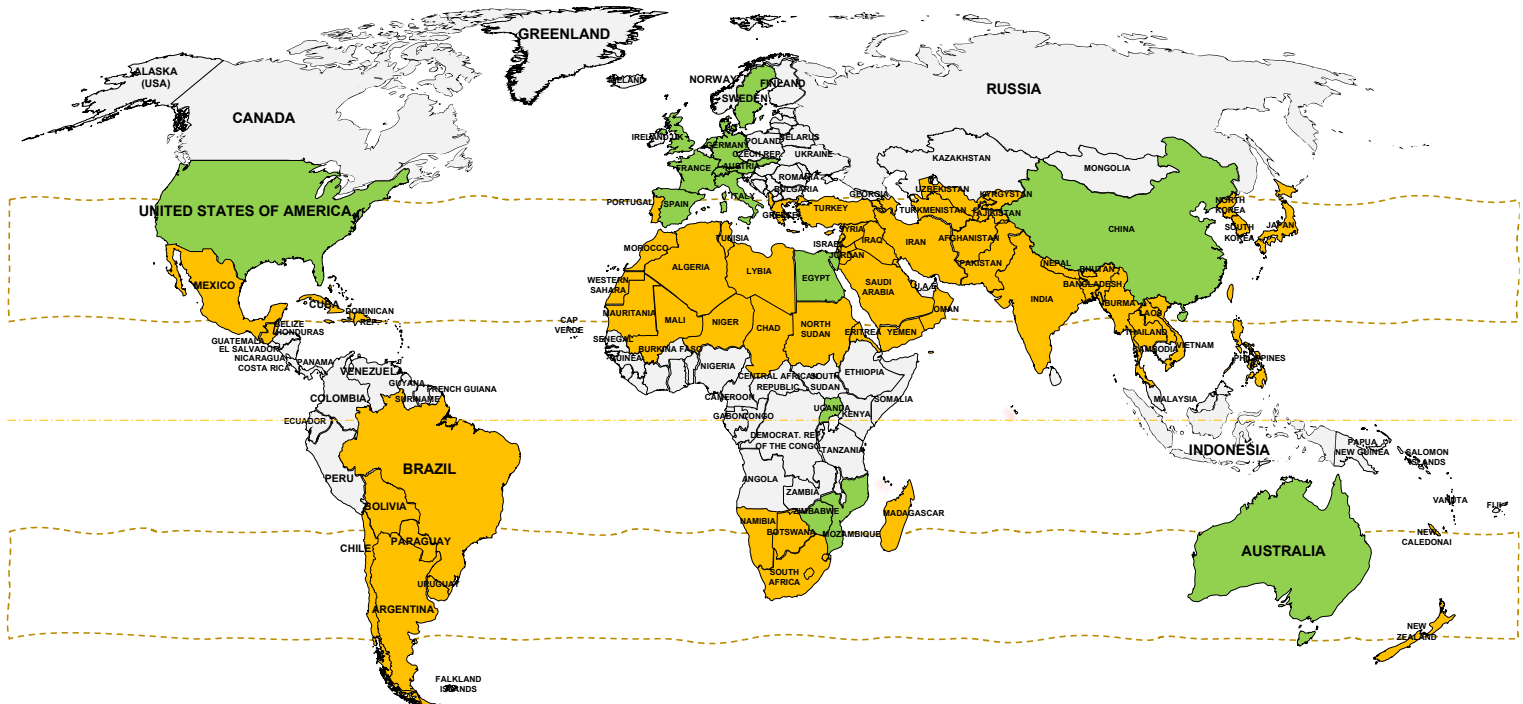


Design Tools and Models



IEA SHC TASK 65 | SOLAR COOLING FOR THE SUNBELT REGIONS

Design Tools and Models

**This is a report from SHC Task 65:
Solar Cooling for the Sunbelt Regions
and work performed in
Subtask C: Assessment and Tools**

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Cover photo credit: World map with Sunbelt regions (marked yellow) and the 18 countries of the participating Task 65 experts (marked green), source: Neyer Brainworks & JER

Solar Heating & Cooling Technology Collaboration Programme (IEA SHC)

The Solar Heating and Cooling Technology Collaboration Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency.

Our mission is *"Through multi-disciplinary international collaborative research and knowledge exchange, as well as market and policy recommendations, the IEA SHC will work to increase the deployment rate of solar heating and cooling systems by breaking down the technical and non-technical barriers."*

IEA SHC members carry out cooperative research, development, demonstrations, and exchanges of information through Tasks (projects) on solar heating and cooling components and systems and their application to advance the deployment and research and development activities in the field of solar heating and cooling.

Our focus areas, with the associated Tasks in parenthesis, include:

- Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44, 54, 69)
- Solar Cooling (Tasks 25, 38, 48, 53, 65)
- Solar Heat for Industrial and Agricultural Processes (Tasks 29, 33, 49, 62, 64, 72)
- Solar District Heating (Tasks 7, 45, 55, 68)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52, 56, 59, 63, 66)
- Solar Thermal & PV (Tasks 16, 35, 60)
- Daylighting/Lighting (Tasks 21, 31, 50, 61, 70)
- Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
- Standards, Certification, and Test Methods (Tasks 14, 24, 34, 43, 57)
- Resource Assessment (Tasks 1, 4, 5, 9, 17, 36, 46, 71)
- Storage of Solar Heat (Tasks 7, 32, 42, 58, 67)

In addition to our Task work, other activities of the IEA SHC include our:

- SHC Solar Academy
- *Solar Heat Worldwide*, annual statistics report
- SHC International Conference

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1 Executive Summary

This is the final report on activity C1, “Design tools and models” of the IEA SHC Task 65 “Solar Cooling for the Sunbelt regions”. The work involved reviewing and adapting tools and models for technical and financial assessment and design for solar cooling and the project phases from pre-feasibility to simulation to monitoring. The main focus is the documentation of the tools and their specific application to provide measured data for validating the tools and the adaptation of selected ones for Sunbelt countries.

Three approaches are used to evaluate tools used worldwide and this IEA SHC Task. First, a (i) generic literature research in Web of Science (WoS), (ii) interviews and questionnaires among the IEA SHC Task Expert, and (iii) interactive questionnaires during Task expert meetings.

A total of 1,216 documents were identified as a result of the search in WoS. The query search string used is ALL=(“solar cooling” OR “solar refrigeration”), and the index dates covered are 1990/01/01-2021/06/30. A network visualization diagram was generated in VOSviewer. A query search string (“solar cooling”) (“design”) AND (“software”) in the topic field produced 38 documents.

The initial data gathered provide a general idea of which components are being used and which software is being implemented. Based on the information provided by the task participants, the following software are currently being implemented in their applications/research: MATLAB, Meteonorm + Excel tool, TRNSYS, EES, and Phyton. This is also reflected in the third evaluation of tools.

Conclusion: Modelling and assessing the technical and economic behavior of solar cooling plants is essential in all design phases up to implementation and optimization. Different tools are used, from sophisticated dynamic simulation models to simple spreadsheet calculations. Companies and their experts often develop their own for their specific components and systems. Generic publicly available models can be found for almost all applications, especially simulation tools. The configuration and data sheets for the entire tool depend on the approach and are often difficult to find.

2 Scope of Activity C1

It is to review and adaptation of tools and models for technical and financial assessment and design for solar cooling and the different project's phases from pre-feasibility to simulation to monitoring. Different solutions are available and of interest among the interested participants (from mobile apps to dynamic simulation models for consultants, manufacturer, researcher, etc.), which need to be discussed and consolidated. Each of the tools and models can support the implementation of solar cooling in sunbelt countries, if it is used target oriented.

