Energy Storage and Transport

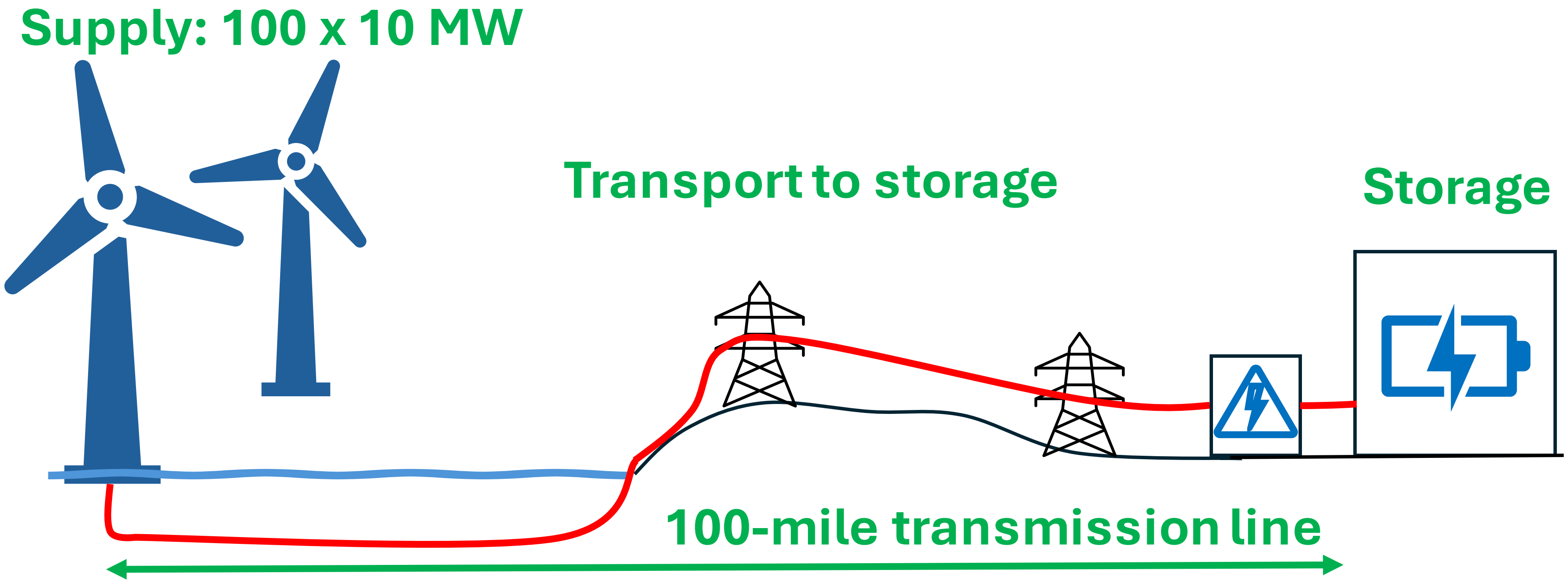
Modeling example

The model development cycle

Modelling objective	Physical phenomena	Model selection	Mathematical elaboration	Implemen-tation	Validation & verification	Reflection
Analyze the context and define an objective for modeling. **Which purpose can a model serve** in the project?	Perform research to understand the physical phenomena that **play a role in the project.** How do they relate to the modelling objective?	Select which phenomena are essential to include and which may be neglected. Which **simplifications and assumptions** can be made?	Define and combine the mathematical relations that describe the physical phenomena and apply the selected simplifications.	Create the model which uses the mathematical relations to predict (an) outcome(s) based on given inputs.	Validate: does the model solve the right equations? Verify: does the model solve the equations correctly?	Is the modelling objective met? What are the uses and limitations of the model? How can it be improved?

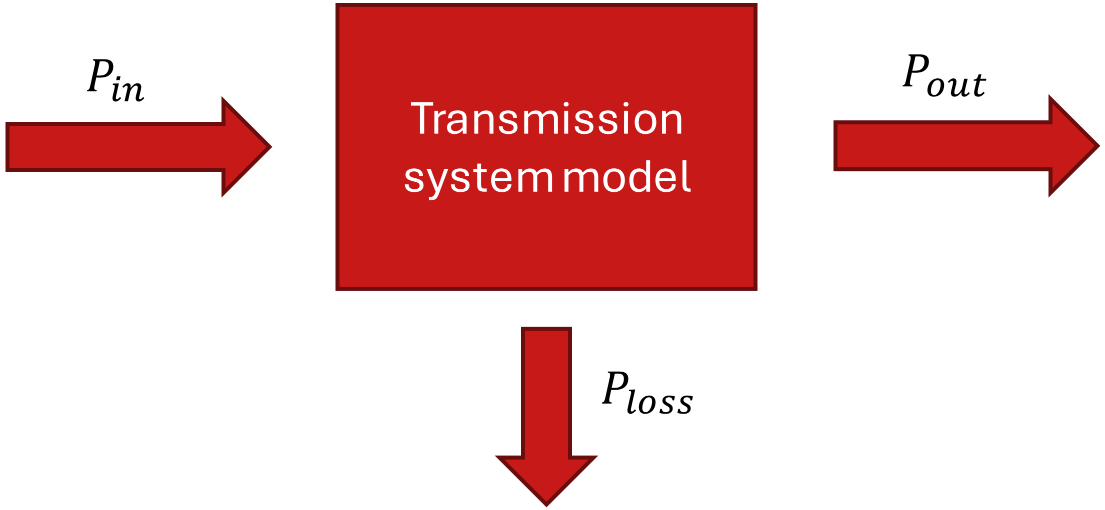
- Modelling objective
- Physical phenomena
- Model selection
- Mathematical elaboration
- Implementation
- Validation & verification
- Reflection

Energy Storage and Transport



- Large off-shore wind farm, transporting electric energy to a hydroelectricity dam using high-voltage transmission lines.
- Topic of this lecture:
  Model development for the transmission lines

