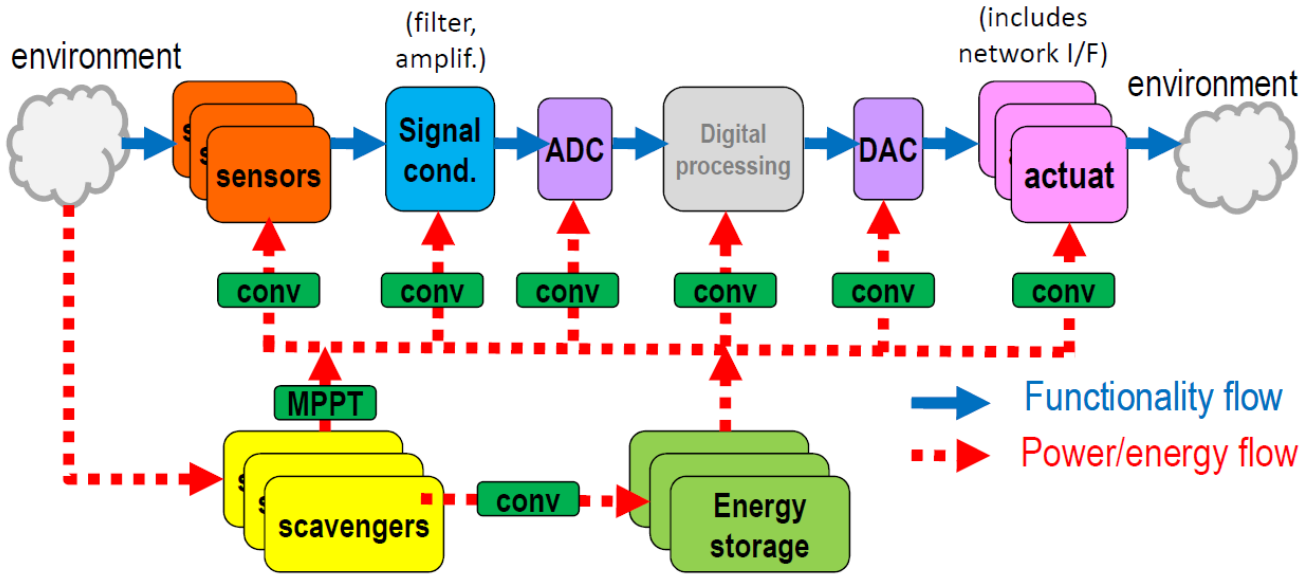
Lab 3
Energy storage, generation and conversion

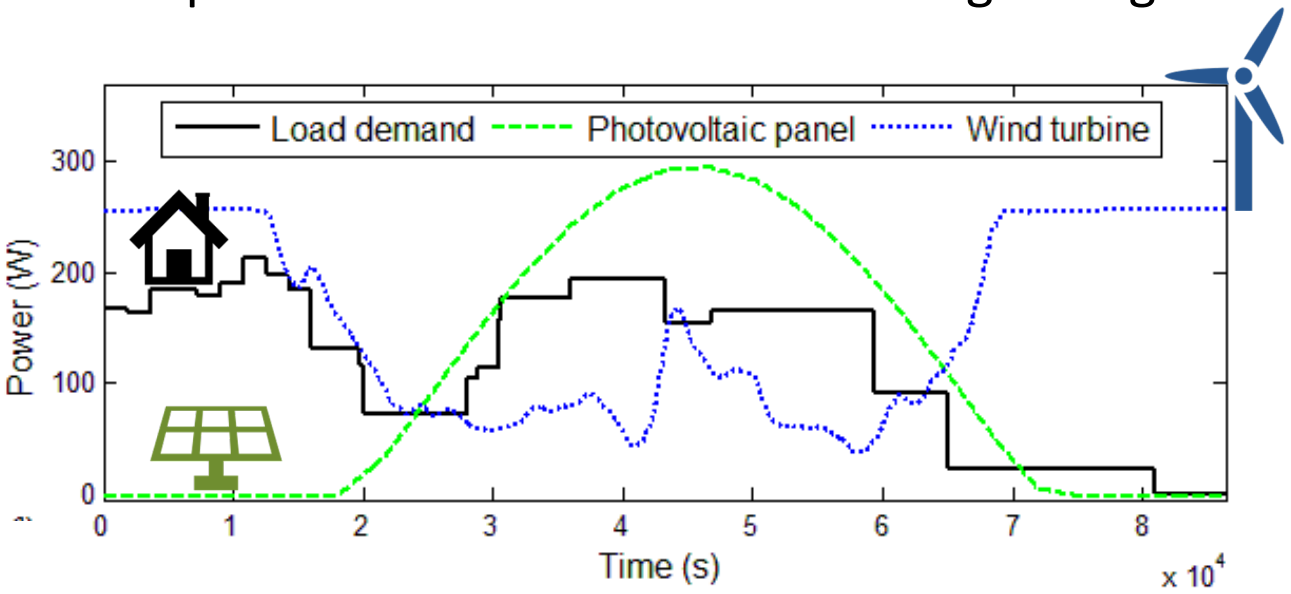
Energy storage, generation and conversion

- Focus: **power perspective of the system**
  - Energy storage: appropriate size to sustain loads?
  - Generation: how much provided by power sources?
  - Any loss due to conversions?



Energy storage, generation and conversion

- Crucial to model and simulate the overall system to validate and estimate the behavior of single components and of the overall system beforehand
  - On any scale of system!
  - Even more crucial when autonomousness must be guaranteed
    - Ensure operation of the IoT device for long enough…



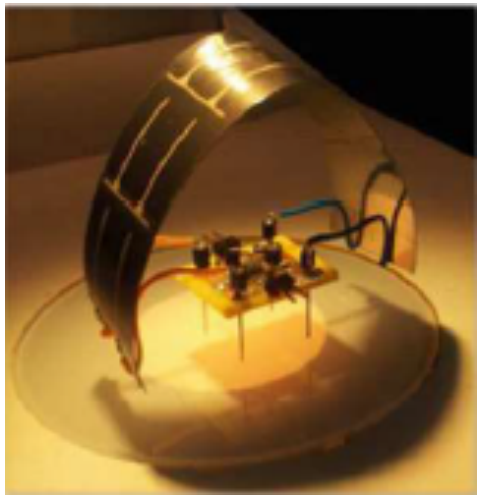
Energy storage, generation and conversion

- Crucial to model and simulate the overall system to validate and estimate the behavior of single components and of the overall system beforehand
  - On any scale of system!
  - Even more crucial when autonomousness must be guaranteed
    - Ensure operation of the IoT device for long enough…
  - Need to create models for the components
    - And to launch simulations to trace quantities

Objective and organization

- Goal of this lab is to simulate an IoT device made of:
  - 4 sensors
  - Memory and control unit
  - A module to transmit data over ZigBee
  - A battery with a DC-DC converter
  - A thin-film photovoltaic module operated at the MPP with a DC-DC converter

ASSUME ALWAY WORKING AT THE MPP
SO NOT TRACKING IS required.



Objective and organization

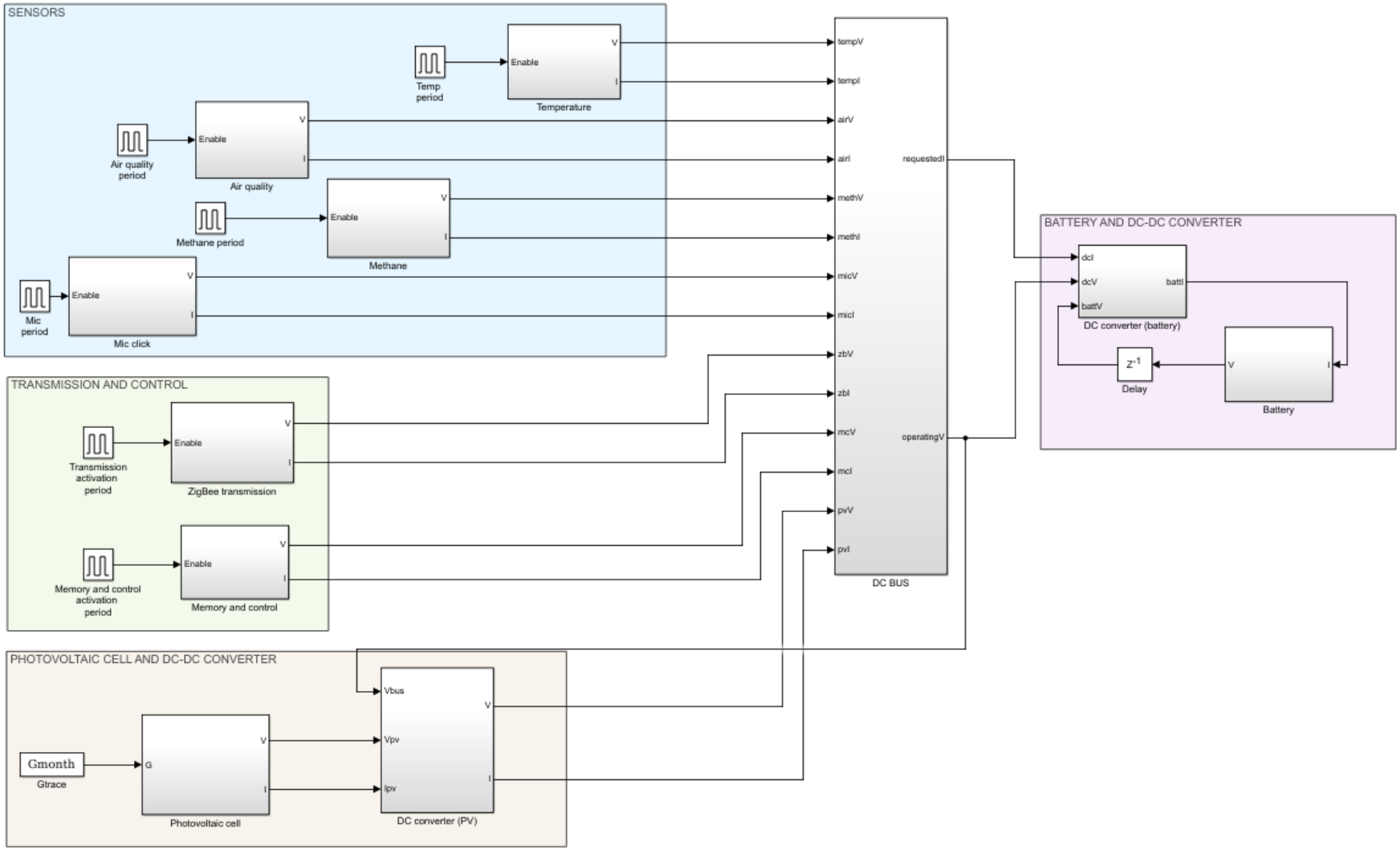
- Goal of this lab is to simulate an IoT device:
  - Implemented in Matlab/Simulink
    - Stardard-de-facto for energy simulation
    - Predefined simulation skeleton
    - To be populated with models for the components
  - Populate the system, analyse and optimize its behavior

Objective and organization

- Organization
  - 1 assignment to deliver
  - 2 days (+ 1 optional session)
    - *Jan 11th 4pm-7pm*
    - *Jan 12th 1pm-2:30pm*
  - Required software: Matlab, Simulink

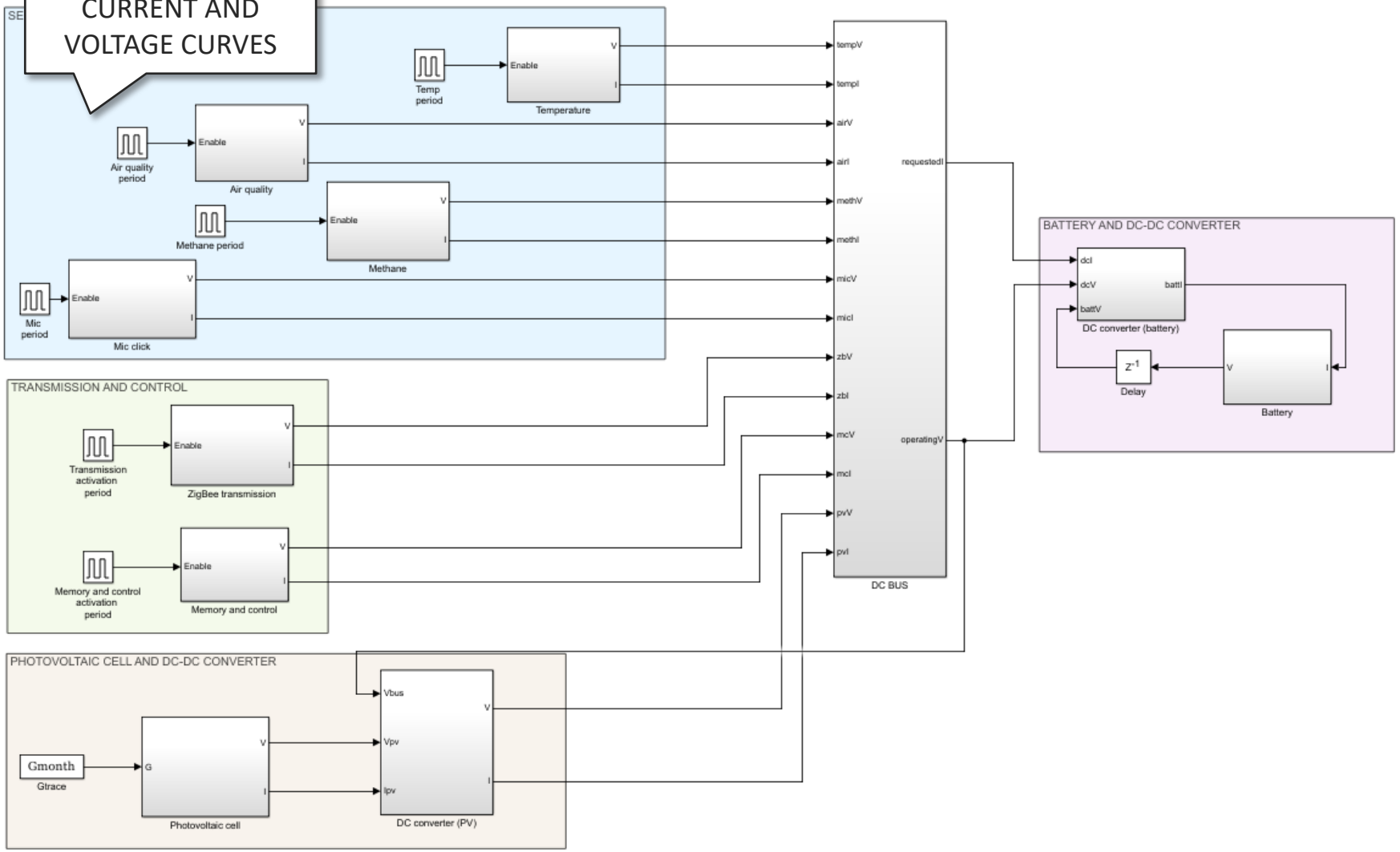
Simulink implementation

Simulink implementation

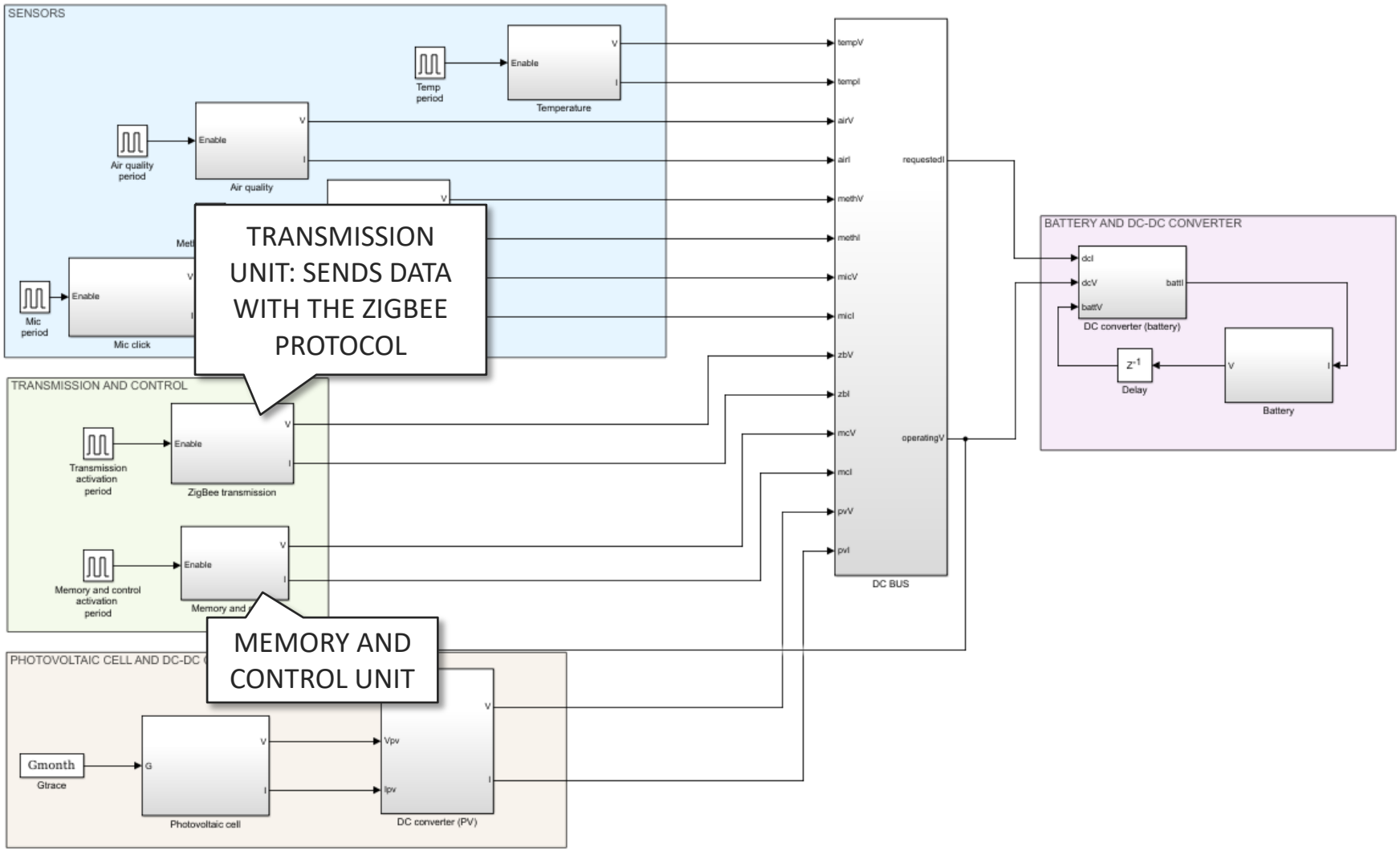


Simulink implementation

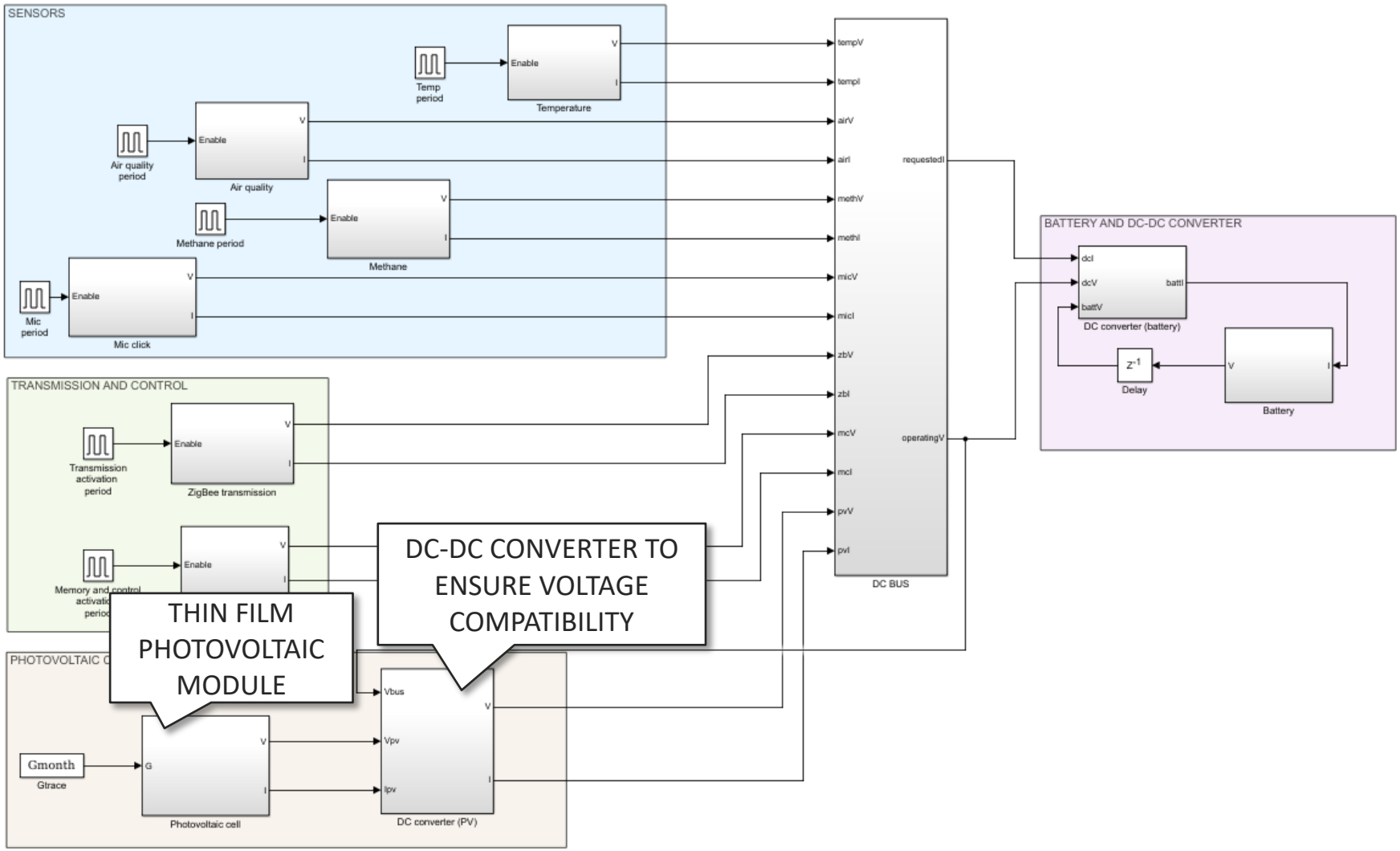
4 SENSORS: MODELED AS CURRENT AND VOLTAGE CURVES