The main focus in this activity is the documentation of the tools and their specific application, to provide measured data for validation of the tools and the adaptation of selected ones for sunbelt countries.

3 Methodology

3.1 Literature Research

A systematic review was conducted to identify solar cooling system design tools and models. The abstract and citation database selected is Web of Science (WoS) core collection. The query search string used is ALL=(“solar cooling” OR “solar refrigeration”), and the index dates covered are 1990/01/01-2021/06/30. The details of the documents identified and the results are presented in Section 4.1 of this report.

3.2 Interviews/Questionnaire

These interviews/questionnaires should provide insight about which tools and applications are being mostly used and implemented by the members of SHC Task 65. For the first step of Activity C1, in order to gather sufficient data to use in its documentation, was a questionnaire developed and sent to the participants. This first questionnaire is in a table format to allow for the formulation of direct questions to facilitate the understanding and analysis of the information.

3.3 Interactive Subtask & Expert Meetings

The subtask and expert meetings are used to generate further feedback and content for Activity C1. With the help of interactive tools (e.g., Mentimeter), closed and open questions on the use of specific tools in the different project phases are collected, discussed, and analysed.

Questions that are raised are for example:

- Type of business you are working for?
- Which tools are in use in your company/institute?
- How often do you use the following tools in different phases of the project?
- ...

Table 1: Software tools applied in solar cooling system research.

No.	Software tool	Reference
1	TRNSYS	(Uckan & Yousif, 2021)
2	MATLAB, EES	(Tashtoush & Nayfeh, 2020)
3	TRNSYS	(Mehmood, Maximov, Chalmers, & Friedrich, 2020)
4	TRNSYS	(Boero & Agyenim, 2020)
5	Meteonorm	(Alahmer, Wang, & Alam, 2020)
6	EES	(Al-Nimr, Tashtoush, & Hasan, 2020)
7	TRNSYS, MATLAB	(Aboelmaaref et al.)
8	EES, Epsilon	(Tashtoush & Algharbawi, 2019)
9	TRNSYS	(Plytaria, Bellos, Tzivanidis, & Antonopoulos, 2019)
10	gPROMS	(Harraz, Freeman, Wang, Mac Dowell, & Markides, 2019)
11	TRNSYS	(Figaj, Szubel, Przenzak, & Filipowicz, 2019)
12	Sage	(Langdon-Arms, Gschwendtner, & Neumaier, 2018)
13	IES	(Hassabou & Khan, 2018)
14	TRNSYS	(Franchini, Brumana, & Perdichizzi, 2018)
15	EES	(Adibi, 2018)
16	EES	(Porumb, Porumb, & Balan, 2017)
17	EnergyPlus	(Ma, Saha, Miller, & Guan, 2017)
18	Sage	(Langdon-Arms, Gschwendtner, & Neumaier, 2017)
19	TRNSYS	(Brumana, Franchini, & Perdichizzi, 2017)
20	TRNSYS	(Vasta, Palomba, Frazzica, Di Bella, & Freni, 2016)
21	FLUENT	(Kalkan & Dagtekin, 2016)
22	TRNSYS	(Wang & Dennis, 2015)
23	TRNSYS	(Vasta, Palomba, Frazzica, Costa, & Freni, 2015)
24	TRNSYS, EES	(Tashtoush, Alshare, & Al-Rifai, 2015)
25	TRNSYS	(Lugo & Garcia-Valladares, 2015)
26	TRNSYS	(Gomez-Moreno, Palomar-Carnicero, & Cruz-Peragon, 2015)
27	IPSEpro	(Abdulrahim & Darwish, 2015)
28	TRNSYS	(Buonomano, Calise, & Ferruzzi, 2013)
29	TRNSYS	(Baniyounes, Rasul, & Khan, 2013)
30	TRNSYS	(Thomas & Andre, 2012)
31	TRNSYS	(Calise, 2011)

In general, solar cooling system components are categorized into four processes: solar energy collection, cooling, distribution, and optional storage. Software tools are applied for estimating design parameters (by sizing tools) and predicting operational performance parameters (by simulation tools). It should be noted that the simulation tools could be used for design optimizations. Optimizations could aim for individual or a combination of technical performance, financial performance, and environmental performance. Based on this knowledge, we have developed a data collection proforma for design software tools. More details about these software tools may be found in the corresponding web pages shown in Table 2.

Table 2: Webpages of the Software tools applied in solar cooling system research

Software tool	Webpage
Epsilon	https://www.ebsilon.com/
EES	https://fchartsoftware.com/ees/
EnergyPlus	https://energyplus.net/
FLUENT	https://www.ansys.com/products/fluids/ansys-fluent
gPROMS	https://www.psenterprise.com/products/qproms
IES	https://www.iesve.com/software
IPSEpro	https://www.simtechnology.com/CMS/index.php/ipsepro
MATLAB	https://www.mathworks.com/products/matlab.html
Meteonorm	https://meteonorm.com/
Sage	http://www.sageofathens.com/
TRNSYS	https://sel.me.wisc.edu/trnsys/

4.2 Interviews/Questionnaire

As previously explained, the first questionnaire sent to the participants has a table format, and one can see the structure in **Error! Reference source not found.**

Table 3: Solar cooling system component design tools

Component→ Design stage or output ↓	Solar collector				Cooling technology					Delivery			Storage	
	Flat plate	Evacuated tube	Trough	PV PV/T	Absorption	Adsorption	Liquid desiccant	Solid desiccant	Vapour compression	Air	Liquid	Electricity	Heat	Battery
Prefeasibility														
Sizing														
Technical performance														
Financial performance														
Hourly simulation	TRNSYS	TRNSYS	TRNSYS	TRNSYS	TRNSYS	-	-	-	TRNSYS	TRNSYS	TRNSYS	TRNSYS	TRNSYS	TRNSYS
...														
...														

The initial data gathered provide a general idea of which components are being used and which software is being implemented. Based on the information provided by the task participants, the following software is currently being implemented in their applications/research:

- MATLAB
- Meteonorm + Excel tool
- TRNSYS
- EES
- Phytion

The software mentioned above can predict or model the behavior of several components. According to the feedback from the Task participants, a summary of the systems and software primarily used is shown in Table 4.

Table 4: Summary of participants' feedback

Component→ Design stage or output ↓	Solar collector				Cooling technology					Delivery			Storage	
	Flat plate	Evacuated tube	Trough	PV PV/T	Absorption	Adsorption	Liquid desiccant	Solid desiccant	Vapour compression	Air	Liquid	Electricity	Heat (cold)	Battery
Prefeasibility	Metonorm + Excel Tool Phytion	Metonorm + Excel Tool Phytion		Metonorm + Excel Tool	MATLAB EES Excel Tool	Phytion				MATLAB EES Excel Tool	x	x	x	MATLAB TRNSYS Excel Tool Phytion
Sizing	Metonorm + Excel Tool	Metonorm + Excel Tool		Metonorm + Excel Tool	MATLAB EES TRNSYS Excel Tool					MATLAB EES TRNSYS Excel Tool			x	MATLAB TRNSYS Excel Tool
Technical performance	Metonorm + Excel Tool	Metonorm + Excel Tool		Metonorm + Excel Tool	MATLAB EES TRNSYS Excel Tool					MATLAB EES TRNSYS Excel Tool				MATLAB TRNSYS Excel Tool
Financial performance	Excel Tool	Excel Tool		Excel Tool	MATLAB EES TRNSYS Excel Tool					MATLAB EES TRNSYS Excel Tool				MATLAB TRNSYS Excel Tool
Hourly simulation	MATLAB TRNSYS Metonorm + Excel Tool	MATLAB TRNSYS Metonorm + Excel Tool	MATLAB	Metonorm + Excel Tool	MATLAB EES TRNSYS Excel Tool	-	-	ENERGYPLUS		MATLAB EES TRNSYS Excel Tool	-	-	-	MATLAB TRNSYS Excel Tool

4.3 Interactive Questionnaire at Subtask & Expert Meetings

Data collection was conducted at the 3rd Expert Meeting (Nov. 2021). The questionnaire was integrated, including open questions with free answer possibilities. Results are shown as a word cloud, where the same answers are clustered and shown in the size of the word/headline compared to other answers.

