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Numerical study of a geothermal rainwater tank for buildings passive cooling

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RÉSUMÉ. L'objet de cet article est la présentation de l'étude numérique d'un nouveau système hybride de récupérateur d'eau de pluie géothermique. Cette solution, qui se veut low-tech, est peu étudiée dans la littérature (stockage d'eau à volume variable et à surface libre) et permet de rafraîchir passivement les bâtiments tout en réduisant les consommations d'eau non potable. Après la présentation du modèle numérique, celui-ci est validé grâce aux données expérimentales d'un prototype échelle 1. En s'appuyant sur ce modèle, une analyse de sensibilité puis un ajustement sur les paramètres influents est réalisé.

MOTS-CLÉS. récupérateur d'eau de pluie, rafraîchissement passif, géocooling, modélisation, analyse de sensibilité, optimisation

ABSTRACT. This communication presents the study of a new hybrid system composed of a buried rainwater tank thermally activated through a water-to-water heat exchanger. This low-tech solution, scarcely studied in the literature (variable level of atmospheric water volume), performs the passive cooling of buildings and reduces domestic water network consumption (for non-potable uses). A numerical model is built and validated thanks to experimental results retrieved from a at-scale prototypes. Sensitivity analysis used for model improvement and parameters fitting will also be discussed.

KEYWORDS. rainwater harvesting, passive cooling, geocooling, modelling, sensitivity analysis, parameters fitting

1. INTRODUCTION

In the well-known context of climate change, with more frequent and severe heatwaves (Masson-Delmotte et al., 2021), the building sector (residential and service sector) is in great need of resilience in terms of summer thermal comfort and reduction of CO₂ emissions. The electricity consumption for air conditioning in France amounts for almost 15.5 TWh (ADEME, 2021). Using surface geothermal energy - a renewable energy - as heat sink instead of the outside air is a good alternative as the COP of geothermal heat pump is higher and do not contribute directly to urban heat island effect (Bayer et al., 2019)

However shallow geothermal energy can also be deployed as passive heat source, meaning without using refrigerant fluid and a compressor, resulting in even lower CO₂ emissions and electricity consumption. According to a French professional association/the AFPG (Association française des professionnels de la géothermie), in France, geothermal systems in general and

ground-coupled heat exchangers for passive cooling of buildings in particular are promising solutions that need to be developed (AFPG, 2023).

In this context, this project aims at developing a new passive system using buried rainwater tanks as geothermal probes by immersing a water-to-water heat exchanger (HX). Indeed, water management is also becoming a major issue, with both intense rainfall events and droughts on the increase (Masson-Delmotte et al., 2021). This hybrid system could therefore address both water management issues as well as providing cooling for buildings in summer.

The literature review shows a lack of detailed studies of such systems. The exploitation of experimental data from cold and hot water tanks connected to a thermo-active building system has been addressed by (Kalz et al., 2010). They demonstrate that a 11 m³ cistern could provide about 1000 kWh of cooling energy over a whole year. Simulation studies have been carried out by (Upshaw et al., 2017) with the study of a non-buried rainwater storage tank. The approach considered the rainwater tank as a means of shifting the electrical peak load of an air conditioning unit. (Gan et al., 2007) and (Marco Marigo et al., 2021) exposed experimental and numerical studies of a buried water tank coupled to a heat pump, respectively with a plate HX and a coiled HX, which differs from the present work. Regarding (Marco Marigo et al., 2021) the ground heat exchanger consists of a helical polyethylene pipe immersed in a concrete water tank. The tank and pipe sizes are very similar to our prototypes; however the water surface remains static (no in or outflow of rainwater). To the best of our knowledge, the modelling of variable free-surface water storage and the associated mass and heat transfer appears to be poorly documented.

This paper aims at bringing a more complete study of a variable free surface water tank with a numerical model and an experimental validation. It is also expected to validate the concept of this type of system as geothermal probe in a passive installation (without the use of a heat pump). To set up the model, the physical equations from both usual domestic water tanks and atmospheric reservoirs were combined, taking into account heat transfer between air and water. More broadly, this research project aims at establishing and validating an equation-based physical model, using the data of two full-scale prototypes in operation since July 2021.

This article proposes a brief description of the full-scale experimental prototype and the corresponding governing equations or hypotheses. Prior to the validation of the model, a sensitivity analysis is lead in order to identify influential parameters and subsequently a fit of these parameters is made, such that the discrepancy with experimental data is minimized.