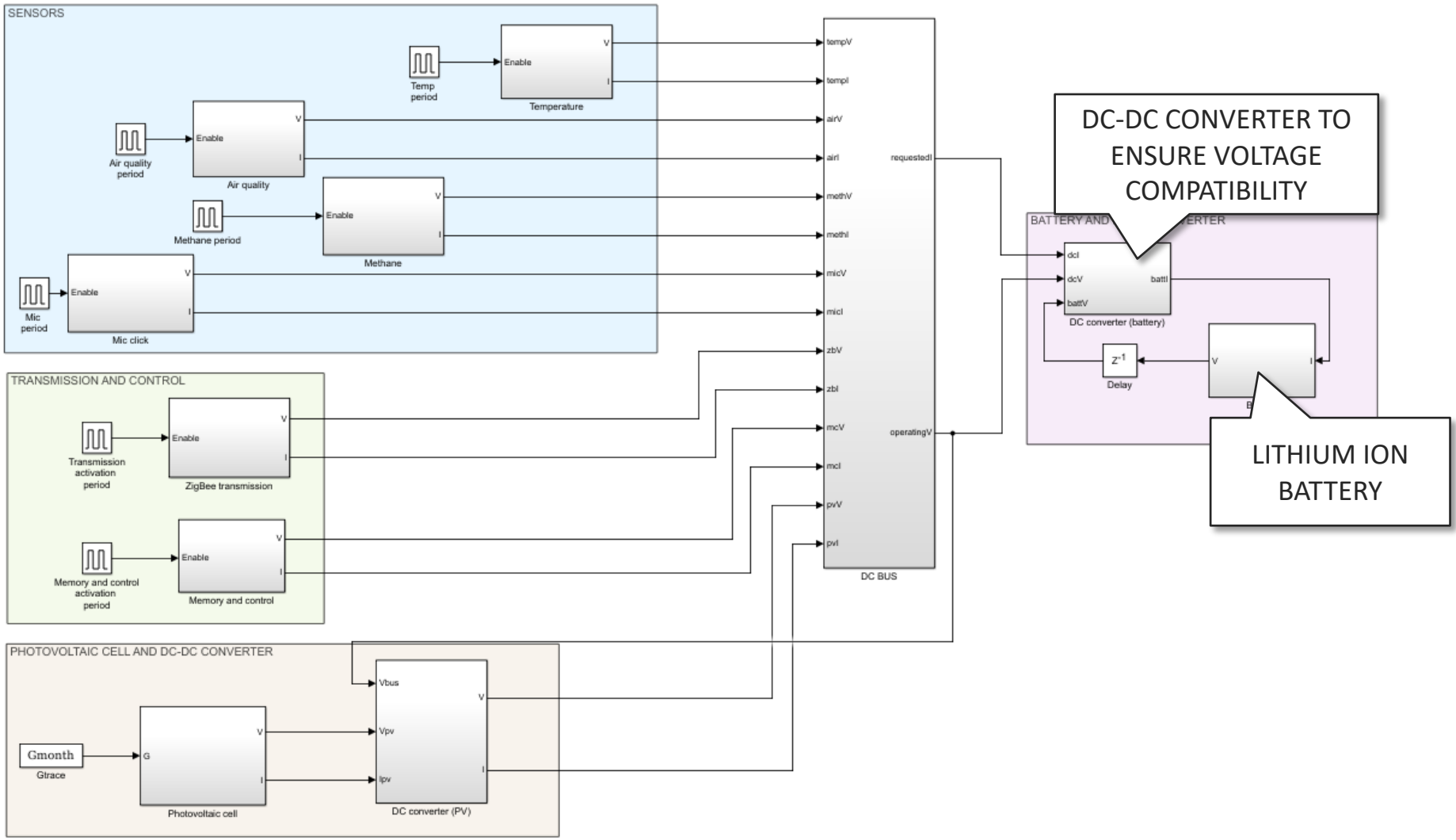
Simulink implementation



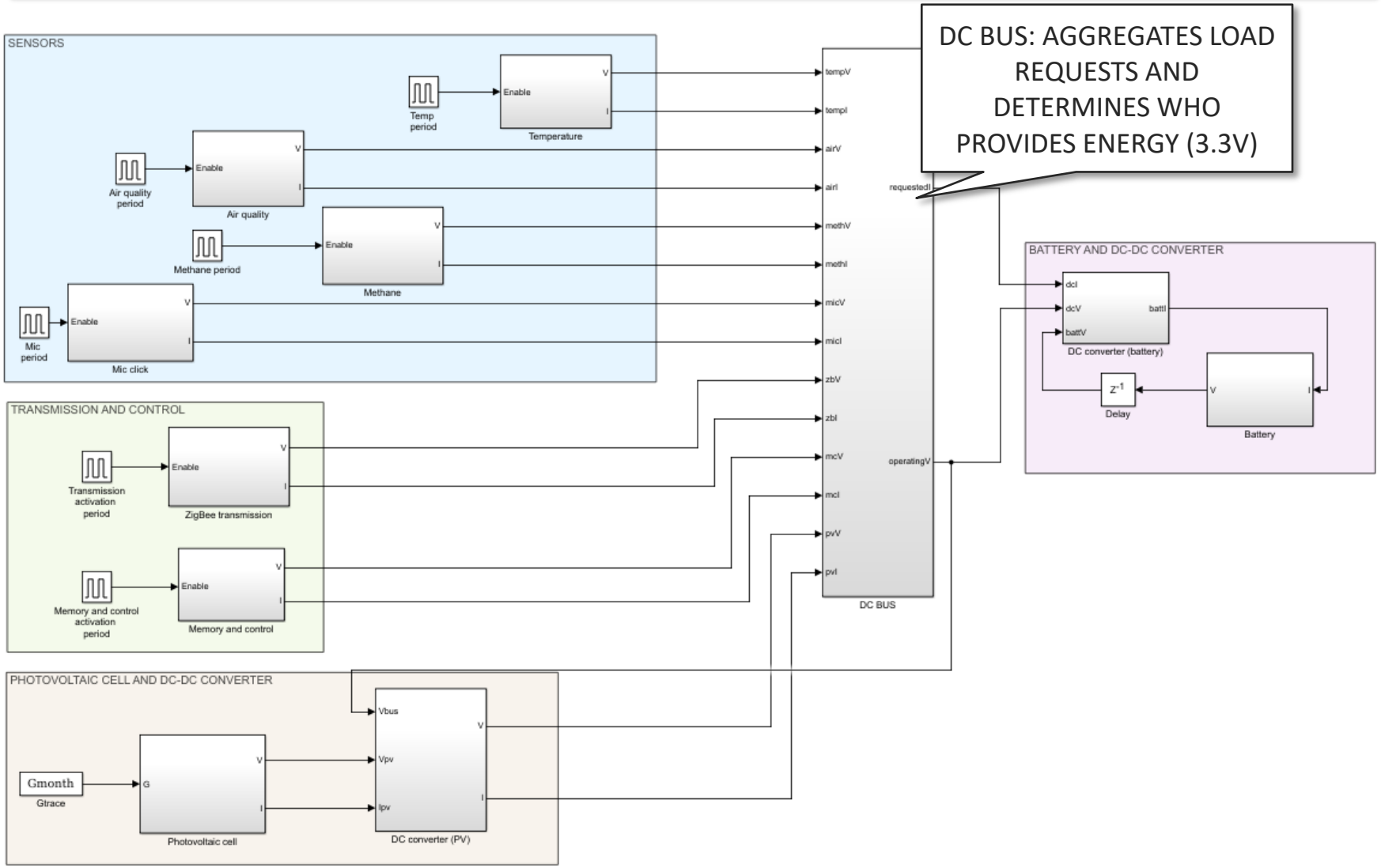
Simulink implementation



Simulink implementation



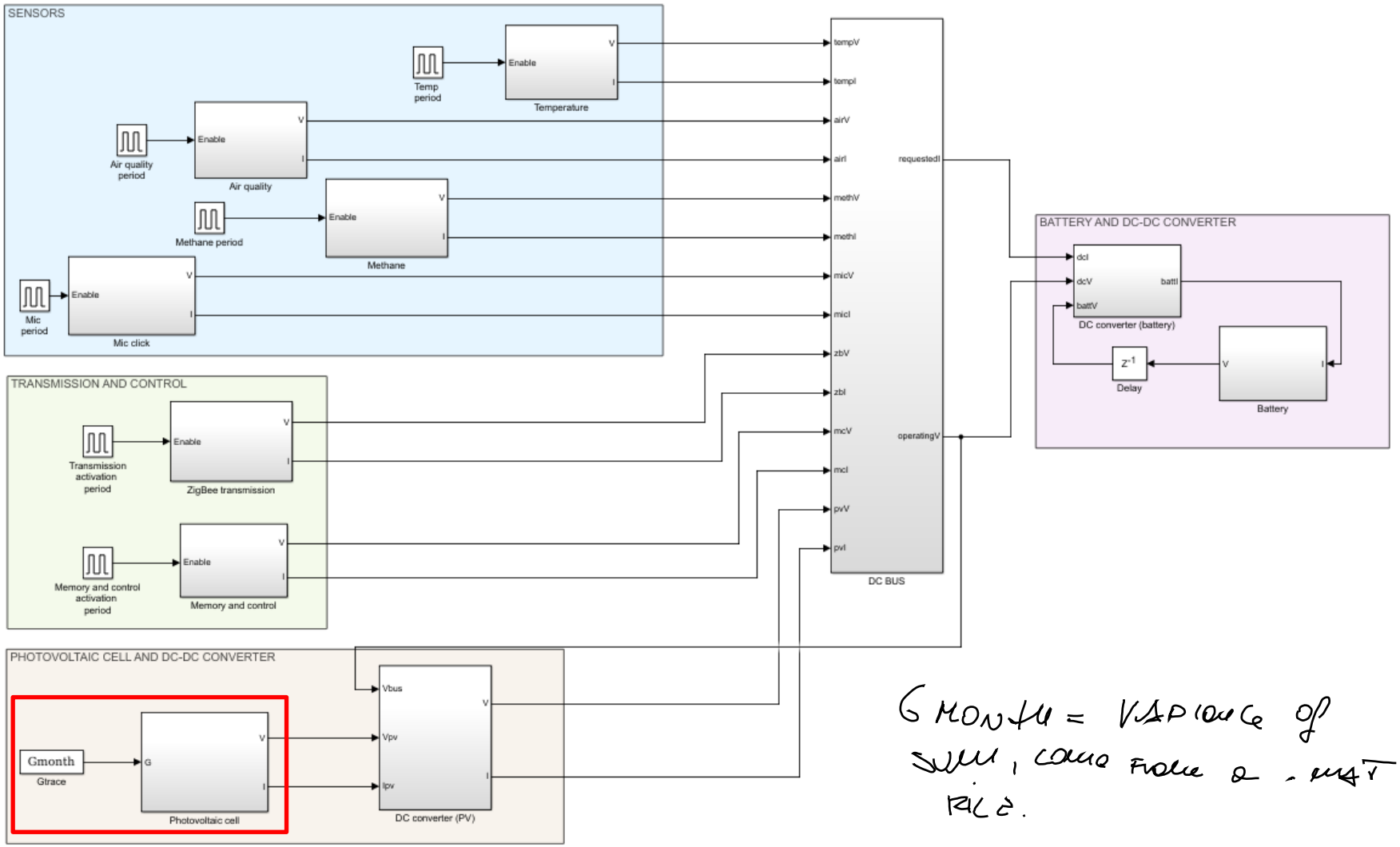
Simulink implementation



Lab 3 – Part 1
Model of the photovoltaic module

FIRST TASK IS BUILD THE MODEL OF PV MODULE

Simulink implementation



6 MONTH = VARIANCE of SUN, COMES FROM a .MAT FILE.

Photovoltaic module

- Gmonth
  - Variable loaded from workspace
    - To load it, type:
      - `load('gmonths.mat')`
  - Values of irradiance over time
    - Input of the photovoltaic cell
    - Two columns matrix:
      - First column: time (in seconds)
      - Second column: irradiance value (in W/m^2)
      - Each line corresponds to a new value of irradiance at a given time

Editor - panel.m

Gmonth

1590x2 double

	1	2
1	0	0
2	900	67.6853
3	1800	77.7214
4	2700	87.3263
5	3600	100.5830
6	4500	124.0773
7	5400	155.2077
8	6300	191.0537
9	7200	233.1320
10	8100	278.4866
11	9000	324.2709
12	9900	370.6427
13	10800	422.2269
14	11700	469.9433
15	12600	514.6853
16	13500	563.9495
17	14400	608.4416
18	15300	653.1028
19	16200	692.3697
20	17100	732.9693
21	18000	759.4004

Photovoltaic module

- Gmonth
  - Irradiance trace for about 3 months
    - Irradiance varies depending on weather (sunny/rainy/cloudy)
    - E.g.:

```
figure
plot(Gmonth(:,1), Gmonth(:,2))
```

Editor - panel.m

Gmonth

1590x2 double

	1	2
1	0	0
2	900	67.6853
3	1800	77.7214
4	2700	87.3263
5	3600	100.5830
6	4500	124.0773
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15	12600	514.6853
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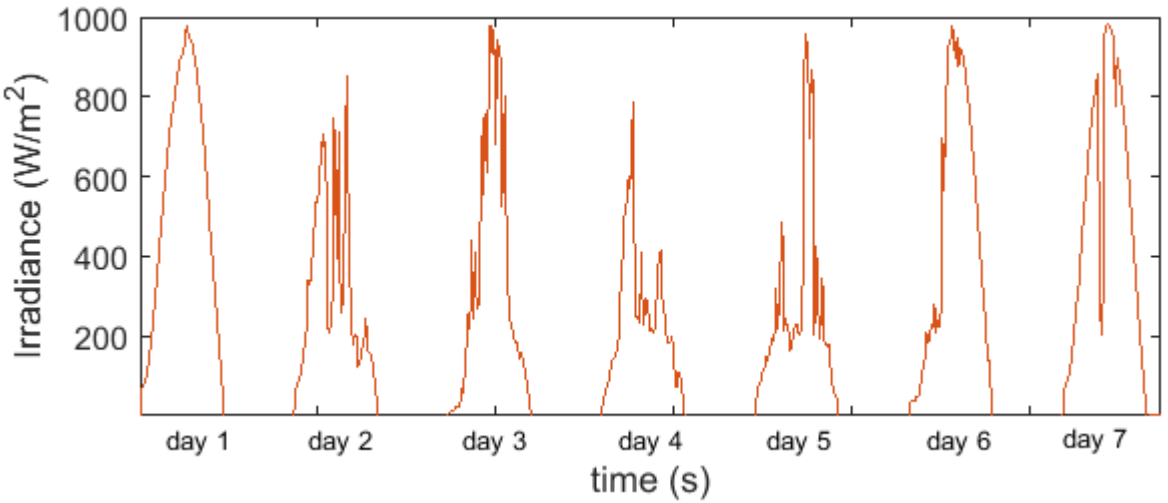
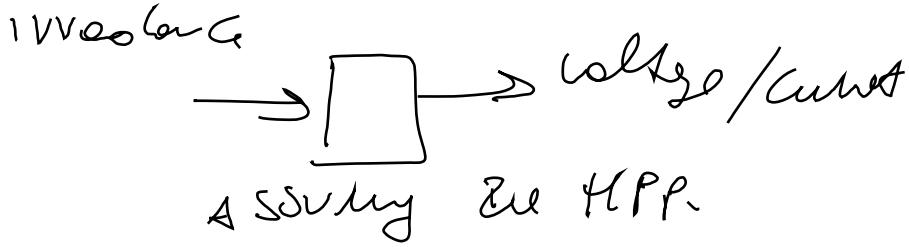
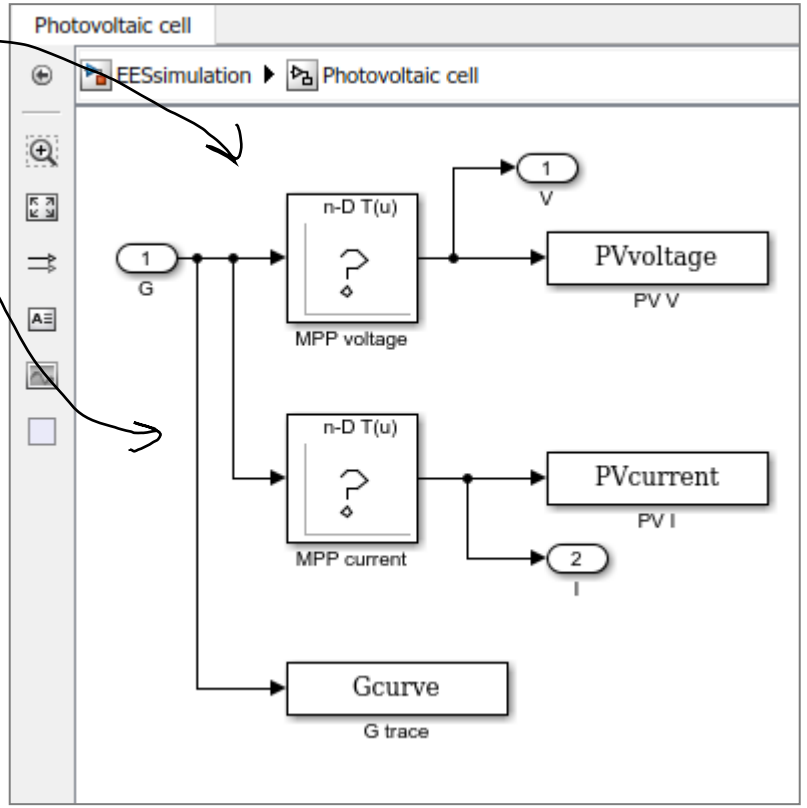
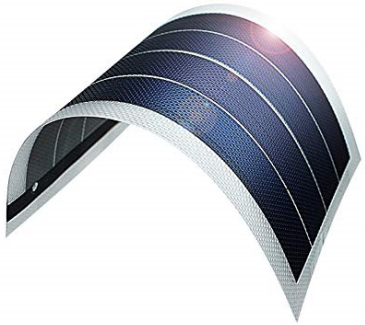


Photovoltaic module

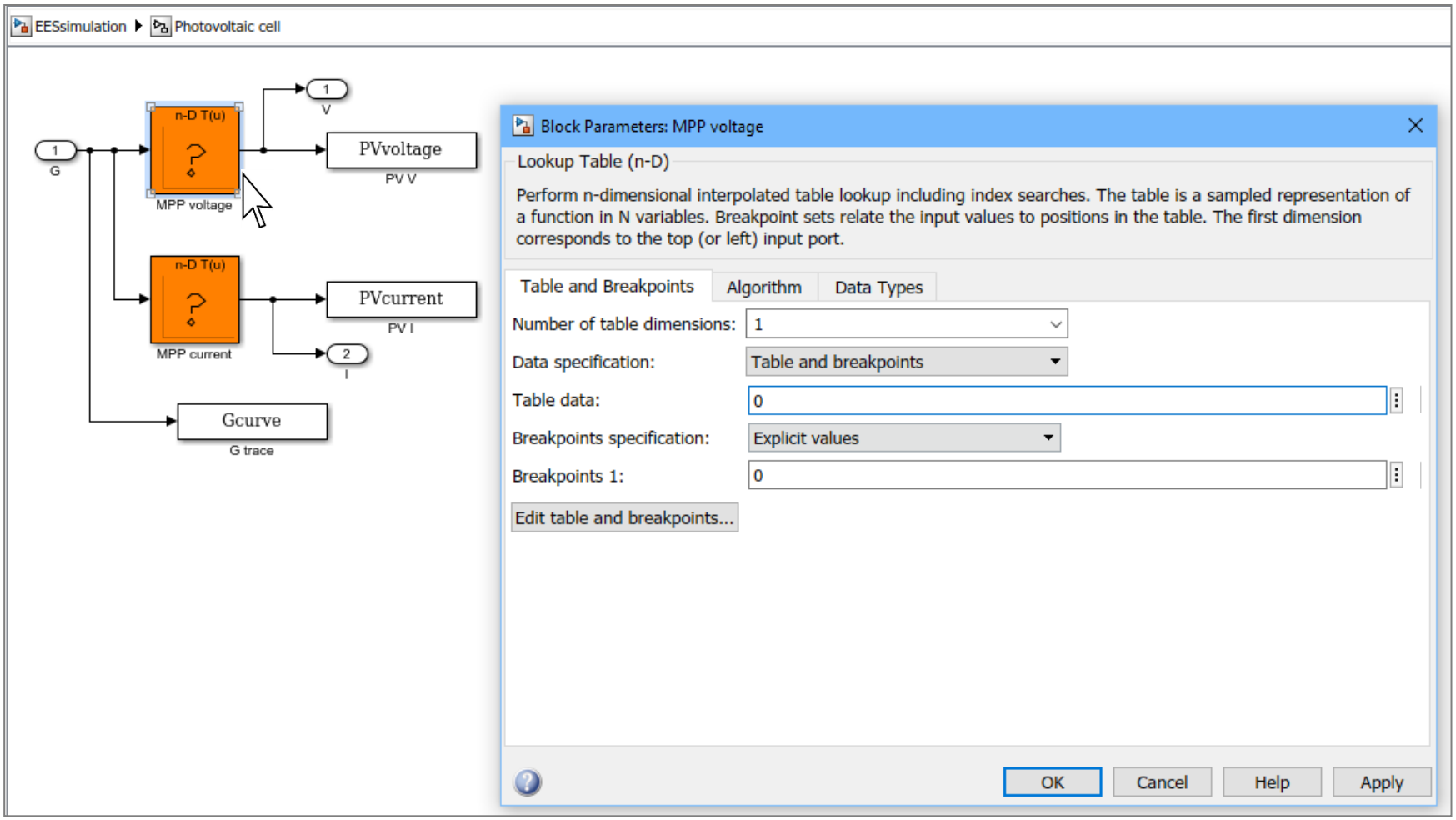
- Photovoltaic module
  - Open the subsystem by double-clicking on block
  - Two lookup tables
    - Voltage and current at the MPP given irradiance in input
    - Must populate the lookup tables!





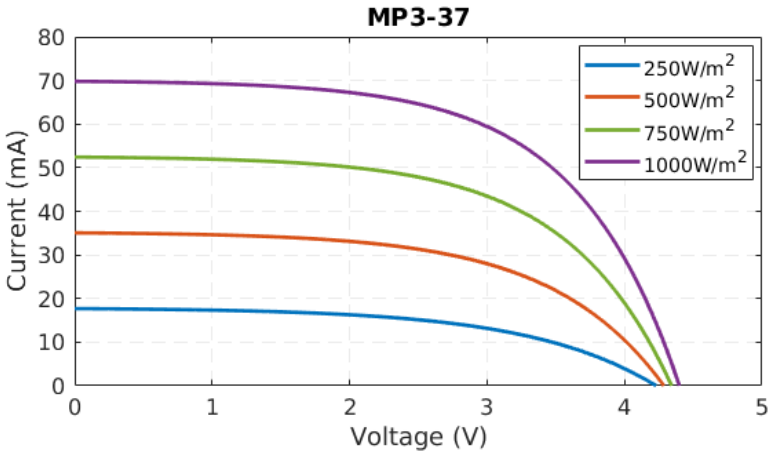


Photovoltaic module



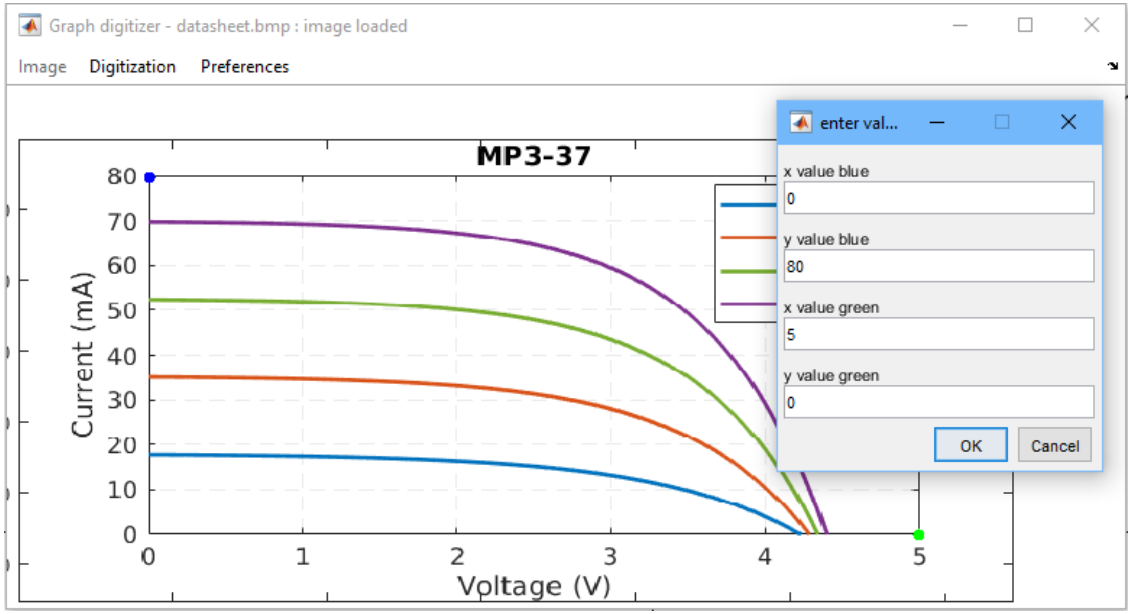
Photovoltaic module

- Open the PVdatasheet.pdf file
- Provides a graph of current versus voltage given different irradiance values
- How to:
  - Save the image
  - For each curve:
    1. Digitize the curve
       - Can use the digitizer tool
    2. Determine the voltage and current at the MPP for that irradiance value
    3. Use the sample for the lookup table



