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(ES TCP)

Task 39 - Large Thermal Energy Storages for District Heating

Subtask C: Round Robin Simulations

Deliverable C1: Numerical models list - Overview and collection of model fact sheets

Task Manager ES TCP Task 39:

Wim van Helden

AEE - Institute for Sustainable Technologies

Austria

AUTHORS

Name	Institution	Role
Thomas Schmidt	Solites, DE	Author, Editor
Abdulrahman Dahash	AIT, AT	Author
Alice Tosatto	UIBK, AT	Author
Fabian Ochs	UIBK, AT	Author
Geoffroy Gauthier	PlanEnergi, DK	Author
Ioannis Sifnaios	DTU, DK	Author
Jeff Thornton	TESS, US	Author
Jianhua Fan	DTU, DK	Author
Julian Formhals	Vattenfall, DE	Author
Michael Reisenbichler-Sommerhofer	AEE, AT	Author
Steven van der Wilk	If Technology, NL	Author

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CONTENT

INTRODUCTION

For the proper design and system integration of Large Thermal Energy Storages (LTES), suitable, accurate and verified simulation models are essential. Various models were developed in the past for different LTES concepts (see Figure 1), simulation platforms and application purposes. Important aspects in an LTES project development are, e.g., the LTES dimensioning, that can only be carried out considering the LTES system integration. Suitable models for this must take into account the short-term interaction with the system's energy producers and sources, as well as energy consumers. Models for this purpose have been mostly developed for system simulation platforms like TRNSYS or Modelica/Dymola. Another important aspect is the detailed component-level design and optimization of an LTES. For this task, models in more detailed and flexible simulation tools (e.g. COMSOL Multiphysics or ANSYS FLUENT) are used.

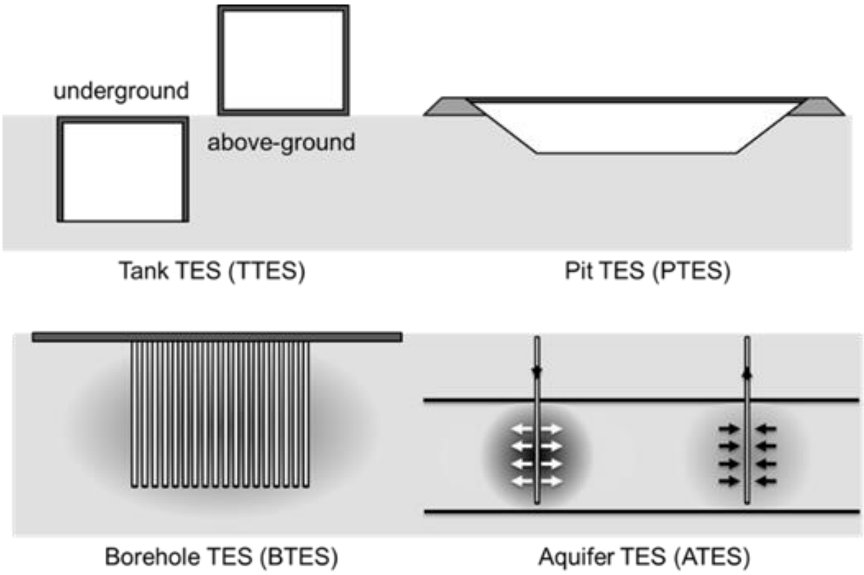

Figure 1: Overview of LTES concepts

This document provides an overview of LTES simulation models used or known by the participants of IEA ES Task 39 Subtask C. However, this does not mean that the list of models is complete. In the following sections, fact sheets are given for most of the models from the model overview. The fact sheets aim to provide information about capabilities, purposes and restrictions of the models, as well as information about availability and corresponding contact details.

MODELS OVERVIEW

Project phase / main purpose Storage type	System simulation	TES design optimization
PTES (truncated cone or pyramid)	**TRNSYS** • Type 343 (cone) • Type 1322 (pyramid) • Types 1535/1301 (cone) • UGSTS **Modelica** • Dymola Dis PlaTES • LargeTESmtk – PTES model • MoSDH library – PTES model **MATLAB Simulink** • Matlab Large-Scale TES	**COMSOL Multiphysics** **ANSYS FLUENT** **OpenFOAM**
TTES (cylinder)	**TRNSYS** • Type 340 (above ground) • Type 342 (buried and above-ground) • Types 534/708 (ground buried) • Type 1534 (above ground) • Types 1534/1302 (ground buried) **Modelica** • Dymola Dis PlaTES • LargeTESmtk – PTES model • MoSDH library – TTES model **MATLAB Simulink** • Matlab Large-Scale TES	**COMSOL Multiphysics** **ANSYS FLUENT** **OpenFOAM**
TTES (cuboid)	**TRNSYS** • Types 1531/957 (ground buried) • Types 1531/1267 (ground buried)	
ATES	**TRNSYS** • Type 345 TRNAST • Type 1380	**FEFLOW** **MODFLOW** **HST2D/3D**
BTES	**TRNSYS** • Type 346 SBM • Type 370 • Type 557 DST • Type 1373 **Modelica** • MoSDH library – BTES model	**COMSOL Multiphysics** **FEFLOW** **ANSYS FLUENT**

FACT SHEETS ON PTES AND TTES MODELS

1 COMSOL TES

GENERAL INFORMATION

Name and Version of the Model	The described model is available in two institution-internal developments: 1. AIT: DePlaTES – Detailed Planning of large-scale seasonal Thermal Energy Storage 2. UIBK: COMSOL TES
Author	Abdulrahman Dahash (AIT, Austria) - DePlaTES and COMSOL TES Fabian Ochs (UIBK, Austria) - COMSOL TES Alice Tosatto (UIBK, Austria) - COMSOL TES
Creation Date	October 2018
Primary Usage	The model is used for detailed design of (seasonal) LTES and is versatile in terms of geometry and other design conditions. The model can be co-simulated with a system simulation. The model also includes time-series profile for the load and supply in DH system and a heat pump
Type of Model	Can be used as a stand-alone model within COMSOL/MATLAB/Java environ-ments
Software Language of Source Code	N/A (Model can be exported as MATLAB or Java code)
Required Software to Use the Model	COMSOL v5.0 or recent versions
Operating System Requirements	No specific requirements, but there should enough RAM to enable running of simulation and sufficient space to update the events log file (this could be up to 30 GBs for groundwater simulations).
Technical Documentation	N/A (Only publications)
Relevant Publications	Dahash et al. (2018), "Detailed axial symmetrical model of large-scale under-ground thermal energy storage," in Proceedings of the 2018 COMSOL Confer-ence, Lausanne (Switzerland), 22-24 October 2018, 2018 Dahash et al. (2020), "Toward efficient numerical modeling and analysis of large-scale thermal energy storage for renewable district heating systems," Ap-plied Energy, vol. 279, 2020 Ochs et al. (2020), “Techno-economic planning and construction of cost-effec-tive large-scale hot water thermal energy storage for Renewable District heat-ing systems”, *Renewable Energy*, vol. 150, pp. 1165-1177

	Dahash et al. (2021), "Understanding the Interaction between Groundwater and Large-Scale Underground Hot-Water Tanks and Pits," *Sustainable Cities and Society,* vol. 71, 2021 Dahash et al. (2021), "Techno-economic and exergy analysis of tank and pit thermal energy storage for renewables district heating systems," *Renewable Energy,* vol. 180, pp. 1358-1379, 2021 Tosatto et al. (2022), "Simulation-based performance evaluation of large-scale thermal energy storage coupled with heat pump in district heating systems", *Journal of Energy Storage,* vol. 61, https://doi.org/10.1016/j.est.2023.106721
Verified with Measured Data?	Calibrated against measured data from Dronninglund PTES in gigaTES project. The calibration included energy flows, temperature and stratification.
Model Availability	Internal use (UIBK/AIT): model exchange for research purposes on request
Contact Information	Abdulrahman Dahash, AIT Austrian Institute of Technology GmbH Abdulrahman.dahash@ait.ac.at Unit of Energy Efficient Building, Universität Innsbruck, Innsbruck, Austria fabian.ochs@uibk.ac.at, alice.tosatto@uibk.ac.at

