricity is not generated from a renewable source, this is a strong reason to use gas heaters. The electricity from the PVs may not cover the buildings’ electricity demand, and since the purchased Australian electricity is very carbon intense, the aim is to reduce the electricity use as much as possible in order to fulfil the Eco-City requirements of fewer emissions (IPART, 2011). The calculations in this report will therefore be based on that gas boosters are used at the buildings in the Eco-City in Sydney, and that the gas is purchased at the same price as mains gas. If the electricity production from the PVs has the chance to greatly exceed the electricity needed for household electricity and space cooling and heating, an electric booster could be worth considering (DCCEE, 2013).

Accumulator Tanks May Influence the Energy Performance

Accumulator tanks used for storing the hot water are produced in different materials, e.g. stainless steel, vitreous enamel (mild steel) and copper, and they can have different locations; at the roof, on the ground and inside the building (DCCEE, 2013). The size of the accumulator tanks depends on the number of solar collectors, but a general rule is 30-50 litres per installed square metre solar collector (S-Solar, 2010). There are larger tanks for seasonal storage as well, but this will not be investigated in this report. This report is not focusing on optimizing material, location or size, but energy losses that may come from e.g. different materials and locations will be taken into account in the sensitivity analysis.

5.2.2.3 Positioning of Solar Energy Installations

The location of the solar energy appliances may be crucial for the energy production. There are mainly three sections on the building envelope where it is suitable to installing solar energy modules:

Roof Installations Often Most Efficient

Roofs are the preferred location for both solar cells and solar collectors, and the modules can be installed on a pitched roof or on flat roofs. The modules are arranged in rows where a sufficient space between the rows is essential in order to avoid one module shadowing another row. The spacing needed depends on the size of the module, the mounting angle and the lowest elevation of the sun at which shadows are undesirable (Weller, 2010).
Facade Installations For Low Sun Conditions

Vertical surfaces are not ideal in a solar yield point of view, but when PV modules also provide other facade functions the deficit can be offset. The PV modules can replace exterior cladding and provide weather protection (Weller, 2010). Façade installations in Stockholm, where the sun has a low position in winter, spring and autumn, can be beneficial for some specific buildings, such as schools that have no energy demand during the summer due to holidays (S-Solar, 2010).

Sunshade Installations Beneficial in Hot Climates

Photovoltaic and sunshade elements are ideal to combine in hot and sunshine intense climates, thus a shading system is positioned to protect against direct sunlight and this also means the optimum orientation for PV-modules. The good ventilation below the modules also helps maximizing the electricity produced. PV-Systems can be used to replace the conventional sun shading building material (Weller, 2010). This may be considered in the Eco-City in Sydney if the available roof area is not large enough for the PV modules.

After having investigated solar energy and different solar energy technologies and be able to make conclusions about whether to install the technologies or not it is necessary to analyse the costs for the different systems.

6 Prices for PV and Thermal Solar Collector Systems

In order to evaluate the economic feasibility of implementing solar energy the cost for the different technologies has to be investigated. The service, maintenance and operating costs are negligible in comparison to the capital cost for solar energy systems (Svensk Solenergi, 2013). Thus the following chapters focusing on the investment cost for the different technologies.

6.1 PV Systems Prices

The price of PV has dropped significantly all over the world the past years. The biggest reasons for this are the government incentive schemes and the increased mass production of solar panels in China that has resulted in a competition on both the installation level and manufacturing level. The competition has driven down the retail system prices by around 45 % per year the past few years. The average system price for larger PV systems in New South Wales, Australia was in April 2013 11.3 SEK per watt installed, this is slightly lower than the average price, 12.9 SEK per watt, for Australia (Solar Choice, 2013). The system price in Europe is similar to the price in Australia. Larger quantities of modules can be bought for approximately 12 SEK per watt (Solelprogrammet, 2010). For the economic calculation in this report it will be assumed that a system price of 12 SEK per watt is installed, both for the Stockholm and Sydney case.

6.2 Solar Thermal Collector Systems Prices

Prices for solar collector and the belonging hot water systems differ greatly between manufacturers and collector types. In general evacuated tube collectors are between 1.2-2 times more expensive than flat plate collectors (Homepower, 2012). The solar hot water system for Combi-systems are more cost intensive than solar water system that just produce hot water for domestic use. Hence the prices for examined solar hot water systems in Stockholm is significantly higher than the once examined for Sydney. Another reason for the smaller cost in Sydney is the higher competition on the installation level. In Sweden it is assumed that a Combi-system is used,
and district heating will be the auxiliary source of energy. An approximately estimation of the total additional cost for such system in comparison to a conventional system with just district heating in Sweden is 4,200 SEK/m² for flat plate collectors and for evacuated tube collectors 6,300 SEK/m² (Dalenbäck, 2013). The additional investment of solar hot water systems compare to conventional hot water systems in Sydney is estimated to be 2,000 SEK/m² for flat plat collectors and 3,000 SEK/m² for evacuated tube collectors (Sustainable Victoria, 2010).

7 The Energy Systems in Sweden and Australia

In order to understand the energy generation and how the energy sources are used in Sweden and Australia today, and to be able to compare the outcome of a system with integrated solar energy, some parts of the countries’ energy systems today must be investigated.

7.1 The Australian Energy System

The energy consumption of Australian buildings is expected to increase a lot in the next ten years. The proportion of energy demand being met by electricity, whose production emits very high amounts of greenhouse gases, is increasing together with the energy consumption while the use of wood, with low greenhouse gas emissions, is decreasing. It is predicted that the growth in energy use in the building sector will result in a significant growth in greenhouse gas emissions (DEWHA, 2008). The Australian energy system needs to be changed to handle this unsustainable outcome, and developing Eco-Cities may be one possible way.

Most electricity in Australia is generated by coal-burning power stations, which emit huge amounts of greenhouse gas. The Australian Greenhouse Office has estimated that over 50 per cent of buildings’ greenhouse gas emissions come from the use of electric appliances and equipment. Therefore it is particularly important to equip Australian buildings with alternative renewable sources to produce electricity, with photovoltaic panels as a good candidate (Low, Gleeson, Green & Radovic, 2005). Figure 7.1 shows a diagram representing different fuel types that constitute the energy production in Australia. Fossil fuels accounted for over 95 per cent of Australia’s primary energy consumption and 90 per cent of the electricity generation during 2010-2011 (DRET, 2012).

Figure 7.1: The Australian Energy Production 1974-2011, by Fuel Type (PJ) (BREE, 2012)
Space heating and cooling together with water heating account for the largest parts of the average energy need in the Australian home. Australian households are using only electricity or electricity in combination with gas to cover their energy demands (IPART, 2011). This report assumes that the buildings not using solar technologies in Sydney use gas for hot water heating and electricity for household electricity and space heating and cooling.

7.2 The Swedish Energy System

According to Statistics Sweden’s (SCB’s) population forecast, the population in the country of Stockholm will increase with one million inhabitants by the year of 2040, which will increase the energy demand in Stockholm significantly. New suburbs have to be built and it is crucial to develop these in a sustainable manner (Boverket, 2013). The energy demand for space heating, hot water heating and electricity is high in Swedish buildings due to cold winters and many dark hours, and the residential sector accounts for about 40 per cent of the total energy consumption in Sweden (Lindén, 2007). District heating is the most common source of heating in multi-dwelling buildings in Sweden and over 90 per cent of the energy used for heating and hot water came from district heating year 2011 (Swedish Energy Agency, 2011a). The buildings not using solar technologies in Stockholm are in this report assumed to use district heating for space heating and domestic hot water heating, and electricity for household electricity. Figure 7.2 shows that the Swedish energy system is not as dependent of fossil fuels as the Australian, and the main reason is the large energy supply from hydro and nuclear power, but it is debated how sustainable those two sources are. Nowadays there are many discussions about decommissioning of nuclear, and it is important that fossil fuels won’t cover the energy demand the nuclear would leave behind. Alternative energy sources should be developed in order to get a more sustainable energy system (Swedish Energy Agency, 2012a).

![Energy supply and use in Sweden in 2010](image)

Figure 7.2: Swedish energy supply and use, by fuel type, in 2010 (Swedish Energy Agency, 2012)
8 Energy Prices

In order to compare the costs for the energy from the selected solar technologies and the usual cost for energy from electricity, gas and district heating grids the different prices must be investigated. Energy prices are changing variables, and therefore the forecast future prices to be presented. It will be assumed that residential buildings, offices and schools pay the same electricity, gas and district heating prices.

8.1 Electricity Price in Sydney

The electricity price in Sydney comprises usage charges per kWh used plus a fixed daily supply charge, and it is most common having a single-rate meter, which means that it is the same price per kWh regardless of electricity usage time. It is also common to have a time-of-use meter, where it is different price at different time of electricity use (Switchwise, 2013). The calculations in this report will only be done at the constant price presented in Table 2. The price is retrieved from one of Australia’s largest electricity producers, AGL, and the exchange rate used to convert the price to Swedish kronor is SEK/AUD=6.7.

Table 2: AGL’s electricity price for households in Sydney during 2013, all taxes and fees included (c/kWh & öre/kWh) (AGL, 2013)

<table>
<thead>
<tr>
<th>Month</th>
<th>Price</th>
<th>Units</th>
<th>Price</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average electricity price</td>
<td>65</td>
<td>c/kWh</td>
<td>437</td>
<td>öre/kWh</td>
</tr>
</tbody>
</table>

Future electricity prices in Australia are expected to increase. Forecasts made 2011 expected an increase of residential electricity prices by 37 per cent in nominal terms (22 per cent in real terms), from 1 July 2011 to 30 June 2014. In New South Wales the prices are forecasted to increase by 42 per cent in nominal terms during this period. The main reasons for the increase is higher maximum demand, carbon price and expected increasing capacity of expensive gas-fired generation (AEMC, 2011). Long term forecasts shows a milder, but steady increase in price forecast for electricity in New South Wales, which can be seen in Figure 8.1, where the different curves present different Australian states. The yellow curve represents New South Wales and the Australian Capital Territory.
8.2 Electricity Price in Stockholm

The Swedish electricity price consists of three parts: governmental fees and taxes, grid fees and electricity consumption (Tekniska Verken, 2013). The state-owned company Vattenfall is the largest electricity producer in Sweden, and the average monthly electricity prices between 2008 and 2012 presented in Table 3 constitute the prices used in the calculations. The electricity price has been quite volatile the last years, and therefore an average is used. Increased demand, deficient energy production and decreased water reservoirs have resulted in higher prices during winter (Swedish Energy Agency, 2011b).

Table 3: Vattenfall’s Average Electricity Price for Households in Stockholm 2008-2012, All Taxes and Fees Included (öre/kWh) (Ekonomifakta & Vattenfall, 2013)

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>öre/kWh</td>
<td>126</td>
<td>131</td>
<td>117</td>
<td>115</td>
<td>112</td>
<td>116</td>
<td>112</td>
<td>116</td>
<td>117</td>
<td>116</td>
<td>118</td>
<td>125</td>
</tr>
</tbody>
</table>

The Swedish future electricity price is hard to forecast. There are many aspects that may affect the price, and some studies show increasing price, when other studies claim that the price may decrease.

8.3 Gas Price in Sydney

The gas price in Sydney is structured as the electricity price comprising usage charges per kWh plus a fixed daily supply charge. The supply charge is the most expensive part of the gas price, and the price presented in Table 4 is an average gas price paid in Sydney.
Table 4: AGL’s Gas Price for Households in Sydney during 2013, All taxes and fees included (c/kWh & öre/kWh) (AGL, 2013)

<table>
<thead>
<tr>
<th></th>
<th>Price</th>
<th>Units</th>
<th>Price</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average gas price</td>
<td>1.1</td>
<td>c/kWh</td>
<td>7.1</td>
<td>öre/kWh</td>
</tr>
<tr>
<td>Supply charge</td>
<td>49</td>
<td>c/day</td>
<td>326</td>
<td>öre/day</td>
</tr>
</tbody>
</table>

There is a large uncertainty surrounding the future gas prices in Australia, but the prices are likely to gradually increase over the next two decades because of increasing demand (Syed A. & Penney, K., 2011). The forecasted prices for gas, coal and oil are showed in Figure 8.2. Western Australia has experienced greatly increasing wholesale prices, and they are forecasted to increase significantly at the eastern market as well. The Bureau of Resources and Energy Economics has reported gas price projections of $7.70-13.90 per GJ, depending on state, by 2020 (RET, 2012). Expressed in kWh and öre, the price projection is 18.6 to 33.5 öre/kWh, which is a large increase compared to the prices today.

![Figure 8.2: Future Gas Price Index in New South Wales (DRET, 2012)](image)

**8.4 District Heating Price in Stockholm**

The price for district heating in Stockholm during 2012 was 87 öre/kWh with tax included (Svensk Fjärrvärme, 2012). The average price for district heating in Stockholm has increased with 34 per cent from 2000 to 2012, if the inflation is taken into account. If no inflation is taken into account, the average price has increased with 56 per cent (Svensk Fjärrvärme, 2012).

The prices for district heating differ greatly between regions and are primarily dependent on the price development of the biofuels that are used in the production. The price of biofuels in 2020 is estimated to be 30 per cent higher than in 2000, which tends to increase the price of district heating. Tax incentives and increasing electricity price may at the same time keep the district heating price low, which makes it hard to forecast the future prices for district heating. (Swedish Energy Agency & Naturvårdsverket, 2004).

The method has so far covered analytic areas, and the following chapters cover topics that need calculations.
9 Methods for Numerical Calculations and Estimations

A central part of this work is to make analysis, estimations and calculations, some of which require numerical methods. The topics that require methods for numerical calculations and estimations are listed in Table 5 together with a description of the method applied. The input to the analysis and calculations are historic values, experience based assumptions, technical performance figures, weather statistics, physical circumstances etc.