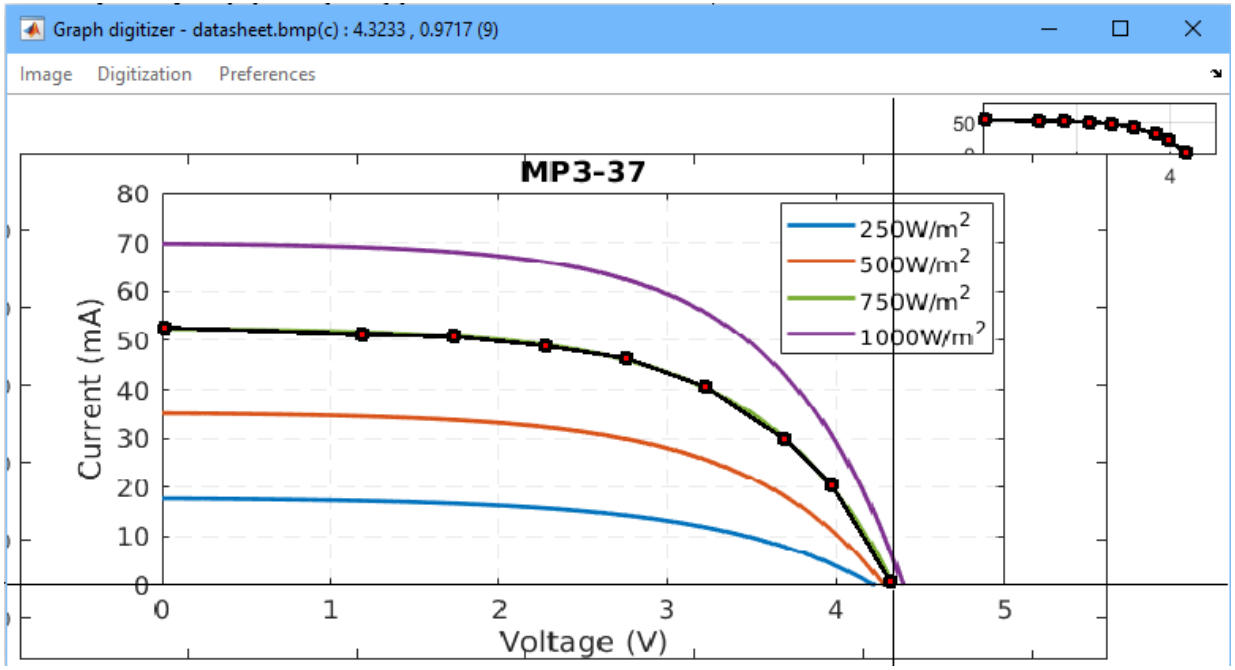
Photovoltaic module

- How to use the digitizer tool:
  1. Load the image
  2. Calibrate the image
     - Select two points and give corresponding x and y values
     - Conversion factor 1
     - 4 decimals precision



Photovoltaic module

- How to use the digitizer tool:
  3. Select samples of one curve
     - Mouse left button = new sample
     - Mouse middle button = stop inserting samples



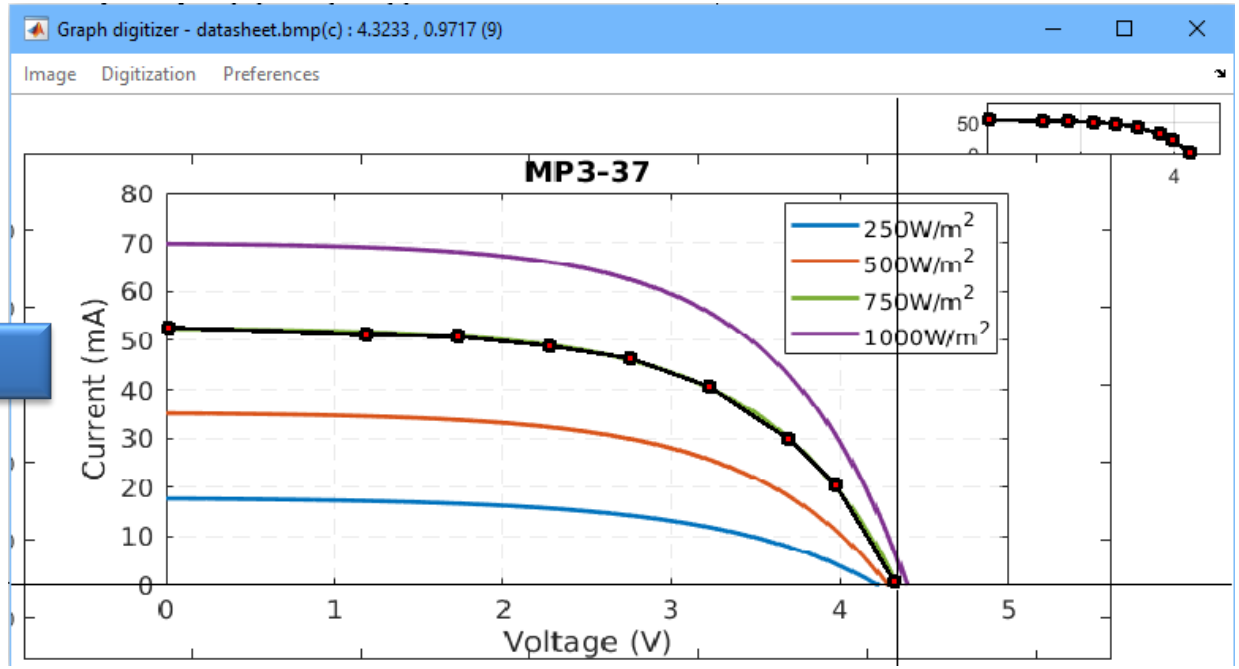
Photovoltaic module

- How to use the digitizer tool:
  3. Select samples of one curve
     - Mouse left button = new sample
     - Mouse middle button = stop inserting samples
  4. Save to file

Save all vectors in a single mat file.

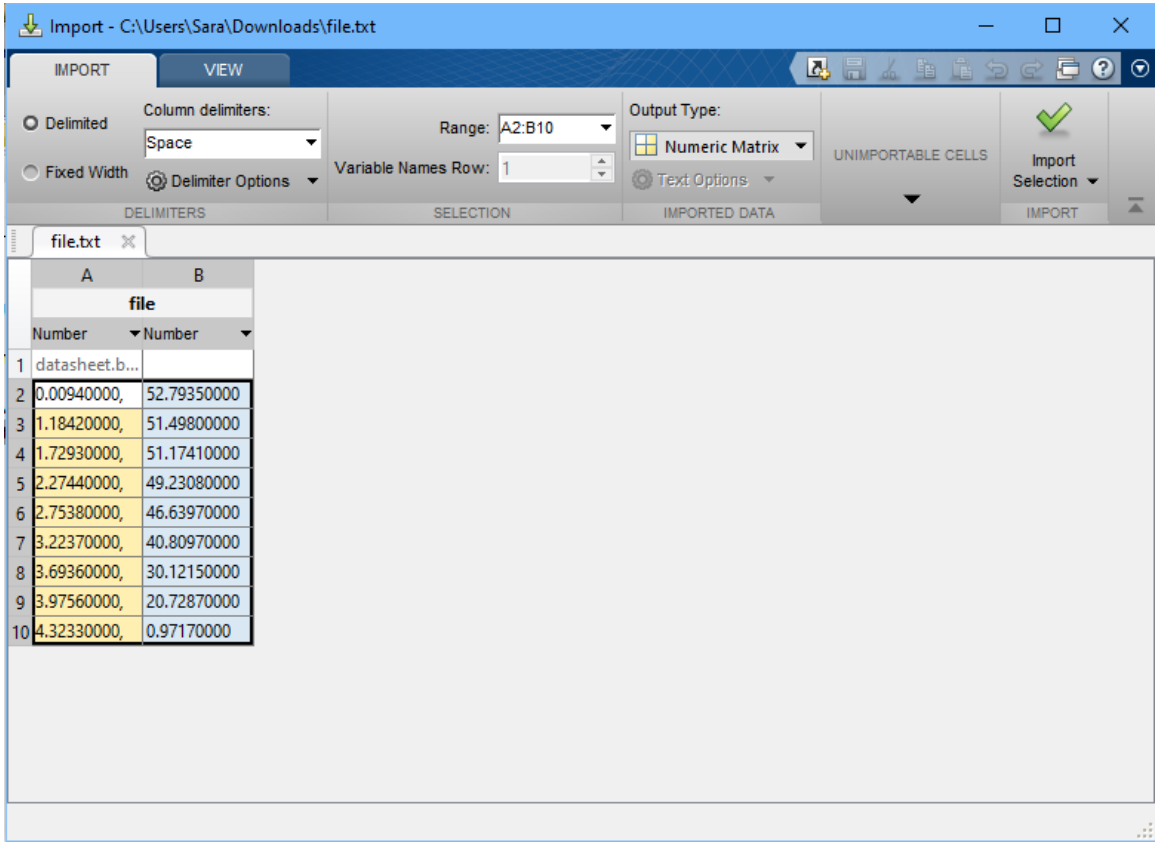
datasheet.txt

```
0.00940000, 52.79350000
1.18420000, 51.49800000
1.72930000, 51.17410000
2.27440000, 49.23080000
2.75380000, 46.63970000
3.22370000, 40.80970000
3.69360000, 30.12150000
3.97560000, 20.72870000
4.32330000,  0.97170000
```



Photovoltaic module

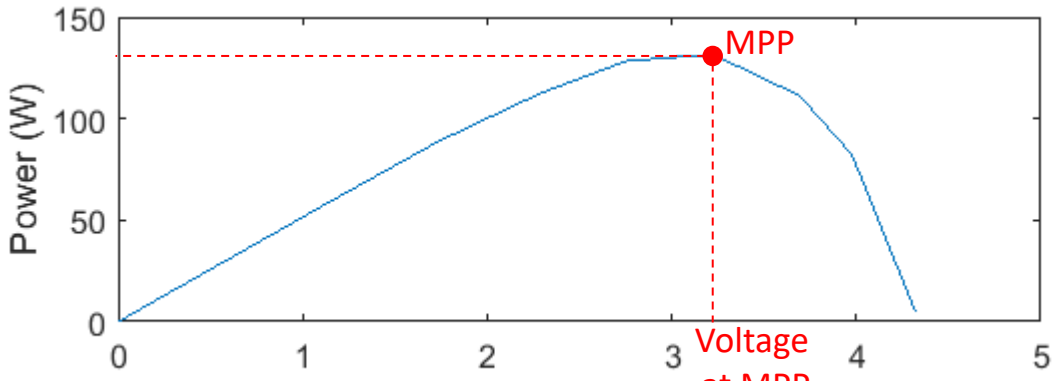
- Each file represents one curve
- Import the file in Matlab:
  - Home > Import data > Select the file
  - File as a matrix variable



Photovoltaic module

- Each file represents one curve
  - Import the file in Matlab as variables
- To extrapolate MPP:
  - Build the corresponding power curve
  - Extrapolate V and I at the MPP
    - I.e., voltage and current corresponding to the maximum value of power for this curve

- MPP voltage is the out of first load row.
- MPP current is the out of the second.



Current at MPP = MPP/Voltage at MPP
e.g., 131.56/3.22 = 40.81

datasheet.txt

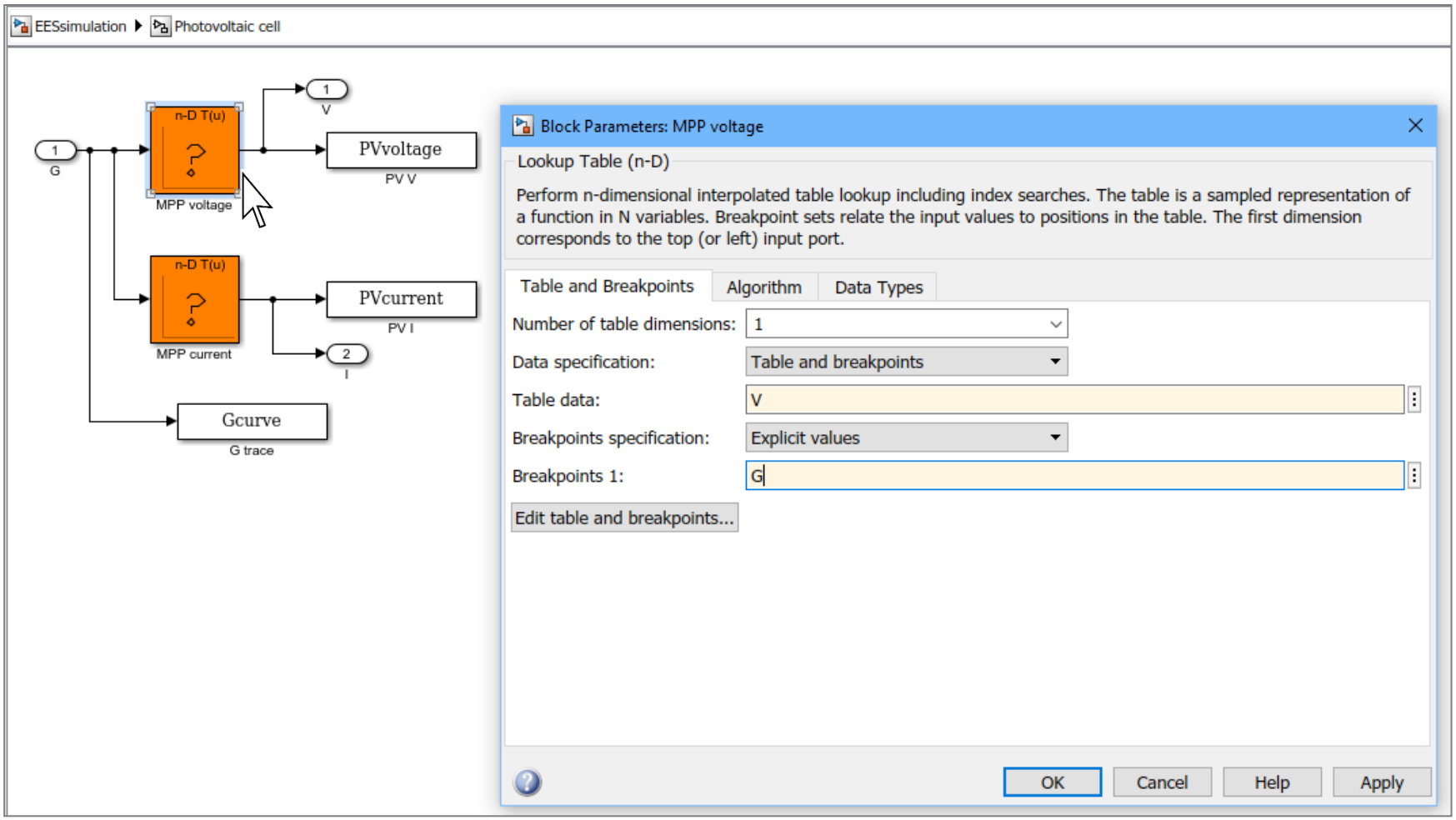
```
0.00940000, 52.79350000
1.18420000, 51.49800000
1.72930000, 51.17410000
2.27440000, 49.23080000
2.75380000, 46.63970000
3.22370000, 40.80970000
3.69360000, 30.12150000
3.97560000, 20.72870000
4.32330000,  0.97170000
```

Photovoltaic module

- Populate the lookup tables:
  - Vector of values of G:
    - `G = [250; 500; 750; 1000];`
  - Vector of corresponding values of current at the MPP
    - `I = [I250; I500; I750; I1000];`
  - Vector of corresponding values of voltage at the MPP
    - `V = [V250; V500; V750; V1000];`
  - Write the name of the variables in the configuration pane of the loopup tables
    - Breakpoints = G
    - Table values = V or I (corresponding values)

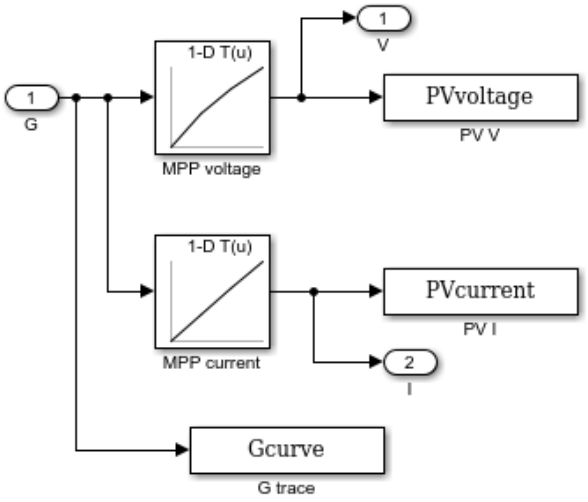
VECTOR of IRRad
curves
colloge.
HAVING only 4 curves we only 4 ROWS IN the look up table so INTERPOLATION is NECCESS.

Photovoltaic module



Photovoltaic module

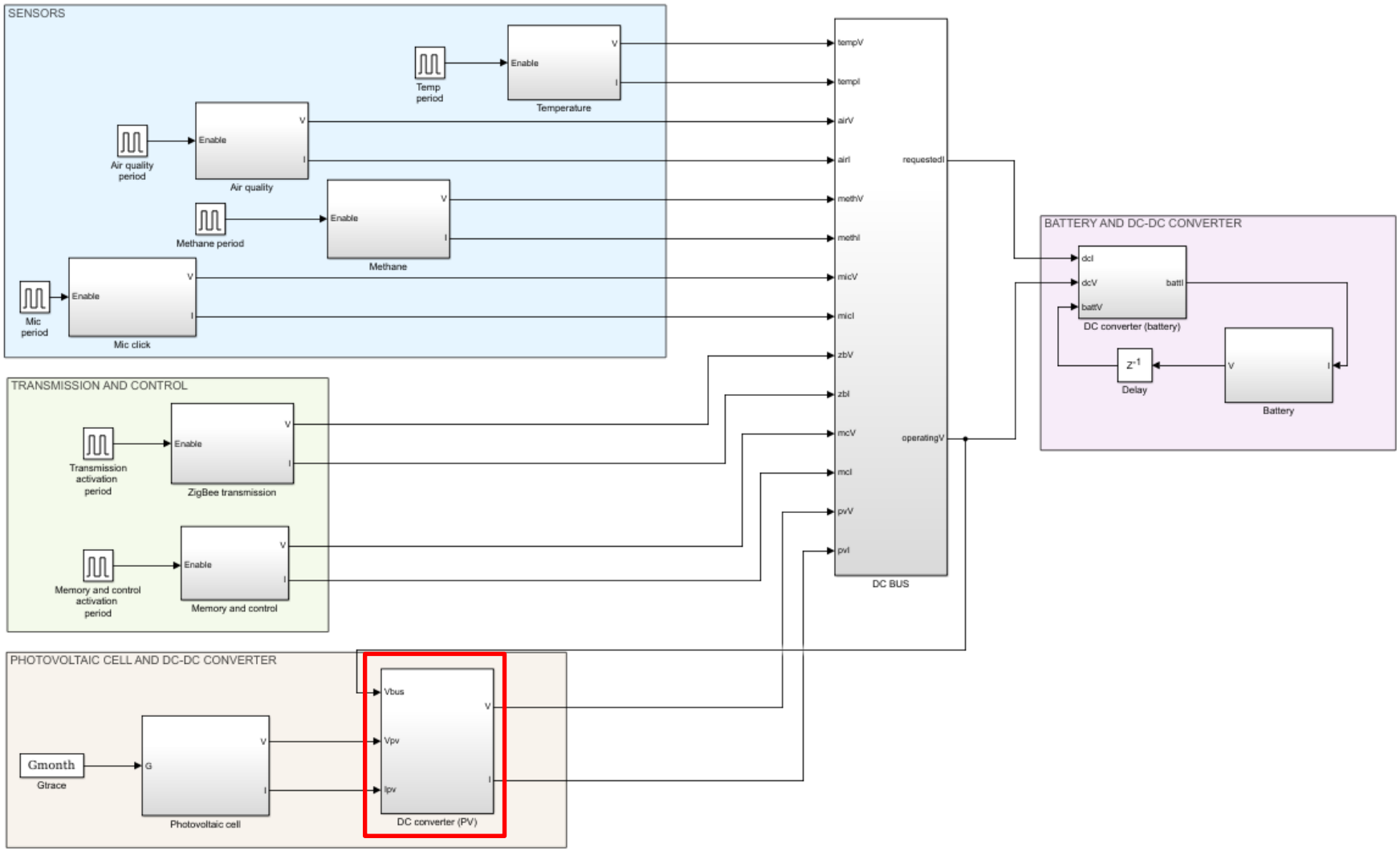
- If everything went well, your lookup tables should now look like:



- Lookup table output:
  - If input irradiance is one of the sampled values, the lookup table outputs the corresponding value of voltage/current
  - Else, the lookup table interpolates between the available samples and estimate the value of voltage/current

Lab 3 – Part 2
Model of DC-DC converters and battery

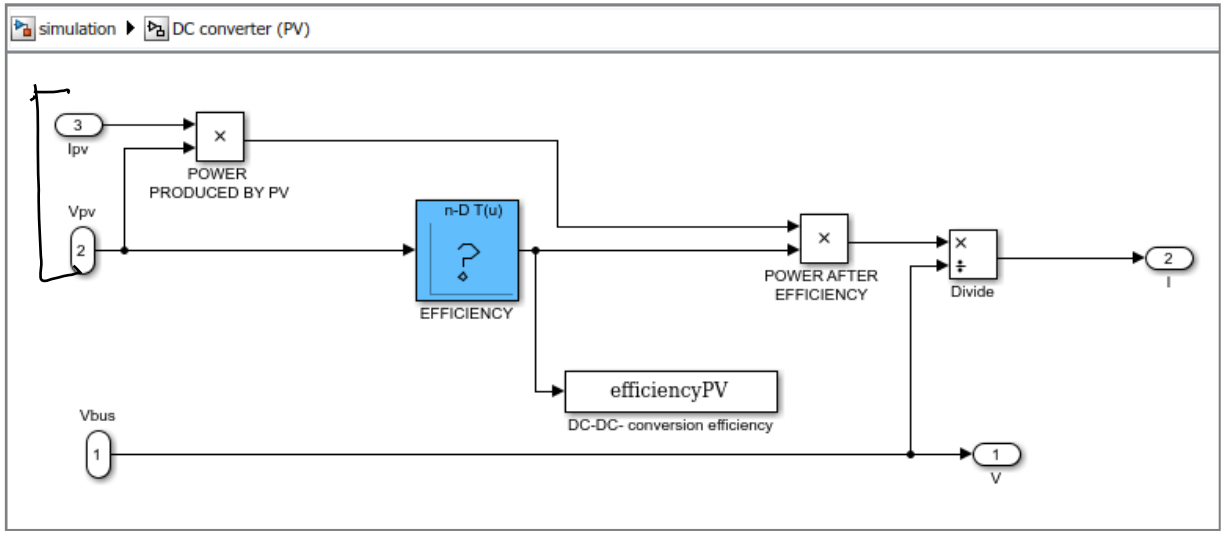
Simulink implementation



DC-DC converter of PV module

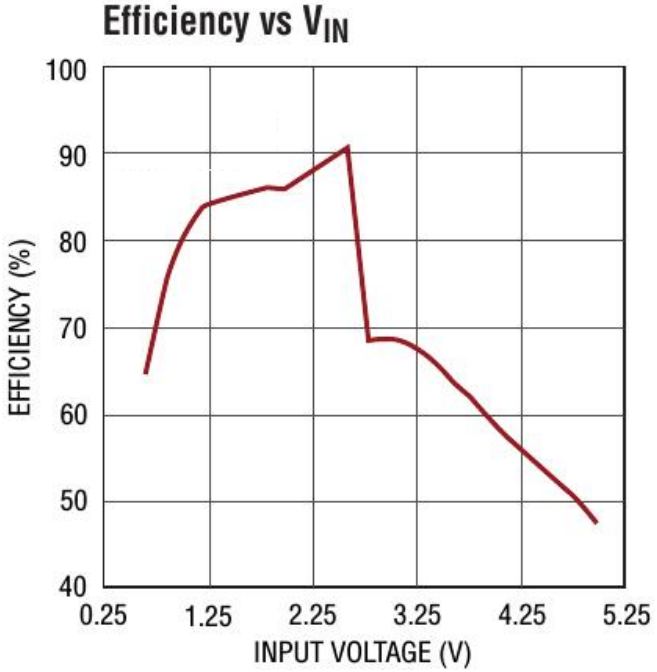
- DC-DC converter of the photovoltaic module
  - Contains a lookup table of efficiency given input PV voltage
    - Efficiency in [0, 1]
  - Block implementation:
    - $(V_{PV} \cdot I_{PV}) \cdot \text{efficiency} = (V_{BUS} \cdot I)$
    - $V_{BUS} = 3.3V$ (DC bus voltage)
    - $I = (V_{PV} \cdot I_{PV} \cdot \text{efficiency})/V_{BUS}$