MODELING DETAILS

Geometry Options	Versatile 2D/3D model (tanks (cylinder, cuboid), pits (cone or pyramid), combination of geometries)
Top Surface Boundary	
Far-Field Boundary	Can be set to: Constant temperature or adiabatic (Used is adiabatic)
Deep Earth Boundary	Can be set to: Constant temperature or adiabatic (Used is adiabatic)
Water Domain Heat Transfer Calculation Method	1-D nodal (FE), power law-based buoyancy model
Water Domain Boundary Heat Transfer Calculation Method	The model is available in two types: One has the physical layers of TES constructions and the other has thermal resistance features for the sidewalls and bottom
Options for In- and Outlet Configuration	Unlimited number of ports and can be located at the desired height. The model has no internal heat exchanger, but it can be easily incorporated.

Insulation Options	The model is available in two types: One has physical layers with variable insulation thickness and the other has thermal resistance that can be variable over the height.
Soil Domain Heat Transfer Calculation Method	3-D finite element
Possibilities for Different Horizontal Ground Layers	Heterogeneous soil
Fluid and Soil Properties	User input and can be set to constant or temperature-dependent thermo-physical properties
Consideration of Groundwater Flow	Possible with subsurface flow (CFD, Darcy flow) 3-D finite element
Other Model Features	TES can be partially/fully buried under a soil. The model can be also above ground. Model is versatile in terms of TES design (e.g. cover, insulation thickness, geometry)
Known Model Limitations	No (detailed) dynamic system simulations for DH, long simulation time
Additional Remarks	COMSOL expertise required

2 Matlab/Simuling Large-Scale TES

GENERAL INFORMATION

Name and Version of the Model	Matlab Large-Scale TES (Matlab/Simulink)
Author	Fabian Ochs (UIBK, Austria)
Creation Date	2014 (update 2022)
Primary Usage	The model is used for detailed design of (seasonal) LTES and is versatile in terms of geometry and other design conditions. The model can be used as stand-alone Model in Matlab, or in a system simulation within Matlab/Simulink environment. The model also includes time-series profile for the load and supply in DH system and a heat pump and other components can be integrated
Type of Model	Can be used as a stand-alone model or as a component model for system-level studies
Software Language of Source Code	Matlab
Required Software to Use the Model	Matlab
Operating System Requirements	No specific requirements
Technical Documentation	N/A (Only publications)
Relevant Publications	Ochs F. (2014), "Large-scale thermal energy stores in district heating systems - simulation based optimization" (2014), 10.18086/eurosun.2014.19.09, EuroSun 2014, France Ochs, F. (2015) "Simulation Based Optimization of Pit and Tank Thermal Energy Storage for Solar District Heating Systems", SDH Conference 2015, Toulouse, France, 2015 Ochs F. (2018) "Primary Energy Based Evaluation of Heat Pumps in District Heating Systems with Multi-functional Thermal Energy Stores", Proceedings of 5th international District Heating Conference, April 2018 Graz, Austria, 2018 Ochs, F.; Dahash, A.; Tosatto, A.; Reisenbichler, M.; O'Donovan, K.; Gauthier, G.; et al. (2022) „Comprehensive comparison of different models for large-Scale thermal energy storage" Proceedings of the International Renewable Energy Storage Conference 2021 (IRES 2021), 8, pp. 36-51, 10.2991/ahe.k.220301.005

	Ochs F., Dahash, A.; Tosatto, A.; Janetti-Bianchi M.; (2020), "Techno-economic planning and construction of cost-effective large-scale hot water thermal energy storage for Renewable District heating systems", Renewable Energy, vol. 150, pp. 1165-1177
Verified with Measured Data?	Cross-validated against other TES models in the framework of the Austrian FFG giga_TES project. The calibration included energy flows, temperature and stratification (Ochs et al. 2022)
Model Availability	Internal use (UIBK)
Contact Information	Unit of Energy Efficient Building, Universität Innsbruck, Innsbruck, Austria fabian.ochs@uibk.ac.at, alice.tosatto@uibk.ac.at

MODELING DETAILS

Geometry Options	Versatile 2D model for tanks (cylinder) and pits (cone stump), or combination of geometries
Top Surface Boundary	(e.g. type of boundary condition, constant/variable temperatures or heat flows, constant/variable heat transfer coefficients etc.)
Far-Field Boundary	Can be set to: Constant temperature or adiabatic (Used is adiabatic)
Deep Earth Boundary	Can be set to: Constant temperature or adiabatic (Used is adiabatic)
Water Domain Heat Transfer Calculation Method	1D nodal (FD), power law-based buoyancy model Variable number of fluid nodes and variable number of edges (solid domain boundary)
Water Domain Boundary Heat Transfer Calculation Method	The model is available in two types: One has the physical layers of TES constructions and the other has thermal resistance features for the sidewalls and bottom. Used is resistance
Options for In- and Outlet Configuration	Unlimited number of ports and can be located at the desired height. The model has no internal heat exchanger, but it can be easily incorporated.
Insulation Options	The model is available in two types: One has physical layers with variable insulation thickness and the other has thermal resistance that can be variable over the height.
Soil Domain Heat Transfer Calculation Method	2D finite element

Possibilities for Different Horizontal Ground Layers	Heterogeneous soil
Fluid and Soil Properties	User input and can be set to constant or temperature-dependent thermophysical properties.
Consideration of Groundwater Flow	Not detailed as it is a 2D model. Can be approximated using different distance of the lower boundary to simulate the location of the groundwater table.
Other Model Features	TES can be partially/fully buried. The model can be also above ground. Model is versatile in terms of TES design (e.g. cover, insulation thickness, geometry).
Known Model Limitations	(2D)
Additional Remarks	

3 Modelica / Dymola TES

GENERAL INFORMATION

Name and Version of the Model	Dis PlaTES (District-level Planning of large-scale seasonal Thermal Energy Storage)
Author	Abdulrahman Dahash
Creation Date	November 2019
Primary Usage	The model is used for detailed design of (seasonal) TTES and system simulation. The model can be co-simulated with other platforms.
Type of Model	Can be used as a stand-alone model within Modelica environment.
Software Language of Source Code	Modelica
Required Software to Use the Model	Dymola
Operating System Requirements	No specific requirements, but there should be enough RAM to enable running of simulation and sufficient space to update the events log file (this could be up to 30 GBs for groundwater simulations).
Technical Documentation	N/A
Relevant Publications	Dahash et al. (2020), "Simulation-based design optimization of large-scale seasonal thermal energy storage in renewable-based district heating systems," in *Proceedings of BauSIM 2020 (Virtual): 8th Conference of IBPSA Germany and Austria*, Graz, Austria, 2020
Verified with Measured Data?	Calibrated against COMSOL TES model that is validated measured data from Dronninglund PTES in gigaTES project. The calibration included energy flows, temperature and stratification.
Model Availability	Internal use
Contact Information	Abdulrahman Dahash, AIT Austrian Institute of Technology GmbH Abdulrahman.dahahs@ait.ac.at

MODELING DETAILS

Geometry Options	Tank with limited possibility to represent cone PTES (tested)
Top Surface Boundary	

