LTB_simple_model program v0

1. Introduction

This document briefly presents how the “LTB_simple_model.py” Python program works. It allows to compute some orders of magnitude of the masses and the dimensions of the Light Tower of Babel (LTB) structure for different configurations that can easily be modified. By executing this program, the main results of the simulation will directly be printed on your screen and three figures will be saved. Figure 1 represents the different vertical profiles of interest saved in the file called “Fig1_profiles_LTB_simple model.png”. Figure 2 shows the shadows projected by the PhotoVoltaic (PV) panel array at the surrounding ground surface for different days of interest in the file called “Fig2_shadows_LTB_simple model.png”. Finally, figure 3 shows the maximum and minimum daily energy production allowed by the LTB located at a given latitude in the file called “Fig3_daily_prod_LTB_simple model.png”.

This program only concerns the orders of magnitude of the tower and the PV panel array at the top of it, it does not compute any number for the surface building of this innovative power station.

2. The LTB_simple_model program

2.1. Structure of the program

The program consists of 4 files:

a) “LTB_simple_model.py” is the main program file which has to be executed in order to have the results associated to the features defined in the other files. *A priori*, for a simple use of the program in order to test different possible configurations of the structure, no changes have to be performed in this file.

b) **“variables.py” is the file containing the variables for which values can easily be modified.** Section “I a)” of this file concerns the hypothesis of the ideal atmosphere and surface in which the simulation will take place. For example, we can change the latitude where the LTB is located geographically, which is equal to 40 degrees North by default, to make it equal to 60 degrees North by modifying the value associated to the “lat” variable:

lat = 60.

Section “I b)” of this file concerns the features of the LTB structure that can be modified. For example, we can change the dimensions of the PV panel array at the top of the tower by modifying the variables “x_pv” and “y_pv”. By default, these two variables are set to 2000 m and 500 m, resulting in a total PV panel surface of 1km².

Section “II” of this file concerns variables which are deducted from simple calculations directly from section “I” variables.

c) “constants.py” is the file containing the physical constants needed by the program to perform all its calculations. *A priori*, unless one wants to reach slightly higher precision calculations (which does not make a lot of sense because of the other rough approximations made elsewhere), this file should not be modified.

d) “functions.py” is the file where all the functions needed by the main program to perform the calculations concerning the atmosphere profile and the masses of the gas volumes considered. This file also contains the functions which plot and save the figures produced for a given simulation.

2.2 Main physical hypotheses of the program

a) For the atmosphere variables and the hydrogen gas:

- Idealized pressure and temperature profiles are calculated. These profiles are good enough for the orders of magnitudes that we wish to estimate in these simulations.
- Air and hydrogen are considered as ideal gases.

b) For the structure elements:

- All casings of the structure containing hydrogen are cubic and have exactly the same dimensions (determined by the unique length variable “x_cube” of the “variables.py” file).
- The simplest way to estimate the mass of each (quasi-)cylindrical module of the tower is the following: we consider that the total mass of the module is proportional to the circular part of the surface of the module. The total mass of the module (all it contains within it, cables, inner structure, …) is then only determined by the “surface mass” corresponding to the variable “dens_surf_mod” of the “variables.py” file, which is equal to 20 kg.m^-2 by default.
- The increase with height of the number of cubic casings filled with hydrogen inside the modules in order to lift the weight of each module follows the integers squares series (1, 4, 9, 16, …) in order to have recurring structures (squares) for the construction of the tower modules.

c) For the calculation concerning the structure’s electricity production:

- We consider by default a 20% efficiency conversion rate from the solar flux into the electricity produced by the PV panel array (“conv_rate-pv” variable in the “variables.py” file).
- We consider that, on average over a year, the PV panel array is exposed perpendicularly to the solar flux direction 11h per day (“hours_day” variable in the “variables.py” file).

2.3 Some examples of running the program

To run the program, you have to go to the folder containing the 4 files described above and execute the following command:

```
python LTB_simple_model.py
```

if an error message is displayed, you might be lacking in your Python environment one of the modules the program needs to import in order to run properly. The program is not very complex and only requires the following three non-standard Python modules: “numpy”, “matplotlib” and “pysolar” (https://pysolar.readthedocs.io/en/latest/). The program should work correctly for any Python 3 version having these three modules installed.

2.3.1 Default simulation

```
(my_env) rodrigo@pc-rodrigo:~/Projets/Python/LTB$ python LTB_simple_model.py

*** Main results from this simulation ***

Main input variables:
x_cube = 20.0 [m]
dens_surf_mod = 20.0 [kg.m^-2]
x_pv = 2000.0 [m]
y_pv = 500.0 [m]

***********

Main structure output variables:
max_mass_pv = 1950.0 [ton]
max_dens_pv = 1.95 [kg.m^-2]
max_mass_tower + max_mass_pv = 50045.0 + 1950.0 [ton] =
total_mass_structure = 51995.0 [ton]
mass_h2_tower + mass_h2_pv = 4127.0 + 144.0 [ton] =
total_mass_h2 = 4271.0 [ton]
total_mass_h2/total_mass_structure =
total_mass_ratio = 0.08214 [no unit]
8.21 % of the mass of the structure is H2
nb_cube_tower + nb_cube_pv = 20979 + 1408 =
total_nb_cube_structure = 22387
total_nb_mod_tower = 600

***********

Main production output variables:
max_power = 260.0 [MW]
day_energy_prod = 2.86 [GWh/day]
year_energy_prod = 1.0439 [TWh/year]

(my_env) rodrigo@pc-rodrigo:~/Projets/Python/LTB$
```

