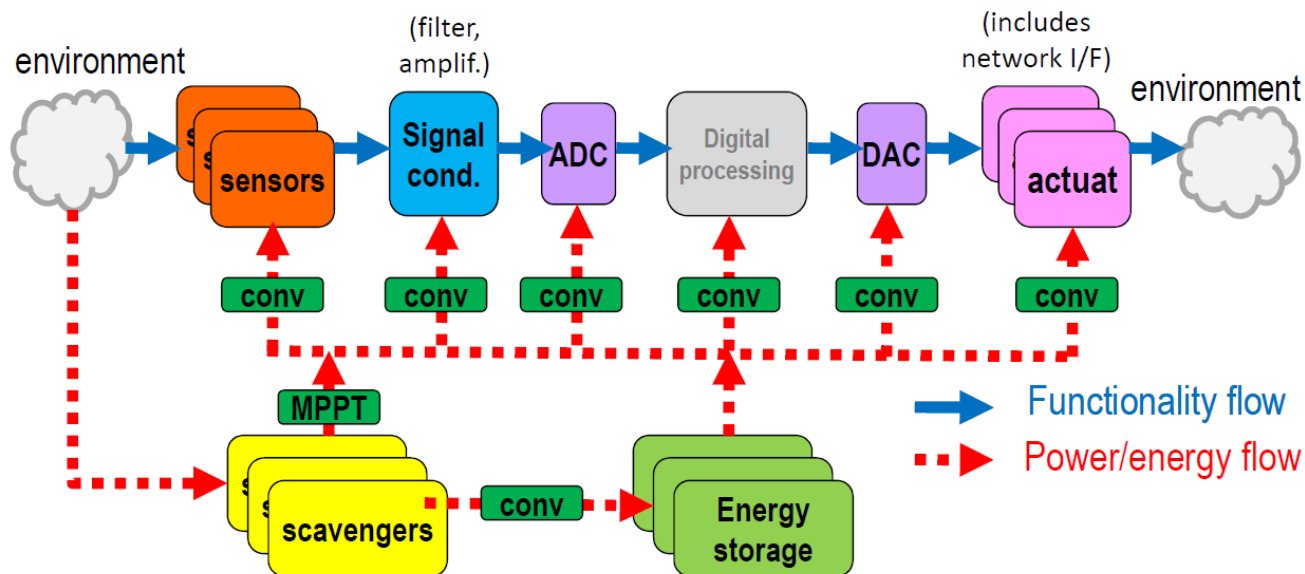# Lab 3
# Energy storage, generation and conversion

# 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…
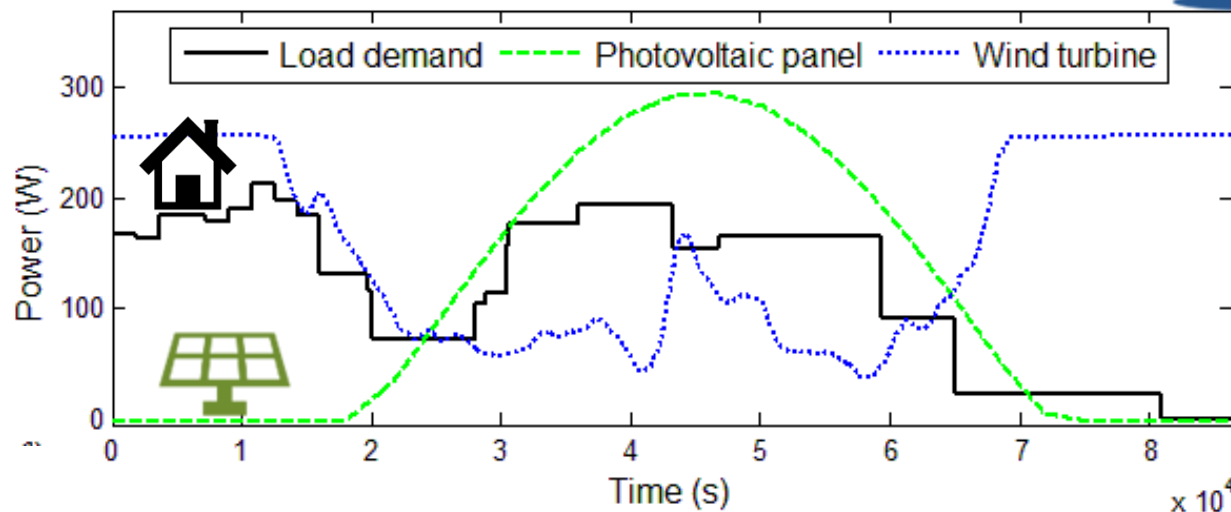
# Energy storage, generation and conversion

- 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 (MCU)
  - A module to transmit data over ZigBee (RF Radio)
  - A battery with a DC-DC converter
  - A thin-film photovoltaic module operated at the MPP with a DC-DC converter
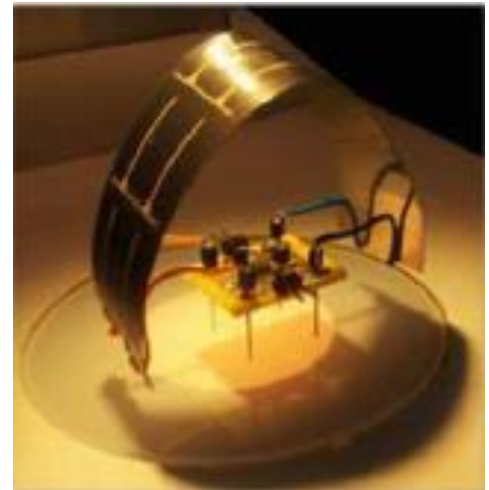
# **Objective and organization**

- Goal of this lab is to simulate an IoT device:
  - Implemented in **SystemC/SystemC-AMS**
    - 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
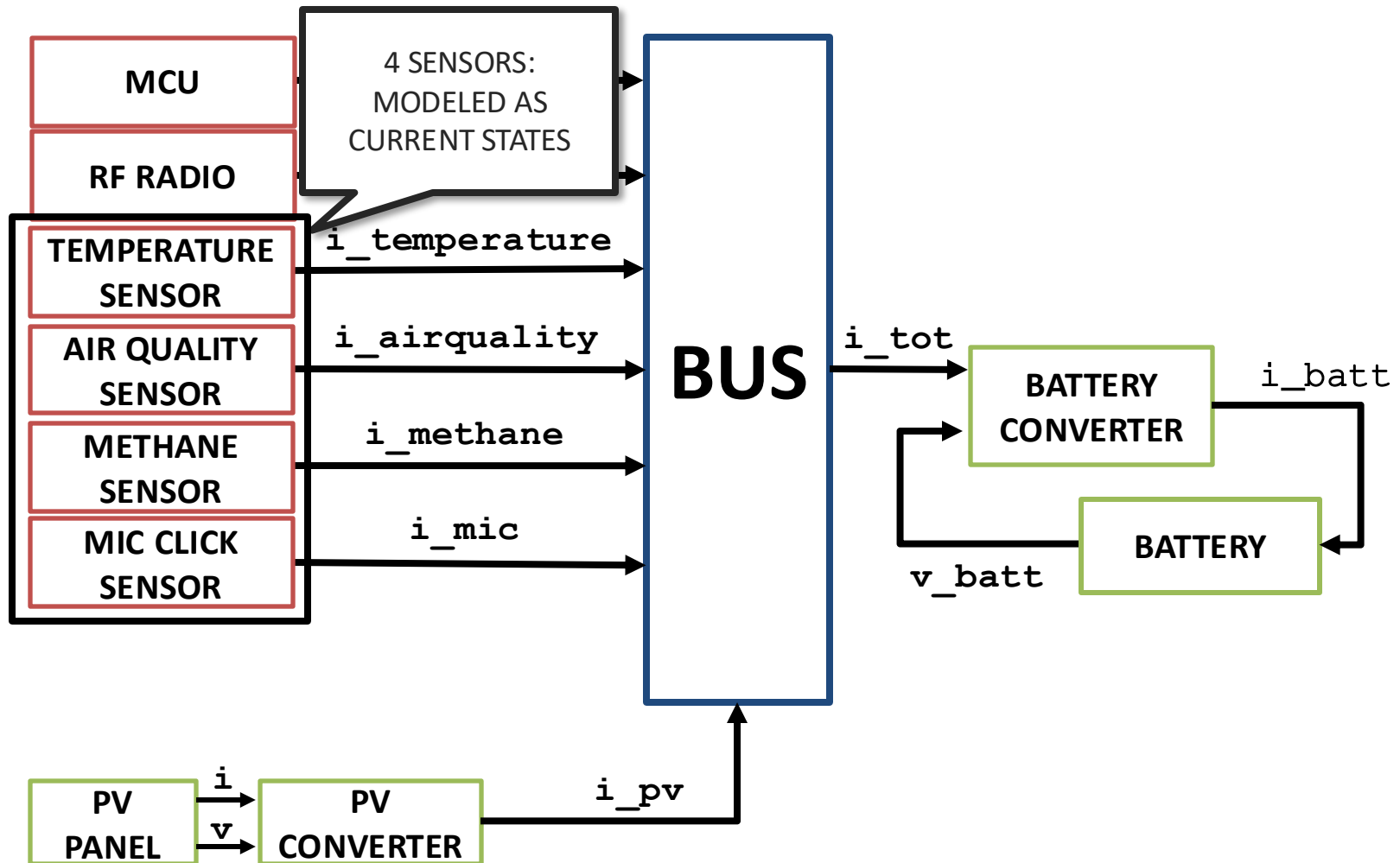
# Objective and organization

