# Solar Energy from Existing Structures

Development of the *SEES* GIS tool that assesses solar irradiance on roofs

Elforsk rapport 11:77

Per Jonsson, Fredrik Lindberg

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**ELFORSK**

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## Förord

Detta projekt ingår i det tillämpade solcellsprogrammet SolEl 08-11. Programmet finansieras av:

- Energimyndigheten
- Svenska Byggbranschens Utvecklingsfond via NCC och JM
- Vattenfall
- E.ON Sverige
- Fortum
- ABB Corporate Research
- Göteborg Energi
- Exotech
- HSB
- Malmö stad Serviceförvaltningen
- Sharp Electronics Nordic
- Switchpower
- Mälarenergi
- Tekniska Verken i Linköping AB
- Jämtkraft
- Umeå Energi
- Falkenberg Energi
- Växjö Energi Elnät

Rapporten finns fritt nedladdningsbar från SolEl-programmets webbsajt: www.solelprogrammet.se.


Bertil Wahlund

Elforsk AB

## Preface

## Sammanfattning

Solen som energikälla förväntas växa i betydelse under kommande decennier, bl a beroende på fortsatt teknikutveckling och lägre tillverkningskostnader för solpaneler. Fastighetsägare, både privata och offentliga, besitter därmed en energikälla som oftast inte är utnyttjad, nämligen solinstrålning på deras byggnadsytor. Dessa ytor kan vara mer eller mindre lämpliga för utvinning av solenergi beroende på deras lutning, riktning, eller beskuggning från andra byggnader och vegetation. För att avgöra olika takytors lämplighet har ett GIS-verktyg utvecklats som visar årlig inkommande solstrålning, *Solar Energy from Existing Structures* (SEES).

Det visas att SEES fungerar i syfte att avgöra solinstrålning på takytor, förutsatt att rätt indata finns tillgänglig. Dessa indata avgör resultatets kvalitet och analysens omfattning. När indatakraven tillfredsställs kan SEES

- beräkna årlig instrålning ($kWh\ m^{-2}\ yr^{-1}$) för tak- och markpixlar i den digitala höjdmodellen
- utvärdera ytor enligt förutbestämda klasser, eller klasser som användaren bestämmer ("poor", "intermediate" eller "good")
- utvärdera den totala tak- och markytan som uppfyller klasserna
- utvärdera solinstrålningen i respektive klass i taknivå, som presenteras i en resultattabell.

Dessa resultat kan i ett senare skede användas för att utvärdera möjlig elproduktion med solceller.

Det visas också att beräkningarna av solinstrålning stämmer väl med uppmätta data, liksom beskuggning av andra objekt.

I en fallstudie av Göteborg visas det att alla byggnadstak som en grupp är olika när det gäller lämplighet att utvinna solenergi: intervallet är ~577– 1 100 $kWh\ m^{-2}\ yr^{-1}$ bland 140 000 hustak i Göteborg. Totala takytor som uppfyller kriteriet "good" minskar dramatiskt då kravet på mininstrålning minskas; det finns ca 1 $km^2$ takytor som uppfyller kravet 1 000 $kWh\ m^{-2}\ yr^{-1}$, en siffra som ökar till 9 $km^2$ om kravet minskas till 950 $kWh\ m^{-2}\ yr^{-1}$. Det årliga uttaget av el kan uppskattningsvis uppgå till 129 miljoner kWh för det högre kravet och 918 miljoner kWh för det lägre kravet. Denna elproduktion motsvarar ca 2 % respektive 20 % av Göteborgs totala årliga elanvändning.

# Summary

Solar energy is projected to increase in importance as a global energy source. In such a scenario electricity from photovoltaic (PV) systems will be important due to increasing performance, decreasing production costs, and increasing costs for electricity from other energy sources. Solar energy also holds a position as a democratic energy source, available for anyone to explore and utilise.

Owners of buildings (residential, industrial, tenement) possess solar energy resources that usually are unexplored, namely the solar radiation on the surfaces of their buildings. These surfaces might be directed toward the sun in a favourable angle, while obstructed by neighbouring houses and vegetation. Altogether, it is likely that roofs in built-up areas are more or less suitable for PV installation. In order to evaluate the suitability for any roof a GIS tool has been developed that will calculate the amount of incoming solar radiation and possible shading effects.

Firstly, it is shown that the SEES tool functions, given that the user has access to necessary input data. The output is directly dependent on the input data in that it dictates the geographical extent and resolution of the analysis. When this is given, the user has the possibility to

- calculate the annual total irradiance ($kWh\ m^{-2}\ yr^{-1}$) for roofs and ground pixels

- assess areas in terms of default or user defined limits denominating area fractions in classes "poor", "intermediate" or "good"

- estimate the total estimated roof and ground area of each class

- estimate the total irradiance in each class at roof level, presented in output table.

Given this information, the user can estimate the maximum electricity output depending on solar cell efficiency (STC) and performance ratio (PR).

Secondly, the evaluation of the irradiance itself has been proved accurate. The shading of objects by other structures is shown to be accurately reproduced.

Thirdly, it is evident that as a group, all roof surfaces are quite different in terms of suitability for solar energy production. The range is from ~577–1 100 $kWh\ m^{-2}\ yr^{-1}$. It is obvious that the available roof surface increases dramatically as the requirement of what is considered "good" decreases; there is approximately 1 $km^2$ of roof surfaces that meet the higher requirement of 1 000 $kWh\ m^{-2}\ yr^{-1}$, while this number increases to 9 $km^2$ if the requirement is lowered to 950 $kWh\ m^{-2}\ yr^{-1}$. The annual electricity output should amount to 129 million kWh for the higher requirements and 918 million kWh for the lower requirement. This fictional electricity production would cover approximately 2 % and 20 % respectively of the Göteborg total annual electricity demand.

# Table of contents

# 1   Introduction

SEES (Solar Energy from Existing Structures) is a computer software model which can be used to estimate potential energy from roof installed solar panels in urban areas. This document describes the computer software and the graphical user-friendly interface that has been developed for the SEES model.

SEES is written in MATLAB programming language. This involves a certain number of advantages for the aim of this model, as matrices processing are required continuously, a requirement that MATLAB covers perfectly. Therefore better, fast and efficient results are obtained. The Graphical user interface is written in Java and makes use of a runtime engine called the MCR (MATLAB Compiler Runtime), which makes it possible to run MATLAB applications outside the MATLAB environment. The MCR is deployed royalty-free. Considering that SEES is a software model the present report mainly covers operation instructions. Following that, an evaluation scheme of the SEES model is presented where modelled and observed shading effects of ground surfaces are compared. Finally, SEES is used to assess all roofs in the Göteborg municipality according to a set of conditions, and the annual production of electricity generated by solar panels.

# 2   Objectives

The objective of this report is threefold:

1. The SEES model software is introduced by a careful dissemination of the software´s function from a user perspective
2. The SEES model is evaluated by comparing observed shading effects of buildings to that simulated in the SEES model, and lastly
3. The SEES model is used to determine the amount of electricity that can be produced by using photovoltaics (PV) in the Göteborg municipality. A complementary case study is designed to assess the annual PV electricity production.

# 3   Methods

## 3.1   Estimation of solar radiation in SEES

SEES use the unobstructed three components of shortwave radiation: direct (I), diffuse (D) and global (G). As these are not commonly available the model also allows calculation of $D$ from $G$ using the Riendl et al. (1990) approach. Direct shortwave radiation ($I$) on a surface perpendicular to the Sun is then estimated:

$$(1)$$

where $\eta$ is the sun's altitude angle above the horizon. Typically within the urban environment the sky may be obscured by objects (e.g. buildings or threes). Thus, the incoming shortwave radiation ($K_\downarrow$) for a grid cell (x,y) is a function of D, I and G as well as view factors ($\Psi$). For clarity, the equations are written without the spatial subscript:

$$(2)$$

where S accounts for shadow as a  Boolean value (presence = 0 or absence =1), for buildings (subscript b) and vegetation (v); the  $\Psi$ subscripts indicate what aspects are being accounted for (e.g. sky seen by building) and $a$ is the albedo. Currently, $a$ is treated as a constant with a default value of 0.15. $\tau$ is the transmissivity of shortwave radiation through vegetation, $\omega$ is the sun incidence angle. The first and second terms on the right-hand side of (2) represent direct and diffuse radiation fluxes, respectively. The third term in (2) is a simplified representation of reflected radiation.

# 4 SEES operation instructions

This chapter will help the user to install and run the SEES model using the Graphical user interface (GUI).

## 4.1 Changes from previous versions

*Version 1.1*
Computational time reduced by pre-processing of the meteorological data before main computations is performed.
*Version 1.0*
Model incorporated in the GUI

## 4.2 Installation

This section gives you information on how to install the SEES graphical user-friendly Interface on a regular PC.

## 4.3 System requirements

The Interface runs under WINDOWS NT/2000/XP/Vista/7 platforms.

## 4.4 Other applications needed before installing the software

There are two additional applications that have to be installed on the PC before being able to run SEES:
Upgrade (or install) Java Runtime Environment, JRE (version Java 6). This is easiest made online.
Install the MCR (MATLAB Compiler Runtime 7.13). This can be downloaded from the Urban Climate Group webpage.