Figure 1: Idealized atmosphere and LTB profiles

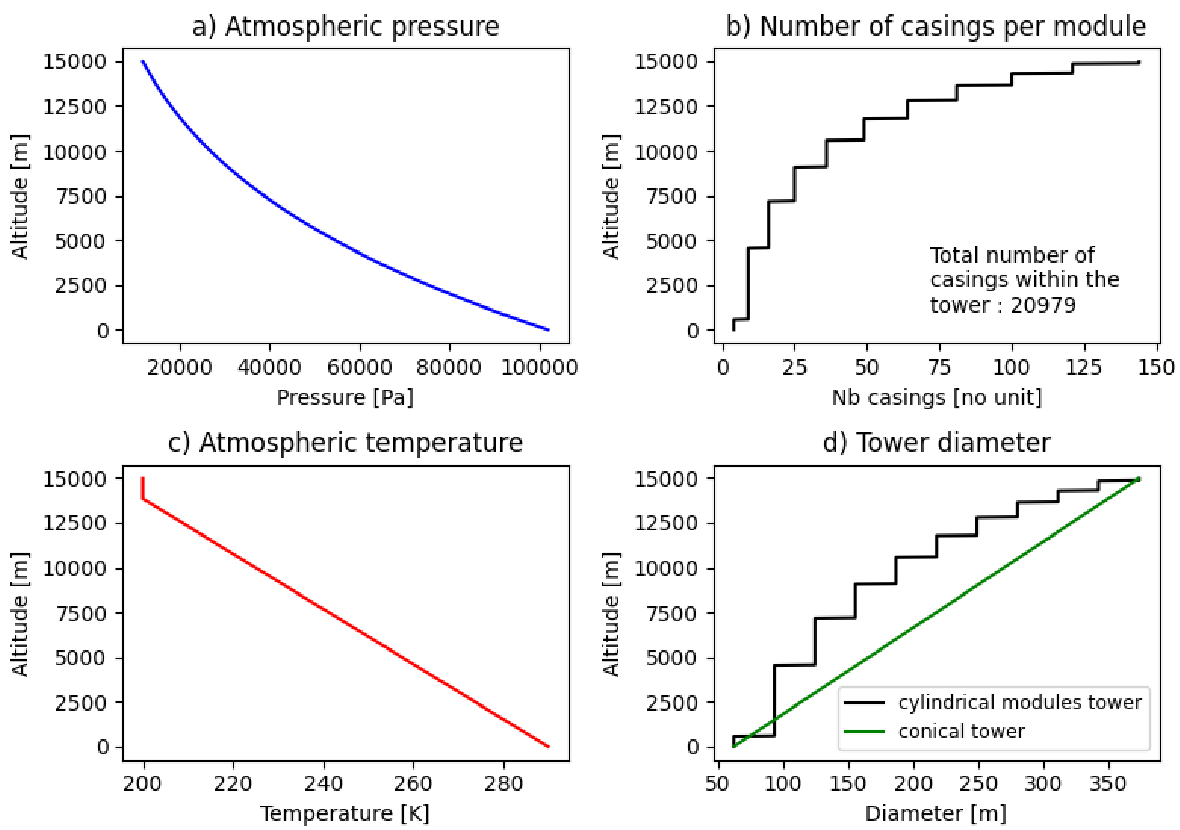


Figure 2: Surface shadows in the surrounding LTB area caused by the PV panel array in clear-sky conditions

