Technical Release No. 1

August 2018

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

FONA Resource Land
BMBF

INOLA Software Documentation

– The Solar Energy Component –

Solar Power and Solar Heat Modules

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This technical release was issued in the context of the project INOLA (Innovations for a sustainable land and energy management on a regional scale) which is funded by the German Federal Ministry of Education and Research (BMBF) under the grant code 033L155AN in the period from 2014 to 2019. The author(s) is/are responsible for content and results of this study.

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INOLA-Technical Release No. 1:	*INOLA Software Documentation. The Solar Energy Component*
INOLA-Technical Release No. 2:	*INOLA Software Documentation. The Wind Power Component*
INOLA-Technical Release No. 3:	*INOLA Software Documentation. The Geothermal Energy and Hydropower Component*
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1 The Solar Energy Component

The Solar Energy Component aims to simulate power and heat production via photovoltaic and solar thermic devices. The component consists of two models: The SolarEnergy and the SolarHeat model. Within both models, at first, the hourly solar radiation is calculated depending on slope and orientation of each individual device. In a second step, power and heat yield is determined based on device specifications such as rated output and efficiencies as well as air temperature influence.

2 The SolarEnergy Model

The SolarEnergy model computes electricity production via photovoltaic (PV) modules. It calculates yields for building-related PV systems and open space PV systems. Equations, required information and program environment are described in the following.

2.1 General Equations

2.1.1 Solar Radiation Module

The solar radiation module is based on QUASCHNING (2013) and takes into account the slope and exposition of each individual device, and the solar zenith and azimuth angles at any hour. Diffuse and direct solar irradiance on the inclined plane as well as background reflection are calculated as shown in Equations (1) to (5).

At first, the incidence angle of the sun on the inclined plane is computed:

$$\theta_{incl} = \cos^{-1}(-\cos\gamma_S * \sin\gamma_P * \cos(\alpha_S - \alpha_P) + \sin\gamma_S * \cos\gamma_P) \quad (1)$$

with:

γ_S	=	*Solar zenith*	$[rad]$
γ_P	=	*Slope of solar module plane*	$[rad]$
α_S	=	*Solar azimuth*	$[rad]$
α_P	=	*Orientation of solar module plane*	$[rad]$

It describes the angle between the surface normal vector of the inclined plane (n) and the direction vector of the incident solar radiation (s) as shown in Figure 2-1.

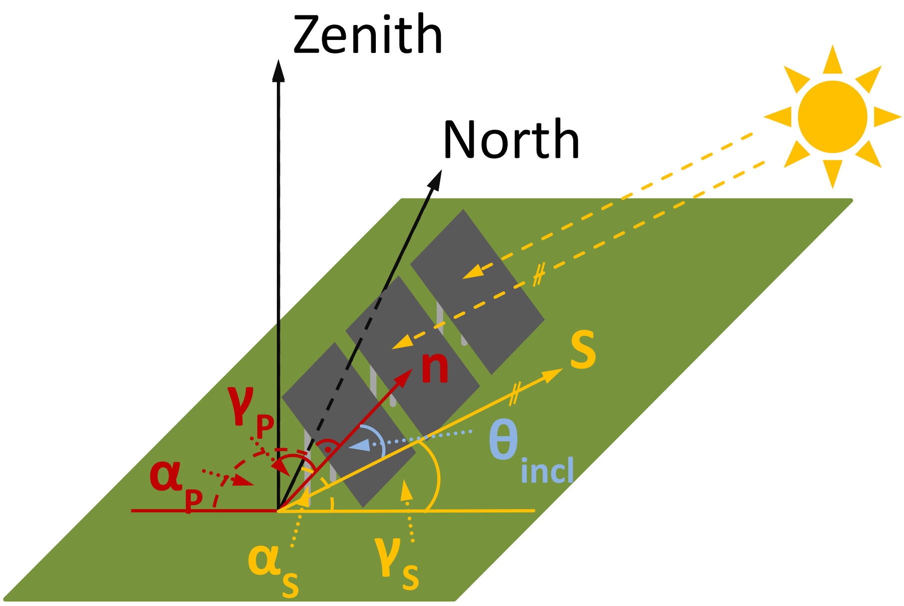

Figure 2-1: Angular relationships for calculation of solar incidence angle on the inclined photovoltaic module.