The model as a black box

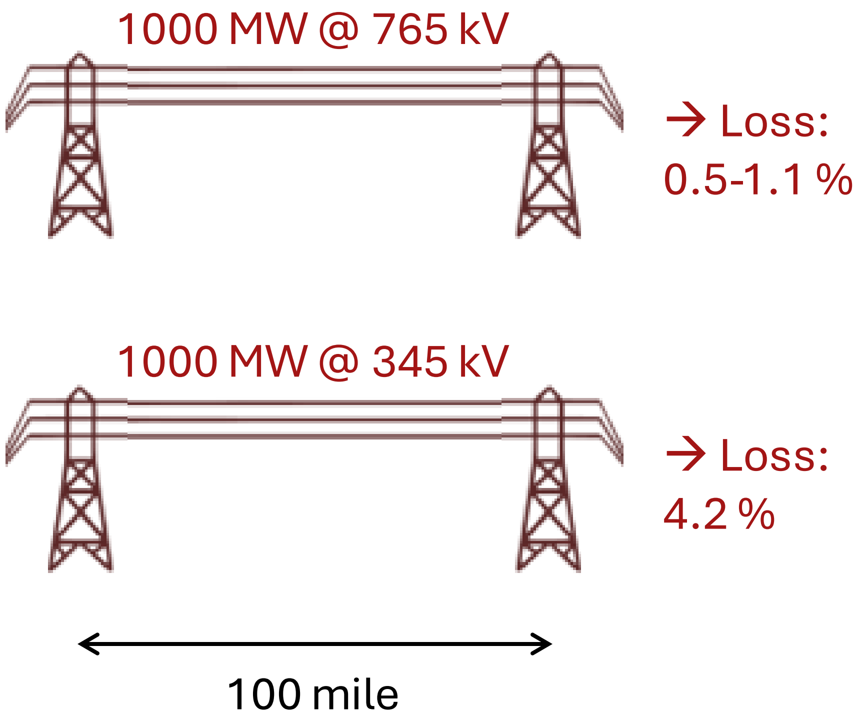


- The transmission line model should provide a relation between:
  - **Input:** power supplied by the turbines
  - **Output:** power delivered to the storage

Modeling questions

- How much energy is lost in the transmission lines?
- How do these losses depend on the transport system parameters?
  - Length of the transmission lines
  - Electricity transport voltage and power
  - Type of transmission cables
  - Type of transformers
  - Etc.

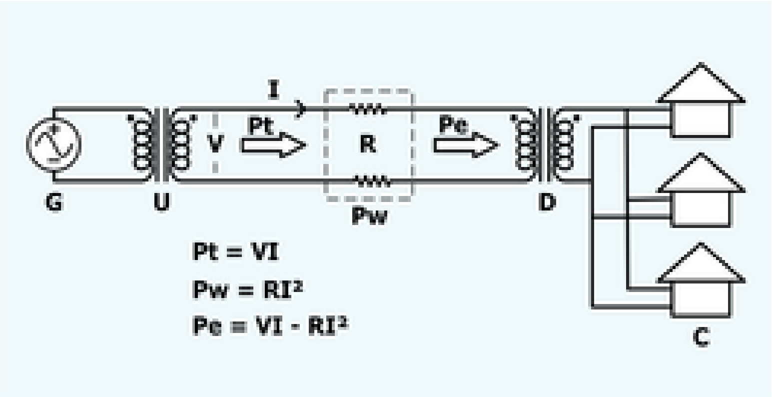
What are typical losses?



Example from literature:

- A 100 mi (160 km) span at 765 kV carrying 1000 MW of power can have losses of 0.5% to 1.1%.
- A 345 kV line carrying the same load across the same distance has losses of 4.2%.

Why is a higher voltage better?



- Transported power = voltage [V] x current (A):
  - $P = VI$
- Power losses = resistance [Ohm] x current (A)^2
  - $P_{loss} = RI^2$

- Best to transport energy at a low current
- Given a fixed transport power, the current can be lowered by increasing the voltage

What causes the losses?