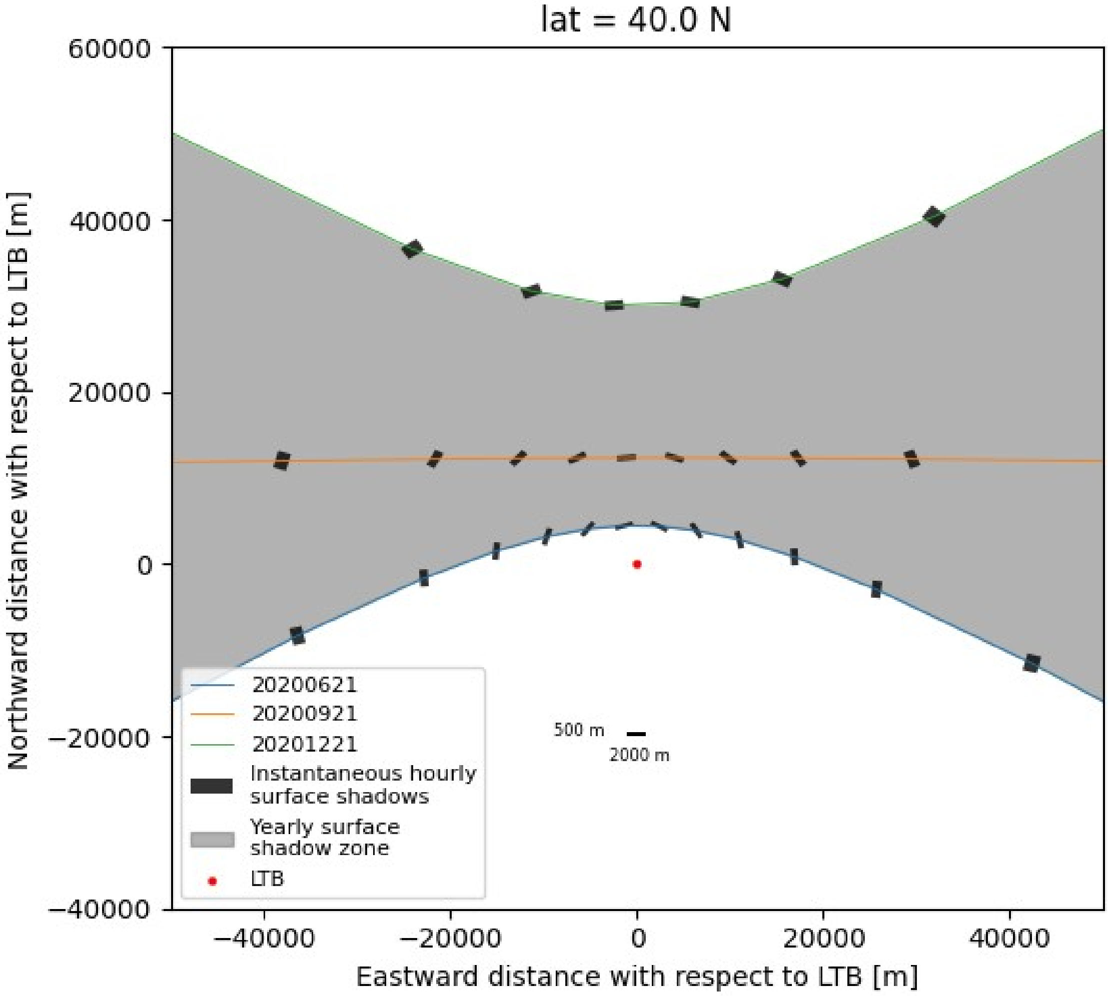
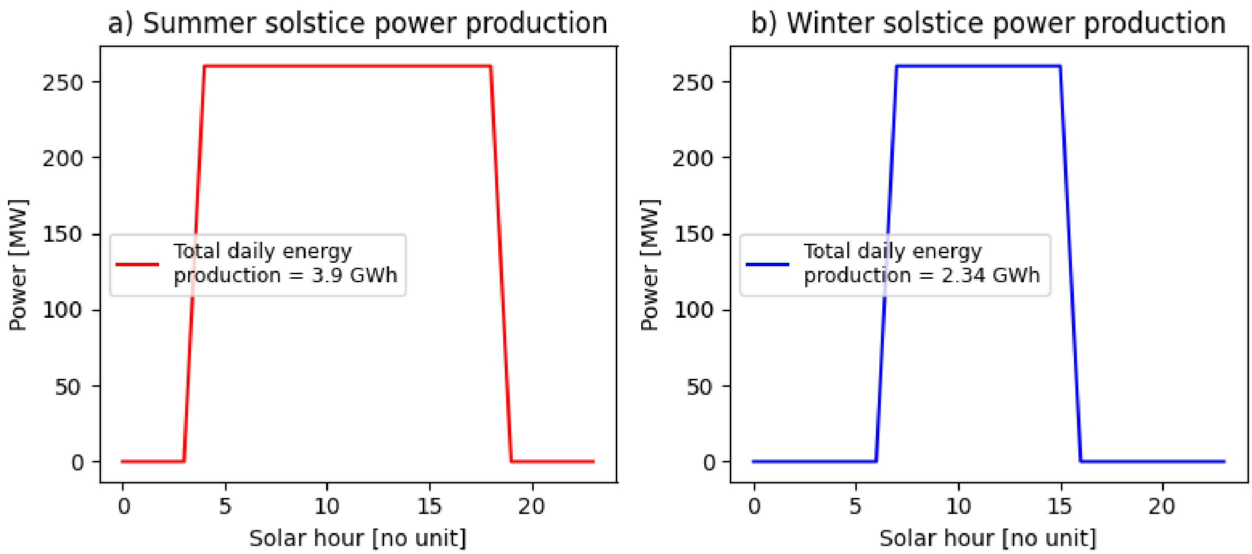


Figure 3: Maximum and minimum daily energy production, lat = 40.0 N



The main results of the simulation are displayed in the terminal in three blocks:

a) The first block recalls the main input values used for the simulation. Indeed, under the line “Main input variables :” we find the default values for the “x_cube”, “dens_surf_mod”, “x_p” and “y_pv” variables. All input variables for the simulation are not displayed, but you only need to have a look at the “variables.py” file in order to know all the values used for the other input variables which are not displayed in this first block.

b) The second block (starting with the line “Main structure output variables :”) summarizes the main features of the tower and the PV panel array resulting from the hypotheses given as inputs. The maximum mass for the PV panel array is given (“max_mass_pv”) and also its maximum surface density (“max_dens_pv”) allowed by the hypotheses. Are also displayed the different maximum masses for the tower (“max_mass_tower”), the PV panel array (“max_mass_pv”) and the masses of hydrogen needed to lift these two major components of the structure (“mass_h2_tower” and “mass_h2_pv”, respectively). The total mass of the deployed structure (tower + PV panel array, “total_mass_structure”), the total mass of hydrogen needed to lift this structure (“total_mass_h2”) and the ratio between the total hydrogen needed and the total mass of the structure are also given. This last value is given in order to highlight that a non-negligible fraction of the total mass of the structure deployed is composed of hydrogen (“total_mass_ratio”). Finally, counting the number of cubic casings needed to lift the tower (“nb_cube_tower”), the PV panel array (“nb_cube_pv”), and the entire structure (“total_nb_cube_structure”) are given, as are given the number of (quasi-)cylindrical modules needed to build the tower (“total_nb_mod_tower”).

c) The third and last results block (starting with the line “Main production output variables :”) of the displayed information gives us the three main variables concerning the structure’s electricity production: the theoretical maximum power produced by the PV panel array (“max_power”), the expected mean daily energy production (“day_energy_prod”) and the maximum energy production for a full year (“year_energy_prod”).