- Organization
  - 1 assignment to deliver
  - 3 days
    - *Dec 9th (3.0h)*
    - *Dec 16th (3.0h)*
  - Required software: C++ Compiler, SystemC, SystemC-AMS
  - Additional useful software: Python Intepreter
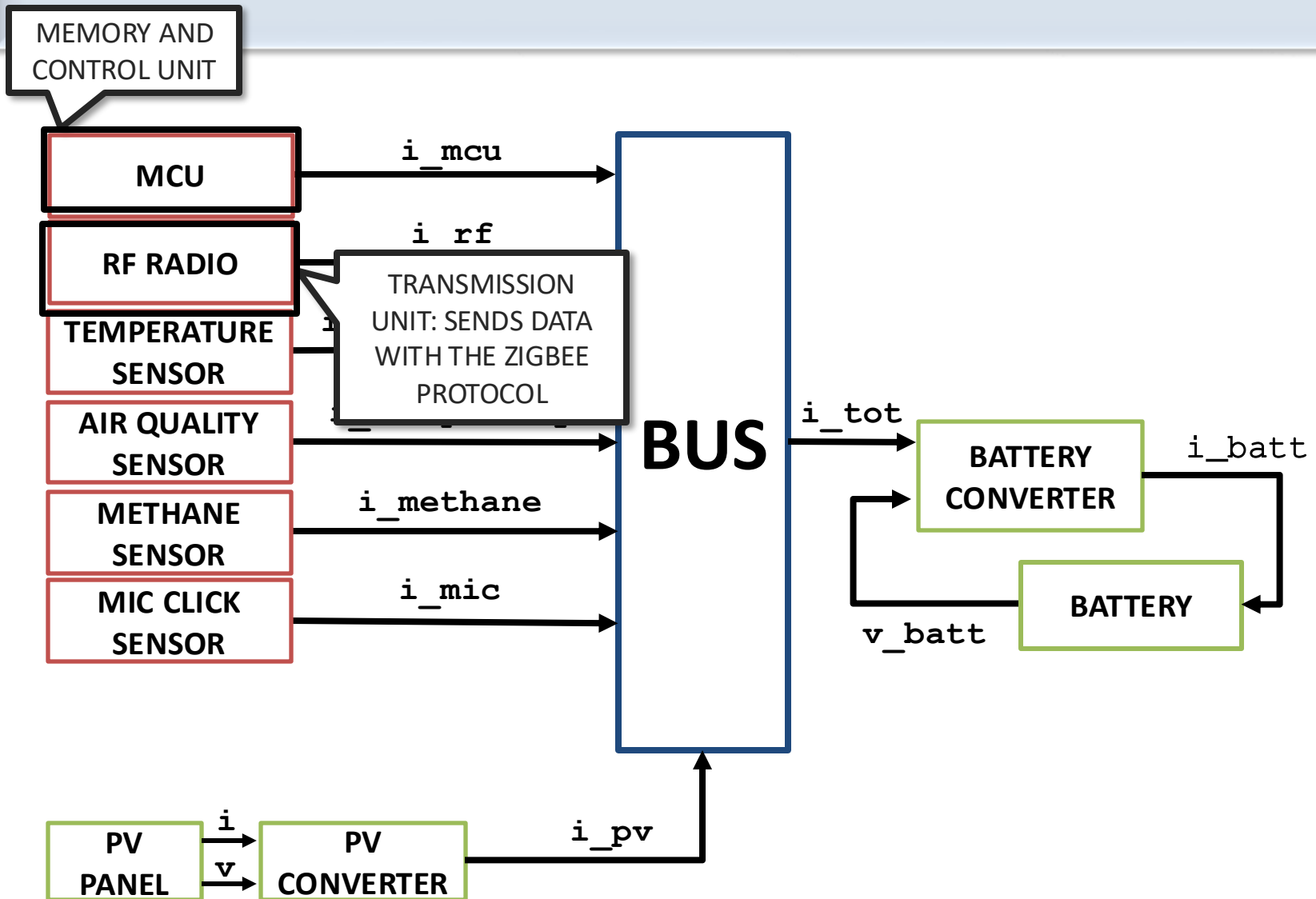
# SystemC Simulator

# Simulator Overview
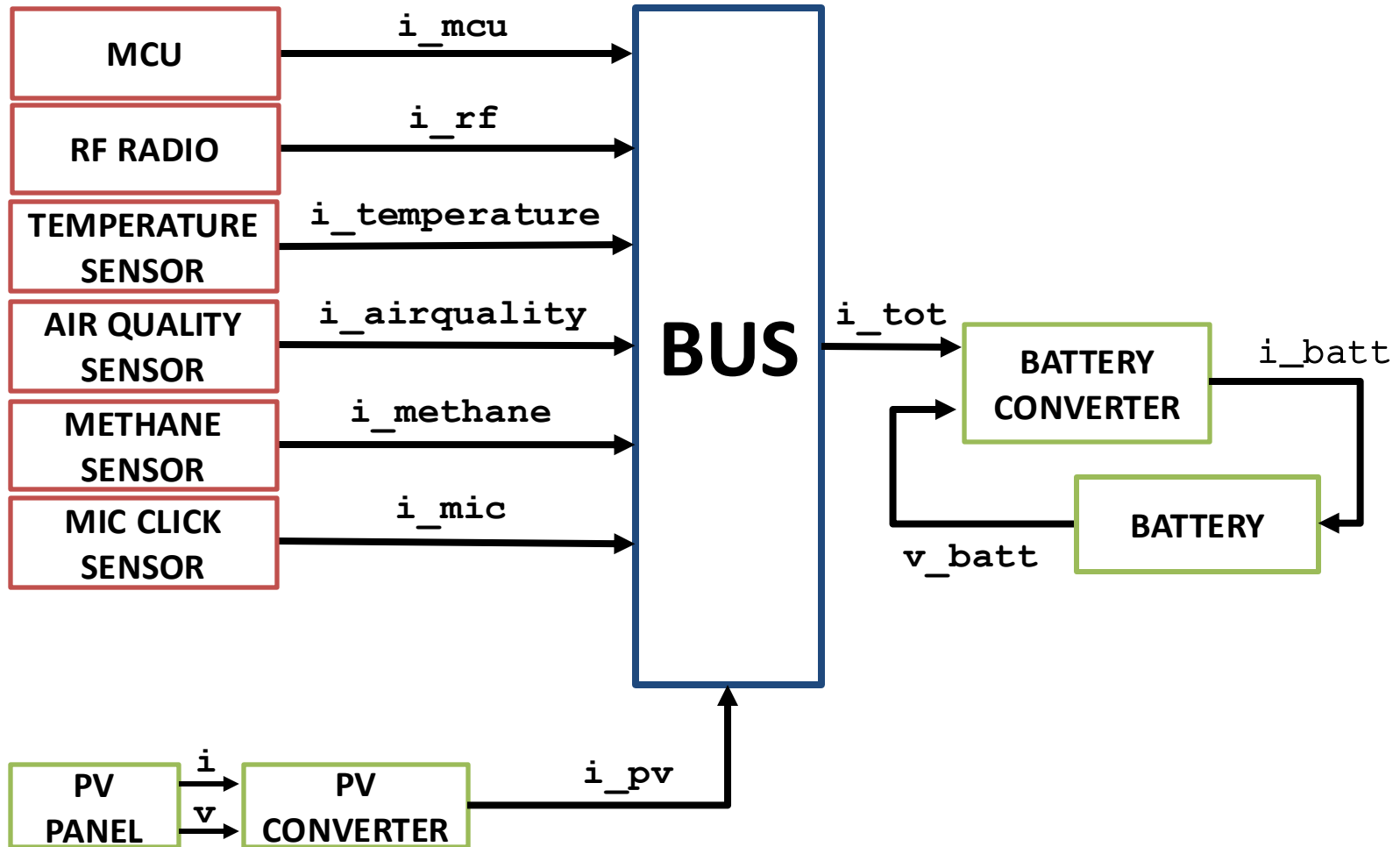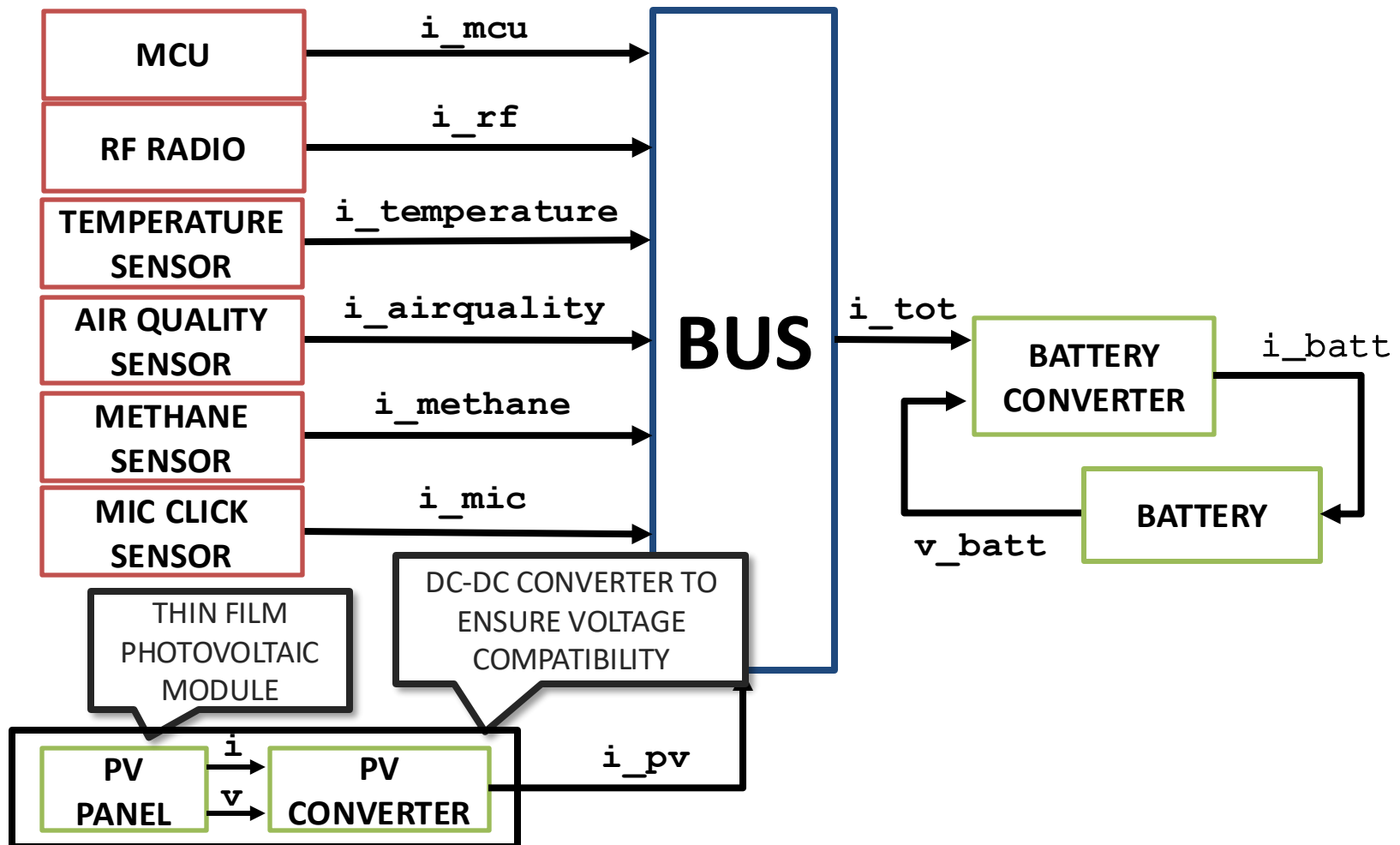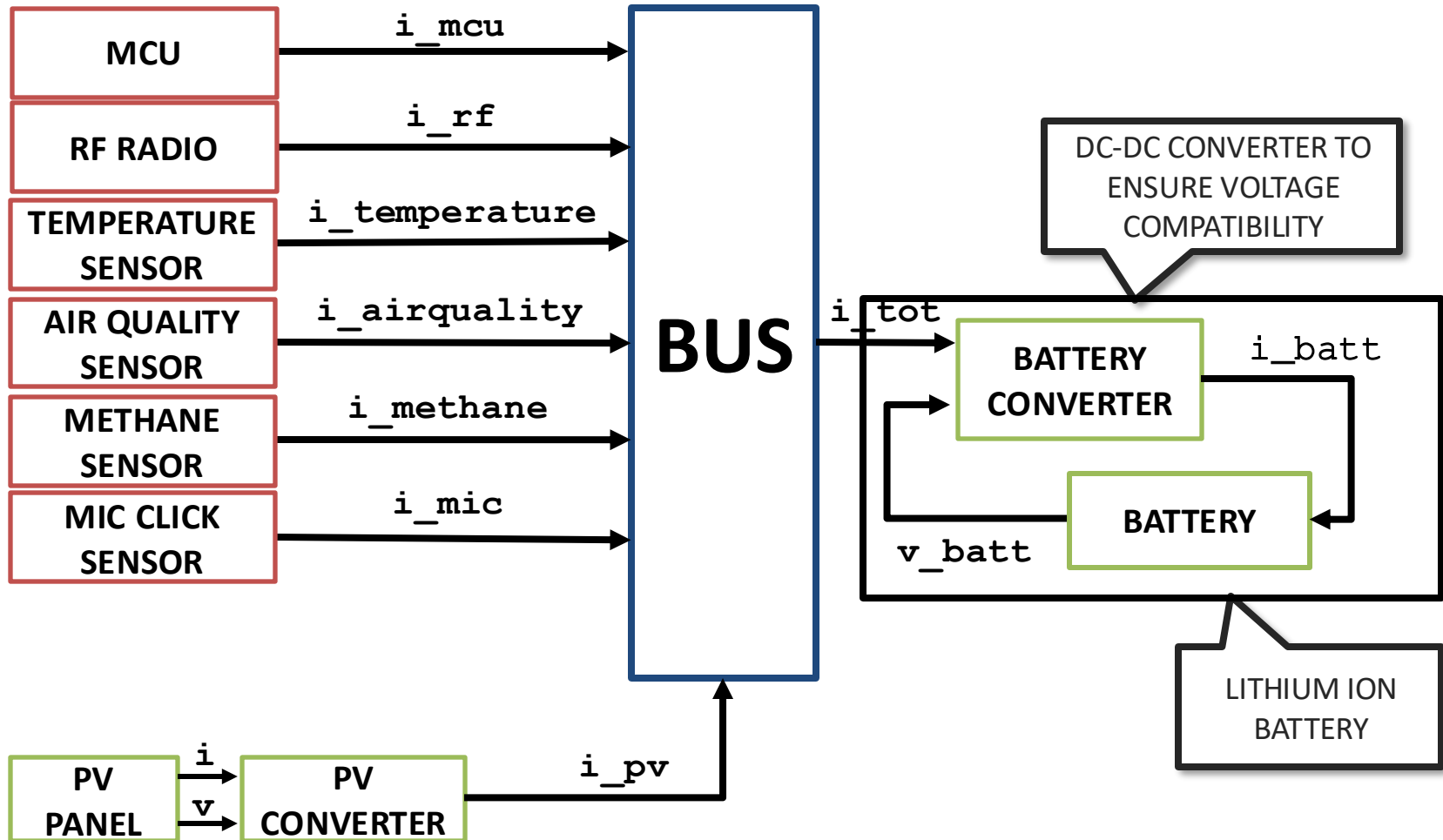
# Simulator Overview