Knowing the incidence angle of the sun, the incident solar radiation on the inclined plane can be computed from diffuse and direct irradiance as well as background reflection as shown in Equations (2) – (5).

$$I_{G,incl} = I_{dir,incl} + I_{dif,incl} + I_{refl,incl} \tag{2}$$

with:

$I_{dir,incl}$	=	*Direct solar irradiance on the inclined plane*	$\left[\frac{W}{m^2}\right]$
$I_{dif,incl}$	=	*Diffuse solar irradiance on the inclined plane*	$\left[\frac{W}{m^2}\right]$
$I_{refl,incl}$	=	*Background reflection on the inclined plane*	$\left[\frac{W}{m^2}\right]$

Direct solar irradiance on the inclined plane is calculated by:

$$I_{dir,incl} = I_{dir,hor} * (\sin\theta_{incl} * \cos\gamma_P - \sin\gamma_P * \cos\theta_{incl} * \sin(\alpha_S - \alpha_P)) \tag{3}$$

with:

$I_{dir,hor}$	=	*Direct solar irradiance on a horizontal plane*	$\left[\frac{W}{m^2}\right]$

Diffuse solar irradiance on the inclined plane is calculated by:

$$I_{dif,incl} = I_{dif,hor} * \left(\frac{1}{2} * (1 - F) * (1 + \cos\gamma_P) + \left(F * \frac{\cos\theta_{incl}}{\cos(90° - \gamma_P)}\right)\right) \tag{4}$$

with:

$F = \frac{I_{dir,incl}}{I_O} = F$

I_0	=	*Solar constant (on average: 1,367)*	$\left[\frac{W}{m^2}\right]$
$I_{dif,hor}$	=	*Diffuse solar irradiance on a horizontal plane*	$\left[\frac{W}{m^2}\right]$

Background reflection is calculated by:

$$I_{refl,incl} = I_{G,hor} * A * \sin^2\left(\frac{\gamma_P}{2}\right) \quad (5)$$

with:

$I_{G,hor}$	=	*Solar irradiance on a horizontal plane*	$\left[\frac{W}{m^2}\right]$
A	=	*Albedo*	$[-]$

Table 2-1: Description of parameters used in the solar radiation module with associated variable names

Symbol	Description	Unit	Variable name(s)
γ_S	Solar zenith	$[rad]$	solZenith
γ_P	Slope of solar module plane	$[rad]$	SolPowSlope(NSolPow)
α_S	Solar azimuth	$[rad]$	solAzimuth
α_P	Orientation of solar module plane	$[rad]$	SolPowOrient(NSolPow)
$I_{G,incl}$	Global solar irradiance on the inclined plane	$\left[\frac{W}{m^2}\right]$	globIrrIncl
$I_{dir,incl}$	Direct solar irradiance on the inclined plane	$\left[\frac{W}{m^2}\right]$	dirIrrIncl
$I_{dif,incl}$	Diffuse solar irradiance on the inclined plane	$\left[\frac{W}{m^2}\right]$	difIrrIncl
$I_{refl,incl}$	Background reflection on the inclined plane	$\left[\frac{W}{m^2}\right]$	reflection
$I_{dir,hor}$	Direct solar irradiance on the horizontal plane	$\left[\frac{W}{m^2}\right]$	dirIrr
$I_{dif,hor}$	Diffuse solar irradiance on the horizontal plane	$\left[\frac{W}{m^2}\right]$	difIrr
I_0	Solar constant	$\left[\frac{W}{m^2}\right]$	solarConst
$I_{G,hor}$	Global solar irradiance on the inclined plane	$\left[\frac{W}{m^2}\right]$	globIrr
A	Albedo	$[-]$	Albedo

2.1.2 Electric Power Production Module

The electric power production module is also based on QUASCHNING (2013) and takes into account the PV module area and material, technical efficiencies, losses due to ageing of the device as well as surrounding air temperature and snow cover. If snow cover is below a thickness of 2 cm, electric power output is calculated as shown in Equations (6) to (8).