The first figure which completes this display (“Fig1_profiles_LTB_simple model.png”) recalls the atmosphere’s pressure (Fig. 1a) and temperature (Fig. 1c) profiles used for the simulation. It also shows the tower profile in terms of the number of casings that each module has to be within it in order to lift the mass of the module (Fig. 1b), which constrains a minimum diameter to each module of the tower (Fig. 1d). This last subplot also shows (green line) the vertical evolution of the tower’s diameter if the tower has to have a cylindrical shape in order to better resist the strong winds applying mechanical constraints along the tower throughout the troposphere.

The second figure (“Fig2_shadows_LTB_simple model.png”) illustrates how the LTB will produce a shadow at the ground and hence slightly cool the surrounding surface. The figure is centered on the LTB position (red dot, origin of the axes) and shows two main features concerning this shadow. On one hand, it shows hourly instantaneous surface shadows (dark boxes) for selected days (the two solstices and one equinox by default), which allow to have an idea of the size and the location of the shadow at the ground, and also its evolution throughout these selected days (defined in the “variables.py” file). The shadow trajectory for each day is illustrated by colored solid lines (identified in the legend box by the date in the format “yyyymmdd”, yyyy=year, mm=month, dd=day). On the other hand, this figure shows the entire surface zone where the shadow will appear at some point during the year for clear-sky conditions (grey zone). The shadow will “scan” this whole region twice every year, back and forth. This illustration then gives an idea of the extent of the surface region that will slightly be cooled by the shadow produced by the PV panel array at the top of the LTB. Estimating the actual cooling rate caused by this shadow at the surface is out of the scope of this first analysis as it requires detailed understanding of the diurnal and seasonal cycles of cloudiness and surface albedo of the region considered.

The third and last figure (“Fig3_daily_prod_LTB_simple model.png”) illustrates the two annual extremes in terms of daily energy production for the LTB at a given latitude. Figure 3a shows the LTB summer solstice power production diurnal cycle, and gives the maximum total daily energy production within the subplot. Figure 3b shows the LTB winter solstice power production diurnal cycle, and gives the minimum total daily energy production within the subplot.

Analysis of the default simulation:

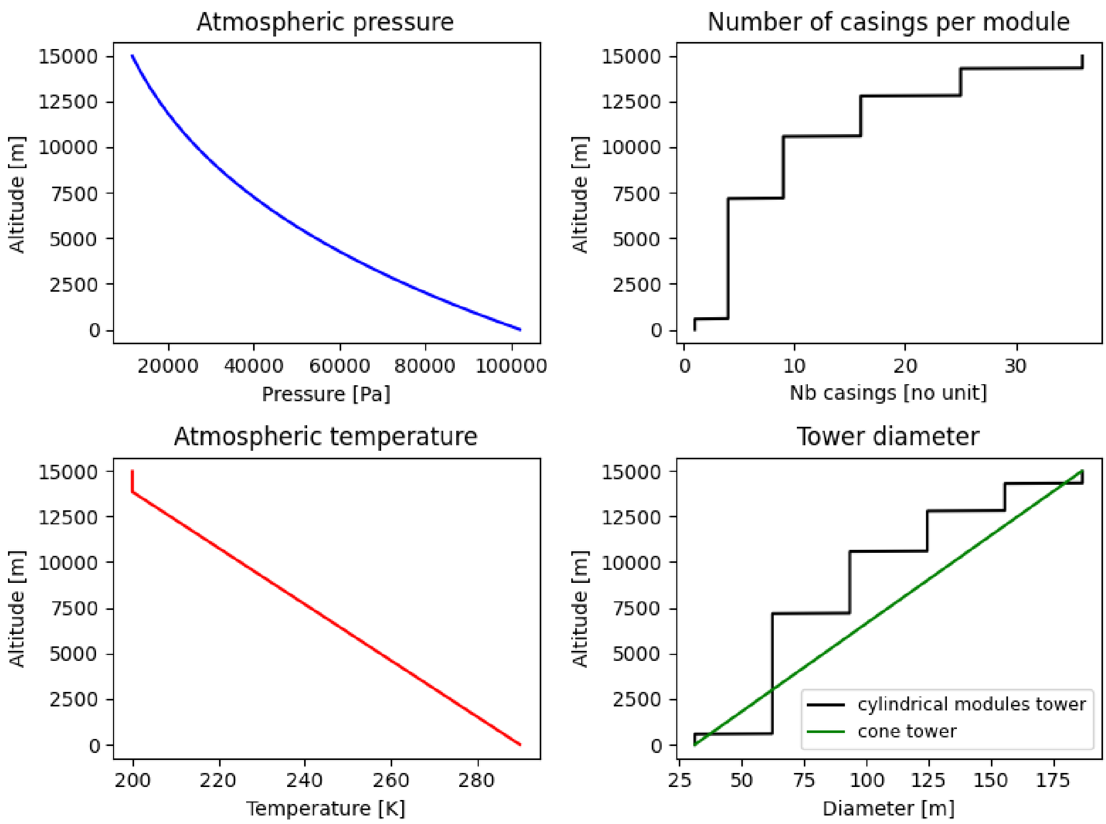
The default simulation considers 20 m long cubic casings (8000 m^3 maximum volume), a surface density of the modules of 20 kg.m^-2 and a PV panel array of 1 km^2. Even though it does not appear in the results displayed or the saved in the figure, there is a variable called “max_vol_margin” in the “variables.py” file which defines a security margin in order not to reach the maximum volume of the cubic casings. By default, this variable is equal to 10%, which means that, in the simulation’s conditions, the volumes of the casings are deployed at 90% of their full possible volume capacity. In this reference simulation, all cubic casings are then deployed filled with a hydrogen mass that uses 7200 m^3 of the 8000 m^3 theoretically available at the pressure and temperature conditions corresponding to their final deployment altitude.