# Simulator Overview

# Simulator Overview

# Simulator Overview
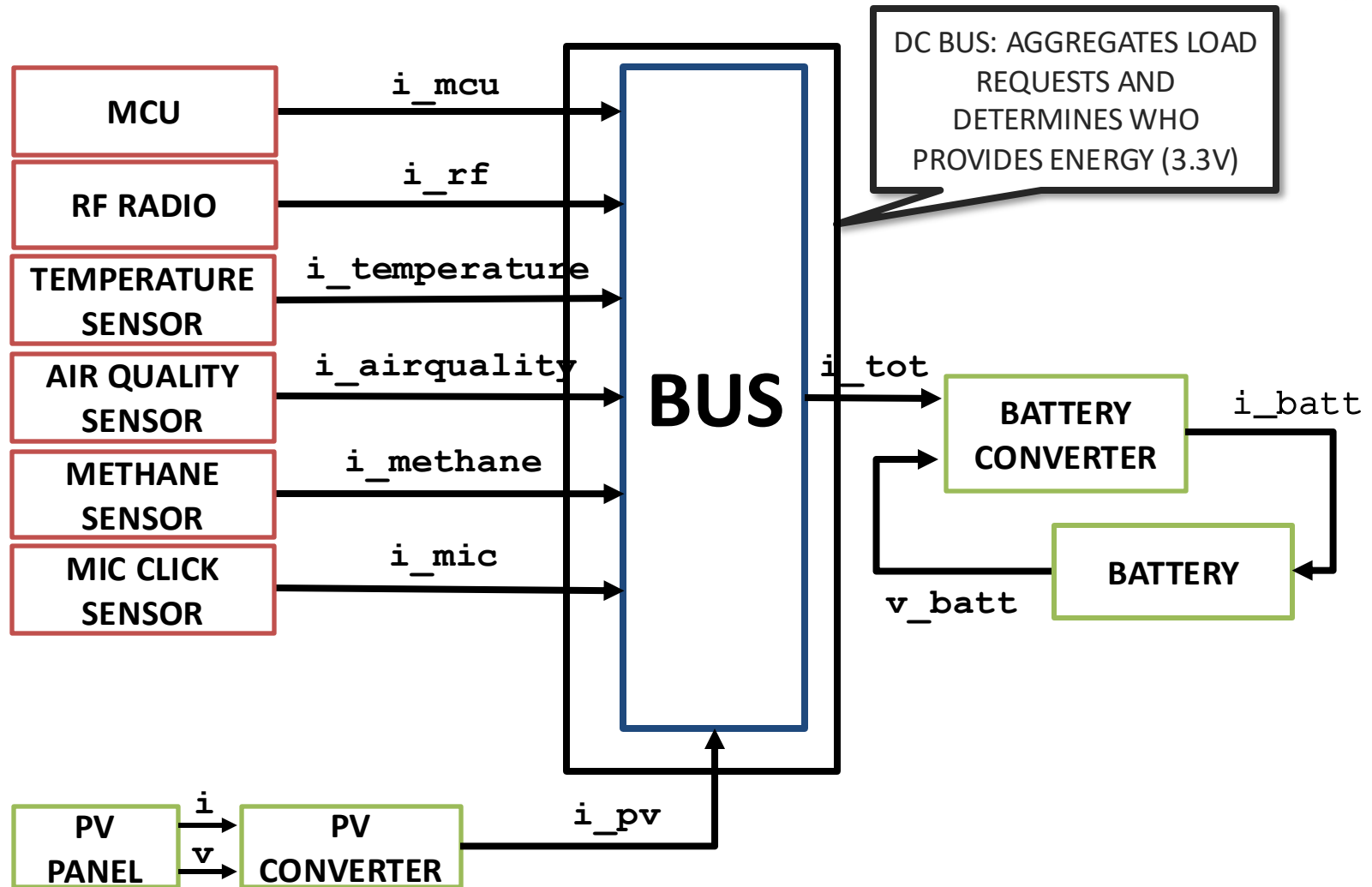
# Simulator Overview
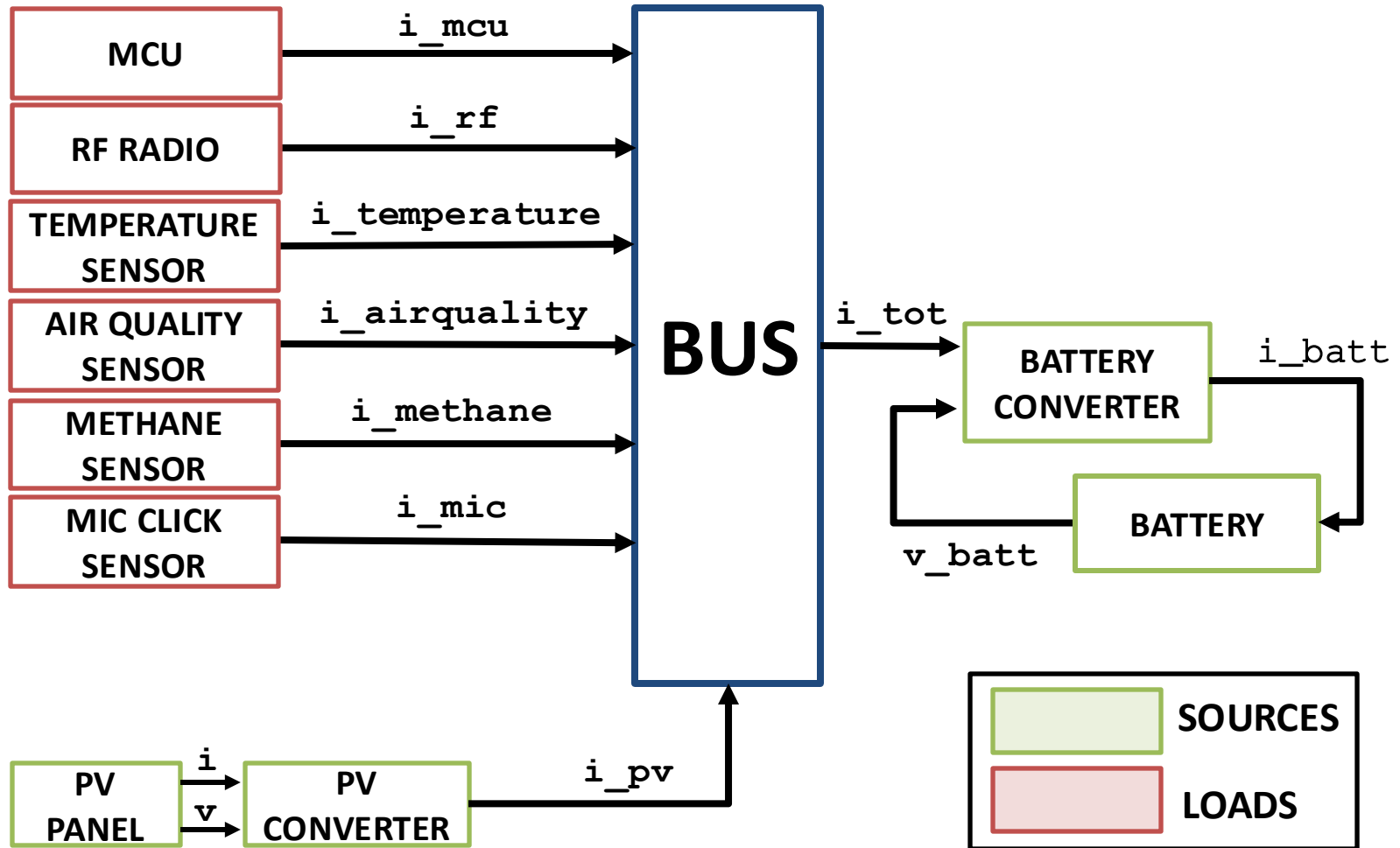
# Lab 3 – Part 0
# Simulator Setup

# Download Simulator

- Clone the github repository at:
  https://github.com/eml-eda/lab3-em4iot

# Install SystemC

- **Requirements: g++, make**
- Download the `systemc-2.3.3.tar.gz` from course website.
- Expand archive.
- Follow instructions contained in the INSTALL file.
- **Export SYSTEMC_HOME env variable pointing to your SystemC directory:**
  - **$ `export SYSTEMC_HOME="path"`**
  - **Suggest to put this command in your .bashrc**

# Install SystemC-AMS

- **Requirements: g++, make**
- Download the `systemc-ams-2.3.tar.gz` from course website.
- Expand archive.
- Follow instructions contained in the INSTALL file.
- **Export AMS_HOME env variable pointing to your SystemC-AMS directory:**
  - **`$ export AMS_HOME="path"`**
  - **Suggest to put this command in your .bashrc**