Joule heating
resistance of wires

Dependent on properties of cables and power current

→ Assumption: **main source of loss**

Inductance
caused by magnetic field

Only relevant for alternating current

→ Assumption: **direct current is used**

Corona losses
air ionization

Only relevant when voltage exceeds the corona threshold

Dependent on weather conditions and temperature

→ Assumption: **can be neglected**

Leakage
to ground

Minimal in a correctly designed system

→ Assumption: **can be neglected**

Transformer losses
efficiency of transformer

Expected to be small, but significant

→ Assumption: **take into account**

Modelling objective

Physical phenomena

Model selection

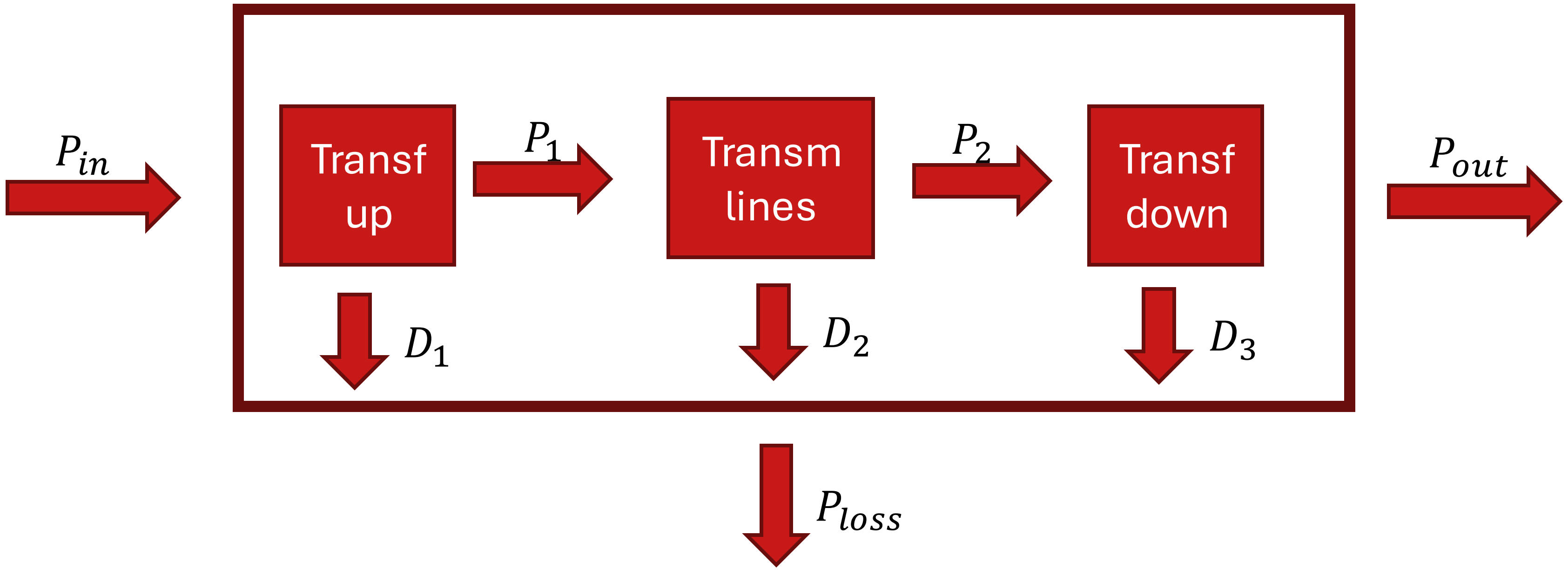
Mathematical elaboration

Implementation

Validation & verification

Reflection

The energy flow diagram



- The structure of your model:
  - How do the sub-components connect ?
  - Where are the losses?

Modelling objective

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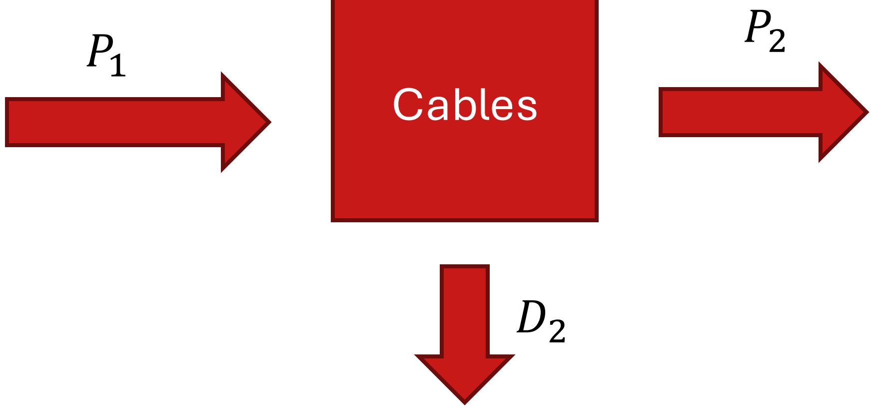
The transmission lines



- Joule heating losses in Watts [W]:

$$P_{loss} = R \times I^2 = R \times \left(\frac{P_1}{V}\right)^2$$

  - *R*: resistance in Ohm [Ω]
  - *I*: electric current in Amperes [A]

- Wire resistance:

$$R = L \times R'$$

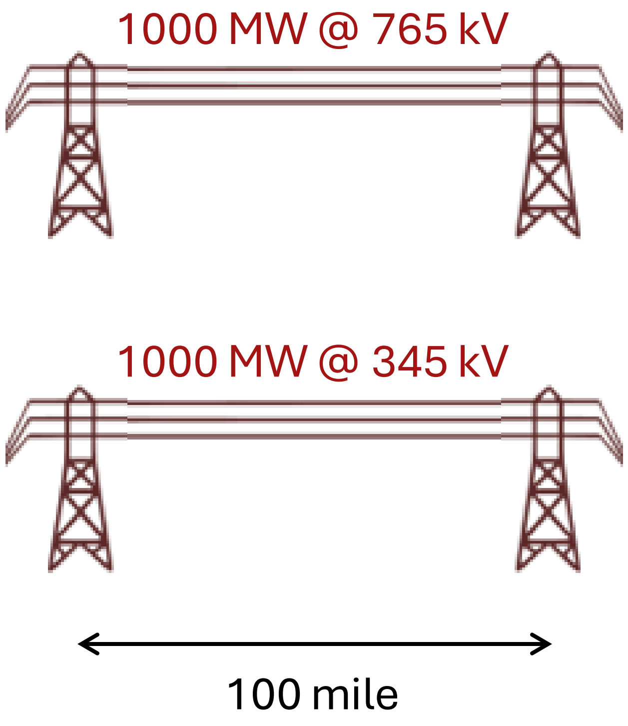
  - *L*: Length of cable
  - *R'*: Resistance per unit length

- Power balance:

$$P_1 - P_2 = L \times R' \times \left(\frac{P_1}{V}\right)^2$$

- Modelling objective
- Physical phenomena
- Model selection
- Mathematical relations
- Implementation
- **Validation & verification**
- Reflection

Does it make sense?



→ Loss: 0.5-1.1 %

→ Loss: 4.2 %

ACSR cable spec sheet:
$R' = 0.03\ [\Omega/\mathrm{km}]$

$$\frac{P_1 - P_2}{P_1} = L \times R' \times \frac{P_1}{V^2} = 160 \times 0.03 \times \frac{1000}{765^2} = 0.82\%$$

$$\frac{P_1 - P_2}{P_1} = L \times R' \times \frac{P_1}{V^2} = 160 \times 0.03 \times \frac{1000}{345^2} = 4.0\%$$