From this default hypotheses, it results a maximum mass for the PV panel array of 1950 tons, hence corresponding to a surface density of 1.95 kg/m^2 for this part of the structure. The maximum mass for the tower in these conditions is 52000 tons approximately, and the hydrogen mass needed to lift the whole structure is the order of 4300 tons, representing a bit more than 8% of the total mass of the structure to be lifted. All this gas would be contained in 22500 cubic casings, 1500 at the PV panel array level (lower stratosphere) and 21000 vertically distributed in the 600 modules that would allow to build the tower. Figure 1d shows us that the tower would have a 60 m diameter at the surface and would reach almost 400 m of diameter at the lower stratosphere level. Knowing that the Eiffel tower has a mass of the order of 10000 tons, this whole structure (tower + PV panal array) as described in this default simulation would “only” be 5 to 6 times the Eiffel tower’s mass for an altitude 50 times higher.

The energy production results of this structure only depend on the extent of the surface of the PV panel array, the efficiency of the PV panels and the average number of hours per day this power station would be producing electricity. The different simulations analyzed in this document will always give the same energy production results as none of these three variables will be modified. With the default values chosen, the maximum electrical power delivered is equal to 260 MW, the mean daily production corresponds to 3 GWh, and the maximum energy production over a year reaches 1 TWh. Figure 3 shows that the maximum daily energy production is close to 4 GWh during the summer solstice, while its minimum daily energy production is slightly above 2 GWh during the winter solstice.

2.3.2 Lighter modules simulation

```
(my_env) rodrigo@pc-rodrigo:~/Projets/Python/LTB$ python LTB_simple_model.py

*** Main results from this simulation ***

Main input variables:
x_cube = 20.0 [m]
dens_surf_mod = 10.0 [kg.m^-2]
x_pv = 2000.0 [m]
y_pv = 500.0 [m]

***********

Main structure output variables:
max_mass_pv = 1950.0 [ton]
max_dens_pv = 1.95 [kg.m^-2]
max_mass_tower + max_mass_pv = 13830.0 + 1950.0 [ton] =
total_mass_structure = 15780.0 [ton]
mass_h2_tower + mass_h2_pv = 1286.0 + 144.0 [ton] =
total_mass_h2 = 1430.0 [ton]
total_mass_h2/total_mass_structure =
total_mass_ratio = 0.09064 [no unit]
9.06 % of the mass of the structure is H2
nb_cube_tower + nb_cube_pv = 6200 + 1408 =
total_nb_cube_structure = 7608
total_nb_mod_tower = 600

***********

Main production output variables:
max_power = 260.0 [MW]
day_energy_prod = 2.86 [GWh/day]
year_energy_prod = 1.0439 [TWh/year]

(my_env) rodrigo@pc-rodrigo:~/Projets/Python/LTB$
```

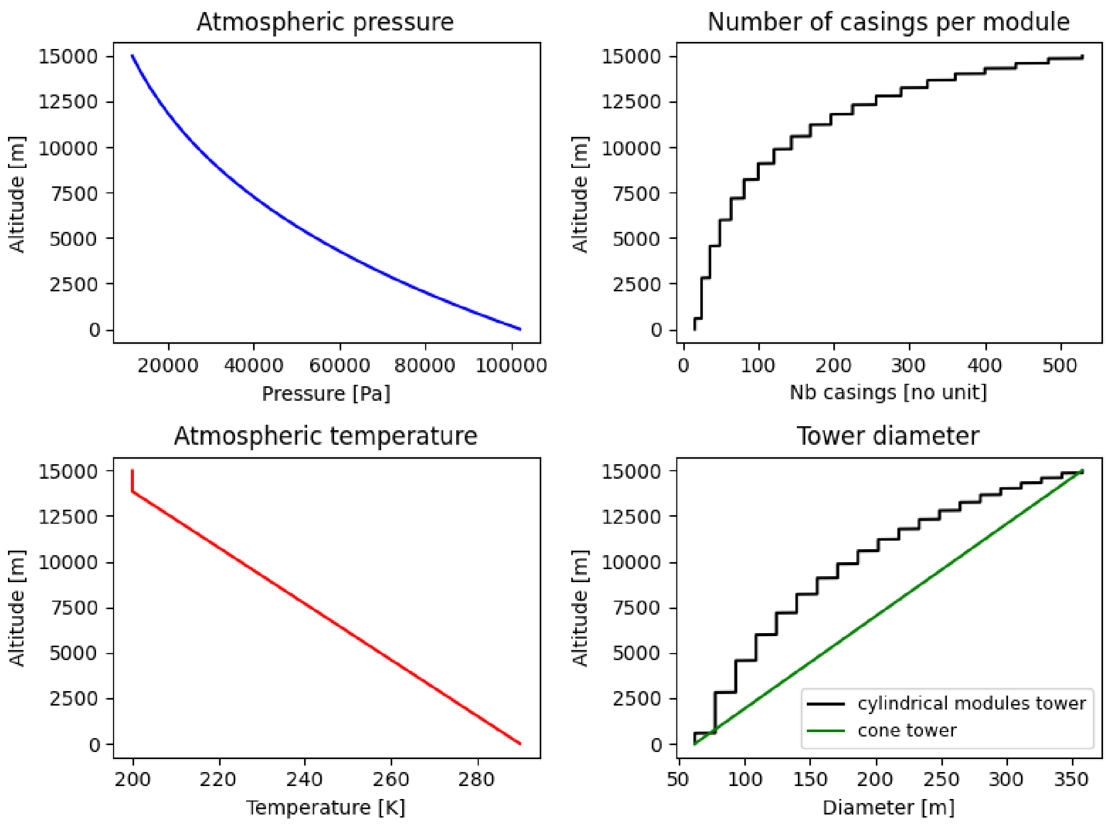


In this second simulation, we only have modified the “dens_surf_mod” variable from the “variables.py” file with respect to the default simulation. As we can read it on the results display, this variable is no longer equal to 20 kg.m^-2 but only to 10 kg.m^-2.