The results show the use of tools in SHC Task 65 in different project phases, from pre-feasibility to detailed simulations and analyses of technical and economic performance.

For prefeasibility, the experts mainly use calculation tools based on Excel or other spreadsheets. However, even in prefeasibility, TRNSYS, MATLAB, or Polysun are also used.

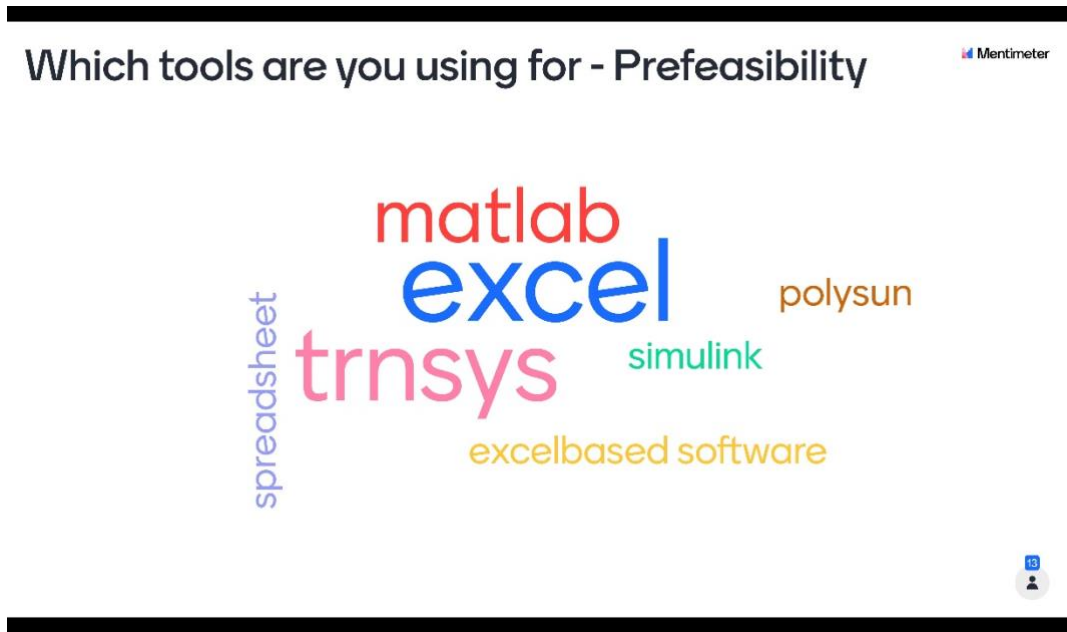


Figure 2: Results of the Mentimeter from 3rd Expert Meeting about tools in prefeasibility studies

The dominant tool is simulation tools like TRNSYS, Polysun, or Excel spreadsheets.

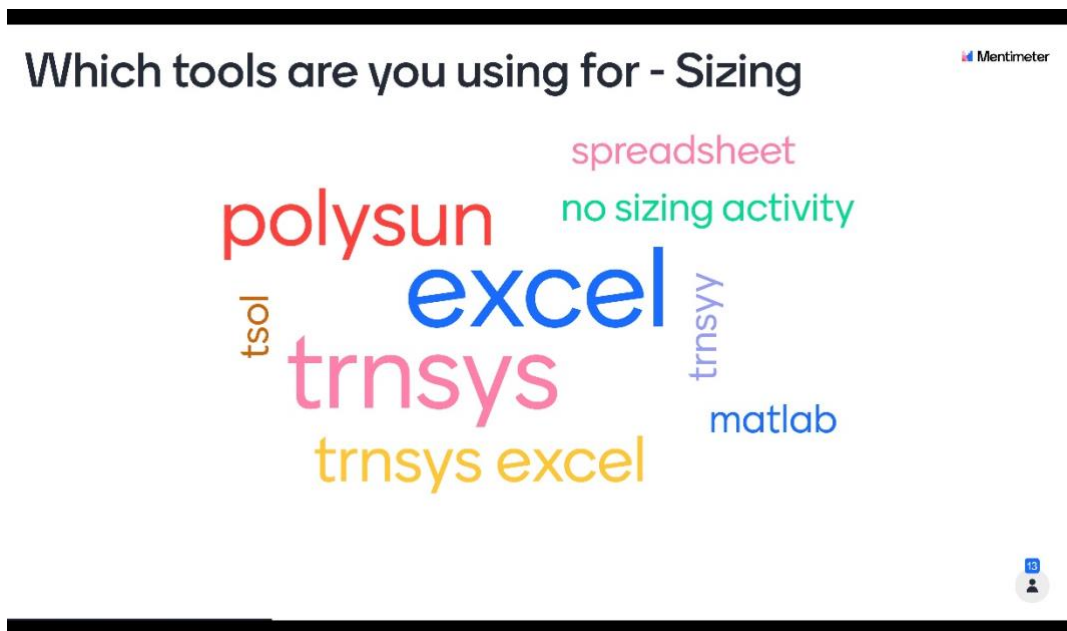


Figure 3: Results of the Mentimeter from 3rd Expert Meeting about tools in sizing of components

Simulation tools are mainly used for technical analyses and performance evaluation (TRNSYS, MATLAB).

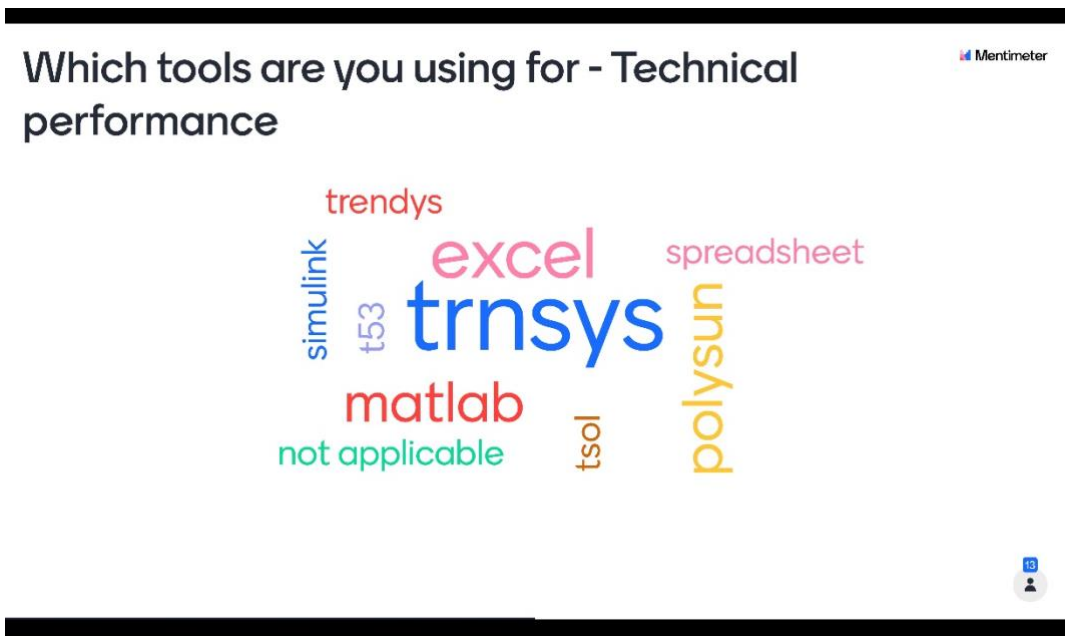


Figure 4: Results of the Mentimeter on tools to analyze technical performance from the 3rd Task Expert Meeting

For analyzing economic performance, mainly Excel-based tools are in use.

