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(ES TCP)

Task 39 - Large Thermal Energy Storages for District Heating

Subtask C: Round Robin Simulations

Deliverable C2a: Modelling guidelines - Round robin test case description (for comparative simulations)

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	Contributor
Fabian Ochs	UIBK, AT	Contributor
Geoffroy Gauthier	PlanEnergi, DK	Contributor
Ioannis Sifnaios	DTU, DK	Contributor
Jeff Thornton	TESS, US	Contributor
Julian Formhals	Vattenfall Berlin, DE	Contributor
Michael Reisenbichler-Sommerhofer	AEE Intec, AT	Contributor
Peter Oerlemans	If Technology, NL	Contributor

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CONTENT

NOMENCLATURE

SYMBOLS

Parameter	Unit	Description
c_p	J/(kgK)	Specific heat capacity
C	J/(m³K)	Volumetric heat capacity
λ	W/(mK)	Thermal conductivity
ρ	kg/m³	Density
µ	(Ns)/m²	Dynamic Viscosity
β	1/K	Volumetric thermal expansion coefficient
φ	%	Porosity
k_F	m/s	Hydraulic conductivity
H	m	Height
D	m	Diameter
d	m	Diameter
s	m	Thickness
R_T	m	Thermal radius
R_b	(mK)/W	Borehole thermal resistance
h	W(m²K)	Heat transfer coefficient
V	m³	Volume
U	W/(m²K)	Heat transfer coefficient
T	°C	Temperature
$\dot{V}_{\text{TES}}$	m³/h	Flow rate

INDICES

Index	Description
a	Aquifer
I	Insulation
s	Soil
th	Thermal
w	Water
eff	Effective
inj	Injected
avg	Average

ABBREVIATIONS

Abbreviation	Description
ATES	Aquifer thermal energy storage
BTES	Borehole thermal energy storage
LTES	Large thermal energy storage
PTES	Pit thermal energy storage
TES	Thermal energy storage
TTES	Tank thermal energy storage
BHE	Borehole heat exchanger
AG	Above-ground
UG	Underground
C	Truncated cylindrical geometry
P	Truncated pyramidal geometry
CH	Charging
DC	Discharging
DH	District Heating
M	Month
No.	Number

INTRODUCTION

For the design, planning and integration of large-scale thermal energy storage (LTES) systems, a number of LTES models have been developed within various numerical simulation tools, both recently and in the past. Some of the models allow the users to comprehend the component simulation (LTES, cover, insulation and others) next to the investigation of the interaction between the LTES and the surrounding ground and potentially flowing groundwater. Other models allow to investigate the LTES and surroundings together with the DH system. The latter models might be, however, incapable of investigating groundwater impact on LTES. Other advanced tools enable users to dynamically investigate the operation of DH systems with a great potential in optimizing such systems – including LTES. Simulation models in e.g. Modelica/Dymola and TRNSYS are ideally suited for investigations on LTES integration in DH systems.

In IEA-ES Task 39 Subtask C, the quality of results and the usability of various LTES simulation models were investigated. A verification of numerical models in general can be done in different ways. Commonly used approaches include e.g. a comparison of results with analytical solutions or with measurement data, or a cross-validation between different numerical models. Because of the high complexity in the present case, it is difficult to find reasonable test cases for which analytical solutions are available. Also, high-quality measurement data is hard to find as realized projects are large-scale operative projects and associated monitoring systems are rather designed for operational purposes than scientific investigations. Completeness and quality of measurement data can therefore not satisfy scientific requirements in many cases. For these reasons, this subtask uses a cross-validation approach to compare simulation results of various simulation models for a set of representative and precisely specified test cases. The focus of the work is on accuracy, applicability and usefulness of the models.

The comparative simulations are foreseen in a two- stage approach. In a first stage (‘stage 1’), a set of representative, but basic, test cases with simplified operation profiles was defined and applied by the participating partners. With these basic test cases, a baseline for the following, more detailed investigations in the second stage (‘stage 2’) was created. Stage 2 comprises more application-related operation profiles and sensitivity analyses for the most important design parameters of the LTES. The stage 1 investigations were done within IEA ES Task 39, stage 2 investigations will be done in IEA ES Task 45 starting in 2024.

This report documents the complete set of specifications for the stage 1 test cases that allows other users and model developers to verify their models with results from this work. The results derived in the frameworks of IEA ES Task 39 are provided in deliverables C3a (*IEA-ES Task 39 WPC, Deliverable C3a: Results of stage 1 round robin test case simulations - Analysis*) and C3b (various files with the same nomenclature:
IEA-ES_Task39_WPC_Deliverable_C3b_Stage1_Result_file _source_tool_user_testcase_date.xlsx).

TEST CASES

In this section, the LTES configurations and operational profiles are defined for a set of test cases. Six test cases are defined for the following storage concepts, see also Figure 1:

- Aquifer Thermal Energy Storage (ATES)
- Borehole Thermal Energy Storage (BTES)
- Pit Thermal Energy Storage (PTES) – conical and pyramidal geometries
- Tank Thermal Energy Storage (TTES) – above-ground and underground

To achieve comparable results in a comparative simulation with different simulation models, it is important to specify each test case as detailed as possible and to adhere to these specifications as closely as possible when applying the test case. However, if any of the specifications cannot be considered as described in a particular simulation model, the user should approximate it as closely as possible. Necessary adjustments in the configurations should be indicated in the corresponding result files.

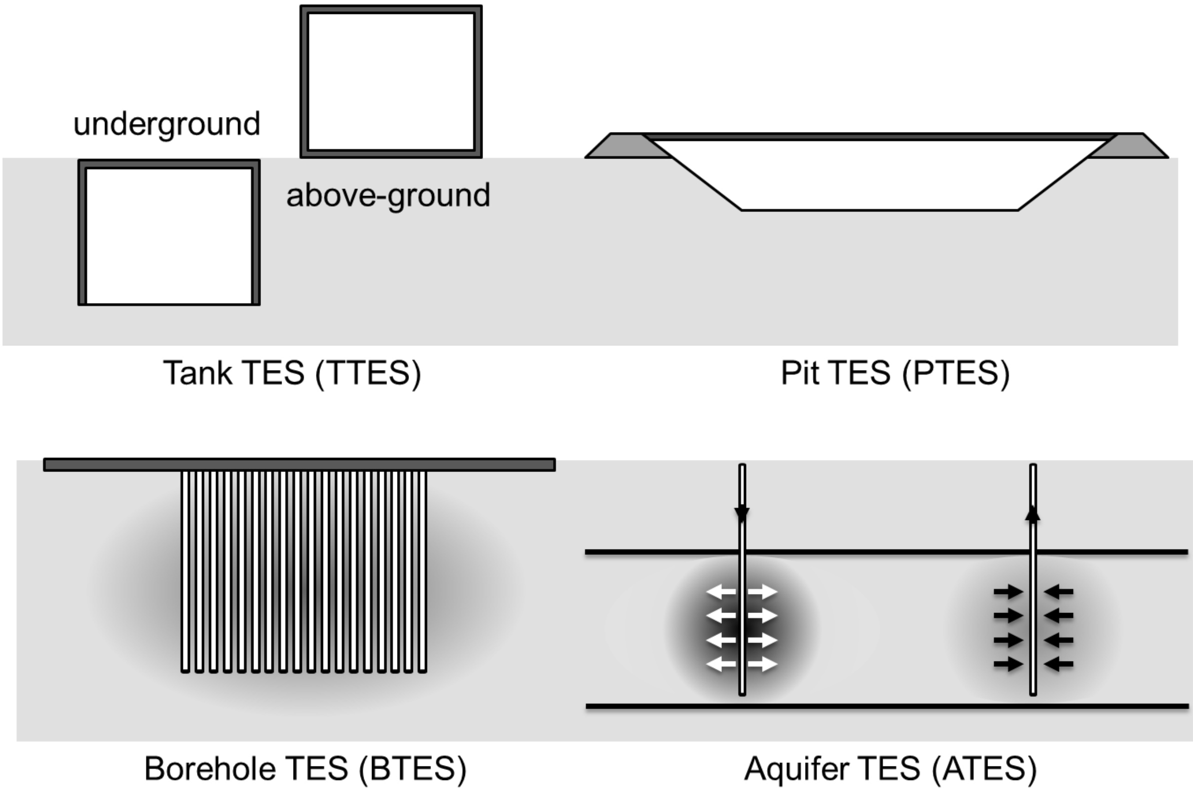


Figure 1: Overview of LTES types for the test case definitions

In the test cases, only the LTES components are considered, and no additional system components are included.

1 Thermophysical Properties

Table 1 gives an overview of the thermophysical properties to be used in the test case simulations.