## 4.5 Installing the Interface

Download the executable installation file (SEES Setup.exe) of the Interface from the Urban Climate Group webpage and follow the installation procedure as shown below (Figure 1):
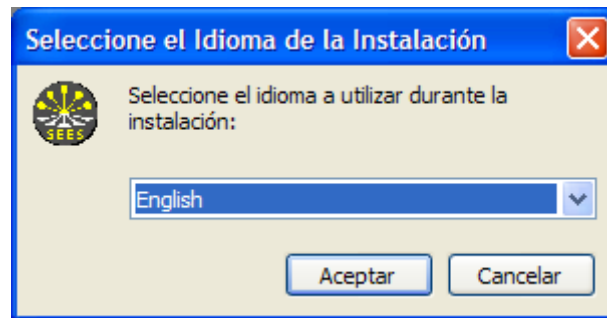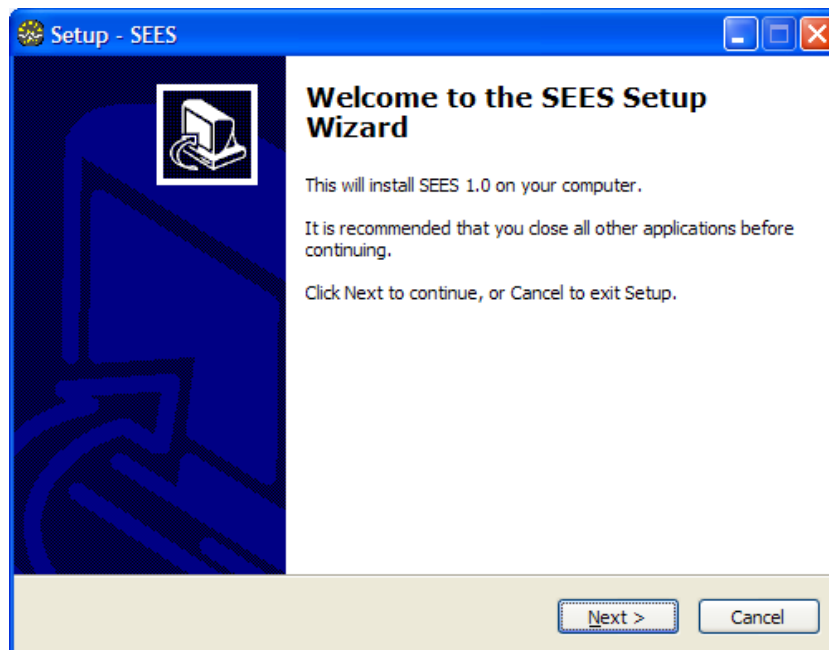
**Figure 1. Select setup language.**



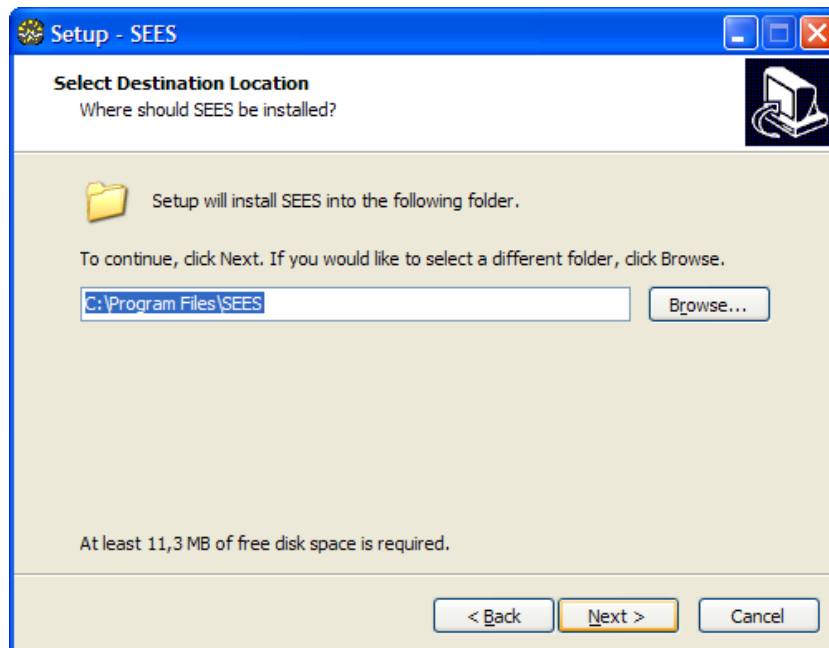**Figure 2. SEES setup welcome window.**

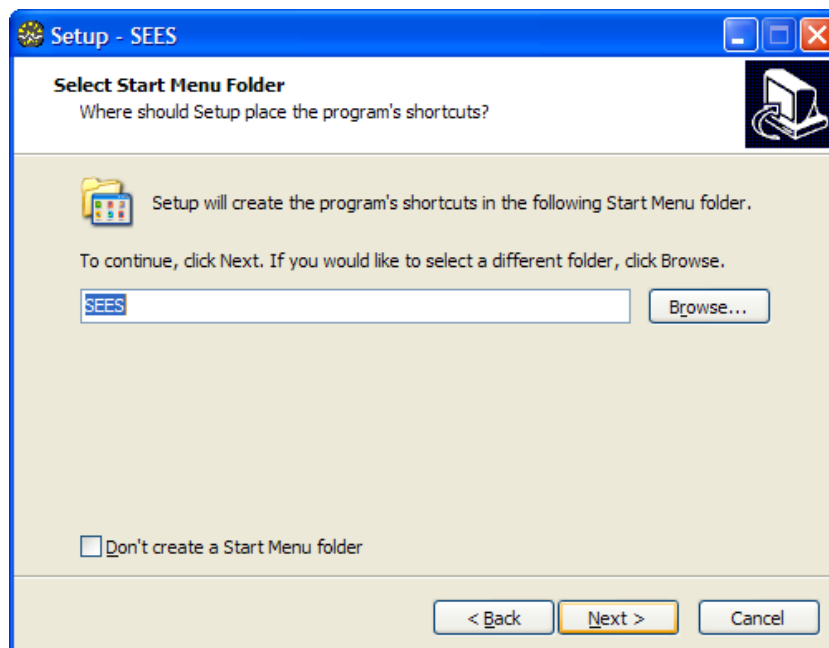**Figure 3. Select destination location.**
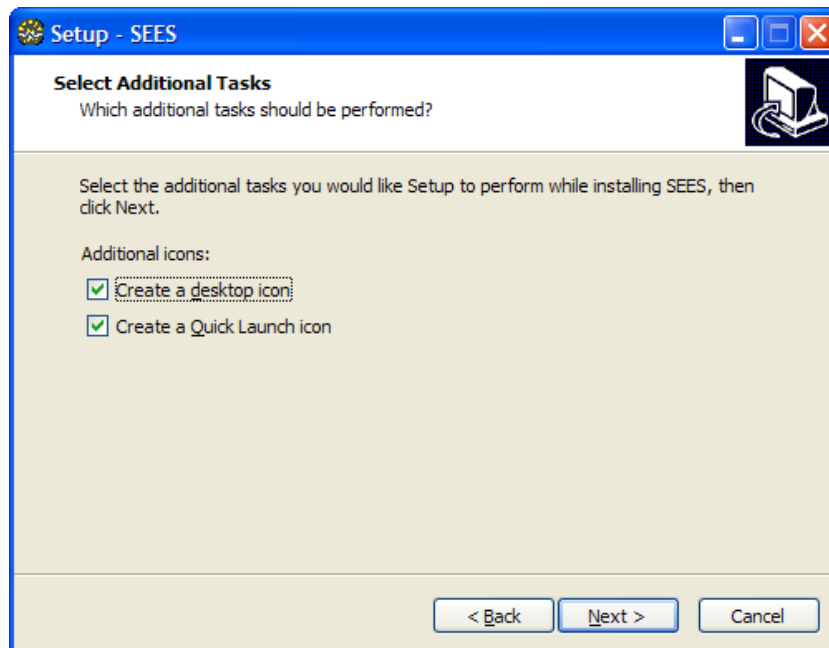


**Figure 4. Select start menu folder.**

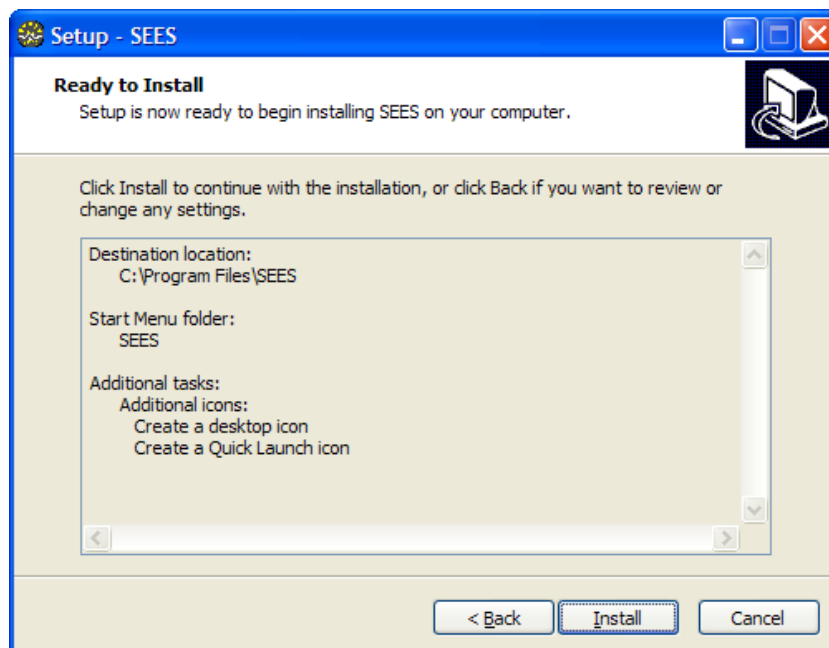**Figure 5. Create desktop and quick launch icons.**



**Figure 6. Ready to install SEES on the computer.**

## 4.6   The graphical user-friendly Interface for SEES

This section explains in detail all the steps that have to be taken in order to run the SEES model by using the Interface. For each step of the model, some

screenshots will be shown along with descriptions explaining the step's functionality and data that should be used and loaded.