The transformers

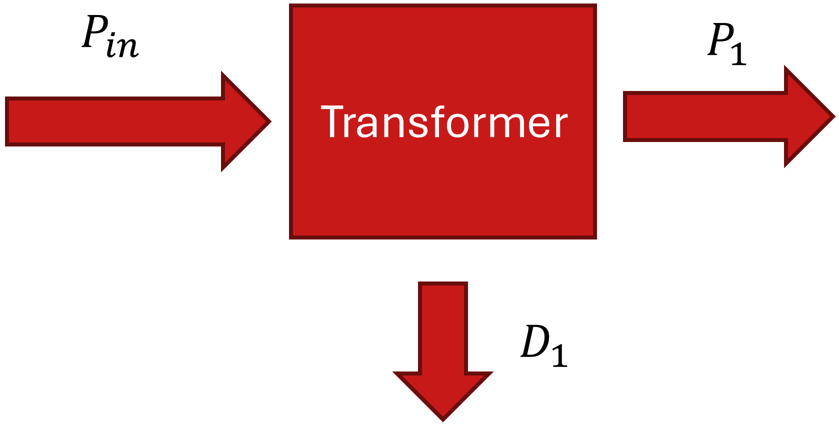
- Heat losses scale with the input power [W]:
  - $D_1 = a \times P_{in}$
  - a: loss coefficient $[-]$
- Loss coefficient is related to efficiency:

$$\eta = \frac{P_1}{P_{in}} = \frac{P_{in} - D_1}{P_{in}} = 1 - a$$

- Power balance:

$$P_1 - P_{in} = (1 - \eta)P_{in}$$

$$P_{out} - P_2 = (1 - \eta)P_2$$



Modelling objective

Physical phenomena

Model selection

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Implementation

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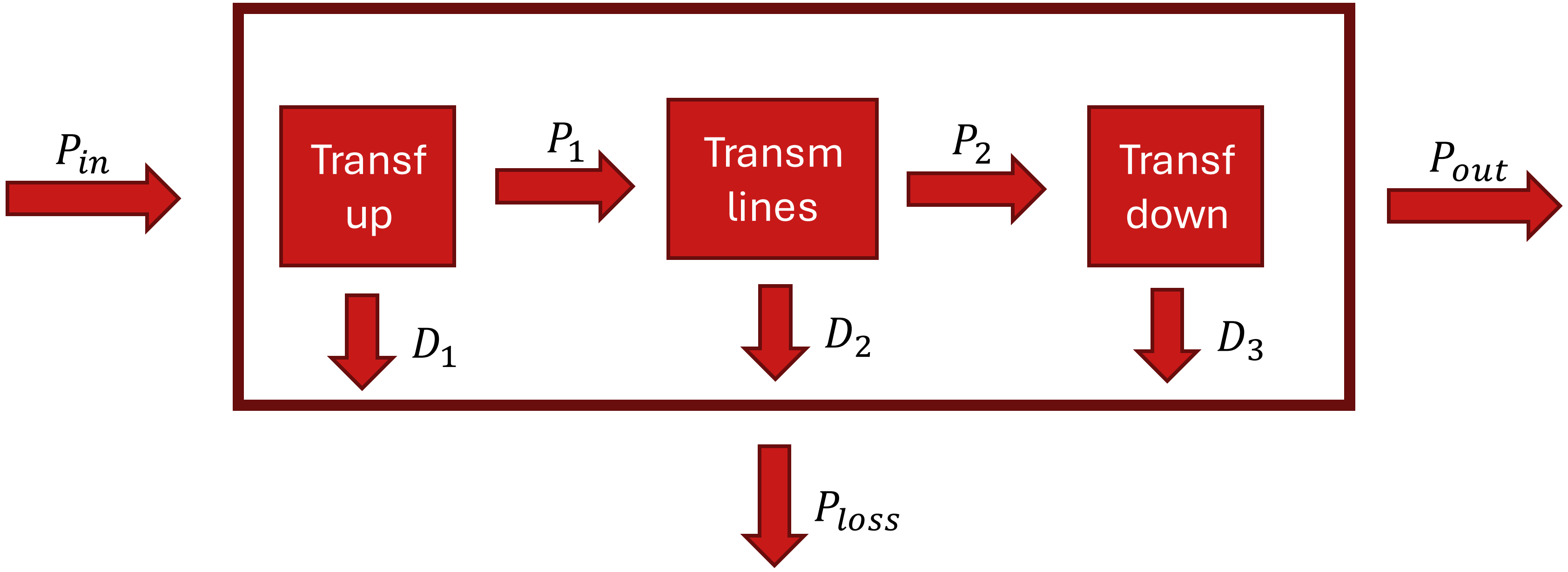
Reflection

Putting the model together



$$P_1 = \eta P_{in}$$

$$P_2 = P_1 - L \times R' \times \left(\frac{P_1}{V}\right)^2 = \eta P_{in} - L \times R' \times \left(\frac{\eta P_{in}}{V}\right)^2$$

$$P_{out} = \eta P_2 = \eta^2 P_{in} - \eta^3 L \times R' \times \left(\frac{P_{in}}{V}\right)^2$$

$$P_{out} = \eta^2 P_{in} - \eta^3 L \times R' \times \left(\frac{P_{in}}{V}\right)^2$$