# Python

- **Requirements: Python3.8>**

# Alternative: Virtual Machine

- In alternative, you can use the provided Virtual Machine image `energy-simulator.ova`.
  - **N.B., MUST BE USED WITH VIRTUALBOX**
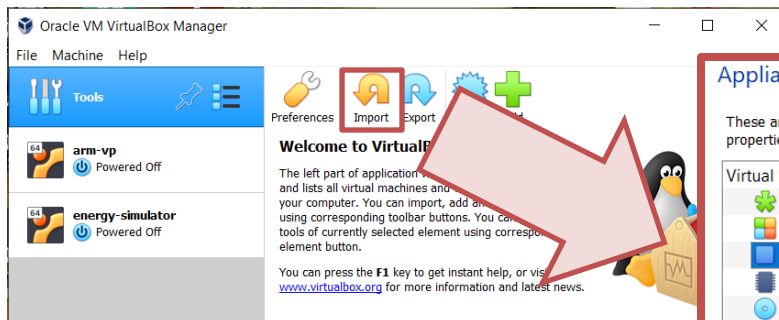


**User: stud**
**Pass: lab3em4iot**

N.B., select 2 cores!!!
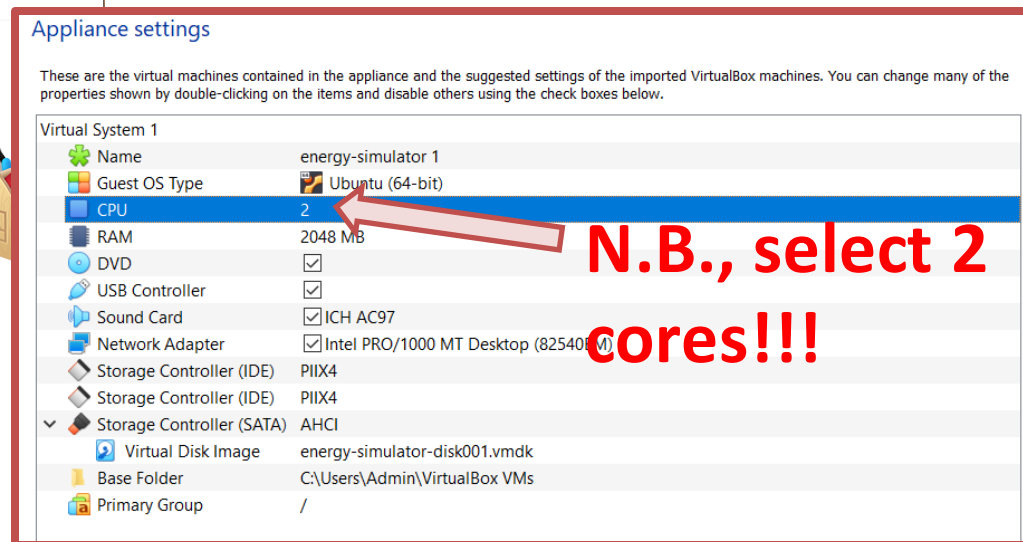
- How to setup shared folder in virtualbox: https://unix.stackexchange.com/a/156469
- How to change keyboard language: `sudo dpkg-reconfigure keyboard-configuration`
- Remember to shutdown the vm using: `shutdown -h now`

# Alternative: Docker Container

- For **Apple Silicon** users: Docker + enable Rosetta


- If you need help let me know…

- Ask me, I will provide the Dockerfile for setting up the docker

# SystemC-AMS Primer

- **User Guide: [LINK](#).**
- Each module is described by two files:

**.h file**

Include library

```
1   #include <systemc-ams.h>
2
3   #include "config.h"
4
5
6   SCA_TDF_MODULE(methane_sensor)
7   {
8       sca_tdf::sca_out<double> i;  // Consumed current
9
10      SCA_CTOR(methane_sensor): i("i"), cnt(0) {}
11
12      void set_attributes();
13      void initialize();
14      void processing();
15
16      private:
17          int cnt;
18  };
```

Define module as a child class of
***SCA_TDF_MODULE***

Interface: input and output ports (somehow similar to HDL)

Constructor: give names to ports and initializes other class private internal variables

Module's methods, always to be declared

Other internal variables

# SystemC-AMS Primer (cont'd)

- **User Guide: LINK.**
- Each module is described by two files:

**.cpp file**

```
1   #include "methane_sensor.h"
2
3
4   void methane_sensor::set_attributes()
5   {
6       i.set_timestep(SIM_STEP, sc_core::SC_SEC);
7   }
8
9   void methane_sensor::initialize() {}
10
11  void methane_sensor::processing()
12  {
13      if(cnt >= METHANE_SENSOR_T_ACT &&
14         cnt < METHANE_SENSOR_T_ACT + METHANE_SENSOR_T_ON)
15      {
16          i.write(METHANE_SENSOR_I_ON);
17          cnt = (cnt + 1) % PERIOD;
18      }
19      else
20      {
21          i.write(METHANE_SENSOR_I_IDLE);
22          cnt = (cnt + 1) % PERIOD;
23      }
24  }
```

Include .h file
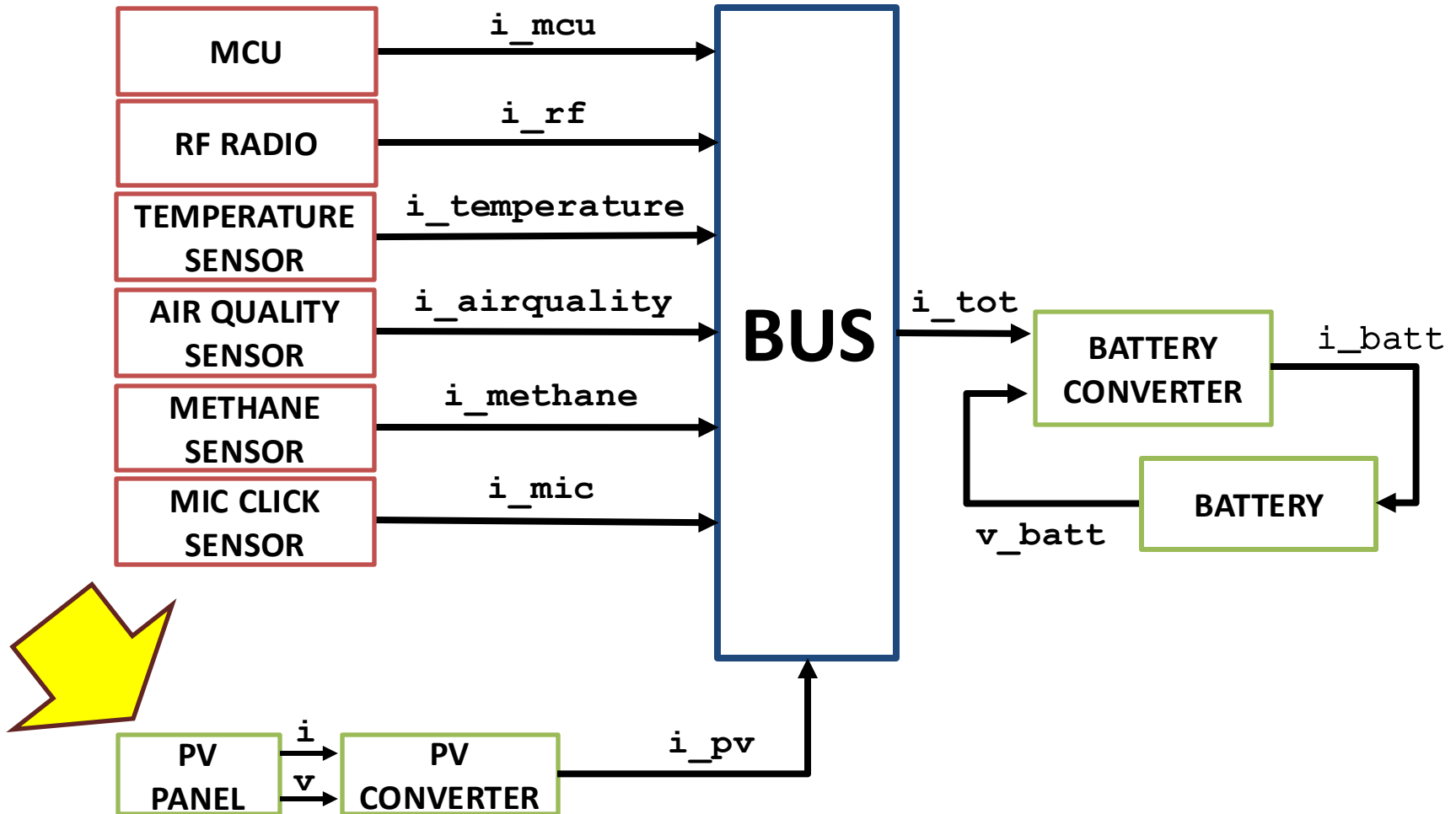
Define *set_attributes* method.

Define *initialize* method.

Define *processing* method. Is the core of the simulation and defines the behavior of the module.
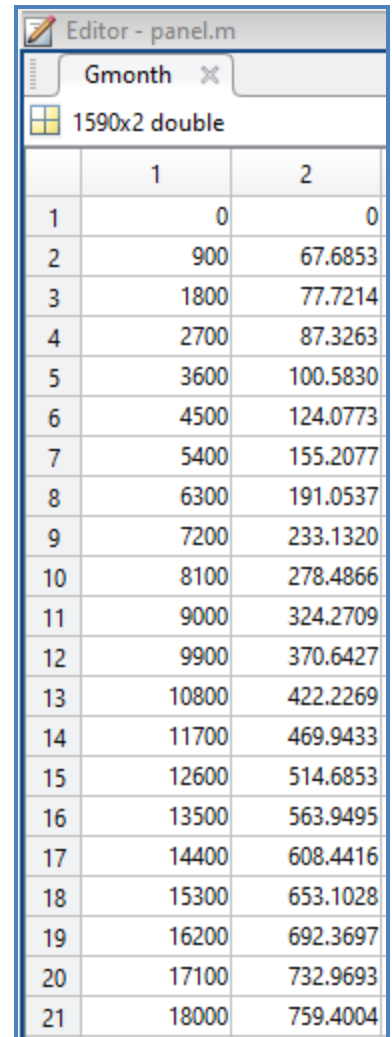
# Lab 3 – Part 1
# Model of the photovoltaic module

# Simulator overview

# **Photovoltaic module**

- Gmonth
  - Can be inspected in python
    - To load it, type:
      - `scipy.io('gmonths.mat')`
  - Or you can refer to `gmonths.txt` inside simulator (more info later)