Table 1: Thermophysical properties

	Symbol	Unit	Value
Water (at 50 °C)			
Specific heat capacity	$c_{p,w}$	J/(kg·K)	4'181
Thermal conductivity	λ_w	W/(m·K)	0.64
Density	ρ_w	kg/m³	988.1
Dynamic Viscosity	μ_w	(N·s)/m²	0.000547
Volumetric thermal expansion coefficient	$\beta_{th,w}$	1/K	0.0004367
Thermal insulation			
Specific heat capacity	$c_{p,I}$	J/(kg·K)	1'000
Thermal conductivity	λ_I	W/(m·K)	0.08
Density	ρ_I	kg/m³	200
Soil properties[1] for TTES, PTES, ATES caprock and bedrock (solid + liquid, water-saturated clay/silt)			
Specific heat capacity	$c_{p,s}$	J/(kg·K)	1'333.3
Volumetric heat capacity	$C_{,s}$	kJ/(m³·K)	2'800
Thermal conductivity	λ_s	W/(m·K)	1.8
Density	ρ_s	kg/m³	2100
Soil properties[1] for BTES (solid + liquid, sedimentary rock)			
Specific heat capacity	$c_{p,s}$	J/(kg·K)	1'000
Volumetric heat capacity	$C_{,s}$	kJ/(m³·K)	2'400
Thermal conductivity	λ_s	W/(m·K)	2.5
Density	ρ_s	kg/m³	2'400
Soil properties[1] for ATES - aquifer layer (solid + liquid, water-saturated sand)			
Specific heat capacity	$c_{p,A}$	J/(kg·K)	1'333.3
Volumetric heat capacity	$C_{,A}$	kJ/(m³·K)	2'800
Thermal conductivity	λ_A	W/(m·K)	2.4
Density	ρ_A	kg/m³	2'100
Porosity	φ_A	%	35
Hydraulic conductivity (at 15 °C)	k_F	m/s	$1.15*10^{-4}$

[1] Source: VDI-Guideline 4640-1 (2010)

2 Configurations for Test Cases

Table 2 presents the configuration parameters for the stage 1 test cases.

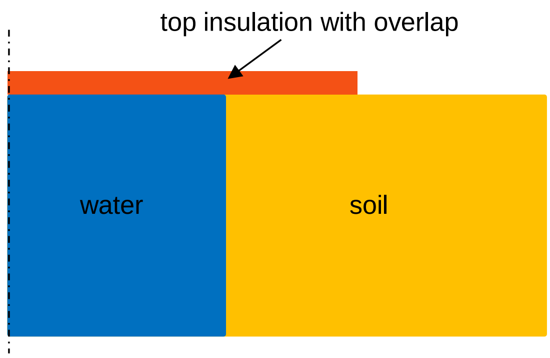
Table 2: Configuration parameters for the stage 1 test cases

Test case 1 label	TTES-1-UG	TTES-1-AG	PTES-1-C	PTES-1-P	ATES-1	BTES-1
Location	**Underground (UG)**	**Above ground (AG)**	Underground	Underground	Underground	Underground
Storage medium	Water	Water	Water	Water	Soil-water	Soil
TES rounded volume(3)	100’000 m³ water volume	50’000 m³ water volume	100’000 m³ water volume	100’000 m³ water volume	375’000 m³ soil volume(9)	80’000 m³ soil volume
TES exact volume	**100’961 m³** water volume	**50’385 m³** water volume	**99’404 m³** water volume	**100’325 m³** water volume	**373’253** m³ soil volume (only warm well side)	**80’646** m³ soil volume
Geometry (storage volume dimensions)	Cylinder H/D = 0.4 H = 27 m, D = 69 m	Cylinder(8) H/D = 1.0 H = 40 m D = 40 m	**Cone (C)**, (truncated, inverted) H = 16 m, wall slope: 1:2 (26.6°) D(top) = 119 m , d(bottom) = 55 m	**Pyramid (P)**, (truncated, inverted) H = 16 m, wall slope: 1:2 (26.6°) D(top) = 109 m , d(bottom) = 45 m	2-well configuration depths: 200 m thickness aquifer-layer: 40 m, 160 – 200 m below ground surface R_T (4) = 54.5 m	Cylinder H/D = 1.8 H = 70 m, D = 38.3 m 128 BHE, BHE distance: 3 m, see also 1
Insulation(5)	Only top insulation(1) U_{top} = 0.1 W/(m²K), horizontal extension beyond the edge of the storage volume: 5 m; h_{side} = h_{bottom} = 90 W/(m²K)	Fully insulated(8) U_{top} = 0.1 W/(m²K); U_{side} = U_{bottom} = 0.2 W/(m²K)	Only top insulation(1) U_{top} = 0.1 W/(m²K), horizontal extension beyond the edge of the storage volume: 5 m; h_{side} = h_{bottom} = 90 W/(m²K)	Only top insulation(1) U_{top} = 0.1 W/(m²K), horizontal extension beyond the edge of the storage volume: 5 m; h_{side} = h_{bottom} = 90 W/(m²K)	No insulation	Top insulation(2) U_{top} = 0.1 W/(m²K), horizontal extension beyond the edge of the storage volume: 5 m
Hydraulic connections for CH / DC	Top inlet / outlet: 0.5 m below top, bottom inlet / outlet: 0.5 m above bottom	Top inlet / outlet: 0.5 m below top, bottom inlet / outlet: 0.5 m above bottom	Top inlet / outlet: 0.5 m below top, bottom inlet / outlet: 0.5 m above bottom	Top inlet / outlet: 0.5 m below top, bottom inlet / outlet: 0.5 m above bottom	2 wells, well screen section 160 – 200 m below ground surface, horizontal well distance = 250 m	Single U-pipe BHEs, d_{pipe}=32x2.9 mm, CH from centre to edge, DC from edge to centre, 4 BHEs in series; $R_{b,eff}$(6) = 0.0926 (mK)/W
Water domain discretization	Number (No.) of vertical nodes for 1-D representation: 50				Not applicable	

Test case 1 label	TTES-1-UG	TTES-1-AG	PTES-1-C	PTES-1-P	ATES-1	BTES-1
Soil parameters	See Table 1					
Ground discretization(7)	Smallest cell size: 0.2 m in horizontal direction and 0.2 m in vertical direction; cell size multiplication factor: 2 (increase of cell dimensions from fluid domain boundaries towards far field boundaries)					
Horizontal far-field boundary	50 m + D/2, adiabatic				125 m from wells, adiabatic	50 m + D/2, adiabatic
Vertical far-field boundary	50 m + H, adiabatic					
Ground surface	Heat transfer coefficient h_{air} = 25 W/(m²K) Radiation / wind on ground surface is neglected (0 W/m², 0 m/s)					
TES and ground initial temperature	10°C (no consideration of ambient air effects and geothermal temperature gradient)					
Ambient temperature	10°C constant (no consideration of daily and seasonal variation)					
Operating profile (M: months, CH: charging, DC: discharging) **see also section 3 and hourly load file**	4M CH with 90°C, 30 m³/h; 1M idle; 4M DC with 30°C; 30 m³/h, 3M idle	4M CH with 90°C, 14 m³/h; 1M idle; 4M DC with 30°C, 14 m³/h; 3M idle	4M CH with 90°C, 30 m³/h; 1M idle; 4M DC with 30°C, 30 m³/h; 3M idle	4M CH with 90°C, 30 m³/h; 1M idle; 4M DC with 30°C, 30 m³/h; 3M idle	4M CH with 80°C, 85 m³/h; 1M Idle; 4M DC with 30°C, 85 m³/h; 3M idle	4M CH with 80°C, 30 m³/h; 1M Idle; 4M DC with 30°C, 30 m³/h; 3M idle
Simulation time / time step (no leap years)	5 * 12 months = 43,800 h / ≤ 1 hour				10 * 12 months = 87,600 h / ≤ 1 hour	5 * 12 months = 43,800 h / ≤ 1 hour

Explanatory notes to Table 2:

(1) The water top surface is located at the same level as the ground surface. A top insulation is located on top of the common water and ground surface, see exemplary figure for TTES-1-UG:



The horizontal overlap of the top insulation shall be considered in case of a physical representation of the top insulation as well as in case of a simplified representation by a thermal resistance.

(2) BHE header and horizontal piping are located at ground surface level. The insulation layer is placed on top of the horizontal piping and is directly exposed to the ambient air without an additional layer of soil.

(3) Rounded values for labelling, reporting, dissemination etc. Exact geometry values must be used for model configuration.

(4) Thermal radius $R_T = \sqrt{\frac{C_W \cdot V_{\text{inj}}}{\pi \cdot H \cdot C_a}}$, with V_{inj}: injected water volume during one storage cycle in m³; C_a and C_W: volume-related specific heat capacities of aquifer and water in kJ/(m³·K); H: height of aquifer layer.

(5) U_{top} = 0.1 W/(m²·K) with h_{air} = 25 W/(m²·K), $h_{water,top}$ = 90 W/(m²·K), $s_{insulation}$ = 0.8 m, $\lambda_{insulation}$ = 0.08 W/(m·K); U_{side} = U_{bottom} = 0.2 W/(m²·K) with h_{water} = 90 W/(m²·K), $s_{insulation}$ = 0.4 m, $\lambda_{insulation}$ = 0.08 W/(m·K)

(6) Borehole thermal resistance, parameters for $R_{b,eff}$ calculation see 1.