Modelling objective

Physical phenomena

Model selection

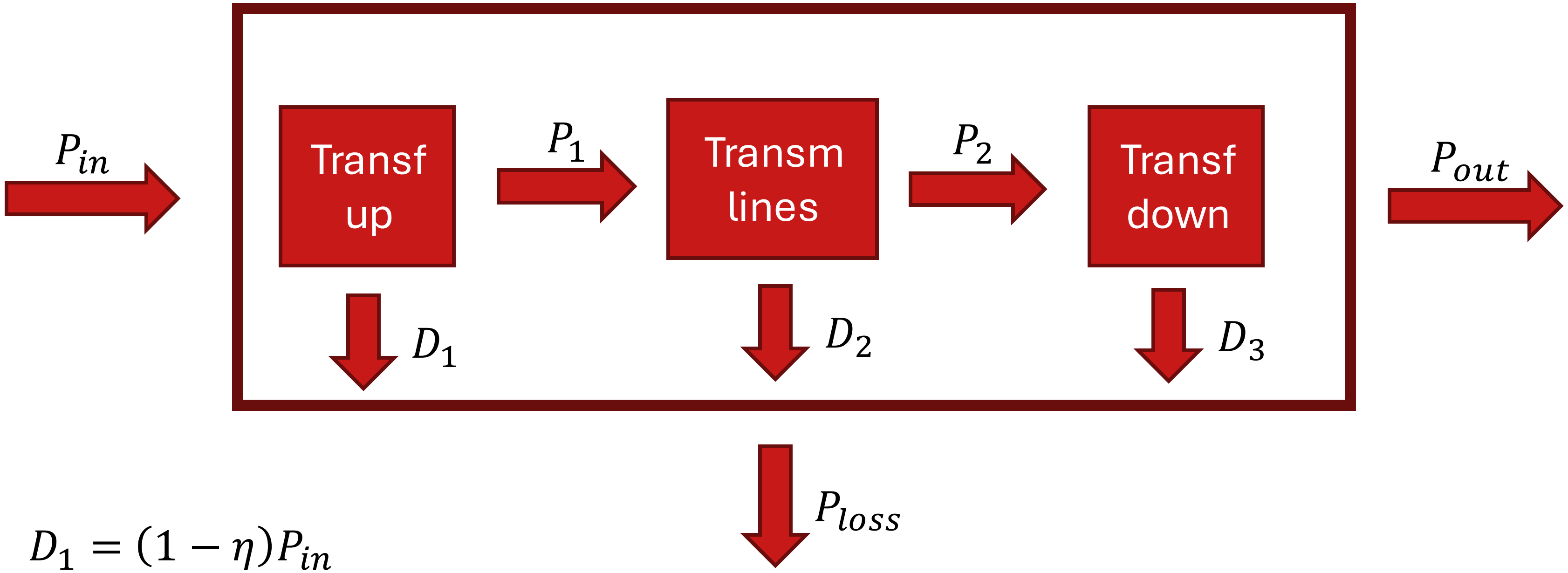
Mathematical relations

Implementation

Validation & verification

Reflection

Checking the result



$$D_1 = (1-\eta)P_{in}$$

$$D_2 = L \times R' \times \left(\frac{\eta P_{in}}{V}\right)^2$$

$$D_3 = (1-\eta)\left(\eta P_{in} - L \times R' \times \left(\frac{\eta P_{in}}{V}\right)^2\right)$$

+

$$P_{loss} = (1-\eta^2)P_{in} + \eta^3 L \times R' \times \left(\frac{P_{in}}{V}\right)^2 \Rightarrow P_{loss} = P_{in} - P_{out}$$

Modelling objective

Physical phenomena

Model selection

Mathematical elaboration

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Does the result make sense?

- Estimating parameters from spec sheets:
  - High-voltage transformer:

$$\eta = 99\%$$

  - ACSR cable:

$$L = 160\ [km]$$
$$R' = 0.03\ [\Omega/\mathrm{km}]$$

- Losses at 1000 MW and 765 kV:

$$P_{loss} = (1 - 0.99^2) \times 1000 + 0.99^3 \times 160 \times 0.03 \times \left(\frac{1000}{765}\right)^2 = 27.9\ [MW] = 2.79\%$$

Modelling objective

Physical phenomena

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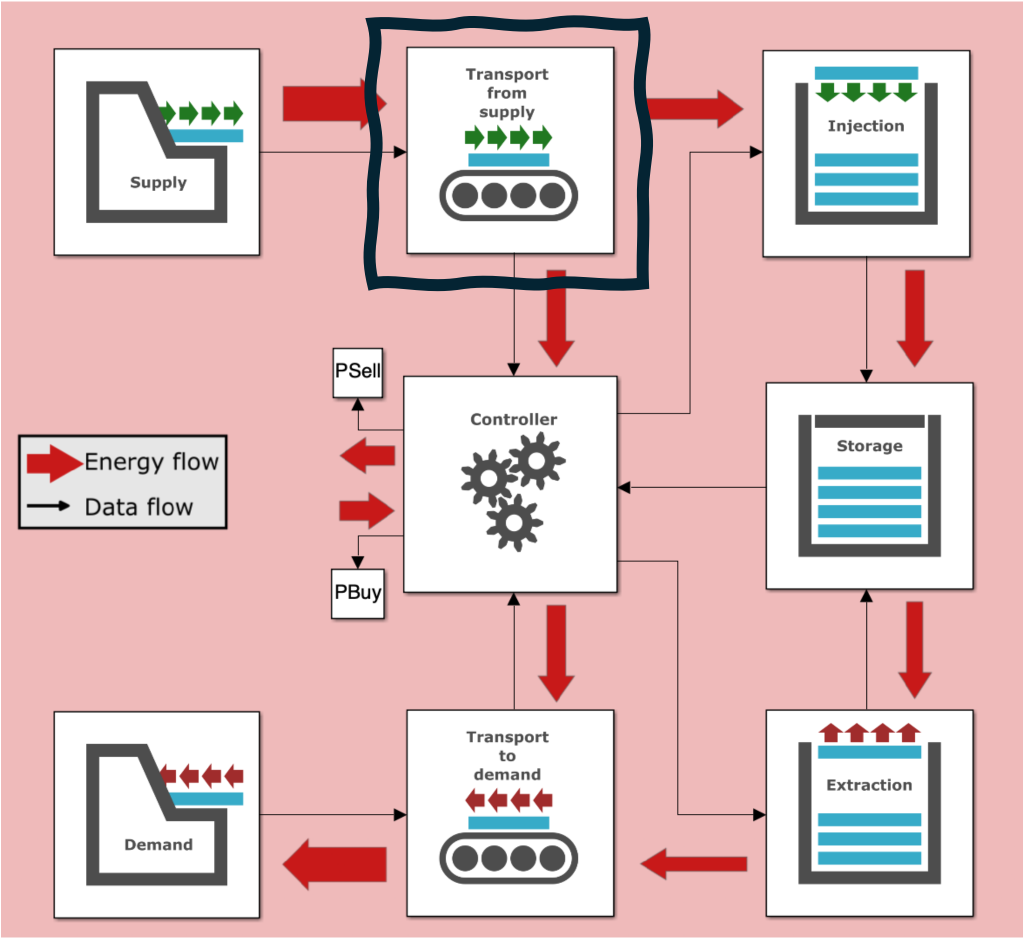
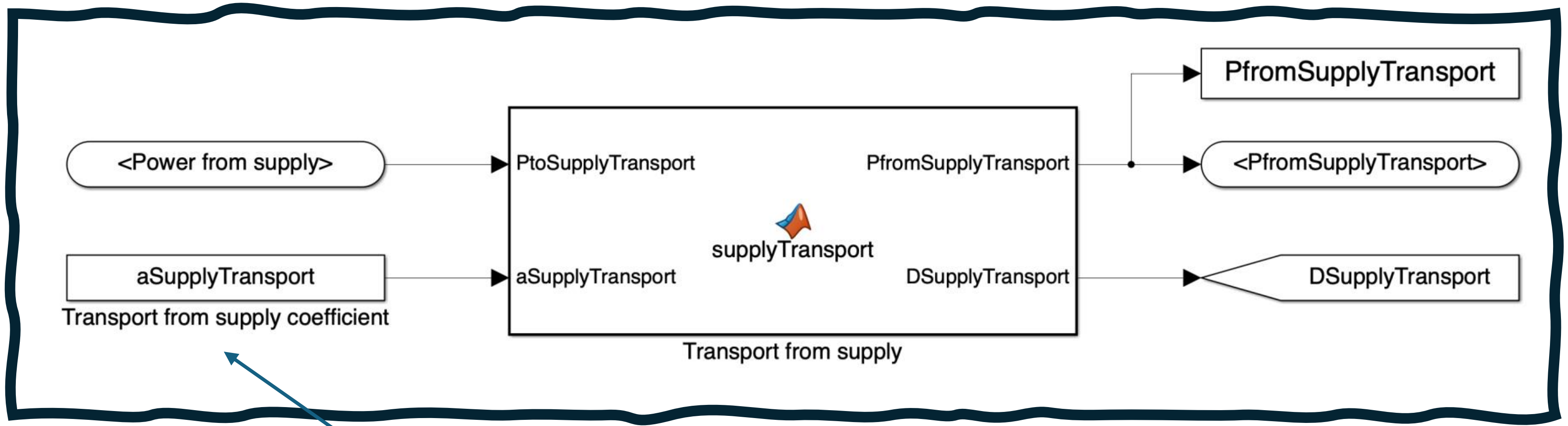
The transport function block