2. MAIN CONCEPT OF GEOTHERMAL RAINWATER TANK

The basis of our solution consists in a new or existing buried rainwater tank (see Figure 1), initially used for rainwater collection as non-potable domestic water and the relief of sewage networks. These tanks are generally sized according to the amount of water that can be recovered (from the roof and rainfall) and typically have a capacity of about 10 m³. In France, the water resources management legislation locally enforces the water management at parcel level which could democratize the use of such rainwater tank (Communauté d'Agglomération de Haguenau, 2017). The collected rainwater is mostly used for gardening but also for toilet flushing.

A helical water-to-water heat exchanger in copper or polyethylene is placed in the tank in order to take advantage of the heat storage capacity of water as a by-product. Using an air-to-water heat exchanger connected to the ventilation supply duct, the tank provides cooling energy to the building during summer (Fig. 2).

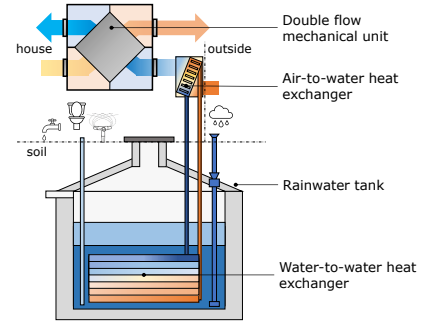
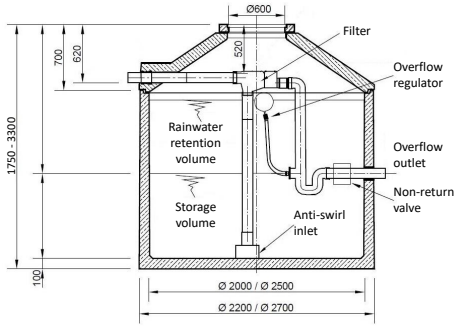


Figure 1 : Datasheet of the rainwater retention and storage tank - PLUVIAU (translated).

Figure 2 : Schematic diagram of a geothermal rainwater tank.

The principle is to use the same installation for three purposes (rainwater harvesting, water management, cooling the building), which in principle allows savings in terms of costs and materials (to be quantified), for example by avoiding the ground boreholes for geothermal probes or the construction of a Canadian well.

3. PHYSICAL MODEL

In this section, the underlying physical models are described.

3.1. TANK AND SYSTEMS

In the first approach the tank is modelled with two temperature nodes, the ambient air temperature T_a and the water temperature T_w . The two heat balances are presented with the detailed heat fluxes and schematize below (Figure 3).

$$\rho_w c_{p_w} \frac{dV_w T_w}{dt} = -Q_{loss,w} - \dot{Q}_{cv} - \dot{Q}_{rad} - \dot{Q}_{evap} + \dot{Q}_{HX} + \dot{Q}_{rain} + \dot{Q}_{dcw} + \dot{Q}_{toil} + \dot{Q}_{gard} + \dot{Q}_{ov} \quad (1)$$

$$\rho_a c_{p_a} \frac{dV_a T_a}{dt} = -Q_{loss,a} + \dot{Q}_{cv} - \dot{Q}_{out} - \dot{Q}_{in} \quad (2)$$

Concerning the water node T_w , the different heat fluxes are detailed below.

The conduction and convection loss to the ground are calculated with a heat transfer coefficient $U_{w,gr}$ adapted to the surface (horizontal or vertical).

$$Q_{loss,w} = U_{w,gr} S_w (\overline{T_{w,gr}} - T_w) \quad (3)$$

The radiative heat flux between the water and the walls above it is computed with a linearized radiative coefficient.

$$\dot{Q}_{rad} = h_{r,w} S_w (\overline{T_{wall,a}} - T_w) \quad (4)$$

The convection loss to the air inside the tank is computed with a convection coefficient correlation from (Auer, 1996) dependant of the wind speed at the water surface.

$$\dot{Q}_{cv} = h_{cv,a-w} S_{w-a} (\overline{T_a} - T_w) \quad (5)$$

$$h_{cv,a-w} = 3.1 + 4.1 u_a^{0.5} \quad (6)$$

The evaporative latent heat flux is calculated with (Hens, 2009) correlation that involve the vapour pressure difference between the saturated air at the water surface and the air inside the tank for the mass flow rate estimation. The evaporation heat flux which is extracted from water is not transferred to the air because this flux is turned into steam.