Table 5: Topics that Require Methods for Numerical Calculations and Estimations

<table>
<thead>
<tr>
<th>Topic</th>
<th>Description of Topic Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available Roof Area for Solar Energy Production</td>
<td>The available roof area for solar energy production in the two Eco-Cities is assumed to be equivalent to the ground area of the buildings. Further the ground area that is dedicated for buildings is given from the structure of the two Eco-cities. What affect the available area, and more specific how the area is estimated is presented in Chapter 10.</td>
</tr>
<tr>
<td>Energy Demand</td>
<td>The different energy demands for buildings are derived from both historically average values and from standards for energy efficient buildings. Some values, such tap water use in offices, are assumed to be the same for Sydney and Stockholm. See Chapter 11.</td>
</tr>
<tr>
<td>Energy Production</td>
<td>Calculated through 2 online programs;</td>
</tr>
<tr>
<td></td>
<td>• PVWATTS, description in Chapter 12.</td>
</tr>
<tr>
<td></td>
<td>• ScenoCalc, description in Chapter 12.</td>
</tr>
<tr>
<td></td>
<td>Inputs are based on average values from different solar collectors/panels, derived from literature.</td>
</tr>
<tr>
<td>Total Area Coverage</td>
<td>In order to examine the roof coverage, which solar modules require, the needed spacing between the rows of modules has to be taken in consideration. The spacing needed depends on the width, ( b ) of the modules, the mounting angle, ( \beta ) and angle ( \gamma ), that corresponds to the lowest elevation of the sun at which shadows are undesirable. The geometrical relationship between the angles and module is shown in Figure 9.1.</td>
</tr>
</tbody>
</table>

![Figure 9.1: Required Module Spacing depending on the width \( b \), the mounting angle, \( \beta \) and elevation angle, \( \gamma \)](image)

The module space can therefore be derived by the formula (Weller, 2010):

\[
\text{Module Spacing} = \frac{b \times \sin(\beta)}{\tan(\gamma)}
\]

(Eq. 1)
Hence one module, with the module width, $b$ and the length, $L$, requires the roof space, $S$, and can be calculated as:

$$ S = \left( \frac{b \times \sin(\beta)}{\tan(\beta)} + b \times \cos(\beta) \right) \times L \quad \text{(Eq. 2)} $$

For PVs in Sydney it is recommended that the row spacing avoid shading between 10 am and 2 pm at Winter Solstice, which corresponds to the altitude angle, $\gamma = 26^\circ$. (Energy Efficiency and Renewable Energy Bulletin, 2010). Hence this angle will be assumed for PV cells in Sydney when calculating the roof area required for PV modules. Since the performance from solar collector are not as sensitive for shading a slightly higher angle, $\gamma = 28^\circ$, will be assumed. For PVs in Stockholm it will be assumed that the row spacing avoid shading between 10 am and 2 pm in the beginning of March, which corresponds to the angle, $\gamma = 21^\circ$ (Motions of the Sun Simulator, 2013). For Solar collectors in Stockholm calculations are based on the angle, $\gamma = 23^\circ$. The extra losses for PV in Stockholm due to shading are taken in consideration by lowering the performance by 5% for PVs in Stockholm.

In Appendix 16.1 the required area for the different the examined modules types for different tilt angles, $\beta$, compare to the active aperture area are presented. The reason that Evacuated Tube Collectors requires more area is that these typical have more inactive module area compare to Flat Plate Collectors.

**Economical Analysis**

The economical feasibility for solar collectors for hot water production and solar cells for electricity production is examined by calculating the Equivalent Annual Cost for each system, $EAC_{SYSTEM}$. The equivalent annual cost is the cost per year of owning and operating an asset based on its lifespan and discount rate and is typical useful when evaluating a solar energy system investment. Thus operating costs are assumed to be negligible the Equivalent Annual Cost is calculated as: (SP Technical Research Institute of Sweden, 2008).

$$ EAC_{SYSTEM} = I \times \frac{r}{1-(1+r)^{-n}} \quad \text{(Eq. 3)} $$

$I =$ Total Initial Investment Cost (including installation)
$r =$ discount rate
$n =$ lifetime of the installation. Set to be 25 years, since this is an average lifetime of solar thermal collectors and solar panels.

Further the Energy Production Cost (SEK/kWh) can be derived by:

$$ \text{Production Cost} = \frac{EAC_{SYSTEM}}{\text{Total Annual Production}} \quad \text{(Eq. 4)} $$

In order to be able to compare systems that produce different amount of energy and to compare it with the cost of just conventional procurement of energy. The total annual cost (SEK/year) will be calculated as:

$$ \text{Total Annual System Cost} = EAC_{SYSTEM} + \text{Costs for Auxiliary Energy Procurement} \quad \text{(Eq. 5)} $$

For the economic analysis for PV systems, net-metering agreement on a monthly basis will be assumed. Further, the months when electricity production exceeds the electricity demand the electricity assumes to be sold for the market spot price. The market spot price is derived from historical values for the specific month and the income will be processed as a negative cost.
10 The Structure and Components of the Two Eco-Cities

The Eco-Cities developed in this report are formed as suburbs to two larger cities, Stockholm and Sydney, and constitute home for 10,000 residents. The key objective is to reflect a whole standalone city and important elements that are found in entire cities, such as dwelling houses, schools, offices and parks will be found in the Eco-Cities. Some other elements buildings included in a city, such as retailers, sport centres, libraries etc. are not taken into account in the calculations. The reason is both an increasing complexity and the small energy consumption (compared to dwellings and offices) that will not be determining factors when deciding whether to implement solar energy or not. If the conclusion is that the use of solar energy is feasible for housing, offices and schools, it may be possible to concluded that it is feasible for sport centres, libraries etc. as well. The calculations do not cover energy intense elements as industries and transport. The two Eco-Cities are assumed to have subway or tram connection to the centres of Stockholm and Sydney.

Buildings are separated by their type, and their building specific energy demands, as well as the buildings’ potential for energy generation are investigated separately in order to evaluate different Eco-City buildings’ chance to be self-sufficing in energy and meet their own need with the on-building produced energy. The design of the Eco-Cities is formed by a number of factors presented in the following subchapters.

Importance of Innovation and Information Centre in an Eco-City

A centre for innovation and information will be included in the Eco-Cities in order to maximize the overall benefits of an Eco-City. There are many advantages of integrating a centre for innovation and information, and several existing Eco-Cities have such centres.

Hammarby Sjöstad, the earlier mentioned Eco-City project in Stockholm, has a centre for environmental information and communication with the purpose of giving advise to the city’s residents, such as how to make less environmental impact and conserve resources. The centre enlightens the importance of the residents’ involvement and hosts exhibitions about current environmental issues (Hammarby Sjöstad, 2013). The centre informs visitors about the whole Eco-City project, and the environmental programme it based on and following (Stockholm Vatten, 2010). In Abu Dhabi’s Eco-City project Masdar, the “Renewables & Innovation Training Center” can be found, having the purpose of providing knowledge and resources to support sustainability energy growth. The centre offers a “portfolio” of renewable and innovation development courses for energy education, aiming to increase the city and its companies chances to succeed in the renewables area (Masdar City, 2013).

The Innovation and Information centres in the two Eco-Cities developed in this report are planned to be located in the city centre next to the school, in order to maximise the availability and promote students’ interest in a sustainable development. The centres should have activities integrated with school projects, and be open for visits from all residents as well as people visiting the Eco-City. Information and education will work for increasing the residents’ overall interest for the city; educate the residents in how to increase their energy efficiency, and what they can do to help meeting the overall requirements that come with the Eco-City concept.
Total Urban Area

In Chapter 3, it is stated that sustainable housing is achieved by having 200 persons or more per hectare, and that figure will be the base scenario area for the suburb. One hectare equals 10,000 square metres and therefore 10,000 persons need in total 500,000 m².

Dwelling Houses Area

Compact housing results in greater energy efficiency, but the living space must at the same time be socially accepted to fulfil Eco-City requirements. In Sydney, the average living space per person is approximately 80 m², and in Stockholm the housing is more compact: 40 m² per person (ABS, 2011 & Stockholms Stad, 2004). It is therefore assumed that 40 m² is quite compact and socially accepted, and will therefore be the living space per person used in the calculations. No consideration is taken for stairwells or basements, and the total area for dwelling houses will be 400,000 m².

Office Area

The Swedish Work Environment Authority recommends an area of 25 m² per person, including spaces as meeting rooms, corridors, personnel facilities etc. (Swedish Work Environment Authority, 2013). The average office in the Central Business District in Sydney has 19 m² per worker, but the used figure in the calculations will be 25 m² due to the social aspect that constitutes an important part of the Eco-City concept (Bibby, 2009). Approximately 50 per cent of the Swedish and Australian populations work, resulting in an assumption of 5,000 people working in the two Eco-Cities (Ekonomifakta, 2012 & ABS, 2013). This leads to a total office area of 125,000 m². The Innovation and Information Centre is counted as an office building and is therefore included in the office area.

The total area needed for dwelling houses and offices is therefore 525,000 m² in each Eco-City. In order to adhere to the set total urban area of 500,000 m², and include parks, school, streets etc. it is concluded that block of flats are required. In an energy point of view it is preferable to have houses with several floors, because buildings with three or four stories are more energy efficient (Edwards, 2012). The offices are, as presented earlier in the report, located at the ground floor of the dwelling houses in order to even out the in urban areas common difference between supply and demand during the day.

School Area

In Sweden 14.6 per cent of the population is attending school, and the same figure is assumed to apply in Australia, which leads to 1,460 students in school in the two Eco-Cities (The Swedish National Agency for Education, 2012). Too many persons at the same area increases the risk of infection, bad air quality and high noise levels, and therefore the recommended area in school is 7.5 m² per person (Stockholms Stad, 2007). Even if smaller area may be more economically viable, the social aspect is as essential. Thus total required area for the Eco-City school is 10,950 m². If the school is assumed to be a two-storey building the covered ground area would be approximately 5,475 m². This is assumed to be equivalent to the roof area available for solar energy appliances specifically used to cover the school building’s energy demand.

Open Areas

The base scenario area for open areas, including parks, greens spaces and other open areas, is set to 25 m² per person, which equals a total open area of 250,000 m². This leads to open area
coverage of 50 per cent of the total urban area, a figure that greatly limits the space available for buildings and streets.

**Streets and Paths for Pedestrians and Bikes**

The area consisting of asphalt surface for roads and parking is minimised by e.g. building as few roads as possible and having parking under the buildings. Priority is instead given to walkways and cycle paths, which leads to better social welfare through reduced air pollution and noise. The maximum are for asphalt surfaces is set to 20 per cent of the total urban area. Table 6 presents a summary of the different areas in the Eco-Cities.

**Table 6: The Area Structure of the Eco-Cities**

<table>
<thead>
<tr>
<th>City Element</th>
<th>Case 1 25 m² Open Areas per Person</th>
<th>Case 2 15 m² Open Areas per person</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Urban Area</td>
<td>500,000 m²</td>
<td>500,000 m²</td>
</tr>
<tr>
<td>Open Areas</td>
<td>250,000 m²</td>
<td>150,000 m²</td>
</tr>
<tr>
<td>Streets and Paths for Pedestrians and Bikes</td>
<td>100,000 m²</td>
<td>100,000 m²</td>
</tr>
<tr>
<td>(20 per cent of total urban area)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>School Area</td>
<td>5,475 m²</td>
<td>5,475 m²</td>
</tr>
<tr>
<td>Ground Area available for residential and offices</td>
<td>144,525 m²</td>
<td>244,525 m²</td>
</tr>
</tbody>
</table>

The figures presented in this chapter are not fixed, and it is important to underline that there are no figures describing exactly what is right or wrong. Large green areas confer social and ecological advantages but limit the number of buildings, which reduces the energy efficiency and the area available for solar energy applications. Every Eco-City must find the balance between e.g. green areas per person and not letting the urban area use too much nature resources. The aim of this report is not to find the most optimized proportion of open areas and buildings, but to investigate how the solar energy utilization is affected by different urban design, varied within a sustainable framework. After having determined what buildings to include in the calculations, and how large area they represent, the next step is to determine the different energy demands that are linked to the different types of buildings. The estimations and calculations that give the energy demand are presented in the following chapter.
11 The Energy Demand of Buildings in an Eco-City

In order to investigate how adequate a solar energy system is for a specific building, it is vital to obtain the building’s energy demand profile, including the demand curve over the year. Since this report focuses on solar integration in buildings and in a newly developed Eco-City, the buildings are assumed to follow high energy-standards based on energy efficient buildings such as passive houses. The passive building concept is a construction concept that can be applied in all climate zones and in all kind of buildings such as residential buildings, offices, and schools. It allows energy savings, provides a comfortable indoor climate and is affordable at the same time. An efficient use of the sun leads to heating savings for internal heat sources and heat recovery during winter, and active cooling is reduced through the use of cooling techniques such as strategic shadings (Passive House Institute, 2012). Buildings with “Passive House certification” are described as the most energy-efficient buildings anywhere in the world (Electrical Solutions, 2013).

When estimating the energy demand in buildings it is common to do the calculations in kWh/m², and in order to compare the total energy production in kWh from the collectors with the total energy demand, the demand in kWh/m² is multiplied with the total amount of m² in the different buildings. The demand and production are therefore presented in kWh in the results in Chapter 13.

11.1 Total Energy Consumption in Residences

In a residence the energy consumption can be divided in the categories: space heating and cooling, hot water heating and household electricity. The calculations in this report do not account for stairways and cellar areas.

11.1.1 Space Heating and Cooling

According to the passive house standard the annual cooling and heating demand should not exceed 15 kWh/m² (Passive House Institute, 2012).

Space Heating in Sweden

For a passive house in Sweden, with a cold climate, the maximal energy consumption for heating may be exceeded. Therefore, based on measurements from passive house projects, the average heating required is approximately 15-25 kWh/m² per year. The value can be expected to vary from year to year which will be considered in the sensitivity analysis (Isover Energi, 2012 & Forum För Energieffektiva Byggnader, 2008). In the base scenario the energy demand for heating will be set to 20 kWh/m². There is no need for cooling in dwellings in Sweden.

Space Heating in Australia

The vast majority of Australian homes have some form of heating or cooling, and the most common forms of heating and cooling in new dwellings are reversed air conditioners.

An average Sydney household with reverse cycle air conditioner uses the air conditioner 200 hours for space heating, and 180 hours for space cooling in a year (EES, 2006). The air conditioners that are used in Sydney have an average power output at 5-6 kW, which results in a total energy use of 1,900-2,280 kWh per year (Government of South Australia, 2011). The
average household floor area of 210 m² leads to an energy consumption of 9-11 kWh/m² per year (ABS, 2011).

For passive buildings in some climate zones in Australia the need for heating and cooling can be very low and in some cases eliminated (Australians guide to environmentally sustainable homes, 2010). It is therefore reasonable to assume a lower demand than 15 kWh/m². Using energy efficient buildings reduces the heating and cooling demand by up to 60 per cent compared to average modern 5 stars homes built in New South Wales (ICHIJO, 2013). Since these figures are based on investigations made by a company selling and building energy efficient houses the results might be based on calculations that are advantageous for the company. On the other hand, the majority of buildings in Sydney are not 5 stars rated (Mitchell, 2009). They are therefore not that energy efficient, and the heating and cooling demand may be reduced by more than 60 per cent. The conclusion is that calculations in this report will be based on a heating and cooling demand reduction of approximately 50 per cent, resulting in a base scenario energy use of 5 kWh/m² per year.

Heating is used 53 per cent (200 of 380 hours) of the air conditioning operation hours, which represents 2.6 kWh/m², and it is assumed that these hours are equally distributed in the three winter months: June, July and August. Cooling is used 47 per cent (180 of 380 hours) of the air conditioning operation hours, which represents 2.4 kWh/m², and it is assumed that these hours are equally distributed in the three summer months: December, January and February.

11.1.2 Hot Water Use in Residences

In order to calculate how much energy the solar thermal collectors need to produce for warming up the hot tap water, the water use of today must be investigated.

Hot water use in Swedish residences

The average domestic water consumption per person in Stockholm is 200 litres per day (Stockholm Vatten, 2011), but in the Eco-City Hammarby Sjöstad in Stockholm, the average water use is 150 litres per person per day. The 25 per cent water savings result from effective taps, toilets, dishwashers and dishwashing machines (Stockholm Vatten, 2010). Since the two Eco-Cities that are developed in this report are newly built urban areas it is assumed that these water use-reducing solutions are used in all buildings, leading to a water use of 150 litres per person per day in the Eco-City in Stockholm.

Hot water use in Australian residences

In a high-density suburb with non energy-efficient multi-dwellings in Sydney, the average water consumption per capita is 81,000 litres per year, which equals 222 litres per person per day (Randolph et al., 2006). By implementing water saving solutions like the ones mentioned above, this figure is assumed to be reduced 25 per cent, to 166 litres per person per day.