(7) Comparable mesh sizes in the soil domain are desired to avoid large deviations in results due to strongly deviating mesh sizes. Detailed mesh configurations are difficult to specify as meshing routines in simulation models/tools can be different. The two parameters "smallest cell size" and "scaling factor for increase of cell size with increasing distance from LTES walls" can be specified in most of the models in one way or another. It is accepted that meshes will still be different, a similar level of detail should however be achievable in this way. The total number of mesh cells of the models should be reported with the results for comparison. If the mesh size cannot be adjusted in a specific model, this should be reported with the simulation results as well.

(8) The AG-tank is a non-pressurized flat-bottom tank. Any extra foundation is neglected, bottom thermal losses occur to the subsurface and not to the ambient air. Bottom thermal insulation does not extend horizontally beyond side walls. For simplification, no air gap between the water surface and the roof of the tank is considered.

(9) For ATES, the pumped ground water volume is often specified instead of the ground volume. The pumped ground water volume is 250’000 m³ in this case.

3 Operating profiles

In Figure 2 to Figure 5, the operating profiles for the stage 1 test cases from Table 2 are illustrated. They are also available as hourly profiles in deliverable C2b *IEA-ES_Task39_WPC_Deliverable_C2b_Stage1_Load_profiles_for_test_cases.xlsx*.

For possibly necessary unit conversions, the thermophysical properties from Table 1 must be used as constant values.

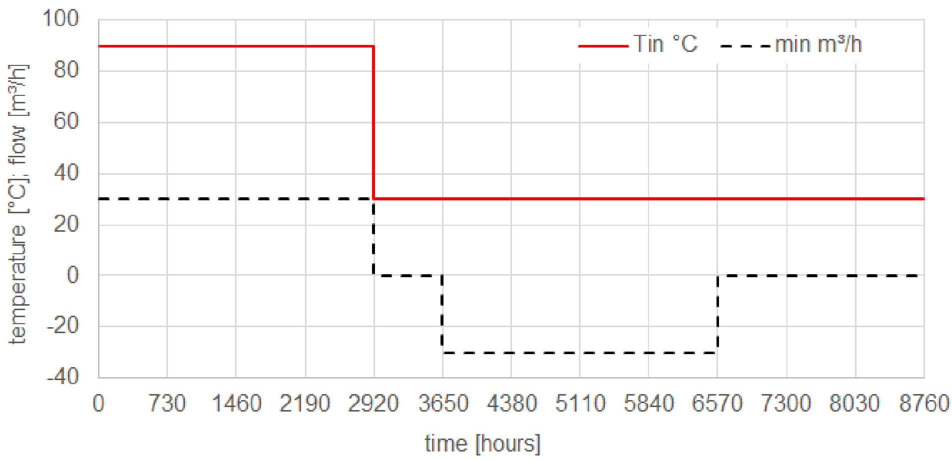


Figure 2: Stage 1 operation profile for test cases **TTES-UG, PTES-C** and **PTES-P** (positive flow rate for charging operation, negative flow rate for discharging operation)

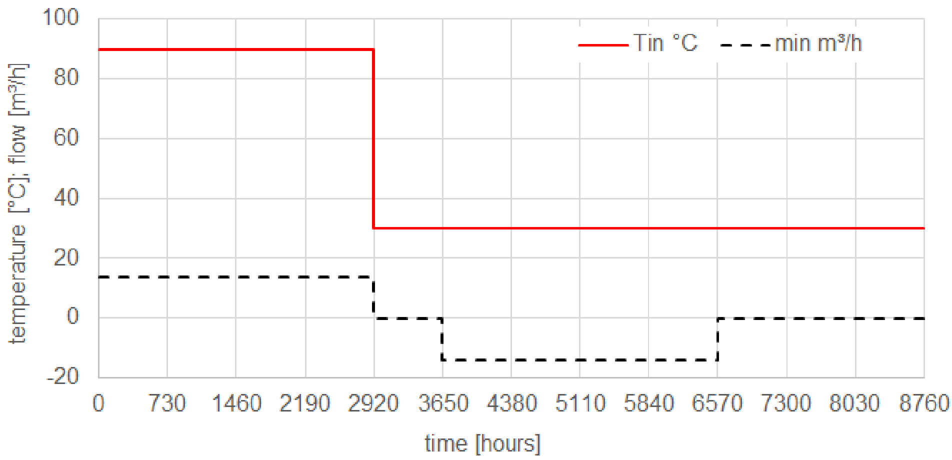


Figure 3: Stage 1 operation profile for test case **TTES-AG** (positive flow rate for charging operation, negative flow rate for discharging operation)

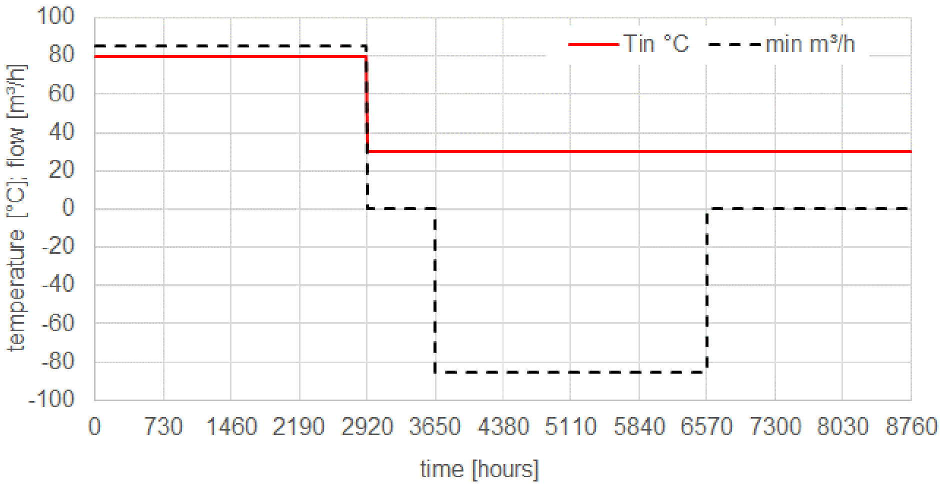


Figure 4: Stage 1 operation profile for test case **ATES-1** (positive flow rate for charging operation, negative flow rate for discharging operation)

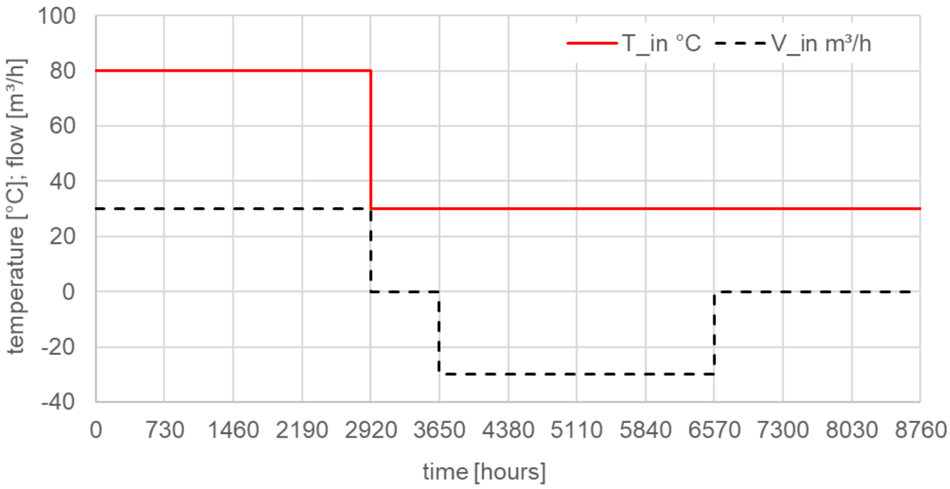


Figure 5: Stage 1 operation profile for test case **BTES-1** (positive flow rate for charging operation, negative flow rate for discharging operation)

4 Output Configuration

4.1 Assessment Criteria

This section provides a general overview of parameters used for the evaluation of simulation results and the model comparison. Based on this, a detailed definition of simulation outputs for the considered test cases is described in section 4.2.

4.1.1 Heat Flows

The following result values are used for evaluation and comparison:

- Charged and discharged amounts of heat,
- Evolution of internal energy content (reference temperature: 10°C),
- Thermal losses (total, top / side / bottom)

4.1.2 Temperatures

The following result values are used for evaluation and comparison:

- TES outlet temperatures during charging and discharging,
- Temperatures in the water domain (only for TTES and PTES cases):
  - Min. / max. temperatures
  - Development of thermal stratification
    - Water temperatures at different heights
    - Stratification coefficient:

$$St = \sum_{n=1}^{N} \frac{m_i \bullet (T_i - T_{avg})^2}{m_{total}}$$

T_i: Temperature of i^th^ layer
M_i: mass of i^th^ layer
T_{avg}: average storage temperature

- Temperature development at selected positions in the soil domain

4.1.3 Numerical Performance

The following result values are used for evaluation and comparison:

- Time required to create the test case model from scratch (user estimation)
- Calculation time for test case
- Computer specifications: CPU (type, frequency, no. of cores), RAM, operating system

4.2 Definition of Simulation Outputs

For the evaluation of simulation results according to section 4.1, the following simulation outputs must be configured. If not stated otherwise, results for these outputs must be provided **for the last year of the simulation period** given in Table 2.