$$\dot{Q}_{evap} = -q_{m,evap}L_v \quad (7)$$

$$q_{m,evap} = 4.09e^{-5}S_{w-a}(p_{sat}(T_w) - p_{vap}(T_a)) \quad (8)$$

The heat flux from the heat exchanger is computed with the inlet and outlet temperature. Both are computed with the efficiency equations of the two HXs.

$$\dot{Q}_{HX} = q_{m,HX}c_{p,gw}(T_{HX,out} - T_{HX,in}) \quad (9)$$

Incomming advection fluxes are of the following form, with X beeing the different input of water, namely the rain and the district cold water when the level falls under its minimum level :

$$\dot{Q}_X = q_{m,X}c_{p,w}T_X \quad (10)$$

Outgoing fluxes are of the form, with X beeing the different output of water, namely the use of rainwater for toilet flushing, gardening or the overflow (when the level hit its maximum) :

$$\dot{Q}_X = -q_{m,X}c_{p,w}T_w \quad (11)$$

Concerning the heat flux balance on the air node T_a , the convective heat transfer is described with Eq. (5). The conducto-convective losses are computed in the same manner as Eq. (3) with adapted heat transfer coefficient $U_{a,gr}$ and temperature T_a and $T_{gr,a}$. The leakage due to volume variation and leakage through the cover are also treated as advection fluxes.

$$\dot{Q}_{out} = -(q_{m,out} + q_{m,leak})T_a \quad (12)$$

$$\dot{Q}_{in} = (q_{m,in} + q_{m,leak})T_{ext} \quad (13)$$

3.2. GROUND

The ground is simply modeled thanks to a finite element discretization of the heat equation (2D cylindrical with an axial symmetry at the centre of the tank). The following boundaries conditions are applied : imposed temperature at the bottom of the domain, adiabatic on the left and right side due to symmetry and vertical heat flux far from the perturbation respectively, convective heat flux and solar radiation at the top (Figure 4).

4. NUMERICAL MODEL AND VALIDATION

4.1. DESCRIPTION

The chosen numerical method is Crank-Nicolson's semi-implicit scheme, which has the advantage of unconditional stability and being of second order in time. It may be argued that explicit schemes, such as DuFort-Frankel's, are less computationally intensive, especially for the ground part. Considering the variation of heat transfer coefficients or of the ground properties as well as the severe advection fluxes in the tank originating from the collection of rainfall, the choice of an implicit scheme appeared to be sound. Future developments of the model, including a coupled soil moisture model and the future integration of temperature stratification in the water tank also promote the choice of such a scheme.

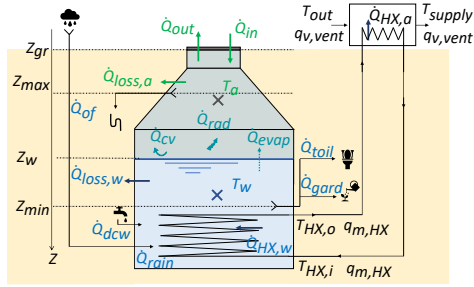


Figure 3 : Schematic diagram of the heat and mass flow in and around the model.

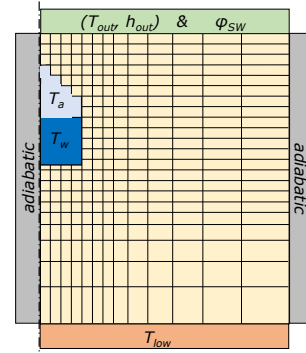


Figure 4 : Illustration of the mesh and boundary conditions for the discretized ground model.

4.2. REDUCING THE COMPUTATIONAL EXPENSE

Before taking further steps into the modelling process involving multiple simulations, a particular effort was made in order to reduce the computational burden. The steps taken were the following and are explicated for potentially interested readers :

- The finite volume two-dimensional conduction problem in the ground exhibits a very sparse matrix. For an equal number of nodes in both directions, non-zero values are in the order of $\simeq \frac{5n}{n^2} = \frac{5}{n}$. Avoiding multiplying zeros by using the dedicated sparse linear algebra methods in `scipy` is an efficient means for the reduction of computation time.
- Another remarkable gain was however obtained simply with the banded matrix algebra tool of the same package. It relies in putting together the non-zero diagonal terms in order to reduce matrix operations. The computational burden for a (n, m) matrix boils down from $(n \times m)^2$ to $2n \times nm$ and yielded a twofold speed-up, with a minor increase in complexity for the programmer (*i.e.* a remarkable ratio between the gain and the time spent debugging).
- A blunt use of "just-in-time" compilation for recurrent functions of the script also provided another 20% time gain with the `numba` package.

