Energy Transition Project Montreal

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Outline

- **Base case**
  - **Basic case**
  - **Wind generation adjusted**
- Uncertainty
  - Load growth forecast
  - Weather uncertainties
- Sector Coupling
  - Hourly TER of the heat pump
  - Thermal storage

Base case study

Technologies considered:

- Hydro (run of river)
- Wind turbines
- PV panels
- Biomass power plant
- Pumped-hydro storage

Hydro (run of river)

Montreal river is the Saint Laurent (2 km wide)

Hypotheses:

- 1% of the width ➔ 20m wide power plant
- 2 tides per day (https://tides.gc.ca/en/stations/00755)
- H = 2m
- Q = [60;100]m^3/s (https://www.cehq.gouv.qc.ca/suivihydro/graphique.asp?NoStation=001003)
- $P^{rated} = [900; 1500]kW$ ➔ $P^{rated} = 1MW$ (fixed to respect the nature of the river which iconic in Montreal. It can be seen as a government regulation limit)

Hydro (run of river)

$P^{real} \in [600 ; 1000]$ kW (function of the flow rate)

Flow rate can thus be used to model an availibility factor of the hydro power plant.

Base case structure

The structure of the code is exactly the same as in the course (sets, parameters, model, variables)

All technologies and global parameters can be seen in the different files of the project folder.

The Demand is composed of the electrical demand plus the thermal demand divided by the average TER (4) of the Heat pump.

Base case results

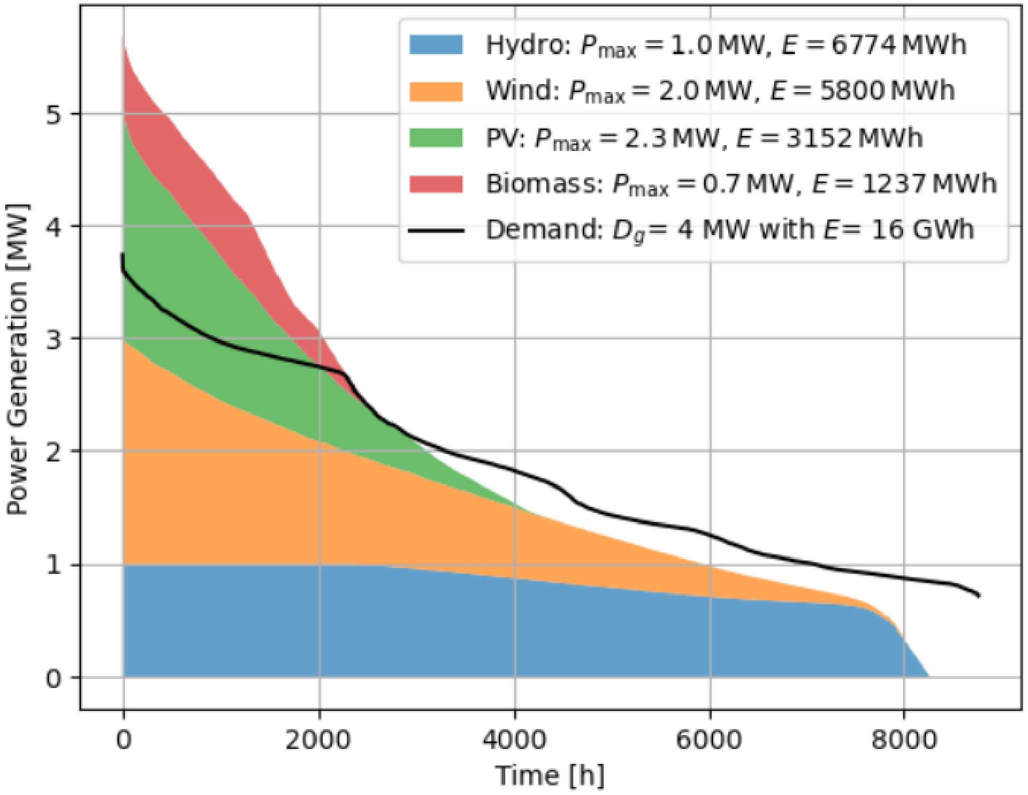

Fig 1: First jet of the energy mix.