### 4.6.1 Starting the Interface

The time it takes for the interface to actually start is relatively long compared to its size (3Mb). This is because the MCR is also initialized, which is a considerably larger application than the Interface itself.

### 4.6.2 Understanding the Interface

Main frame
Figure 7 shows the initial window (or main frame) that will be displayed every time the application is launched:
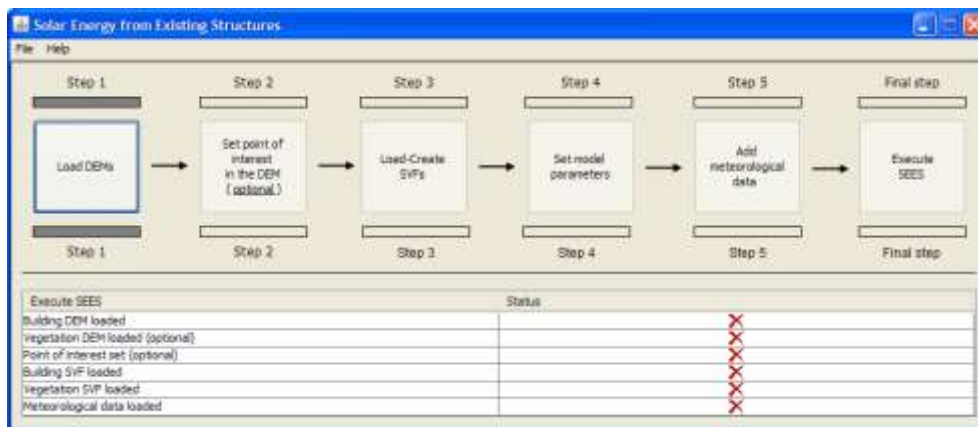


**Figure 7. Main frame at the beginning**

As it can be seen in Figure 7, the different steps of the model are shown in the shape of buttons (located between the menu bar and the status tables at the bottom of the frame). The flowchart has six steps, starting from the "Load DEMs" step and ending with "Execute SEES".
A status table (bottom of the frame) indicates the current situation of the input data (that is, the files and information that must be loaded in order to execute the SEES model). At the beginning, they are all unloaded and marked with red cross icons.
Regarding the buttons, in the beginning there is only one which is allowed to be clicked. This indicates the starting point for running the model. In Figure 7, the only button which is allowed to be clicked represents the step one.
After loading the first required files (those corresponding to the step one – "Load DEMs"), step button number 2 "Set point of interest in the DEM", which is optional, and step button number 3 "Load-Create SVFs" will be able to be used (marked in grey, see Figure 8). As shown, the status table has marked (with blue tick icons) the input data that has been loaded at this point.
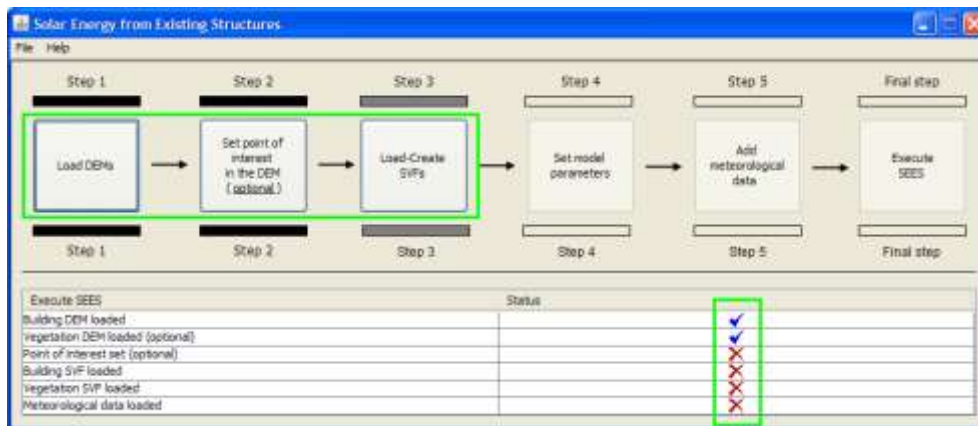
**Figure 8. Main frame with the third step active**

The Interface will continue enabling the remaining steps (buttons) of the model when the corresponding and required input data is loaded on the active step (marked in grey colour). When this happens, the main frame will have the shape shown in Figure 9.



**Figure 9. Main frame ready to launch the model**

In this situation, the model will be ready to be launched.

Load DEMs
When a button from the main frame is clicked, a new dialog pops up with all the functionality and input data related to one step of the model. In Figure 10 the "Load DEMs" step is shown in a new dialog.

**Figure 10. Load DEMs step at the beginning**

Figure 10 shows how the Interface specifies the action that has to be performed in order to load the input data correctly (this is done by enabling the corresponding button, in this case cal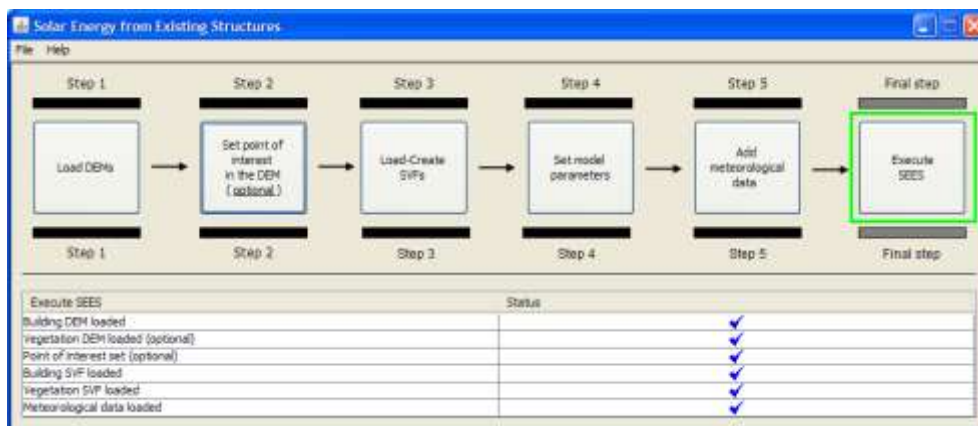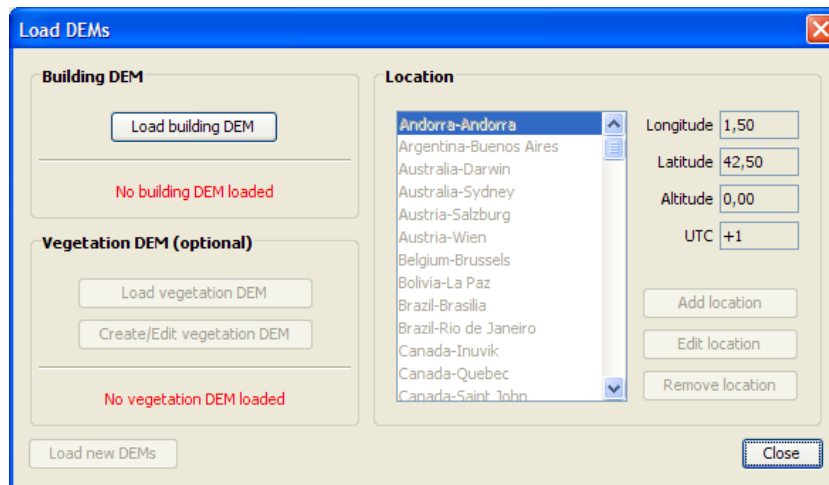led "Load building DEM"). After loading the corresponding data, the Interface enables all the buttons shown in the figure above. By clicking the "Create/Edit vegetation DEM" button, two new dialogs are displayed (see Figures 11 and 12). The location part (right side of the dialog) is used to locate the model domain at a geographic location on Earth. By default, the Interface provides a list of cities and their location, which can be edited or removed. Besides, new locations can be added if the desired city does not appear on the list.

**Note:** all the edited and new locations that might be added are stored in a separate file that can be reused by SEES's future versions. Thus, there will not exist the need of re-edit and/nor re-add them again. We will also appreciate comments suggesting adding new locations in our default file of locations.