Alternately proceeding to a Gaussian elimination of such an outrigger matrix would potentially save some computational expense, however at the cost of a more complex preconditioning of the matrix. The technique explained is described in the very clear (Yano et al., 2012). It will be explored in future developments.

4.3. EXPERIMENTAL DATA COLLECTION AS VALIDATION DATASET

With state-of-art parameter values, such as convective coefficients, ground thermal properties *etc* a first simulation has been undertaken and numerical results are compared to an experimental data set collected on at-scale prototypes (Striegel et al., 2023). The results obtained show that the dynamics and amplitude of the phenomenon are respected, with a root mean square error between 1.1 and 1.8 [K], as summarised in Table 1. This first result is acceptable, however one can observe on Figure 5 that large differences do exist between the model and the experimental results, especially as far as the tank's air and water temperature are concerned. Aiming at a reduction of this discrepancy, a sensitivity analysis of the model parameters is presented in the following section, followed by a parameter fit. Figure 6 shows the ground temperature distribution and the perturbation induced by the tank until about 6 m distance. The reduction of the ground domain is a potential means of reducing the computational expense.

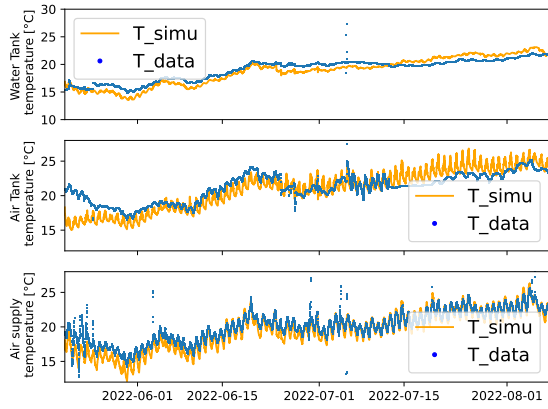
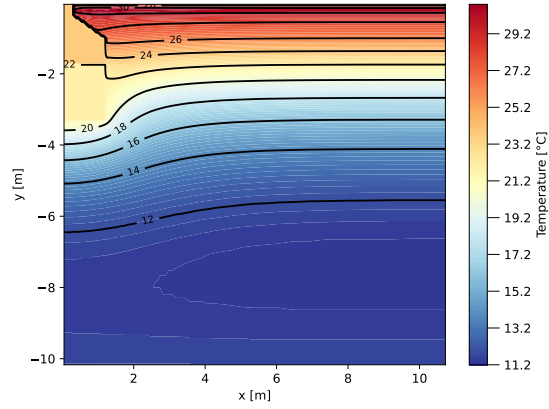
Figure 5 : 1st simulation results (summer period).

Figure 6 : Ground temperature distribution.

	Air temperature (Tank)	Water temperature (tank)	Supply air temperature
RMSE (°C)	1.8	1.2	1.1

Tableau 1 : RMSE with modelled temperatures using state-of-the-art parameter values

5. SENSITIVITY ANALYSIS & PARAMETER FITTING

In this section the results of a sensitivity analysis are presented and a subsequent parameter fit is lead.

5.1. SENSITIVITY ANALYSIS

Sensitivity analysis is used as a means of discriminating the influential parameters of the model. A "one at-a-time" experiment was lead after Morris' method. In brief, changing one parameter of the model at a time for different values of the model parameters set allows to isolate the mean parameter effect, named "elementary effect" and its standard deviation, which provides an insight on possible parameter interactions or non-linearities – see (Morris, 1991). The sensitivity analysis was led on the water and air temperature inside the tank and on the air to water heat exchanger's inlet and outlet, with the parameters and their range of variation described on Table 2. The parameters were chosen based on the literature, their importance in the equation and their variability.

The results obtained are presented on Figure 7 for the blown air temperature, but are fairly the same for the other four temperatures, where one can see that the density and specific heat capacity of the ground are the first and second influential parameters. The convection coefficient at the air-water interface and the tank wall-air come as third and fourth. The ground conductivity comes as fifth most influent parameter. Noticeably, the wall-to-water convection coefficient is less important, which is consistent with its higher value, implying that the tank wall temperature is close to the water's whatever the coefficient value takes within the given range.

The parameters fitting procedure will focus on all parameters except the water-to-water heat exchanger efficiency, ϵ_w . Furthermore, the product of the ground density and thermal capacity ρC_p never intervenes separately in the model equations, hence for the sake of reducing the number of variables to be fitted, they were merged into an equivalent density ρ^* for a constant specific heat capacity, chosen as $C_p = 1000$ [J/kg/K].