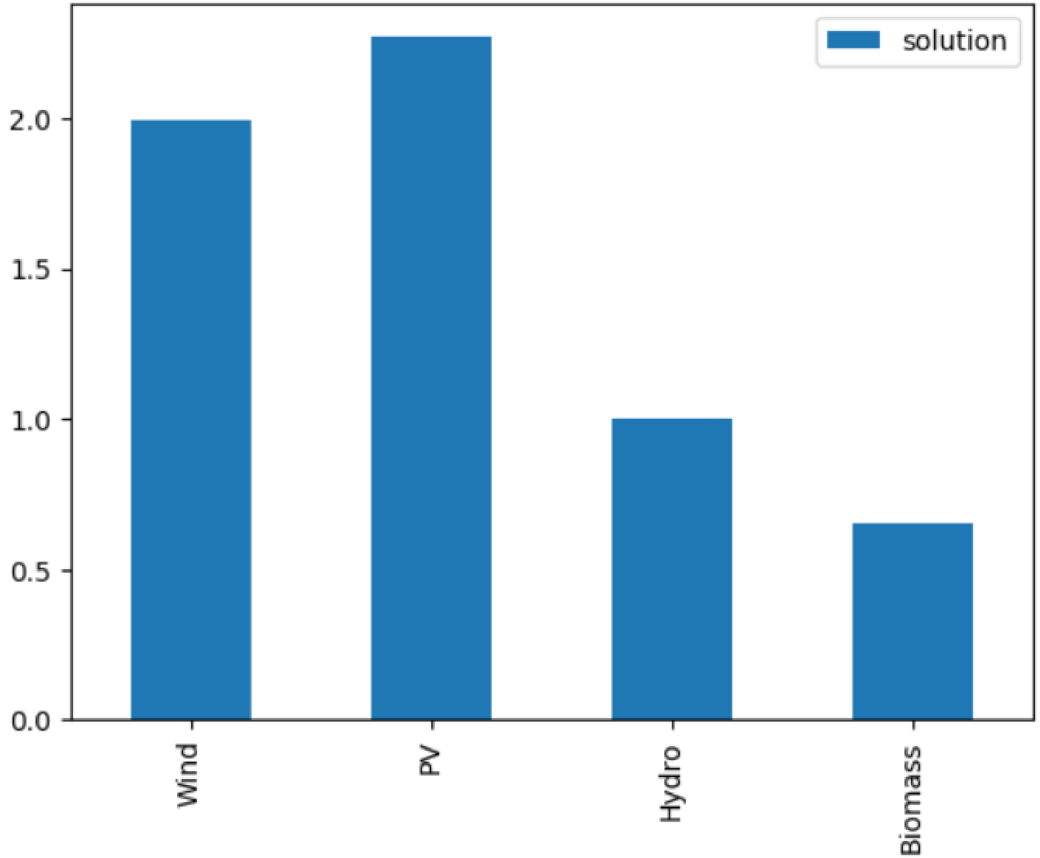

Fig 2: Technologies distribution.

$LCOE = 101.3€/MWh$

$Curt = 1003.42MWh$

$CO_2 emissions = 75.55t$

Base case analysis

Hydro

- Maxed out capacity – production varies with river flow rate

Wind

- > 8 000 operating hours/year
- Nominal (rated) power only reached for a few hours/year

Solar PV

- Highest installed capacity of all sources
- Low capacity factor → actual output limited

Biomass

- Provides dispatchable, flexible power to balance variability

Pumped-Storage

- Installed: ?? MWh (< 58 MWh limit)
- Short-term storage to smooth supply & demand

Cut-out wind speed

In Fig 1, it can be seen that the energy mix proposes a wind turbine production shape that do not match with the curve of power of a wind turbine.

It should describe an AF close to 1 for every wind speed between 15 and 25 m/s for the Vestas V66 and reaching its maximum power output (Fig 3), as seen in the Renewable Energy course of Mr. Dewallef.

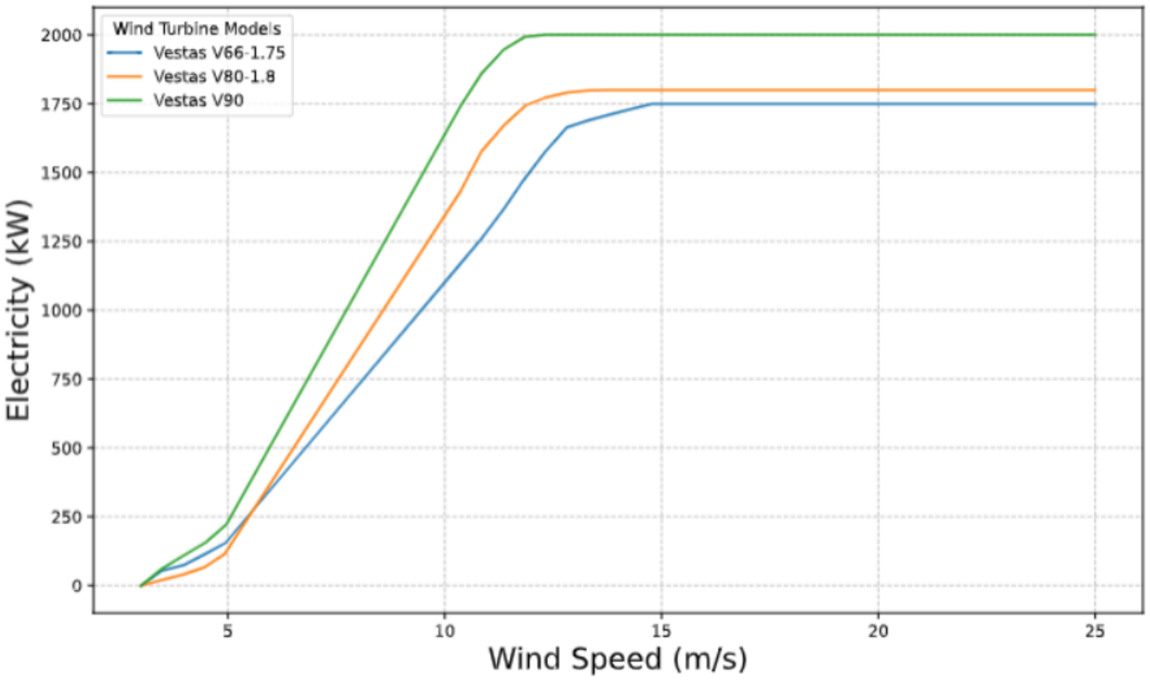

Fig 3: Wind turbine power as a function of wind speed.

Calculation of the wind capacity factor

After checking the AF (capacity factor) values, we noticed that the AF was not equal to 1 from 15[m/s] to 25[m/s] which is not correct. To solve that problem, we used a function from the Renewable Energy course that permits to determine the AF of a wind turbine based on its dimensions and the air density variation throughout the year.

$$AF = \min\left(1, \max\left(0, \frac{P^{avail}}{P^{rated}}\right)\right)$$

with

$$P^{avail} = \eta_{alt}\left(P^{raw} - P^{loss}\right) \text{ and } P^{raw} = \frac{1}{2}\rho S C_{p_{max}} {V_{eff}}^3$$

New wind capacity factor

We obtained a new AF file which is now well considering the curve of power of the turbine.