  - 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

| | 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 |

Editor - panel.m
Gmonth
1590x2 double

# Photovoltaic module

- # Gmonth
  - – Irradiance trace for about 3 months
    - • Irradiance varies depending on weather (sunny/rainy/cloudy)
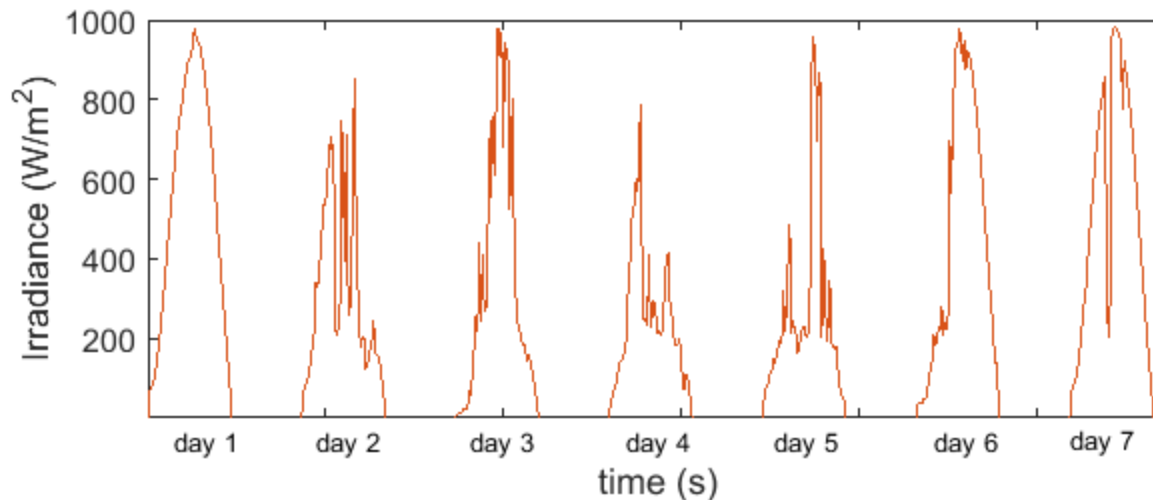


| Editor - panel.m | | |
| --- | --- | --- |
| Gmonth | | |
| 1590x2 double | | |
|  | 1 | 2 |
| 1 | 0 | 0 |
| 2 | 900 | 67.6853 |
| 3 | 1800 | 77.7214 |
| 4 | 2700 | 87.3263 |
| 5 | 3600 | 100.5830 |
| 6 | 4500 | 124.0773 |
| 7 | 5400 | 155.2077 |
| 8 | 6300 | 191.0537 |
| 9 | 7200 | 233.1320 |
| 10 | 8100 | 278.4866 |
| 11 | 9000 | 324.2709 |
| 12 | 9900 | 370.6427 |
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| 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**

- Photovoltaic module
  - Two lookup tables (**LUT**)
    - Voltage and current at the MPP given irradiance in input
    - Must populate the lookup tables!

**inc/pv_panel.h**

```cpp
#include "config.h"
#include "config_pv.h"
#include "lut.h"


SCA_TDF_MODULE(pv_panel)
{
    sca_tdf::sca_out<double> i; // Output current at mpp
    sca_tdf::sca_out<double> v; // Output voltage at mpp

    SCA_CTOR(pv_panel): i("i"), v("v") {}

    void set_attributes();
    void initialize();
    void processing();

    private:
        int cnt; // when cnt % TRACE_PERIOD == 0 a new measure of irradiance
                 // is read from the file
        ifstream top; // file from which irradiance values are retrieved
        double g_top;
        LUT lut_i = LUT(G, I_MPP, SIZE_PV);
        LUT lut_v = LUT(G, V_MPP, SIZE_PV);
};
```

config_pv.h

```
           PV
gmonths.txt  PANEL        i

                          v
```
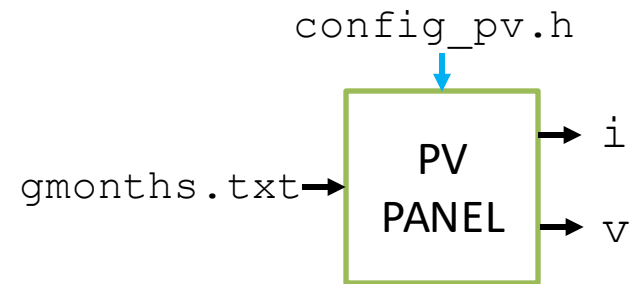
**inc/config_pv.h**

```cpp
#define TRACE_PERIOD 900
#define SIZE_PV 4
static const double G[SIZE_PV] = {TO-BE-POPULATED};
static const double I_MPP[SIZE_PV] = {TO-BE-POPULATED};
static const double V_MPP[SIZE_PV] = {TO-BE-POPULATED};
```

**TO-BE-POPULATED**

# **Photovoltaic module**

- Open the PVdatasheet.pdf file
- Provides a graph of current versus voltage given different irradiance values
- **Your Task:**
  - Save the image
  - For each curve:
    1. Digitize the curve
       - Can use the online app [PlotDigitizer](#)
    2. Determine the voltage and current at the MPP for that irradiance value
    3. Use the sample for the lookup table
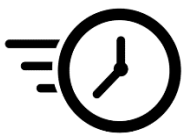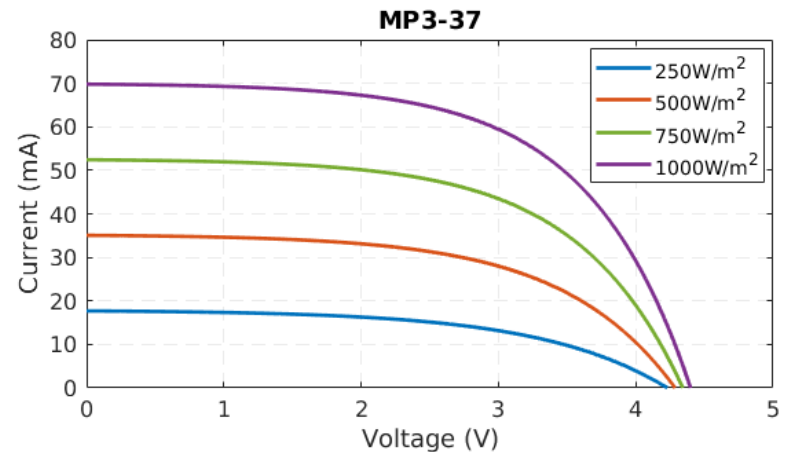
# **Photovoltaic module**

- *Suggestion: use online App PlotDigitizer*
- How to use the tool:
  1. Load the image
  2. Calibrate the image
     - Drag the four points (X1, Y1) and (X2, Y2) and give corresponding x and y values
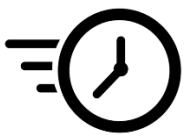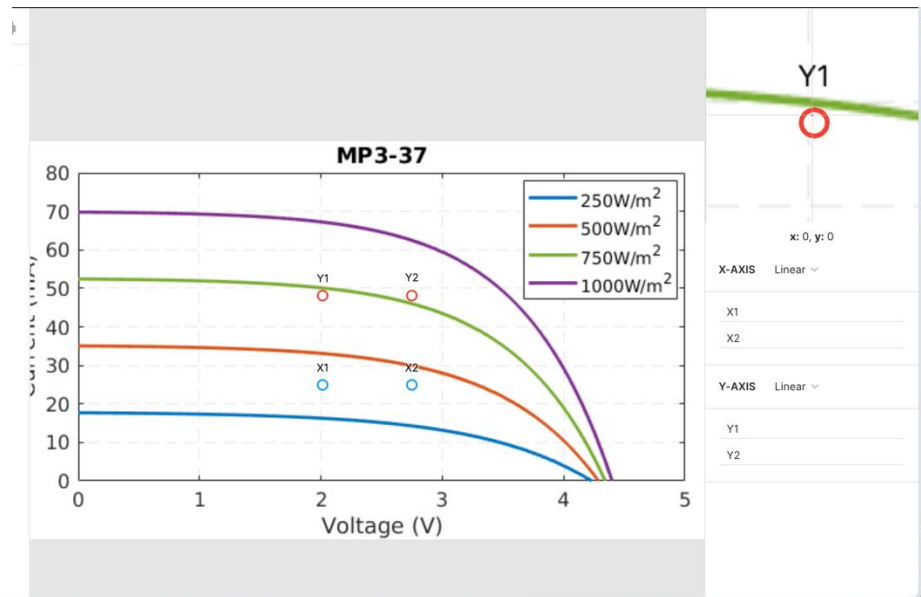
# **Photovoltaic module**

- How to use the digitizer tool:
  3. Select samples of one curve
     - Mouse left button = new sample -> white dots
       – Sampled points are written on the left
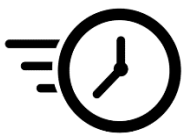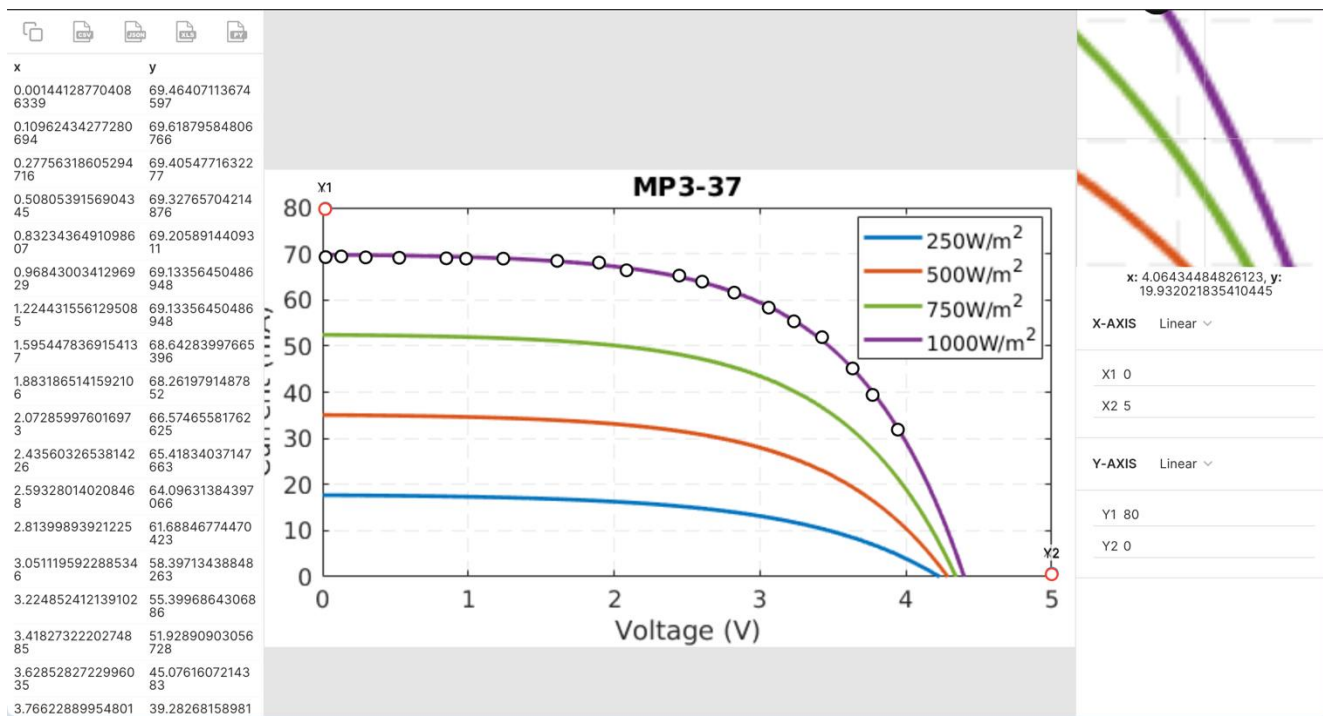
# **Photovoltaic module**