At first, temperature impact is computed depending on air temperature and PV module material as shown in Equations (6) and (7).

$$T_{mod} = T_{air} + c_{mod} * \frac{I_{G,incl}}{1000} \quad (6)$$

with:

T_{air}	=	*Air temperature*	$[°C]$
c_{mod}	=	*Material constant*	$[°C]$

$$Impact_T = 1 - \left((T_{mod} - T_{STC}) * \left(\frac{-Coeff_{Temp}}{100} \right) \right) \quad (7)$$

with:

T_{STC}	=	*Temperature at Standard Test Conditions = 25°C*	$[°C]$
$Coeff_T$	=	*Coefficient of temperature, depends on PV module material. Describes the change of efficiency with deviation of module temperature from STC*	$\left[\frac{\%}{K}\right]$

Power production can then be calculated via the following Equation:

$$E_{solar} = \left(\frac{I_{G,incl}}{1000} * A_{mod} \right) * \eta_{mod} * \eta_{inv} * impact_T * (1 - age_{mod} * impact_{age}) \quad (8)$$

with:

A_{mod}	=	*Module area*	$[m^2]$
η_{mod}	=	*Module efficiency*	$[-]$
η_{inv}	=	*Inverter efficiency*	$[-]$
age_{mod}	=	*Operating age of the PV module*	$[a]$
$impact_{age}$	=	*Loss of efficiency per year of operating age*	$[-]$

2.2 Pre-processing

The pre-processing includes the identification of all existent PV devices within the region under assessment with their exact positions and technical parameters. Positions as well as rated output of devices within the EWO region were taken from BAYSTMWI (2015) and ENERGYMAP (2015). To get slope and aspect of the building-related PV devices, the two data sets were merged by address with LDBV (2015), a GIS building data set which is based on laser scanning data. For open space devices, slope and aspect were set to southward orientation and a slope of 32.5 ° (QUASCHNING 2013). Technical efficiencies, their development since 1990 and a continuation until 2035 as well as ageing per year were taken and derived from FRAUNHOFER ISE (2017). Areas were derived from the technical module efficiencies. Typical values for material constant and coefficient of temperature were taken from QUASCHNING (2013).

2.3 Input Data and Format

The setup file contains the following sections:

- [General]:

Table 2-2: Description of the input-file for the Solar Power Model, Section General

Input Parameters	Description	Unit	Data format
ObjectType	Type of renewable energy = solarp	[-]	character
ObjectName	Explicit Name of device	[-]	character
ObjectID	Explicit ID of device	[-]	integer
Position-Proxel	Row and column of position within the model rectangle; divided by multiple spaces	[-]	Integer

- [SolarPowerModel]:

Table 2-3: Description of the input-file for the Solar Power Model, Section SolarPowerModel

Input Parameters	Description	Unit	Data format
SolarPowerActive	Status of the Power Plant	[-]	integer
SolarPowerYear, SolarPowerMonth,	Start time of the Power Plant	[-]	integer
SolarPowerType	Type of device – roof, façade, open space	[-]	integer
RatedOutput	Rated output of device	[kW]	real
Area	Module area	[m²]	real
Slope	Slope of device	[°]	real
Aspect	Orientation of device	[°]	real
Constant	Material constant	[°C]	real
TempCoeff	Temperature coefficient	[%/K]	real
EffMod	Module efficiency	[-]	real
EffInv	Inverter efficiency	[-]	real
Ageing	Ageing impact on efficiency per year	[-]	real

Example setup for a PV power plant:

```
[General]
ObjectType              solarp
ObjectName              E21875011000000000000295598000000
ObjectId                1
Position-Proxel         315         523
[end]

[SolarPowerModel]
SolarPowerActive        1
SolarPowerYear          1994
SolarPowerMonth         07
SolarPowerDay           01
SolarPowerType          2
RatedOutput             10.000000
Area                    70.422535
Slope                   51.636000
Aspect                  11.739000
Constant                31.250000
TempCoeff               0.450000
EffMod                  0.101000
EffInv                  0.911900
Ageing                  0.003000
[end]
```

Figure 2-2: Example of the input file for the Solar Power Model

2.4 Output

The output of the solar power model includes the produced electrical energy in kWh on hourly resolution.