A raster DEM is essential for the SEES model to work and it could consist of both ground and building heights, but also of only building structures with ground elevation equals to zero. A raster DEM could be created in almost any GIS software's. A brief guide on how to create a DEM in ArcGIS can be found at the Urban Climate Group webpage. By default, the Interface will allow all types of file extensions in where a building DEM can be stored. In order for the DEM to be successfully loaded, it has to follow the **ERSI ASCII Grid** format (including the order of the headers):
*ncols?#        (# = a float number greater than zero = number of columns of the matrix)*
*nrows?#        (# = a float number greater than zero = number of rows of the matrix)*
*xllcorner or xllcenter?#    (# = a positive or negative decimal number = geographic "x" coordinate of the lower corner of the matrix). Can be either xllcorner or xllcenter.*

*yllcorner or yllcenter?#   (# = a positive or negative decimal number = geographic "y" coordinate of the left side of the matrix). Must be yllcorner when using xllcorner and yllcenter when using xllcenter.*
*cellsize?#    (# = a positive decimal number, from 0 = size of 1 pixel)*
*NODATA_value?#        (# = a positive or negative decimal number = the value of no data)*
*The matrix of positive and/or negative decimal numbers representing the DEM.*
*Each row is separated by a new line and each column by a blank character.*
*The size is the one specified in the "ncols" and "nrows" headers.*

**Note:** *(? = 1 or more blank characters, including tabs).*
An example of the above building DEM format is shown below:
*ncols        350*
*nrows        350*
*xllcorner    39250*
*yllcorner    27993*
*cellsize     1*
*NODATA_value  -9999*
*0.723 0.207 0.341 0.408 0.439 0.455 0.463 0.461 0.445 0.409 0.371 0.36 0.347*
*0.337 0.319 0.312 0.312 0.301 0.297 0.294 0.289 0.285 0.276 0.275 0.268 0.257*
*0.244 0.199 0.924 0.924 0.923 0.928 0.924 0.931 0.931 0.934 0.935 0.937 0.939*

**Note:** it is allowed to load both square and non-square building DEMs.
SEES provides the option to set a vegetation scheme along with the building DEM. Vegetation will be represented as an additional DEM consisting of trees and bushes. Generation of vegetation units will be executed in a number of steps presented below. First, all buildings have to be marked as shown in Figure 11. All edges greater than 2 meter will be marked as a building wall pixel. Locations of buildings are also used even if no vegetation DEM is used. Hence, it is suggested to go through the first step in the generation of a vegetation DEM process as shown below.
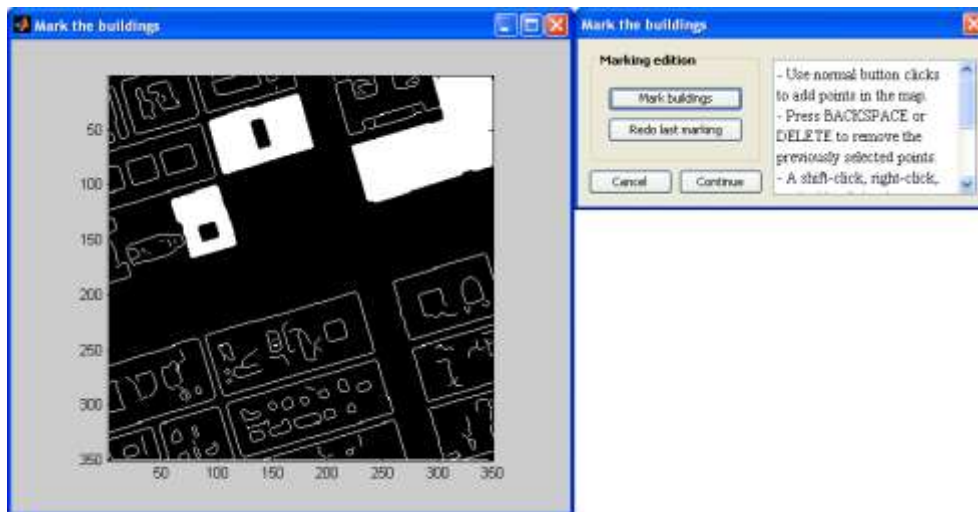
**Figure 11. Load DEMs step when marking the buildings**

Figure 12 shows the two dialogs, which represent a third-level dialog where the vegetation DEM is generated. First, one of the three standard vegetation shapes has to be selected: conifer, deciduous or bush. The Interface will then generate a vegetation unit based on the measures inserted (diameter, tree height and trunk height). Finally, the vegetation unit has to be located somewhere within the model domain. This procedure can be repeated or a vegetation unit can also be removed.
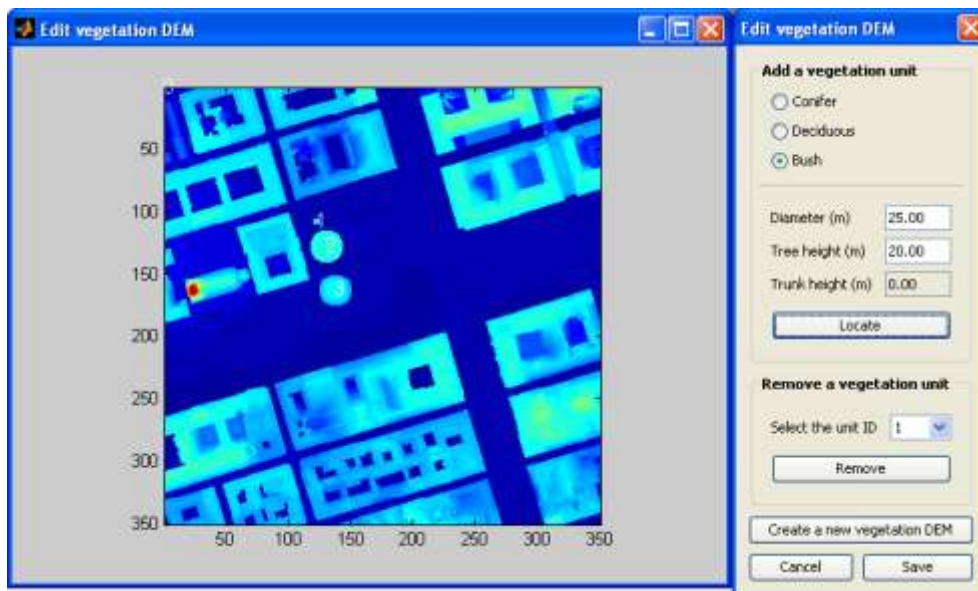


**Figure 12. Load DEMs step when setting the vegetation units**

By default, the Interface will allow all types of file extensions in which a vegetation DEM can be stored. In order to be successfully loaded, it has to follow the following format (including the order of the headers):

| ID | ttype | dia | height | trunk | x | y |
|---|---|---|---|---|---|---|
| | build | | | | | |
| i | t | d | h | tr | x | y |
| | b | | | | | |

*Where all the columns are separated by a tab and:*
*- i = tree identifier (a round number from 1 to infinity).*
*- t = tree type (a round number that can only have the three following values: 1 = Conifer; 2 = Deciduous; 3 = Bush).*
*- d = tree diameter in meters (a decimal number from 0 to infinity).*
*- h = tree height in meters (a decimal number from 0 to infinity).*
*- tr = tree trunk size in meters (a decimal number from 0 to infinity). This value cannot be equal or greater than the tree height. Besides, the bush tree will always have a value of 0.0 for this column.*
*- x = 'x' coordinate from the building DEM where the tree is located (a round number from 1 to the maximum 'x' value of the building DEM).*
*- y = 'y' coordinate from the building DEM where the tree is located (a round number from 1 to the maximum 'y' value of the building DEM).*
*- b = an area that corresponds with a marked building from the building DEM. This value is automatically assigned by the application the first time the user marks the buildings. Therefore if new trees are added manually, this value has to be 0.0 (decimal format). On the contrary, if there are marked buildings but not trees, there will be entries with values 0.0 in all the columns excepting in the "build" one.*

An example of the above vegetation DEM format is shown below:

| ID | ttype | dia | height | trunk | x | y |
|---|---|---|---|---|---|---|
| | build | | | | | |
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 16873.0 | | | | | |
| 2.0 | 1.0 | 10.0 | 30.0 | 5.0 | 128.0 | 133.0 |
| | 17307.0 | | | | | |
| 3.0 | 3.0 | 5.0 | 5.0 | 0.0 | 182.0 | 58.0 |
| | 10155.0 | | | | | |
| 4.0 | 2.0 | 15.0 | 20.0 | 5.0 | 133.0 | 40.0 |
| | 23081.0 | | | | | |
| 5.0 | 1.0 | 5.0 | 6.0 | 5.0 | 144.0 | 234.0 |
| | 19425.0 | | | | | |

**Important:** every time a new vegetation file is saved (or loaded) within the interface, a new vegetation SVF must be created (or loaded) as well (see below).