For a convenient evaluation and provision of the results defined in this chapter an excel template file is available, see deliverable C2c *IEA-ES_Task39_WPC_Deliverable_C2c_Stage1_Result_template_for_test_cases.xlsx*.

1. **Hourly mean values** of LTES outlet temperature and flow rate in the LTES charging and discharging circuit (outlet flowrate: positive values for charging mode, negative values for discharging mode)

2. **Hourly mean values** of heat charged into and discharged from TES:
   a. $\dot{Q}_{\mathrm{ch}} = (\rho \cdot \dot{V}_{\mathrm{TES}}) \cdot c_p \cdot (T_{\mathrm{TES,\,in}} - T_{\mathrm{TES,\,out}})$ positive values in kW
   b. $\dot{Q}_{\mathrm{dc}} = (\rho \cdot \dot{V}_{\mathrm{TES}}) \cdot c_p \cdot (T_{\mathrm{TES,\,out}} - T_{\mathrm{TES,\,in}})$ positive values in kW

3. **Hourly mean values** of LTES energy content

   Referred to a reference temperature of 10 °C. Normally available as model output[2]. Formula valid for water LTES only:

[2] It may be necessary to adjust the reference temperature

$$Q_{\mathrm{IE}} = \sum_{i=1}^{n} (\rho \cdot V_{\mathrm{node}\,i}) \cdot c_p \cdot (T_{\mathrm{node}\,i} - T_{\mathrm{Ref}})$$ positive values in kWh

4. **Hourly mean values** of LTES thermal losses to the top, side walls and bottom:
   a. $\dot{Q}_{\mathrm{l,top}}$ negative values in kW
   b. $\dot{Q}_{\mathrm{l,side}}$ negative values in kW
   c. $\dot{Q}_{\mathrm{l,bot}}$ negative values in kW

5. **Hourly mean values** of LTES temperatures (°C)

   For details see following subsections 4.2.1 to 4.2.6.

6. **Daily mean values** of ground temperatures at selected positions.

   For details see following subsections 4.2.1 to 4.2.6.

   If the model does **not** allow for a continuous output of ground temperatures at selected positions:

   Some models offer the possibility to print soil temperature fields at regular intervals that can also be used for ground temperature comparison. These field outputs can either be evaluated automatically to obtain results for the specified sensor positions, e.g. by means of scripts, or manually. In this case, also bigger time steps than daily are possible, depending on the feasibility of the solution. In case of manual evaluation, the following dates are important for a basic model comparison (hour values refer to the first year of simulation and have to be continued for the entire simulation period):

   - Hour 0 in the evaluation period (beginning of charging period)
   - Hour 2920 in the evaluation period (end of charging period)
   - Hour 3650 in the evaluation period (beginning of discharging period)
   - Hour 6570 in the evaluation period (end of discharging period)
   - Hour 8760 in the evaluation period (end of simulation period)

   Note: in contrast to the other results the ground temperatures should be provided for the entire simulation period.

   Note 2: see also notes regarding evaluation of ground temperature sensor positions in ground meshes in Annex 2.

7. **Simulation performance**

   The following details should be provided with the test case results in order to be able to assess the time effort for model creation and simulation.

   - Time required to create the test case model (from scratch, user estimation)
   - Calculation time for test case
   - No. of CPU cores used for the simulation
   - Computer specifications:
     - CPU (type, frequency, no. of cores)
     - RAM
     - Operating system

8. **Description of specific model approaches, type of solver etc.**

Depending on simulation model, according to user assessment.

4.2.1 Temperature sensor positions for TTES-1-UG

Temperature sensor positions in the water volume are defined as follows.

Table 3: Temperature sensor positions in the water volume for test case TTES-1-UG (hourly mean values, 50 nodes with equal volume, height 0 m: bottom of TES, node 1: top of TES)

Pos. No.	Relative height	Sensor label	Height in TES	Node no.	Center height of node
[-]	*[-]*	*[-]*	*[m]*	*[-]*	*[m]*
1	0.95	T_v0.95	25.65	3	25.65
2	0.85	T_v0.85	22.95	8	22.95
3	0.75	T_v0.75	20.25	13	20.25
4	0.65	T_v0.65	17.55	18	17.55
5	0.55	T_v0.55	14.85	23	14.85
6	0.45	T_v0.45	12.15	28	12.15
7	0.35	T_v0.35	9.45	33	9.45
8	0.25	T_v0.25	6.75	38	6.75
9	0.15	T_v0.15	4.05	43	4.05
10	0.05	T_v0.05	1.35	48	1.35

Ground temperature sensor positions are defined as follows.

Table 4: Ground temperature sensor positions and data point labels for case **TTES-1-UG**, see also Figure 6; daily mean values

Horizontal distance from centre [m]	0	17	36.5	39.5	54.5
Vertical distance from ground surface [m]					
2			T_36.5_2	T_39.5_2	T_54.5_2
13.5			T_36.5_13.5	T_39.5_13.5	T_54.5_13.5
29	T_0_29	T_17_29	T_36.5_29	T_39.5_29	T_54.5_29

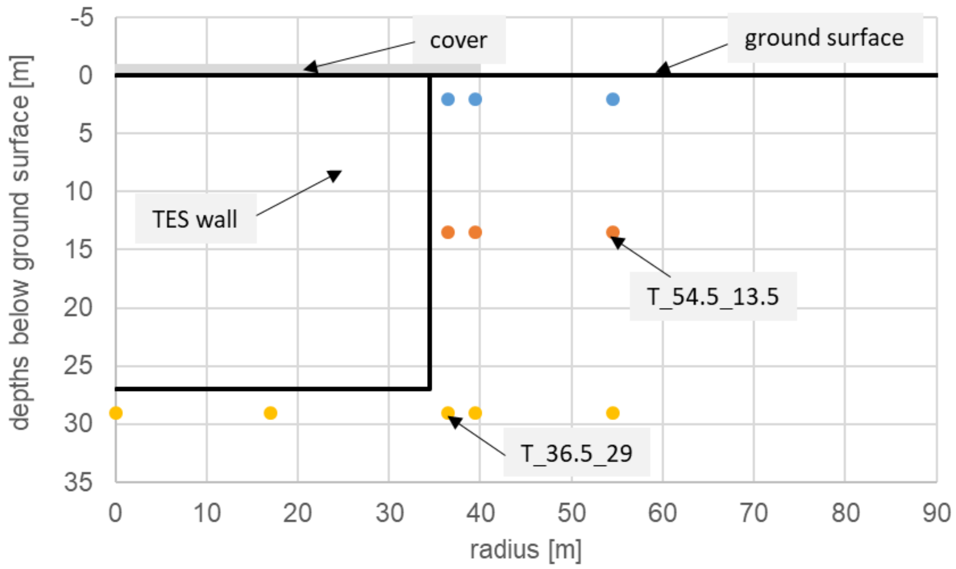


Figure 6: Ground temperature sensor positions for case TTES-1-UG, see also Table 4.

4.2.2 Temperature sensor positions for TTES-1-AG

Temperature sensor positions in the water volume are defined as follows.

Table 5 Temperature sensor positions in the water domain for test case TTES-1-AG (hourly mean values, 50 nodes with equal volume, height 0 m: bottom of TES, node 1: top of TES)

Pos. No.	Relative height	Sensor label	Height in TES	Node no.	Center of node
[-]	*[-]*	*[-]*	*[m]*	*[-]*	*[m]*
1	0.95	T_v0.95	38.00	3	38.00
2	0.85	T_v0.85	34.00	8	34.00
3	0.75	T_v0.75	30.00	13	30.00
4	0.65	T_v0.65	26.00	18	26.00
5	0.55	T_v0.55	22.00	23	22.00
6	0.45	T_v0.45	18.00	28	18.00
7	0.35	T_v0.35	14.00	33	14.00
8	0.25	T_v0.25	10.00	38	10.00
9	0.15	T_v0.15	6.00	43	6.00
10	0.05	T_v0.05	2.00	48	2.00

4.2.3 Temperature sensor positions for PTES-1-C

Temperature sensor positions in the water volume are defined as follows.