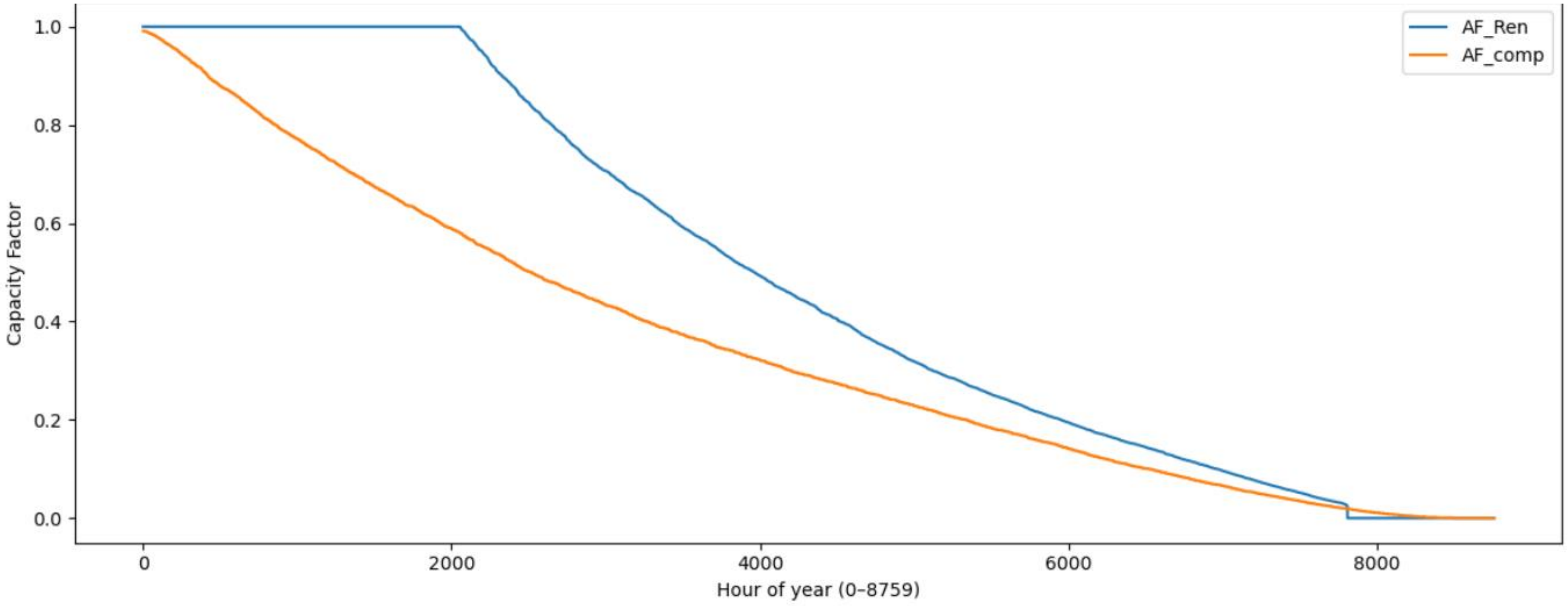

Fig 4: AF initial (orange), AF recalculated (blue).

Energy mix updated

Taking into account that new AF, we obtained the following results:

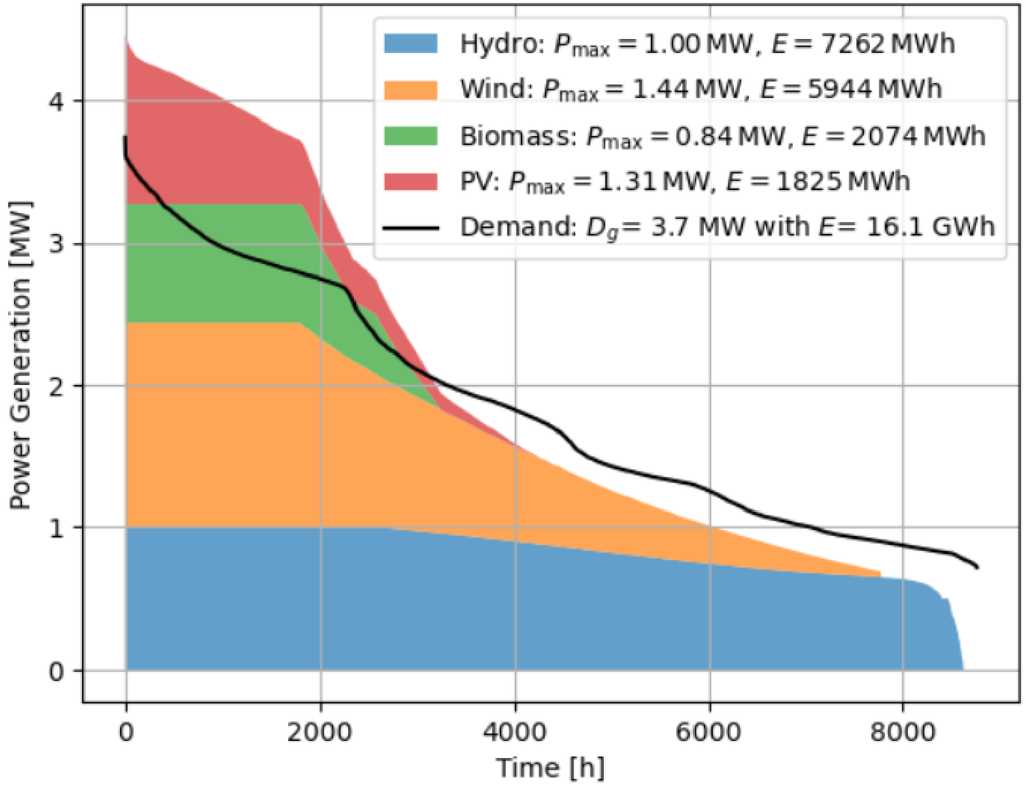

Fig 5: Final energy mix.