Figure 13 shows how the "Load DEMs" dialog looks like after both the building and vegetation DEMs have been loaded.
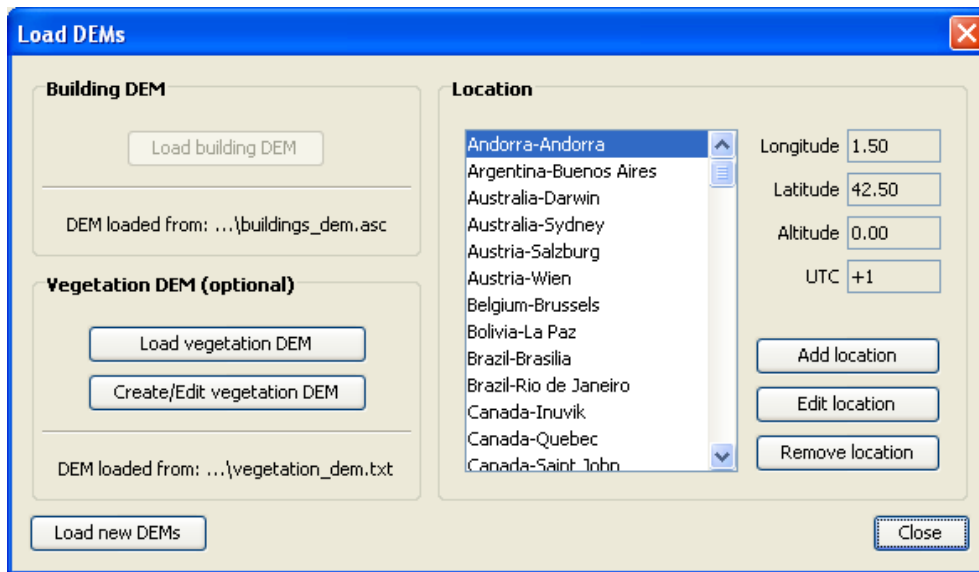
**Figure 13. Load DEMs step when both DEMs are loaded**

SEES will allow re-loading, re-creating or re-selecting all the input data if necessary. The only exception is the building DEM, which is the main element of the model. However, it can be re-loaded by clicking on the button "Load new DEMs" (see Figure 13). By doing this, SEES will restart all the elements, so, excepting the meteorological file, the remaining data will have to be loaded, created or selected again.

By clicking on the "Close" button, the dialog will be hidden and the Interface will go back to the main frame. Before clicking on the "Close" button, the geographical location of the model domain (DEM) should be specified.

### 4.6.3 Set point of interest in the DEM

Figure 14 shows the dialog that pops up when the button "Set point of interest in the DEM" is clicked on the main frame.
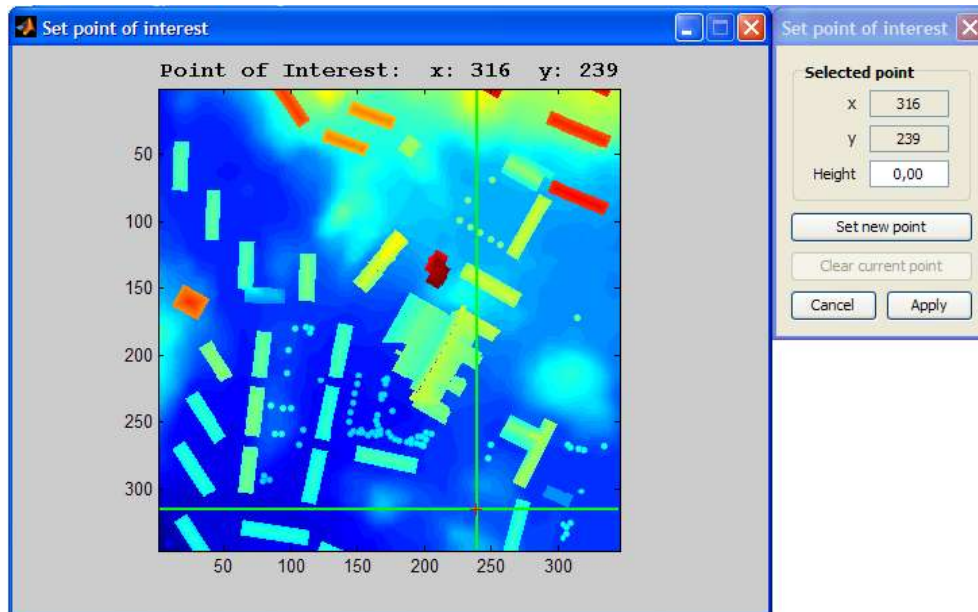


**Figure 14. Set point of interest with point set**

Clicking on the "Set new point" button will activate the MATLAB window (at the left, Figure 14), which will show the building DEM and the vegetation on it if there is vegetation DEM loaded. In order to specify a point of interest, the mouse cursor has to be used to point the cursor over the shown DEM and then click on the desired area within the map. For this purpose, the coordinates the cursor is pointing to in real time is shown to facilitate the point's selection. After this interaction, the Java window will get the selected coordinate and show it on its window ("x" and "y" boxes at the top of the Java window). The height is referring to the height above the surface of the DEM and can be altered to any positive value.

The point of interest is a location where more detailed information of the model can be extracted. The text-file generated includes the following attributes:

altitude     altitude of the point on the hemisphere (in degrees)
azimuth      azimuth of the point on the hemisphere (in degrees)
Energy_kWh Total energy output from point on hemisphere
The point of interest can be unselected by clicking on the button "Clear current point".

### 4.6.4 Load-Create SVFs

The Interface can also be used to obtain images of sky view factor values. Figure 15 shows the dialog that is popped up when the "Load-Create SVFs" button is clicked in the main frame. This is the most time consuming part of the model execution. The output of the SVF images generated is again as ESRI ASCII Grids.
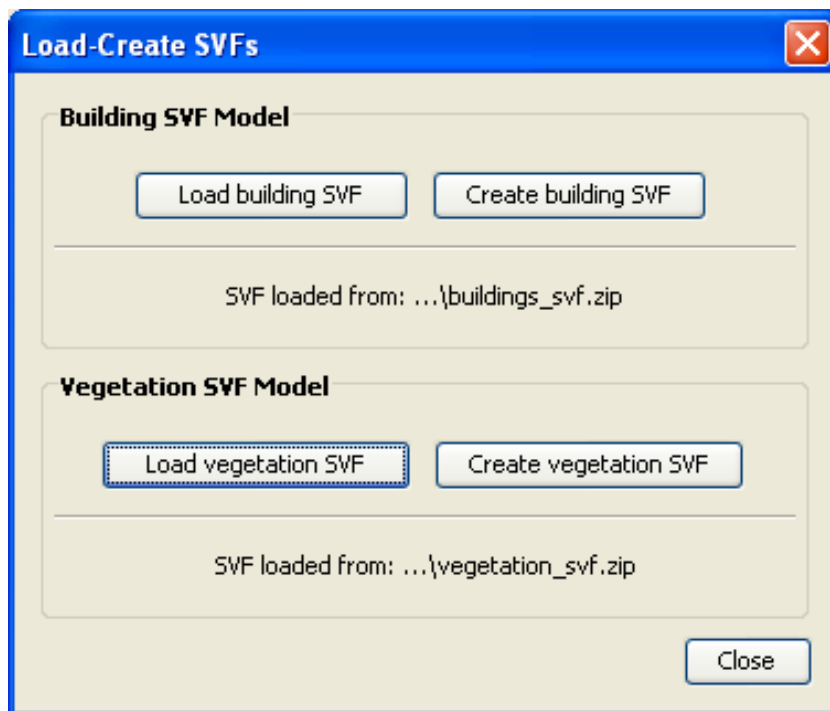


**Figure 15. Load-Create SVFs when both SVFs are loaded**

This step allows loading existing SVF or creating them if they do not exist. They are saved in a zip-file that has to be specified before creating the images.

In Figure 15, the input data is already loaded; thus, by clicking on "Close" button (bottom right) the dialog will be hidden and the Interface will go back to the main frame, which now will have enabled the step buttons number four and five of the flowchart.

### 4.6.5 Set model parameters

Figure 16 shows the dialog which corresponds to the window that is popped up when the "Set model parameters" button is clicked in the main frame. It is possible to use the default values or to specify new values in the right most column. The model parameters are divided into urban and vegetation parameters and suitability map settings.