Far-Field Boundary	Can be set to: Constant temperature or adiabatic (Used is adiabatic)
Deep Earth Boundary	Can be set to: Constant temperature or adiabatic (Used is adiabatic)
Water Domain Heat Transfer Calculation Method	1-D nodal
Water Domain Boundary Heat Transfer Calculation Method	The model is available in two types: One has the physical layer for TES cover and the sidewalls and bottom are implemented with thermal resistance features.
Options for In- and Outlet Configuration	Unlimited number of ports and can be located at the desired height. The model has no internal heat exchanger, but it can be easily incorporated.
Insulation Options	The model is available in two types: One has physical layers with variable insulation thickness and the other has thermal resistance that can be variable over the height.
Soil Domain Heat Transfer Calculation Method	2-D finite difference
Possibilities for Different Horizontal Ground Layers	Heterogeneous soil
Fluid and Soil Properties	User input and can be set to constant or temperature-dependent thermophysical properties.
Consideration of Groundwater Flow	Not possible (trial version is possible with some deviation)
Other Model Features	TES can be partially/fully buried under a soil. The model can be also above ground. Model is versatile in terms of TES design (e.g. cover, insulation thickness, geometry). It enables the user to choose the buoyancy function for the simulation with the desired mixing time. Initial stratified or constant temperature profile can be set.
Known Model Limitations	Current version limited to TTES, no groundwater flow
Additional Remarks	

4 Modelica LargeTESModelingToolkit (LargeTESmtk)

GENERAL INFORMATION

Name and Version of the Model	Modelica LargeTESModelingToolkit (LargeTESmtk) – TTES and PTES models of the Modelica library
Author	Michael Reisenbichler-Sommerhofer
Creation Date	2020 (TTES model), 2021 (PTES model)
Primary Usage	From pre-design studies to more detailed system and storage design studies. For instance, to address storage design questions (e.g. storage volume, storage geometry, insulation quality), to examine long-term effects (the development of storage performance in the first years of operation during the heat-up of the surrounding ground) or to investigate system integration concepts (e.g. post-heating concepts via large heat pumps) and storage operation strategies.
Type of Model	Part of the LargeTESModelingToolkit (A Modelica Library for Large-scale Thermal Energy Storage Modeling and Simulation, see [3])
Software Language of Source Code	Modelica
Required Software to Use the Model	Modelica/Dymola
Operating System Requirements	No specific requirements. Only the requirements for running the simulation environment (e.g., Dymola)
Technical Documentation	See publications below
Relevant Publications	[1] Reisenbichler, Michael, Keith O'Donovan, Carles Ribas Tugores, Wim van Helden, and Franz Wotawa. "Towards More Efficient Modeling and Simulation of Large-Scale Thermal Energy Storages in Future Local and District Energy Systems." In *Proceedings of the 17th IBPSA Conference*, 2155–62. Bruges, Belgium: International Building Performance Simulation Association, 2021. https://doi.org/10.26868/25222708.2021.30911 [2] Ochs, Fabian, Abdulrahman Dahash, Alice Tosatto, Michael Reisenbichler, Keith O'Donovan, Geoffroy Gauthier, Christian Kok Skov, and Thomas Schmidt. "Comprehensive Comparison of Different Models for Large-Scale Thermal Energy Storage." In *Proceedings of the International Renewable Energy Storage Conference 2021 (IRES 2021)*, 36–51. Atlantis Press, 2022. https://doi.org/10.2991/ahe.k.220301.005 [3] Reisenbichler-S., Michael, Franz Wotawa, Keith O'Donovan, Carles Ribas Tugores, and Franz Hengel. "LargeTESModelingToolkit: A Modelica Library for Large-Scale Thermal Energy Storage Modeling and Simulation."

	In *Proceedings of the 15th International Modelica Conference*, 337–46. Aachen (DE), 2023. https://doi.org/10.3384/ecp204337
Verified with Measured Data?	Yes. The TTES model was validated in a validation case study against measurement data of the PTES in Dronninglund, Denmark, and was part of a cross-comparison study with other numerical models (see publications [1] and [2]). The PTES model was part of similar cross-comparison studies with other numerical models. A validation case study against measurement data of real PTES is in progress. Corresponding publications are in preparation
Model Availability	Internal use (at the moment) Free availability and publication planned in the future
Contact Information	Michael Reisenbichler-Sommerhofer (m.reisenbichler@aee.at) AEE INTEC (www.aee-intec.at/en)

MODELING DETAILS

Geometry Options	TTES: Cylinder (fully buried, partly buried, free-standing) PTES: Truncated cone (fully buried, partly buried) Cuboid and truncated pyramid geometry possible to a limited extent (with corresponding adaptations of the heat transfer coefficients between fluid and ground)
Top Surface Boundary	Constant/variable temperatures and constant/variable heat transfer coefficients
Far-Field Boundary	Adiabatic by default (constant/variable temperatures or heat flows are also possible)
Deep Earth Boundary	Adiabatic by default (constant/variable temperatures or heat flows are also possible)
Water Domain Heat Transfer Calculation Method	FDM: 1D multi-node model or approach (with buoyancy model)
Water Domain Boundary Heat Transfer Calculation Method	Optional: Pure thermal resistance or consideration of thermal resistance and capacitance (discretized and consideration of the thermal mass)
Options for In- and Outlet Configuration	Variable number and positions of inlet/outlet diffusers
Insulation Options	Optional: Pure thermal resistance or consideration of thermal resistance and capacitance (discretized and consideration of the thermal mass)

	Consideration of an insulation extension (overlap) of the cover insulation possible
Soil Domain Heat Transfer Calculation Method	2-D FDM (two-dimensional transient heat conduction in cylindrical coordinates)
Possibilities for Different Horizontal Ground Layers	Yes (Also, different radial ground layers are possible)
Fluid and Soil Properties	Constant thermophysical properties by user input.
Consideration of Groundwater Flow	Not possible
Other Model Features	The models are part of the LargeTESmtk Modelica library (see [3]). Along with other features, the library provides a wide range of model configuration options in terms of geometry (e.g. cylindrical or conical geometries), heat transfer mechanisms (e.g. pure convection or combined convection and radiation) or ground properties (e.g. uniform ground or specific ground layers) that can be tailored specifically to the wanted application and level of detail.
Known Model Limitations	Ground domain model is restricted to axisymmetric geometries Mass transfer in the ground (ground water) is not modeled
Additional Remarks	

5 Modelica MoSDH PTES model

GENERAL INFORMATION

Name and Version of the Model	MoSDH PTES model Version 1.1
Author	J. Formhals, X. Kirschstein
Creation Date	2020
Primary Usage	PTES model designed for dynamic system simulation studies (pre-design, operational optimization, storage design optimization)
Type of Model	Part of the Modelica Solar District Heating library
Software Language of Source Code	Modelica/ MSL Version 4.0.0
Required Software to Use the Model	Tested with Open Modelica 1.20, Dymola 2022, SimulationX 3.4
Operating System Requirements	-
Technical Documentation	http://mosdh.eu
Relevant Publications	Modelling, simulation and analysis of the integration of seasonal underground thermal energy storages into Campus Lichtwiese district heating grid (X. Kirschetin, 2020)
Verified with Measured Data?	No, model cross-validation study in preparation.
Model Availability	Open-Source
Contact Information	info@mosdh.eu

MODELING DETAILS

Geometry Options	Truncated cone
Top Surface Boundary	Average location ambient temperature or dynamic temperature from weather data. Constant lid/ground to air heat transfer coefficient.
Far-Field Boundary	Temperature fixed to undisturbed ground temperature.
Deep Earth Boundary	Temperature fixed to undisturbed ground temperature.