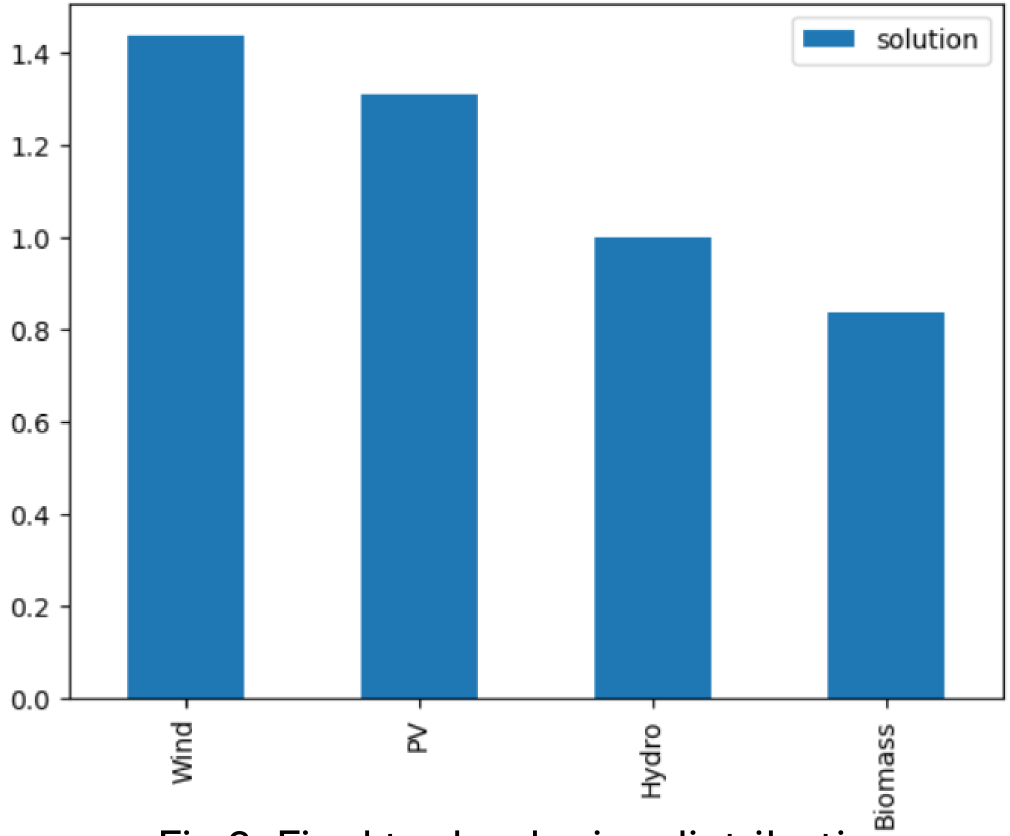

Fig 6: Final technologies distribution.

$LCOE = 103.4€/MWh$

$Curt = 208.19MWh$

$CO_2 emissions = 162.88t$

Energy mix comments

First of all, the mix is quite well balanced.

The wind is the first energy source which is relevant in a country quite windy as Canada. After updating the AF, its installed capacity has increased as the AF did. The capacity factor has been computed considering the Vestas V66 1650 model attributes, which has a hub height of 80m and a diameter of 66m. This model has an installed capacity of $1{,}66MW$.

The second is PV panels. Using a maximum power output per squared meter of $227{,}7W/m^2$ (*) with a $P^{rated} = 1{,}3MW$, it represents a surface of $5\ 709m^2$. Divided in 4 to distrubted on each districts, it gives a surface of $1\ 427m^2$ which is easy to meet with only 2 large building' roofs.

* : https://vertexsplus.trinasolar.com/wp-content/uploads/2025/02/Datasheet_Vertex-S_NEG9R.25_EN_2025_A_web.pdf

Energy mix comments

Hydro has already discuss before but an observation is that it directly reach the maximum power rated that we fixed which makes sense as it is a very cheap and efficient kind of energy.

For the biomass, the most important number is the amount of energy produced: $2\ 074MWh$. Knowing that energy yield by the miscanthus is $0{,}16GWh/ha/year$, the required area to grow miscanthus is equal to:

$$S_{farm} = \frac{2{,}074}{0{,}16} = 12{,}96ha$$

* : https://vertexsplus.trinasolar.com/wp-content/uploads/2025/02/Datasheet_Vertex-S_NEG9R.25_EN_2025_A_web.pdf

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Uncertainty

The third part of the project is to consider potential uncertainties regarding our model. We decided to study 2 types of uncertainties:

- Increase of the total demand (ex: campus expansion, EV's increasing, etc.) Two scenarios:
    - Demand x 1,5
    - Demand x 2,5
- Weather variation from one year to another ➔ different PV and Wind AF (2017,2019,2024)

The first one can have different capacities per scenario, the second one cannot.

Demand increase

- Demand x 1,5

The graph shows a doubling of wind capacity, while PV is multiplied by 7 . The biomass reaches it's maximum capacity.

This huge growth is due to the intermittency of the technology available for the optimization.