From PV →



DC-DC converter of PV module

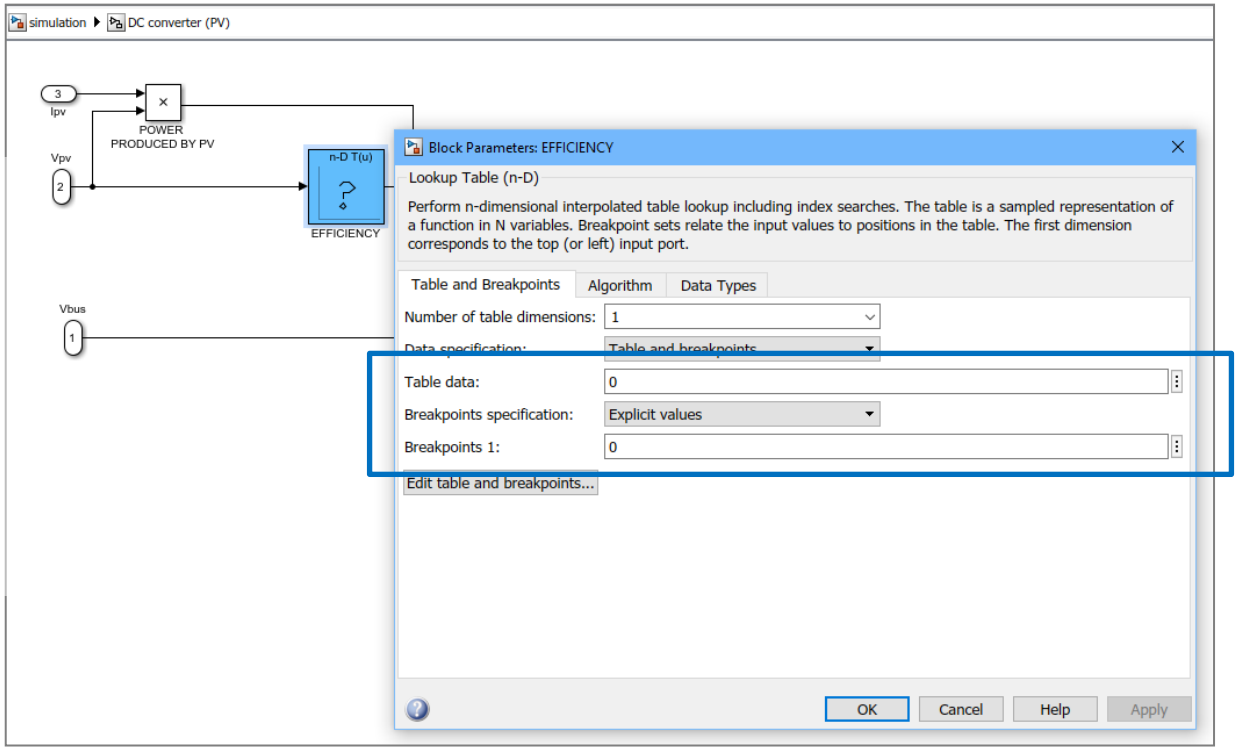
- Must populate the lookup table of efficiency given input voltage of the photovoltaic module
  - Open the **PV_DCDCconverter.pdf** file
    - Page 5: curve of efficiency w.r.t. input voltage
  - Use the samples of the curve to populate the lookup table



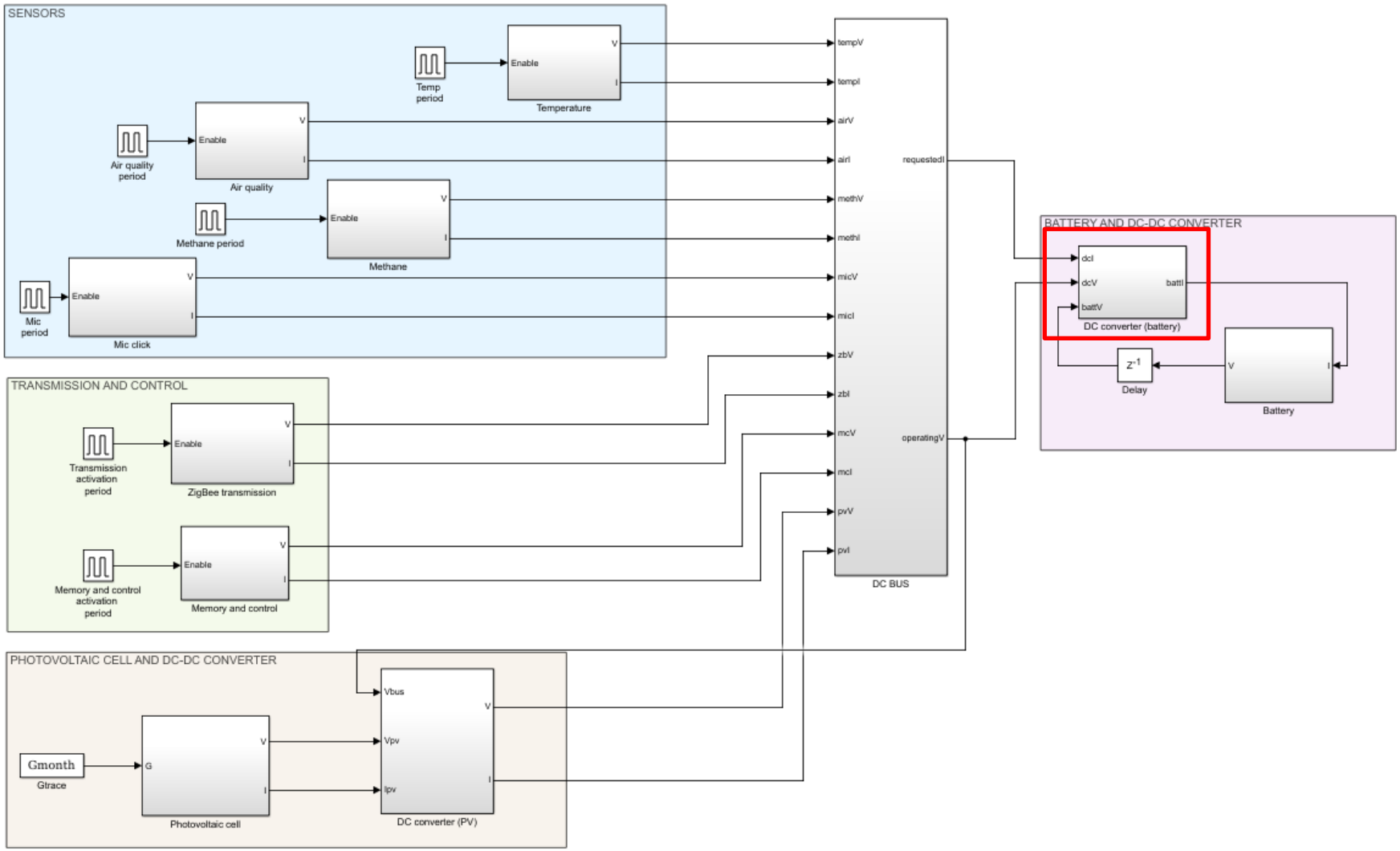
COEFFICIENT MUST BE CONVERTED BETWEEN 0 AND 1.

DC-DC converter of PV module

- How to:
  1. Digitize the curve
  2. Import file in Matlab
  3. Set the lookup table parameters
     - Voltage samples = breakpoints
     - Efficiency samples = table data
     - More digitized samples = more accurate

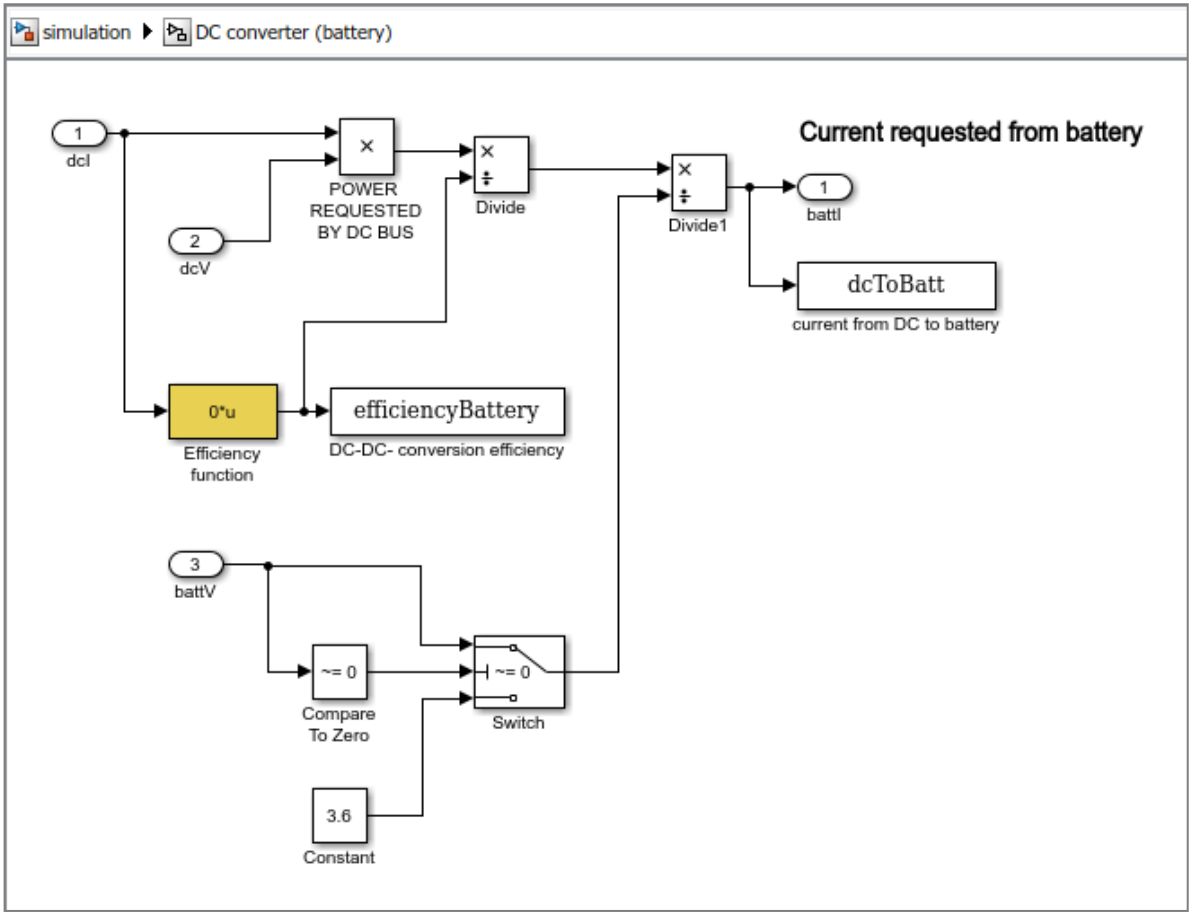


Simulink implementation



DC-DC converter of battery

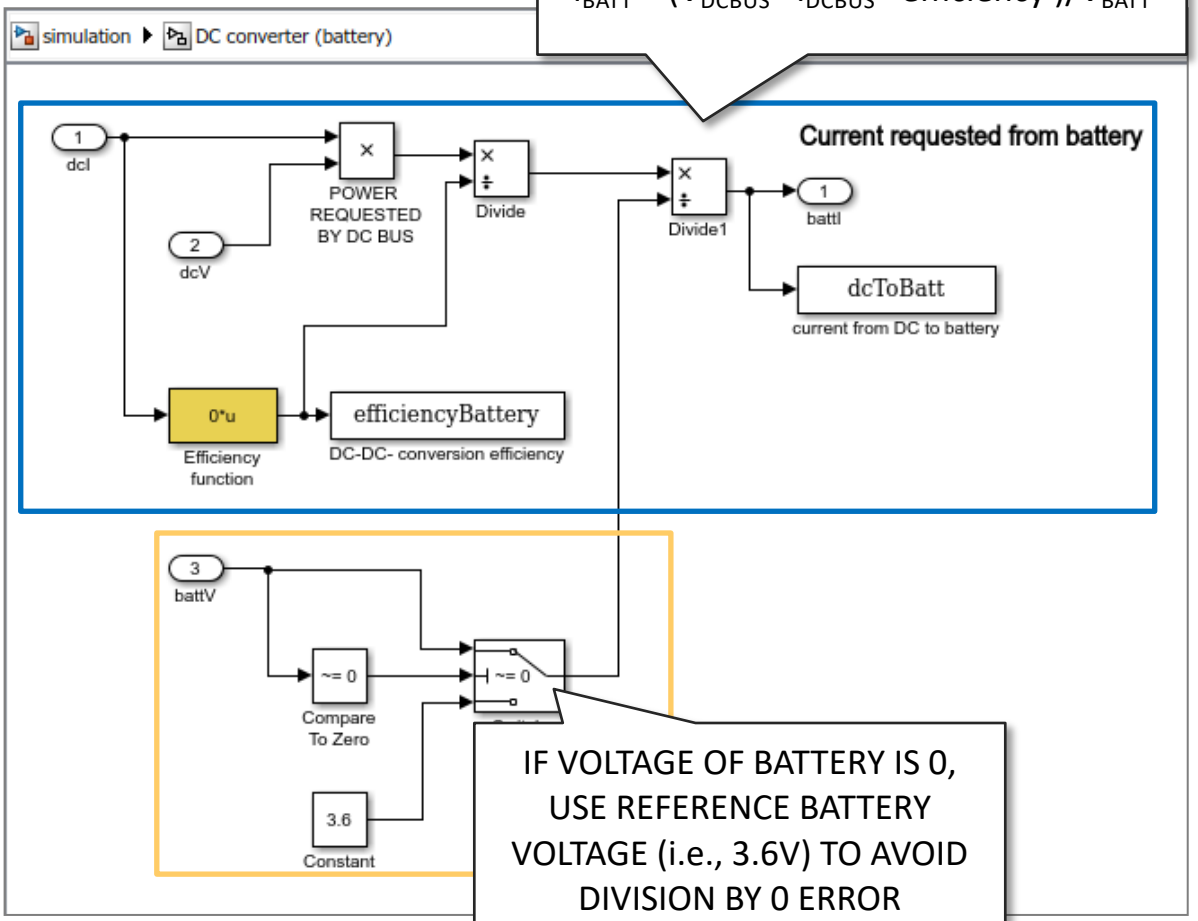
- DC-DC converter of the battery



DC-DC converter of battery

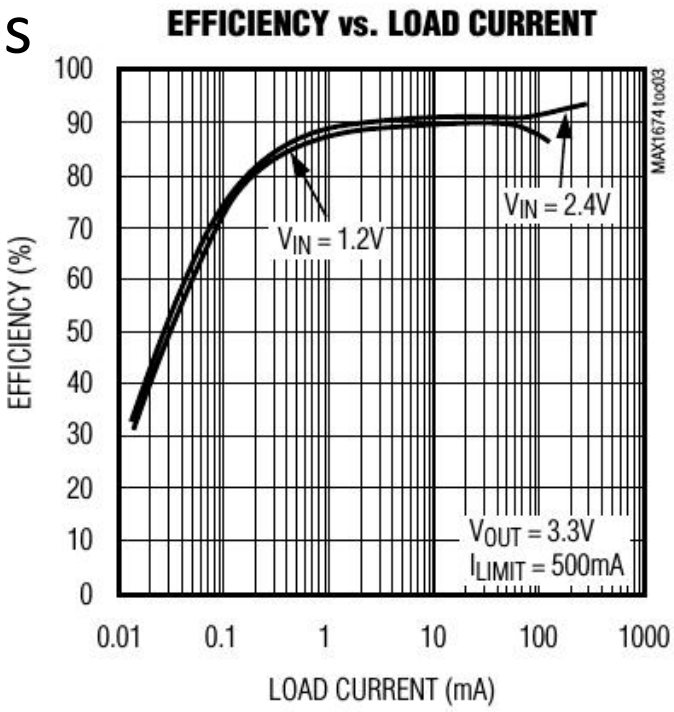
- DC-DC converter of the battery

$(V_{DCBUS} \cdot I_{DCBUS}) \cdot efficiency = (V_{BATT} \cdot I_{BATT})$
$I_{BATT} = (V_{DCBUS} \cdot I_{DCBUS} \cdot efficiency)/V_{BATT}$



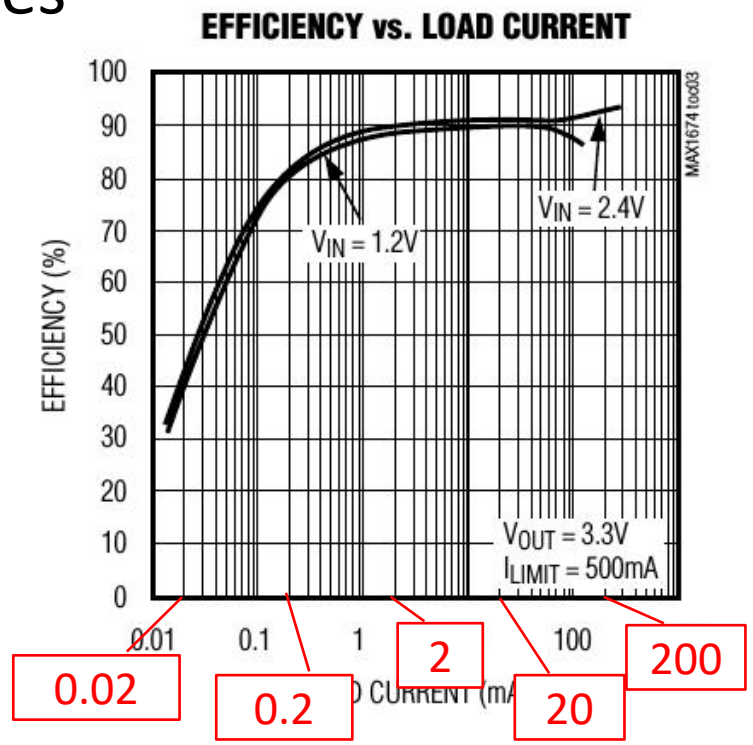
DC-DC converter of battery

- Open the **BATT_DCDCconv.pdf** file
  - Page 4: curve of efficiency given input current with voltage to the bus = 3.3V
- How to:
  1. Digitize one of the two curves
     - We avoid dependency from battery voltage
  2. Import the data in Matlab

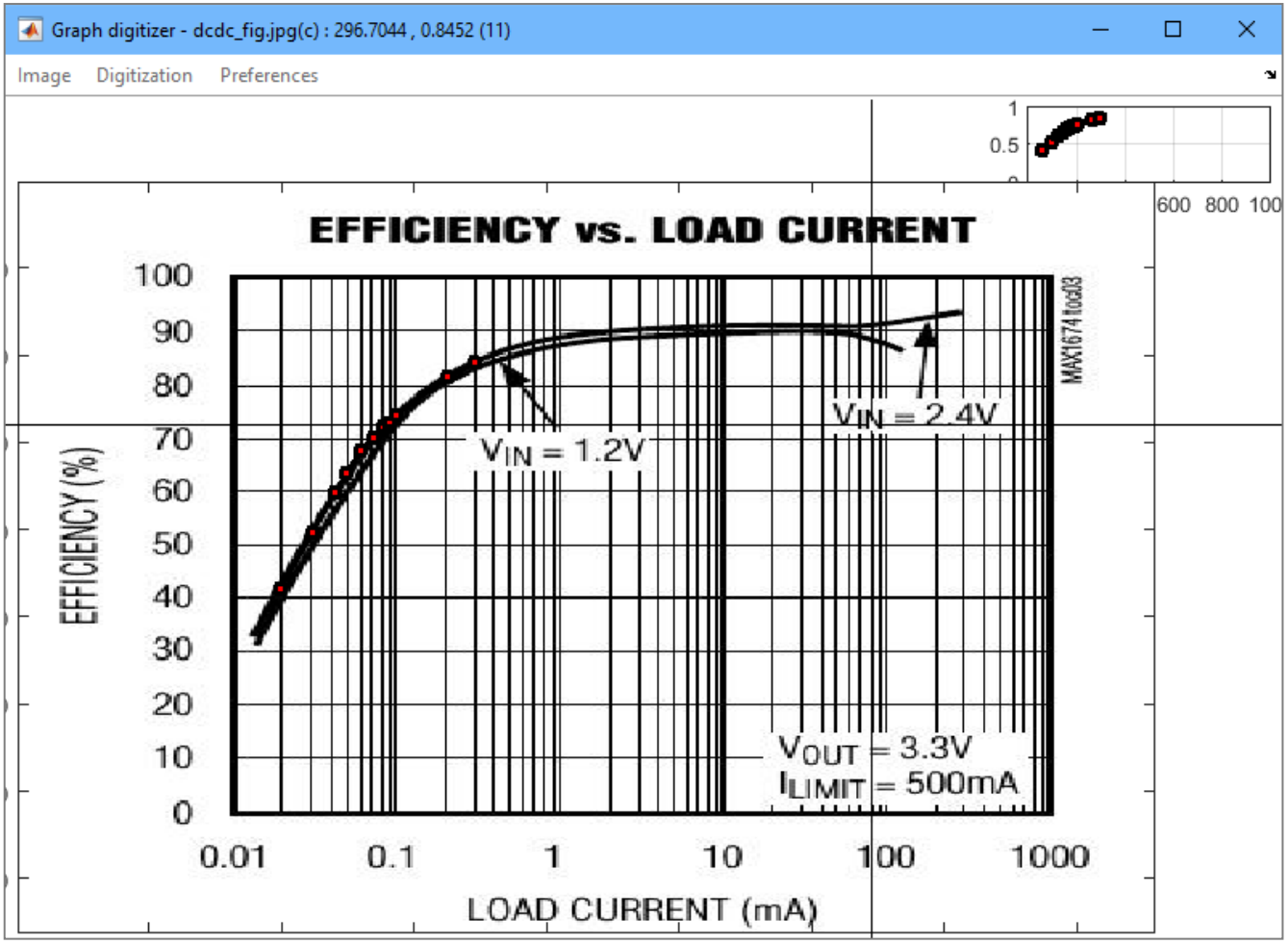


DC-DC converter of battery

- Open the **BATT_DCDCconv.pdf** file
  - Page 4: curve of efficiency given input current with voltage to the bus = 3.3V
- How to:
  1. Digitize one of the two curves
     - We avoid dependency from battery voltage
     - **ISSUE: x axis is in logarithmic scale**
       - **Sample points corresponding to the vertical lines**
       - **Can replace the x coordinate of samples with known values**
  2. Import the data in Matlab