3 The SolarHeat Model

The SolarHeat model computes heat production via solar thermic (ST) modules. It calculates yields for building-related ST systems as well as open space ST systems. Equations, required information and program environment are described in the following.

3.1 General Equations

3.1.1 Solar Radiation Module

The solar radiation module is analogous to the Solar Power Model as described in Section 2.1.1 via Equations (1) to (5).

3.1.2 Heat Production Module

The heat production module is also based on QUASCHNING (2013) and takes into account the ST collector area, technical and optical efficiencies and snow cover. If snow cover is below a thickness of 2 cm, heat output is calculated as shown in Equation (9).

$$H_{solar} = \left(\frac{I_{G,incl}}{1000} * A_{coll}\right) * \eta_{coll} * \eta_{opt} * \eta_{pump} \tag{9}$$

with:

A_{coll}	=	*Collector area*	$[m^2]$
η_{coll}	=	*Collector efficiency*	$[-]$
η_{opt}	=	*Optical efficiency (dependent on material)*	$[-]$
η_{pump}	=	*Circulating pump efficiency*	$[-]$

3.2 Pre-processing

The pre-processing includes the identification of all existent ST devices within the region under assessment with their exact positions and technical parameters. Number and size of existent devices had to be derived from BSW (2015), which only provided total area and heat production per community. Average sizes of ST collectors were derived from average heat demands per m² and average living area per community (BAYLFSTAD 2011, BAYSTMUV et al. 2011, WALBERG 2012, BAYLFSTAD 2015a, b). Positions for ST devices were randomly distributed within each community via the building data set that also provided slope and aspect of the chosen building (LDBV 2015). There are no open space ST devices in the EWO region yet, but the possibility was implemented with regard to future expansion. System efficiencies were taken from EICKER (2012).

3.3 Input Data and Format

The setup file contains the following sections:

- [General]:

Table 3-1: Description of the input-file for the Solar Heat Model, Section General

Input Parameters	Description	Unit	Data format
ObjectType	Type of renewable energy = solarh	[-]	character
ObjectName	Explicit Name of device	[-]	character
ObjectID	Explicit ID of device	[-]	integer
Position-Proxel	Row and column of position within the model rectangle; divided by multiple spaces	[-]	Integer

- [SolarHeatModel]:

Table 3-2: Description of the input-file for the Solar Heat Model, Section SolarPowerModel

Input Parameters	Description	Unit	Data format
SolarHeatActive	Status of the Power Plant	[-]	integer
SolarHeatYear, SolarHeatMonth, SolarHeatDay	Start time of the solar thermic plant	[-]	integer
SolarHeatType	Type of device – roof, façade, open space	[-]	integer
Area	Area of Collector	[m²]	real
Slope	Slope of device	[°]	real
Aspect	Orientation of device	[°]	real
EffOpt	Optical efficiency	[-]	real
EffColl	Collector efficiency	[-]	real
EffPump	Circulation pump efficiency	[-]	real

Example setup for a ST plant:

```
[General]
ObjectType              solarh
ObjectName              DEBY_LOD2_2162160_7ce5a5e2-70f5-4a1f-b0ac-564cf8a5
ObjectId                1
Position-Proxel         289         61
[end]

[SolarHeatModel]
SolarHeatActive         1
SolarHeatYear           2007
SolarHeatMonth          1
SolarHeatDay            1
SolarHeatType           1
Kollektorflaeche[m²]    11.445142
Slope [°]               25.105000
Aspect [°]              -146.391000
EffOpt [%]              0.825000
EffColl [%]             0.656000
EffPump [%]             0.700000
[end]
```

Figure 3-1: Example of the input file for the Solar Heat Model

3.4 Output

The output of the solar heat model includes the produced heat energy in kWh on hourly resolution.