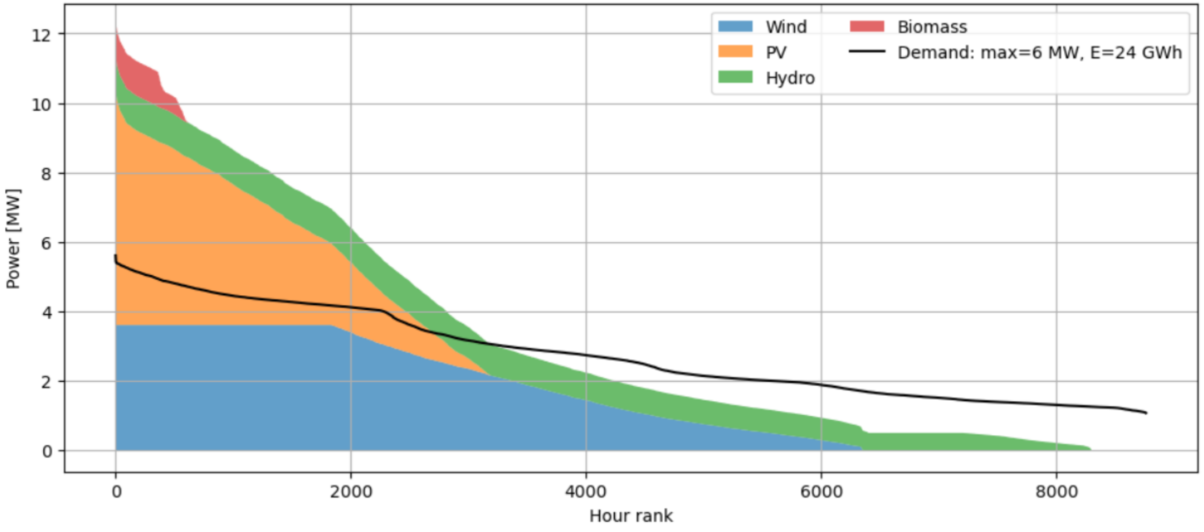

Fig 7: Energy mix case 1,5

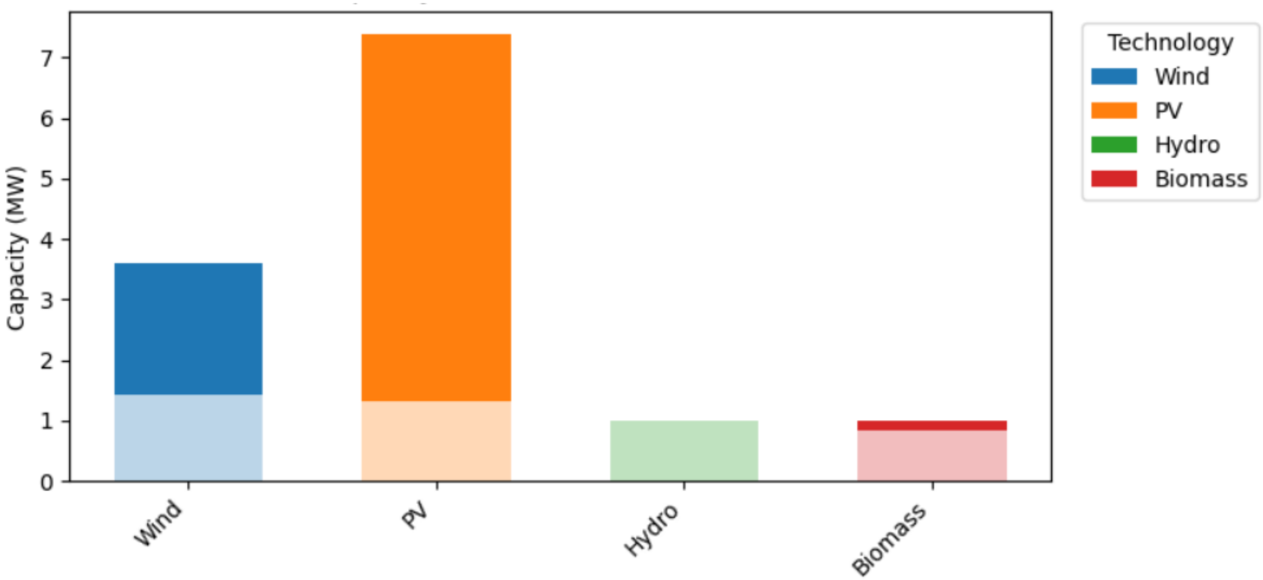

Fig 8: Capacity distribution case 1,5

Demand increase

- Demand x 2,5

The wind is multiplied by almost 4 times the factor 2,5 while PV is multiplied by almost 6 times that factor.

This increase is due to the same reason as the 1,5 case.