Water Domain Heat Transfer Calculation Method	1-D Nodal
Water Domain Boundary Heat Transfer Calculation Method	Dynamic calculation of heat transfer coefficients
Options for In- and Outlet Configuration	Top, mid and bottom inlet/outlet ports. The approximate height of the mid port can be defined by parameter and the closest tank layer is chosen accordingly.
Insulation Options	Wall and bottom insulation can be defined independently by thermal resistances. The lid is modeled by a thermal resistance and capacitance model consisting of a user defined number of layers with temperature dependent thermal conductivity. The width of the lid overlap on the dam top can be defined approximately.
Soil Domain Heat Transfer Calculation Method	2D Finite-Differences-Method for conductive heat transfer
Possibilities for Different Horizontal Ground Layers	No
Fluid and Soil Properties	(e.g. user input or fixed values, constant or temperature-dependent thermo-physical properties)
Consideration of Groundwater Flow	No
Other Model Features	Modeling of the dam (height and width)
Known Model Limitations	Dam has to be defined. High number of pit layers results in excessive ground mesh.
Additional Remarks	-

6 Modelica MoSDH TTES model

GENERAL INFORMATION

Name and Version of the Model	MoSDH TTES model Version 1.1
Author	J. Formhals, X. Kirschstein
Creation Date	2020
Primary Usage	TTES model designed for dynamic system simulation studies (pre-design, operational optimization)
Type of Model	Part of the Modelica Solar District Heating library
Software Language of Source Code	Modelica/ MSL Version 4.0.0
Required Software to Use the Model	Tested with Open Modelica 1.20, Dymola 2022, SimulationX 3.4
Operating System Requirements	-
Technical Documentation	http://mosdh.eu
Relevant Publications	Modelling, simulation and analysis of the integration of seasonal underground thermal energy storages into Campus Lichtwiese district heating grid (X. Kirschetin, 2020)
Verified with Measured Data?	No
Model Availability	Open-Source
Contact Information	info@mosdh.eu

MODELING DETAILS

Geometry Options	Stratified cylinder tank model
Top Surface Boundary	Average location ambient temperature or dynamic temperature from weather data. No heat transfer coefficient used
Far-Field Boundary	Average location ambient temperature or dynamic temperature from weather data. No heat transfer coefficient used
Deep Earth Boundary	Average location ground temperature and steady state thermal resistance for a round plate on an half-infinite medium

Water Domain Heat Transfer Calculation Method	1-D Nodal
Water Domain Boundary Heat Transfer Calculation Method	Dynamic calculation of heat transfer coefficients
Options for In- and Outlet Configuration	Top and bottom ports for source and load side. Additional ports can be modeled
Insulation Options	Thermal resistance for top, wall and bottom insulation respectively
Soil Domain Heat Transfer Calculation Method	Average location ground temperature and steady state thermal resistance for a round plate on a half-infinite medium
Possibilities for Different Horizontal Ground Layers	No
Fluid and Soil Properties	Constant thermophysical properties
Consideration of Groundwater Flow	No
Other Model Features	Choice of different buoyancy modelling approaches
Known Model Limitations	-
Additional Remarks	-

7 TRNSYS Type 342 XST

GENERAL INFORMATION

Name and Version of the Model	TRNSYS Type 342 MULTI-FLOWS STRATIFIED TEMPERATURE STORAGE MODEL WITH FULL-MIXED STORAGE LAYERS
Author	L.MAZZARELLA
Creation Date	2009
Primary Usage	System simulation
Type of Model	Trynsys
Software Language of Source Code	Fortran
Required Software to Use the Model	Trnsys
Operating System Requirements	Trnsys, Windows
Detailed Technical Documentation Available?	Yes
Validated to Measured Data?	Ongoing
Relevant Publications	-
Open-Source Model / Freely Available?	No
Contact for More Information	Jianhua Fan Department of Civil Engineering, Technical University of Denmark https://orbit.dtu.dk/en/persons/jianhua-fan/publications/

MODELING DETAILS

Geometry Options	2D, Cylindrical shape PTES
Top Surface Boundary	Circle lid

Far-Field Boundary	Adiabatic condition, constant temperature
Deep Earth Boundary	Adiabatic condition, constant temperature
Water Domain Heat Transfer Calculation Method	1 D Nodal
Soil Domain Heat Transfer Calculation Method	2D, conduction
Fluid and Soil Properties	User input possible
Insulation Options	Use specification
Groundwater Flow Allowed?	No
Other Model Features	
Known Model Limitations	Number of ports

8 TRNSYS Type 343 ICEPIT

GENERAL INFORMATION

Name and Version of the Model	Trnys type 343 ICEPIT
Author	Dr. Martin Hornberger
Creation Date	2009, modified in 2021
Primary Usage	System simulation
Type of Model	Trynsys
Software Language of Source Code	Fortran
Required Software to Use the Model	Trnsys
Operating System Requirements	Trnsys, Windows
Detailed Technical Documentation Available?	Yes
Validated to Measured Data?	Yes
Relevant Publications	Numerical investigations of long-term thermal performance of a large water pit heat storage Xie, Z., Xiang, Y., Wang, D., Kusyy, O., Kong, W., Furbo, S. & Fan, J., 2021, In: Solar Energy. 224, p. 808-822
Open-Source Model / Freely Available?	No
Contact for More Information	Jianhua Fan Department of Civil Engineering, Technical University of Denmark https://orbit.dtu.dk/en/persons/jianhua-fan/publications/

MODELING DETAILS

Geometry Options	2D, cone shape PTES
Top Surface Boundary	Circle lid

Far-Field Boundary	Adiabatic condition, constant temperature
Deep Earth Boundary	Adiabatic condition, constant temperature
Water Domain Heat Transfer Calculation Method	1 D Nodal
Soil Domain Heat Transfer Calculation Method	2D, conduction
Fluid and Soil Properties	User input possible
Insulation Options	Use specification
Groundwater Flow Allowed?	No
Other Model Features	
Known Model Limitations	Node number < 21

9 TRNSYS Type 1322

GENERAL INFORMATION

Name and Version of the Model	TRNSYS Type 1322, version 30
Author	Jeff Thornton
Creation Date	December 2014
Primary Usage	Detailed design of a PTES with pyramid stump geometry. Can be used for system simulations but it is very detailed and therefore slow to run
Type of Model	Part of TRNSYS
Software Language of Source Code	Source code in Fortran 90
Required Software to Use the Model	TRNSYS v17 or v18
Operating System Requirements	No specific requirements, should have enough space available if printing of soil layer outputs is decided (large output files) for a high number of timesteps.
Technical Documentation	
Relevant Publications	
Verified with Measured Data?	Calibrated against measured data from Dronninglund as a part of the HeatStore project (Danish contribution to deliverables 2.3 and 5.3) https://www.heatstore.eu/documents/HEATSTORE_WP2_D2.3-Danish%20PTES%20and%20BTES%20installations_Final_2020.11.02.pdf https://www.heatstore.eu/documents/HEATSTORE_WP5_D5.3_Final_2021.10.31.pdf
Model Availability	Model not commercially available, developed specifically for a client's needs
Contact Information	Jeff Thornton, thornton@tess-inc.com or TechSupport@tess-inc.com

MODELING DETAILS

Geometry Options	Truncated pyramid geometry only
Top Surface Boundary	Constant emissivity/absorptance of the cover, the cover extension and the soil exposed to the ambient. 3 possible modes:

	1 = Surface temperature calculated using an energy balance on the surface 2 = Surface temperature set from long-term average conditions (varies with time) 3 = User-provided surface temperature
Far-Field Boundary	Conductive boundary condition
Deep Earth Boundary	Conductive boundary condition
Water Domain Heat Transfer Calculation Method	1D-nodal
Water Domain Boundary Heat Transfer Calculation Method	Conduction between the water segments based on physical properties of the fluid in the storage
Options for In- and Outlet Configuration	Maximum of 5 ports, each port has a fixed pair of inlet and outlet, which are attributed to a given water node/segment (at the height of that segment, not a specified height
Insulation Options	Constant thermal resistance, insulation extension option
Soil Domain Heat Transfer Calculation Method	3D Finite Difference
Possibilities for Different Horizontal Ground Layers	Maximum of 25 ground layers with different physical properties
Fluid and Soil Properties	Constant/fixed values
Consideration of Groundwater Flow	Not possible
Other Model Features	Storage can be buried under a soil layer
Known Model Limitations	The top insulation isn't a physical layer, the calculation time is very long, the soil output files are large, the number of ports is limited
Additional Remarks	

10 TRNSYS Type 1535+1301

GENERAL INFORMATION

Name and Version of the Model	TESS Types 1301 (Inverted Truncated Conical Tank Soil Wrapper) and 1535 (Inverted Truncated Conical Tank) for TRNSYS
Author	Jeff W Thornton
Creation Date	2014
Primary Usage	These models are intended to be used as component in a dynamic system simulation package
Type of Model	Intended for use in the TRNSYS simulation software package
Software Language of Source Code	Fortran
Required Software to Use the Model	TRNSYS v18
Operating System Requirements	Microsoft Windows
Technical Documentation	Available as part of the TESS Storage Tank Library documentation (Type 1535) and the TESS Ground Coupling Library documentation (Type 1301)
Relevant Publications	N/A
Verified with Measured Data?	By others, not directly by TESS
Model Availability	Part of the TESS Libraries for TRNSYS (commercial product)
Contact Information	Jeff Thornton c/o TESS LLC 3 N. Pinckney Street – Suite 202, Madison WI USA (608) 274-2577 thornton@tess-inc.com www.trnsys.com

MODELING DETAILS

Geometry Options	There are soil wrapper models for inverted cones, inverted pyramids, vertical cylindrical tanks, and cuboid tanks. There are TTES models for the same configurations plus horizontal cylinders, and spherical tanks.
Top Surface Boundary	There are three options for the top surfaces; User-provided input temperature, Sinusoidal temperature profile (function of time of year) using user provided

	parameters, or a full energy balance on the soil surface. Additionally, the surface mode may be different for the top of the tank, the insulated soil above/around the tank, and the uninsulated soil surface.
Far-Field Boundary	Conductive boundary to far-field boundary temperature which is set by the depth, time of year, and soil properties. An adiabatic boundary may also be set if so desired.
Deep Earth Boundary	Conductive boundary to deep-earth boundary temperature which is set by the depth, time of year, and soil properties. An adiabatic boundary may also be set if so desired.
Water Domain Heat Transfer Calculation Method	1-D energy balance nodal solution with constant volume nodes. Conduction between nodes is considered. Adiabatic mixing is induced upon temperature inversions.
Water Domain Boundary Heat Transfer Calculation Method	The TES wall and internal convection resistance are treated as a single, user-defined value, but this value is an input and can therefore change throughout the simulation.
Options for In- and Outlet Configuration	Almost unlimited number of paired inlet and outlet ports allowed. Users can set the port locations, have them calculated each timestep to maximize stratification, or choose a location and specify a jetting factor to avoid all of the inlet water mixing with a node before moving into the next node. The model also allows for multiple heat exchangers in the storage including coiled tube, serpentine and both vertical and horizontal tube banks.
Insulation Options	Insulation is represented simply as a resistance and can be applied to any part of the tank surface (including different values along the wall). The top of the tank may also be exposed or buried under the soil surface and the user can specify the insulation on top of the soil above the tank, on top of the tank, and also any insulation extending radially from the tank.
Soil Domain Heat Transfer Calculation Method	2-D (radial and vertical) finite difference nodal energy balance calculations for each node in the soil.
Possibilities for Different Horizontal Ground Layers	The version used for this study assumes only one soil type for the calculations, but other internal-use TESS models have been developed that allow for multiple soil layers.
Fluid and Soil Properties	User-provided, constant values for the soil and fluid properties
Consideration of Groundwater Flow	Planned but not currently implemented
Other Model Features	

Known Model Limitations	1-D water domain, buoyancy induced flows are modeled as a simple mixing to eliminate temperature inversions. Natural groundwater flow is not considered. Evapotranspiration is not considered in the soil surface energy balance.
Additional Remarks	

11 TRNSYS Type 1534+1302

GENERAL INFORMATION

Name and Version of the Model	TESS Types 1302 (Vertical Cylindrical Tank Soil Wrapper) and 1534 (Vertical Cylindrical Storage Tank) for TRNSYS
Author	Jeff W Thornton
Creation Date	2010
Primary Usage	These models are intended to be used as component in a dynamic system simulation package
Type of Model	Intended for use in the TRNSYS simulation software package
Software Language of Source Code	Fortran
Required Software to Use the Model	TRNSYS v18
Operating System Requirements	Microsoft Windows
Technical Documentation	Available as part of the TESS Storage Tank Library documentation (Type 1534) and the TESS Ground Coupling Library documentation (Type 1302)
Relevant Publications	N/A
Verified with Measured Data?	The tank model has been tuned/calibrated many times but not to my knowledge with the soil wrapper attached.
Model Availability	Part of the TESS Libraries for TRNSYS (commercial product)
Contact Information	Jeff Thornton c/o TESS LLC 3 N. Pinckney Street – Suite 202, Madison WI USA (608) 274-2577 thornton@tess-inc.com www.trnsys.com

MODELING DETAILS

Geometry Options	There are soil wrapper models for inverted cones, inverted pyramids, vertical cylindrical tanks, and cuboid tanks. There are TTES models for the same configurations plus horizontal cylinders, and spherical tanks.
Top Surface Boundary	There are three options for the top surfaces; User-provided input temperature, Sinusoidal temperature profile (function of time of year) using user provided

	parameters, or a full energy balance on the soil surface. Additionally, the surface mode may be different for the top of the tank, the insulated soil above/around the tank, and the uninsulated soil surface.
Far-Field Boundary	Conductive boundary to far-field boundary temperature which is set by the depth, time of year, and soil properties. An adiabatic boundary may also be set if so desired.
Deep Earth Boundary	Conductive boundary to deep-earth boundary temperature which is set by the depth, time of year, and soil properties. An adiabatic boundary may also be set if so desired.
Water Domain Heat Transfer Calculation Method	1-D energy balance nodal solution with constant volume nodes. Conduction between nodes is considered. Adiabatic mixing is induced upon temperature inversions.
Water Domain Boundary Heat Transfer Calculation Method	The TES wall and internal convection resistance are treated as a single, user-defined value, but this value is an input and can therefore change throughout the simulation.
Options for In- and Outlet Configuration	Almost unlimited number of paired inlet and outlet ports allowed. Users can set the port locations, have them calculated each timestep to maximize stratification, or choose a location and specify a jetting factor to avoid all of the inlet water mixing with a node before moving into the next node. The model also allows for multiple heat exchangers in the storage including coiled tube, serpentine and both vertical and horizontal tube banks.
Insulation Options	Insulation is represented simply as a resistance and can be applied to any part of the tank surface (including different values along the wall). The top of the tank may also be exposed or buried under the soil surface and the user can specify the insulation on top of the soil above the tank, on top of the tank, and also any insulation extending radially from the tank.
Soil Domain Heat Transfer Calculation Method	2-D (radial and vertical) finite difference nodal energy balance calculations for each node in the soil.
Possibilities for Different Horizontal Ground Layers	The version used for this study assumes only one soil type for the calculations, but other internal-use TESS models have been developed that allow for multiple soil layers.
Fluid and Soil Properties	User-provided, constant values for the soil and fluid properties
Consideration of Groundwater Flow	Planned but not currently implemented
Other Model Features	