Table 6: Temperature sensor positions in the water domain for test case PTES-1-C (hourly mean values, 50 nodes with equal volume, height 0 m: bottom of TES, node 1: top of TES)

Pos. No.	Relative height	Sensor label	Height in TES	Node no.	Center of node
[-]	*[-]*	*[-]*	*[m]*	*[-]*	*[m]*
1	0.95	T_v0.95	15.20	5	15.17

Pos. No.	Relative height	Sensor label	Height in TES	Node no.	Center of node
2	0.85	T_v0.85	13.60	13	13.57
3	0.75	T_v0.75	12.00	20	12.00
4	0.65	T_v0.65	10.40	26	10.48
5	0.55	T_v0.55	8.80	32	8.74
6	0.45	T_v0.45	7.20	37	7.05
7	0.35	T_v0.35	5.60	41	5.48
8	0.25	T_v0.25	4.00	44	4.09
9	0.15	T_v0.15	2.40	47	2.46
10	0.05	T_v0.05	0.80	49	1.15

Ground temperature sensor positions are defined as follows.

Table 7: Ground temperature sensor positions for case **PTES-1-C**, see also Figure 7; daily mean values

Horizontal distance from centre [m]	**0**	**27.5**	**45.5**	**48.5**	**57.5**	**60.5**	**80**
Vertical distance from ground surface [m]							
2					T_57.5_2	T_60.5_2	T_80_2
8			T_45.5_8	T_48.5_8		T_60.5_8	T_80_8
18	T_0_18	T_27.5_18		T_48.5_18		T_60.5_18	T_80_18

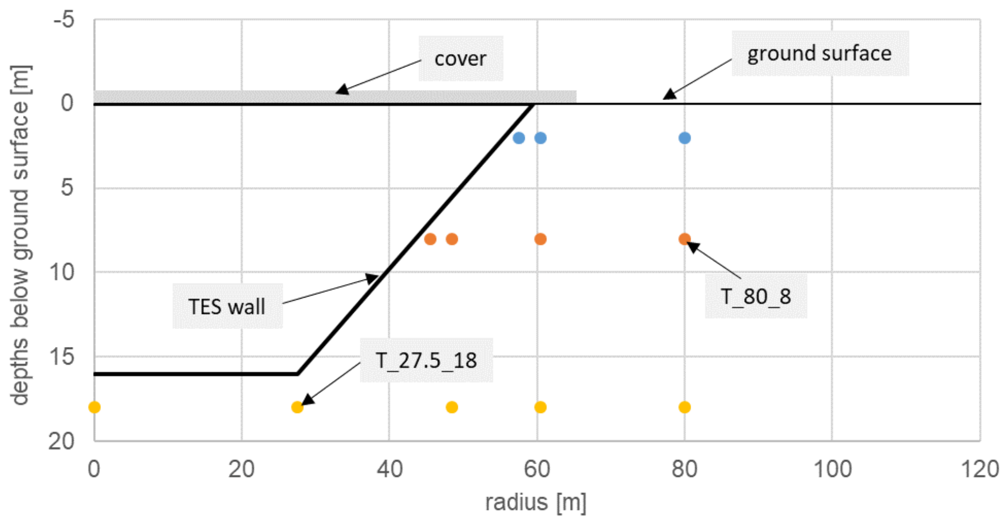


Figure 7: Ground temperature sensor positions for case PTES-1-C, see also Table 7.

4.2.4 Temperature sensor positions for PTES-1-P

Temperature sensor positions in the water volume are defined as follows.

Table 8: Temperature sensor positions in the water domain for test case PTES-1-P (hourly mean values, 50 nodes with equal volume, height 0 m: bottom of TES, node 1: top of TES)

Pos. No.	Relative height	Sensor label	Height in TES	Node no.	Center of node
[-]	*[-]*	*[-]*	*[m]*	*[-]*	*[m]*
1	0.95	T_v0.95	15.20	5	15.22
2	0.85	T_v0.85	13.60	13	13.70
3	0.75	T_v0.75	12.00	21	11.97
4	0.65	T_v0.65	10.40	27	10.48
5	0.55	T_v0.55	8.80	33	8.76
6	0.45	T_v0.45	7.20	38	7.05
7	0.35	T_v0.35	5.60	42	5.40
8	0.25	T_v0.25	4.00	45	3.92
9	0.15	T_v0.15	2.40	48	2.06
10	0.05	T_v0.05	0.80	50	0.46

Table 9: Ground temperature sensor positions for case **PTES-1-P**, see also Figure 7; daily mean values

Horizontal distance from centre [m]	0	22.5	40.5	43.5	52.5	55.5	75
Vertical distance from ground surface [m]							
2					T_52.5_2	T_55.5_2	T_75_2
8			T_40.5_8	T_43.5_8		T_55.5_8	T_75_8
18	T_0_18	T_22.5_18		T_43.5_18		T_55.5_18	T_75_18

Ground temperature sensor positions are defined as follows.

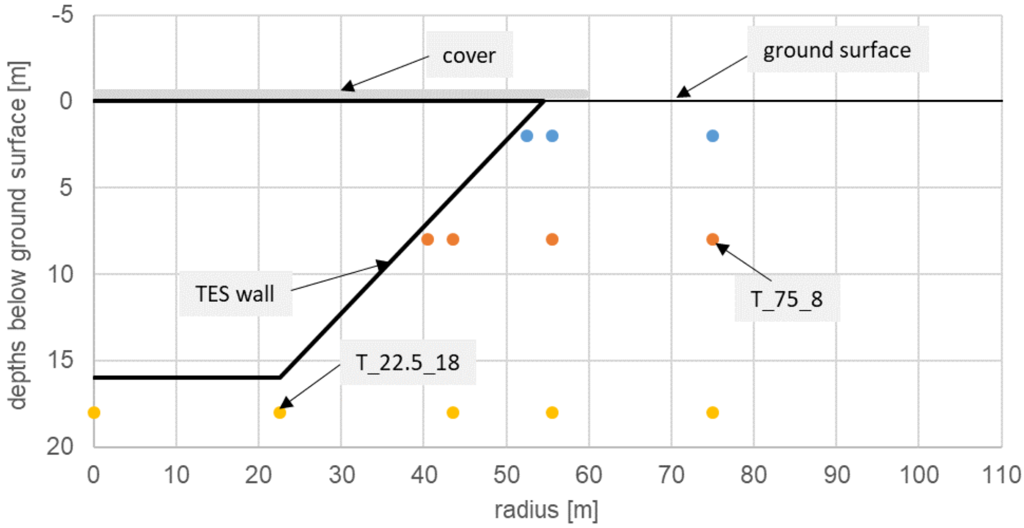


Figure 8: Ground temperature sensor positions for case PTES-1-P, see also Table 9.

4.2.5 Temperature sensor positions for ATES-1

Ground temperature sensor positions are defined as follows.

Table 10: Ground temperature sensor positions for case **ATES-1**, see also Figure 7; daily mean values

Horizontal distance from centre [m]	**-20**	**-5**	**0**	**5**	**20**	**40**
Vertical distance from ground surface [m]						
150	T_-20_150		T_0_150		T_20_150	
165	T_-20_165	T_-5_165		T_5_165	T_20_165	T_40_165
180	T_-20_180	T_-5_180		T_5_180	T_20_180	T_40_180
195	T_-20_195	T_-5_195		T_5_195	T_20_195	T_40_195
210	T_-20_210		T_0_210		T_20_210	

Horizontal distance from centre [m]	**125**	**210**	**230**	**245**	**250**	**255**	**270**
Vertical distance from ground surface [m]							
150			T_230_150		T_250_150		T_270_150
165	T_125_165	T_210_165	T_230_165	T_145_165		T_255_165	T_270_165
180	T_125_180	T_210_180	T_230_180	T_145_180		T_255_180	T_270_180
195	T_125_195	T_210_195	T_230_195	T_145_195		T_255_195	T_270_195
210			T_230_210		T_250_210		T_270_210

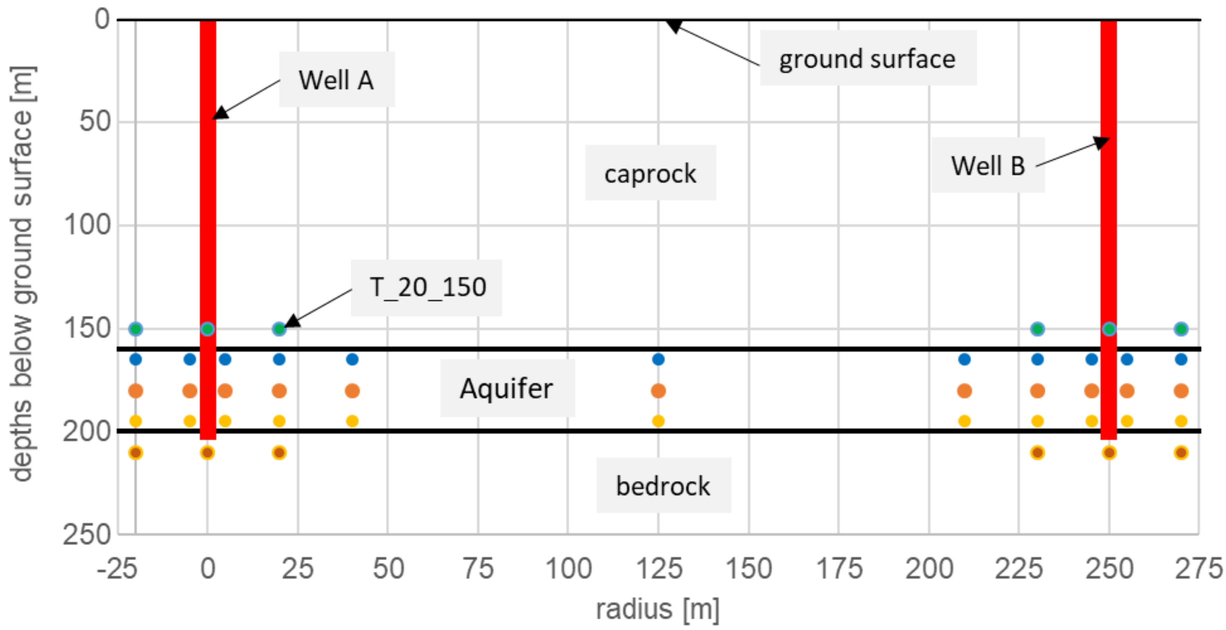


Figure 9: Ground temperature sensor positions for case ATES-1, see also Table 10.