This does not have any consequences on the PV panel array which keeps the same maximum mass and surface density values. Contrariwise, the maximum mass of the tower is now of the order of 14000 tons, and the hydrogen mass needed to lift this whole structure is only about 1500 tons, hence 9% of the total mass of the structure to be deployed. The number of casings within the modules is also significantly smaller (7600 instead of 21000). With this simulation, we understand why the development of a solid but the lightest possible tower structure is a critical element for this innovative power plant in order to save as much materials as possible (and also reduce land use).

2.3.3 Smaller casings simulation

```
(my_env) rodrigo@pc-rodrigo:~/Projets/Python/LTB$ python LTB_simple_model.py

*** Main results from this simulation ***

Main input variables:
x_cube = 10.0 [m]
dens_surf_mod = 20.0 [kg.m^-2]
x_pv = 2000.0 [m]
y_pv = 500.0 [m]

***********

Main structure output variables:
max_mass_pv = 995.0 [ton]
max_dens_pv = 0.995 [kg.m^-2]
max_mass_tower + max_mass_pv = 47641.0 + 995.0 [ton] =
total_mass_structure = 48636.0 [ton]
mass_h2_tower + mass_h2_pv = 3717.0 + 74.0 [ton] =
total_mass_h2 = 3791.0 [ton]
total_mass_h2/total_mass_structure =
total_mass_ratio = 0.07794 [no unit]
7.79 % of the mass of the structure is H2
nb_cube_tower + nb_cube_pv = 154920 + 5760 =
total_nb_cube_structure = 160680
total_nb_mod_tower = 1200

***********

Main production output variables:
max_power = 260.0 [MW]
day_energy_prod = 2.86 [GWh/day]
year_energy_prod = 1.0439 [TWh/year]

(my_env) rodrigo@pc-rodrigo:~/Projets/Python/LTB$
```

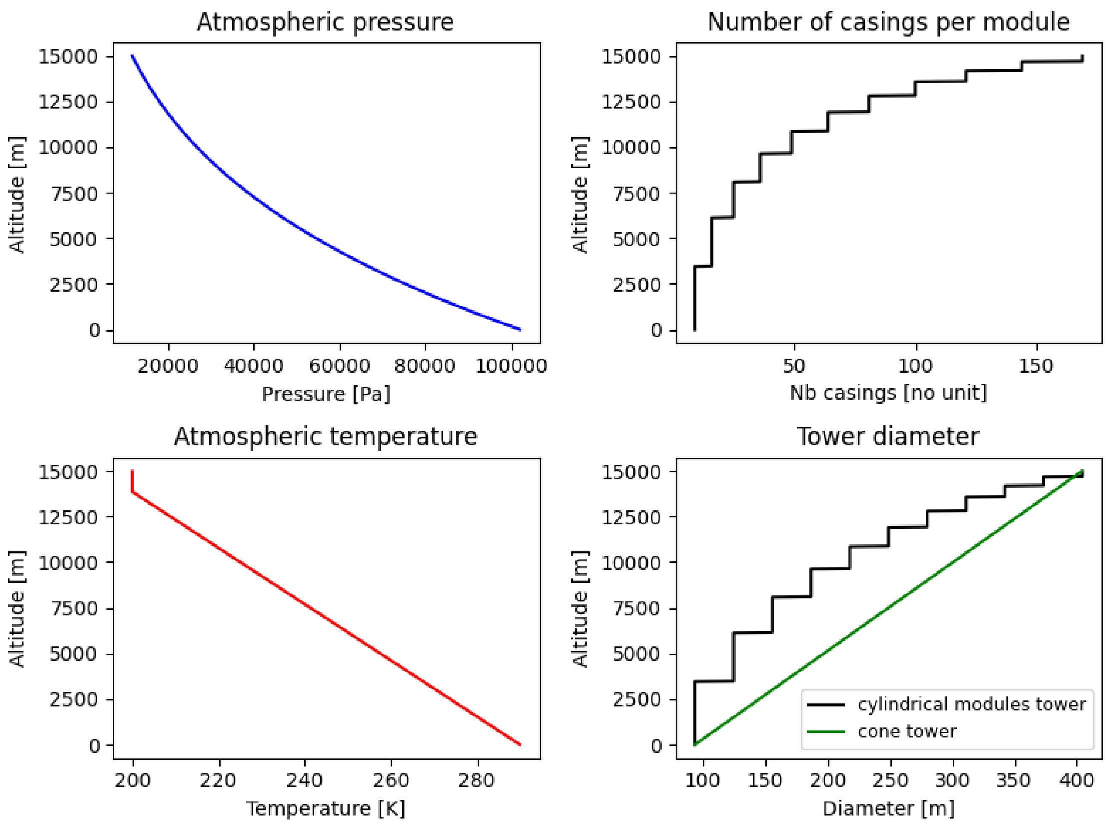


In this third simulation, we only have changed the “x_cube” variable from the “variables.py” file with respect to the default simulation. As we can read it on the results display, this variable is no longer equal to 20 m but only 10 m long.