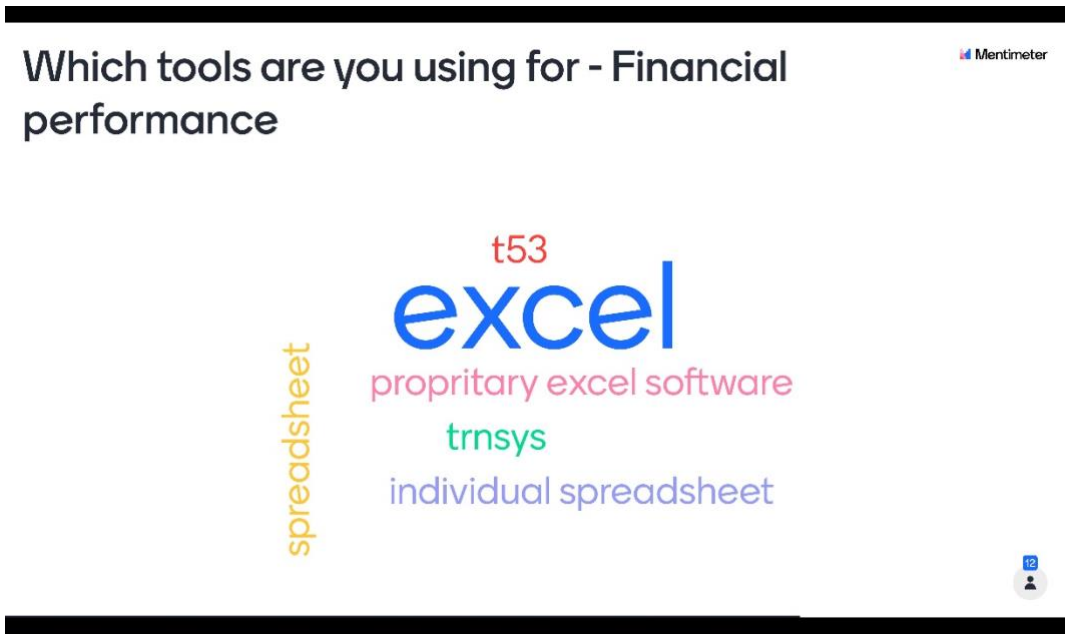


Figure 5: Results of the Mentimeter on tools for analyzing financial performance from 3rd Task Expert Meeting

For more detailed hourly simulation, TRNSYS, MATLAB, and other software are used; however, also Excel is used for this.

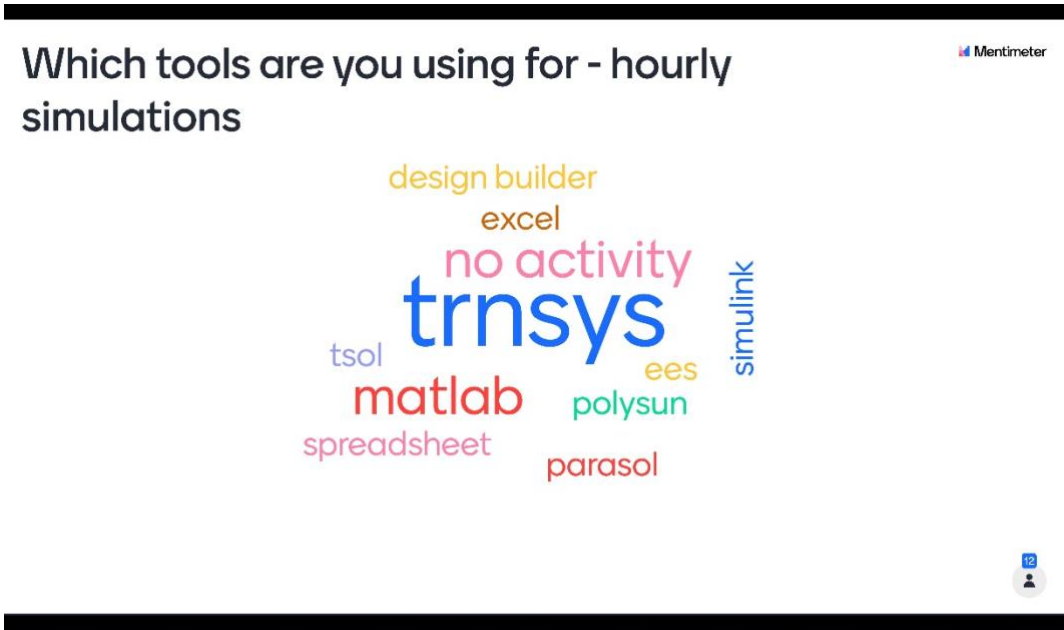


Figure 6: Results of the Mentimeter on tools for plant simulations from the 3rd Task Expert Meeting

5 Available Tools

As previously listed in Table 2, this section provides an overview and a brief description of the different types of software the Task 65 participants utilized. Compared to earlier SHC Tasks, the aim is not to evaluate or validate any model nor compare their results in specific cases. It is more of an overview of tools frequently used and hints at their models for solar cooling and heating systems. Through this report, no claim to completeness is set!

A very detailed description of various simulation tools used in solar cooling was presented in IEA SHC Task 38. The related publications can be downloaded under <https://task38.iea-shc.org/publications>. At that time (2009), new developments in simulation tools and models, as well as their validation, are described under https://task38.iea-shc.org/Data/Sites/1/publications/Report_C2A_final.pdf. A benchmark analysis for comparison of system simulation tools with a focus on absorption chillers is given under https://task38.iea-shc.org/Data/Sites/1/publications/Report_C2B_final.pdf.

5.1 TRNSYS

TRNSYS is a software tool with a graphical user interface, mainly used to simulate the behavior of transient systems. This software can be used to model several dynamic systems, for example, thermal and electrical energy systems, optimizations, power plants planning, etc. It is extensively used worldwide for many applications in several different working fields.

TRNSYS has an extensive library of components and models. It is structured so that the users can modify the existing components and also write their own models, which increases the tool's capabilities.

Figure 7 provides a graphical user interface of a typical simulation with TRNSYS and shows what it looks like.

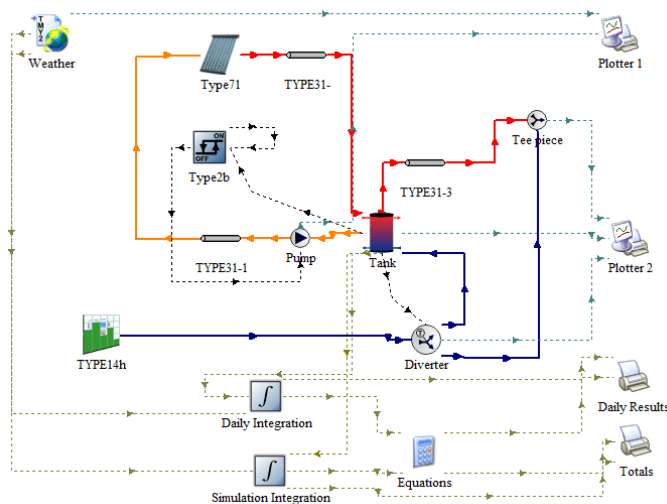


Figure 7: Example of a TRNSYS simulation interface. Source: (Leal-Chavez, Beltran-Chacon, Cardenas-Terrazas, Islas, & Velázquez, 2019)

TRNSYS components available to model solar cooling are listed in Table (5).