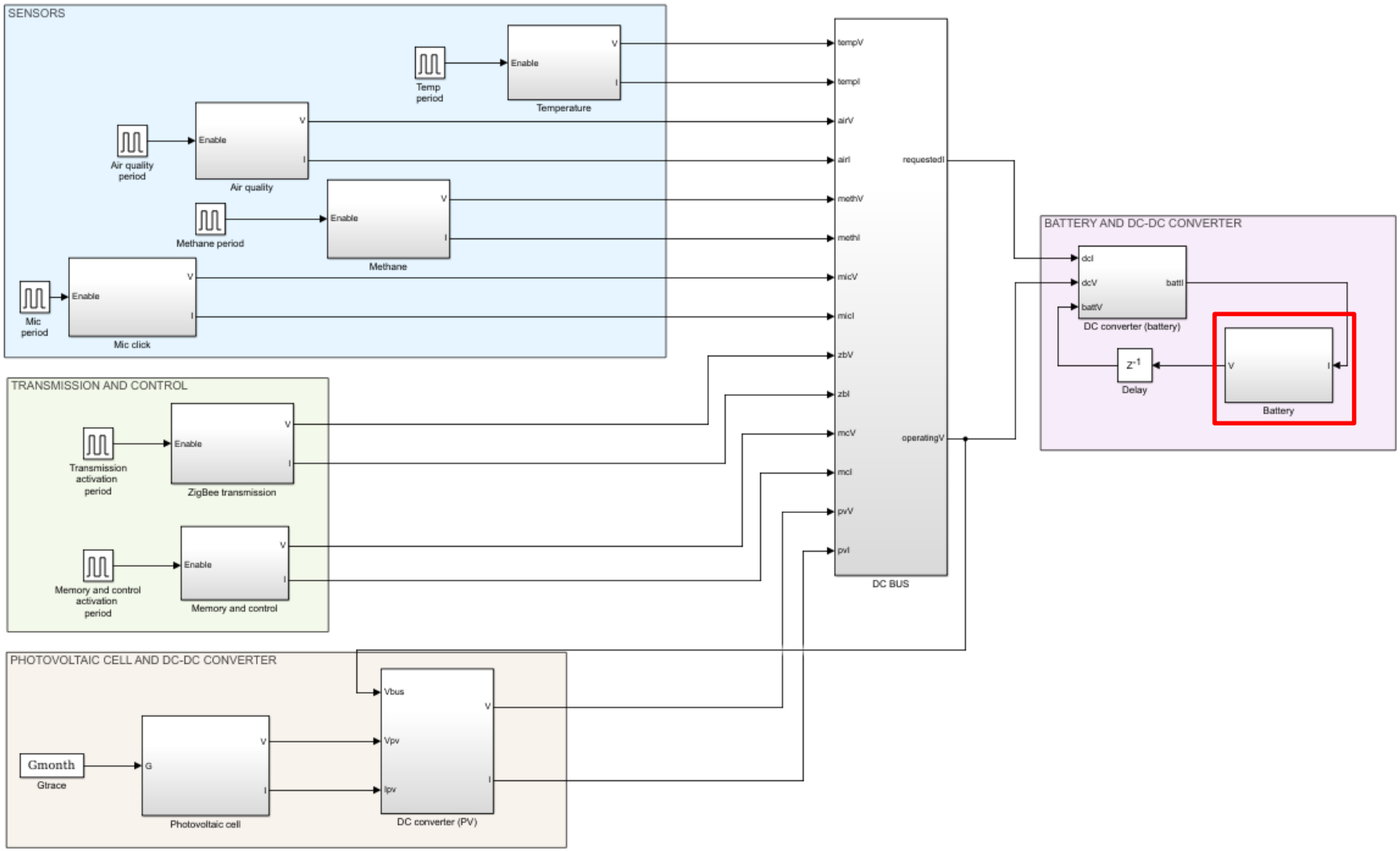
DC-DC converter of battery



DC-DC converter of battery

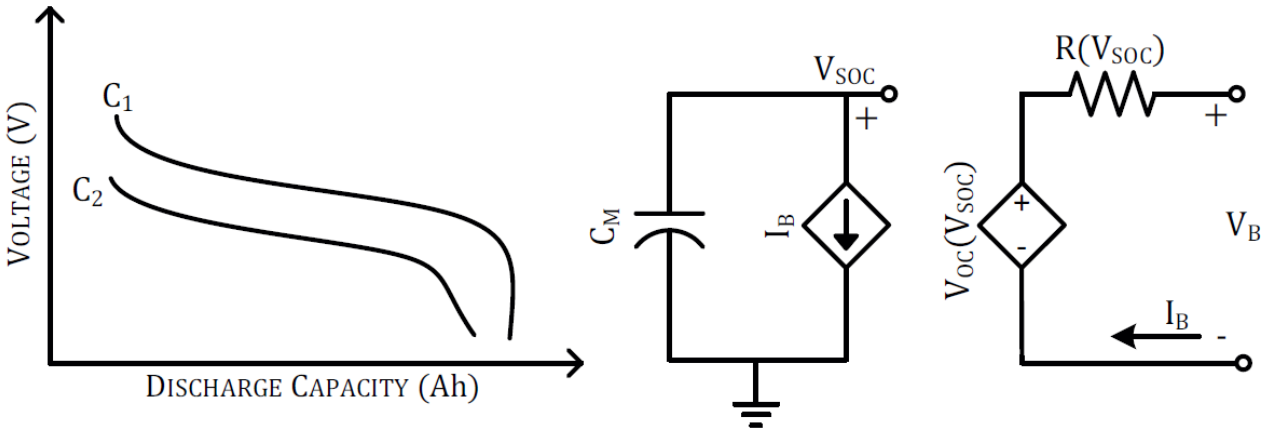
- How to:
  3. Set the lookup table parameters (as before):
     - Current samples = breakpoints
     - Efficiency samples = table data
     - More digitized samples = more accurate

Simulink implementation



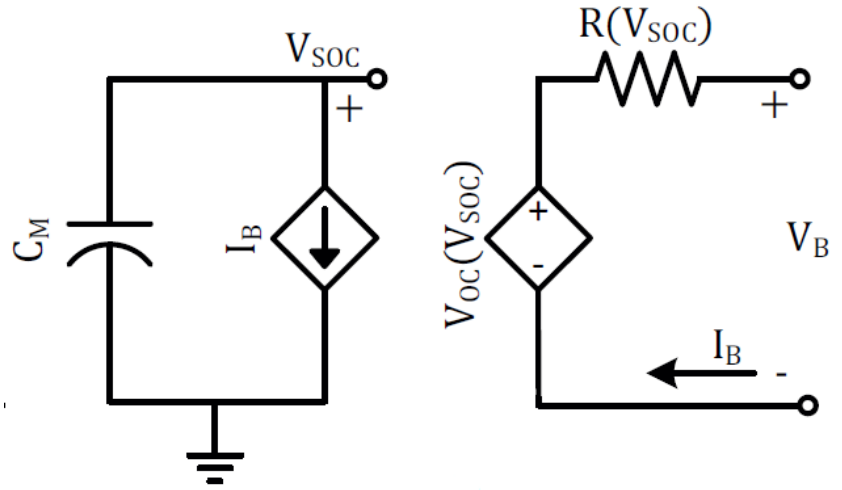
Battery model

- Model: a circuit model
  - Configuration and settings extracted solely from data provided in the datasheet
  - Model made of two branches:
    - Left: models battery lifetime and the SOC
    - Right: models battery dynamics



Battery model

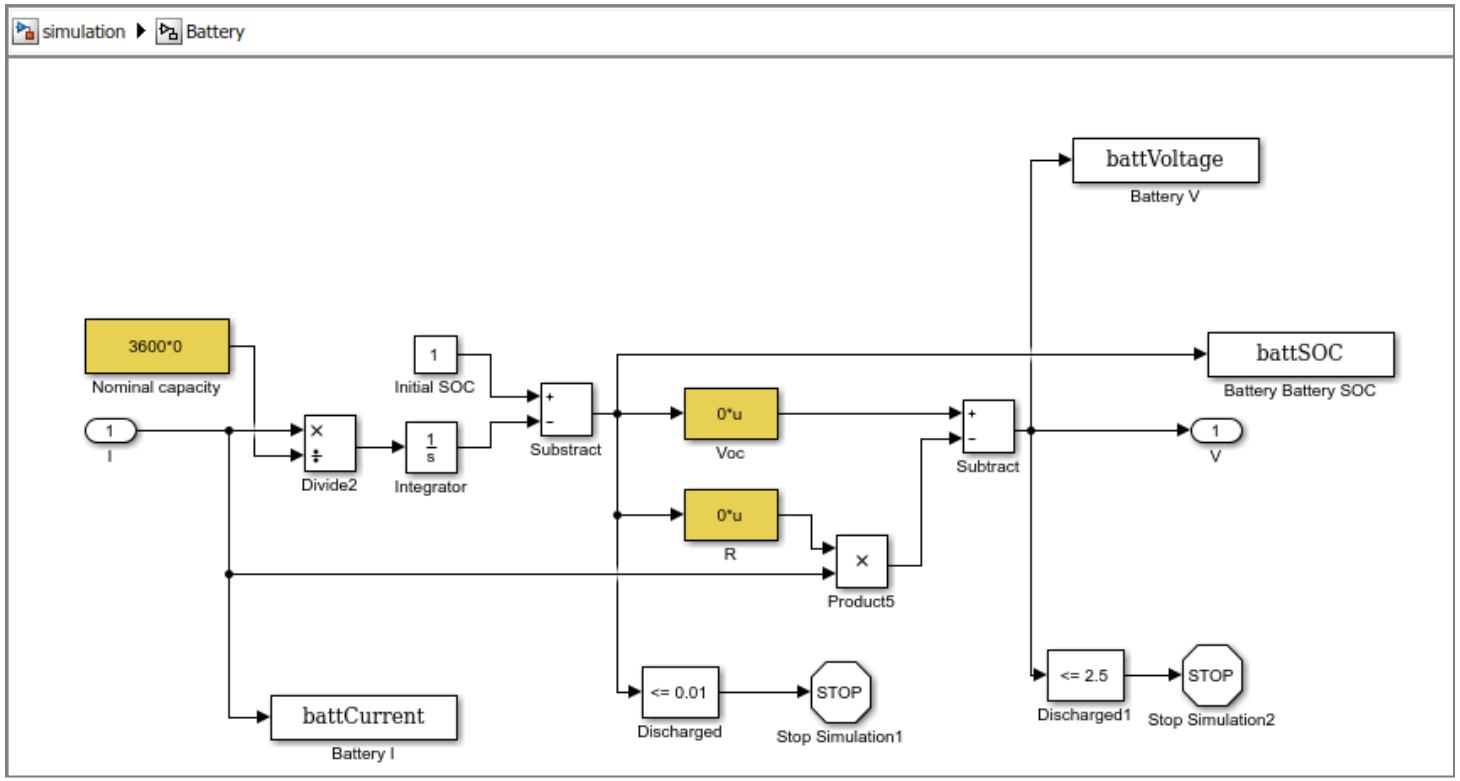
- Left:
  - C_M available usable capacity
  - I_B discharge current
  - V_{SOC} state of charge



- Right:
  - V_{OC} models the dependency between battery voltage vs. the SOC
  - I_B discharge current
  - R series resistance modeling voltage drop due to ohmic losses (i.e., the internal resistance of the battery)
  - V_B is battery voltage

Battery model

- Not implemented as a circuit but as equations solving the circuit
  - Simulation faster than implementing the circuit



Battery model

- Not implemented as a circuit but as equations solving the circuit
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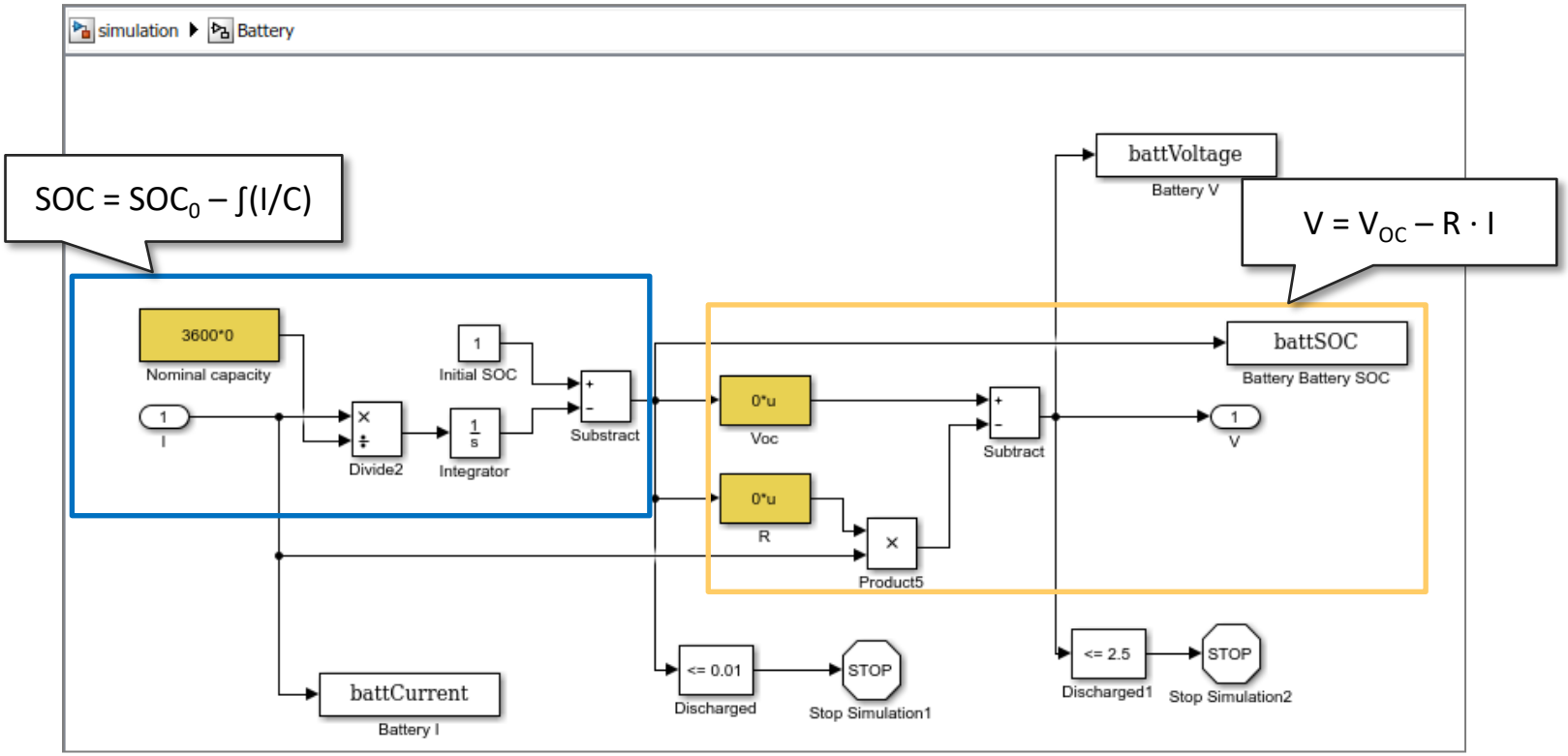
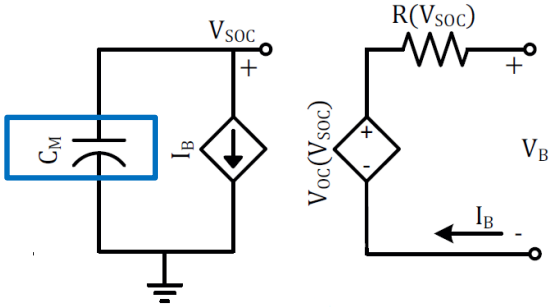


Battery model

- We must reconstruct the values for the single elements of the circuit from the datasheet

- Capacity
  - 3200mAh (3.2 Ah)
  - Timestep is 1s
    - Multiply per 3600 (seconds in 1 hour)

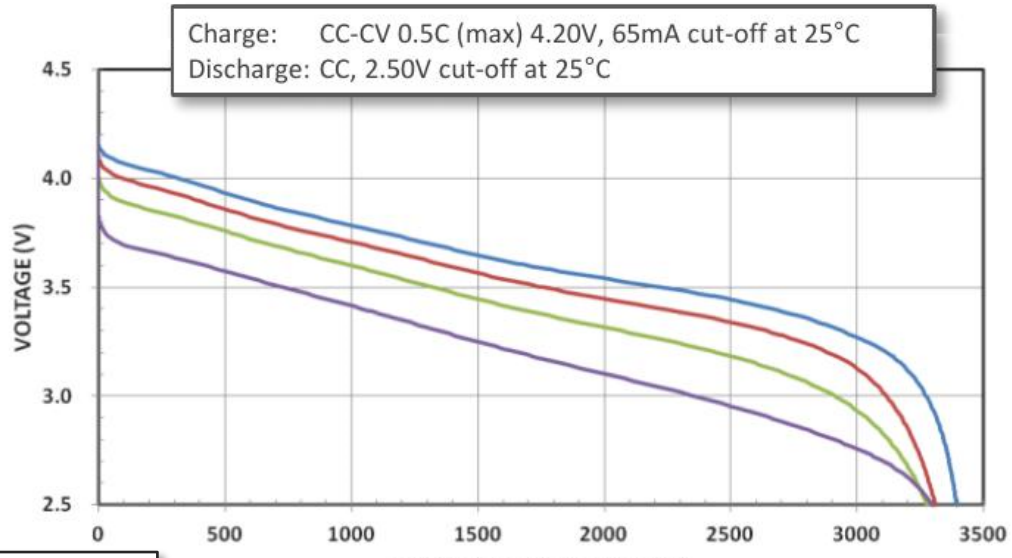


Specifications

Rated capacity(1)	Min. 3200mAh
Capacity(2)	Min. 3250mAh Typ. 3350mAh
Nominal voltage	3.6V
Charging	CC-CV, Std. 1625mA, 4.20V, 4.0 hrs
Weight (max.)	48.5 g
Temperature	Charge*: 0 to +45°C Discharge: -20 to +60°C Storage: -20 to +50°C
Energy density(3)	Volumetric: 676 Wh/l Gravimetric: 243 Wh/kg

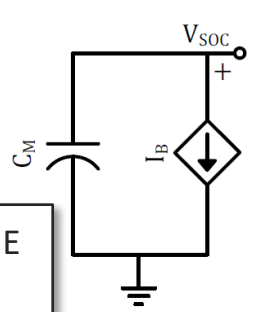
Battery model

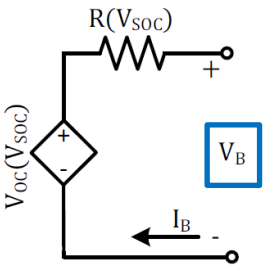
- V_B battery voltage
  - Function of the load current and of the SOC



REMINDER:
1C = current to have total discharge in 1 hour

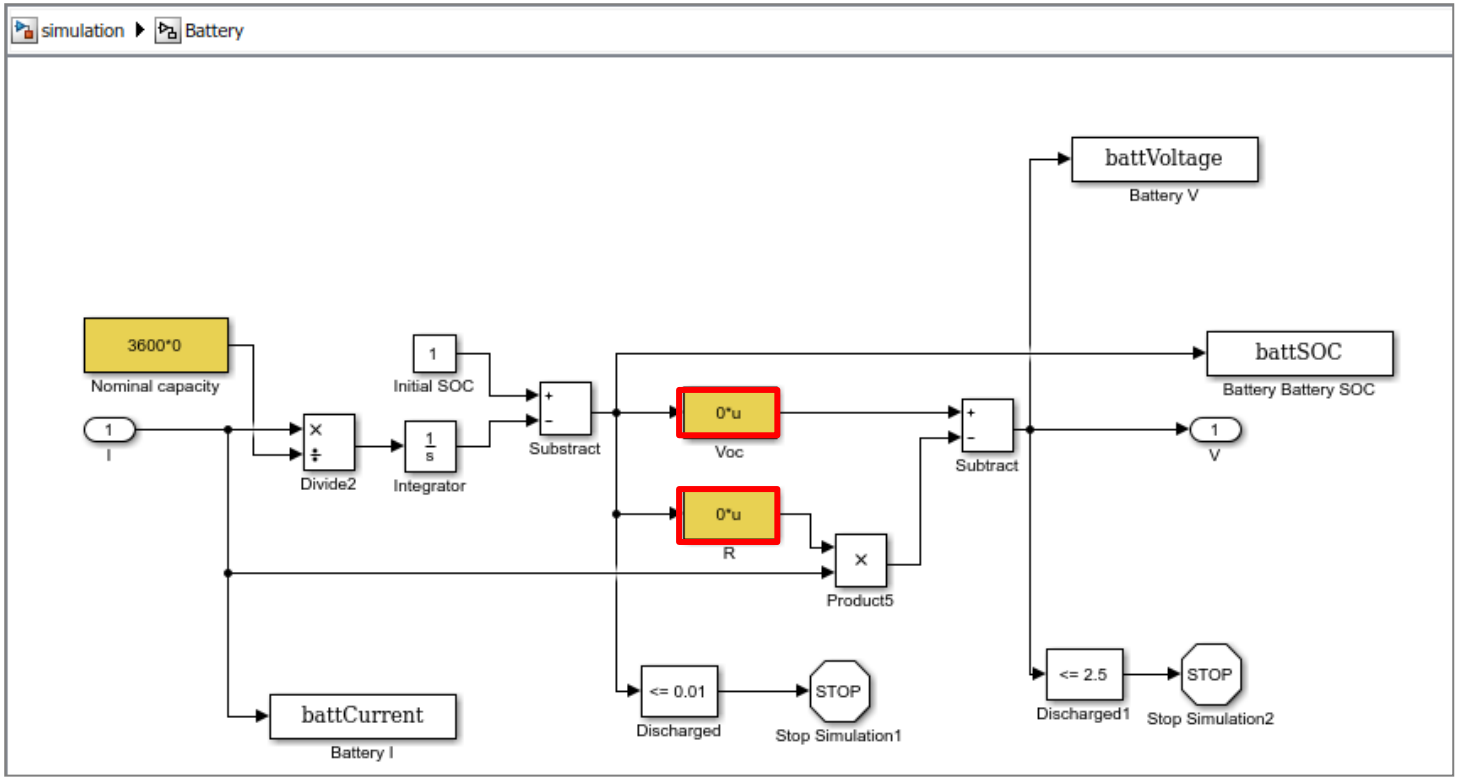
≈ STATE OF CHARGE OF THE BATTERY





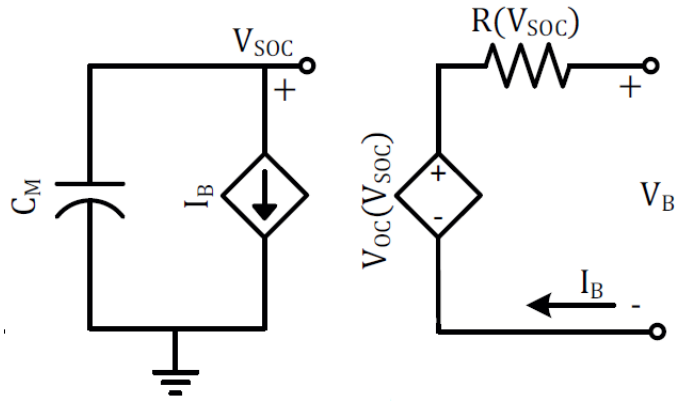
Simulink implementation

- Simulink models the battery as V_{OC} and R as a function of SOC
  - How can we relate V_{OC} and R to V, and thus SOC?



Battery model

- Derive V_{OC} and R as a function of V
  - Solving the equations associated with the right hand side branch of the circuit
  - $V_{OC} = V_{curve1} + R \cdot I_{curve1}$
  - $R = \frac{V_{curve2} - V_{curve1}}{I_{curve1} - I_{curve2}}$



  - Notation:
    - $curve1$ and $curve2$ refer to the operation with two different discharge currents, i.e., to two different discharge curves obtained with different discharge current values

Battery model

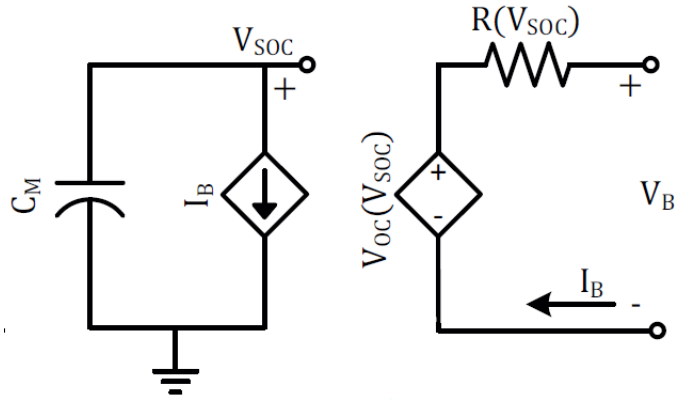
- In case you were wondering how we got here…
  - Equation solving the system:
    - $V_{OC} = R\,I + V$
  - Applied for both currents:
    - $\begin{cases} V_{OC} = RI_{curve1} + V_{curve1} \\ V_{OC} = RI_{curve2} + V_{curve2} \end{cases}$

- $V_{OC} = RI_{curve1} + V_{curve1} = RI_{curve2} + V_{curve2}$
- $R(I_{curve1} - I_{curve2}) = V_{curve2} - V_{curve1}$
- $R = \frac{V_{curve2} - V_{curve1}}{I_{curve1} - I_{curve2}}$

Battery model

- Derive V_{OC} and R as a function of V
  - Solving the equations associated with the right hand side branch of the circuit

  - $V_{OC} = V_{curve1} + R \cdot I_{curve1}$
  - $R = \frac{V_{curve2} - V_{curve1}}{I_{curve1} - I_{curve2}}$

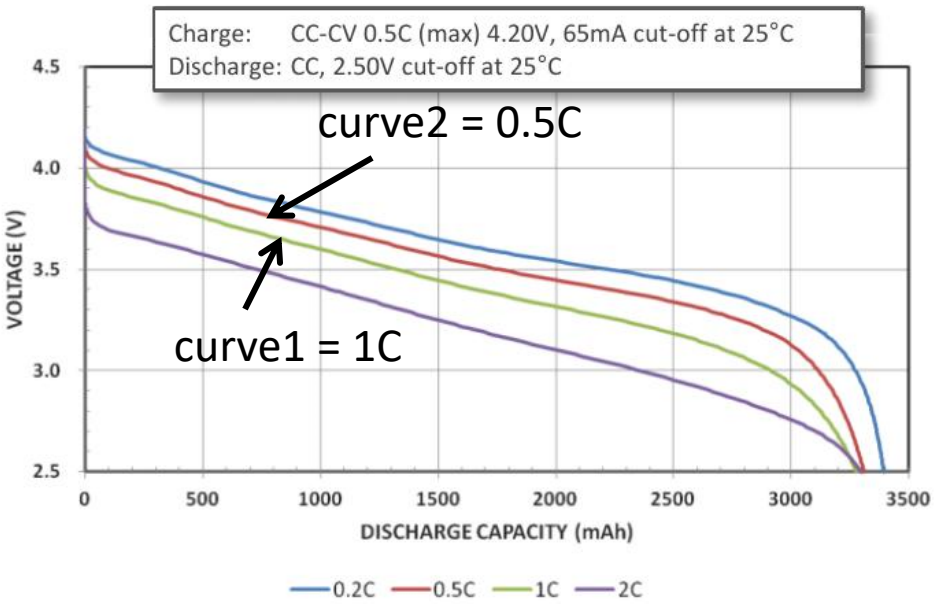


  - How do we populate the equations?