Case studies made in Sweden showed that the proportion of hot water use of the total water use is 31.5 per cent, a figure that is presumed to apply also in Sydney (Swedish Energy Agency, 2010). According to the above reasoning, the residents in the Eco-City in Stockholm will be using 150 litres per day, of which 47 litres is hot water, and the residents in the Eco-City in Sydney will be using 166 litres per day, of which 52 litres is hot water. The hot water use is assumed to be the same all year round.
The energy needed to heat up the water can be calculated by using the following equation: (Sveriges Centrum för Nollenerghus, 2012):

\[ E_{\text{HW}} = V_{\text{HW}} \times C_{\text{HW}} \]  

(Eq. 6)

where

\( V_{\text{HW}} = \) Amount used hot water (m\(^3\))

\( C_{\text{HW}} = \) Conversion constant, 55 (kWh/m\(^3\)), which is the energy required to rise the water's temperature with 47 degrees.

The consumption over one year and per square metre is therefore for:

Stockholm: 943,525 kWh → one person with \( A = 40 \text{ m}^2 \) → \( E_{\text{HW}} = 23.6 \text{ kWh/m}^2 \)

Sydney: 1,043,900 kWh → one person with \( A = 40 \text{ m}^2 \) → \( E_{\text{HW}} = 26.1 \text{ kWh/m}^2 \)

A possible source of error by using the same equation for both Eco-Cities may be that the Australian water is slightly warmer before the heating, but that is disregarded in the calculations. The calculations lead to an energy consumption of 23.6 kWh/m\(^2\) per year to heat the hot tap water in the Eco-City in Stockholm, and a consumption of 26.1 kWh/m\(^2\) per year to heat the hot tap water in the Eco-City in Sydney. Figures 11.1 and 11.2 show the hot water demand in the two Eco-Cities. The hot water needed for space heating in Stockholm is included in Figure 11.1, since it is this total hot water demand that needs to be covered by the solar collectors.

![Hot Water Heating and Space Heating, Residences Stockholm (kWh/m\(^2\))]
11.1.3 Electricity Consumptions in Residences

In order to calculate how much electricity the PV panels need to produce for satisfying the electricity demand, the electricity use of today is investigated.

Household Electricity Consumption in Sweden

In Sweden, the average total household electricity consumption for small houses and apartment buildings that are classified as passive houses is 30 kWh/m² floor area. The consumption is varying from month to month, which is shown in Figure 11.3 (Sveriges Centrum för Nollenergihus, 2012).
The average household electricity for a Swedish household is 6,000 kWh per year (Swedish Energy Agency, 2012b). With an average floor area of 149 m² this corresponds to a consumption of 40 kWh/m² floor area per year. Passive houses are still few compared to ordinary houses in Sweden, and less than 5 per cent of new apartments are built according to the passive house frames (Svensson, 2012). It may therefore be concluded that 40 kWh/m² per year is a figure representing the electricity consumption for ordinary houses that are not passive houses. Thus a passive house has an electricity consumption of 75 per cent (30 kWh/m² instead of 40 kWh/m²) of the ordinary consumption.

**Household Electricity Consumption in Sydney**

The reduction of household electricity consumption that can be seen in Swedish passive houses, due to e.g. energy-efficient appliances and changed behaviour resulting from increased awareness through visible meters, is assumed to apply also in Sydney. Therefore the use of passive houses in Sydney will lower the ordinary average household electricity at the same amount as in Sweden; 25 per cent. The average household electricity consumption per multi-unit dwelling in Sydney is 3,150 kWh per year (Randolph et al., 2006). An average apartment floor area of 127 m² leads to a household electricity consumption of 25 kWh/m² per year (ABS, 2006). A multi-unit passive house dwelling in the Eco-City in Sydney would therefore have a household electricity consumption of 19 kWh/m² per year. It is assumed that the electricity use in Sydney is equally distributed over the year, since the difference in number of daylight hours during the year is smaller than in Sweden. A possible source of error could be that the electricity use might be slightly higher during the winter than during the summer due to more dark hours, but that is disregarded in the calculations. Figure 11.4 is showing the monthly household electricity demand for the Eco-City in Sydney. The electricity needed for space heating and cooling in Sydney is included in Figure 11.4, since it is this total electricity demand that need to be covered by the PV panels.

![Figure 11.4: Energy Demand for Household Electricity and Space Heating & Cooling, Residences Sydney (kWh/m²)](image-url)
11.1.4 Hot Water Use in Offices

The hot tap water use in Swedish non energy-efficient offices is equivalent to an energy use of 2 kWh/m$^2$ floor area (SVEBY, 2012). Since the figure is based on average Swedish offices without water saving solutions, an office with installed saving solutions would, with the same reasoning as for residences, need 75 per cent of that energy. That equals an energy use of 1.5 kWh/m$^2$ floor area. This figure will be assumed to be the same in Sydney since the people in Sydney offices are likely to wash their hands, wash dishes etc. to the same extent as the people in Stockholm. The hot tap water use is assumed to be the same all year round, and no account is taken for holidays.

The energy demand for space heating in Swedish offices is assumed to be 75 per cent of the energy for heating in households, since less time is spent there and electrical appliances help heating the space, resulting in an energy consumption of 15 kWh/m$^2$. This energy consumption is assumed to be distributed the same way as the household heating energy. The monthly hot water demand in the both Eco-Cities is shown in Figures 11.5 and 11.6. The hot water needed for space heating in the offices in Stockholm is included in Figure 11.6 to show the total hot water demand that need to be covered by the solar thermal collectors.

![Figure 11.5: Energy Demand for Hot Water Heating, Offices in Sydney (kWh/m$^2$)](image)

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Figure 11.5: Energy Demand for Hot Water Heating, Offices in Sydney (kWh/m$^2$)
11.1.5 Electricity Consumption in Offices

Electricity Consumption in Swedish Offices

Swedish offices in energy efficient buildings use in average office electricity equal to 50 kWh/m² per year, which includes lights, computers, copying machines etc., and this is assumed to be equally distributed over a year (Blomsterberg, Flodberg & Dubois, 2012). As for residences in Sydney, a possible source of error could be that the electricity use might be slightly higher during the winter than during the summer due to more dark hours, but that is disregarded in the calculations. The monthly electricity demand for offices in the Eco-City in Stockholm is presented in Figure 11.7.

Figure 11.6: Energy Demand for Hot Water Heating and Space Heating, Offices in Stockholm (kWh/m²)

Figure 11.7: Energy Demand for Office Electricity, Offices in Sweden (kWh/m²)
Electricity Consumption in Australian Offices

Tenancy non energy-efficient offices in Adelaide have an average energy density of 304 MJ/m² per year, including lights, power, air conditioners etc. (Bannister, 2004). This corresponds to 84 kWh/m² per year, and since the climate in Sydney is similar to the climate in Adelaide, it can be assumed that the energy density is 84 kWh/m² per year in Sydney too. In a passive house the energy consumption would be 25 per cent less; 63 kWh/m² per year.

The energy for space heating in residences (2.6 kWh/m²) represented 11 per cent of the total energy for household electricity and space heating and cooling (2.6 kWh/m² of 24 kWh/m²). The energy for space cooling in residences (2.4 kWh/m²) represented 10 per cent of the total energy for household electricity and space heating and cooling (2.4 kWh/m² of 24 kWh/m²).

Assuming that the same energy ratio applies for offices, leads to a use of 6.8 kWh/m² energy for heating, and 6.3 kWh/m² energy for cooling per year, distributed the same way as the residential electricity for heating and cooling; heating in the three winter months and cooling in the three summer months. The electricity use will therefore be equal to a total energy consumption of 49.9 kWh/m², and this energy is assumed to be equally distributed over a year. Figure 11.8 is showing the monthly electricity demand for offices in the Eco-City in Sydney, with the electricity demand for space heating and cooling included.


![Office Electricity and Space Heating & Cooling](image)

**Figure 11.8:** Energy Demand for Office Electricity and Space Heating & Cooling, Offices in Sydney (kWh/m²)

11.1.6 Energy Consumption in Schools

The schools cover a big area and employ many students, teachers and administrators during the days. Therefore the energy consumption in the school buildings is important to investigate in order to cover the energy demand with solar energy.

Energy Consumption in Swedish Schools

Schools buildings in Sweden that are classified as passive houses use in average 60 kWh/m² for space heating, hot tap water heating and electricity, where of the space heating and hot water
heating accounts for approximately 37 kWh/m² and electricity accounts for 23 kWh/m² (Lindstaf, 2010).

The Swedish schools are assumed being closed July and August due to summer vacation, and therefore the energy use is distributed from September to June. No consideration is taken for Christmas holiday. The energy used for space heating, hot water heating and electricity will have the same distribution as Swedish households. Figures 11.9 and 11.10 show the monthly energy demand for electricity and hot water heating for the school in the Eco-City in Stockholm.

![Electricity](image1)

**Electricity**

School Stockholm (kWh/m²)

0,5 1 1,5 2 2,5 3

Jan Feb Mar Apr May June July Aug Sep Okt Nov Dec

Electricity

![Hot Water Heating and Space Heating](image2)

**Hot Water Heating and Space Heating, School Stockholm (kWh/m²)**

0 0,5 1 1,5 2 2,5 3 3,5 4 4,5 5

Jan Feb Mar Apr May June July Aug Sep Okt Nov Dec

- Hot Tap Water
- Hot Water For Heating

Figure 11.9: Energy Demand for Electricity, School in Stockholm (kWh/m²)

Figure 11.10: Energy Demand for Hot Water Heating and Space Heating, School in Stockholm (kWh/m²)
Energy Consumption in Australian Schools

In order to calculate the energy consumption for schools in Australia, the ratio between households’ and schools’ energy consumption in Sweden is assumed to apply for households and schools in Australia.

In the Swedish school, the energy consumption for space heating and hot water heating, measured per m², is 85 per cent of the corresponding consumption in Swedish households (37 kWh/m² of 43.6 kWh/m²). For electricity usage, the ratio is 77 per cent (23 kWh/m² of 30 kWh/m²).

The reasoning above leads to an energy consumption in Australian schools of 2.2 kWh/m² for space heating, an energy consumption of 2 kWh/m² for space cooling an energy consumption of 14.6 kWh/m² for electricity and an energy consumption of 22.2 kWh/m² for hot water heating.

The Australian schools are assumed being closed December and January due to summer vacation, and therefore the energy use is distributed from February to November. No consideration is taken for the short winter holiday in July. The energy used for space heating, hot water heating and electricity will have the same distribution as Australian households. Two-thirds of the use for space cooling is excluded, since space cooling is needed when the school is closed, and therefore the energy consumption for space heating will be 0.7 kWh/m² used in February. Figures 11.11 and 11.12 show the monthly electricity demand and hot water demand for the school in the Eco-City in Sydney.

![Figure 11.11: Energy Demand for Electricity and Space Heating & Cooling, School in Sydney (kWh/m²)](image-url)
Energy Consumption in the Innovation and Information Centre

The Innovation and Information Centres are assumed to have the same energy consumption as offices, and the centres’ area is a part of the total office area.

After having determined the energy demand of the different buildings investigated in the two Eco-Cities, the next step is to examine the energy produced to cover this demand. The following chapters will first explain the two programs used for calculating the energy output from solar thermal collectors and PV panels, and then present the calculated production, demand coverage and system costs.

12 Energy Production

The energy output from the solar thermal collectors and PV panels is calculated through using the two programs ScenoCalc (Solar Collector Energy Output Calculator) and PVWATTS. ScenoCalc is developed by SP Technical Research Institute of Sweden and it is available at the institute’s website (SP, n.d.). PVWATTS is provided by the National Renewable Energy Laboratory (NREL) of the U.S Department of Energy and is available at NREL’s website (NREL, 2009). This chapter presents the features of the programs, and the different output and input parameters.

12.1 Energy Production From Solar Thermal Collectors

The energy output from the solar thermal collectors is calculated through the calculation tool ScenoCalc. The program calculates the annual energy output for solar collectors available in the market, and is used for e.g. quality labelling and comparison of solar thermal products, and was developed within the EU-project QAIST (Quality Assurance in Solar Thermal Heating and Cooling Technologies). All calculations are made by the VBA code in Excel. Input parameters are based on average solar collectors tested according to Steady State. Table 7 explains the different
input parameters, and Tables 8 and 9 present the different values of the input parameters used in the calculations.

Table 7: Input Parameters for Electricity Generation Calculations in PVWATTS

<table>
<thead>
<tr>
<th>Variable input parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location</strong></td>
<td>Latitude and Longitude</td>
</tr>
<tr>
<td><strong>Weather data</strong></td>
<td>The program provides weather data for Stockholm. Weather data for Sydney is retrieved through the program Meteonorm v.5.1</td>
</tr>
<tr>
<td><strong>Mean operation temperatures</strong></td>
<td>Mean fluid temperature of the collector (0-100°C). Recommendation for calculation for domestic hot water and district heating without seasonal storage is 50°C (ESTIF, 2007).</td>
</tr>
<tr>
<td><strong>Aperture area</strong></td>
<td>Specific for the examined collector, based on an average flat plate or evacuated tube collector area.</td>
</tr>
<tr>
<td><strong>Evaluation method</strong></td>
<td>The test method that has been applied to derive the model parameters. Quasi Dynamic or Steady State with associated parameters</td>
</tr>
<tr>
<td><strong>Zero- loss efficiency ( \eta_0 )</strong></td>
<td>Zero-loss collector efficiency (( \eta_0 )) is the efficiency when the mean collector temperature and the ambient temperature are equal. Aperture specific, based on an average flat plate or evacuated tube collector efficiency.</td>
</tr>
<tr>
<td><strong>Heat loss coefficients</strong></td>
<td>Efficiency depends on the difference between the collector mean temperature and the ambient temperature and decreases with higher over temperature in the collector. The first order heat loss coefficient (( a_1 )) describes the first degree of temperature dependence of the heat losses from the collector and the second order heat loss coefficient (( a_2 )) describes the second degree.</td>
</tr>
<tr>
<td><strong>IAM type</strong></td>
<td>Simple One-Direction constant (( b_0 )) or User Defined IAM constants (( K_{\theta EW} ) &amp; ( K_{\theta NS} )) (constants stated in collector test)</td>
</tr>
<tr>
<td><strong>Type of tracking</strong></td>
<td>No tracking, Vertical axis tracking, 2-axis tracking, horizontal axis tracking</td>
</tr>
<tr>
<td><strong>Tilt Angle ( (^{\circ}, \text{degrees}) )</strong></td>
<td>Described in Chapter 5.</td>
</tr>
<tr>
<td><strong>Azimuth Angle ( (^{\circ}, \text{degrees}) )</strong></td>
<td>Described in Chapter 5.</td>
</tr>
</tbody>
</table>

Table 8: Input Parameters for Energy Calculations, Flat Plate Collectors

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>Sydney</th>
<th>Stockholm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>-33.9°</td>
<td>59.4°</td>
</tr>
<tr>
<td>Longitude</td>
<td>-151°</td>
<td>-18.1°</td>
</tr>
<tr>
<td>Mean operation temperatures</td>
<td>50°C</td>
<td>50°C</td>
</tr>
<tr>
<td>Aperture area</td>
<td>2.57 m²</td>
<td>2.57 m²</td>
</tr>
<tr>
<td>Evaluation method</td>
<td>Steady State</td>
<td>Steady State</td>
</tr>
<tr>
<td>( \eta_0 )</td>
<td>0.78</td>
<td>0.78</td>
</tr>
<tr>
<td>( a_1 )</td>
<td>2.9 W/m²K</td>
<td>2.9 W/m²K</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>0.02 W/m²K²</td>
<td>0.02 W/m²K²</td>
</tr>
<tr>
<td>IAM Type</td>
<td>Simple, one-direction ( b_0=0.16 )</td>
<td>Simple, one-direction ( b_0=0.16 )</td>
</tr>
<tr>
<td>Type of tracking</td>
<td>No tracking</td>
<td>No tracking</td>
</tr>
<tr>
<td>Tilt Angle</td>
<td>45°</td>
<td>45°, 60°, 90°</td>
</tr>
<tr>
<td>Azimuth Angle</td>
<td>180°</td>
<td>0°</td>
</tr>
</tbody>
</table>
The output parameter of the calculation tool is, for every month of the year:

- **Thermal yield (kWh/module per day):** monthly average

In order to get the energy production in kWh/m² thermal yield is divided by the solar collector’s aperture area. The results of the production calculations are presented in the next chapter.