Known Model Limitations	1-D water domain, buoyancy induced flows are modeled as a simple mixing to eliminate temperature inversions. Natural groundwater flow is not considered. Evapotranspiration is not considered in the soil surface energy balance.
Additional Remarks	

12 TRNSYS Type 1534+1401

GENERAL INFORMATION

Name and Version of the Model	TESS Types 1401 (Vertical Cylindrical Tank on Grade Soil Model) and 1534 (Vertical Cylindrical Storage Tank) for TRNSYS
Author	Jeff W Thornton
Creation Date	2010
Primary Usage	These models are intended to be used as component in a dynamic system simulation package.
Type of Model	Intended for use in the TRNSYS simulation software package
Software Language of Source Code	Fortran
Required Software to Use the Model	TRNSYS v18
Operating System Requirements	Microsoft Windows
Technical Documentation	Available as part of the TESS Storage Tank Library documentation (Type 1534) and the TESS Ground Coupling Library documentation (Type 1401)
Relevant Publications	N/A
Verified with Measured Data?	The tank model has been tuned/calibrated many times but not to the author's knowledge with the soil wrapper attached.
Model Availability	Part of the TESS Libraries for TRNSYS (commercial product)
Contact Information	Jeff Thornton c/o TESS LLC 3 N. Pinckney Street – Suite 202, Madison WI USA (608) 274-2577 thornton@tess-inc.com www.trnsys.com

MODELING DETAILS

Geometry Options	There are soil wrapper models for inverted cones, inverted pyramids, vertical cylindrical tanks, and cuboid tanks. There are TTES models for the same configurations plus horizontal cylinders, and spherical tanks.
Top Surface Boundary	There are three options for the topsoil surface; User-provided input temperature, Sinusoidal temperature profile (function of time of year) using user provided parameters, or a full energy balance on the soil surface. Additionally, the

	surface mode may be different for the insulated soil around the tank, and the uninsulated soil surface.
Far-Field Boundary	Conductive boundary to far-field boundary temperature which is set by the depth, time of year, and soil properties. An adiabatic boundary may also be set if so desired.
Deep Earth Boundary	Conductive boundary to deep-earth boundary temperature which is set by the depth, time of year, and soil properties. An adiabatic boundary may also be set if so desired.
Water Domain Heat Transfer Calculation Method	1-D energy balance nodal solution with constant volume nodes. Conduction between nodes is considered. Adiabatic mixing is induced upon temperature inversions.
Water Domain Boundary Heat Transfer Calculation Method	The TES wall and internal convection resistance are treated as a single, user-defined value, but this value is an input and can therefore change throughout the simulation.
Options for In- and Outlet Configuration	Almost unlimited number of paired inlet and outlet ports allowed. Users can set the port locations, have them calculated each timestep to maximize stratification, or choose a location and specify a jetting factor to avoid all of the inlet water mixing with a node before moving into the next node. The model also allows for multiple heat exchangers in the storage including coiled tube, serpentine and both vertical and horizontal tube banks.
Insulation Options	Insulation is represented simply as a resistance and can be applied to any part of the tank surface (including different values along the wall). The user can also specify the insulation on top of the soil surrounding the tank and extending radially from the tank.
Soil Domain Heat Transfer Calculation Method	2-D (radial and vertical) finite difference nodal energy balance calculations for each node in the soil.
Possibilities for Different Horizontal Ground Layers	The version used for this study assumes only one soil type for the calculations, but other internal-use TESS models have been developed that allow for multiple soil layers.
Fluid and Soil Properties	User-provided, constant values for the soil and fluid properties
Consideration of Groundwater Flow	Planned but not currently implemented
Other Model Features	

Known Model Limitations	1-D water domain, buoyancy induced flows are modeled as a simple mixing to eliminate temperature inversions. Natural groundwater flow is not considered. Evapotranspiration is not considered in the soil surface energy balance.
Additional Remarks	

13 TRNSYS Type UGSTS

GENERAL INFORMATION

Name and Version of the Model	Trnys type UGSTS Under Ground Solar Thermal Storage model
Author	Yakai Bai, CAS IEE
Creation Date	2018
Primary Usage	System simulation
Type of Model	Trnsys
Software Language of Source Code	C
Required Software to Use the Model	Trnsys
Operating System Requirements	Trnsys, Windows
Detailed Technical Documentation Available?	No
Validated to Measured Data?	Yes
Relevant Publications	Influence of geometry on the thermal performance of water pit seasonal heat storages for solar district heating Bai, Y., Yang, M., Fan, J., Li, X., Chen, L., Yuan, G. & Wang, Z., 2020, In: Building Simulation. 21 p. Numerical and experimental study of an underground water pit for seasonal heat storage Bai, Y., Wang, Z., Fan, J., Yang, M., Li, X., Chen, L., Yuan, G. & Yang, J., 2020, In: Renewable Energy. 150, p. 487-508
Model / Freely Available?	No
Contact for More Information	Jianhua Fan Department of Civil Engineering, Technical University of Denmark https://orbit.dtu.dk/en/persons/jianhua-fan/publications/

MODELING DETAILS

Geometry Options	2D, Cylindrical shape PTES
Top Surface Boundary	Circle lid
Far-Field Boundary	Adiabatic condition, constant temperature
Deep Earth Boundary	Adiabatic condition, constant temperature
Water Domain Heat Transfer Calculation Method	1 D Nodal
Soil Domain Heat Transfer Calculation Method	2D, conduction
Fluid and Soil Properties	User input possible
Insulation Options	Use specification
Groundwater Flow Allowed?	No
Other Model Features	
Known Model Limitations	

FACT SHEETS ON ATES MODELS

1 HstWin-3D

GENERAL INFORMATION

Name and Version of the Model	HstWin-3D
Author	S. van der Wilk
Creation Date	7-4-2023
Primary Usage	HST3D simulates groundwater flow and associated heat and solute transport in three dimensions.
Type of Model	Stand Alone
Software Language of Source Code	Fortran 90
Required Software to Use the Model	No specific required software as it can be run as an executable
Operating System Requirements	Windows
Technical Documentation	https://wwwbrr.cr.usgs.gov/projects/GW_Solute/hst/
Relevant Publications	• Garvin, G. and Person, M., 1989, Three-dimensional models of groundwater flow, heat transfer, and mass transport within the Rhine graben, Final report to Bundesanstalt fur Geowissenschaften und Rohstoffe, P.O. Box 51 01 53, D-3000 Hannover, Germany, 39p. • Knochenmus, L.A. and Thompson, T.H., 1991, Hydrogeology and simulated development of the brackish ground-water resources in Pinellas County, Florida: U.S. Geological Survey Water-Resources Investigations Report 91-4026, 78p. • Brantley, S.L., Rowe, G.L., Konikow, L.F., and Sanford, W.E., 1992, Natural toxic waters of Poas Volcano, Coasta Rica, National Geographic Research & Exploration, v.8, n.3, p.328-337. • Hutchinson, C.B., 1992, Assessment of hydrogeologic conditions with emphasis on water quality and wastewater injection, Southwest Sarasota and West Charlotte Counties, Florida: U.S. Geological Survey Water-Supply Paper 2371, 74p. • Ghassemi, A.J., Jakeman, A.J., Jacobson, G., and Howard, K.W.F., 1996, Simulation of seawater intrusion with 2D and 3D models: Nauru Island case study, Hydrogeology Journal, v.4, n.3, p.4-22.