Table 5. TRNSYS components available for solar colling system simulation.

Category	Component	TRNSYS Type	Source	Reference where implemented
Solar collector	Flat plate collector	Type 1: Quadratic Efficiency Collector Type 72: Performance Map Collector Type 73: Theoretical Flat-Plate Collector	Std.	
	Evacuated tube	Type 71: Evacuated Tube Collector	Std.	
	Trough	Type 30: Parabolic Trough Arrays	Std.	
	PV	Type 103: Basic Model – w/wo MPPT Type 190: Advanced Model – w/wo MPPT – w/wo Inverter	Std.	
	PV/T	Type 50: PV-Thermal Collectors Type 560: Combined PV/T Solar Collector Type 562: Simple Glazed Or Unglazed PV Panel	Std. TESS	
Cooling technology	Absorption	Type 107: Absorption Chiller (Hot-Water Fired, Single Effect)	Std.	
		Type 676: Double-Effect Steam-Fired Absorption Chiller Type 677: Double-Effect Hot Water-Fired Absorption Chiller	TESS	
		Type 1001: Absorption with dynamic elements	Non-std.	Neyer et al
	Adsorption	Type 909: Adsorption Chiller (Performance Map)	TESS	
	Liquid desiccant			
	Solid desiccant		Non-std.	AIT / Antia Preisler / Markus Brychta
Vapour compression		Type 118: Air-Cooled Chiller Type 142: Water-Cooled Chiller	Std.	
		Type 666: Water Cooled Chiller	TESS	
Coolth delivery	Air distribution	Type 11: Controlled Flow Mixer Type 145: Duct Type 148: Tee-Piece Flow Mixer	Std.	
	Water distribution	Type 31: Pipe	Std.	
	Electricity distribution	Type 188: Busbar	Std.	
Storage	Heat	Type 340:	Non-Std.	
	Electricity	Type 47: Batteries Type 185: Quasi-static mathematical model of lead-acid battery	Std.	
Financial	LCC	Type 582: Life Cycle Cost Analysis	TESS	

5.2 MATLAB

This software combines iterative analysis and design processes with a programming language that directly expresses matrix and array mathematics and was developed by MathWorks (MathWorks, 2021). MATLAB can perform several activities, including machine learning, developing algorithms, control systems, predictive maintenance, signal processing, and many more.

MATLAB is built around a high-level programming language, which can be combined with other programming languages like C/C++, Fortran, Java, and Python.

This is one of the few software that includes pre-built apps and allows the user to build and modify its components. MATLAB can be extended by installing extra packages and toolboxes that are available online. The additional package Simulink adds graphical multi-domain simulation environment and model-based design for dynamic and embedded systems. Figure 8 displays the interface of the Simulink environment.

5.2.1. Components

In this section, some of the most used components in MATLAB regarding solar cooling technologies will be briefly presented and explained. It is important to observe that the models presented here are part of the CARNOT Blockset (Juelich, 10/2018).

A. Storage Models (CARNOT Blockset)

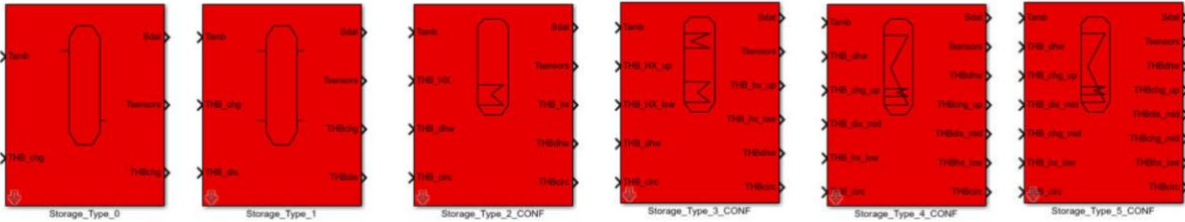


Figure 9: Storage models included in the CARNOT Blockset in MATLAB

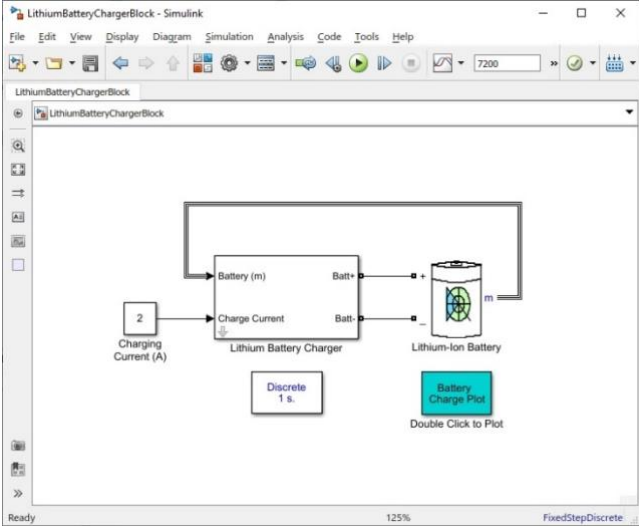


Figure 8: Example of a Simulink simulation interface
Source:(Tan, 2021)

The basic concept of the thermal storage models included in the CARNOT Blockset is a multiport one-dimensional model. The blocks are usually connected to other CARNOT components by a variable number of port blocks. The energy flow in the Thermal Hydraulic Bus (THB) is translated by these ports into the energy and mass balances of the storage. Pressure drop and changes due to static height are calculated in the ports. For example, the port can be a pipe ending at the storage wall and releasing the fluid in the storage, or it can be a heat exchanger charging or discharging the storage with an energy flow.

In each model, the parameters represent the geometric and thermodynamic data of the storage. The top mask defines the number of ports, the number of temperature sensors, and the number of nodes in the storage.

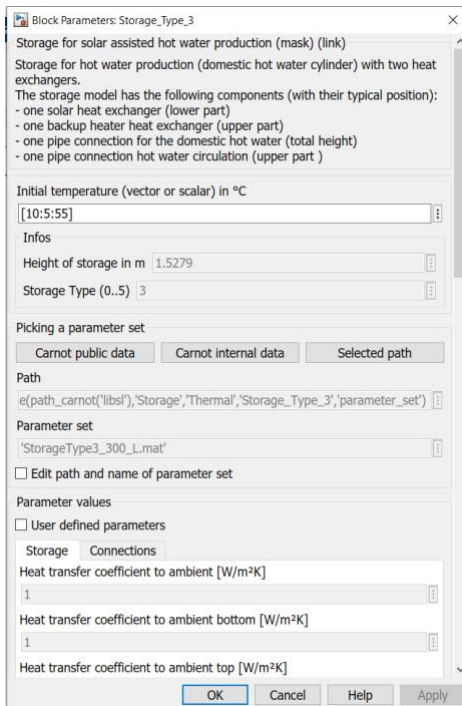
Figure 10 presents the dialog box, where the most important data of the storage can be modified according to the simulation purposes. In the Help section, the user can find more information about the mathematical model used to describe the storage models and how the pipe connections and the internal mass flow are defined and calculated.