Modelling objective
Physical phenomena
Model selection
Mathematical elaboration
Implementation
Validation & verification
Reflection

The transport function block

Inside the "Transport from supply" block:



Effective loss parameter in baseline implementation

preprocessing.m

```
%% System parameters

% transport from supply
aSupplyTransport = 0.01; % Dissipation coefficient

% injection system
aInjection = 0.1; % Dissipation coefficient

% storage system
EStorageMax     = 10.*unit("kWh"); % Maximum energy
EStorageMin     = 0.0*unit("kWh"); % Minimum energy
EStorageInitial = 2.0*unit("kWh"); % Initial energy
bStorage        = 1e-6/unit("s");  % Storage dissipation coefficient

% extraction system
aExtraction = 0.1; % Dissipation coefficient
```

Modelling objective

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The implementation of the model

Inside the "supplyTransport" function block:

```
function [PfromSupplyTransport, DSupplyTransport] = supplyTransport(PtoSupplyTransport, aSupplyTransport)
    DSupplyTransport = aSupplyTransport * PtoSupplyTransport;
    PfromSupplyTransport = PtoSupplyTransport - DSupplyTransport;
```

$$P_{out} = \eta^2 P_{in} - \eta^3 L \times R' \times \left(\frac{P_{in}}{V}\right)^2$$

Not of the form same form due to quadratic dependence on the input power.

Requires new implementation of the Matlab function.

The implementation of the model

Inside the "supplyTransport" function block:

```
function [PfromSupplyTransport, DSupplyTransport] = supplyTransport(PtoSupplyTransport, aSupplyTransport)
    DSupplyTransport = aSupplyTransport * PtoSupplyTransport;
    PfromSupplyTransport = PtoSupplyTransport - DSupplyTransport;
```

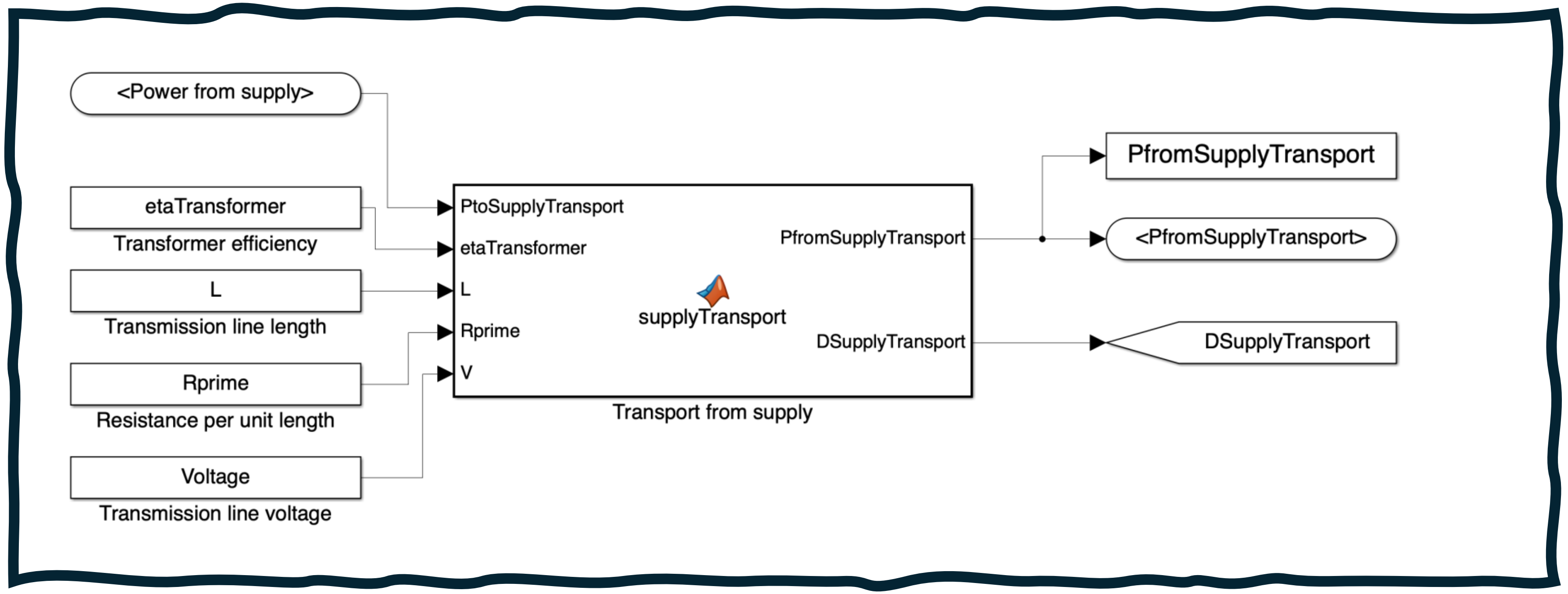
$$P_{out} = \eta^2 P_{in} - \eta^3 L \times R' \times \left(\frac{P_{in}}{V}\right)^2$$

```
function [PfromSupplyTransport, DSupplyTransport] = supplyTransport(PtoSupplyTransport, etaTransformer, L, Rprime, V)

    % Model for transformers and transmission line
    PfromSupplyTransport = (etaTransformer^2)*PtoSupplyTransport - (etaTransformer^3)*L*Rprime*(PtoSupplyTransport/V)^2;
    DSupplyTransport = PtoSupplyTransport - PfromSupplyTransport;
```