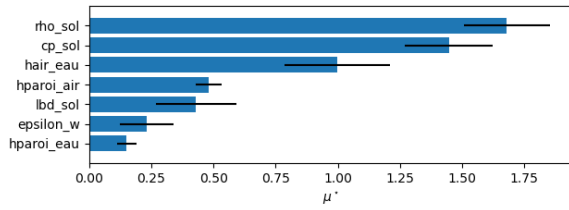


Figure 7 : Result of the sensitivity analysis on the supply air temperature.

Variable bounds	
ρ_{sol} [kg/m ³]	[800 - 3000]
C_p [J/kg/K]	[400 - 1400]
$h_{air-eau}$ [W/m ² /K]	[1 - 10]
lbd_{sol} [W/m/K]	[0.3 - 5]
$h_{paroi-eau}$ [W/m ² /K]	[1 - 10]
$h_{paroi-eau}$ [W/m ² /K]	[50 - 500]
ϵ_w [-]	[0.3 - 0.9]

Tableau 2 : Range of variation of the parameters.

5.2. PARAMETER FITTING

Given the influential parameters, an optimization procedure was set up in order to minimize the discrepancy between the model and measurements. The minimization objective was set as the average RMSE of the tank water temperature and tank air temperature. Gradient-based procedures proved to be inefficient, hence a basic genetic algorithm for single objective problems from (Blank and Deb, 2020) was bluntly used in this first approach. As the computational burden was high with regard to the paper submission deadline, ten generations with ten individuals were computed. The default parameters of mutation, selection and crossover were used and will be investigated in further works. A convergence indicator also needs to be implemented to evaluate the progress of the algorithm, *e.g.* the computation of the hypervolume. In the current problem, using a heuristic initialisation of the population with the combinations of parameters yielding the best RMSE obtained from the sensitivity analysis stage may allow to save some computational effort.

The optimum set of parameters is presented in Table 3, showing that an enhancement in heat transfer from the ground to the water helps matching the data. The initial values were hence conservative with regard to the results obtained. Notably, the optimized thermal conductivity is high compared to typical ground conductivity. The RMSE is 0.91 [K] for the tank water temperature and 1.61 [K] for the tank air temperature, meaning the discrepancy was reduced by ~ 0.3 [K] in both cases compared to the initial results.

ρ^* [kg/m ³]	λ [W/m/K]	$h_{cv,a}$ [W/m ² /K]	h_w [W/m ² /K]	$h_{w,a}$ [W/m ² /K]
2017	4.39	5.16	359	5.58

Tableau 3 : Values of the influential parameters that minimize the RMSE : water, air temperatures inside the tank

The RMSE of the supply air temperature, of the inlet and outlet temperature at the water-to-water HX are also reduced using the fitted parameters (~ 0.95 [K] for each of them). The reduction of the discrepancies between the operational and simulated data will also be undertaken with a complexification the model, for example using a zonal model for the tank, using heat exchanger plume or boundary layers equations, as per (Kenjo et al., 2007).

6. CONCLUSION

This work deals with passive cooling using rainwater tanks as a means to evacuate heat from the outdoor air supplied into dwellings. A fully instrumented prototype serves as a basis to