**Note:** *The vegetation parameters are enabled only if there is a vegetation DEM loaded.*

**Figure 16. Set model parameters**

### 4.6.6 Add meteorological data

Figure 17 shows the dialog that is popped up when the "Add meteorological data" button is clicked in the main frame. SEES need a full year of hourly data in order to execute. More than one year of data can be used as long full years are used. The model is able to run using only hourly values of global solar radiation for a full year. However, to get more accurate model results both direct and diffuse shortwave radiation should be included. Since diffuse and direct components of short wave radiation is not common data, it is also possible to calculate diffuse (*radD*) and direct (*radI*) shortwave radiation by ticking the box in Figure 17 Reindl et al. (1990). To get the most accurate estimation of *radD* and *radI*, air temperature (*Ta*) and relative humidity (*RH*) should be included in the meteorological data. If the box is ticked and Ta or RH is not available **-99** should be used as no data in the meteorological file.
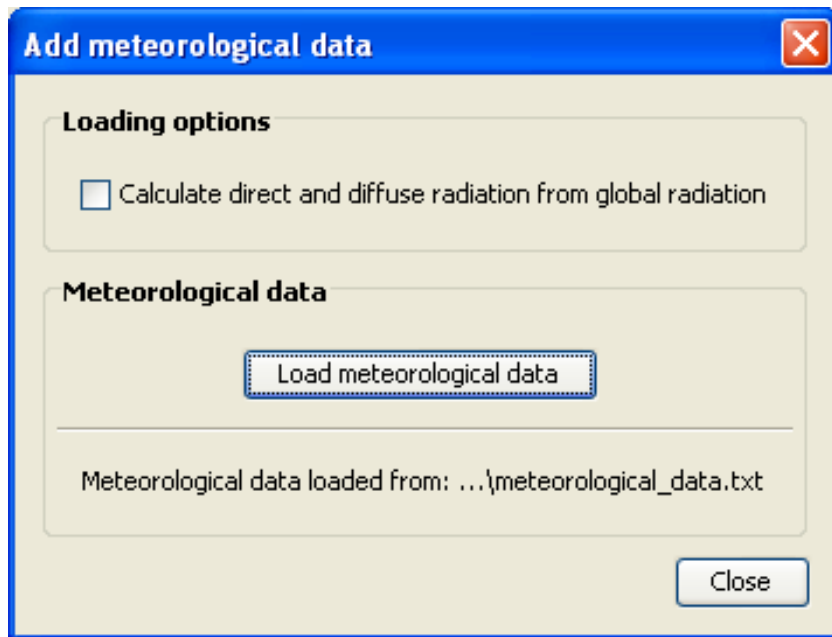
**Figure 17. Add meteorological data with data loaded.**

By default, the Interface will allow all types of file extensions in which the meteorological data can be stored. In order to be successfully loaded, it has to follow the following format including the order of the columns. The header names must also be specified as below:

| year | month | day | hour | Ta | RH | radG | radD |
|------|-------|-----|------|-----|-----|------|------|
| | radI | | | | | | |
| yyyy | mm | dd | h | a | b | c | d |
| | e | | | | | | |

*Where all the columns are separated by a tab and:*
*- yyyy = a year with 4 digits.*
*- mm = a month (a round number between 1 and 12, including both).*
*- dd = a day (a round number between 1 and 31, including both. The values 29, 30 and 31 can appear depending on the chosen month and year, as it is specified in the Gregorian calendar).*
*- h = an hour (a round number between 1 and 24, including both).*
*- a = the air temperature (a positive or negative decimal number).*
*- b = the relative humidity (a positive or negative decimal number).*
*- c = the global shortwave radiation (a decimal number from -50 to infinity).*
*- d = the diffuse shortwave radiation (a decimal number from -50 to infinity).*
*- e = the direct shortwave radiation (a decimal number from -50 to infinity).*

An example of the above format is shown below:

| year | month | day | hour | Ta | RH | radG | radD |
|------|-------|-----|------|------|-----|------|------|
| | radI | | | | | | |
| 2005 | 10 | 11 | 1 | 12.9 | | 92 | 0 |
| | 0 | | 0 | | | | |
| 2005 | 10 | 11 | 2 | 12.6 | | 92 | 0 |
| | 0 | | 0 | | | | |

| 2005 | 10 5.1 | 11 | 3 0 | 11.9 | 89 | 5.1 |
| 2005 | 10 39.3 | 11 | 4 222.1 | 12.5 | 86 | 63.2 |
| 2005 | 10 59.8 | 11 | 5 499.1 | 14.3 | 78 | 172 |
| 2005 | 10 75.5 | 11 | 6 695.7 | 17.5 | 64 | 347.2 |

**IMPORTANT!** The direct-beam radiation (radI) used as input in the SEES model is **not** the direct shortwave radiation on a horizontal surface but on a surface perpendicular to the light source. Hence, the relationship between global radiation and the two separate components are:
*radG = radI sin(h) + radD*
where *h* is the sun altitude.

## 4.6.7 Execute SEES

Figure 18 shows the dialog, which pops up when the "Execute SEES" button is clicked in the main frame.

By clicking on the "Execute SEES" button (bottom right), the SEES model will be launched. Before that, an output folder must be specified. Besides, there is the possibility to execute the model without taking into account the vegetation DEM, in case there is one loaded. This can be useful to compare the results with and without vegetation on the building DEM.

It's possible to store the results in two different file format types: ASCII and TIFF. All the output images options can be selected at one time by clicking on the button "Select all". If, on the contrary, they all want to be unselected at one time, the button "Clear all" will do so. If the option "Do not show the temporal images during the execution" is selected, the results will not be shown on real time.

It is important to note that due to the complexity of defining building foot prints from a building DEM, the output files is not separated into buildings and ground. This means that all surfaces are included in the analysis. If ASCII output is chosen two more datasets are included:

1. An algorithm is included trying to detect and classify building structures. This output is included for post-processing opportunities. This is a possibility largely dependent on input data quality: for the algorithm to function well, the delimitation of buildings needs to be well defined. Also, the resolution of the input data determines to some extent whether buildings are detected by the algorithm; the higher the resolution the higher the likelihood.
2. A raster image of estimated actual area for each pixel (i.e. inclination) is also included.
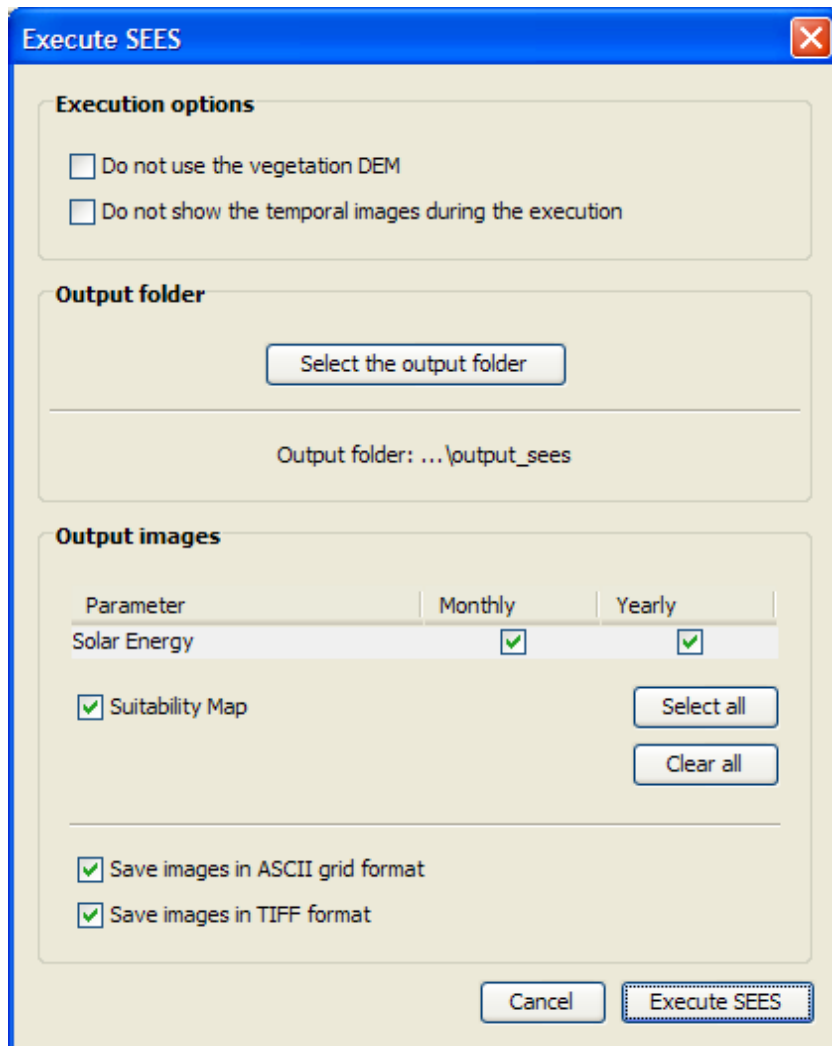
**Figure 18. Execute SEES before executing the model.**

# 5   Evaluation of SEES

## 5.1   Earlier work on solar radiation

The algorithm used to calculate incoming shortwave radiation with obstructing elements such as buildings and vegetation present was originally presented in Lindberg (2007). It has been evaluated for different urban environments in different regional contexts and has been proven to produce very satisfactory results compared to field measurement (Lindberg et al 2008, Lindberg and Grimmond 2010). The inclusion of solar incidence angle to take non-horizontal roof structures into account is based on commonly used radiation geometry (e.g. Oke 1987, Yo et al. 2010).