### 12.2 Electricity Production From PV Cells

The electricity production from the PV cells is calculated through the online tool PVWATTS, a program developed to permit non-expert researchers to obtain performance estimates for grid-connected PV systems. The calculations are based on average Monocrystalline and Polycrystalline solar panels, and Amorphous thin-film panels. The input parameters used in the calculation tool are presented in Table 9, and Table 10 presents the different values of the input parameters used in the calculations.

#### Table 9: Input Parameters for Energy Calculations, Evacuated Type Collectors

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>Sydney</th>
<th>Stockholm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>-33.9°</td>
<td>59.4°</td>
</tr>
<tr>
<td>Longitude</td>
<td>-151°</td>
<td>-18.1°</td>
</tr>
<tr>
<td>Mean operation temperatures</td>
<td>50°C</td>
<td>50°C</td>
</tr>
<tr>
<td>Aperture area</td>
<td>3.03 m²</td>
<td>3.03 m²</td>
</tr>
<tr>
<td>Evaluation method</td>
<td>Steady State</td>
<td>Steady State</td>
</tr>
<tr>
<td>η₀</td>
<td>0.73</td>
<td>0.73</td>
</tr>
<tr>
<td>a₁</td>
<td>1.5 W/m²K</td>
<td>1.5 W/m²K</td>
</tr>
<tr>
<td>a₂</td>
<td>0.009 W/m²K²</td>
<td>0.009 W/m²K²</td>
</tr>
<tr>
<td>IAM Type</td>
<td>User Defined (See Appendix 16.2)</td>
<td>User Defined (See Appendix 16.2)</td>
</tr>
<tr>
<td>Type of tracking</td>
<td>No tracking</td>
<td>No tracking</td>
</tr>
<tr>
<td>Tilt Angle</td>
<td>35°, 45°, 60°</td>
<td>45°, 60°, 90°</td>
</tr>
<tr>
<td>Azimuth Angle</td>
<td>180°</td>
<td>0°</td>
</tr>
</tbody>
</table>

The output parameter of the calculation tool is, for every month of the year:

- **Thermal yield (kWh/module per day):** monthly average

#### Table 10: Input Parameters for Electricity Generation Calculations in PVWATTS

<table>
<thead>
<tr>
<th>Variable input parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location</strong></td>
<td>Latitude, Longitude and Elevation.</td>
</tr>
<tr>
<td><strong>Weather data</strong></td>
<td>The program retrieves Typical Meteorological Year (TWM) long-term average weather data from the International Weather for Energy Calculations (IWEC).</td>
</tr>
<tr>
<td><strong>DC-rating (kW)</strong></td>
<td>The size of the PV-system. The installed module power in the calculations are set to 1 kW.</td>
</tr>
<tr>
<td><strong>DC-to-AC Derate Factor</strong></td>
<td>Determines the AC power rating, accounting for losses from the DV nameplate power rating and is the product of the derate factors for the PV system components. Examples of component derate factors are: Inverter, transformer, soiling, shading, sun tracking and age. A derate factor of 0.77 means that the AC power rating is 77 per cent of the DC power rating at the nameplate. Variation in the derate factor is taken into account in the sensitivity analysis where additional losses' influence on the output is investigated.</td>
</tr>
<tr>
<td><strong>Array Type</strong></td>
<td>Fixed, 1-axis tracking or 2-axis tracking. Described in Chapter 5.</td>
</tr>
<tr>
<td><strong>Array Tilt (°, degrees)</strong></td>
<td>Described in Chapter 5.</td>
</tr>
<tr>
<td><strong>Array Azimuth (°, degrees)</strong></td>
<td>Described in Chapter 5.</td>
</tr>
</tbody>
</table>
The input parameters that vary in the calculations are:

- **Array Tilt**: Sydney: 34°, 40°, 90°  
  Stockholm: 45°, 60°, 90°

The base scenario angles of 34° and 45° are described in Chapter 5, the angles of 40° and 60° are investigated because they are better suited for lower sun and might give larger demand coverage, and the angle of 90° is chosen to investigate the possibility of having façade installed panels.

The output of the calculation tool is, for every month of the year:

- **AC Energy (kWh)**: monthly generated energy

In order to get the energy production in kWh/m² the panel specific power-to-size ratios are used. The average power-to-size ratios for the different solar panels used in the calculation are (Solar Choice, 2009):

- **Monocrystalline**: 0.1525 kW/m²  
- **Polycrystalline**: 0.145 kW/m²  
- **Amorphous Thin-Film**: 0.07 kW/m²

The results of the production calculations are presented in the next chapter.
13 Results and Discussion

This chapter will present the calculated energy production from solar thermal collectors and PV panels, together with area coverage and a cost analysis.

The different solar technology systems are designed to cover one month’s energy demand, since it could be unsustainable to have larger capacity of energy production than energy demand. This will probably lead to a totally covered demand during months with high production and low demand, and not entirely covered demand during months with lower production and higher demand. The calculations are based on the assumption that energy will be purchased when the demand is not totally covered. There might be a more beneficial scenario with larger demand coverage leading to that the demand sometimes is more than satisfied, but it is beyond this report’s field to find the optimized ratio of produced and purchased energy.

Two different area cases will be presented, where the total roof area available for solar appliances is dependent on how much area used for green spaces. As earlier discussed the green spaces are important for the social well-being, but roof area is necessary for installing the solar appliances. The two cases are chosen to show the impact available roof area may have on the total production, and the two total available roof areas for residential and office buildings are: 144,525 m² and 244,525 m². In the first case the area of green spaces is 25 m² per person, and in the second case the area is 15 m² per person. It is assumed that the schools’ available roof area is not affected by the area changes, and only one area case will be investigated.

The cost for the energy production and the total system cost will be presented in order to compare to the cost of only purchasing the needed energy. The comparison will lead to the conclusion if the installed solar technology systems may imply savings or extra costs.

The two schools are assumed not having any energy demand during two months of the year due to holidays. The solar thermal collectors will be switched off during these months, since it is not possible to sell the hot water for the investigated hot water systems. Buildings nearby are assumed to cover their hot water demand with their own solar thermal collectors. In the case of PV panels, during the holiday months, the assumption is that produced excess electricity is sold to the larger electricity grid outside the Eco-City suburb. For both Sydney and Stockholm it is assumed that the electricity is sold for 20 öre/kWh. This number is based on historical spot market prices during summer months when the price is typical low (AEOMO, 2013 & Nord Pool Spot, 2013).

13.1 Solar Thermal Collectors

This subchapter presents the results of the calculations made on solar thermal collectors’ energy production, and compares the costs of the solar collector systems to the costs of purchasing energy.

13.1.1 The Energy Production of Solar Thermal Collectors in Sydney

The first Eco-City analysed is the one in Sydney, and this subchapter will present the production, demand, area coverage and costs for the chosen solar thermal collector systems in the residences, offices and school.
Residential and Offices in Sydney

Figure 13.1 is showing Flat Plate Collectors’ and Evacuated Tube Collector’s coverage of the total hot water demand for residential and offices in the Eco-City in Sydney. In order to produce the energy needed for covering one month’s demand the Flat Plate 45° used 13,120 m² of active aperture area, the Evacuated Tube 35° used 9,740 m² of active aperture area, and the Evacuated Tube 45° used 10,090 m² of active aperture area. The coverage is quite good during a large part of the year, but is worse during the winter months due to less irradiation. The production from the two collectors with a tilt angle of 45° is slightly larger than the one with tilt angle 35° during the winter months, due to a lower sun. There is no obviously superior collector, since they produce different amounts of energy during different months and which one producing the most is shifting. To decide which collector to choose to integrate in the Eco-City in Sydney, area coverage and annual cost savings will be investigated in Tables 12 and 13.

Table 12 is showing the total required roof area (the module area and the area between modules) the collectors need to produce the energy covering one month’s demand, and how large part of the total roof area available that is covered. The coverage will be important when later planning the whole system of thermal collectors, PVs and green roofs. Since Flat Plate Collectors are less efficient, it is logical that they require more area, and the 35° Evacuated Tube Collectors have the best angle towards the sun, leading to higher production per m². But less area needed is not equal to less cost, which is shown in Table 13. The production cost is based on the total cost per square meter collector, yearly operation costs and costs for purchased energy to cover the demand, divided by total production. This is compared to the cost of only purchasing gas to heat the hot water (based on gas prices in Chapter 8), and the result is that the cheaper square metre prise for Flat Plate Collectors leads to the largest annual savings of 64 per cent. The choice of which collector to use will therefore depend on area savings through the 35° Evacuated Tube Collectors.
Collectors or money savings through the 45° Flat Plate Collectors, which will be discussed further in the conclusion.

Table 12: Area Coverage, Different Solar Thermal Collectors, Residential and Offices in Sydney

<table>
<thead>
<tr>
<th>Collector Type and Tilt Angle</th>
<th>Total Area Required (m²)</th>
<th>Area Available Case 1 (m²)</th>
<th>Area Available Case 2 (m²)</th>
<th>Area Coverage Case 1</th>
<th>Area Coverage Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Plate, 45°</td>
<td>26,246</td>
<td>144,525</td>
<td>244,525</td>
<td>18%</td>
<td>11%</td>
</tr>
<tr>
<td>Evacuated Tube, 35°</td>
<td>22,146</td>
<td>144,525</td>
<td>244,525</td>
<td>15%</td>
<td>9%</td>
</tr>
<tr>
<td>Evacuated Tube, 45°</td>
<td>24,603</td>
<td>144,525</td>
<td>244,525</td>
<td>17%</td>
<td>10%</td>
</tr>
</tbody>
</table>

Table 13: Solar System Cost Compared to Only Purchased Energy Cost, Residential and Offices in Sydney

<table>
<thead>
<tr>
<th>Collector Type and Tilt Angle</th>
<th>Production Cost (öre/kWh)</th>
<th>Total System Cost (SEK)</th>
<th>Cost Purchased Energy (SEK)</th>
<th>Annual Savings (SEK)</th>
<th>Annual Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Plate, 45°</td>
<td>18.8</td>
<td>2,148,927</td>
<td>5,937,466</td>
<td>3,788,539</td>
<td>64%</td>
</tr>
<tr>
<td>Evacuated Tube, 35°</td>
<td>20.5</td>
<td>2,343,034</td>
<td>5,937,466</td>
<td>3,594,432</td>
<td>61%</td>
</tr>
<tr>
<td>Evacuated Tube, 45°</td>
<td>21.4</td>
<td>2,420,102</td>
<td>5,937,466</td>
<td>3,517,364</td>
<td>59%</td>
</tr>
</tbody>
</table>

School in Sydney

Figure 13.2 is showing Flat Plate Collectors’ and Evacuated Tube Collector’s coverage of the total hot water demand for the school in the Eco-City in Sydney. The aperture area needed to cover one month’s demand was 300 m² for the Flat Plate Collectors, 230 m² for the 45° Evacuated Tube Collectors and 220 m² for the 35° Evacuated Tube Collectors. The coverage is very similar the one in Figure 13.1, except for December and January when the school is assumed to be closed.
Table 14: Area Coverage, Different Solar Thermal Collectors, School in Sydney

<table>
<thead>
<tr>
<th>Collector Type and Tilt Angle</th>
<th>Total Area Required (m²)</th>
<th>Area Available (m²)</th>
<th>Area Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Plate, 45°</td>
<td>685</td>
<td>5,475</td>
<td>13%</td>
</tr>
<tr>
<td>Evacuated Tube, 35°</td>
<td>509</td>
<td>5,475</td>
<td>9%</td>
</tr>
<tr>
<td>Evacuated Tube, 45°</td>
<td>505</td>
<td>5,475</td>
<td>9%</td>
</tr>
</tbody>
</table>

The school’s area is assumed not being affected by the green space area, and therefore only one area case is studied. As in Table 12, it is shown in Table 14 that the Flat Plate Collectors cover larger area of the total roof area available while the Evacuated Tube Collectors need smaller area. The cost savings shown in Table 15 are less than for residential and offices, and the reason is that the school doesn’t utilize the hot water that could have been produced during the summer. This effect is reinforced by not using energy that could have been generated during irradiation intense months.

Table 15: Solar System Cost Compared to Only Purchased Energy Cost, School in Sydney

<table>
<thead>
<tr>
<th>Collector Type and Tilt Angle</th>
<th>Production Cost (öre/kWh)</th>
<th>Total System Cost (SEK)</th>
<th>Cost Purchased Energy (SEK)</th>
<th>Annual Savings (SEK)</th>
<th>Annual Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Plate, 45°</td>
<td>24</td>
<td>50,224</td>
<td>113,660</td>
<td>63,435</td>
<td>56%</td>
</tr>
<tr>
<td>Evacuated Tube, 35°</td>
<td>27</td>
<td>55,632</td>
<td>113,660</td>
<td>58,028</td>
<td>51%</td>
</tr>
<tr>
<td>Evacuated Tube, 45°</td>
<td>27</td>
<td>56,944</td>
<td>113,660</td>
<td>56,716</td>
<td>50%</td>
</tr>
</tbody>
</table>

13.1.2 The Energy Production of Solar Thermal Collectors in Stockholm

This subchapter covers the analysis of the Eco-City in Stockholm, and the production, demand, area coverage and costs for the chosen solar thermal collector systems in the residences, offices and school will be presented.

Residential and offices in Stockholm

Flat Plate Collectors’ and Evacuated Collectors’ energy productions are separated in two different diagrams, since three different angles need to be investigated for each collector.
Figure 13.3 is showing Flat Plate Collectors’ coverage of the total hot water demand for residential and offices in the Eco-City in Stockholm. The angles of 60° and 90° are investigated in order to see if it is possible to take advantage of the lower sun during spring, autumn and winter. In order to produce the energy needed for covering one month’s demand, the active aperture area needed was 18,200 m² for the 45° collector, 20,900 m² for the 60° collector and 36,150 m² for the 90° collector. This diagram shows a much larger mismatch between demand and supply than the diagram for Sydney shown in Figure 13.1, since much hot water is needed for space heating during the winter when the irradiation is low, and it is a low need of hot water for space heating during the summer when the irradiation is higher. It is clearly shown that the 90° collector covers more of the demand during spring, autumn and winter, and less during the summer. But the 90° collector requires much more area which is, as later presented in Table 17, expensive.