Battery model

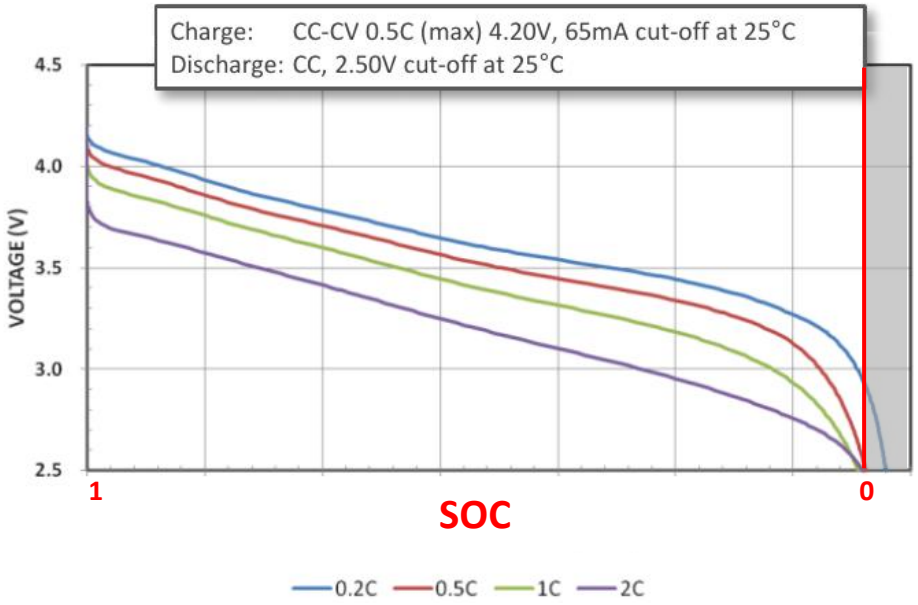
- Derive V_{OC} and R as a function of V
  - $V_{OC} = V_{curve1} + R \cdot I_{curve1}$
  - $R = \frac{V_{curve2} - V_{curve1}}{I_{curve1} - I_{curve2}}$

  - Need two curves of V given the discharge capacity
    - See example →
    - Values of V given SOC and discharge current



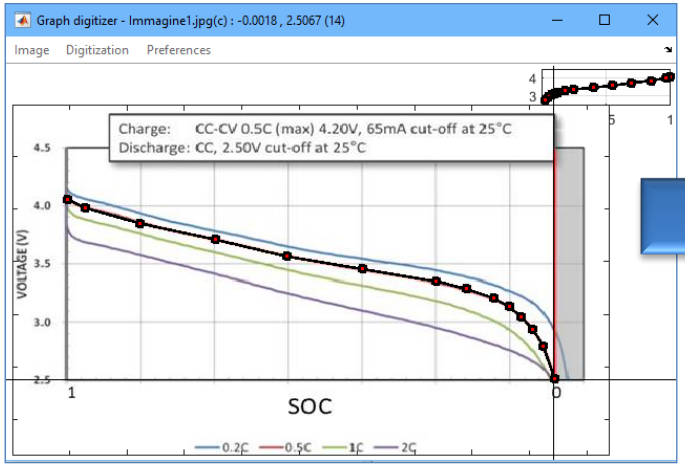
Battery model

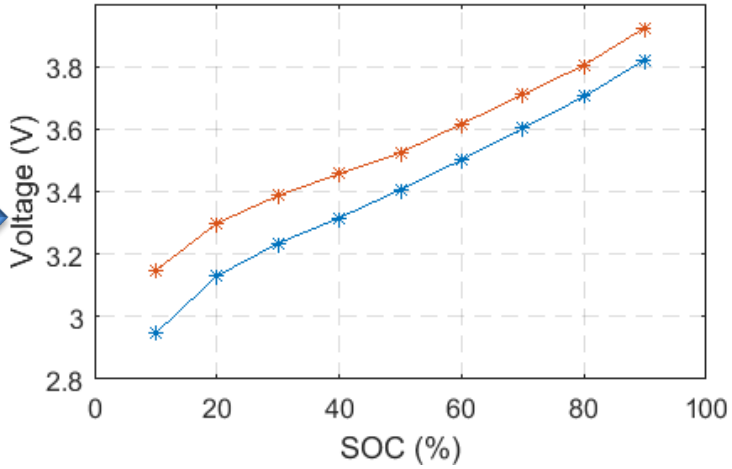
- V battery voltage: how to
  1. Download the datasheet figure (course website)
  2. Determine SOC axis
     - Fix the origin where the lower curve ends



Battery model

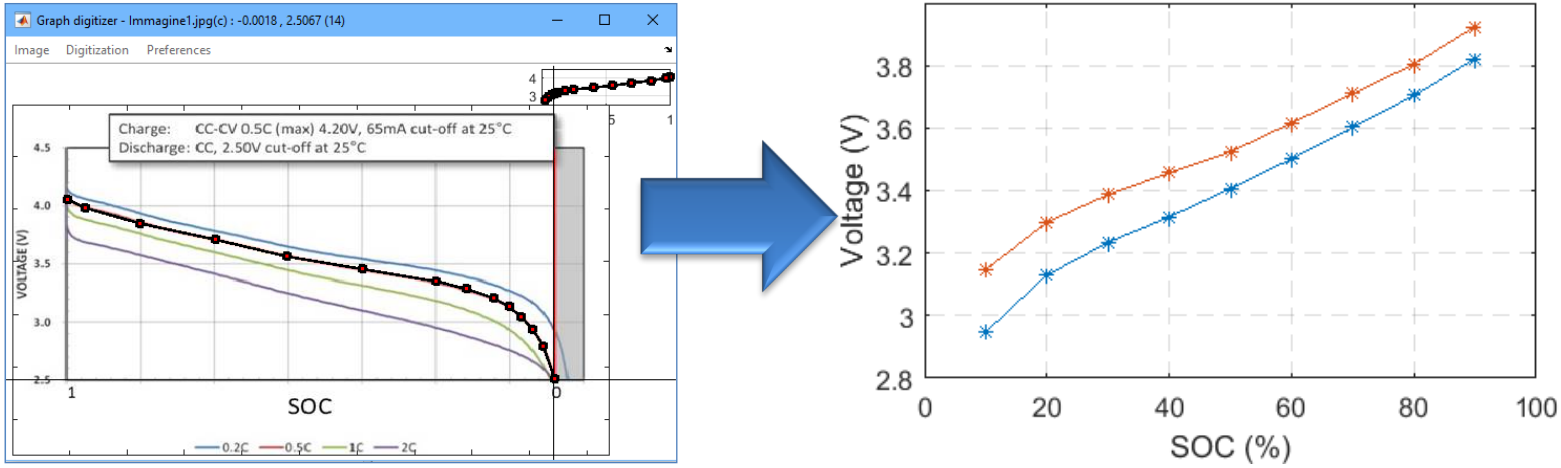
- V battery voltage: how to
  3. Use the digitizer to extract data from the figure
     - Extract values of two of the voltage vs. SOC curves
  4. Interpolate the two data sets
     - Given the same value of SOC, we have the corresponding value of V for both the curves





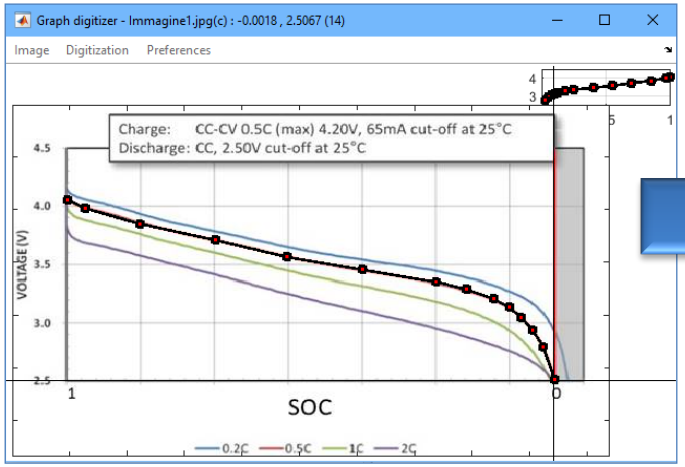
Battery model

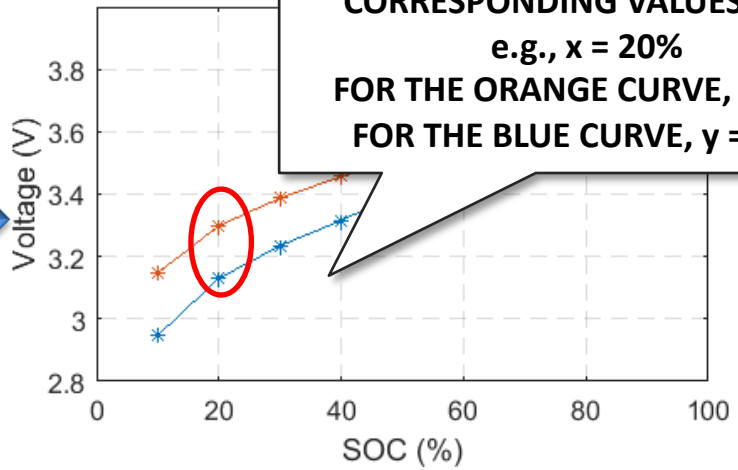
- Interpolation: Matlab function `interp1` (link)
  - `newY = interp1(x,y,newX)`
    - Given the known samples: x values and corresponding y values
    - And the new x values newX
    - Calculate the corresponding y values newY
  - In our case:
    - x and y are the coordinates of the digitized samples
    - newX are samples of SOC (e.g., from 0 to 1 with step 0.1)



Battery model

- Why do we need interpolation?
  - The samples of the two curves will most probably correspond to different values of SOC (i.e., x)
  - Thus we can not compare the two curves!
    - We have y values corresponding to different x coordinates!





Battery model

- Derive V_{OC} and R
  - Solving the equations associated with the right hand side branch of the circuit

  - $V_{OC} = V_{curve1} + R \cdot I_{curve1}$
  - $R = \frac{V_{curve2} - V_{curve1}}{I_{curve1} - I_{curve2}}$

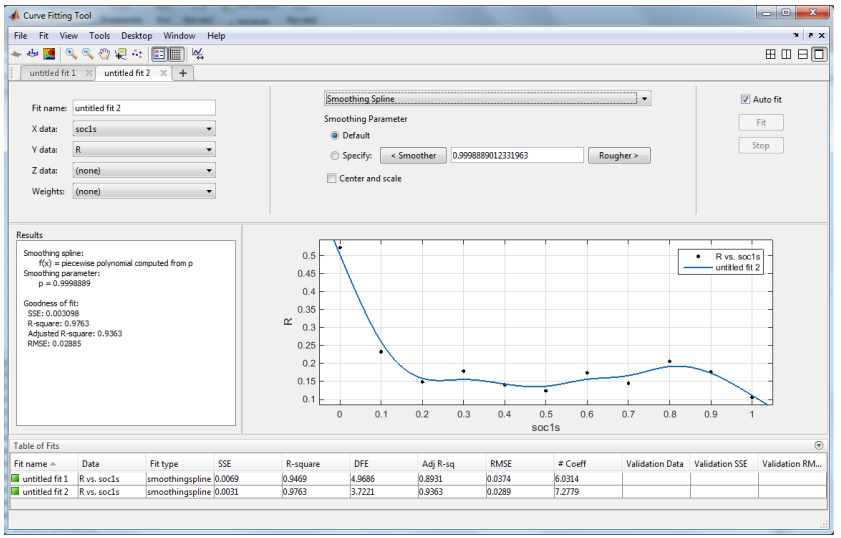
- Obtain values for the parameters of our battery model in *some points* of the SOC range
  - $SOC \rightarrow V \rightarrow V_{OC}, R$

WE KNOW FROM THE SAMPLES

WE DERIVE FROM THE EQUATIONS

Battery model

- So we fit the resulting data into functions by using the CurveFit app (link)
  - Express V_{OC} and R as functions of V_{SOC}, i.e., of the state of charge
  - Allow to derive V_{OC} and R for any value of SOC as some function/polynomial



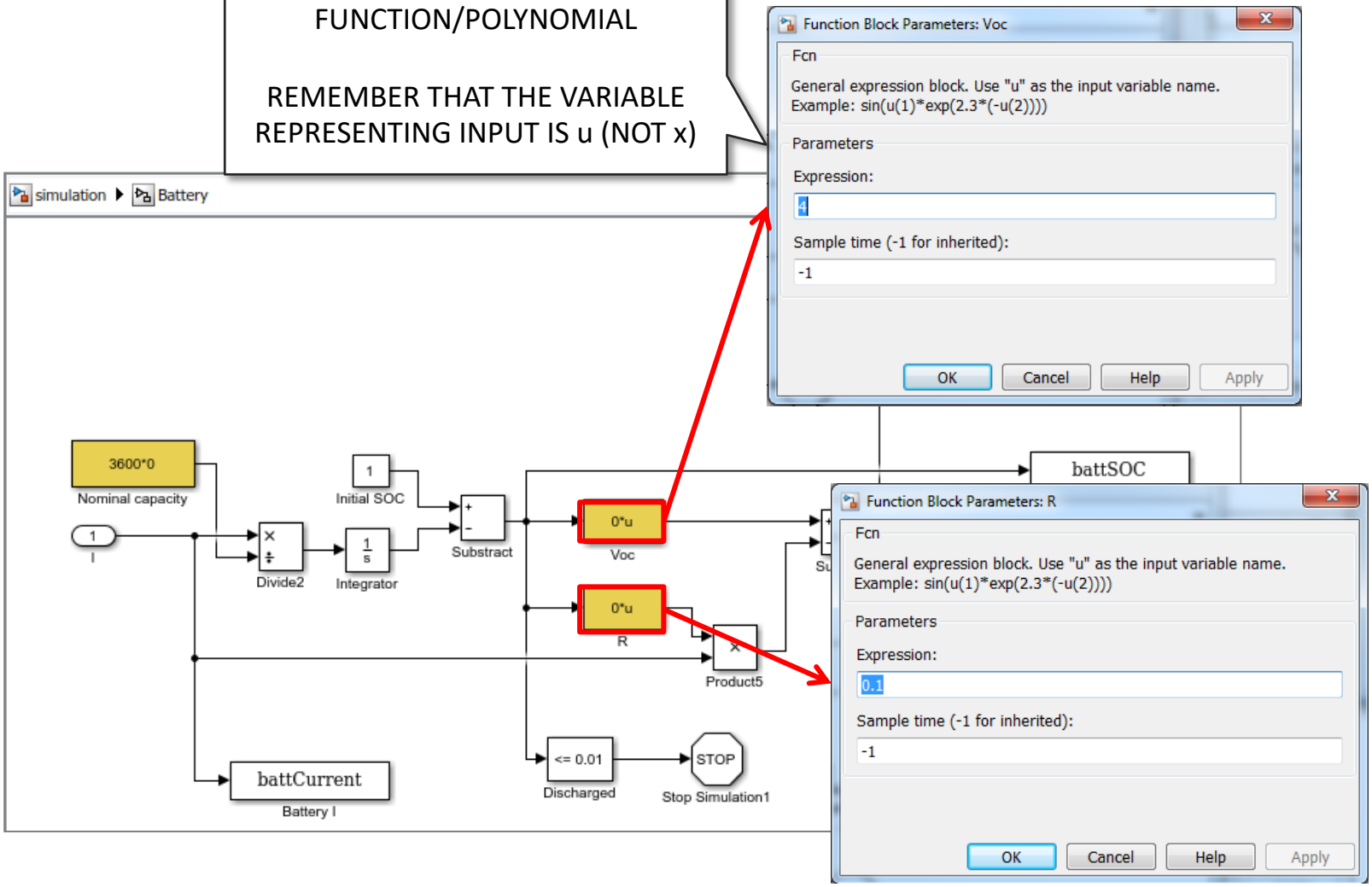
Battery model

- This gives us all information to populate the battery model!
  - We derived the values or the equations modeling the various elements of the circuit

Simulink implementation

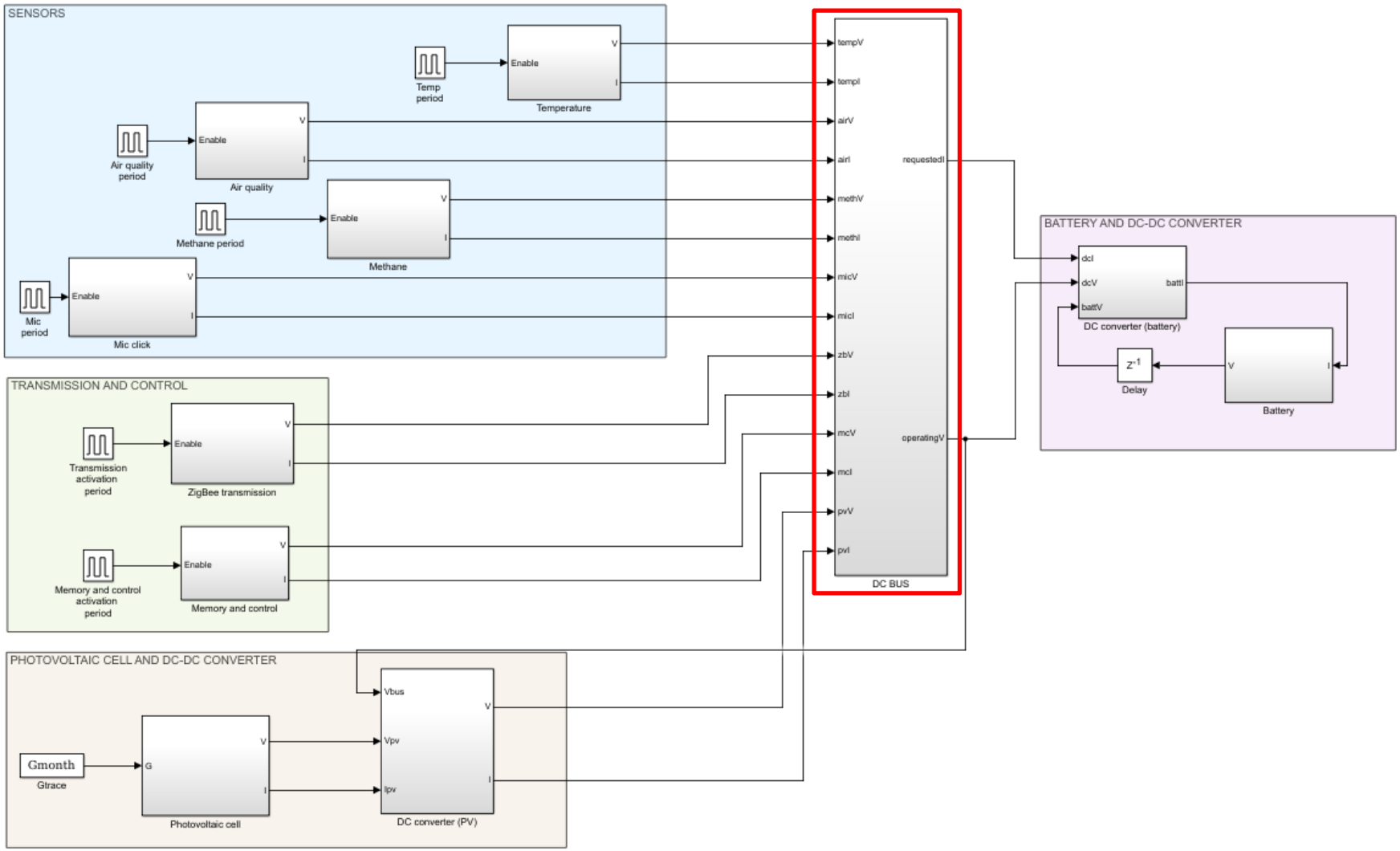
PUT IN THE FUNCTION BLOCKS THE FUNCTION/POLYNOMIAL

REMEMBER THAT THE VARIABLE REPRESENTING INPUT IS u (NOT x)



Lab 3 – Part 3
Load modeling and scheduling

Simulink implementation

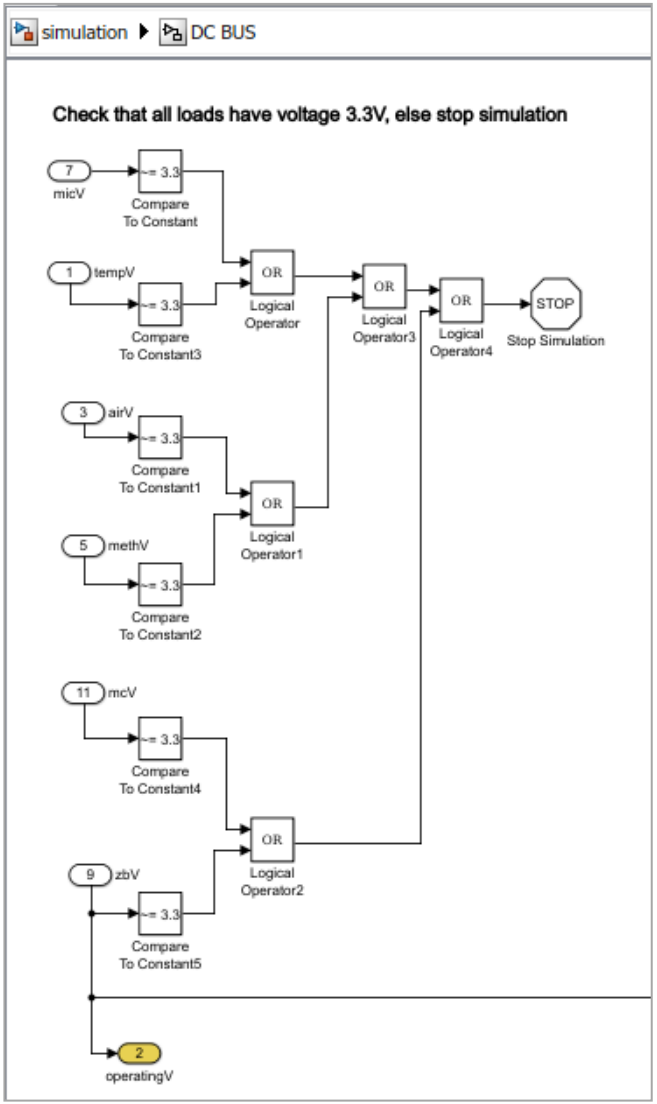


DC bus

- Two-fold goal:
  - Provide a **reference voltage** for the system (3.3V)
  - **Rule the energy flow** in the system
    - Determine what is the total power consumption of loads
    - Collect the power production of the photovoltaic module
    - Decide how to use the battery:
      - If the photovoltaic power is higher or equal to total load demand, no need to use the battery
        - » I can even charge the battery!
      - Else, estimate how much current must be drained from the battery
- **How long will my IoT system survive?**

DC bus

- **Part 1:**
  - Guarantee that all current requests happen at the same voltage
  - If any voltage is different from 3.3V, stop the simulation!
    - Maybe someDC-DC converter is missing?