- How to use the digitizer tool:
    3. Select samples of one curve
        - Mouse left button = new sample
    4. Save to file
        - Click the copy button and copypoints in a txt file

datasheet.txt
0.001441287704086339, 69.46407113674597
0.10962434277280694, 69.61879584806766
0.27756318605294716, 69.4054771632277
0.5080539156904345, 69.32765704214876
0.8323436491098607, 69.2058914409311
0.9684300341296929, 69.13356450486948
1.2244315561295085, 69.13356450486948
1.5954478369154137, 68.64283997665396
1.8831865141592106, 68.2619791487852

| x | y |
| --- | --- |
| 0.00144128770408 6339 | 69.46407113674 597 |
| 0.10962434277280 694 | 69.61879584806 766 |
| 0.27756318605294 716 | 69.40547716322 77 |
| 0.50805391569043 45 | 69.32765704214 876 |
| 0.83234364910986 07 | 69.20589144093 11 |

# Photovoltaic module

- Each file represents one curve
  - Import the file in python 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



datasheet.txt
0.001441287704086339, 69.46407113674597
0.10962434277280694, 69.61879584806766
0.27756318605294716, 69.4054771632277
0.5080539156904345, 69.32765704214876
0.8323436491098607, 69.2058914409311
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1.2244315561295085, 69.13356450486948
1.5954478369154137, 68.64283997665396
1.8831865141592106, 68.2619791487852

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

# **Photovoltaic module**

- Populate the array in `inc/config_pv.h`:

  - Vector of values of G:
    - `G[SIZE_PV] = {250, 500, 750, 1000};`

  - Vector of corresponding values of current at the MPP
    - `I_MPP[SIZE_PV] = {I250, I500, I750, I1000};`

  - Vector of corresponding values of voltage at the MPP
    - `V_MPP[SIZE_PV] = {V250, V500, V750, V1000};`

**N.B., Take care of units!! We want voltages in [V] and currents in [mA]**

# **Photovoltaic module**

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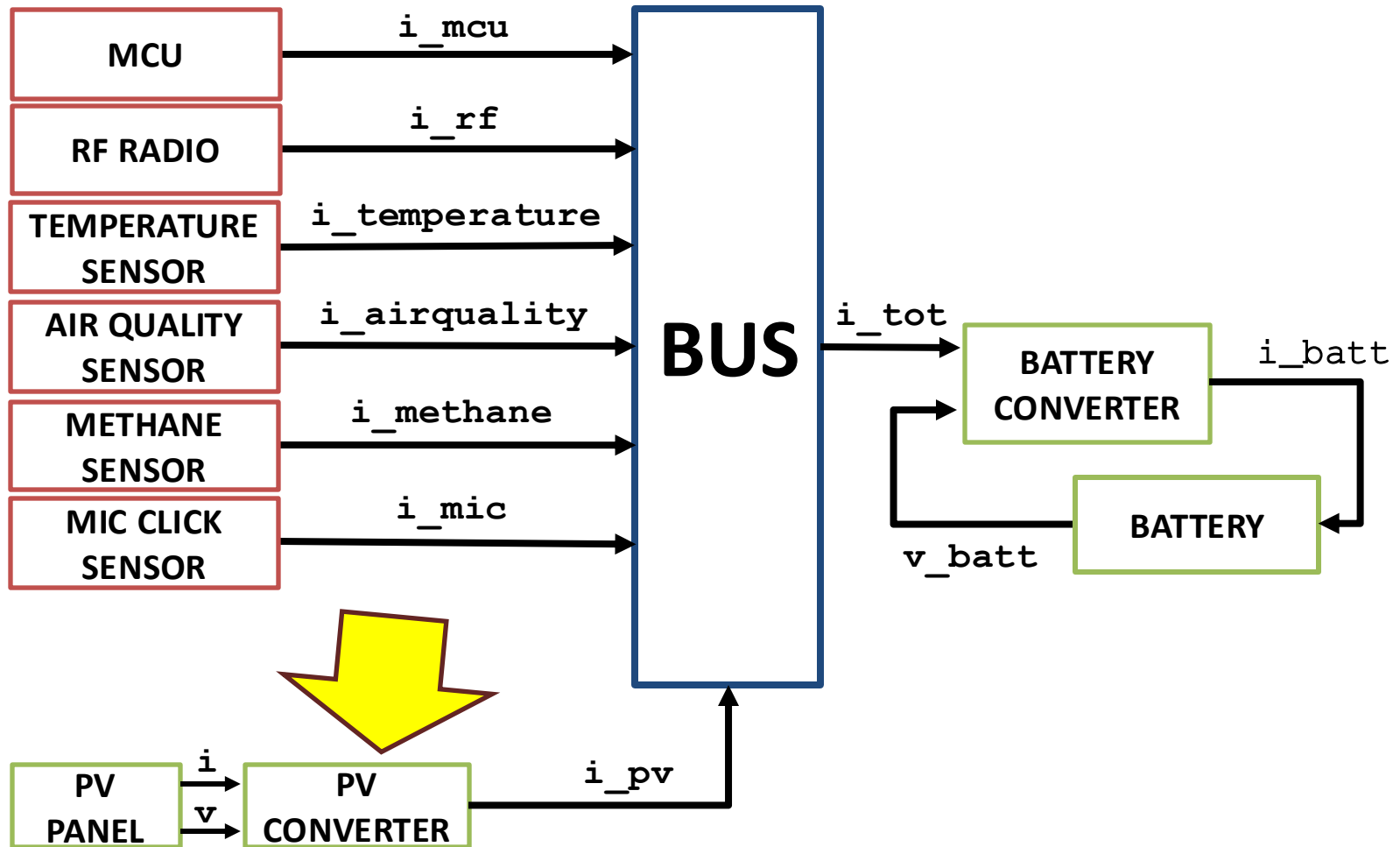
# Lab 3 – Part 2
# Model of DC-DC converters and battery

# Simulator overview

# DC-DC converter of PV module

- DC-DC converter of the photovoltaic module
  - Contains a **LUT** of efficiency given input PV voltage
    - **Efficiency (eta) in [0, 100]**
  - Block implementation (in `src/converter_pv.cpp`):
    - $(V_{PV} \cdot I_{PV}) \cdot eta = (V_{BUS} \cdot I) \rightarrow I = (V_{PV} \cdot I_{PV} \cdot eta)/V_{BUS}$

`inc/converter_pv.h`

```cpp
#include "config.h"
#include "config_converter_pv.h"
#include "lut.h"


SCA_TDF_MODULE(converter_pv)
{
    sca_tdf::sca_in<double> i_in; // Current from PV panel
    sca_tdf::sca_in<double> v_in; // Voltage from PV panel
    sca_tdf::sca_out<double> i_out; // Current generated delivered to the BUS

    SCA_CTOR(converter_pv): i_in("i_in"),
                            v_in("v_in"),
                            i_out("i_out") {};

    void set_attributes();
    void initialize();
    void processing();

    private:
        LUT lut_eta = LUT(V_CONV_PV, ETA_CONV_PV, SIZE_CONV_PV);
};
```

`config_converter_pv.h`

i_in → **PV CONVERTER** → i_out

v_in →

`inc/config_converter_pv.h`

```cpp
#define SIZE_CONV_PV DEPENDS-ON-NUM-DIGITIZED-SAMPLES
static const double V_CONV_PV[SIZE_CONV_PV] = {TO-BE-POPULATED};
static const double ETA_CONV_PV[SIZE_CONV_PV] = {TO-BE-POPULATED};
```

**TO-BE-POPULATED**

# 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

**Efficiency vs V$_{IN}$**

# DC-DC converter of PV module

- Your Task:
    1. Digitize the curve
    2. Export digitized samples
    3. Set the parameters in `inc/config_converter_pv.h`:
        - `#define SIZE_CONV_PV #NUM-SAMPLES`

        - `V_CONV_PV[SIZE_PV] = {S1, S2, ...,};`

        - `ETA_CONV_PV[SIZE_PV] = {S1, S2, ...,};`

        - More digitized samples = more accurate!!!
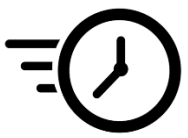
# Simulator overview
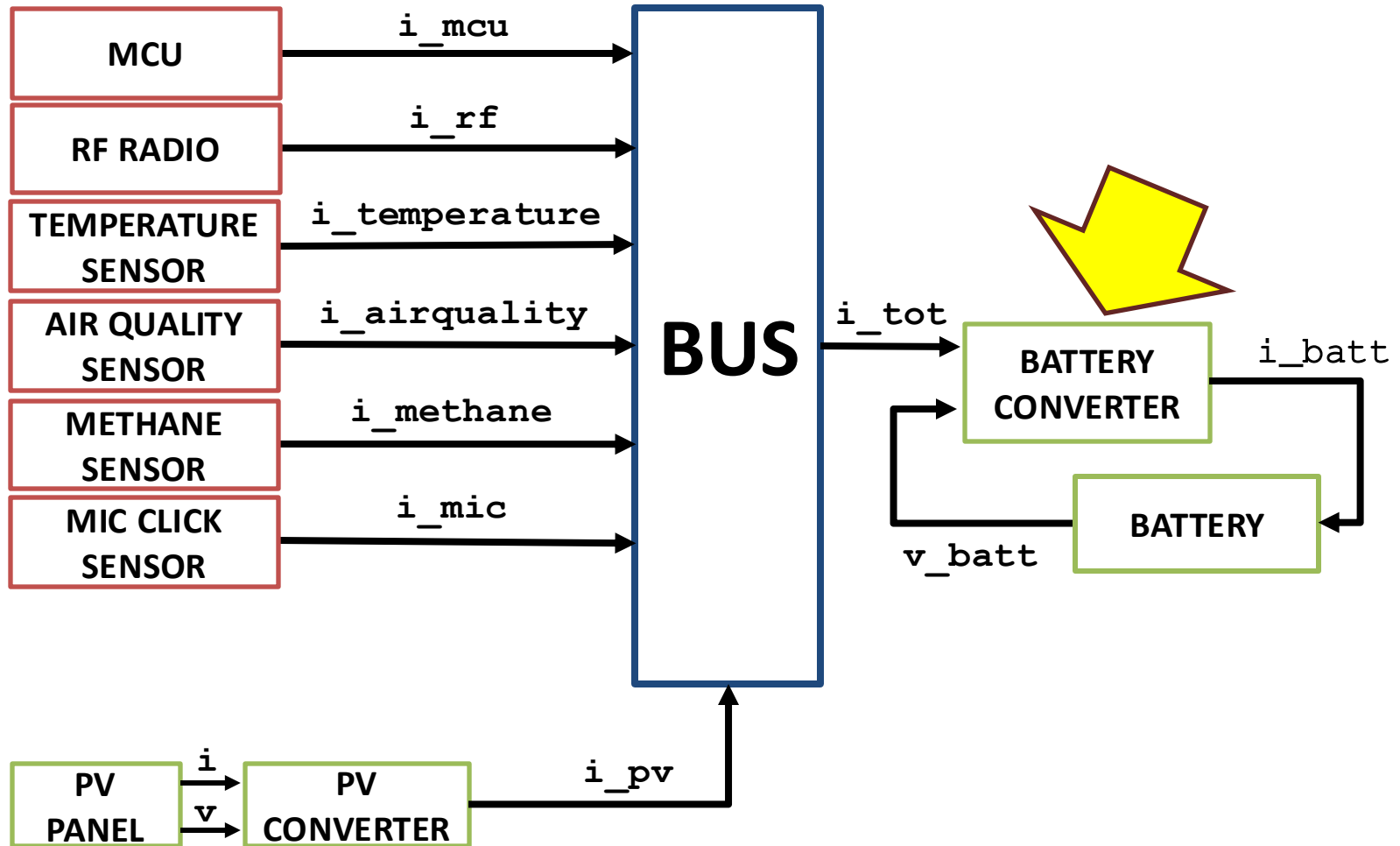
# DC-DC converter of battery