The transport function block

Inside the "Transport from supply" block:



The physical input parameters

preprocessing.m

```
%% System parameters

% transmission line transport from supply
etaTransformer = 0.99;     % Transformer efficiency [-]
L              = 160e3;    % Transmission line length [m]
Rprime         = 3e-5;     % Resistance per unit length [Ohm/m]
V              = 765e3;    % Transmission line voltage [V]

% injection system
aInjection = 0.1; % Dissipation coefficient

% storage system
EStorageMax     = 10.*unit("kWh"); % Maximum energy
EStorageMin     = 0.0*unit("kWh"); % Minimum energy
EStorageInitial = 2.0*unit("kWh"); % Initial energy
bStorage        = 1e-6/unit("s");  % Storage dissipation coefficient

% extraction system
aExtraction = 0.1; % Dissipation coefficient

% transport to demand
aDemandTransport = 0.01; % Dissipation coefficient
```

Debugging

```
Invalid setting in 'EST/Transport from supply/Transmission line voltage' for parameter 'Value'.
Caused by:
  • Error evaluating parameter 'Value' in 'EST/Transport from supply/Transmission line voltage'
    ◦ Unrecognized function or variable 'Voltage'.
      ▪ Variable 'Voltage' does not exist.
```

- Study the error message to understand what is wrong.
- If you cannot find the bug, revert to the version that worked, and then make step-by-step changes.
- Create test cases to track the bug.

The physical input parameters

preprocessing.m

```matlab
%% System parameters

% transmission line transport from supply
etaTransformer = 0.99;    % Transformer efficiency [-]
L              = 160e3;   % Transmission line length [m]
Rprime         = 3e-5;    % Resistance per unit length [Ohm/m]
Voltage        = 765e3;   % Transmission line voltage [V]

% injection system
aInjection = 0.1; % Dissipation coefficient

% storage system
EStorageMax     = 10.*unit("kWh"); % Maximum energy
EStorageMin     = 0.0*unit("kWh"); % Minimum energy
EStorageInitial = 2.0*unit("kWh"); % Initial energy
bStorage        = 1e-6/unit("s");  % Storage dissipation coefficient

% extraction system
aExtraction = 0.1; % Dissipation coefficient

% transport to demand
aDemandTransport = 0.01; % Dissipation coefficient
```