This has a direct consequence on the PV panel array for which its maximum mass and surface density values have been halved (1000 tons and 1 kg.m^-2 respectively). The maximum mass for the tower keeps close to 50000 tons, and the hydrogen mass needed to lift the whole structure stays around 4000 tons, a bit less than 8% of the total mass of the structure to be deployed. On the other hand, the number of casings within the modules and at the PV panel array level is significantly larger (155000 and 6000 respectively) than for the default simulation. Indeed, with a maximum volume 8 times smaller than for the casings of the default simulation, the number of casings has to increase considerably in order to lift an equivalent mass. But perhaps the strongest constraint of having casings able to contain only such small volumes is the maximum mass the PV panel array is allowed to have. With a surface density of only 1 kg.m^-2, the PV panel array and its structure will have to be made of extremely light materials in order to stay below this limit.

2.3.4 Casing volumes larger security margins simulation

```
(my_env) rodrigo@pc-rodrigo:~/Projets/Python/LTB$ python LTB_simple_model.py

*** Main results from this simulation ***

Main input variables:
x_cube = 20.0 [m]
dens_surf_mod = 20.0 [kg.m^-2]
x_pv = 2000.0 [m]
y_pv = 500.0 [m]

***********

Main structure output variables:
max_mass_pv = 1734.0 [ton]
max_dens_pv = 1.734 [kg.m^-2]
max_mass_tower + max_mass_pv = 55692.0 + 1734.0 [ton] =
total_mass_structure = 57425.0 [ton]
mass_h2_tower + mass_h2_pv = 4534.0 + 128.0 [ton] =
total_mass_h2 = 4662.0 [ton]
total_mass_h2/total_mass_structure =
total_mass_ratio = 0.08119 [no unit]
8.12 % of the mass of the structure is H2
nb_cube_tower + nb_cube_pv = 26062 + 1408 =
total_nb_cube_structure = 27470
total_nb_mod_tower = 600

***********

Main production output variables:
max_power = 260.0 [MW]
day_energy_prod = 2.86 [GWh/day]
year_energy_prod = 1.0439 [TWh/year]

(my_env) rodrigo@pc-rodrigo:~/Projets/Python/LTB$
```



In this fourth simulation, we only have changed the “max_vol_margin” variable from the “variables.py” file with respect to the default simulation. As we can see it on the results display, this variable does not appear as one of the main input variables, but this does not mean that it does not bring relatively important changes to the results. Its default value was 10% and in this simulation we put it at 20%, so the volumes of the cubic casings are only used at 80% instead of 90% of their theoretical maximum capacity.

This has a direct consequence on the PV panel array which shows a ~12% decrease of its maximum mass and surface density values (1750 tons and 1,75 kg.m^-2 respectively). The tower maximum mass increases by 12% (56000 tons), and the hydrogen mass needed to lift the whole structure stays close to 4500 tons, a little bit more than 8% of the total mass of the structure to be deployed. On the other hand, the number of cubic casings within the modules is larger (26000 instead of 21000) than for the default simulation. Indeed, with a maximum allowed volume slightly inferior with respect to the casings in the default simulation, the number of these has to increase in a non-negligible way in order to lift an equivalent mass. This implies a slightly larger tower diameter near the surface (90 m of diameter instead of 60 m) and at the top of the tower near the lower stratosphere (400 m instead of 370 m).

2.3.5 Higher latitude simulation

Figure 2: Surface shadows in the surrounding LTB area caused by the PV panel array in clear-sky conditions