## 5.2   Shading effects: comparison of simulated and observed shading of ground surfaces

The shadow casting algorithm used in SEES, originally developed by Ratti and Richens (1999, 2005) and developed further by Lindberg and Grimmond (2011), has been proven to be both accurate and effective since it is designed for raster based environments (e.g. Brown et al 2001, Lindberg 2005, Gal et al. 2009, Lindberg and Grimmond 2011). An example of computed shadow patterns and a high resolution aerial photograph can be seen in Fig 19. Note that the current algorithm is able to generate shadow under vegetation. Also note that shadows from buildings seem shorter in the aerial photograph, especially at the upper part of the image. This is an artefact created in the aerial photograph has an orthographic projection (i.e. one observer point (camera lens)) which makes the buildings "lean over" the shadows on the ground.
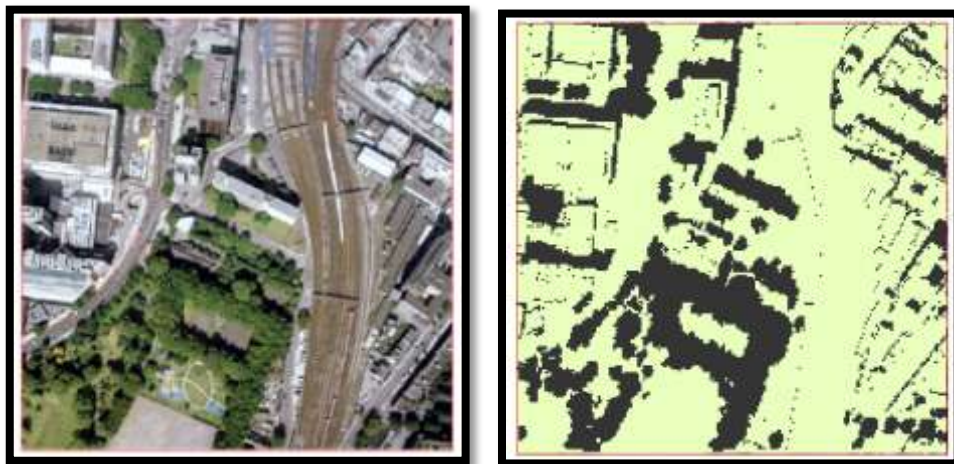


**Figure 19. A snapshot comparison of shadow patterns from an aerial photograph (left) and the shadow casting algorithm used in SEES (right).**

# 6 SEES case study: solar irradiance on roof surfaces and its use in assessing potential PV electricity production

## 6.1 Investigated areas in Göteborg

Göteborg is an administrative unit (municipality) that does not necessarily contain all buildings usually perceived as Göteborg. The following statistics are based upon data from the Building and Planning office, City of Göteborg. Neighbouring municipalities such as Mölndal and Partille are therefore not included. Roof structure data sets required for the SEES analysis are not available for the entire municipality (see Figure 20 for included areas). A building foot print polygon dataset was used for the following statistical analysis in this section.
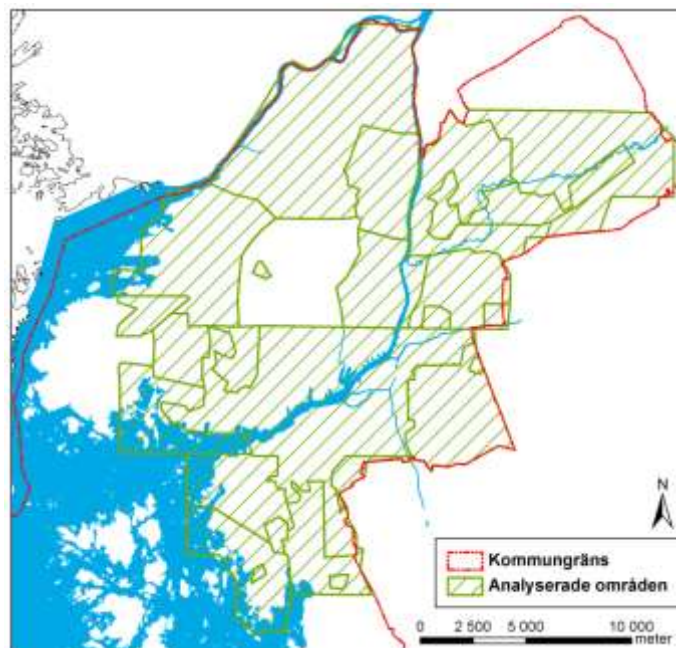


**Figure 20. Map showing investigated areas in Göteborg. Red line delimits the Göteborg Municipality and the areas marked in green show investigated areas based on data availability.**

## 6.2 Typical meteorological data for the Göteborg area

All calculations that have been used in the following SEES calculations are based on measured values of all components of shortwave radiation (global, direct and diffuse).  The dataset used consists of hourly meteorological data

for 1977 from the Swedish Meteorological and Hydrological Institute (SMHI) weather station in Säve (at the city airport), just outside the city of Gothenburg. The climate of 1977 is considered to represent the typical climate of Gothenburg for the period 1965–1984, exhibiting all the normalities and extremes (Skanska Software, 1990).

The observed values of diffuse and direct radiation are presented in in Figure 21 (hourly values for the entire year).
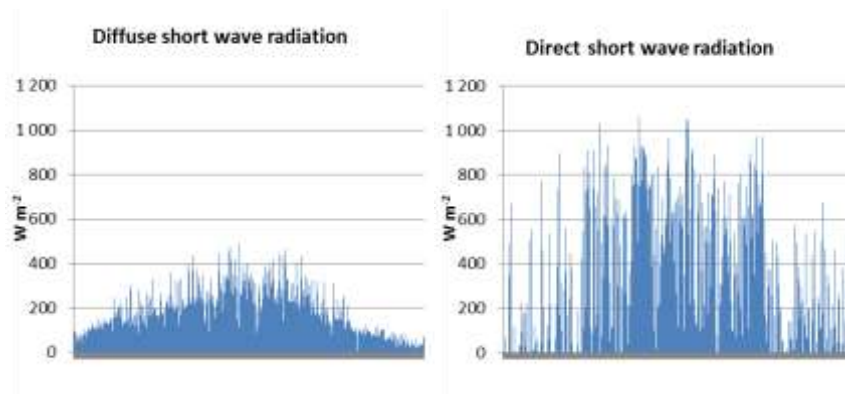


**Figure 21. Diffuse and direct incidence angle short wave radiation observed at the Säve airport, Göteborg area, for a typical meteorological year (1977).**

It is obvious that the short wave radiation follows the annual cycle, although the diffuse fraction is less variable in comparison to the direct fraction. This can in part be explained by the quick formation of cumuli form clouds during summer.

The annual average air temperature at the observation point was 7,2 °C. Air temperature has not been taken into consideration when the potential PV output has been assessed.

### 6.2.1 Göteborg buildings statistics

In total, 181 443 buildings were identified covering 24 km$^2$ of the Göteborg area. Not all of these have been analysed with SEES since they were deemed to small and may have been dog houses, tool sheds etc. 139 268 of these buildings were however deemed as proper buildings based on a foot print area in excess of 10 m$^2$. These buildings constituted a foot print are of approximately 21 km$^2$ yielding an average foot print area of 148 m$^2$. All buildings were included in the analysis, i.e. residential, commercial and public.

## 6.3 SEES analysis of the entire city of Göteborg (resolution 1×1 m)

While operating SEES, the user has the possibility to define what is considered "good", "moderate" and "bad" roof surfaces. In the case of assessing the entire city of Göteborg with SEES, two different requirements were set: >1 000 kWh m$^{-2}$ yr$^{-1}$ irradiance and >950 kWh m$^{-2}$ yr$^{-1}$ irradiance. These choices were based on a histogram analysis (see Figure 22).
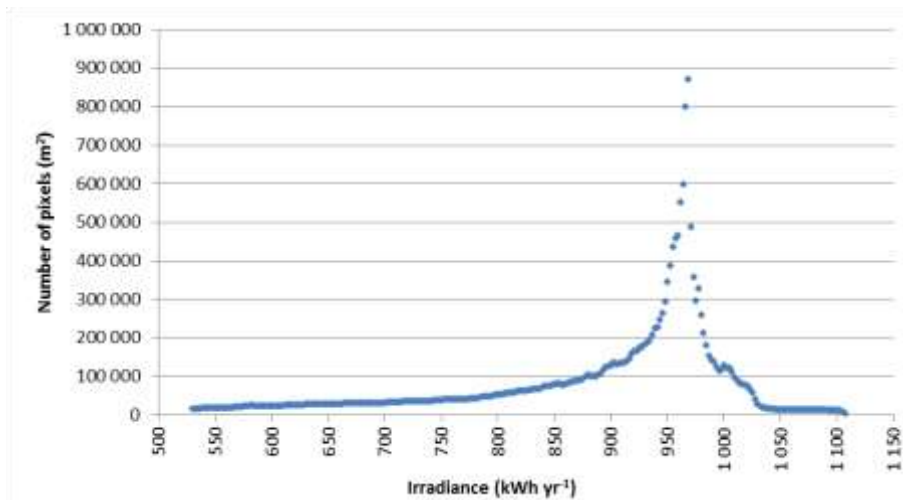
**Figure 22. Histogram showing the number of pixels (foot print square meters) in each irradiance class.**

From the histogram it is evident that as a group, all roof surfaces are quite different in terms of suitability for solar energy production. The range is from ~577–1 100 kWh m$^{-2}$ yr$^{-1}$, where the higher end indicates roof surfaces most suitable for solar energy production. However, the bulk of roof surfaces are in the range of 900–1 000 kWh m$^{-2}$ yr$^{-1}$. Two scenarios were therefore calculated, one in which the requirement was set to 1 000 kWh m$^{-2}$ yr$^{-1}$ and a second in which the requirement was set to 950 kWh m$^{-2}$ yr$^{-1}$. In addition, a minimum coherent surface criterion of 10 m$^2$ was formulated. This was done in order to eliminate the risk of including several small suitable surfaces scattered across a roof. Results of the SEES analysis for the two requirements are shown in Table 1.