	• Jiao, J.J., Zheng, C., and Hennet, R.J.C., 1997, Analysis of underpressured reservoirs for waste disposal, Hydrogeology Journal, v.5, n.3,p.19-31. • Mason, J.L. and Kipp, K.L., Jr., 1997, Hydrology of the Bonneville Salt Flats, northwestern Utah, and the simulation of ground-water flow and solute transport in the shallow-brine aquifer: U.S. Geological Survey Professional Paper 1585, 108 p. • Bravo, H.R., Jiang, F., and Hunt, R.J., 2002, Using groundwater temperature data to constrain parameter estimation in a groundwater flow model of a wetland system, Water Resources Research, v.38, n.8, p.28-1,28-14.
Verified with Measured Data?	Yes
Model Availability	Commercial. Free trial version available through usgs
Contact for More Information	Nick Buik. N.buik@iftechnology.nl

MODELING DETAILS

Well Configuration Options	Two ATES wells and 45 observation wells
Top Surface Boundary	Specified Value Boundary Conditions on all boundaries for temperature, pressure and concentration (salinity/pollution). Model domain boundaries do not influence simulation results.
Far-Field Boundary	Specified Value Boundary Conditions on all boundaries for temperature, pressure and salinity. Model domain boundaries do not influence simulation results.
Deep Earth Boundary	Specified Value Boundary Conditions on all boundaries for temperature, pressure and salinity. Model domain boundaries do not influence simulation results.
Aquifer Layer Heat Transfer Calculation Method	3D conduction, advection, convection
Caprock and Bedrock Heat Transfer Calculation Method	3D conduction, advection, convection
Possibilities for Different Horizontal Ground Layers	Different horizontal ground layers defined and zones and can be given different depth, thickness, hydraulic conductivity (xyz), porosity, storage, heat capacity and thermal conductivity. Within a layer, parameters can differ horizontally allowing for heterogeneity

Fluid and Soil Properties	Fluid properties (density and viscosity) are dependent of pressure, temperature and salinity. Soil properties are fixed values
Consideration of Groundwater Flow	One groundwater flow direction and velocity can be determined. The direction will apply to all horizontal layers. The groundwater flow is determined by the hydraulic conductivity of the layer.
Other Model Features	Besides an ATES system HST3D can also be used for an open loop system or groundwater extraction.
Known Model Limitations	Thickness of layers cannot deviate within the model
Additional Remarks	

2 TRNSYS Type 345 TRNAST

GENERAL INFORMATION

Name and Version of the Model	TRNSYS Type 345 – TRNAST, V 1.21
Author	TRNSYS model TRNAST developed by Thomas Schmidt (Solites), based on AST model from Göran Hellström, Johan Bennet, and Johan Claesson (Lund University)
Creation Date	14.11.2014
Primary Usage	TRNAST is a two-well ATES model and is intended for system level simulations in pre-design and detailed design phases.
Type of Model	ATES model intended for use with TRNSYS simulation software
Software Language of Source Code	Fortran
Required Software to Use the Model	TRNSYS v16, v17 or v18 (32 bit)
Operating System Requirements	Microsoft Windows
Technical Documentation	Schmidt, T. (2005): Aquifer Thermal Energy Storage – TRNAST – two well model for TRNSYS, Manual, Solites - Steinbeis Research Institute for Solar and Sustainable Thermal energy Systems, Stuttgart, Germany Hellström G., Bennet J. and Claesson J. (1986): Aquifer Thermal Energy Storage – Single well model – Manual for Computer Code, University of Lund, Department of Mathematical Physics, Lund, Sweden
Relevant Publications	Kranz, S., Bartels, J. (2009): Simulation and data based identification of parameters affecting seasonal ATES efficiency, 11th International Conference on Thermal Energy Storage - Effstock 2009 (Stockholm, Sweden 2009).
Verified with Measured Data?	Verified with measured data from ATES in Rostock (DE) in 2002 (see Mangold D., Riegger M., Schmidt T. (2007): Solare Nahwärme und Langzeit-Wärmespeicher, Final report to BMU project 0329607L, Solites Solites - Steinbeis Research Institute for Solar and Sustainable Thermal energy Systems, Stuttgart, Germany)
Model Availability	Available from Solites - Steinbeis Research Institute for Solar and Sustainable Thermal energy Systems, Stuttgart, Germany, info@solites.de, www.solites.de
Contact for More Information	Thomas Schmidt (schmidt@solites.de) Solites - Steinbeis Research Institute for Solar and Sustainable Thermal energy Systems, Meitnerstr. 8, 70563 Stuttgart, Germany, info@solites.de

MODELING DETAILS

Well Configuration Options	Two individual wells, no interaction between wells
Top Surface Boundary	Variable ambient temperature is a model input
Far-Field Boundary	Adiabatic boundary condition
Deep Earth Boundary	Adiabatic boundary condition
Aquifer Layer Heat Transfer Calculation Method	2-D radial symmetric, 2-D conduction and radial convection
Caprock and Bedrock Heat Transfer Calculation Method	2-D radial symmetric, 2-D conduction
Possibilities for Different Horizontal Ground Layers	Multiple layers can be defined
Fluid and Soil Properties	Fluid and soil properties can be defined by the user, constant properties are assumed
Consideration of Groundwater Flow	No natural groundwater flow is considered
Other Model Features	Numerical dispersion is avoided with entropy-conservation method
Known Model Limitations	Only two well configuration is possible, interaction between wells is neglected, buoyancy flow in aquifer layer is neglected, no natural groundwater flow is considered
Additional Remarks	Because of the 2-D approach the model is very fast and therefore well suited for multi-year simulation periods and parameter studies

3 TRNSYS Type 1380

GENERAL INFORMATION

Name and Version of the Model	TESS Type 1380 for TRNSYS
Author	Jeff W Thornton
Creation Date	June 2020
Primary Usage	This model is intended to be used as a component in a system simulation package.
Type of Model	Intended for use in the TRNSYS simulation software package
Software Language of Source Code	Fortran
Required Software to Use the Model	TRNSYS v18
Operating System Requirements	Microsoft Windows
Technical Documentation	In Progress
Relevant Publications	N/A
Verified with Measured Data?	
Model Availability	Part of the TESS Libraries for TRNSYS and sold as an individual component model
Contact for More Information	Jeff Thornton c/o TESS LLC 3 N. Pinckney Street – Suite 202, Madison WI USA (608) 274-2577 thornton@tess-inc.com www.trnsys.com

MODELING DETAILS

Well Configuration Options	Individual well. Multiple instances may be used but the models/wells have no interaction
Top Surface Boundary	Surface temperature parameters are used to impose a sinusoidal temperature profile on the soil surface as a function of time

Far-Field Boundary	Conductive boundary to far-field boundary temperature which is set by the depth, time of year, and soil properties
Deep Earth Boundary	Conductive boundary to deep-earth boundary temperature which is set by the depth, time of year, and soil properties
Aquifer Layer Heat Transfer Calculation Method	2-D (radial and vertical) finite difference nodal energy balance calculations where the water in each node of the aquifer layer and the soil in each node of the aquifer layer are solved independently - but are tightly coupled.
Caprock and Bedrock Heat Transfer Calculation Method	2-D (radial and vertical) finite difference nodal energy balance calculations for each node in the soil
Possibilities for Different Horizontal Ground Layers	Multiple layers may be defined including multiple aquifer layers
Fluid and Soil Properties	The fluid and soil properties are assumed to be constants and are set by the user as parameters to the model
Consideration of Groundwater Flow	Not currently considered in the 2-D radial geometry solution. Future 3-D models will likely have this feature
Other Model Features	Allows for different vertical and horizontal thermal conductivities for each layer
Known Model Limitations	Buoyancy induced flow is not currently considered. Natural groundwater flow is not considered. Multi-well interactions are not modeled
Additional Remarks	The 2-D geometry makes this model quite fast to simulate – even with highly noded soil patterns