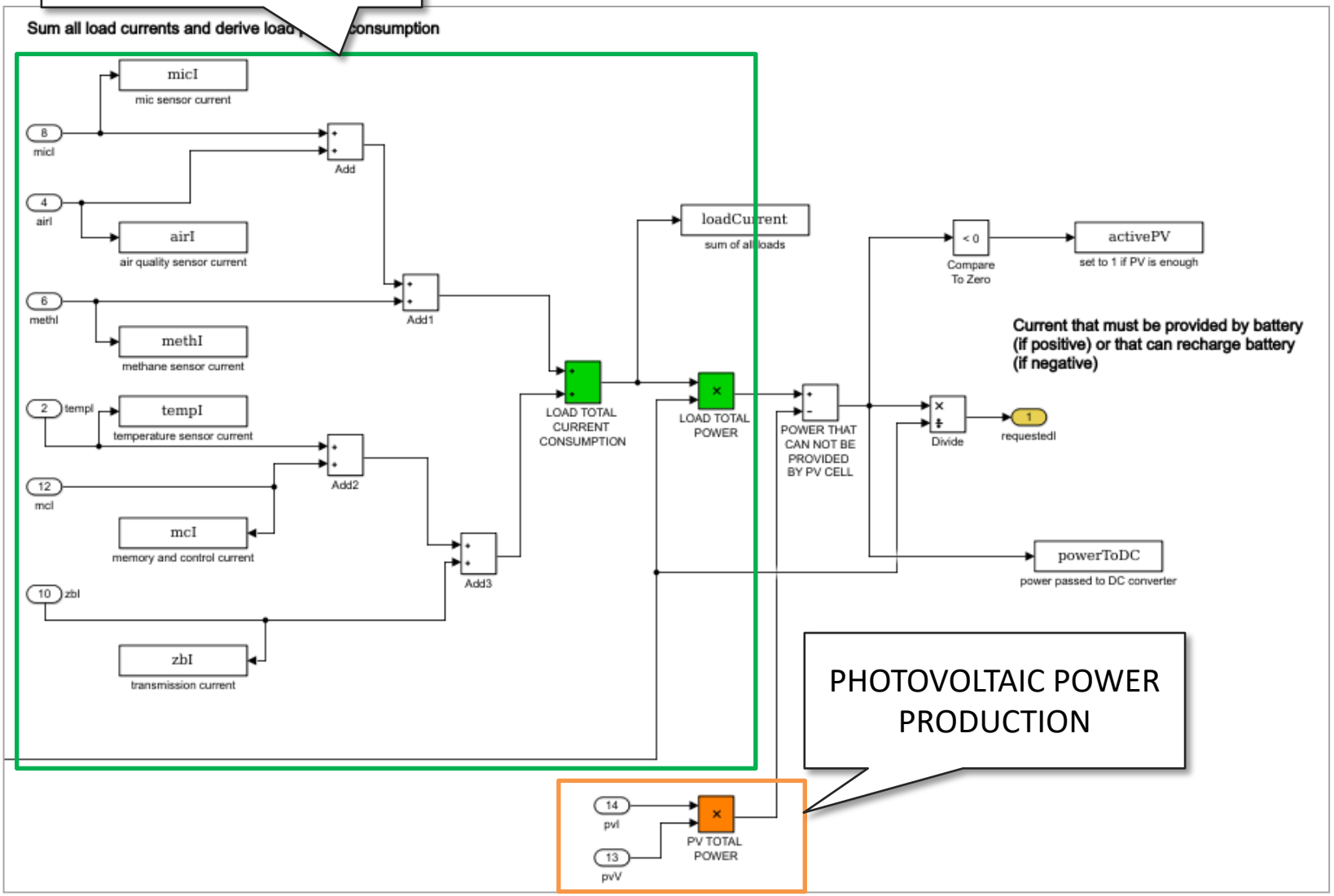


DC bus

- **Part 2:**
  - Estimate the energy flow
    1. Estimate total load power consumption
    2. Derive photovoltaic power production
    3. Calculate the difference: $P_{LOAD} - P_{PV}$
       - If the difference is positive, that power must be provided by the battery (photovoltaic module is not enough!)
       - If the difference is negative, that power can be used to charge the battery (unused power!)
    4. Battery current is thus: $\frac{P_{LOAD} - PPV}{3.3V}$

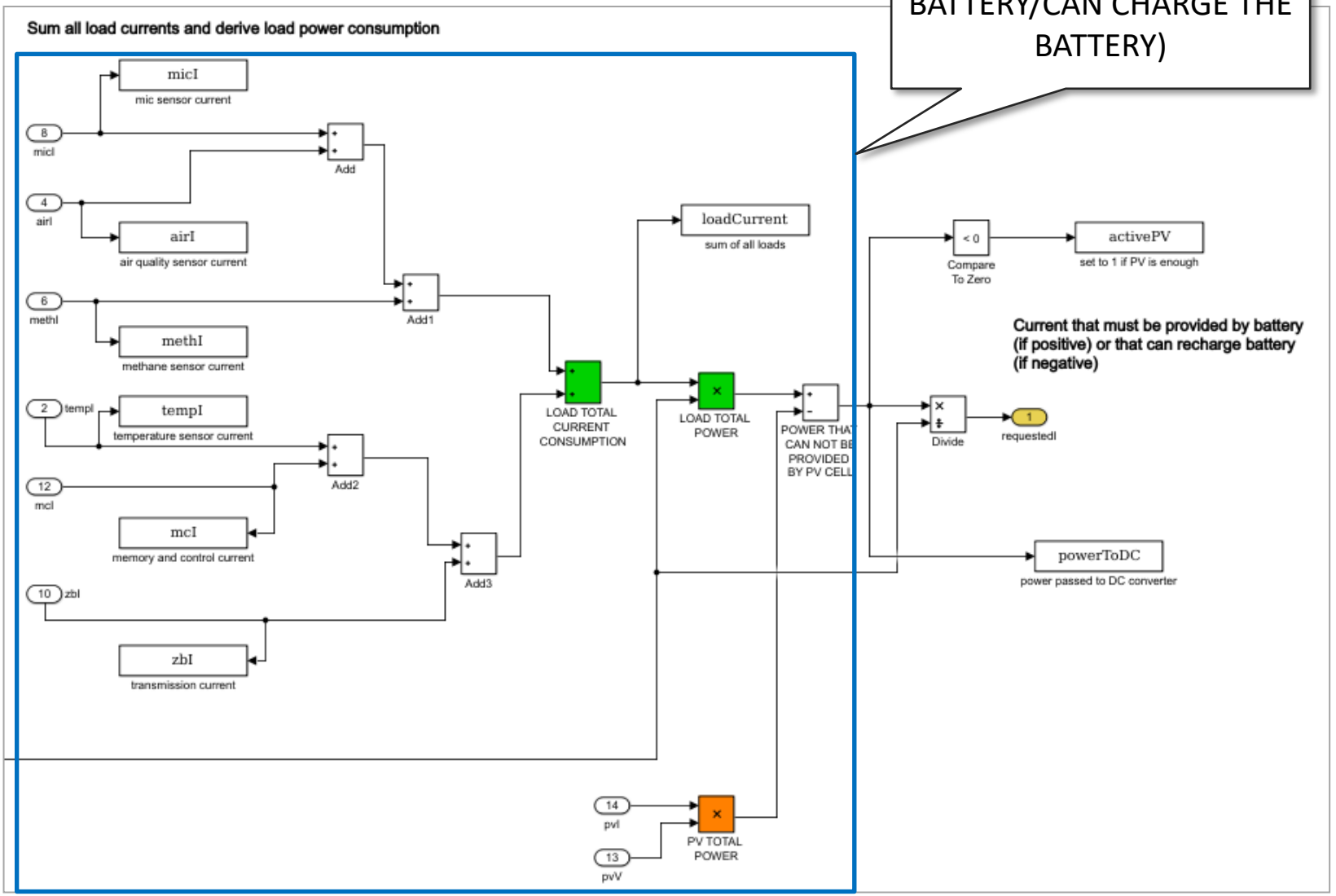
DC bus

TOTAL LOAD POWER CONSUMPTION

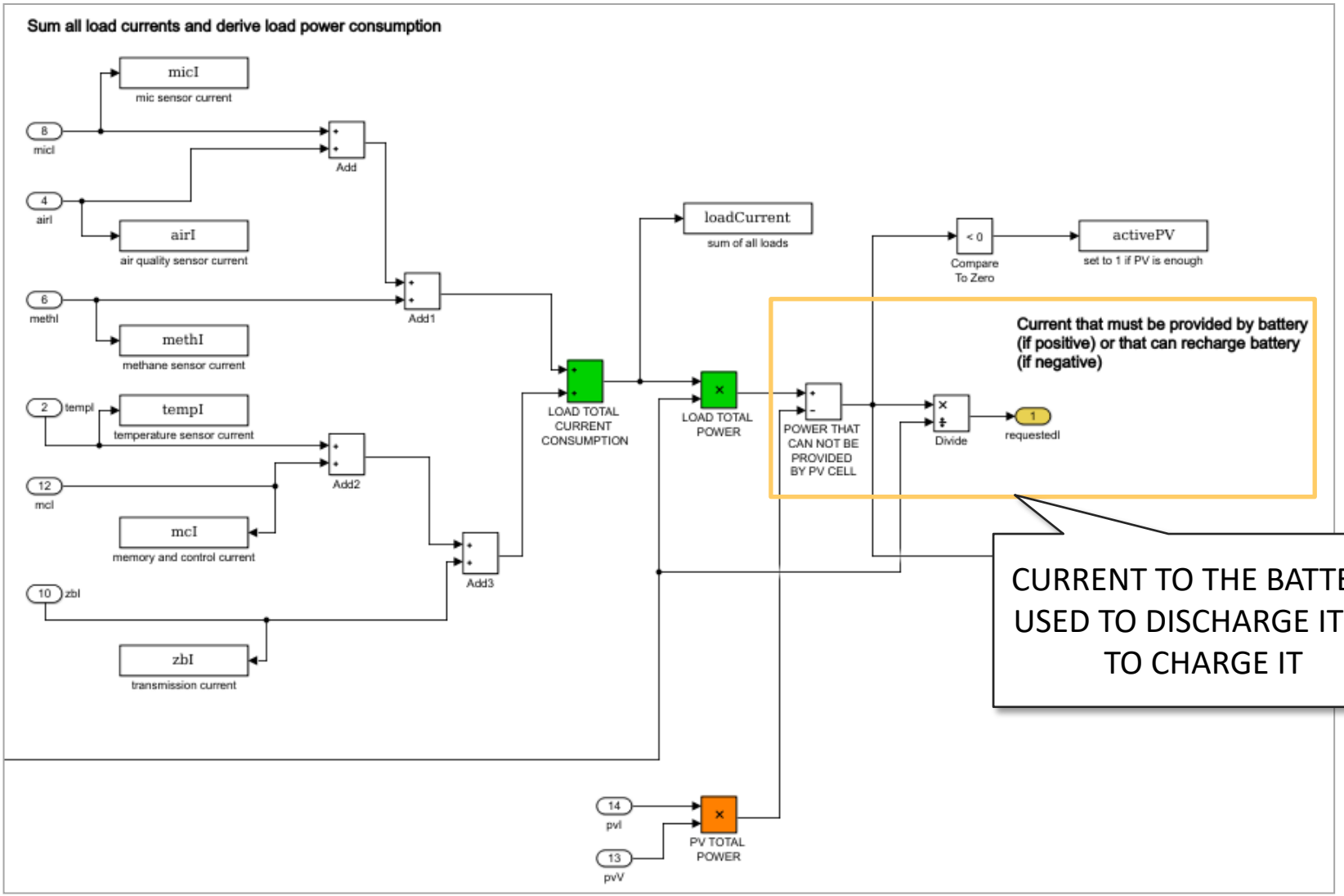


DC bus

POWER MISSING/STILL AVAILABLE
(MUST DISCHARGE THE BATTERY/CAN CHARGE THE BATTERY)

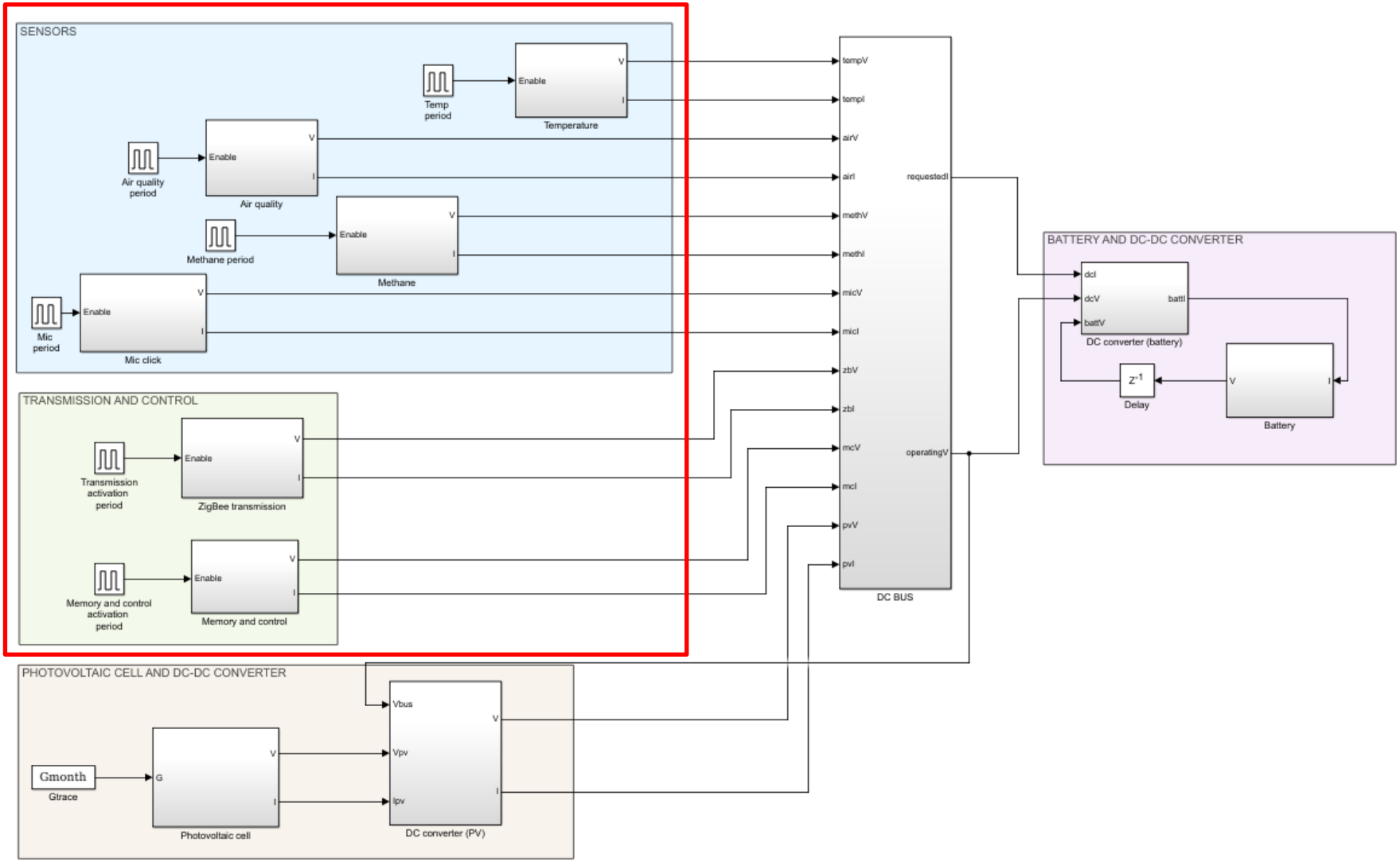


DC bus



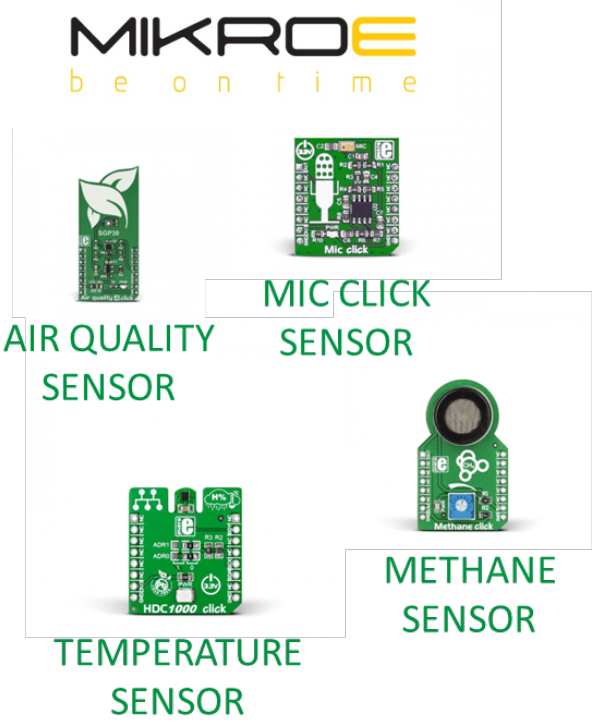
CURRENT TO THE BATTERY: USED TO DISCHARGE IT OR TO CHARGE IT

Simulink implementation



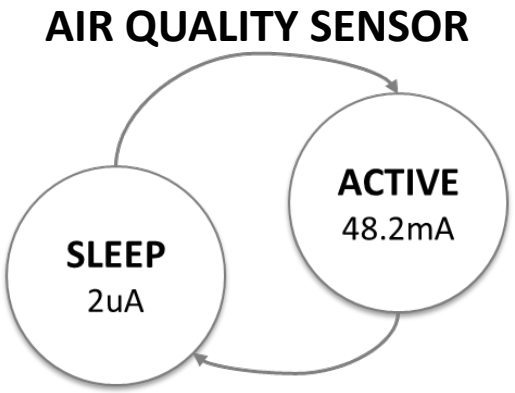
Loads

- 6 loads
  - Temperature sensor
    - Humidity and temperature sensor
  - Methane sensor
    - CH4 sensor
  - Air quality sensor
    - Metal-oxide, H2 and Ethanol sensing
  - Mic click sensor
    - Silicon microphone
  - Memory and control unit
  - A module to transmit data over ZigBee



Loads

- Loads are implemented as simple PSM
  - Fixed voltage, same as DC bus (3.3V)
  - Varying current
    - One active state (higher consumption)
    - One sleep state (lower consumption)
- Data taken from load datasheets
  - Typical current consumption depending on activity



LOAD	ACTIVE (mA)	SLEEP (mA)
Air quality sensor	48.2	0.002
Methane sensor	18	0.002
Temperature sensor	3	0.002
Mic click sensor	0.15	0.002
ZigBee transmission	0.1	0.001
Memory and control	13	0.002

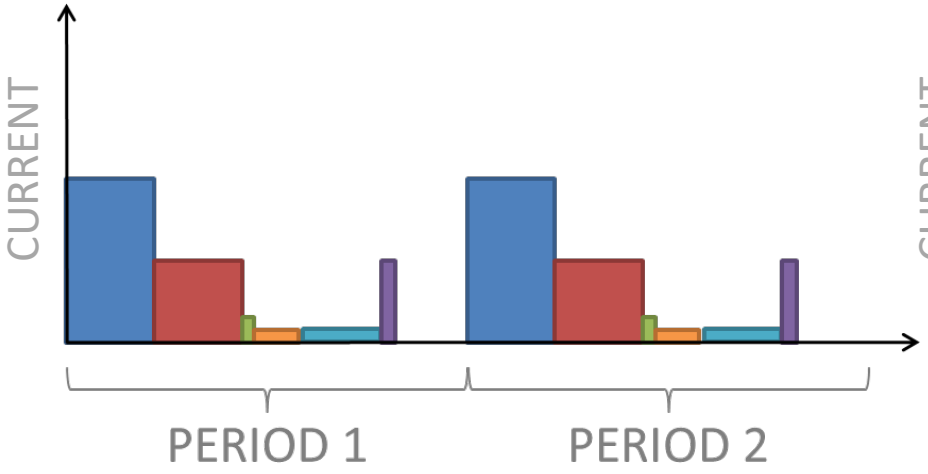
Loads

- Loads behavior is periodic
  - Active time is fixed for each load
    - Depends on the requirements of the component
    - E.g., how long it takes for the sensor to make the measurements
    - Given as input specification

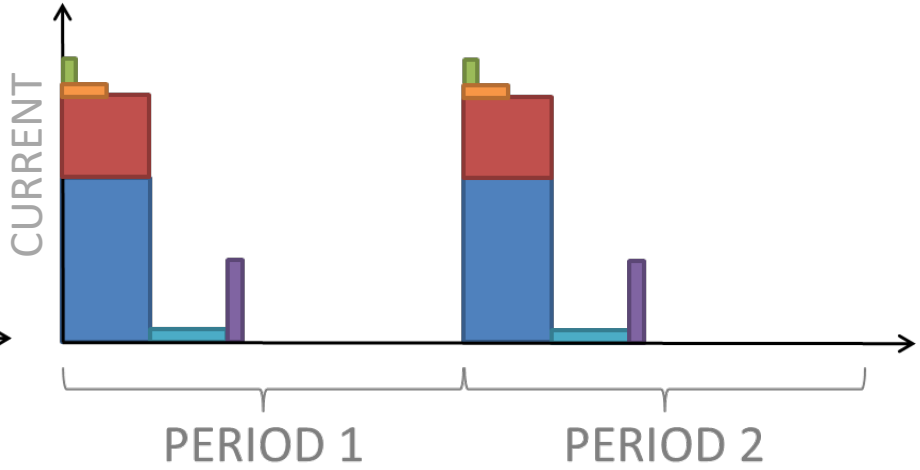
LOAD	TIME (s)
Air quality sensor	30
Methane sensor	30
Temperature sensor	6
Mic click sensor	12
ZigBee transmission	24
Memory and control	6

Loads

- Loads behavior is periodic
  - Load activation depends on a schedule
    - Fixed order: first sensors, then memory and control, then transmission
    - Sensors can be activated sequentially or in parallel



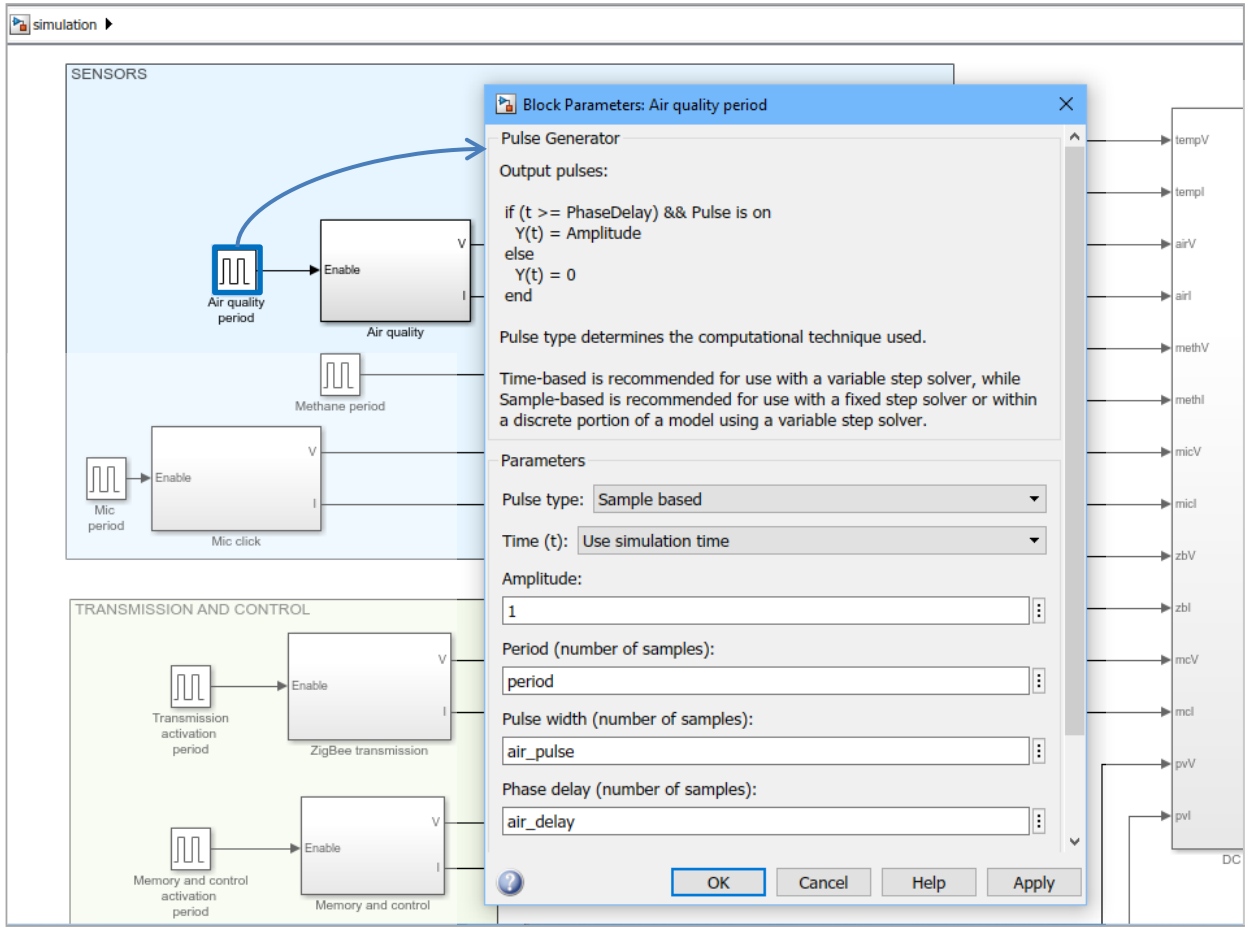
SEQUENTIAL ACTIVATION OF SENSORS



PARALLEL ACTIVATION OF SENSORS

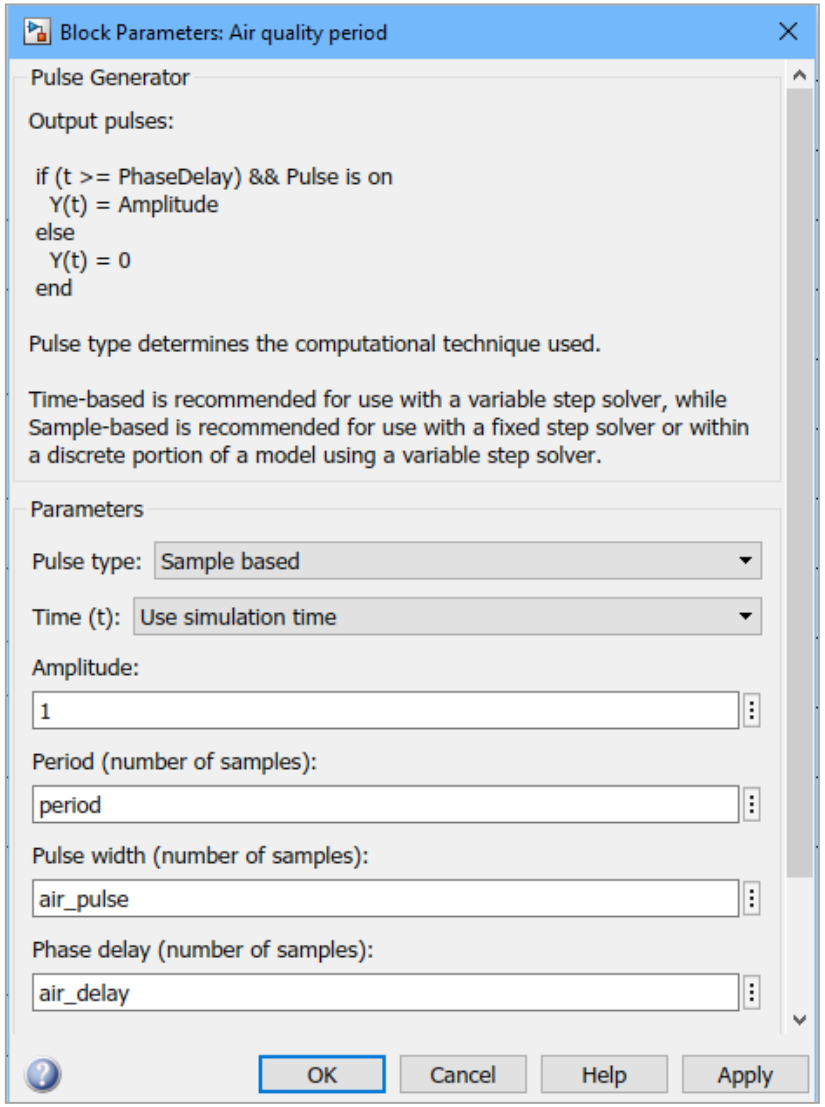
Loads

- Who controls load activation?