B. Ground Storage

The thermal ground storage model is three-dimensional, and the heat is transferred to the ground by a pipe heat exchanger in an S-form. The pipe lies in the depth z_{pipe} in a rectangular area (similar to an earth collector for a heat pump). The heat transport in the ground is calculated with a finite difference scheme.

$$\rho \cdot c_p \cdot \frac{dT}{dt} = \text{div}(\text{cond} \cdot \text{grad} T) + S$$

$$S = U \cdot \frac{A}{dV} \cdot (T_{\text{fluid}} - T)$$



Where:

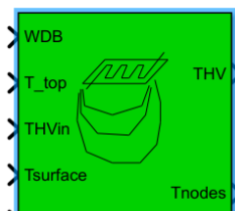
- c_p : specific heat capacity (J/m³*k)
- T : temperature (°C)
- t : time (s)
- cond : conductivity (W/(m*k))
- S : source term
- A : area (m²)
- V : volume (m³)
- U : thermal transmittance (W/m²*k)
- THVin

The thermal conductivity and capacity of the soil around the storage are extracted from a table and implemented in the model. The main inputs and outputs of the model are described below:

Figure 10: Parameters dialog box of storage model

Inputs:

- Weather data vector



- Temperature above the heat exchanger area (°C)
- Temperature at ground surface (°C)
- Temperature below storage (°C)

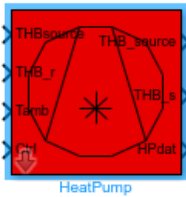
Outputs:

- Temperature at measurement points (°C)
- THVout

Figure 11: Ground Storage Parameters dialog box

the measurement points are located below the outlet of the pipe and the sensors are distributed over the height (first sensor at the top and last at the bottom).

C. Heat Pump



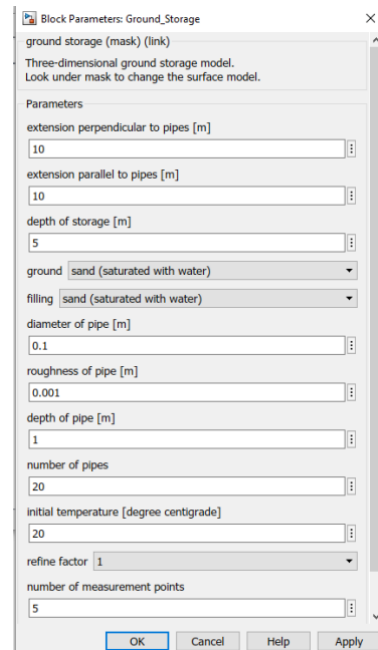
This model is used to calculate a fluid-to-fluid heat pump system, where the dynamic behavior is computed using an empirical model. The calculation is based on the static characteristics of the heat pump according to the German standard DIN 8900. The heating, electric and source powers are given for different temperatures in the primary and secondary cycles. The following linear equations are used to approximate the characteristics

$$\text{heating}_{power} = K1 * T_{primary,in} + K2 * T_{secondary,out} + K3$$

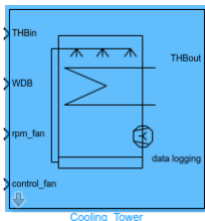
$$\text{electric}_{power} = K4 * T_{primary,in} + K5 * T_{secondary,out} + K6$$

$$\text{source}_{power} = -K7 * T_{primary,in} + K8 * T_{secondary,out} + K9$$

The parameters K1 to K9 are given in an extra m.file in MATLAB, which is automatically called for the model during the calculations and can also be seen in the parameters dialog box. Due its linear nature, the model only needs the powers at lowest and highest temperatures, all the others will be interpolated.



D. Cooling Tower



This block calculates the output Thermal Hydraulic Bus (THB), the energy and water consumption of the closed circuited cooling tower. The output temperature depends on air temperature, humidity, rotation per minute (rpm) of the fan, flow rate and glycol content. The saturation pressure is calculated with the simplified approximation of Glück. The parameter dialog box provides an overview of the performance data, and the distribution of the data logging signals.

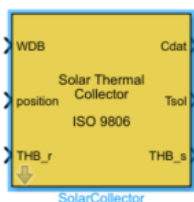
Inputs:

- THBin: input of fluid-type water/glycol
- Weather – weather data vector
- Rpm_fan: in rounds per minute, limited to the range 0 – 824 l/min
- Control_fan: limited to the range 0 to 1

Outputs:

- THBout
- Data logging

E. Solar Thermal Collector



This model follows the EN 12975 standard. The energy balance is calculated using the following equation:

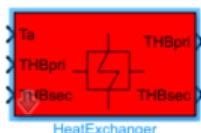
$$\begin{aligned} \dot{m} * c_p * (T_{out} - T_{in}) / A &= F'(\tau_{\alpha}) * K_{dir} * I_{dir} + F'(\tau_{\alpha}) * K_{dfu} * I_{dfu} - c1 (T_m - T_{amb}) - c2 (T_m - T_{amb})^2 - c3 * v_{wind} * (T_m - T_a) - c6 * v_{wind} * I_{glb} + c4 (E_{Longwave} - \sigma_{SB} * (T_{amb} + 273.15)^4) - c5 dT_m/dt \end{aligned}$$

The parameters are described in Table 5.

Table 5: Energy balance equation parameters

Symbol	Unit	Description
F'	-	collector fin efficiency factor
TauAlfa	-	effective transmittance absorptance product for direct solar radiation at normal incidence
Kdir	-	incidence angle modifier for direct solar radiation
Idir	(W/m ²)	direct solar radiation on the collector plane
Kdfu	-	incidence angle modifier for diffuse solar radiation
Idfu	(W/m ²)	diffuse solar radiation on the collector plane
Tm	(°C)	mean collector temperature
Tamb	(°C)	ambient temperature
V_wind	(m/s)	Wind velocity
Iglb	(W/m ²)	global solar radiation on the collector plane
ELongwave	(W/m ²)	longwave irradiance with wave length > 3000 nm
sigmaSB	(W/(m ² k ⁴))	Stefan-Boltzmann constant = 5.67e-8 W/(m ² K ⁴)
c1	W/(m ² K)	heat loss coefficient at (Tm - Ta)=0
c2	W/(m ² K ²)	temperature dependence of the heat loss coefficient
c3	J/(m ³ K)	wind speed dependence of the heat loss coefficient
c4	W/(m ² K)	sky temperature dependence of the heat loss coefficient
c5	J/(m ² K)	effective thermal capacity
c6	s/m	wind dependence in the zero loss efficiency

F. Heat Exchanger

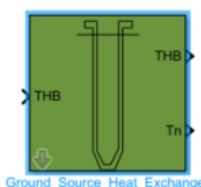


This model calculates the Thermal Hydraulic Bus output of the hot and cold fluid of a heat exchanger. In this block, parallel, cross and counter flow are possible. The heat exchanger is characterized by the number of transfer units (NTU) and the input temperatures are delayed by the hat capacity of the exchanger. The delay of the inlet temperature is calculated as follows:

$$(0.5 * cap) * \frac{dT}{dt} = (T_{in} - T) - U_{Aloss} * (T_{amb} - T)$$

Where cap represents the heat capacity (J/K), U is the thermal transmittance (W/m²K) and Tamb the ambient temperature (°C)

G. Ground Source Heat Exchanger



This is a transient model for dynamic simulation of borehole heat exchangers or so-called vertical ground heat exchangers. The model is based on the equations described by (Huber A, 1997) and has been implemented using the state space model of Matlab/Simulink (A., 2006). The main input is the THB vector from the source side of the heat pump, and the main output is the THB vector to the heat pump.

Parameters and Dialog Box

- Average annual outdoor temperature in °C
- Temperature gradient in K/m, typical 0.025 to 0.04
- Thermal conductivity ground in W/m/K
- Heat capacity of the ground in J/kg/K
- Density of the ground in kg/m³
- Thermal conductivity filling in W/m/K
- Heat capacity of the filling in J/kg/K
- Density of the filling in kg/m³
- H: Length of earth probe in m
- B: probe distance in m
- Diameter of tube in m
- Diameter of drilled hole in m
- Field geometry (1 probe; 2 probes B/H = 0.1; 2 probes B/H = 0.05; 3x6 probes B/H = 0.1; 5x10 probes B/H = 0.1)
- Number of parallel tubes (on the hydraulic side)
- No. of nodes in axial direction (typical 10)
- No. of nodes in radial direction (typical 10)
- grid factor (typical 2.5)

The user can refer to (Juelich, 10/2018.) for a more detailed library of components and systems

5.3 Meteonorm

Meteonorm provides monthly meteorological data for any location on Earth. It can also generate synthetic hourly values from these monthly values using stochastic models. It has a database with over 8,000 weather stations, five geostationary satellites, and a globally calibrated aerosol climatology (Meteonorm, 2021).