Figure 13.4 is showing Evacuated Plate Collectors’ coverage of the total hot water demand for residential and offices in the Eco-City in Stockholm. In order to produce the energy needed for covering one month’s hot water demand, the active aperture area needed was 14,120 m² for the 45° collector, 14,900 m² for the 60° collector and 19,880 m² for the 90° collector. As in the diagram for Flat Plate Collectors, the 90° Evacuated Tube Collector covers more during months with low sun, but some months the Flat Plate Collector produces more. The reason may be that the area for the 90° Evacuated Tube Collector is much smaller than the area for the 90° Flat Plate Collector.
Figure 13.4: Residential and Offices Hot Water Demand Coverage from Evacuated Tube Collectors in Stockholm (kWh)

Table 16: Area Coverage, Different Solar Thermal Collectors, Residential and Offices in Stockholm

<table>
<thead>
<tr>
<th>Collector Type and Tilt Angle</th>
<th>Total Area Required (m²)</th>
<th>Area Available Case 1 (m²)</th>
<th>Area Available Case 2 (m²)</th>
<th>Area Coverage Case 1</th>
<th>Area Coverage Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Plate, 45°</td>
<td>41,364</td>
<td>144,525</td>
<td>244,525</td>
<td>29%</td>
<td>17%</td>
</tr>
<tr>
<td>Flat Plate, 60°</td>
<td>48,675</td>
<td>144,525</td>
<td>244,525</td>
<td>34%</td>
<td>20%</td>
</tr>
<tr>
<td>Evacuated Tube, 45°</td>
<td>38,173</td>
<td>144,525</td>
<td>244,525</td>
<td>26%</td>
<td>16%</td>
</tr>
<tr>
<td>Evacuated Tube, 60°</td>
<td>42,561</td>
<td>144,525</td>
<td>244,525</td>
<td>29%</td>
<td>17%</td>
</tr>
</tbody>
</table>

The collectors at 90° are not presented in Table 16 since they are planned to be located at façades and cover therefore no roof area. As stated in previous tables, Flat Plate Collectors cover larger area than the Evacuated Tube Collectors. Compared to the Sydney case (presented in Table 12), the area required for the collectors in Stockholm is much larger due to less irradiance, leading to much higher roof area coverage.

Table 17: Solar System Cost Compared to Only Purchased Energy Cost, Residential and Offices in Sydney

<table>
<thead>
<tr>
<th>Collector Type and Tilt Angle</th>
<th>Production Cost (öre/kWh)</th>
<th>Total System Cost (SEK)</th>
<th>Cost Only Purchased Energy (SEK)</th>
<th>Annual Savings (SEK)</th>
<th>Annual Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Plate, 45°</td>
<td>70</td>
<td>17,489,869</td>
<td>18,811,534</td>
<td>1,321,665</td>
<td>7%</td>
</tr>
<tr>
<td>Flat Plate, 60°</td>
<td>74</td>
<td>17,720,088</td>
<td>18,811,534</td>
<td>1,091,447</td>
<td>6%</td>
</tr>
<tr>
<td>Flat Plate, 90°</td>
<td>102</td>
<td>20,417,841</td>
<td>18,811,534</td>
<td>-1,606,306</td>
<td>-9%</td>
</tr>
<tr>
<td>Evacuated Tube, 45°</td>
<td>75</td>
<td>17,876,695</td>
<td>18,811,534</td>
<td>934,840</td>
<td>5%</td>
</tr>
<tr>
<td>Evacuated Tube, 60°</td>
<td>78</td>
<td>18,070,667</td>
<td>18,811,534</td>
<td>740,867</td>
<td>4%</td>
</tr>
<tr>
<td>Evacuated Tube, 90°</td>
<td>96</td>
<td>19,696,423</td>
<td>18,811,534</td>
<td>-884,888</td>
<td>-5%</td>
</tr>
</tbody>
</table>
The costs presented in Table 17 are much higher than the costs in Sydney, where the production costs were little more than 20 öre/kWh, compared to over 70 öre/kWh in Stockholm. The high production costs are mainly due to less energy produced per square meter but also due to higher costs for installation. The annual savings are low and the costs for having collectors at 90° are even higher than the costs of only purchasing district heating for hot water.

School in Stockholm

Figure 13.5 is showing Flat Plate Collectors’ coverage of the total hot water demand for the school in the Eco-City in Stockholm. The aperture area needed to cover one month’s demand was 410 m² for the collector at 45°, 480 m² for the 60° collector and 1,010 m² for the collector at 90°. The 90° collector is, as in Figure 13.4, covering a large part of the spring and autumn hot water demand, but the coverage of the winter demand is very low. The school is closed during July and August, and there is no production or demand.

Figure 13.5: The School’s Hot Water Demand Coverage from Flat Plate Collectors in Stockholm (kWh)
Figure 13.6 is showing Evacuated Tube Collectors’ coverage of the total hot water demand for the school in the Eco-City in Stockholm. The collectors need aperture areas to cover one month’s demand of 320 m² for the collector at 45°, 335 m² for the 60° collector and 510 m² for the collector at 90°. As for residential and offices in Stockholm, the 90° Evacuated Tube Collector is producing slightly less energy than the Flat Plate Collector in spring and autumn.

Table 18: Area Coverage, Different Solar Thermal Collectors, School in Stockholm

<table>
<thead>
<tr>
<th>Collector Type and Tilt Angle</th>
<th>Total Area Required (m²)</th>
<th>Area Available (m²)</th>
<th>Area Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Plate, 45°</td>
<td>933</td>
<td>5,475</td>
<td>17%</td>
</tr>
<tr>
<td>Flat Plate, 60°</td>
<td>1,112</td>
<td>5,475</td>
<td>20%</td>
</tr>
<tr>
<td>Evacuated Tube, 45°</td>
<td>859</td>
<td>5,475</td>
<td>16%</td>
</tr>
<tr>
<td>Evacuated Tube, 60°</td>
<td>957</td>
<td>5,475</td>
<td>17%</td>
</tr>
</tbody>
</table>

As in the case of residential and offices in Stockholm, the collectors at 90° are not presented in Table 18 since they are planned to be located at façades and cover therefore no roof area. As stated in the previous table representing the school in Sydney, only one area case is investigated. The annual cost savings shown in Table 19 are all negative, and using solar thermal collectors at the school in Stockholm seems like a bad investment. Most expensive are the 90° collectors due to very large aperture areas. The production costs are very high and by having summer holidays the school misses a lot of energy that that could have been generated during the irradiation intense summer months.
Table 19: Solar System Cost Compared to Only Purchased Energy Cost, School in Stockholm

<table>
<thead>
<tr>
<th>Collector Type and Tilt Angle</th>
<th>Production Cost (öre/kWh)</th>
<th>Total System Cost (SEK)</th>
<th>Cost Only Purchased Energy (SEK)</th>
<th>Annual Savings (SEK)</th>
<th>Annual Savings %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Plate, 45°</td>
<td>101</td>
<td>227,686</td>
<td>210,236</td>
<td>-17,450</td>
<td>-8%</td>
</tr>
<tr>
<td>Flat Plate, 60°</td>
<td>104</td>
<td>234,550</td>
<td>210,236</td>
<td>-24,314</td>
<td>-12%</td>
</tr>
<tr>
<td>Flat Plate, 90°</td>
<td>159</td>
<td>347,644</td>
<td>210,236</td>
<td>-137,408</td>
<td>-65%</td>
</tr>
<tr>
<td>Evacuated Tube, 45°</td>
<td>105</td>
<td>235,497</td>
<td>210,236</td>
<td>-25,261</td>
<td>-12%</td>
</tr>
<tr>
<td>Evacuated Tube, 60°</td>
<td>108</td>
<td>240,315</td>
<td>210,236</td>
<td>-30,078</td>
<td>-14%</td>
</tr>
<tr>
<td>Evacuated Tube, 90°</td>
<td>130</td>
<td>286,591</td>
<td>210,236</td>
<td>-76,355</td>
<td>-36%</td>
</tr>
</tbody>
</table>

13.2 Electricity Production from PVs

This subchapter presents the results of the calculations made on the electricity production from PVs, and compares the costs of the PV systems to the costs of purchasing electricity.

13.2.1 PV Electricity Production in Sydney

Residential and offices in Sydney

The monthly demand is highest during summer and winter months because of space cooling and heating, and therefore the highest demand coverage from PVs is during spring and autumn (See Figure 13.7), and not during the summer as for the hot water. Since the only difference between the different PVs is produced kWh/m², the demand coverage is the same for Monocrystalline, Polycrystalline and Amorphous Thin-Film during the year and the only difference is the area needed for the production. Therefore only the different angles’ demand coverage is presented in Figure 13.8, and it is shown that the panels at 34° produce most during summer, panels at 40° produce most in early autumn, and the panels at 90° produce most during months with low sun.
Figure 13.7: Residential and Offices Electricity Demand Coverage from PVs in Sydney (kWh)

Figure 13.8: Required Aperture Area to Meet Electricity Demand, Different Solar Cell Types and Tilt Angles, Residential and Offices in Sydney (m²)

Figure 13.8 is showing how much area the different PVs need at different tilt angles to cover one month's demand. It is clear that Amorphous Thin-Film use a lot more area to produce the electricity needed, and the Polycrystalline needs slightly more than the Monocrystalline, which is logic since Monocrystalline is the panel producing most kWh/m². It is also shown that panels located at facades need much more area than the ones at the roof, which is explained by a high sun during large parts of the year. Since the price per kWh is the same for the three different
types of PVs, and the area is limited the Amorphous Thin-Film panels is assumed to use too much area and will not be investigated further.

Table 20 shows the total area required for the Monocrystalline and Polycrystalline apertures and the distance between the modules, and the roof area coverage in the two different area cases. Compared to the area needed for hot water heating in Sydney (presented in Table 12), the coverage is very high. The collector area coverage for hot water was below 9-18 per cent. The reason is probably both a very high electricity demand, since it is used both for household electricity and space heating and cooling while the hot water demand is only for tap water, and the solar thermal hot water collectors produce more kWh/m². The roof area coverage for Case 1 is close to 100 per cent, and this may lead to that green areas must be reduced in order to get the roof area available in Case 2. This will be further discussed in the conclusion.

<table>
<thead>
<tr>
<th>PV Type and Tilt Angle</th>
<th>Total Area Required (m²)</th>
<th>Area Available Case 1 (m²)</th>
<th>Area Available Case 2 (m²)</th>
<th>Area Coverage Case 1</th>
<th>Area Coverage Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monocrystalline 34°</td>
<td>114,564</td>
<td>144,525</td>
<td>244,525</td>
<td>79%</td>
<td>47%</td>
</tr>
<tr>
<td>Monocrystalline 40°</td>
<td>123,066</td>
<td>144,525</td>
<td>244,525</td>
<td>85%</td>
<td>50%</td>
</tr>
<tr>
<td>Polycrystalline 34°</td>
<td>120,489</td>
<td>144,525</td>
<td>244,525</td>
<td>83%</td>
<td>49%</td>
</tr>
<tr>
<td>Polycrystalline 40°</td>
<td>129,432</td>
<td>144,525</td>
<td>244,525</td>
<td>90%</td>
<td>53%</td>
</tr>
</tbody>
</table>

The total system, cost is based on the total annual capital cost per square meter PV and yearly maintenance costs and costs for purchased energy to cover the demand. This is compared to the cost of only purchasing energy to cover the electricity demand (based on electricity prices in Chapter 8), and the result is quite high annual savings of around 50 per cent (See Table 20). The reason to the high savings is likely due to less need of purchasing the very expensive electricity in Sydney. Monocrystalline and Polycrystalline panels are presented together since the cost per kWh is the same, and therefore not dependent on the aperture area. The highest annual savings of 56 per cent is not for the panels at 34° with lowest production cost, but for the panels at 40°. The reason for this is more active aperture area installed which results in a higher total annual production. One reason may also be a slightly better utilization of lower sun, and therefore less need for purchased electricity during long periods of the year. Even though panels at 90° need much aperture area, which causes high investment costs, the annual savings are quite high, and this shows even more clearly that the high electricity price is crucial. Since the costs and annual savings is the same for Monocrystalline and Polycrystalline, and the available area is limited due to the fact that green roofs are desirable in an Eco-City, it is reasonable to focus on using Monocrystalline panels.

Table 21: PV System Cost Compared to Only Purchased Energy Cost, Residential and Offices in Sydney

<table>
<thead>
<tr>
<th>PV Type and Tilt Angle</th>
<th>Production Cost (SEK/kWh)</th>
<th>Total System Cost (SEK)</th>
<th>Cost Only Purchased Energy (SEK)</th>
<th>Annual Savings (SEK)</th>
<th>Annual Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monocrystalline/Polycrystalline 34°</td>
<td>68</td>
<td>34,275,797</td>
<td>76,309,684</td>
<td>42,033,887</td>
<td>55%</td>
</tr>
<tr>
<td>Monocrystalline/Polycrystalline 40°</td>
<td>69</td>
<td>33,749,039</td>
<td>76,309,684</td>
<td>42,560,645</td>
<td>56%</td>
</tr>
<tr>
<td>Monocrystalline/Polycrystalline 90°</td>
<td>122</td>
<td>35,039,534</td>
<td>76,309,684</td>
<td>41,270,150</td>
<td>54%</td>
</tr>
</tbody>
</table>
School in Sydney

The school in the Eco-City in Sydney has highest electricity demand during summer and winter months due to need of space cooling and heating, but compared to residential and offices the total electricity demand is reduced quite much due to deleting two electricity intense summer months’ demand during holidays. Figure 13.9 is showing the school’s electricity demand and production. The demand coverage from the PVs at different angles looks the same as the coverage for residential and offices seen in Figure 13.7, and the amount of area required at the different angles, seen in Figure 13.10, follows the same pattern as for residential and offices: very large area for the 90° panels. The electricity production during December and January is also shown, since the school is assumed to be able to sell that electricity.

![Monthly Electricity Demand Coverage](image)

Figure 13.9: School Electricity Demand Coverage from PVs in Sydney (kWh)
Figure 13.10: Required Aperture Area to Meet Electricity Demand, Different Solar Cell Types and Tilt Angles, School in Sydney (m²)

Table 22 presents the total roof area coverage for the Monocrystalline and Polycrystalline panels, and, as before, the 90° façade panels are not included in the roof area coverage. The panels’ coverage of the roof area available is much smaller for the school than for residential and offices, where the coverage was about 50 or 80 per cent depending on which area case investigated. The reason for this is a smaller electricity demand per square metre roof area.