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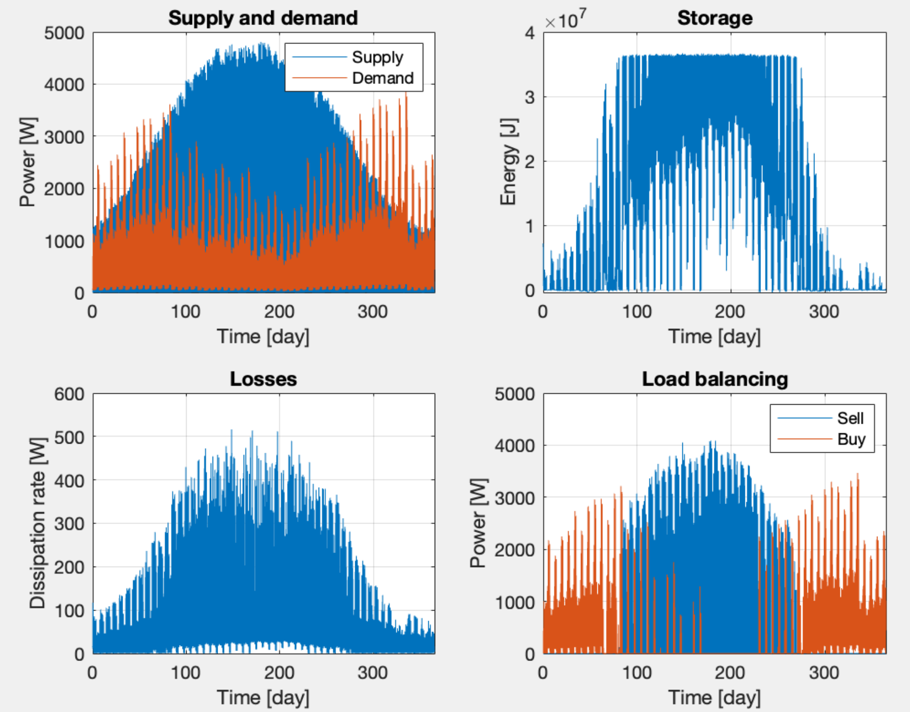
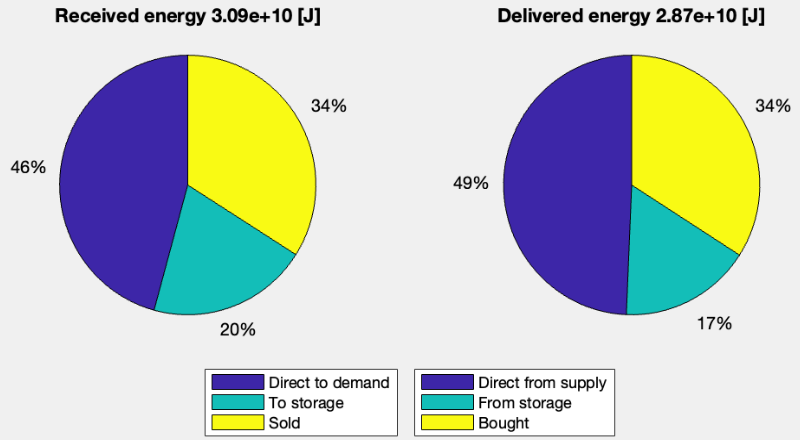
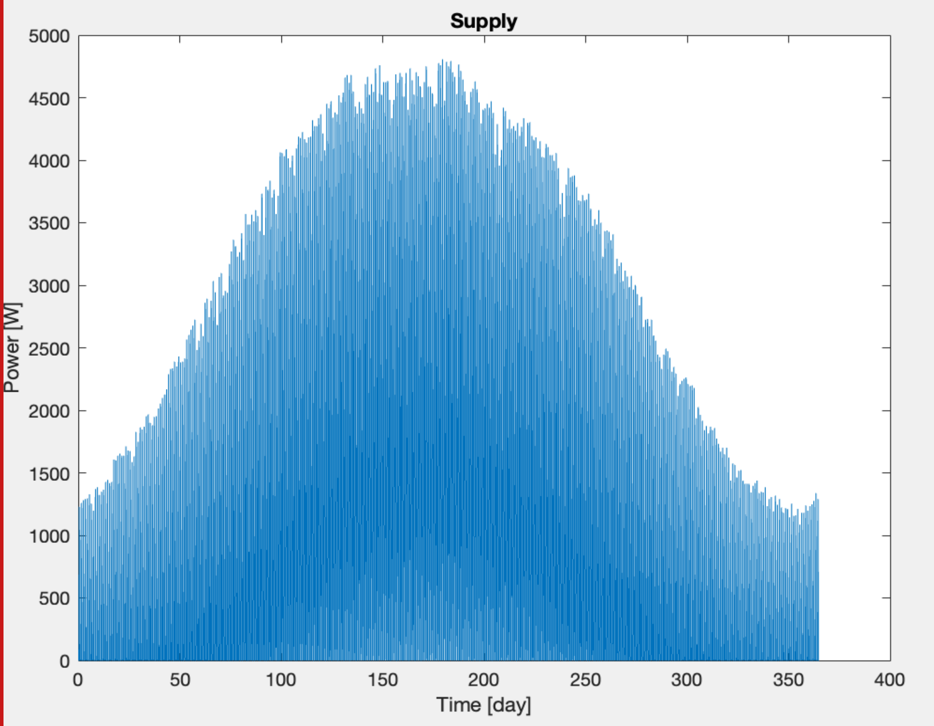
Do the results make sense?

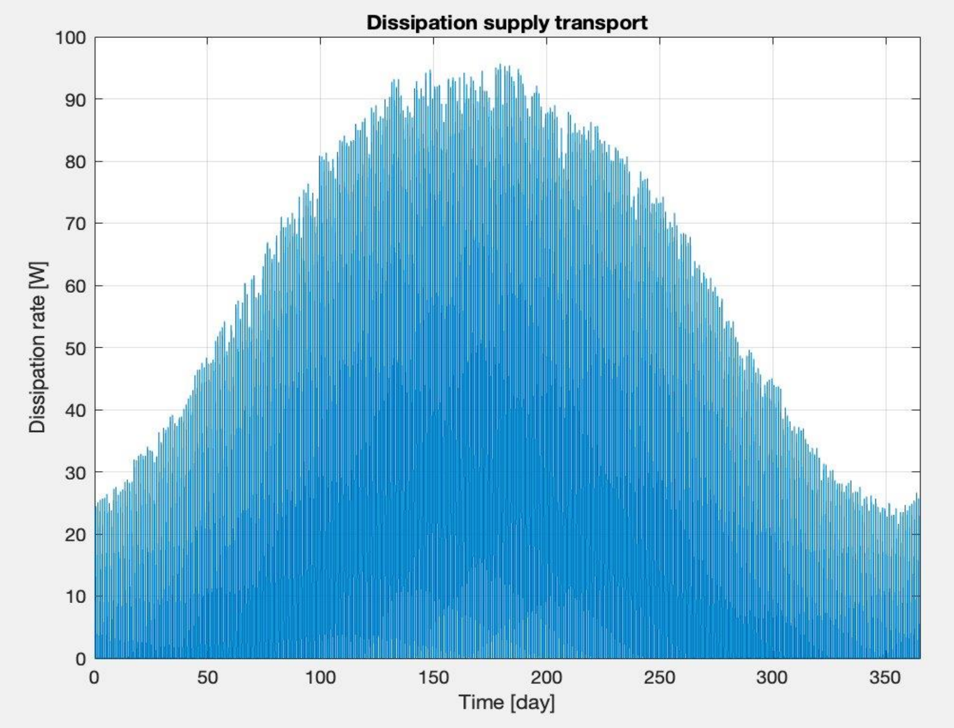




- Standard output does not properly visualize the change.
- Add additional output to assess model change.

Do the results make sense?





- Losses around 2%
- Dominated by transformers because of low power
- Additional testing at high powers needed

What can the model do?

- Provide estimate of power losses in DC transmission lines
- Model allows variation of:
  - Length of transmission line
  - Resistance of lines (material property)
  - Voltage in transmission line
  - Transformer efficiencies
- Results correspond well with literature observations

What can be improved?

- Further validation by considering higher powers
- Extend to AC transmission lines by including inductance in the model
- Add an improved model for the transformers

Energy Storage and Transport

Modeling example