With Meteonorm, the user can access historical data on irradiation, temperature, humidity, precipitation, and wind speed, thus all the relevant meteorological information required for planning solar applications.

5.4 Excel tool

Microsoft Excel is part of the Microsoft Office suite of Software. It has a spreadsheet format, which features calculations, graphing tools, pivot tables, and a macro programming language known as Visual Basic for Applications (VBA).

Many companies and experts created private tools for pre-design, design, and analyses of technical and economic characteristics. Most of them are kept internal as they often comprise details on the components or key system compositions of these manufacturers. However, a few of the tools are available through former IEA SHC Tasks, e.g., IEA SHC Task 48 (<https://task48.iea-shc.org/publications>) or further developed and with increased capabilities in IEA SHC Task 53 (<https://task53.iea-shc.org/publications>)

- ➔ IEA SHC Task 48: <https://task48.iea-shc.org/tools>
- ➔ PISTACHE Tool (Presizing tool for solar cooling, heating, and domestic hot water production systems)
The PISTACHE software is a tool to pre-size and evaluate the performances of solar installation for cooling, heating, and domestic hot water preparation, with or without energy back-up system.
- ➔ LCA Method Tool. The LCA Method Tool is a tool for applying the Life Cycle Assessment (LCA) methodology, which assesses the energy and environmental impacts associated with all stages of a product's life cycle from cradle to grave.
- ➔ IEA SHC Task 53: <https://task53.iea-shc.org/software-tools>
- ➔ ELISA Tool: Life Cycle Analysis for Solar Cooling Systems. Another Excel-based tool is the Environmental Life Cycle Impacts of Solar Air-conditioning Systems (ELISA).
- ➔ T53E4 Tool – To Assess a System's Technical and Economic Potential. T53E4, a technical and economic assessment tool, rates and benchmarks new developments at the system level (proper design and operation).

5.5 EES

EES (pronounced 'ease') is a general equation-solving program that can numerically solve coupled non-linear algebraic and differential equations. The program can also be used to solve differential and integral equations, do optimization, provide uncertainty analyses, perform linear and non-linear regression, convert units, check unit consistency, and generate publication-quality plots. One of the main characteristics of EES is the high-accuracy thermodynamic and transport property database that is provided for substances in a manner that allows it to be used with the equation-solving capability (F-ChartSoftware, 2021).

5.6 ParaSol

It is a user-friendly energy simulation tool for comparison of energy demand and peak loads for heating/cooling for different glazing and shading devices. It can be used to design and renovate buildings like offices, schools, and dwellings. It is free to download at the Lund University in Sweden website.

5.7 Polysun

Polysun is a holistic energy system simulation tool for buildings and district planners. Polysun Designer depicts your energy system at an early planning stage. Systems can be built up quickly, and the potential for optimization is

revealed. This gives you planning security and convinces your customers with sophisticated and economical energy concepts. Polysun Designer intelligently combines applications to meet heating, cooling, electricity, and electromobility requirements.

Using simple drag-and-drop, you can choose from 150,000 system components that are always up-to-date and simulate the interaction of the energy system in dynamic time steps up to a resolution of steps in seconds. You can define an intelligent control logic in a completely flexible manner, thereby additionally increasing the energy and cost efficiency of your solution.



6 Conclusions

Modeling and assessing solar cooling plants' technical and economic behavior is essential in all design phases up to implementation and optimization. Different tools can be used to do this, from sophisticated dynamic simulation models to simple spreadsheet calculations. Companies and their experts often develop their own tools for their specific components and systems. But generic, publicly available models can be found for almost all applications, especially simulation tools.

7 References

- Abdulrahim, H. K., & Darwish, M. A. (2015). Thermal desalination and air conditioning using absorption cycle. *Desalination and Water Treatment*, 55(12), 3310-3329. doi:10.1080/19443994.2014.939492
- Aboelmaaref, M. M., Zayed, M. E., Elsheikh, A. H., Askalany, A. A., Zhao, J., Li, W. J., . . . Ahmed, M. S. Design and performance analysis of a thermoelectric air-conditioning system driven by solar photovoltaic panels. *Proceedings of the Institution of Mechanical Engineers Part C-Journal of Mechanical Engineering Science*, 14. doi:10.1177/0954406220976164
- Adibi, T. (2018). Evaluation of using solar ammonia absorption cooling system for major cities of the Middle East. *International Journal of Heat and Technology*, 36(3), 840-846. doi:10.18280/ijht.360309
- Al-Nimr, M. A., Tashtoush, B., & Hasan, A. (2020). A novel hybrid solar ejector cooling system with thermoelectric generators. *Energy*, 198, 17. doi:10.1016/j.energy.2020.117318
- Alahmer, A., Wang, X. L., & Alam, K. C. A. (2020). Dynamic and Economic Investigation of a Solar Thermal-Driven Two-Bed Adsorption Chiller under Perth Climatic Conditions. *Energies*, 13(4), 19. doi:10.3390/en13041005
- Baniyounes, A. M., Rasul, M. G., & Khan, M. M. K. (2013). Assessment of solar assisted air conditioning in Central Queensland's subtropical climate, Australia. *Renewable Energy*, 50, 334-341. doi:10.1016/j.renene.2012.06.042
- Bleyl, J. W., Bareit, M., Casas, M. A., Chatterjee, S., Coolen, J., Hulshoff, A., . . . Üрге-Vorsatz, D. (2019). Office building deep energy retrofit: life cycle cost benefit analyses using cash flow analysis and multiple benefits on project level. *Energy Efficiency*, 12(1), 261-279. doi:10.1007/s12053-018-9707-8
- Boero, A., & Agyenim, F. (2020). Modeling and simulation of a small-scale solar-powered absorption cooling system in three cities with a tropical climate. *International Journal of Low-Carbon Technologies*, 15(1), 1-16. doi:10.1093/ijlct/ctz040
- Brumana, G., Franchini, G., & Perdichizzi, A. (2017). Design and Performance Prediction of an Energy plus Building in Dubai. In B. Fortunato, A. Ficarella, & M. Torresi (Eds.), *Ati 2017 - 72nd Conference of the Italian Thermal Machines Engineering Association* (Vol. 126, pp. 155-162). Amsterdam: Elsevier Science BV.
- Buonomano, A., Calise, F., & Ferruzzi, G. (2013). Thermoeconomic analysis of storage systems for solar heating and cooling systems: A comparison between variable-volume and fixed-volume tanks. *Energy*, 59, 600-616. doi:10.1016/j.energy.2013.06.063
- Calise, F. (2011). Design of a hybrid polygeneration system with solar collectors and a Solid Oxide Fuel Cell: Dynamic simulation and economic assessment. *International Journal of Hydrogen Energy*, 36(10), 6128-6150. doi:10.1016/j.ijhydene.2011.02.057
- F-Chart Software. (2021, September 22). Retrieved from <https://fchartsoftware.com/ees/>
- Figaj, R., Szubel, M., Przenzak, E., & Filipowicz, M. (2019). Feasibility of a small-scale hybrid dish/flat-plate solar collector system as a heat source for an absorption cooling unit. *Applied Thermal Engineering*, 163, 10. doi:10.1016/j.applthermaleng.2019.114399
- Franchini, G., Brumana, G., & Perdichizzi, A. (2018). Performance prediction of a solar district cooling system in Riyadh, Saudi Arabia - A case study. *Energy Conversion and Management*, 166, 372-384. doi:10.1016/j.enconman.2018.04.048
- Gomez-Moreno, A., Palomar-Carnicero, J. M., & Cruz-Peragon, F. (2015). Teaching different types of air conditioning systems using simulation software. In L. G. Chova, A. L. Martinez, & I. C. Torres (Eds.), *Inted2015: 9th International Technology, Education and Development Conference* (pp. 5183-5192). Valenica: Iated-Int Assoc Technology Education & Development.
- Harraz, A. A., Freeman, J., Wang, K., Mac Dowell, N., & Markides, C. N. (2019). Diffusion-absorption refrigeration cycle simulations in gPROMS using SAFT-gamma Mie. In J. Yan, H. X. Yang, H. Li, & X. Chen (Eds.), *Innovative Solutions for Energy Transitions* (Vol. 158, pp. 2360-2365). Amsterdam: Elsevier Science BV.
- Hassabou, A. M., & Khan, M. A. (2018). *Energy Efficient & Sustainable Buildings: Integration with solar assisted air-conditioning technology in Qatar - A Step towards Grid Free Zero Carbon Living*. Freiburg: Intl Solar Energy Soc.
- Kalkan, N., & Dagtekin, I. (2016). Passive cooling technology by using solar chimney for mild or warm climates. *Thermal Science*, 20(6), 2125-2136. doi:10.2298/tsci150608168k
- Langdon-Arms, S., Gschwendtner, M., & Neumaier, M. (2017). Development of a solar-powered liquid piston Stirling refrigerator. In J. Yan, J. Wu, & H. Li (Eds.), *Proceedings of the 9th International Conference on Applied Energy* (Vol. 142, pp. 570-575). Amsterdam: Elsevier Science BV.