FACT SHEETS ON BTES MODELS

1 Modelica MoSDH BTES model

GENERAL INFORMATION

Name and Version of the Model	MoSDH BTES v1.1
Author	J. Formhals
Creation Date	2019
Primary Usage	Borehole model for storage and heat extraction applications. Designed for dynamic system simulation studies (pre-design, operational optimization, storage design optimization)
Type of Model	Part of the Modelica Solar District Heating library
Software Language of Source Code	Modelica/ MSL Version 4.0.0
Required Software to Use the Model	Tested with Open Modelica 1.20, Dymola 2022, SimulationX 3.4
Operating System Requirements	
Technical Documentation	http://mosdh.eu
Relevant Publications	A Modelica Toolbox for the Simulation of Borehole Thermal Energy Storage Systems (Formhals et al., 2020) – link here Strategies for a transition towards a solar district heating grid with integrated seasonal geothermal energy storage (Formhals et al., 2021) – link here Object-oriented modelling of solar district heating grids with underground thermal energy storage (Formhals, 2022) – link here
Verified with Measured Data?	Verified with monitoring data from the Brædstrup BTES system
Model Availability	Open-Source
Contact for More Information	info@mosdh.eu

MODELING DETAILS

In-Bore Geometry Options	Single-U, Double-U and Coaxial (TRM & TRCM); Borehole can be subdivided in an upper and lower part for the use of different grouting materials

Top Surface Boundary	Average location ambient temperature or dynamic temperature from weather data. No heat transfer coefficient used
Far-Field Boundary	Temperature fixed to undisturbed ground temperature (average ground surface temperature & geothermal gradient)
Deep Earth Boundary	Temperature fixed to undisturbed ground temperature (average ground surface temperature & geothermal gradient)
In-Bore Solution Method	Thermal resistance and capacitance model with thermal capacities of the fluid and grout sections (TRCM) or fluid only (TRM)
Soil Heat Transfer Calculation Method	2D Finite-Differences-Method for conductive heat transfer
Radial Zoning and Hydraulic Connection Options	Radial zoning is either implicitly defined by the size of the BHE array (parallel BHE connection) or by the number of serially connected BHEs. By default, hydraulic connection of the BHEs is constant during simulation, but it can be easily adapted to change during runtime (cf. Formhals et al. 2021).
Possibilities for Different Horizontal Ground Layers	Up to 5 horizontal layers can be defined
Fluid and Soil Properties	Constant thermophysical properties
Grouting Material Properties	Constant thermophysical properties
Consideration of Horizontal Piping	No
Insulation Options	No explicit insulation options. However, the BHE head depth can be adapted to be below the first horizontal ground layer, which can be parametrized as an insulation layer
Consideration of Groundwater Flow	No
Other Model Features	Pressure drop calculation; Reversal of flow direction
Known Model Limitations	No groundwater flow; (Approximately) symmetrical BHE array layouts
Additional Remarks	

2 TRNSYS Type 557 DST

GENERAL INFORMATION

Name of Model	TRNSYS Type 557 (DST)
Author	Goran Hellstrom and Daniel Pahud
Primary Usage	Modeling/simulation of vertical u-tube ground heat exchanger fields.
Creation Date	1977
Type of Model: (Stand Alone or Part of Larger Simulation Tool)	A component in the TRNSYS simulation software package.
Required Software to Use the Model	TRNSYS v17 or later
Operating System Requirements	Microsoft Windows primarily but can be compiled into other platforms.
Detailed Technical Documentation Available?	Yes. A detailed technical manual from the original source code is available
Validated to Measured Data?	Yes, on multiple projects by TESS LLC.
Relevant Publications	Several papers using the DST model are listed and presented here: Publications - TESS: Thermal Energy System Specialists (tess-inc.com)
Open-Source Model / Freely Available?	No – this is a commercial product
Contact Person for More Information	TESS LLC (techsupport@tess-inc.com)

MODELING DETAILS

In-Bore Geometry Options	Single U-Tube, Multiple U-Tube, Tube-in-Tube
Top Surface Boundary	User provides the air temperature above the storage volume and above the surrounding soil
Far-Field Boundary	Conductive boundary calculated from meshing properties and length of analysis

Deep Earth Boundary	Conductive boundary calculated from meshing properties and length of analysis
In-Bore Solution Method	Borehole thermal resistance calculations (Hellström)
Soil Heat Transfer Calculation Method	2-D radial conduction in the storage volume and the soil solution. Internal meshing defined for finite-difference scheme
Radial Stratification of the Storage	Yes, but only when the boreholes are connected in series
Fluid and Soil Properties	Constant / Constant but multiple soil layers can be defined in both the storage volume and the surrounding soil
Mass of Fluid Considered?	No
Horizontal Piping Considered?	Horizontal pipes can be defined leading to/from the BTES in separate TRNSYS models but horizontal runs between bores are not considered
Insulation Options?	Surface insulation with a user-defined extension beyond the edge of the storage region. Vertical insulation at a user-defined depth at the edge of the storage region
Groundwater Flow Allowed?	No
Other Model Features	Allows the user to reverse the flow (center → edge or edge → center) during the simulation
Known Model Limitations	Model is designed for boreholes clustered in a cylindrical. It is not recommended for highly linear borehole placements. Angled boreholes and non-uniform placement of boreholes are not considered. Fluid mass and thermal mass within the borehole are not considered

3 TRNSYS Type 1373

GENERAL INFORMATION

Name of Model	TESS Type 1373
Author	Jeff W. Thornton (TESS LLC)
Primary Usage	Modeling/simulation of vertical u-tube ground heat exchanger fields
Creation Date	2020
Type of Model: (Stand Alone or Part of Larger Simulation Tool)	A component in the TRNSYS simulation software package
Required Software to Use the Model	TRNSYS v18 or later
Operating System Requirements	Microsoft Windows primarily but can be compiled into other platforms
Detailed Technical Documentation Available?	In progress. Target completion of 1/1/2022
Validated to Measured Data?	Limited validation as the model has just been introduced
Relevant Publications	None yet
Open-Source Model / Freely Available?	No, this is a commercial product
Contact Person for More Information	Jeff Thornton (techsupport@tess-inc.com)

MODELING DETAILS

In-Bore Geometry Options	Single U-Tube
Top Surface Boundary	User-Defined Surface Temperature (Energy Balance, Kasuda, Fixed, etc.)
Far-Field Boundary	Conductive Boundary at User-Defined Distance
Deep Earth Boundary	Conductive Boundary at User-Defined Distance

In-Bore Solution Method	Borehole thermal resistance calculations (Hellström)
Soil Heat Transfer Calculation Method	2-D radial conduction in both the near-bore solution and the soil solution. User-defined meshing parameters for finite-difference scheme
Radial Stratification of the Storage	Yes – the user can set up multiple radial regions within the storage volume regardless of flow patterns
Fluid and Soil Properties	Constant / Constant
Mass of Fluid Considered?	Yes
Horizontal Piping Considered?	Horizontal pipes can be defined leading to/from the BTES in separate TRNSYS models. Additional component pipe models could be added between radial regions in the storage volume, but this would slow the simulation down
Insulation Options?	Surface insulation with a user-defined extension beyond the edge of the storage region
Groundwater Flow Allowed?	Not yet but planned
Other Model Features	Allows the user to set up multiple flow patterns through the storage (center→edge, edge→center, plus other arbitrary patterns) and then switch between these patterns during the simulation.
Known Model Limitations	Model is intended for boreholes clustered in a cylindrical pattern but makes adjustments for non-cylindrical patterns. Not recommended for highly linear borehole placements without careful set up of borehole geometry. Angled boreholes and non-uniform placement of boreholes not considered