Table 22: Area Coverage, Different PVs, School in Sydney

<table>
<thead>
<tr>
<th>PV Type and Tilt Angle</th>
<th>Total Roof Area Required (m²)</th>
<th>Area Available (m²)</th>
<th>Area Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monocrystalline 34°</td>
<td>1,592</td>
<td>5,475</td>
<td>29%</td>
</tr>
<tr>
<td>Monocrystalline 40°</td>
<td>1,710</td>
<td>5,475</td>
<td>31%</td>
</tr>
<tr>
<td>Polycrystalline 34°</td>
<td>1,798</td>
<td>5,475</td>
<td>33%</td>
</tr>
<tr>
<td>Polycrystalline 40°</td>
<td>821</td>
<td>5,475</td>
<td>15%</td>
</tr>
</tbody>
</table>

The annual savings for PVs at the school roof and façade presented in Table 23 are a little bit lower than for residential and offices, which were 55, 56 and 54 per cent. The reason is that the school is selling the electricity produced, and the price they get paid is lower than they buy it for, and thus utilizing own-produced electricity, as the residential and offices, is better than selling. The annual savings from the 40° PVs are largest, and the reasons are highest total yearly production and a slightly higher production than 34° during the colder months when the school needs the electricity, which results in smaller need of purchased electricity. The 34° produces a little bit more electricity during the summer which can be sold, but as stated above the price for selling is lower than purchasing, and contributes therefore not very much to the annual savings.
Table 23: PV System Cost Compared to Only Purchased Energy Cost, School in Sydney

<table>
<thead>
<tr>
<th>PV Type and Tilt Angle</th>
<th>Production Cost (öre/kWh)</th>
<th>Total System Cost (SEK)</th>
<th>Cost Only Purchased Energy (SEK)</th>
<th>Annual Savings (SEK)</th>
<th>Annual Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monocrystalline/Polycrystalline 34°</td>
<td>68</td>
<td>383,174</td>
<td>837,762</td>
<td>454,588</td>
<td>54%</td>
</tr>
<tr>
<td>Monocrystalline/Polycrystalline 40°</td>
<td>69</td>
<td>373,070</td>
<td>837,762</td>
<td>464,691</td>
<td>55%</td>
</tr>
<tr>
<td>Monocrystalline/Polycrystalline 90°</td>
<td>122</td>
<td>427,089</td>
<td>837,762</td>
<td>410,673</td>
<td>49%</td>
</tr>
</tbody>
</table>

### 13.2.2 PV Electricity Production in Stockholm

**Residential and Offices in Stockholm**

As for solar thermal collectors there is a mismatch between supply and demand, and the electricity demand is highest during the winter when the sun is low and the production is low. Figure 13.11 presents the electricity production from PVs at three different angles: 45°, 60° and 90°. It is quite clear that the panels at 90° cover most demand and the panels at 45° least, except for the summer months, which is due to a low sun during large parts of the year. It is interesting that all angles maximize the production during May, which must depend on very intense irradiation at all angles. In Sydney the 90° panels maximize their production during the winter, but in Stockholm the production is lowest during that period due to the very low sun and few bright hours.

![Monthly Electricity Demand Coverage Residential & Offices in Stockholm (kWh)](image)

*Figure 13.11: Residential and Offices Electricity Demand Coverage from PVs in Stockholm (kWh)*
Figure 13.12 is showing the different aperture areas required to cover the electricity demand in residential and offices in Stockholm in May. As in Sydney, the panels at 90° requires more area than the other panels at lower angle, but the difference is not as great in Sweden, and the reason is likely to be that the façade panels are able to assimilate the low sun better. Table 24 presents the total area required for Monocrystalline and Polycrystalline panels to cover the demand in May, and the area coverage in the two area cases. Amorphous Thin-Film is not presented since too large area is required. The 90° panels are not represented since they are placed at the façade. In the case where the green areas are large, the panels need more area than available roof area, and it is therefore not possible to cover the electricity demand with panels at the roofs. In Case 2, where the green areas are reduced, it is possible to use the panels at 45°, but not the ones at 60° that cover more than 100 per cent. Since it appears to be short of space at the roofs for PVs and solar thermal collectors, it may be necessary to choose the Monocrystalline panels that cover least amount of area, and because of that Table 25 only shows the economic analysis for Monocrystalline panels.

Table 24: Area Coverage, Different PVs, Residential and Offices in Stockholm

<table>
<thead>
<tr>
<th>PV Type and Tilt Angle</th>
<th>Total Area Required (m²)</th>
<th>Area Available Case 1 (m²)</th>
<th>Area Available Case 2 (m²)</th>
<th>Area Coverage Case 1</th>
<th>Area Coverage Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monocrystalline 45°</td>
<td>176,655</td>
<td>144,525</td>
<td>244,525</td>
<td>122%</td>
<td>72%</td>
</tr>
<tr>
<td>Monocrystalline 60°</td>
<td>255,168</td>
<td>144,525</td>
<td>244,525</td>
<td>177%</td>
<td>104%</td>
</tr>
<tr>
<td>Polycrystalline 45°</td>
<td>185,792</td>
<td>144,525</td>
<td>244,525</td>
<td>129%</td>
<td>76%</td>
</tr>
<tr>
<td>Polycrystalline 60°</td>
<td>268,367</td>
<td>144,525</td>
<td>244,525</td>
<td>186%</td>
<td>110%</td>
</tr>
</tbody>
</table>

Table 25 presents the production costs and total annual system costs for Monocrystalline panels, and the cost for only purchasing electricity. The result is that the costs for producing own electricity through PVs are higher than only purchasing the needed electricity. The production costs are much higher in Stockholm than Sydney, and the reason is higher investment costs due to larger aperture area, leading to a very high price per gained watt. The Monocrystalline at 45°
has the lowest production cost at 117 öre/kWh due to least need of aperture area, and the total system cost is almost the same cost as only purchasing electricity, leading to annual “savings” of -0.4%.

Table 25: PV System Cost Compared to Only Purchased Energy Cost, Residential and Offices in Stockholm

<table>
<thead>
<tr>
<th>PV Type and Tilt Angle</th>
<th>Production Cost (öre/kWh)</th>
<th>Total System Cost (SEK)</th>
<th>Cost Only Purchased Energy (SEK)</th>
<th>Annual Savings (SEK)</th>
<th>Annual Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monocrystalline 45°</td>
<td>117</td>
<td>21,827,752</td>
<td>21,737,316</td>
<td>-90,436</td>
<td>-0.4%</td>
</tr>
<tr>
<td>Monocrystalline 60°</td>
<td>122</td>
<td>22,242,813</td>
<td>21,737,316</td>
<td>-5,054,97</td>
<td>-2%</td>
</tr>
<tr>
<td>Monocrystalline 90°</td>
<td>162</td>
<td>24,727,214</td>
<td>21,737,316</td>
<td>-2,989,898</td>
<td>-14%</td>
</tr>
</tbody>
</table>

School in Stockholm

The school in the Eco-City in Stockholm has highest electricity demand during the winter, due to many dark hours a day, when the electricity production from the PVs is lowest. This is shown in Figure 13.13. Due to the summer holidays the school is closed during two months of high electricity production. The school is able to sell the electricity produced during July and August, but to a lower price than the price for purchasing the electricity needed during the months when the demand is not covered. The aperture areas the PVs need at the different angles is presented in Figure 13.14, and as before, the façade panels need much more aperture area than the other two panels at smaller angle.

![Monthly Electricity Demand Coverage](image)

Figure 13.13: School Electricity Demand Coverage from PVs in Stockholm (kWh)
Table 26 presents the total area required for Monocrystalline and Polycrystalline panels to cover the demand in May, and as in the case for the Sydney school only one area case is investigated since the schools’ roof area is not influenced by the amount of green spaces. Compared to residential and offices, the area coverage is much smaller in all angle cases and does not exceed the roof area. The reason for this is that the school has smaller electricity demand per square metre. Panels at both $45^\circ$ and $60^\circ$ could be used since the solar thermal collectors need up to 20 per cent of the schools’ roof area (See Table 18), and therefore the costs and desired amount of green roofs will be the deciding factors when choosing tilt angle. As in the case before, the area is limited and it might be more beneficial in an Eco-City perspective to use the Monocrystalline panels since they require less area and the price per kWh is the same for Polycrystalline. Therefore only Monocrystalline panels are investigated in Table 27.

Table 26: Area Coverage, Different PVs, School in Stockholm

<table>
<thead>
<tr>
<th>PV Type and Tilt Angle</th>
<th>Total Area Required (m²)</th>
<th>Area Available (m²)</th>
<th>Area Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monocrystalline $45^\circ$</td>
<td>2,721</td>
<td>5,475</td>
<td>50%</td>
</tr>
<tr>
<td>Monocrystalline $60^\circ$</td>
<td>3,930</td>
<td>5,475</td>
<td>72%</td>
</tr>
<tr>
<td>Polycrystalline $45^\circ$</td>
<td>2,861</td>
<td>5,475</td>
<td>52%</td>
</tr>
<tr>
<td>Polycrystalline $60^\circ$</td>
<td>4,133</td>
<td>5,475</td>
<td>75%</td>
</tr>
</tbody>
</table>

Table 26 shows the costs for the Monocrystalline panel systems, and the cost for purchasing all the electricity needed, and the result is that the costs for the PVs are higher than the purchasing electricity costs. The $60^\circ$ panel leads to lowest costs, which is not the same result as for residential and offices in Stockholm where panels at $45^\circ$ led to lowest costs. The reason for this is that the panels at $60^\circ$ produce more energy when the demand is higher, and thus a smaller amount of electricity needs to be purchased. The panels at $45^\circ$ have high system costs due to having very high production during summer when electricity is sold, and as stated before, the price paid for selling is lower than the price for purchasing which leads to small income when
selling electricity compared to the cost for purchasing electricity later when the sun is lower and the 45° panels are producing less electricity.

### Table 27: PV System Cost Compared to Only Purchased Energy Cost, School in Stockholm

<table>
<thead>
<tr>
<th>PV Type and Tilt Angle</th>
<th>Production Cost (öre/kWh)</th>
<th>Total System Cost (SEK)</th>
<th>Cost Only Purchased Energy (SEK)</th>
<th>Annual Savings (SEK)</th>
<th>Annual Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monocrystalline 45°</td>
<td>105</td>
<td>327,824</td>
<td>302,402</td>
<td>-25,422</td>
<td>-8%</td>
</tr>
<tr>
<td>Monocrystalline 60°</td>
<td>110</td>
<td>310,187</td>
<td>302,402</td>
<td>-7,785</td>
<td>-3%</td>
</tr>
<tr>
<td>Monocrystalline 90°</td>
<td>146</td>
<td>362,479</td>
<td>302,402</td>
<td>-60,077</td>
<td>-20%</td>
</tr>
</tbody>
</table>

After having calculated the energy production and the costs of solar technology systems, the robustness of the results must be tested. As discussed several times in the report the different figures used in the calculations are based on estimations and average values. Some of the input parameters may greatly affect the outcome, and this will be investigated further in the sensitivity analysis in the next chapter.

### 13.3 Sensitivity Analysis

Since the parameters used in the numerical method are difficult to estimate, a sensitivity analysis is needed to investigate how the uncertainty in inputs affects the output. The inputs that may cause significant uncertainty in the output are presented in Table 28.

### Table 28: Input Parameters Investigated in the Sensitivity Analysis

<table>
<thead>
<tr>
<th>Uncertain Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Future energy prices</td>
<td>The future prices for gas, electricity and district heating depend on very uncertain factors such as the global economy, different countries’ economic situation, access to raw materials, that are hard to predict. The sensitivity analysis will therefore examine both increasing and decreasing energy prices. The analysis does not take into account the compounding effect, but assumes a constant energy price over the period.</td>
</tr>
<tr>
<td>Discount rate</td>
<td>Economic parameters as the discount rate may be critical when calculating the cost effectiveness of an investment. In order to ensure that the selected discount rate used in the calculations is appropriate and not solely responsible for the outcome, it is necessary to do a sensitivity analysis, both increasing and decreasing the discount rate.</td>
</tr>
<tr>
<td>Losses</td>
<td>There are potential losses due to shadings and losses in the solar appliances, such as thermal losses and losses in the inverter and the wirings, and the influence of losses at the outcome must be investigated</td>
</tr>
<tr>
<td>Demand</td>
<td>The energy demand from the different buildings in the city may vary from year to year, mostly depending on the weather. The weather is hard to predict and the sensitivity analysis examines the uncertainty’s impact on the outcome. The analysis is made for hot water demand in Stockholm and electricity demand in Sydney. The reason is that hot water is used for space heating in Stockholm, and the demand might increase during unusually cold winters or decrease due to mild winters. Electricity is used for space heating and cooling in Sydney, and extreme weather may influence the electricity demand.</td>
</tr>
</tbody>
</table>
13.3.1 Sensitivity Analysis of the Thermal Solar Collectors

The following chapter presents a sensitivity analysis of thermal collectors. Both Evacuated Tube Collectors and Flat Plate Collectors are investigated for Sydney and Stockholm. The reason for this is that they show similar performances and it is interesting to investigate all these further.

Analysis of Solar Thermal Collectors in the Eco-City in Sydney

Table 29: Sensitivity Analysis for Flat Plate Collectors 45°, Residential and Offices in Sydney

<table>
<thead>
<tr>
<th>Scenario Analysis</th>
<th>Energy Price (öre/kWh) + Supply Charge (öre/day)</th>
<th>Discount rate</th>
<th>Additional Losses</th>
<th>Production Cost (öre/kWh)</th>
<th>Annual Savings (SEK)</th>
<th>Annual Savings</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Base Scenario</td>
<td>7.1 + 326</td>
<td>5%</td>
<td>0%</td>
<td>19</td>
<td>3,788,539</td>
<td>64%</td>
<td>0%</td>
</tr>
<tr>
<td>2 - Low Energy Price</td>
<td>(7.1 + 326) - 10%</td>
<td>5%</td>
<td>0%</td>
<td>19</td>
<td>3,222,468</td>
<td>60%</td>
<td>-5%</td>
</tr>
<tr>
<td>3 - High Energy Price</td>
<td>(7.1 + 326) + 10%</td>
<td>5%</td>
<td>0%</td>
<td>19</td>
<td>4,354,611</td>
<td>67%</td>
<td>4%</td>
</tr>
<tr>
<td>4 - Very High Energy Price</td>
<td>(7.1 + 326) + 20%</td>
<td>5%</td>
<td>0%</td>
<td>19</td>
<td>4,920,682</td>
<td>69%</td>
<td>8%</td>
</tr>
<tr>
<td>5 - Decreased Discount rate</td>
<td>7.1 + 326</td>
<td>5-3%</td>
<td>0%</td>
<td>14</td>
<td>4,306,423</td>
<td>73%</td>
<td>14%</td>
</tr>
<tr>
<td>6 - Increased Discount rate</td>
<td>7.1 + 326</td>
<td>5+3%</td>
<td>0%</td>
<td>25</td>
<td>3,192,067</td>
<td>54%</td>
<td>-16%</td>
</tr>
<tr>
<td>7 - Increased losses 10 %</td>
<td>7.1 + 326</td>
<td>5%</td>
<td>10%</td>
<td>21</td>
<td>3,688,223</td>
<td>62%</td>
<td>-3%</td>
</tr>
<tr>
<td>8 - Increased losses 20 %</td>
<td>7.1 + 326</td>
<td>5%</td>
<td>20%</td>
<td>23</td>
<td>3,587,907</td>
<td>60%</td>
<td>-5%</td>
</tr>
</tbody>
</table>

Table 29 shows the result of the sensitivity analysis for Flat Plate Collectors with tilt angle 45° at residential and offices buildings in the Eco-City in Sydney. A decreased gas price results in lower annual savings, and the reason is that a larger part of the total used energy is produced than purchased. The cost benefits of heating the water from collectors are reduced when the price is lower, and the benefit of purchasing gas to the boosters at lower gas price is insignificant since only small amounts of purchased gas is needed. Higher gas price leads to higher savings since the benefits of having collectors become larger, and outweigh the extra costs for the gas purchased to the boosters. Table 29 also shows that a large change in discount rate may change the annual savings quite much, and therefore it is crucial to consider and evaluate the discount rate when calculating on savings through installing solar thermal collectors. Increased losses didn’t affect the annual savings very much, and the reason may be that one of the largest cost savings with solar thermal collectors is that buildings with collectors do not need to pay the daily supply charge that constitutes the major part of the costs for being connected to the gas grid, and purchasing extra gas is therefore not very expensive.