- DC-DC converter of the battery
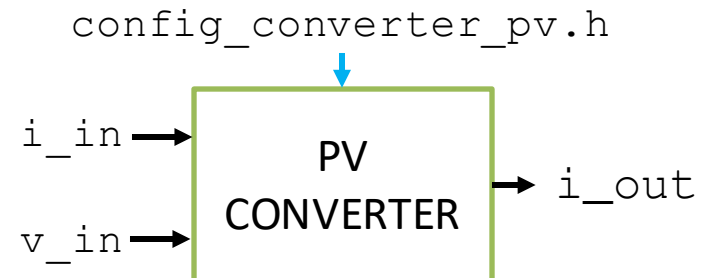
**inc/converter_battery.h**

```cpp
#include "config.h"
#include "config_converter_battery.h"
#include "lut.h"


SCA_TDF_MODULE(converter_battery)
{
    sca_tdf::sca_in<double> i_bus; // Current requested/delivered to battery conv
    sca_tdf::sca_in<double> v_batt; // Battery voltage
    sca_tdf::sca_out<double> i_batt; // Battery current

    SCA_CTOR(converter_battery): i_bus("i_bus"),
                                 v_batt("v_batt"),
                                 i_batt("i_batt") {};

    void set_attributes();
    void initialize();
    void processing();

    private:
        LUT lut_eta = LUT(I_CONV_BATT, ETA_CONV_BATT, SIZE_CONV_BATT);     You,
};
```
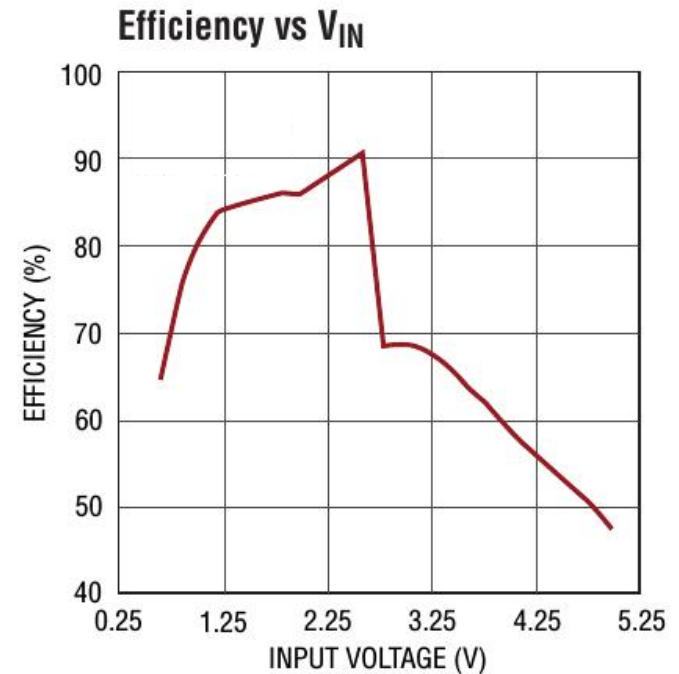
config_converter_battery.h

```
          ┌─────────────┐
i_bus ───▶ │   BATTERY   │ ───▶ i_batt
          │  CONVERTER  │
v_batt ──▶ │             │
          └─────────────┘
```
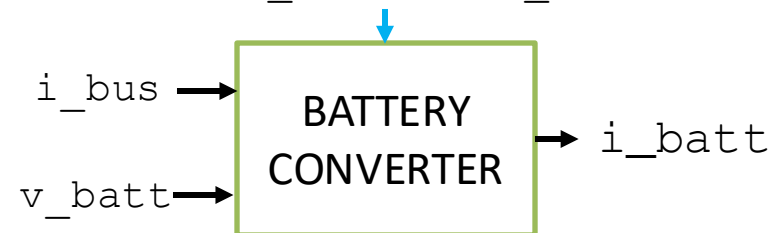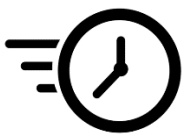
**inc/config_converter_battery.h**

```cpp
#define SIZE_CONV_BATT DEPENDS-ON-NUM-DIGITIZED-SAMPLES
static const double I_CONV_BATT[SIZE_CONV_BATT] = {TO-BE-POPULATED};
static const double ETA_CONV_BATT[SIZE_CONV_BATT] = {TO-BE-POPULATED};
```

**TO-BE-POPULATED**

# 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

- Your Task:
  1. Digitize one of the two curves
     - We avoid dependency from battery voltage
  2. Export the samples
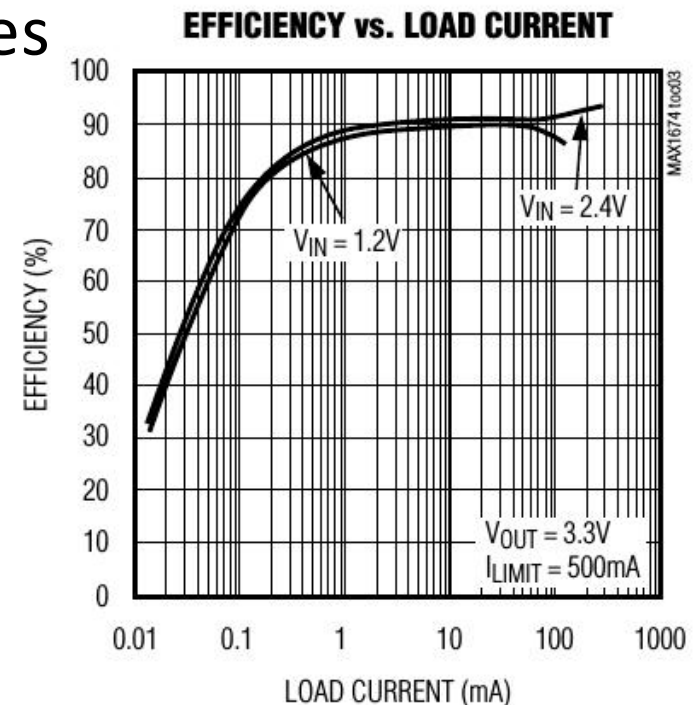
**EFFICIENCY vs. LOAD CURRENT**

$V_{IN} = 1.2V$

$V_{IN} = 2.4V$

$V_{OUT} = 3.3V$
$I_{LIMIT} = 500mA$

EFFICIENCY (%)

LOAD CURRENT (mA)

# 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

- Your Task:
  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. Export the samples

**EFFICIENCY vs. LOAD CURRENT**

MAX1674 toc03

$V_{IN} = 1.2V$

$V_{IN} = 2.4V$

EFFICIENCY (%)

$V_{OUT} = 3.3V$
$I_{LIMIT} = 500mA$

CURRENT (mA)

0.02   0.2   2   20   200
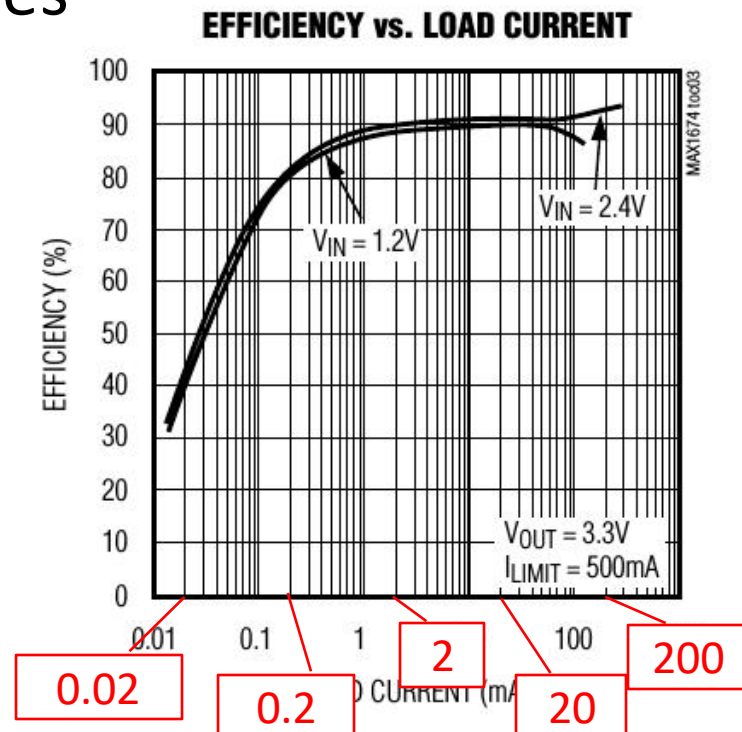
# **DC-DC converter of battery**

- Your Task:
    3. Set the parameters in
       `inc/config_converter_battery.h` (as before).
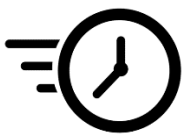
# Simulator overview
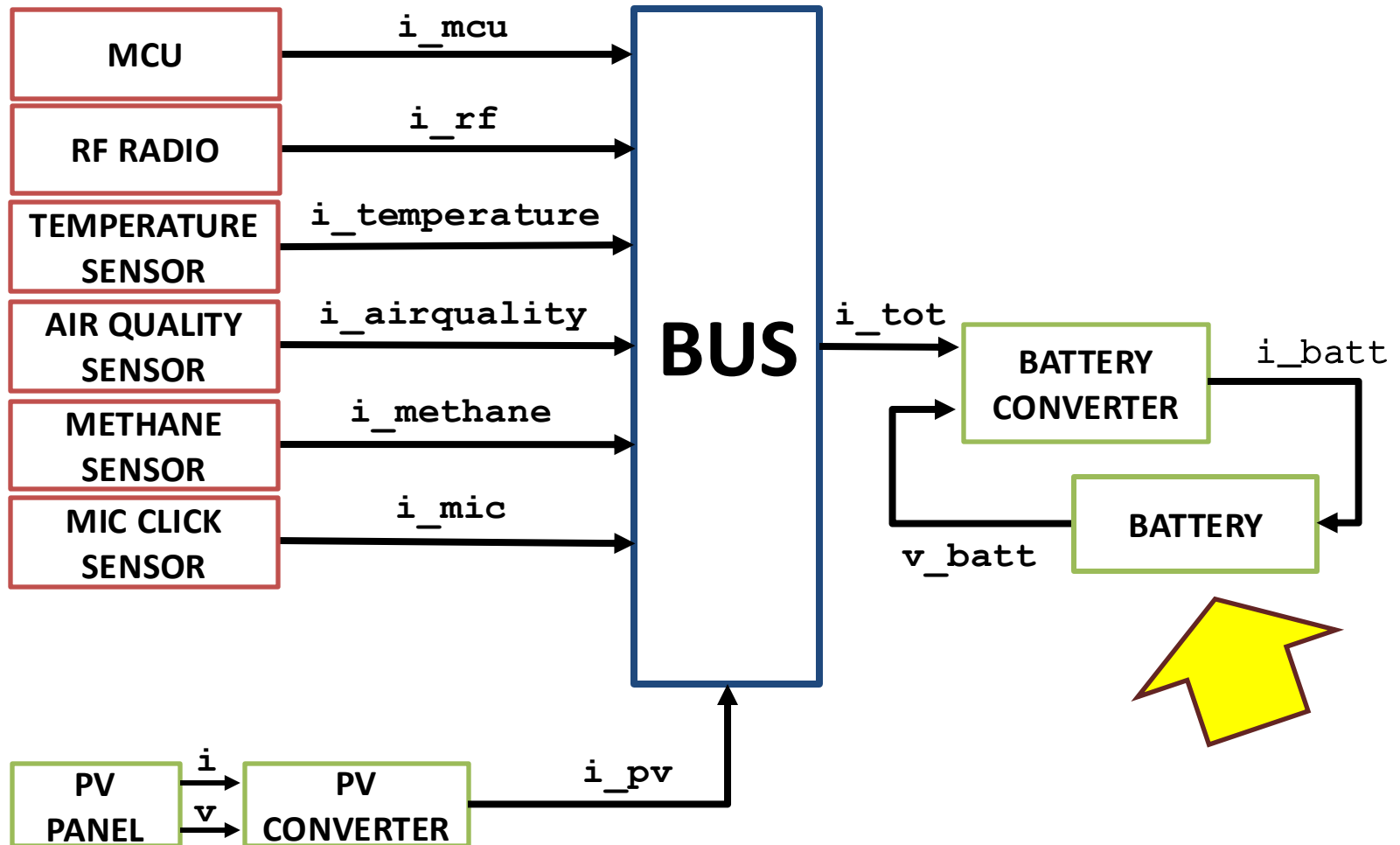
# Battery model