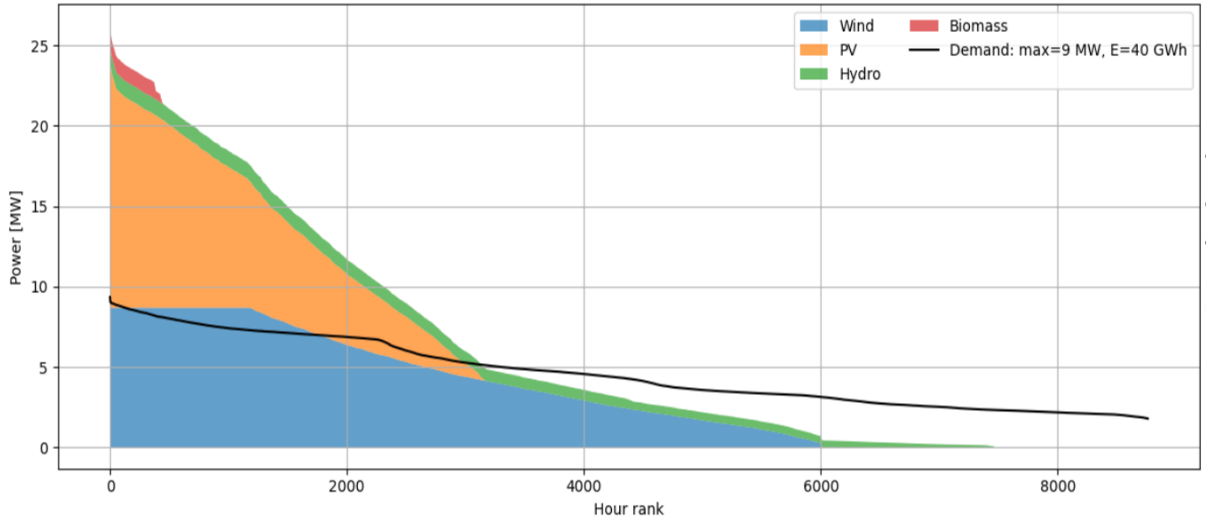

Fig 9: Energy mix case 2,5

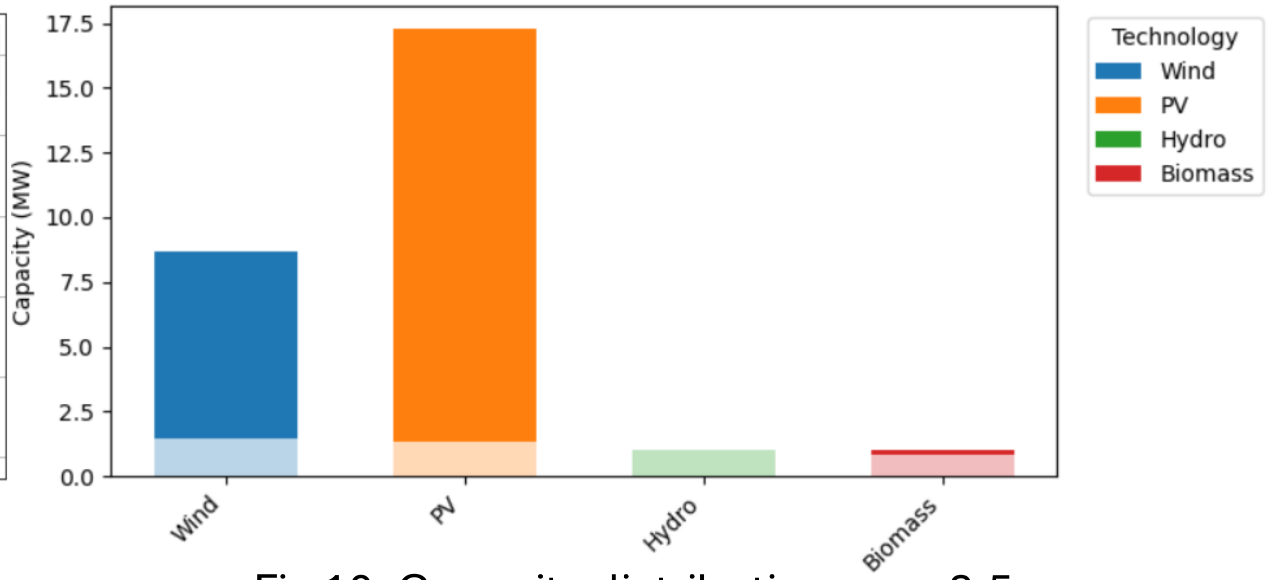

Fig 10: Capacity distribution case 2,5

Demand increase comments

When we rely solely on solar PV and wind to meet a growing load, installed capacity must rise much faster than demand. In our case, a 2,5× increase in peak demand (from 3,7 MW to 9 MW) requires roughly a 5 - 6× increase in generation capacity, from 4,5 MW of PV/wind up to 26 MW.

This overbuild reflects the intermittent nature of these resources: extra capacity is needed so that, on sunny or windy days, we can both meet real-time demand and charge storage, then discharge later when output falls but demand remains high. Consequently, a large portion of the installed capacity remains unused, leading to high curtailment since full output is rarely required.

Demand increase

To add more flexibility, considering cheaper and longer storage, or non-intermittent technologies could help.

One strange thing is that the storage duration acts as a growing constraint when it increases. We could think that it would help to have a larger storage duration, but in the model it does not. In fact, the bigger the storage duration, the smaller the maximum charge and discharge value is, and thus the less flexibility the variable has.

Costs for 1,5 scenario are 1,5 M€ and for 2,5 scenario are 6,6 M€. This non-linear increase is also due to the lack of flexibility.

Weather variation

In this part, 3 years were chosen to analyse the impact of the weather of a given year on the energy mix.

This yields a more reliable energy mix as it considers 3 different scenario to choose the installed capacity of the different technologies.

Weather variation

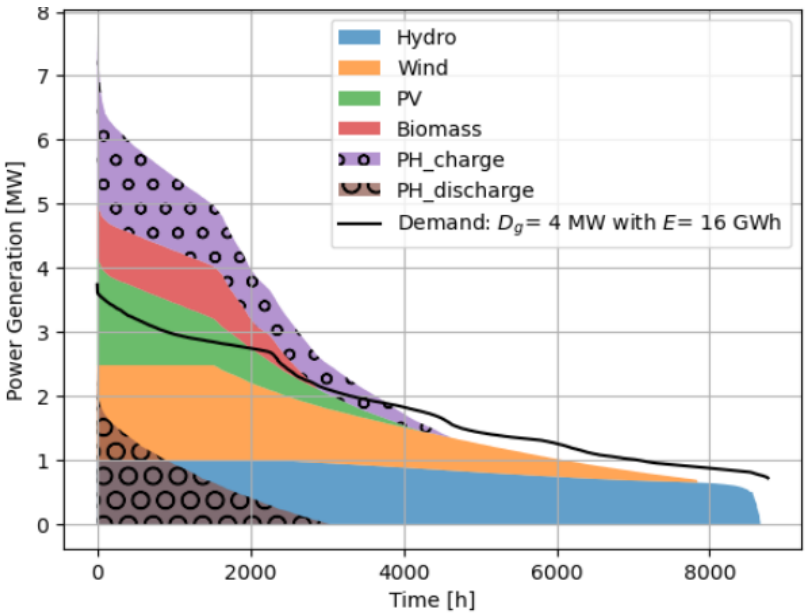

Fig 11: Energy mix with AF_{2017}
$CO_2 emissions = 105.56t$
$LCOE = 109.9€/MWh$
$Curt = 303.63MWh$

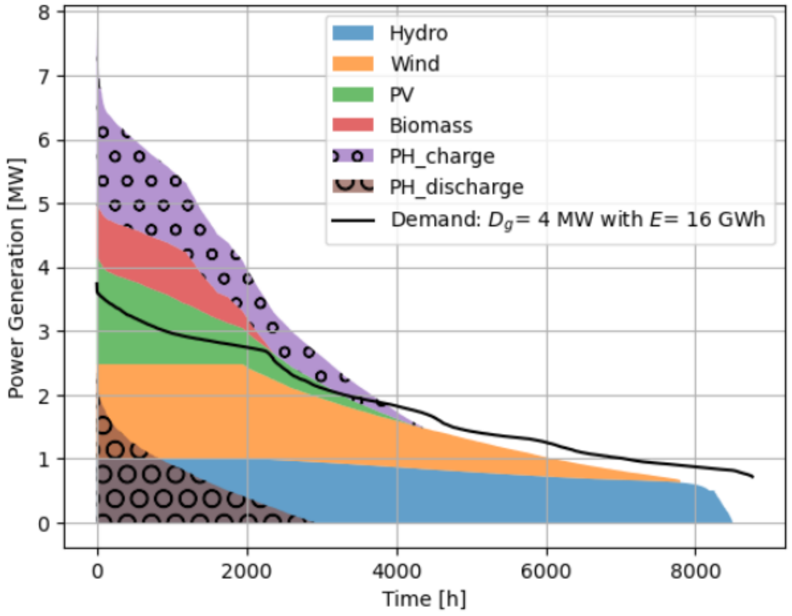

Fig 12: Energy mix with AF_{2019}
$CO_2 emissions = 82.55t$
$LCOE = 109.9€/MWh$
$Curt = 737.32MWh$