The sensitivity analysis of Evacuated Tube Collectors with tilt angles of 35° and 45° shown in Table 30 and Table 31 present similar results as for the Flat Plate Collector with tilt angle 45°, and the changes of annual savings are due to the same reasons. Higher energy prices and lower discount rates lead to higher annual savings, and higher losses leads to lower savings. Flat Plate Collectors and Evacuated Tube Collectors seem to be equally sensitive to uncertain input parameters.
Table 30: Sensitivity Analysis for Evacuated Tube Collectors 35°, Residential and Offices in Sydney

<table>
<thead>
<tr>
<th>Scenario Analysis</th>
<th>Energy Price (öre/kWh) + Supply Charge (öre/day)</th>
<th>Discount rate</th>
<th>Additional Losses</th>
<th>Production Cost (öre/kWh)</th>
<th>Annual Savings (SEK)</th>
<th>Annual Savings</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Base Scenario</td>
<td>7.1 + 326</td>
<td>5%</td>
<td>0%</td>
<td>21</td>
<td>3,594,432</td>
<td>61%</td>
<td>0%</td>
</tr>
<tr>
<td>2 - Low Energy Price</td>
<td>(7.1 + 326) - 10%</td>
<td>5%</td>
<td>0%</td>
<td>21</td>
<td>3,026,566</td>
<td>57%</td>
<td>-6%</td>
</tr>
<tr>
<td>3 - High Energy Price</td>
<td>(7.1 + 326) + 10%</td>
<td>5%</td>
<td>0%</td>
<td>21</td>
<td>4,162,299</td>
<td>64%</td>
<td>6%</td>
</tr>
<tr>
<td>4 - Very High Energy Price</td>
<td>(7.1 + 326) + 20%</td>
<td>5%</td>
<td>0%</td>
<td>21</td>
<td>4,730,165</td>
<td>66%</td>
<td>9%</td>
</tr>
<tr>
<td>5 - Decreased Discount rate</td>
<td>7.1 + 326</td>
<td>5 - 3%</td>
<td>0%</td>
<td>15</td>
<td>4,171,240</td>
<td>70%</td>
<td>16%</td>
</tr>
<tr>
<td>6 - Increased Discount rate</td>
<td>7.1 + 326</td>
<td>5 + 3%</td>
<td>0%</td>
<td>27</td>
<td>2,930,095</td>
<td>49%</td>
<td>-18%</td>
</tr>
<tr>
<td>7 - Increased losses 10%</td>
<td>7.1 + 326</td>
<td>5%</td>
<td>10%</td>
<td>23</td>
<td>3,390,245</td>
<td>59%</td>
<td>-3%</td>
</tr>
<tr>
<td>8 - Increased losses 20%</td>
<td>7.1 + 326</td>
<td>5%</td>
<td>20%</td>
<td>26</td>
<td>3,390,245</td>
<td>57%</td>
<td>-6%</td>
</tr>
</tbody>
</table>

Table 31: Sensitivity Analysis for Evacuated Tube Collectors 45°, Residential and Offices in Sydney

<table>
<thead>
<tr>
<th>Scenario Analysis</th>
<th>Energy Price (öre/kWh) + Supply Charge (öre/day)</th>
<th>Discount rate</th>
<th>Additional Losses</th>
<th>Production Cost (öre/kWh)</th>
<th>Annual Savings (SEK)</th>
<th>Annual Savings</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Base Scenario</td>
<td>7.1 + 326</td>
<td>5%</td>
<td>0%</td>
<td>21</td>
<td>3,788,539</td>
<td>64%</td>
<td>0%</td>
</tr>
<tr>
<td>2 - Low Energy Price</td>
<td>(7.1 + 326) - 10%</td>
<td>5%</td>
<td>0%</td>
<td>21</td>
<td>3,222,468</td>
<td>60%</td>
<td>-5%</td>
</tr>
<tr>
<td>3 - High Energy Price</td>
<td>(7.1 + 326) + 10%</td>
<td>5%</td>
<td>0%</td>
<td>21</td>
<td>4,354,611</td>
<td>67%</td>
<td>5%</td>
</tr>
<tr>
<td>4 - Very High Energy Price</td>
<td>(7.1 + 326) + 20%</td>
<td>5%</td>
<td>0%</td>
<td>21</td>
<td>4,920,682</td>
<td>69%</td>
<td>8%</td>
</tr>
<tr>
<td>5 - Decreased Discount rate</td>
<td>7.1 + 326</td>
<td>5 - 3%</td>
<td>0%</td>
<td>15</td>
<td>4,114,495</td>
<td>69%</td>
<td>17%</td>
</tr>
<tr>
<td>6 - Increased Discount rate</td>
<td>7.1 + 326</td>
<td>5 + 3%</td>
<td>0%</td>
<td>28</td>
<td>2,829,619</td>
<td>48%</td>
<td>-20%</td>
</tr>
<tr>
<td>7 - Increased losses 10%</td>
<td>7.1 + 326</td>
<td>5%</td>
<td>10%</td>
<td>24</td>
<td>3,415,670</td>
<td>58%</td>
<td>-3%</td>
</tr>
<tr>
<td>8 - Increased losses 20%</td>
<td>7.1 + 326</td>
<td>5%</td>
<td>20%</td>
<td>27</td>
<td>3,313,975</td>
<td>56%</td>
<td>-6%</td>
</tr>
</tbody>
</table>

Analysis of Solar Thermal Collectors in the Eco-City in Stockholm

Table 32 is showing the sensitivity analysis for Flat Plate Collectors with tilt angle 45° in the Eco-City in Stockholm. The effects of the changed input parameters are similar to the Sydney case, but the movements are larger. The main reason may be that the annual savings are low in the base scenario, and small input changes may lead to large output changes in percentage terms. It is clear that the discount rate is crucial and a high rate may lead to higher costs than savings. Table 32 also presents an analysis of how the output is affected by changed hot water demand. Since the need of purchased hot water is more than 20 per cent of the total hot water demand, it is only the purchased part that is affected by a 20 per cent increase or decrease. The annual savings in monetary terms are the same, but a decreased demand leads to greater savings due to less purchased amount of hot water.
Table 32: Sensitivity Analysis for Flat Plate Collectors 45°, Residential and Offices in Stockholm

<table>
<thead>
<tr>
<th>Scenario Analysis</th>
<th>Energy Price (öre/kWh)</th>
<th>Discount rate</th>
<th>Additional Losses</th>
<th>Demand</th>
<th>Production Cost (öre/kWh)</th>
<th>Annual Savings (SEK)</th>
<th>Annual Savings Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Base scenario</td>
<td>8.6 5% 0% 100% 70</td>
<td>1,321,665</td>
<td>7% 0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 - Low Energy Price</td>
<td>8.6 - 10% 5% 0% 100% 70</td>
<td>646,355</td>
<td>4% -46%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 - High Energy price</td>
<td>8.6 + 10% 5% 0% 100% 70</td>
<td>1,996,976</td>
<td>10% 37%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 - Very High Energy Price</td>
<td>8.6 + 20% 5% 0% 100% 70</td>
<td>2,672,286</td>
<td>12% 68%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 - Decreased Discount rate</td>
<td>8.6 5-3% 0% 100% 50</td>
<td>2,829,989</td>
<td>15% 114%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 - Increased Discount rate</td>
<td>8.6 5+3% 0% 100% 92</td>
<td>-415,545</td>
<td>-2% -131%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 - Increased losses 10%</td>
<td>8.6 5% 10% 100% 77</td>
<td>647,135</td>
<td>3% -51%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 - Increased losses 20%</td>
<td>8.6 5% 20% 100% 87</td>
<td>-27,395 0% -102%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 - Decreased Demand 20%</td>
<td>8.6 5% 0% 80% 70</td>
<td>1,321,665</td>
<td>9% 25%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 - Increased Demand 20%</td>
<td>8.6 5% 0% 120% 70</td>
<td>1,321,665</td>
<td>6% -17%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In Table 33 the same analysis for Evacuated Tube Collectors at 45° in Stockholm is shown, and the output changes are similar but even greater than the ones for Flat Plate Collectors. The main reason is that the annual savings are slightly lower for the Evacuated Tube Collectors in the base scenario, which leads to larger percentage changes.

Table 33: Sensitivity Analysis for Evacuated Tube Collectors 45°, Residential and Offices in Stockholm

<table>
<thead>
<tr>
<th>Scenario Analysis</th>
<th>Energy Price (öre/kWh)</th>
<th>Discount rate</th>
<th>Additional Losses</th>
<th>Demand</th>
<th>Production Cost (öre/kWh)</th>
<th>Annual Savings (SEK)</th>
<th>Annual Savings Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Base scenario</td>
<td>8.6 5% 0% 100% 75</td>
<td>93,4840 5% 0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 - Low Energy Price</td>
<td>8.6 - 10% 5% 0% 100% 75</td>
<td>20,9174 1% -75%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 - High Energy price</td>
<td>8.6 + 10% 5% 0% 100% 75</td>
<td>166,9506 8% 61%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 - Very High Energy Price</td>
<td>8.6 + 20% 5% 0% 100% 75</td>
<td>238,6172 11% 113%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 - Decreased Discount rate</td>
<td>8.6 5-3% 0% 100% 54</td>
<td>269,0619 14% 188%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 - Increased Discount rate</td>
<td>8.6 5+3% 0% 100% 100</td>
<td>1,087,376 -6% -216%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 - Increased losses 10%</td>
<td>8.6 5% 10% 100% 84</td>
<td>210,012 1% -78%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 - Increased losses 20%</td>
<td>8.6 5% 20% 100% 94</td>
<td>-514,815 -3% -155%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 - Decreased Demand 20%</td>
<td>8.6 5% 0% 80% 75</td>
<td>934,840 6% 25%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 - Increased Demand 20%</td>
<td>8.6 5% 0% 120% 75</td>
<td>934,840 4% -17%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
13.3.2 Sensitivity Analysis of the PVs

In the sensitivity analysis for photovoltaics, the Monocrystalline panels with a tilt angle of 34° in Sydney, and Monocrystalline panels with tilt angle 45° in Stockholm are investigated. These are chosen thus these showed the lowest electricity production cost and have the highest potential of being implemented in the two Eco-Cities.

Analysis of PVs in the Eco-City in Sydney

Table 34: Sensitivity Analysis for Monocrystalline PVs 34°, Residential and Offices in Sydney

<table>
<thead>
<tr>
<th>Scenario Analysis</th>
<th>Energy Price (öre/kWh)</th>
<th>Discount rate</th>
<th>Additional losses</th>
<th>Demand</th>
<th>Production Cost (öre/kWh)</th>
<th>Annual Savings (SEK)</th>
<th>Annual Savings</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Base scenario</td>
<td>437</td>
<td>5%</td>
<td>0%</td>
<td>100%</td>
<td>68.0</td>
<td>42,033,887</td>
<td>55%</td>
<td>0%</td>
</tr>
<tr>
<td>2 - Low Energy price</td>
<td>437 - 10%</td>
<td>5%</td>
<td>0%</td>
<td>100%</td>
<td>68.0</td>
<td>37,055,744</td>
<td>54%</td>
<td>-2%</td>
</tr>
<tr>
<td>3 - High Energy price</td>
<td>437 + 10%</td>
<td>5%</td>
<td>0%</td>
<td>100%</td>
<td>68.0</td>
<td>47,012,031</td>
<td>56%</td>
<td>2%</td>
</tr>
<tr>
<td>4 - Very high Energy price</td>
<td>437 + 20%</td>
<td>5%</td>
<td>0%</td>
<td>100%</td>
<td>68.0</td>
<td>51,990,174</td>
<td>57%</td>
<td>3%</td>
</tr>
<tr>
<td>5 - Decreased Discount rate</td>
<td>437</td>
<td>5-3%</td>
<td>0%</td>
<td>100%</td>
<td>49.1</td>
<td>44,188,495</td>
<td>58%</td>
<td>5%</td>
</tr>
<tr>
<td>6 - Increased Discount rate</td>
<td>437</td>
<td>5+3%</td>
<td>0%</td>
<td>100%</td>
<td>89.7</td>
<td>39,552,321</td>
<td>52%</td>
<td>-6%</td>
</tr>
<tr>
<td>7 - Increased losses 10 %</td>
<td>437</td>
<td>5%</td>
<td>10%</td>
<td>100%</td>
<td>75.5</td>
<td>37,055,908</td>
<td>49%</td>
<td>-12%</td>
</tr>
<tr>
<td>8 - Increased losses 20 %</td>
<td>437</td>
<td>5%</td>
<td>20%</td>
<td>100%</td>
<td>85.0</td>
<td>32,077,928</td>
<td>42%</td>
<td>-24%</td>
</tr>
<tr>
<td>9 - Decreased Demand 20 %</td>
<td>437</td>
<td>5%</td>
<td>10%</td>
<td>90%</td>
<td>68.0</td>
<td>34,402,919</td>
<td>50%</td>
<td>-9%</td>
</tr>
<tr>
<td>10 - Increased Demand 20 %</td>
<td>437</td>
<td>5%</td>
<td>20%</td>
<td>110%</td>
<td>68.0</td>
<td>49,664,856</td>
<td>59%</td>
<td>7%</td>
</tr>
</tbody>
</table>

Table 34 presents the different parts of the sensitivity analysis for Monocrystalline panels with tilt angle 34° in Sydney. The annual savings decrease with a low electricity price, and increases with high electricity price, and the reason is that the amount of electricity produced is larger than the amount of purchased electricity. This leads to larger savings when the prices are increasing. The change in discount rate did not affect the annual savings as much as the solar thermal collectors. This may be because of the main reasons for savings through having PVs is a smaller amount of very expensive purchased electricity.