- Langdon-Arms, S., Gschwendtner, M., & Neumaier, M. (2018). A novel solar-powered liquid piston Stirling refrigerator. *Applied Energy*, 229, 603-613. doi:10.1016/j.apenergy.2018.08.040
- Leal-Chavez, D., Beltran-Chacon, R., Cardenas-Terrazas, P., Islas, S., & Velázquez, N. (2019). Design and Analysis of the Domestic Micro-Cogeneration Potential for an ORC System Adapted to a Solar Domestic Hot Water System. *Entropy*, 21(9). doi:10.3390/e21090911
- Lugo, S., & Garcia-Valladares, O. (2015). *Numerical simulation and experimental validation of a solar cooling system in Mexico*. Freiburg: Intl Solar Energy Soc.
- Ma, Y. L., Saha, S. C., Miller, W., & Guan, L. (2017). Comparison of Different Solar-Assisted Air Conditioning Systems for Australian Office Buildings. *Energies*, 10(10), 27. doi:10.3390/en10101463
- MathWorks. (2021, September 17). Retrieved from <https://www.mathworks.com/products/matlab>
- Mehmood, S., Maximov, S. A., Chalmers, H., & Friedrich, D. (2020). Energetic, Economic and Environmental (3E) Assessment and Design of Solar-Powered HVAC Systems in Pakistan. *Energies*, 13(17), 25. doi:10.3390/en13174333
- Meteonorm. (2021, September 22). Retrieved from <https://meteonorm.com/en/>
- Plytaria, M. T., Bellos, E., Tzivanidis, C., & Antonopoulos, K. A. (2019). Numerical simulation of a solar cooling system with and without phase change materials in radiant walls of a building. *Energy Conversion and Management*, 188, 40-53. doi:10.1016/j.enconman.2019.03.042
- Porumb, R., Porumb, B., & Balan, M. (2017). Numerical investigation on solar absorption chiller with LiBr-H₂O operating conditions and performances. In A. Anton, C. Balan, M. C. Balan, F. Bode, W. Bosschaerts, C. Croitoru, C. Inard, A. Meslem, I. Nastase, & M. Sandu (Eds.), *Sustainable Solutions for Energy and Environment, Eenviro 2016* (Vol. 112, pp. 108-117). Amsterdam: Elsevier Science BV.
- Tan, R. (Producer). (2021, September 17). Lithium Battery Charger Block. *MATLAB Central File Exchange*. Retrieved from <https://www.mathworks.com/matlabcentral/fileexchange/72570-lithium-battery-charger-block>
- Tashtoush, B., & Algharbawi, A. B. R. (2019). Parametric study of a Novel Hybrid Solar Variable Geometry Ejector cooling with Organic Rankine Cycles. *Energy Conversion and Management*, 198, 14. doi:10.1016/j.enconman.2019.111910
- Tashtoush, B., Alshare, A., & Al-Rifai, S. (2015). Hourly dynamic simulation of solar ejector cooling system using TRNSYS for Jordanian climate. *Energy Conversion and Management*, 100, 288-299. doi:10.1016/j.enconman.2015.05.010
- Tashtoush, B., & Nayfeh, Y. (2020). Energy and economic analysis of a variable-geometry ejector in solar cooling systems for residential buildings. *Journal of Energy Storage*, 27, 16. doi:10.1016/j.est.2019.101061
- Thomas, S., & Andre, P. (2012). Numerical simulation and performance assessment of an absorption solar air-conditioning system coupled with an office building. *Building Simulation*, 5(3), 243-255. doi:10.1007/s12273-012-0060-0
- Uckan, I., & Yousif, A. A. (2021). Investigation of the effect of various solar collector types on a solar absorption cooling system. *Energy Sources Part a-Recovery Utilization and Environmental Effects*, 43(7), 875-892. doi:10.1080/15567036.2020.1766599
- Vasta, S., Palomba, V., Frazzica, A., Costa, F., & Freni, A. (2015). Dynamic simulation and performance analysis of solar cooling systems in Italy. In A. Cocchi, P. Andreini, & L. Cassitto (Eds.), *69th Conference of the Italian Thermal Engineering Association, Ati 2014* (Vol. 81, pp. 1171-1183). Amsterdam: Elsevier Science BV.
- Vasta, S., Palomba, V., Frazzica, A., Di Bella, G., & Freni, A. (2016). Techno-Economic Analysis of Solar Cooling Systems for Residential Buildings in Italy. *Journal of Solar Energy Engineering-Transactions of the Asme*, 138(3), 11. doi:10.1115/1.4032772
- Wang, X. L., & Dennis, M. (2015). Influencing factors on the energy saving performance of battery storage and phase change cold storage in a PV cooling system. *Energy and Buildings*, 107, 84-92. doi:10.1016/j.enbuild.2015.08.008

8 Nomenclature

Abbreviation

CCREEE	Caribbean Centre for Renewable Energy and Energy Efficiency
EACREEE	East African Centre for Renewable Energy and Energy Efficiency
ECI	European Copper Institute
ECOWAS	Economic Community of West African States ()
EES	Engineering Equation Solver program
IC	Innovation Challenge
ISES	International Solar Energy Society
KPI	Key Performance Indicators
LCC	Life-Cycle Cost
LCCBA	Life-Cycle Cost-Benefit Analysis
MI	Mission Innovation
RCREEE	Regional Center for Renewable Energy and Energy Efficiency
RD&D	Research, Development, and Demonstration
SACREEE	SADC Centre for Renewable Energy and Energy Efficiency
SADC	Southern African Development Community
SICA	Central American Integration System
SICREEE	SICA Centre for Renewable Energy and Energy Efficiency
TRNSYS	TRaNsient SYstems Simulation program
WoS	Web of Science