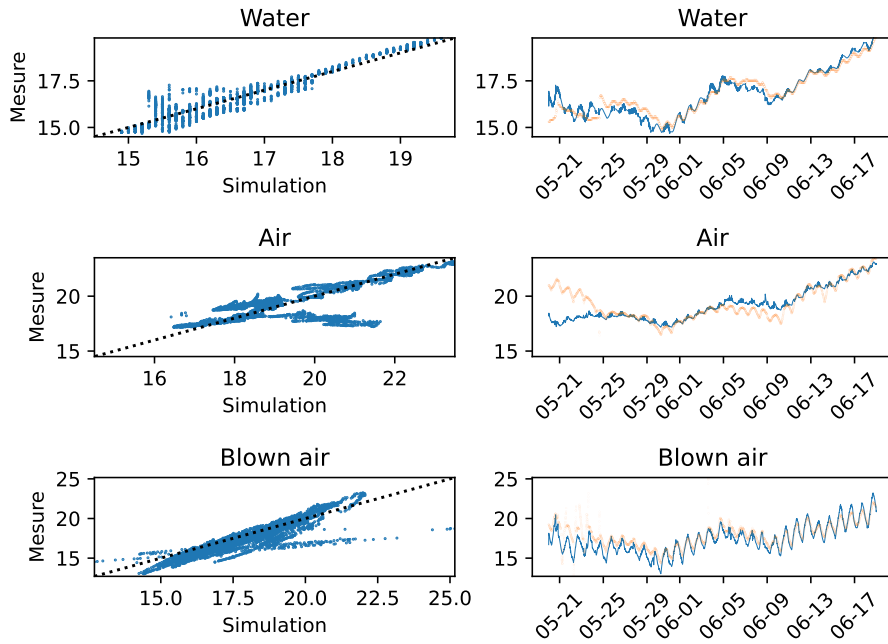


Figure 8 : Comparison of the measured and simulated temperatures (left) and evolution of the temperatures over time with fitted parameters (right)

establish and validate a numerical model.

A sensitivity analysis led on the model allowed to identify its influential parameters, namely the ground properties and convection coefficients around the tank. As a sequel a parameter fit procedure allowed to minimize the discrepancy between the model and measurements to less than ≤ 1 [K] for the tank water temperature.

Noticeably, influential parameters are the ones that are difficult to obtain with precision : the ground properties depend on moisture and composition and are often not precisely known. The purpose of this ongoing research being the derivation of sizing rules for such systems, a particular care should be adopted regarding the hypothesis upon soil properties in future developments.

Other influential parameters of the model are convection coefficients, which depend much on the geometrical configuration, rugosity and fluid temperature difference, amongst other parameters. The tank model is currently improved by the addition of thermal zones with a zonal approach. On the experimental side, measurements are currently made with buoyant temperature sensors immersed at a constant depth from the water surface to capture stratification in a more precise way.

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BIBLIOGRAPHIE

- ADEME (2021). La climatisation dans le bâtiment. Technical report, ADEME and Coda Strategies.
- AFPG (2023). La géothermie en France - Etude de filière 2023. Technical report, Association Française des Professionnels de la Géothermie (AFPG).
- Auer, T. (1996). Trnsys-type 344 : Assessment of an indoor or outdoor swimming pool.
- Bayer, P., Attard, G., Blum, P., and Menberg, K. (2019). The geothermal potential of cities. *Renewable and Sustainable Energy Reviews*, 106 :17–30.
- Blank, J. and Deb, K. (2020). pymoo : Multi-objective optimization in python. *IEEE Access*, 8 :89497–89509.
- Communauté d'Agglomération de Haguenau (2017). Plan Local d'Urbanisme - Annexe III : Annexes Sanitaires : Assainissement. Technical report, Communauté d'Agglomération de Haguenau, Haguenau, France.
- Gan, G., Riffat, S. B., and Chong, C. (2007). A novel rainwater-ground source heat pump – Measurement and simulation. *Applied Thermal Engineering*, 27(2-3) :430–441.
- Hens, H. (2009). Indoor climate and building envelope performance in indoor swimming pools. *Energy efficiency and new approaches*, pages 543–552.
- Kalz, D. E., Wienold, J., Fischer, M., and Cali, D. (2010). Novel heating and cooling concept employing rainwater cisterns and thermo-active building systems for a residential building. *Applied Energy*, 87(2) :650–660.
- Kenjo, L., Inard, C., and Caccavelli, D. (2007). Experimental and numerical study of thermal stratification in a mantle tank of a solar domestic hot water system. *Applied thermal engineering*, 27(11-12) :1986–1995.
- Marco Marigo, Enrico Prativiera, Sara Bordignon, Michele Bottarelli, and Angelo Zarrella (2021). Analysis of the thermal performance of a water storage cell with helical shaped pipe for ground source heat pumps. In *Proc. IBPSA Bruges 2021*, page 8, Bruges, Belgium.
- Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., editors (2021). *Climate Change 2021 : The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Morris, M. D. (1991). Factorial sampling plans for preliminary computational experiments. *Technometrics*, 33(2) :161–174.
- Striegel, L., Bouvenot, J.-B., Walther, E., and Nowamooz, H. (2023). Experimental and numerical study of geothermal rainwater tanks for buildings passive cooling. In *Proceedings of ECOS 2023*, pages 933–943.
- Upshaw, C. R., Rhodes, J. D., and Webber, M. E. (2017). Modeling electric load and water consumption impacts from an integrated thermal energy and rainwater storage system for residential buildings in Texas. *Applied Energy*, 186 :492–508.
- Yano, M., Penn, J. D., Konidaris, G., and Patera, A. T. (2012). Math, numerics, & programming (for mechanical engineers).