4.2.6 Temperature sensor positions for BTES-1

Ground temperature sensor positions are defined as follows.

Table 11: Ground temperature sensor positions for case **BTES-1**, see also Figure 10; daily mean values

Horizontal distance from centre [m]	**0**	**10**	**20**	**25**	**35**
Vertical distance from ground surface [m]					
5	T_0_5	T_10_5	T_20_5	T_25_5	T_35_5
35	T_0_35	T_10_35	T_20_35	T_25_35	T_35_35
60	T_0_60	T_10_60	T_20_60	T_25_60	T_35_60
80	T_0_80	T_10_80	T_20_80	T_25_80	T_35_80

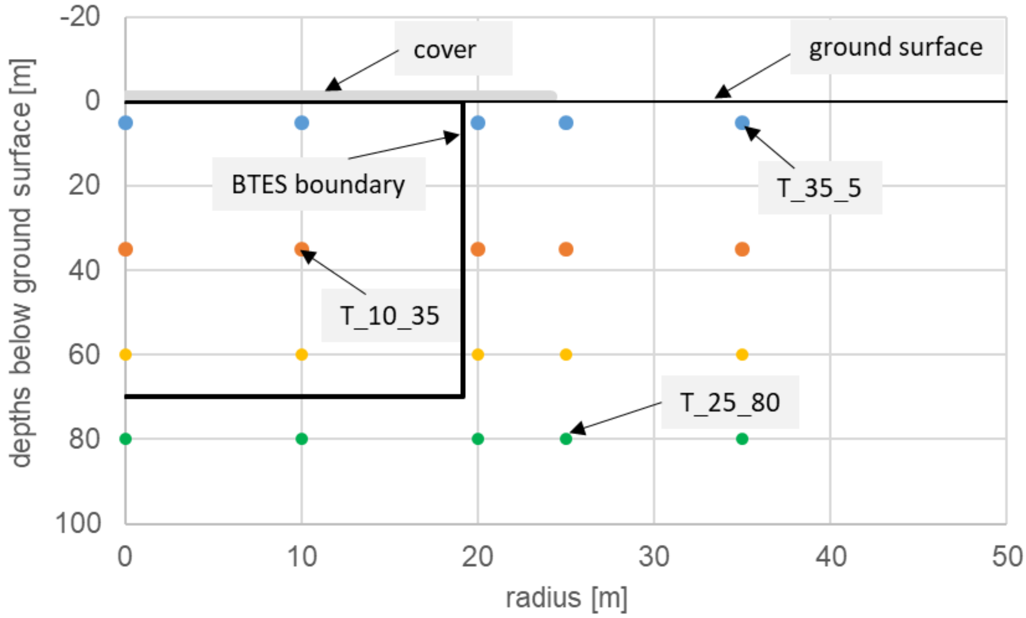


Figure 10: Ground temperature sensor positions for case BTES-1, see also Table 11.

5 Preparatory tests

To make sure that adequate mesh sizes and simulation timesteps are chosen for a specific model, the following independency tests should be conducted for every model based on the test cases defined above.

For the preparatory tests, **no ground temperature data** has to be provided as for model comparisons only yearly energy values and outlet temperatures etc. are used.

Please add the supplementary label given in the following tables to the specific test case label, e.g. "*PTES-1-C-GM03*", to allow a clear identification of the specific configurations.

5.1 Water domain discretisation independency test

This section only applies to TTES and PTES.

The discretisation in the water domain has a large influence on the thermal stratification inside the storage volume, especially for large water storage volumes and dynamic charging and discharging processes.

In many models, the vertical ground mesh structure is coupled to the water domain discretisation. In these cases, the vertical number of ground cells in the subsurface area next to the water domain is also defined by the water domain discretisation.

Label		WD01 / **default**	WD02	WD03	WD04
No. of vertical nodes	-	50	75	100	150

5.2 Ground mesh independency test

Mesh sizes and structure are configured inconsistently in the different simulation models. In most of the models, the two parameters 'smallest cell size' and 'mean multiplication factor' can be defined in the one way or another. The parameters below should be adjusted as close as possible in the simulation models. Deviations should be reported in the results template file.

Label		GM01	GM02 / **default**	GM03	GM04
Smallest cell size: (horizontal & vertical)	*m*	0.1	0.2	0.5	1
Mean cell size multiplication factor:	-	1.5	2	2	2

Smallest cell size: usually used next to LTES surfaces in order to map the closest soil temperatures well for e.g. calculation of thermal losses.

Mean cell size multiplication factor: with increasing distance from the LTES surfaces also the cell sizes can be increased as transport processes are slow and temperature differences from cell to cell decrease.

5.3 Timestep independency test

This section only applies to simulation models with fixed simulations timesteps.

For simulation models working with fixed timesteps over the simulation period, the influence of the timestep on the results should be investigated according to the parameters given below. Models with variable timesteps do not have to perform this test.

Label		TS01	TS05	TS1 / **default**	TS2
Timestep	h	0.1	0.5	1	2

6 Special considerations

For PTES and TTES, thermal losses to the ground surface can be overestimated in certain cases, see Figure 11. This can be the case if:

- The water surface is below the ground surface level
- The top insulation is modelled as a thermal resistance only without a physical representation or a consideration of the physical thickness of the cover construction

As illustrated in Figure 11 (top right), a non-realistic thermal bridge may arise in this configuration in the simplified model which leads to a significant overestimation of the calculated thermal losses to the ambient.

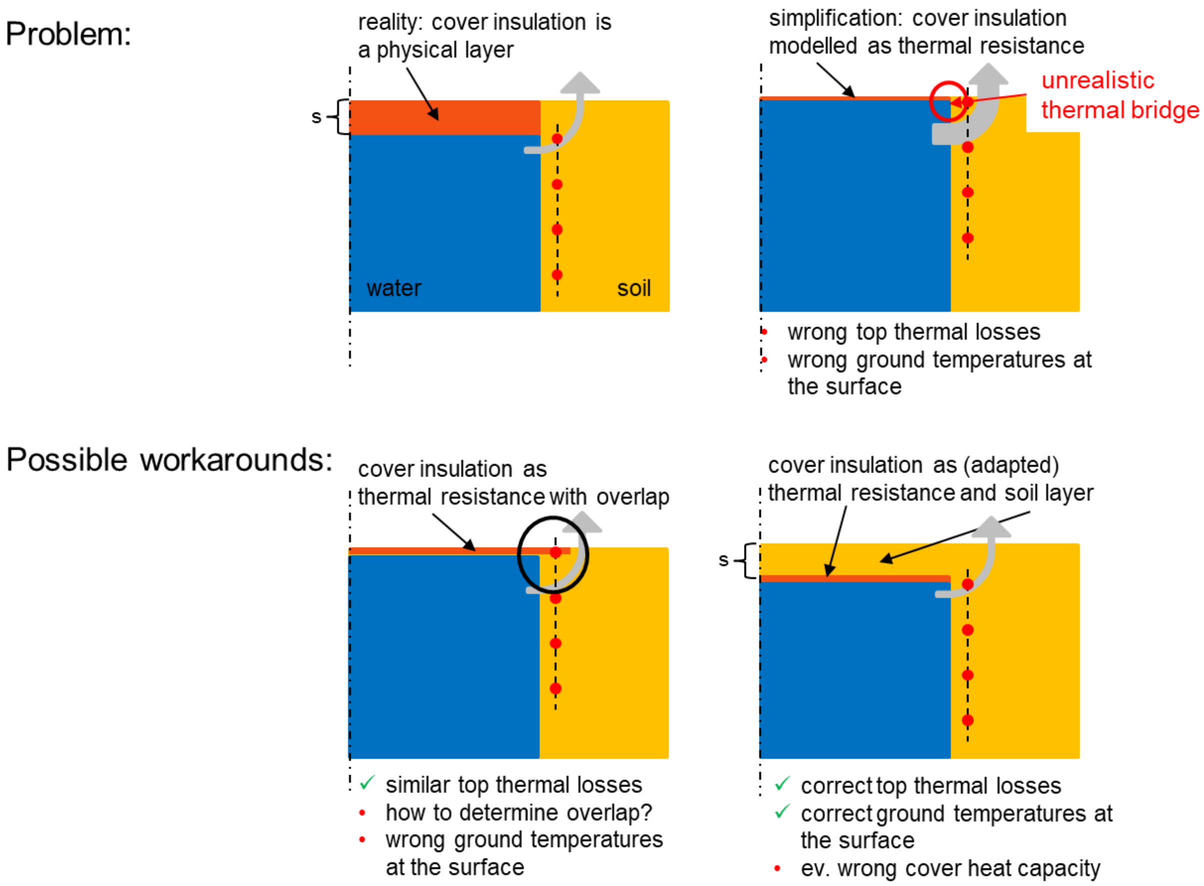


Figure 11: Different possibilities for the consideration of the top insulation layer in a simulation model, the top right configuration leads to an overestimation of thermal losses