Increased system losses in the Monocrystalline system decreased the annual savings much more than losses in solar thermal systems. The reason is probably that increased losses lead to a larger need of purchasing electricity, and the electricity price is much higher than the gas price. Increased demand decreases the annual savings because of the same reason.
Analysis of PVs in the Eco-City in Stockholm

Table 35: Sensitivity Analysis for Monocrystalline PVs 45°, Residential and Offices in Stockholm

<table>
<thead>
<tr>
<th>Scenario Analysis</th>
<th>Energy Price (öre/kWh)</th>
<th>Discount rate</th>
<th>Additional losses</th>
<th>Production Cost (öre/kWh)</th>
<th>Annual Savings (SEK)</th>
<th>Annual Savings Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Base Scenario</td>
<td>118</td>
<td>5%</td>
<td>0%</td>
<td>117</td>
<td>-90,436</td>
<td>-0.4%</td>
</tr>
<tr>
<td>2 - Low Energy Price</td>
<td>118 - 10%</td>
<td>5%</td>
<td>0%</td>
<td>117</td>
<td>-998,889</td>
<td>-5%</td>
</tr>
<tr>
<td>3 - High Energy Price</td>
<td>118+ 10%</td>
<td>5%</td>
<td>0%</td>
<td>117</td>
<td>818,018</td>
<td>2%</td>
</tr>
<tr>
<td>4 - Very High Energy price</td>
<td>118 + 20%</td>
<td>5%</td>
<td>0%</td>
<td>117</td>
<td>2,091,208</td>
<td>11%</td>
</tr>
<tr>
<td>5 - Decreased Discount rate</td>
<td>118</td>
<td>5-3%</td>
<td>0%</td>
<td>84</td>
<td>2,461,142</td>
<td>13%</td>
</tr>
<tr>
<td>6 - Increased Discount rate</td>
<td>118</td>
<td>5+3%</td>
<td>0%</td>
<td>149</td>
<td>-3,029,211</td>
<td>-14%</td>
</tr>
<tr>
<td>7 - Increased losses 10 %</td>
<td>118 - 10%</td>
<td>5%</td>
<td>10%</td>
<td>132</td>
<td>-1,099,828</td>
<td>-5%</td>
</tr>
<tr>
<td>8 - Increased losses 20 %</td>
<td>118 - 20%</td>
<td>5%</td>
<td>20%</td>
<td>150</td>
<td>-2,109,221</td>
<td>-10%</td>
</tr>
</tbody>
</table>

The sensitivity analysis for Monocrystalline PVs with tilt angle 45° in the Eco-City in Stockholm is presented in Table 35. The annual savings in percentage terms are very small in the base scenario, which leads to incredibly large percentage changes when changing the output. One interesting fact is that if the electricity price increases with 10 per cent or more, it may be a good investment to have PV panels in Stockholm, because then the annual savings become positive. The discount rate may also be decisive and a low rate may lead to quite high annual savings, while a high rate leads to larger costs than savings. Increased losses are also leading to lower savings through a larger need of purchased electricity.
14 Conclusion and Future Work

The major objective of this thesis was to investigate the potential of implementing active solar energy applications in two conceptual Eco-Cites, one as a suburb to Sydney and one to Stockholm. The development of Eco-Cities is seen as a possible way of tackling the increasing energy demand connected with the large-scale global urbanization. In order to reach the major objective a method consisting of environmental, technical and economical analyses and calculations was derived. The first step in the method was Eco-City planning, which formed the basis for the whole working process and provided the framework for estimating how much roof area that is potentially available for solar active applications in the two conceptual cities. The Eco-City planning framework also provided demarcation for the work and kept focus on the sustainability approach during the process. After having evaluated the potential of solar technologies to help meeting Eco-City requirements of a sustainable urban area, and concluded that they may contribute to fulfil the ecological, economic and social goals, different sorts of PV and solar thermal collector systems’ features and energy production were investigated. The range of buildings in the two Eco-Cities was limited to cover residential, offices and school buildings. The energy demand and the available roof area of the different buildings formed the basis for the dimensioning of the different solar systems. The report has used two different area cases in the calculations in order to see how the available roof area limits the utilization of solar energy appliances. The first case presents large green areas, which results in smaller available roof area for solar technology systems. In the second case the amount of green spaces is reduced and the available roof area for solar systems is larger.

In order to evaluate the costs and savings of implementing solar technologies, the installation size was set to match the demand during one month. However, evaluating the potential of installing larger areas of solar collectors and solar cells, so that the production exceeds the demand for some months and has a higher total demand coverage over the year, could be valuable and a theme for future work.

In addition to the area, also other parameters proved to have effect on the output of the calculations, and therefore possibly also on the decision whether to install solar technology systems or not. The sensitivity analysis showed that changed energy prices, discount rate and system losses might greatly influence the outcome. Therefore one important conclusion is that it is very important to investigate these and similar parameters before evaluating and investing in solar technology systems.

The rest of this chapter reviews the major results of this thesis and presents further conclusions about the potential outcomes that an integration of solar technology systems in an Eco-City may imply.

Solar Technology Systems in an Eco-City in Sydney

The calculations and evaluations have shown that, in the Sydney area, it may be very beneficial to install solar thermal hot water systems at all kinds of buildings – whether residential, office buildings or school buildings. Installing gas boosted solar collectors for hot water heating might result in large annual savings compared to only purchasing gas to heat the water. Residential and office buildings can experience over 60 per cent in annual savings. The school building may save over 50 per cent, i.e., somewhat lower than the other buildings, since the school is closed during two summer months, not utilizing hot water when the solar potential is the highest. In terms of
technology choice, a system of Flat Plate Collectors generates the highest annual savings, which is
due to lower investment cost. However, using Evacuated Tube collector with higher efficiency
per square metre results in less roof area coverage. The roof area required for Evacuated Tube
Collectors with a tilt angle of 35° to produce an amount of energy matching one month’s hot
water demand for residential and office buildings would cover 9 or 15 per cent of the total
available roof area, depending on which area case is used. For Flat Plate collectors the
corresponding figures are 11 and 18 per cent. Hence, it can be concluded that the area required is
quite small. Also, the difference between the two cases is not very large but it may be decisive if
the roof area available is scarce. The school is only investigated in one area case, and the roof area
coverage is 9 per cent for the Evacuated Tube Collector and 13 per cent for the Flat Plate
Collector.

The calculations have shown that installation of PV panels for electricity production in an Eco-
City in Sydney may also be very cost efficient. Installing Monocrystalline panels at a tilt angle of
34° can result in annual cost savings of around 55 per cent for both residential and office
buildings and school building. The area coverage in the two area cases are 47 and 79 per cent for
the residential and office buildings, and only 29 per cent for the school building.

Both area cases make it possible to combine the two systems for electricity and hot water supply.
Hence the choice of solar thermal collectors and area cases depends on the objectives of the Eco-
City. The city planner may choose between larger parks or lower buildings, and both of them
could contribute to fulfilling the sustainability dimensions. Larger parks can lead to better social
and ecological environment, and higher buildings are more energy efficient. On the other hand,
lower buildings can be preferable from a social point of view, and the resulting increased roof
area could be used for, e.g., green roofs. The sensitivity analysis showed that the benefits from
installing solar technology systems are robust. The annual savings were affected, but still high,
when electricity price decreased and discount rate, losses and demand increased.

The conclusion of implementing solar energy technologies in an Eco-City in the Sydney area is
that the systems very likely can satisfy the three sustainability dimensions. In short, it satisfies the
economic dimension through annual savings, the social dimension through promoting health,
and the ecological dimension through minimizing the impairment of natural environment. Since
the annual savings are high, it could be worth investigating the possibility of increasing the
collector and panel areas, thus having overcapacity during some months, in order to cover the
energy demands during larger part of the year. The investment cost would increase, but would
lead to a larger portion of renewable energy in the total energy system.

**Solar Technology Systems in an Eco-City in Stockholm**

The report has shown that implementing solar technology systems in an Eco-City in the
Stockholm area may not be as favourable as for an Eco-City in Sydney. The main reason for that
is the much lower irradiation and also the, compared to Sydney, cheap and also more
environmentally friendly energy available in Stockholm. The major problem for using solar
energy technologies to satisfy cities’ energy demand in Sweden is that the supply is smallest when
the demand is largest. Dark and cold winters lead to high electricity and hot water demand, but
few bright hours and a low sun result in a very low energy production. Very large areas of
installed solar panels and collectors would be needed to cover that demand, which results in very
high costs and large buildings or paved area in order to provide enough installation space. But
accompanying the systems with purchased energy may lead to a successful integration of solar
technology systems. District heating based on biofuels makes up a good energy source to cover
the demand that solar thermal collectors leave unsatisfied. When covering the hot water needed in residential and office buildings during the summers, Evacuated Tube Collectors with a tilt angle of 45° require the smallest area of the different hot water systems. The available roof area covered is 16 per cent or 26 per cent, depending on which area case is applied. This system results in annual savings of 6 per cent. Using Flat Plate Collectors with the same tilt angle results in slightly higher savings, 7 per cent, with a roof area coverage of 17 or 29 per cent, respectively. Since the school is closed during irradiation intense months, it misses much energy that could have provided the building with hot water. This leads to a not fully utilized hot solar collectors system, and results in much higher costs for the system than only purchasing district heating to heat the water. The conclusion is therefore that, if the school does not provide any other activity with hot water demand during the summer, it may not be favourable for a school building in an Eco-City in Stockholm to install solar thermal collectors. A suggestion of further work could be to investigate a connection of the school’s hot water systems to, e.g., swimming pools. This thesis has shown that choosing the right tilt angle may affect the energy production quite much, and it is essential to investigate the different buildings’ energy demands during different parts of the year in order to match supply and demand. For instance, in the school building case it may be important to design the system at higher angles so that it produces more energy during autumn and spring when the demand is higher than during the summer.

Since the sun is very low in Sweden, it could be assumed that having collectors at the façade may be beneficial, but this report shows that, from an area coverage or cost point of view, it probably is not. The area needed for collectors at 90° to cover one month’s hot water demand is much larger than for collectors at lower angles, which increases the collector costs very much. Both Flat Plate Collectors and Evacuated Tube Collectors installed at 90° lead to negative savings, i.e. higher costs for having the systems than only purchasing district heating.

The report has shown that installing PV systems in the Eco-City in Stockholm might be even less favourable than installing solar thermal collectors. In order to cover one month’s electricity demand in residential and office buildings, both Monocrystalline and Polycrystalline with tilt angle 45° need over 120 per cent or 70 per cent of the available roof area, depending on area case. Hence, only the area case with fewer green areas is feasible. Installing Monocrystalline panels results in the best economical outcome and leads to annual savings of -0.4 per cent, i.e. almost equal costs for the system as only purchasing the electricity. This could be seen as an incentive to invest in PV systems instead of purchasing electricity, since the costs may be equal but the environmental benefit is large. PV panels at the school building result in higher costs for the solar systems than only purchasing electricity.

From an area point of view it would be possible to combine PV panels and solar thermal collectors if using the larger roof area case, and altogether the whole system might lead to positive annual savings. The figures presented from the calculations are not definite and are not stating that it could not be feasible to install solar systems. The input parameters in the calculations are insecure, and the sensitivity analysis showed that, with increased energy prices or lowered discount rate, quite high annual savings can be achieved also in Sweden. Hence, the conclusion is that the economic situation and the future energy prices are essential factors when evaluating the possibility of integrating solar technology systems in an Eco-City in Sweden.

The overall conclusion that can be made is that solar energy has a good chance of constituting an important part of an Eco-City’s energy system and contributing to a sustainable future. But the
analysis has also shown that this is dependent on the environment in which the Eco-City is planned to be developed. The conditions are very good in the Sydney area through high irradiation and high energy prices. In addition, since the energy supply is very carbon intense in Australia, it is of utmost importance to maximize the use of renewable energy sources. The situation is different in Sweden. The low irradiation together with low energy prices makes it harder for solar energy to constitute a large part of the Swedish energy system. But research and development leading to more efficient solar technology systems could certainly lead increased possibilities for solar technologies in Sweden as well.

In future work, when investigating the possibility of integrating solar energy in an Eco-City’s energy system, it is recommended to have an even more holistic view, thus including other elements not covered in this report in order to see if solar energy could help covering the energy demand of larger cities. One area to investigate could, for instance, be the potential of implementing large-scale solar electricity systems in order to provide electricity to electric cars and more energy intense buildings and industries.
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Figure 3.4: Ng E.,(201), Designing High-Density Cities: For Social an Environmental Sustainability, Earthscan, London


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Figure 5.5: Apricus, (2012), *Solar Collector Efficiency*, available at: http://www.apricus.com/html/solar_collector_efficiency.htm#.UXO1hs0pHj4, accessed on 21 April 2013

Figure 5.4: Apricus, (2012), *Solar Collector Efficiency*, available at: http://www.apricus.com/html/solar_collector_efficiency.htm#.UXO1hs0pHj4, accessed on 21 April 2013


Figure 7.2: Swedish Energy Agency, (2012), *Swedish energy supply and use, by fuel type, in 2010*, available at http://energimyndigheten.se/sv/Statistik/Energilaget/, accessed on 27 April 2013

Figure 8.1: Australian Energy Market Operator (AEMO), (2012), *Future Electricity prices in New South Wales*, National Electricity Forecasting, Economic Outlook Information Paper

Figure 8.2: DRET, (2012) Future gas price in New South Wales


### 16 Appendix

#### 16.1 Required Roof Area compared to Active Aperture Area

<table>
<thead>
<tr>
<th>Solar Collectors</th>
<th>Required Roof Area, (m²) compared to Active Aperture Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sydney (γ = 28)</td>
<td></td>
</tr>
<tr>
<td>Flat Plate Collectors</td>
<td></td>
</tr>
<tr>
<td>β = 45°</td>
<td>2</td>
</tr>
<tr>
<td>Evacuated Tube Collectors</td>
<td></td>
</tr>
<tr>
<td>β = 35°</td>
<td>2.2</td>
</tr>
<tr>
<td>Evacuated Tube Collectors</td>
<td></td>
</tr>
<tr>
<td>β = 45°</td>
<td>2.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Solar Collectors</th>
<th>Required Roof Area, (m²) compared to Active Aperture Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stockholm (γ = 25)</td>
<td></td>
</tr>
<tr>
<td>Flat Plate</td>
<td></td>
</tr>
<tr>
<td>β = 45°</td>
<td>2.2</td>
</tr>
<tr>
<td>Evacuated Tube</td>
<td></td>
</tr>
<tr>
<td>β = 45°</td>
<td>2.7</td>
</tr>
<tr>
<td>Flat Plate</td>
<td></td>
</tr>
<tr>
<td>β = 60°</td>
<td>2.3</td>
</tr>
<tr>
<td>Evacuated Tube</td>
<td></td>
</tr>
<tr>
<td>β = 60°</td>
<td>2.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Solar Cells</th>
<th>Required Roof Area, (m²) compared to Active Aperture Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sydney (γ = 26)</td>
<td></td>
</tr>
<tr>
<td>β = 34°</td>
<td>2</td>
</tr>
<tr>
<td>β = 45°</td>
<td>2.2</td>
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</tbody>
</table>
Solar Cells Stockholm (γ = 21°)

<table>
<thead>
<tr>
<th>β</th>
<th>Required Roof Area, (m²) compared to Active Aperture Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45°</td>
<td>2.5</td>
</tr>
<tr>
<td>60°</td>
<td>3.3</td>
</tr>
</tbody>
</table>

16.2 User defined IAM for Evacuated Tube Collectors

Tabell 1 User defined IAM for Evacuated Tube Collectors used in ScenoCalc

<table>
<thead>
<tr>
<th></th>
<th>0°</th>
<th>10°</th>
<th>20°</th>
<th>30°</th>
<th>40°</th>
<th>50°</th>
<th>60°</th>
<th>70°</th>
<th>80°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
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<td>1.00</td>
<td>1.00</td>
<td>0.99</td>
<td>0.97</td>
<td>0.92</td>
<td>0.84</td>
<td>0.70</td>
<td>0.45</td>
<td>0.00</td>
</tr>
<tr>
<td>Transversal</td>
<td>1.00</td>
<td>1.02</td>
<td>1.08</td>
<td>1.18</td>
<td>1.35</td>
<td>1.47</td>
<td>1.39</td>
<td>1.57</td>
<td>0.95</td>
<td>1.00</td>
</tr>
</tbody>
</table>