4 Implementation within the Energy Model

The solar energy model is completely integrated within the energy model. The work flow within the PROMET model and its components for the calculation of the energy paths is shown in Figure 4-1.

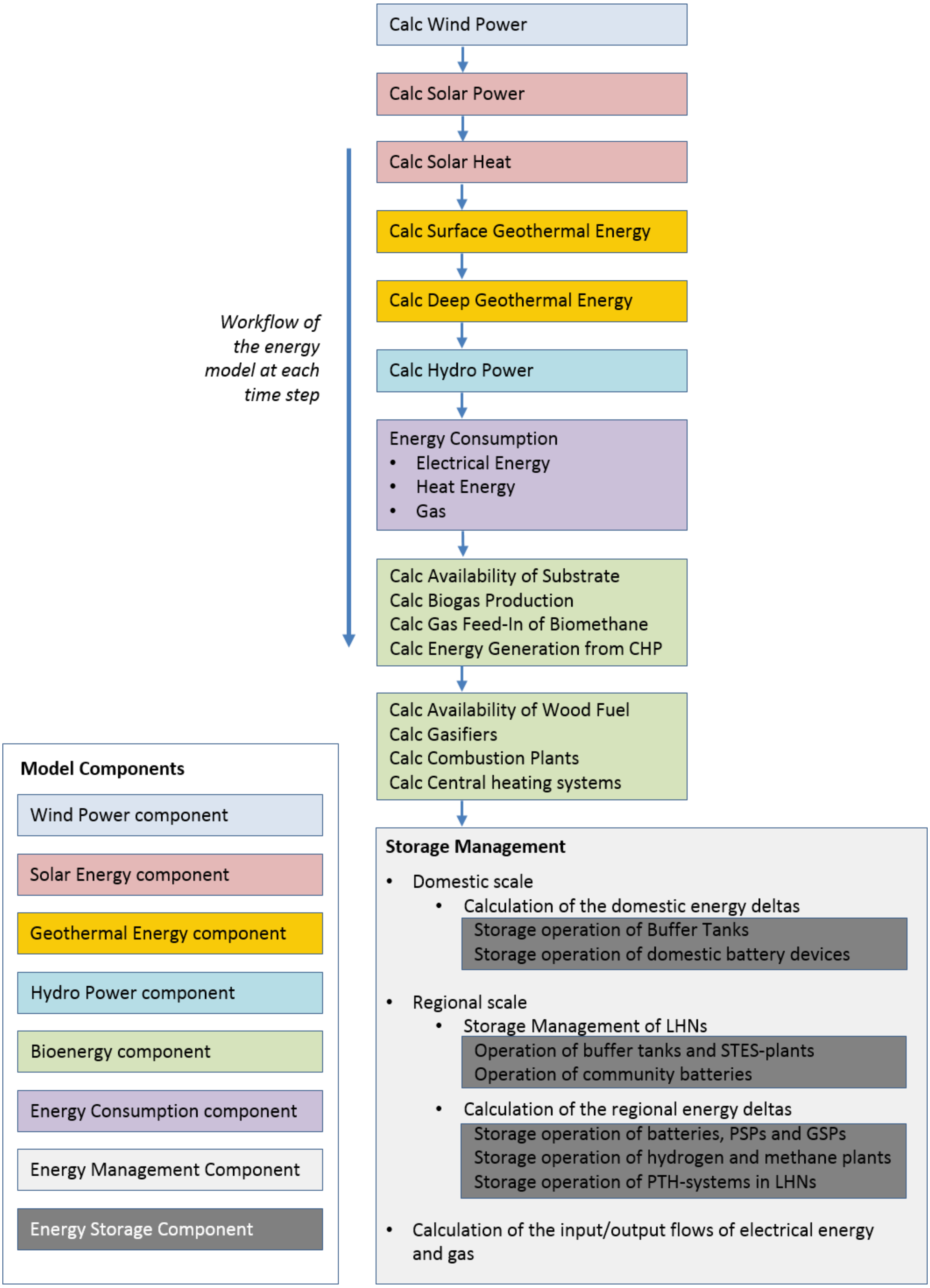

Figure 4-1: Workflow of the Energy model with regarding components

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