Remark: To avoid this problem in test cases, the water top surface is located at ground surface level and a horizontal extension of the cover insulation is defined, see Figure 12. Cover and top insulation layers are located above ground surface level.

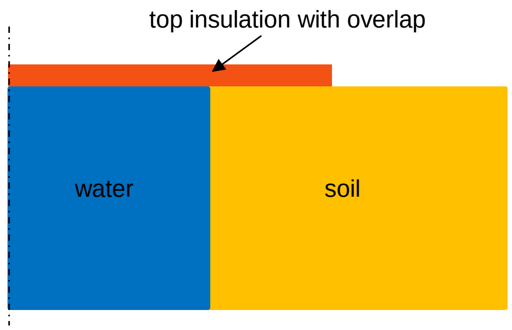


Figure 12: Configuration for test cases

POST-PROCESSING OF RESULT FILES

The simulation results should be inserted into the provided Excel result template file. The Excel file should be renamed to the format given below.

Excel result template file (Deliverable C2c): *IEA-ES_Task39_WPC_Deliverable_C2c_Stage1_Result_template_for_test_cases.xlsx*.

File name convention for completed result files: '*Source_Tool_User_Test-Case_Date.xlsx*'

- Source - institute/company providing the results
- Tool - simulation model used
- User - user initials
- Test-Case - investigated case according to Table 2 and Section 5, e.g. "TTES-1-UG", "PTES-1-C" or "PTES-2-C-WD01-GM01-TS1"
- Date is the simulation date in the format YYYY.MM.DD

Example result file name: *Solites_TRNSYS-Type345_TS_ATES-1-GM01_TS1_2022.05.01.xlsx*.

ANNEX

1 BTES - configuration

This section gives further details to the BTES stage 1 configuration.

Table 12: Geometrical parameters and thermophysical properties for borehole heat exchangers (e.g. for the calculation of model-internal or flow- and temperature-dependent borehole thermal resistance values, if applicable).

Geometrical parameters		Thermophysical properties	
Type of BHE	Single U-pipe (1xU)	λ_p pipe thermal conductivity	0.42 W/(m·K)
d_a (outer pipe diameter)	0.032 m	λ_g grout thermal conductivity	2.0 W/(m·K)
d_i (inner pipe diameter)	0.0262 m	$m_{BHE,1U}$ BHE design mass flow (per 1xU)	0.94 m³/h
S (shank spacing, centre to centre)	0.06 m		
d_b (borehole diameter)	0.115 m		

With the above parameters the following borehole thermal resistances can be calculated:

Borehole thermal resistance R_b: 0.0887 W/(m·K)
Effective borehole thermal resistance $R_{b,eff}$: 0.0926 W/(m·K)
Thermal resistance between upward and downward pipes R_a: 0.3598 W/(m·K)

For an exact horizontal placement of the single BHEs the corresponding coordinates are given in Figure 13 and Table 13. Information on the hydraulic connection of the BHEs can be seen in Figure 14.

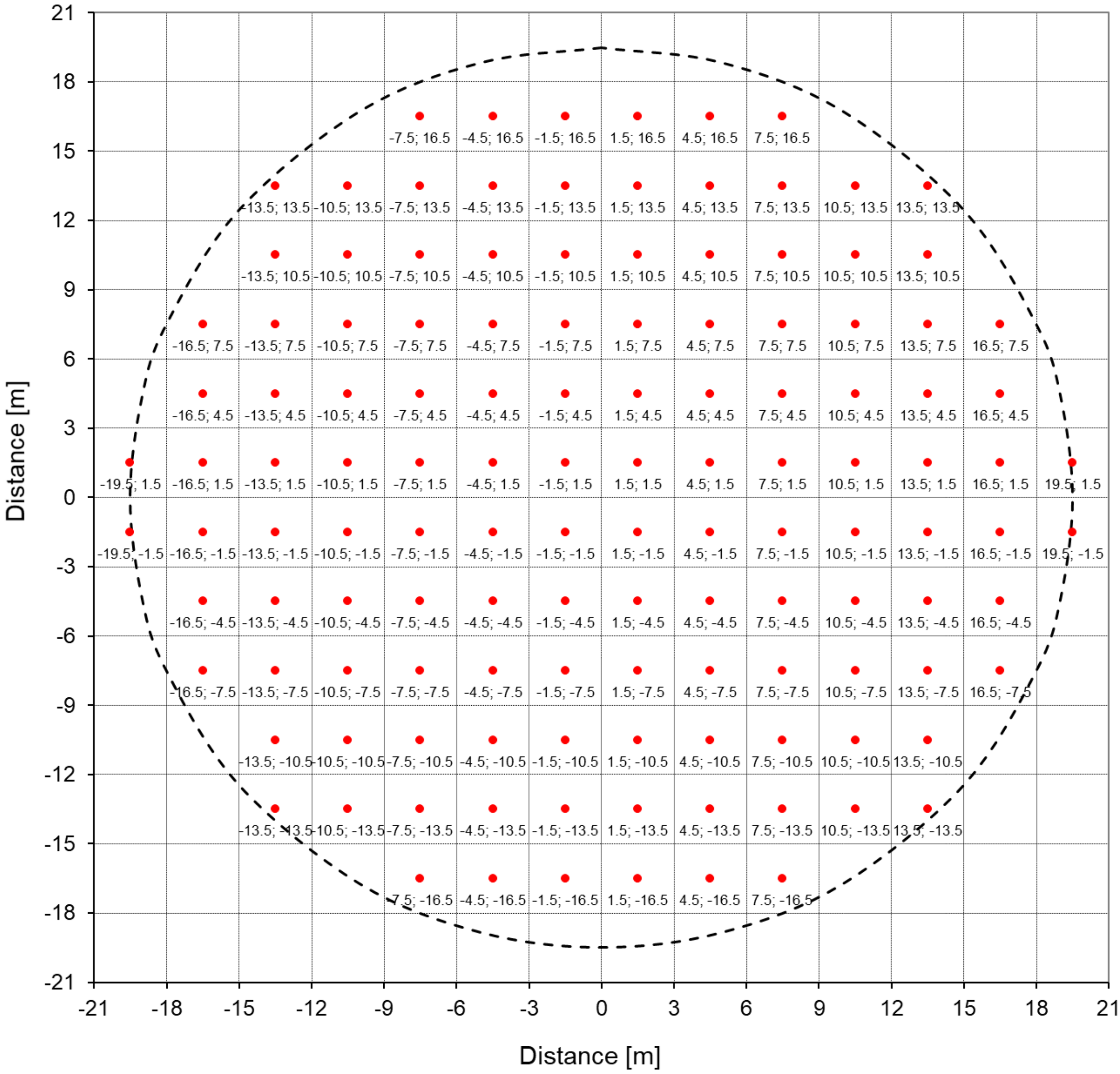


Figure 13: Top view of BTES in stage 1 configuration with coordinates of single BHEs, see also Table 13

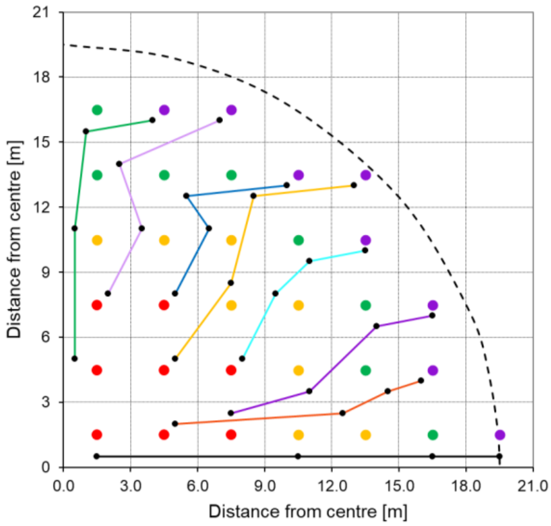


Figure 14: Hydraulic connection of BHEs in 1st quadrant (3 hydraulic/thermal zones: red: zone 1, yellow: zone 2, green: zone 3), symmetric arrangement in other quadrants