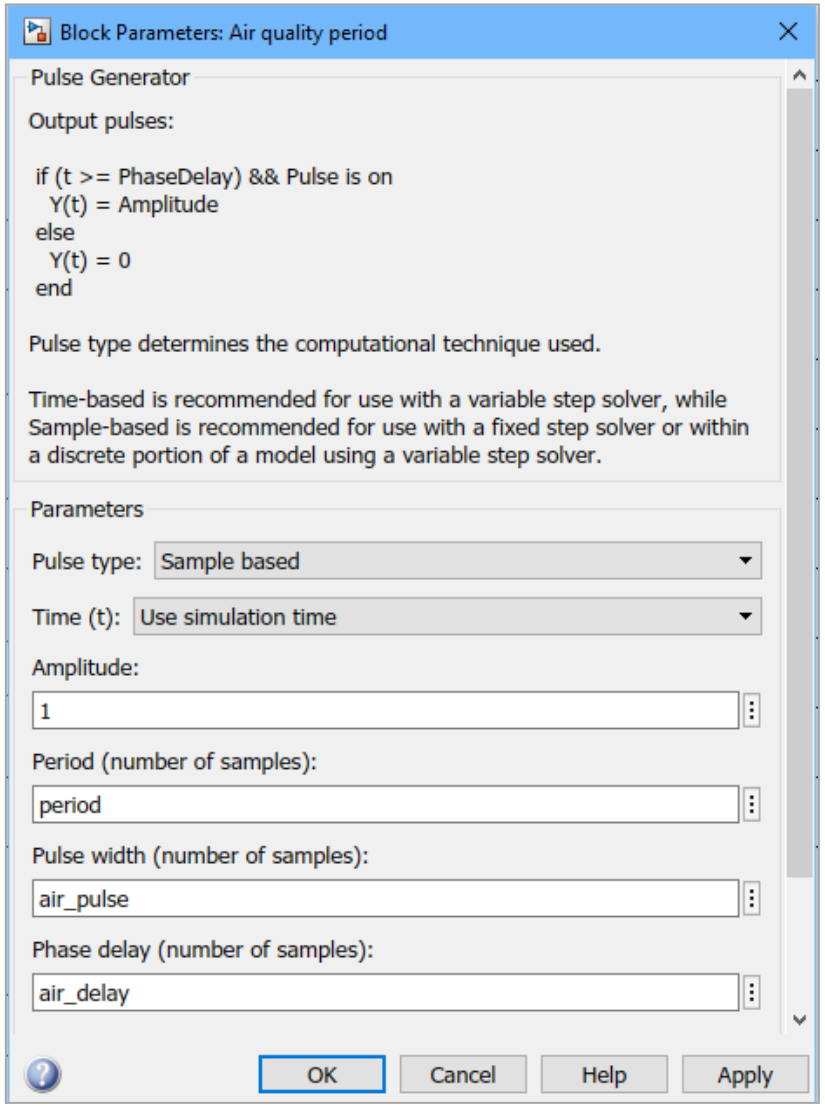
Loads

- **Pulse generator:**
  - Define the *period*
    - Equal for all loads
  - Define the *delay*
    - 0 if load starts at the beginning of each period
    - Else equal to the computation time of preceding loads
  - Define *pulse width*
    - % of period in which the load is active
    - $$\frac{\text{ACTIVE TIME} \cdot 100}{\text{PERIOD}}$$



Loads

- **Pulse generator:**
  - Loads variables from the workspace
    - E.g., for the air quality sensor:
      - Period = `period` variable
      - Delay = `air_delay` variable
      - Pulse width = `air_pulse` variable
  - Starting values provided in the **config.m** file
    - Must be executed before you run the simulation!



LOAD IRRADIANCE TRACE

LENGTH OF ACTIVE TIME FOR EACH LOAD

ACTIVATION DELAY FOR EACH LOAD

(0 MEANS THAT LOAD IS ACTIVATED AT THE BEGINNING OF EACH PERIOD) HERE SENSORS ARE ACTIVATED IN PARALLEL

ACTIVATION PERIOD

(HERE 120s)

PULSE WIDTH FOR EACH LOAD

$$\left(\frac{\text{ACTIVE TIME} \cdot 100}{\text{PERIOD}}\right)$$

SIMULATION LENGTH

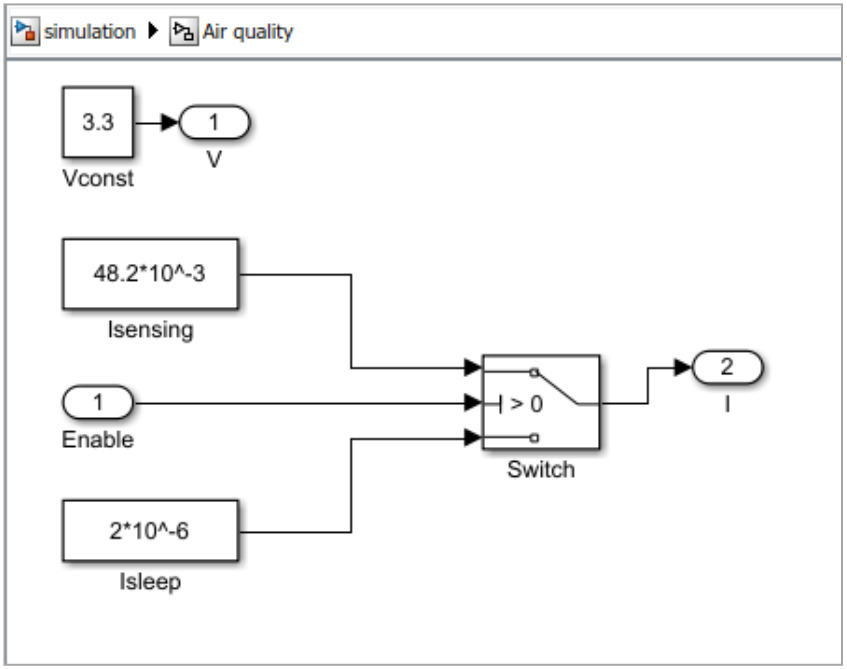
(HERE 30 days)

config.m

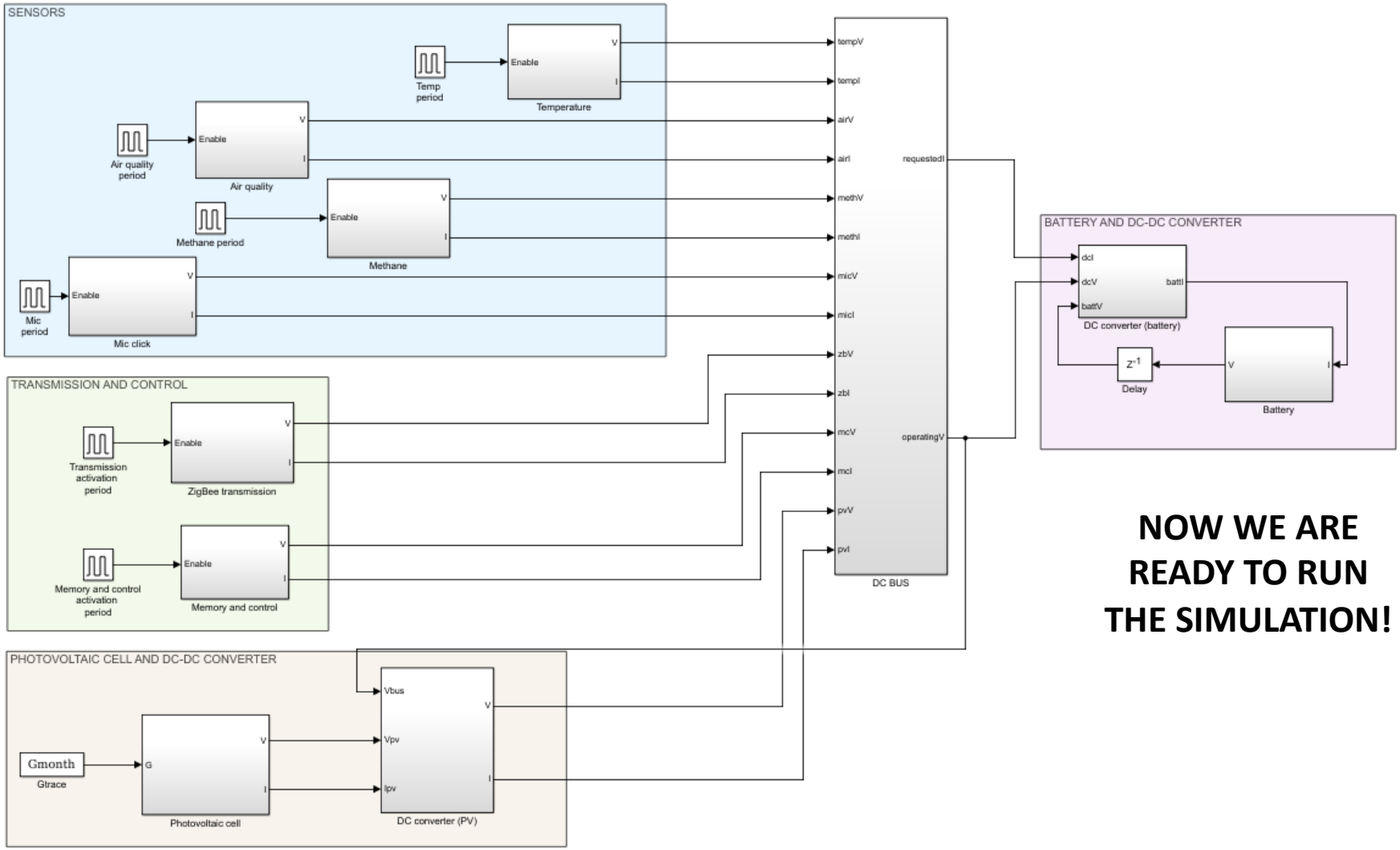
```
1  load('gmonth.mat')
2
3  % sensor activation durantion
4  air_time = 30;
5  methane_time = 30;
6  temp_time = 6;
7  mic_time = 12;
8  transmit_time = 24;
9  mc_time = 6;
10
11 % activation delay
12 % parallel exec
13 air_delay = 0;
14 methane_delay = 0;
15 temp_delay = 0;
16 mic_delay = 0;
17 mc_delay = 30;
18 transmit_delay = mc_delay + mc_time;
19
20 % period
21 % setting 1: 120 (2 minutes)
22 % setting 2: 60*10 (10 minutes)
23 period = 120;
24
25 % pulse width: % of period when sensor is active
26 air_pulse = (air_time * 100)/period;
27 methane_pulse = (methane_time * 100)/period;
28 temp_pulse = (temp_time *100)/period;
29 mic_pulse = (mic_time * 100)/period;
30 mc_pulse = (mc_time*100)/period;
31 transmit_pulse = (transmit_time * 100)/period;
32
33 % simulation length
34 % max simulation length = 1 month (30 days)
35 length = 30*24*60*60;
```

Loads

- Loads react to the pulse:
  - Pulse is 1 → higher current value
    - Active load
  - Pulse is 0 → lower current value
    - Non active load
  - Voltage is fixed
    - Always 3.3V



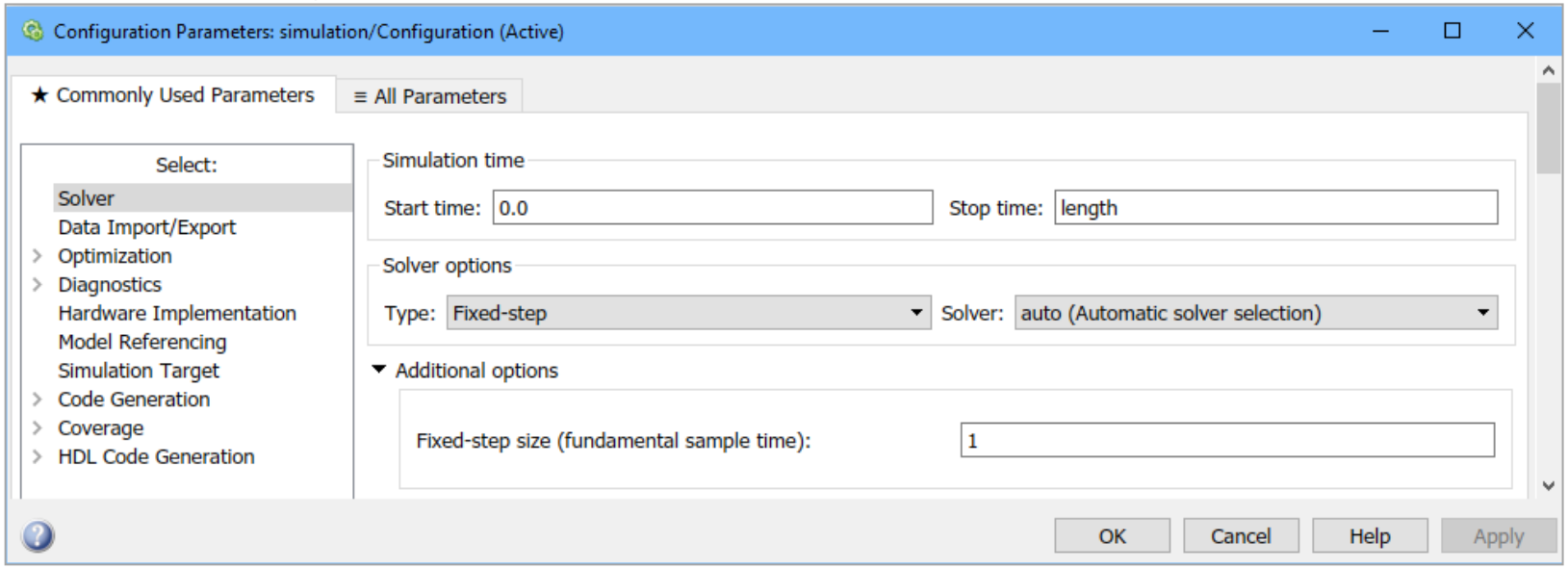
Simulink implementation



NOW WE ARE READY TO RUN THE SIMULATION!

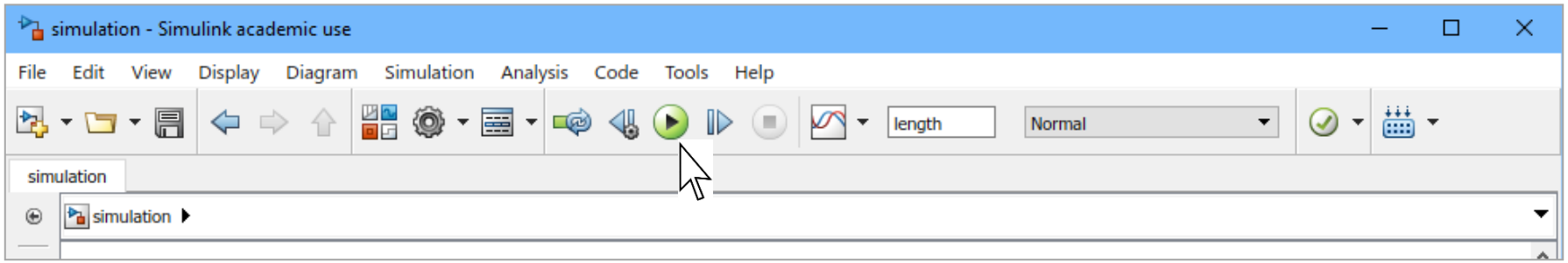
Simulation settings

- **Already set – no need to change them!**
- Simulation length: **sim_length** variable
  - Set equal to the tiem spanned by the Gmonths trace.
- Timestep: 1 second



Simulation settings

- To run the simulation:
  - Click on the green play button
  - Simulation stops when:
    - You reached the defined simulation length (30 days)
    - Any stop has been activated
      - E.g., battery discharged



First analysis of the Lab:

- In the report, no need to comment on the construction of the components

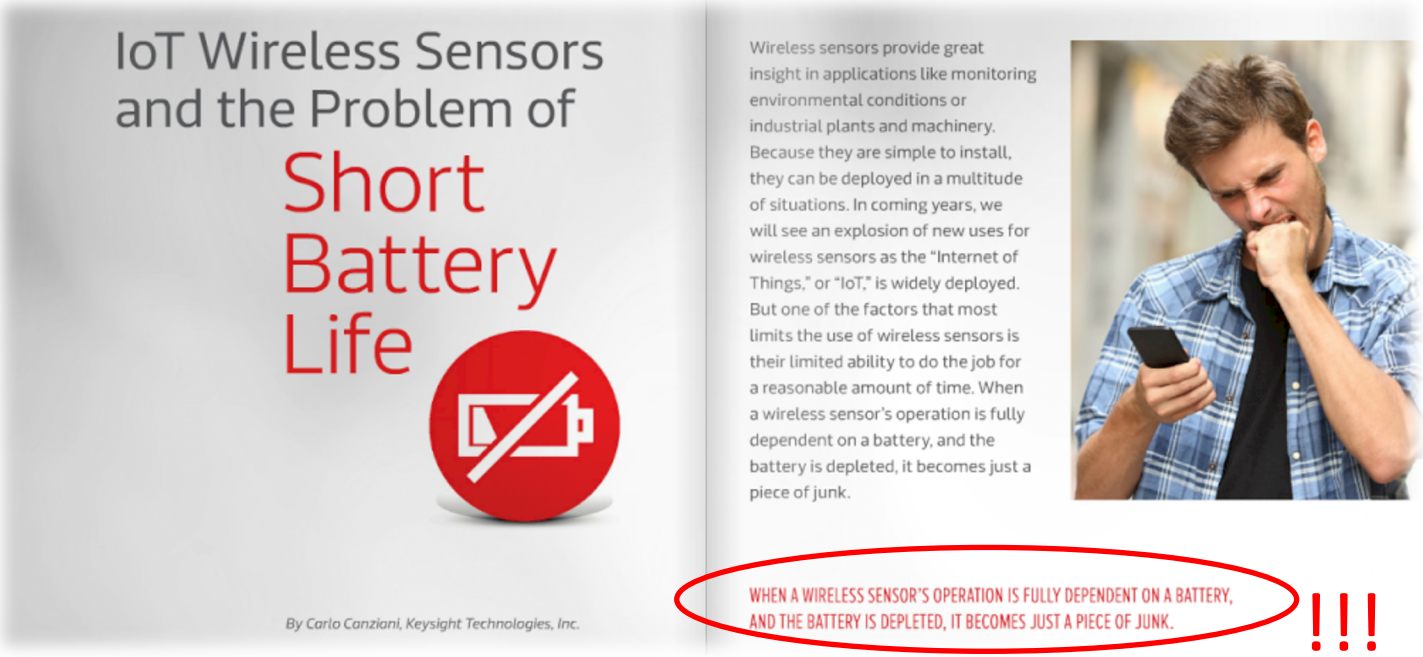
- **Discuss the main features of the simulation** given the provided schedule (parallel sensors)
  1. Exhibit one example trace of the simulation, showing meaningful qualtities
     - E.g., loads power, photovoltaic power, battery power, and battery SOC to show that the system behaves correctly
  2. Efficiency of the converters, to see if we fall in a good area (high efficiency) or not (low efficiency = a lot of wasted power)
  3. How often the battery has to be used to supply power
     - I.e., photovoltaic power is not enough

Second analysis of the Lab:

- **Determine the best scheduling**
  - Allows **longer lifetime** of the system
  - Compare:
    - Different scheduling
      - All sensors in parallel
      - Sequential activation of the sensor
      - Any impact on the evolution battery?
    - **If no impact, why???**

Third analysis of the Lab:

- Propose solutions to increase the lifetime of the IoT system
  - Should be autonomous
  - Should not require frequent battery changes



IoT Wireless Sensors and the Problem of Short Battery Life

By Carlo Canziani, Keysight Technologies, Inc.

Wireless sensors provide great insight in applications like monitoring environmental conditions or industrial plants and machinery. Because they are simple to install, they can be deployed in a multitude of situations. In coming years, we will see an explosion of new uses for wireless sensors as the "Internet of Things," or "IoT," is widely deployed. But one of the factors that most limits the use of wireless sensors is their limited ability to do the job for a reasonable amount of time. When a wireless sensor's operation is fully dependent on a battery, and the battery is depleted, it becomes just a piece of junk.

WHEN A WIRELESS SENSOR'S OPERATION IS FULLY DEPENDENT ON A BATTERY, AND THE BATTERY IS DEPLETED, IT BECOMES JUST A PIECE OF JUNK.

!!!

Third analysis of the Lab:

- Possible solutions:
  1. Increase **photovoltaic power production**
     - E.g., one more identical photovoltaic module connected in series/in parallel
  2. Increase **battery capacity**
     - E.g., one more identical battery connected in series/parallel
     - Consider that adding one battery or one PV module implies a different value of current/voltage depending on the connection
       - DC-DC converter efficiency may change!
  3. … Any other idea that comes to your mind!

Third analysis of the Lab:

- Bear in mind costs in your exploration:
  - Cost of one battery: $4.99
  - Cost of one PV module: $5.50
  - E.g., maximum additional cost: $11.00

- Compare possible solutions and the resulting lifetime
  - Longer irradiance trace available (Gmonths.mat)
    - Up to 3 months

Things to bear in mind:

- Efficiency is a number between 0 and 1 for all converters
  - 0 = 0%, 1 = 100%
- When digitizing, some axis have the milli- prefix (e.g., mA = milli Ampere) – fix the digitization to the correct scale!
  - In the simulation, 1 = 1A, 1V,…
- Don’t forget to set battery capacity