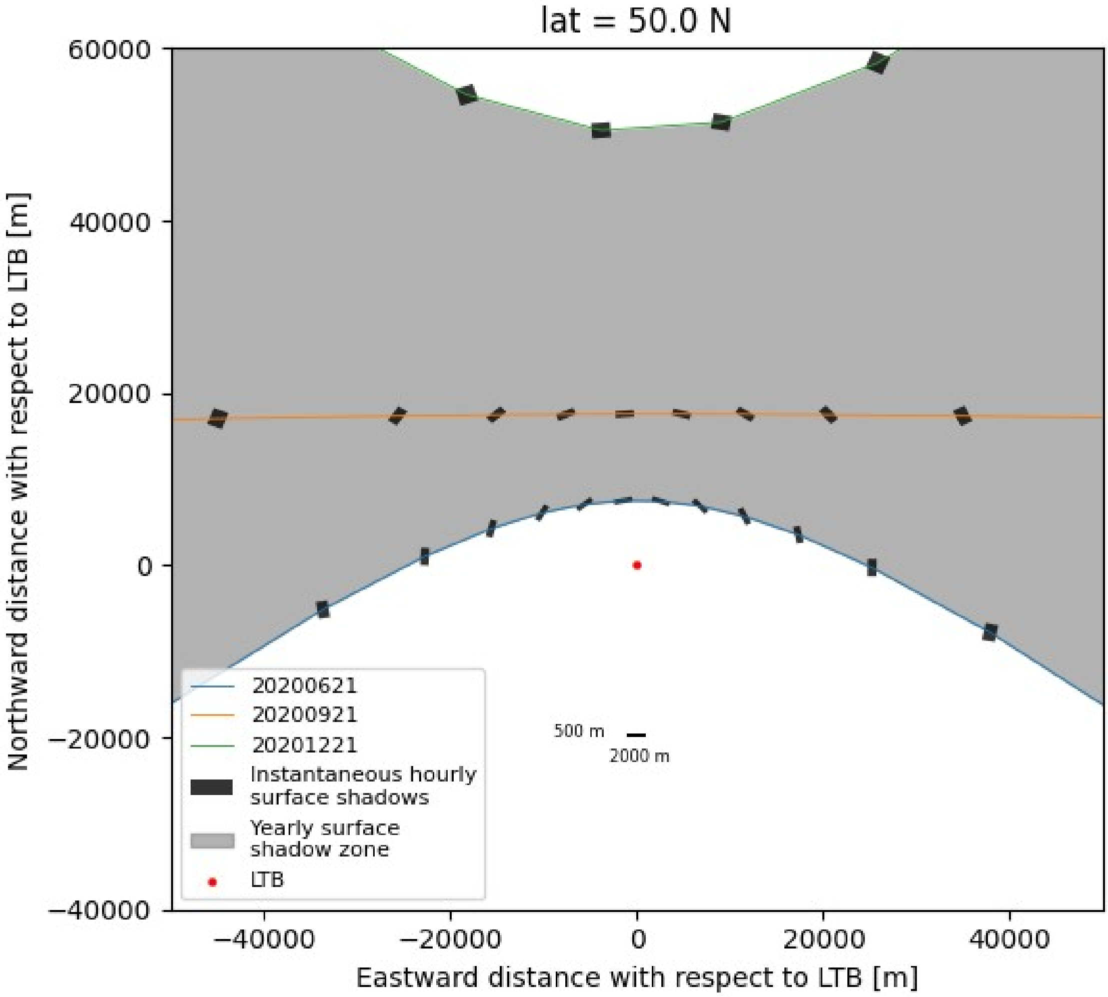
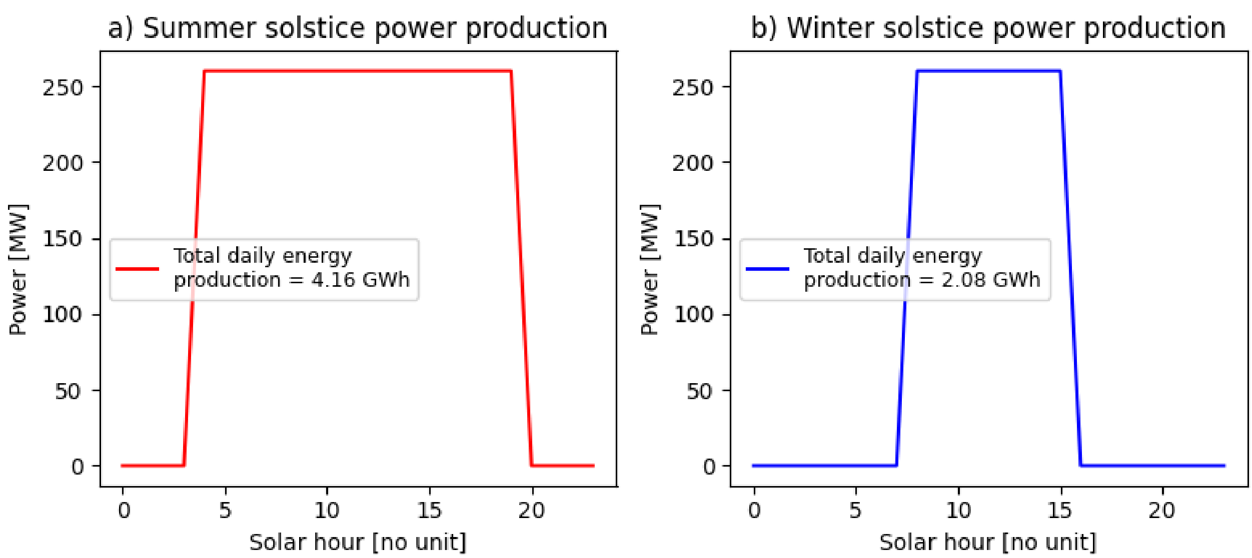


Figure 3: Maximum and minimum daily energy production, lat = 50.0 N



In this fifth and last simulation, we have changed the “lat” variable from the “variables.py” file with respect to the default simulation. It is now set at 50 degrees North instead of 40 degrees North.

By comparing this Figure 2 at latitude 50 degrees North to the 40 degrees North one, we can see that the higher the latitude where the LTB is located, the larger the area of slight cooling at the surface will be. This is mainly due to the fact that, the more poleward the LTB is located, the more the shadow zone will extend towards the Pole because the sun is lower in the sky during the winter season (and also for all other seasons) compared to the default scenario. The yearly shadow zone is also slightly larger towards the equator because the days are longer during the summer season for higher latitude locations, meaning that the sun rises and sets more poleward than for lower latitude conditions. However, the more the surface shadow is far away from the bottom of the LTB, the faster it will move across the shadow zone, and hence the less it will tend to cool the surface at those distant places.

If we compare Figure 3 at 50 degrees North to the 40 degrees North one, we can see that the maximum total daily production slightly increases at the summer solstice (4.16 instead of 3.9 GWh), and the minimum total daily production slightly decreases at the winter solstice (2.08 instead of 2.34 GWh). As the LTB latitude goes poleward, the difference between these two extremes increases, creating a larger ratio between the maximum daily energy produced during the summer season and the minimum daily energy produced during the winter season. This ratio is equal to 1.67 at 40 N while it is equal to 2 at 50 N, meaning that, at this latter location, the LTB roughly produces twice as much energy in summer days than in winter days.