**Table 1. Results of SEES analysis covering the entire city of Göteborg, approximately 140 000 buildings, for the two criteria. Only roof surfaces that form a cluster >10 m$^2$ are considered.**

| *Parameter* | **Irradiance requirement: >1 000 kWh m$^{-2}$ yr$^{-1}$** | **Irradiance requirement: >950 kWh m$^{-2}$ yr$^{-1}$** |
|---|---|---|
| *Foot print area above each criterion, respectively (m$^2$)* | 1 | 10 |
| *Mean foot print area (m$^2$)* | 60 | 170 |
| *Number of individual areas* | 20 580 | 53 900 |
| *Horizontal Irradiance (kWh yr$^{-1}$)* | 1 159 000 000 | 8 756 000 000 |
| *Horizontal Irradiance × 0.1* | 116 000 000 | 876 000 000 |
| *Actual irradiance* | 1 285 000 000 | 9 180 000 000 |
| *Actual irradiance × 0.1* | 129 000 000 | 918 000 000 |

It is obvious that the available roof surface increases dramatically as the requirement of what is considered "good" decreases; there is approximately 1 km$^2$ of roof surfaces that meet the higher requirement of 1 000 kWh m$^{-2}$ yr$^{-1}$, while this number increases to 9 km$^2$ if the requirement is lowered to 950 kWh m$^{-2}$ yr$^{-1}$.

The actual irradiance 1 285 million kWh for the former and 9 180 kWh for the latter of irradiance, i.e. incoming solar energy to the analysed roof surfaces. For the sake of estimating the possible PV output if all surfaces should be covered by solar panels, the system efficiency is set to 10 %. The annual electricity output should amount to 129 million kWh for the higher requirements and 918 million kWh for the lower requirement. This fictional electricity production would cover approximately 2 % and 20 % respectively of the Göteborg total annual electricity demand.

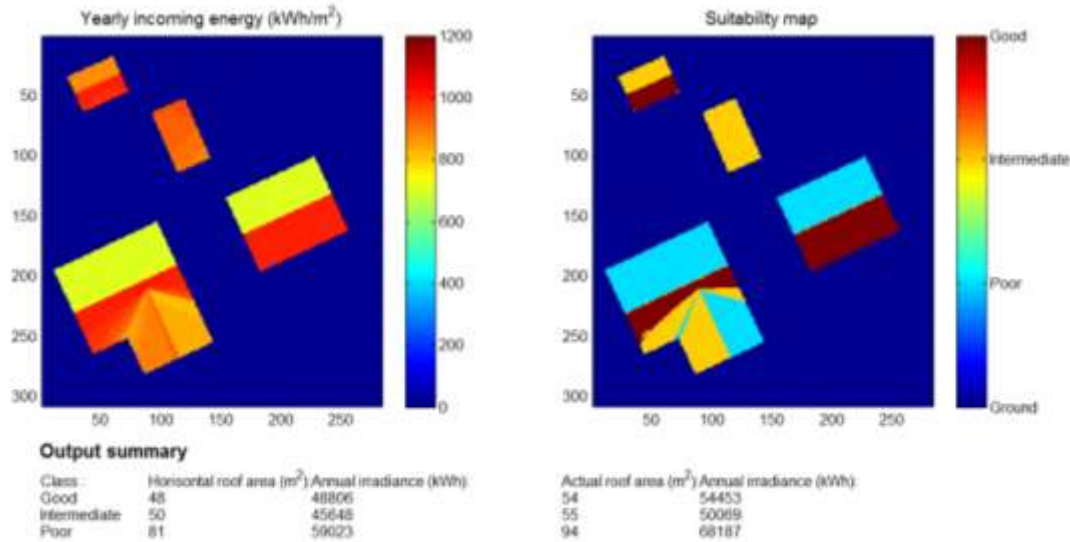An example of processed SEES analysis covering a section of the Göteborg area is shown in Figure 23.
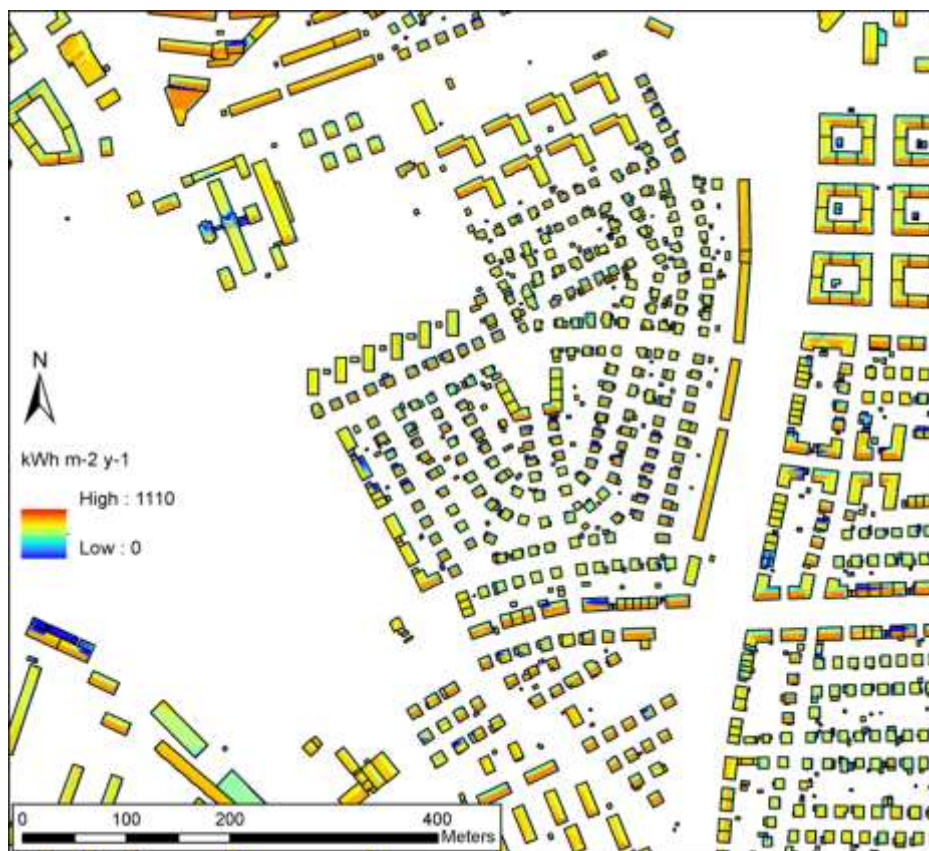


**Figur 23. An outcrop of the SEES analysis (*Härlanda*) of the entire Göteborg area, covering approximately 1 km².**

## 6.4 SEES analysis of individual building in Göteborg (resolution 0.1×0.1 m)

SEES´ versatility is manifested in that both entire cities and individual buildings can be evaluated in terms of suitability for solar energy production. In the previous example it was shown that SEES can be used to estimates a city´s electricity production from solar energy. Also, the most suitable roofs for the purpose can be identified using common GIS software and tools.

In Figure 24 the result of a SEES analysis for an individual building is shown. The requirement for "good" was set to >1 000 kWh m$^{-2}$ yr$^{-1}$ and <850 as



**Output summary**

| Class | Horisontal roof area (m²) | Annual irradiance (kWh) | Actual roof area (m²) | Annual irradiance (kWh) |
|---|---|---|---|---|
| Good | 48 | 48806 | 54 | 54453 |
| Intermediate | 50 | 45648 | 55 | 50069 |
| Poor | 81 | 59023 | 94 | 68187 |

"bad".

**Figur 24. SEES analysis of an individual building.**

The actual roof area (taking into account the slope of the roof) that met the "good" criterion amounted to 54 m$^2$ on the four buildings. On these "good" surfaces, a total of approximately 54 000 kWh of irradiance annually reaches the roofs in question. As in the previous case, a fictive system efficiency can be set to 10 %. Should the "good" surfaces be totally covered by solar panels a total of approximately 5 400 kWh electricity could be produced annually.

For the visual output in SEES, building pixels is classified and used in the statistics table. However, if very complex urban structures are included in the input building DEM it is very difficult to detect building pixels and the output summary would be biased. Therefore, as mentioned earlier, all pixels (both ground and buildings) are included in the output ASCII files for further GIS analysis.

# 7 Concluding remarks

SEES does a good job in evaluating solar irradiance on surfaces, and also including shading effects of objects in the proximity while doing so. This information may be of interest for property owner now and in the future. The quality of the input data is of crucial importance, both regarding building geometries and meteorology. The user should aim at achieving the highest possible quality.

SEES was used on 140 000 buildings in Göteborg, Sweden, which showed the strength of the tool in evaluating large areas. According to scenario analyses, up to 20 % of the city's electricity demand could be met if the best roof areas were to be used for solar panel installations. It should however be remembered that SEES evaluates incoming solar radiation on surfaces. The efficiency of the technology of interest (solar cells, solar collectors) determines the actual output.

# 8 Acronyms and abbreviations

| | |
|---|---|
| **ASCII:** | American Standard Code for Information Interchange |
| **DEM:** | Digital Elevation Model |
| **MCR:** | MATLAB Compiler Runtime |
| **SEES:** | Solar Energy from Existing Structures |
| **SRS:** | Software Requirements Specification |
| **SVF:** | Sky View Factor |
| **UTC:** | Coordinated Universal Time |

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