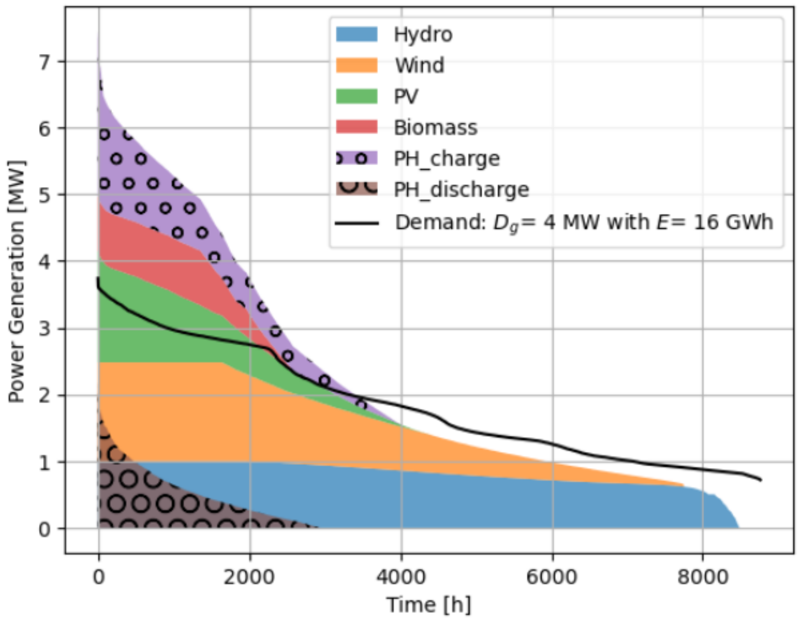

Fig 13: Energy mix with AF_{2024}
$CO_2 emissions = 92.19t$
$LCOE = 109.9€/MWh$
$Curt = 897.25MWh$

Weather variation comments

The installed power is the same for the 3 cases, only the production is modified and hence only the curtailment and CO_2emissions may change.

We observed that the curtailment is increasing significantly throughout the years.

CO_2 emissions fluctuate based on the flexibility needed trough the year, leading to the usage of biomass power plant.

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- **Sector Coupling**
  - **Hourly TER of the heat pump**
  - **Thermal storage**

Sector coupling

The second part of the project consists in distributing the different energy sources on the campus. In others words, to consider the topology of the campus.

Two cases are considered.

- **Hourly TER without thermal storage**: using Maxime's provided TER values directly
- **Fixed COP with thermal storage**

TER factor

- TER ∈ [0,20]; 8 760 hourly values over one year from EES simulations (Maxime Haas)
- Scales thermal loads to electricity demand; high hourly variability alters demand profiles
- Base/uncertainty cases use average TER = 4
- Dynamic TER not analytically defined → all hourly values imported directly

Thermal storage can thus not be considered in this first case as the hourly TER is computed for a given heat/cold demand.

Incidence matrix

The incidence matrix is build based on the network obtained in the Integrated Project.

Hypotheses:

- TFO + 4 districts + centralized thermal demand

(every building cannot be considered as it leads to a too big model)

Maximum technology capacities

Technologies	TFO	Dupéré	Overdale	Hochelaga	Anjou	Thermal
Wind	100	0	0	0	0	0
PV	0	5	5	5	5	0
Biomass	1	0	0	0	0	0
Hydro	1	0	0	0	0	0
Heat Pump	1000	0	0	0	0	0
Pumped_Hydro	58	0	0	0	0	0

Hourly TER without thermal storage

We obtained the following results:

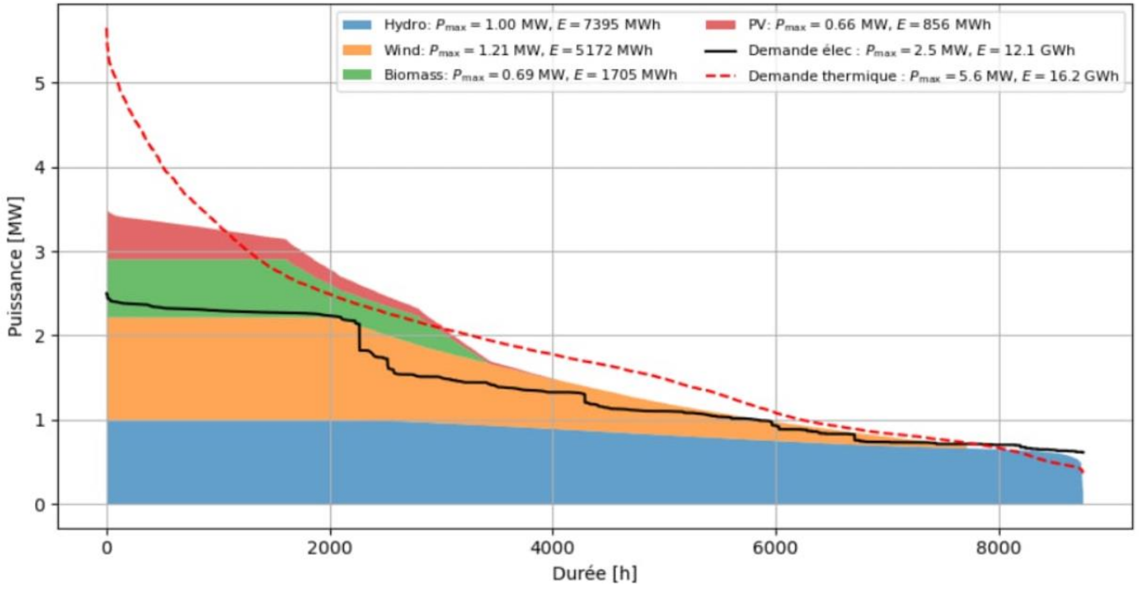

Fig 14: Energy mix with hourly TER

Technology	TFO	Dupere	Overdale	Hochelaga	Anjou	THERMAL
Wind	1.213349	0.000000	0.000000	0.000000	0.000000	0.000000
PV	0.000000	0.159486	0.164653	0.214330	0.119849	0.000000
Hydro	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Biomass	0.690728	0.000000	0.000000	0.000000	0.000000	0.000000

Fig 15: Technologies capacities distribution per district with hourly TER

Hourly TER without thermal storage comments

Incorporating hourly TER lowers electricity demand for heating/cooling, reducing overall installed capacity.

Distributed load patterns and line limits lead to lower PV installation compared to the base case.

Installed generation is concentrated at the TFO, adjacent to storage, heat pump and campus network center while PV utilization decreases.

Thermal storage

This section does not consider the hourly TER, but considers fixed TER and the use of batteries at each district and the use of thermal batteries in the cold and heat sectors.

Thermal storage

Therefore, we adopt a simplification. It can be equal to 3 different values:

- $TER = 4$: when only cooling is required
- $TER = 3{,}5$: when only heating is required
- $TER = 8$: when both are required simultaneously

Example: if a timestep requires $10MWh$ of cooling and $5MWh$ of heating, then $5MWh$ of each is supplied with $TER = 8$. The remaining $5MWh$ of cooling is supplied with $TER = 4$.

Thermal storage

In addition to electrical storage, we introduce three dedicated thermal-storage systems, two for hot water and one for chilled water, that operate with very high round-trip efficiency by storing energy directly in their respective sectors. Because these storage assets buffer the heating and cooling demands independently of the heat-pump’s electrical conversion, they alter the timing and magnitude of thermal supply and therefore the effective hourly TER. For this reason, it is not valid to apply the original hourly TER profile when thermal batteries are included in the system model.

Fixed COP with thermal storage

We obtained the following results:

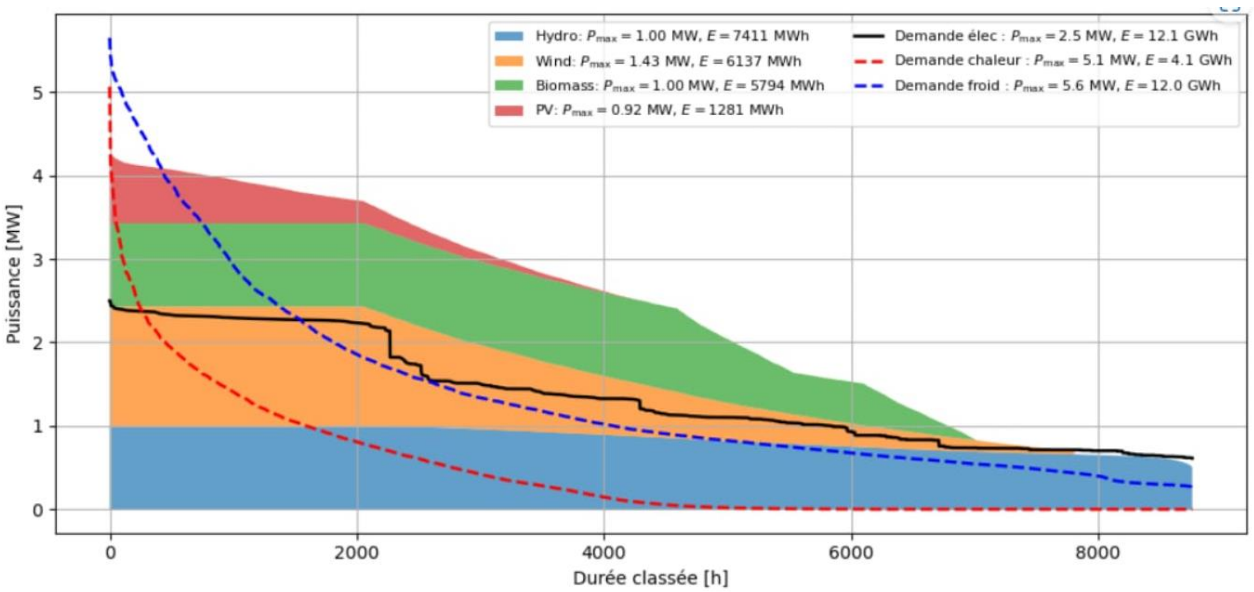

Fig 16: Energy mix with thermal storage

Technology	TFO	Dupere	Overdale	Hochelaga	Anjou	Hot	Cold
Wind	1.428393	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
PV	0.000000	0.000000	0.000000	0.000000	0.920872	0.000000	0.000000
Hydro	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Biomass	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Fig 17: Technologies capacities distribution per district with thermal storage

Fixed COP with thermal storage comments

In this scenario, overall installed capacity is reduced compared to the TER-based case due to the heat pump being modeled with a high constant TER. Despite this reduction, all heating and cooling storage assets are deployed at their maximum capacities, leading the solver to fully leverage the heat pump's eight TER units whenever simultaneous heat and cold generation occurs. Storage installations include 49.5 MWh of pumped hydro at the TFO, approximately 0.85 MWh of batteries in each district, a 20 MWh hot-water tank, 100 MWh of molten-salt storage in the heat sector, and a 15 MWh chilled-water tank in the cold sector. These unexpectedly high storage levels point to a potential error in the optimization model, the root cause of which has not yet been determined.