Table 13: Horizontal coordinates of BHEs for BTES stage 1 configuration

BHE No.	x	y	Zone No.	BHE No.	x	y	Zone No.	BHE No.	x	y	Zone No.	BHE No.	x	y	Zone No.
	m	m			m	m			m	m			m	m	
1	1.5	1.5	1	33	-1.5	1.5	1	65	-1.5	-1.5	1	97	1.5	-1.5	1
2	4.5	1.5	1	34	-4.5	1.5	1	66	-4.5	-1.5	1	98	4.5	-1.5	1
3	7.5	1.5	1	35	-7.5	1.5	1	67	-7.5	-1.5	1	99	7.5	-1.5	1
4	10.5	1.5	2	36	-10.5	1.5	2	68	-10.5	-1.5	2	100	10.5	-1.5	2
5	13.5	1.5	2	37	-13.5	1.5	2	69	-13.5	-1.5	2	101	13.5	-1.5	2
6	16.5	1.5	3	38	-16.5	1.5	3	70	-16.5	-1.5	3	102	16.5	-1.5	3
7	19.5	1.5	4	39	-19.5	1.5	4	71	-19.5	-1.5	4	103	19.5	-1.5	4
8	1.5	4.5	1	40	-1.5	4.5	1	72	-1.5	-4.5	1	104	1.5	-4.5	1
9	4.5	4.5	1	41	-4.5	4.5	1	73	-4.5	-4.5	1	105	4.5	-4.5	1
10	7.5	4.5	1	42	-7.5	4.5	1	74	-7.5	-4.5	1	106	7.5	-4.5	1
11	10.5	4.5	2	43	-10.5	4.5	2	75	-10.5	-4.5	2	107	10.5	-4.5	2
12	13.5	4.5	3	44	-13.5	4.5	3	76	-13.5	-4.5	3	108	13.5	-4.5	3
13	16.5	4.5	4	45	-16.5	4.5	4	77	-16.5	-4.5	4	109	16.5	-4.5	4
14	1.5	7.5	1	46	-1.5	7.5	1	78	-1.5	-7.5	1	110	1.5	-7.5	1
15	4.5	7.5	1	47	-4.5	7.5	1	79	-4.5	-7.5	1	111	4.5	-7.5	1
16	7.5	7.5	2	48	-7.5	7.5	2	80	-7.5	-7.5	2	112	7.5	-7.5	2
17	10.5	7.5	2	49	-10.5	7.5	2	81	-10.5	-7.5	2	113	10.5	-7.5	2
18	13.5	7.5	3	50	-13.5	7.5	3	82	-13.5	-7.5	3	114	13.5	-7.5	3
19	16.5	7.5	4	51	-16.5	7.5	4	83	-16.5	-7.5	4	115	16.5	-7.5	4
20	1.5	10.5	2	52	-1.5	10.5	2	84	-1.5	-10.5	2	116	1.5	-10.5	2
21	4.5	10.5	2	53	-4.5	10.5	2	85	-4.5	-10.5	2	117	4.5	-10.5	2
22	7.5	10.5	2	54	-7.5	10.5	2	86	-7.5	-10.5	2	118	7.5	-10.5	2
23	10.5	10.5	3	55	-10.5	10.5	3	87	-10.5	-10.5	3	119	10.5	-10.5	3
24	13.5	10.5	4	56	-13.5	10.5	4	88	-13.5	-10.5	4	120	13.5	-10.5	4
25	1.5	13.5	3	57	-1.5	13.5	3	89	-1.5	-13.5	3	121	1.5	-13.5	3
26	4.5	13.5	3	58	-4.5	13.5	3	90	-4.5	-13.5	3	122	4.5	-13.5	3
27	7.5	13.5	3	59	-7.5	13.5	3	91	-7.5	-13.5	3	123	7.5	-13.5	3
28	10.5	13.5	4	60	-10.5	13.5	4	92	-10.5	-13.5	4	124	10.5	-13.5	4
29	13.5	13.5	4	61	-13.5	13.5	4	93	-13.5	-13.5	4	125	13.5	-13.5	4
30	1.5	16.5	3	62	-1.5	16.5	3	94	-1.5	-16.5	3	126	1.5	-16.5	3
31	4.5	16.5	4	63	-4.5	16.5	4	95	-4.5	-16.5	4	127	4.5	-16.5	4
32	7.5	16.5	4	64	-7.5	16.5	4	96	-7.5	-16.5	4	128	7.5	-16.5	4

2 Evaluation of ground temperature positions

In most of the simulation models, the underground is represented by a numerical mesh, see example in Figure 15. The temperatures given for single cells represent the temperatures at the positions of the cell centres. If temperatures at positions between cell centres are needed, they must be derived by linear interpolation between cell centres in order to ensure comparable values with reasonable accuracy, see also Figure 16. Interpolation needs to be done in multiple dimensions, if applicable.

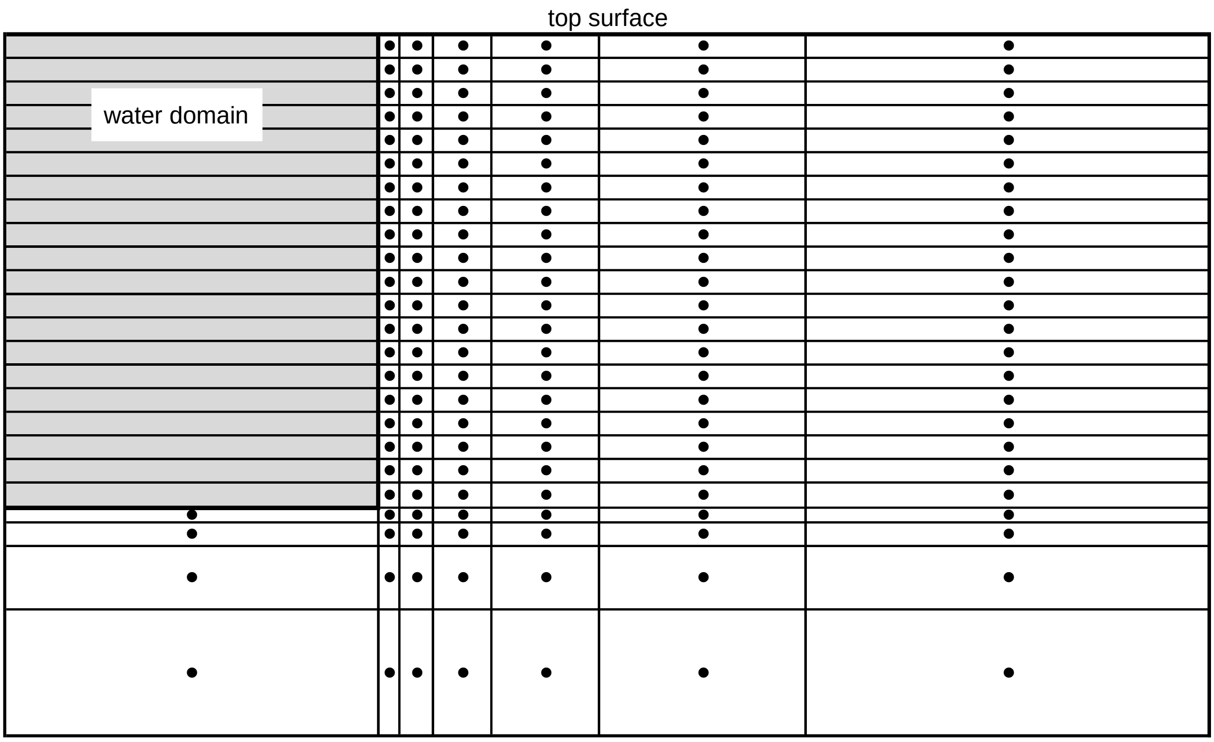


Figure 15: Example representation of a 2-D ground mesh with marked cell centers

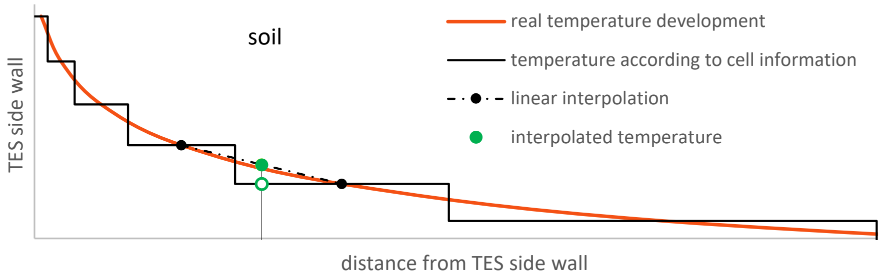


Figure 16: Horizontal ground temperature development next to the LTES side wall (cell structure according to Figure 15)