- ## 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
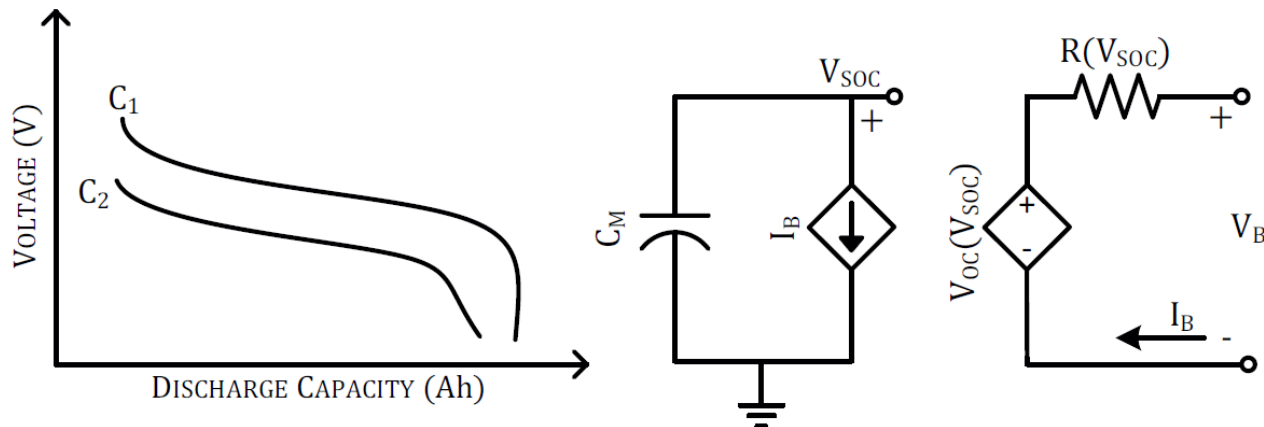
# Battery model

- Left:
  - $C_M$ available usable capacity
  - $I_B$ discharge current
  - $V_{SOC}$ state of charge
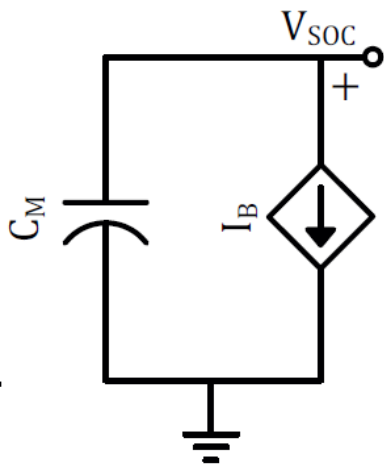
- Right:
  - $V_{OC}$ models the dependency between battery voltage vs. the SOC
  - $I_B$ discharge current
  - $R$ series resistance modeling voltage drop due to Ohmic losses (i.e., the internal resistance of the battery)
  - $V_B$ is battery voltage
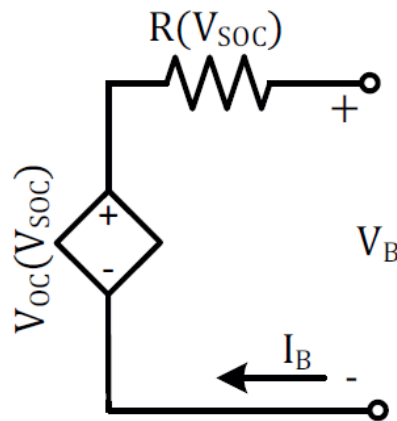
# Battery model

- 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)
  - Current in mA
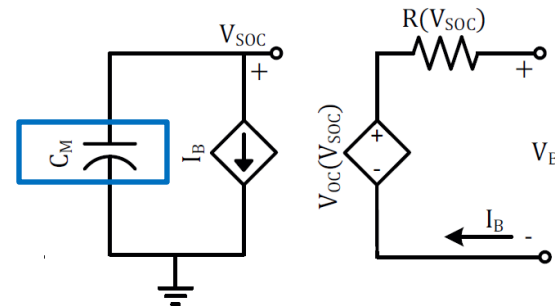


**Specifications**

| | |
|---|---|
| Rated capacity[1] | Min. 3200mAh |
| Capacity[2] | Min. 3250mAh<br>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<br>Discharge: -20 to +60°C<br>Storage: -20 to +50°C |
| Energy density[3] | Volumetric: 676 Wh/l<br>Gravimetric: 243 Wh/kg |

# Battery model

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



Charge:      CC-CV 0.5C (max) 4.20V, 65mA cut-off at 25°C
Discharge: CC, 2.50V cut-off at 25°C
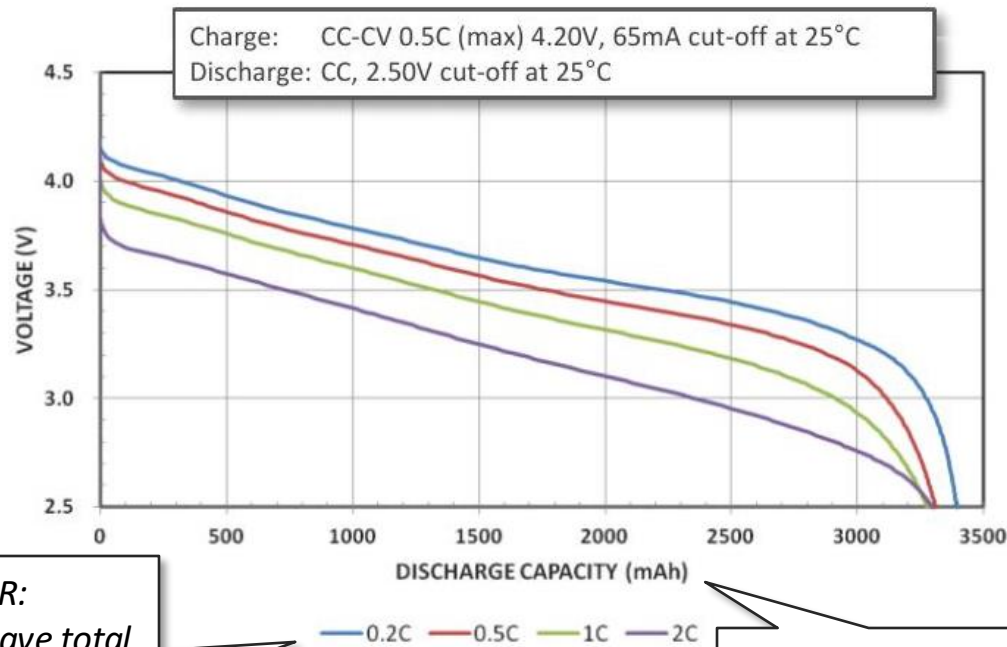
REMINDER:
1C = current to have total discharge in 1 hour

≈ STATE OF CHARGE OF THE BATTERY
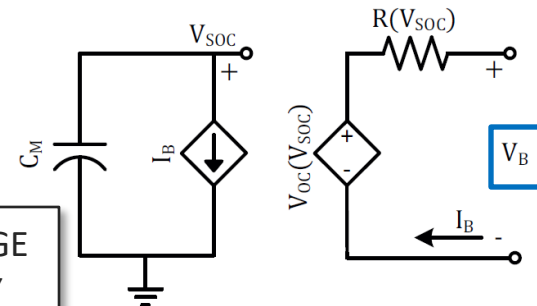
# SystemC implementation

- Battery is defined in `inc/battery.h`
  - Includes two submodules:
    - **inc/battery_voc.h** →
      Implement left part of circuit
    - **inc/battery_char.h** →
      Implement right part of circuit

## inc/battery.h

```cpp
#include "battery_char.h"    ⬅
#include "battery_voc.h"     ⬅


SC_MODULE(battery)
{
    // Interface and internal components declaration
    sca_tdf::sca_in<double> i_batt; // Battery current
    sca_tdf::sca_out<double> v_batt; // Battery voltage
    sca_tdf::sca_out<double> soc; // Battery SOC

    // Connecting signals
    sca_tdf::sca_signal<double> v_oc, r_s;

    // Instantiation of battery componenets
    battery_voc* voc_module;        ⬅
    battery_char* char_module;      ⬅

    SC_CTOR(battery): i_batt("i_batt"),
                      v_batt("v_batt"),
                      soc("soc")      You, last week • ne
    {
        voc_module = new battery_voc("voc");       ⬅
        char_module = new battery_char("batt");    ⬅

        voc_module->i(i_batt);
        voc_module->v_oc(v_oc);
        voc_module->r_s(r_s);
        voc_module->soc(soc);

        char_module->r_s(r_s);
        char_module->i(i_batt);
        char_module->v_oc(v_oc);
        char_module->v(v_batt);
    }
};
```

# SystemC implementation (cont'd)

```cpp
#include "battery_char.h"
#include "battery_voc.h"


SC_MODULE(battery)
{
    // Interface and internal components declaration
    sca_tdf::sca_in<double> i_batt; // Battery current
    sca_tdf::sca_out<double> v_batt; // Battery voltage
    sca_tdf::sca_out<double> soc; // Battery SOC

    // Connecting signals
    sca_tdf::sca_signal<double> v_oc, r_s;

    // Instantiation of battery componenets
    battery_voc* voc_module;
    battery_char* char_module;

    SC_CTOR(battery): i_batt("i_batt"),
                      v_batt("v_batt"),
                      soc("soc")      You, last week • ne
    {
        voc_module = new battery_voc("voc");
        char_module = new battery_char("batt");

        voc_module->i(i_batt);
        voc_module->v_oc(v_oc);
        voc_module->r_s(r_s);
        voc_module->soc(soc);

        char_module->r_s(r_s);
        char_module->i(i_batt);
        char_module->v_oc(v_oc);
        char_module->v(v_batt);
    }
};
```

# SystemC implementation (cont'd)

- **inc/battery_voc.h** → Implement left part of circuit



**src/battery_voc.cpp**
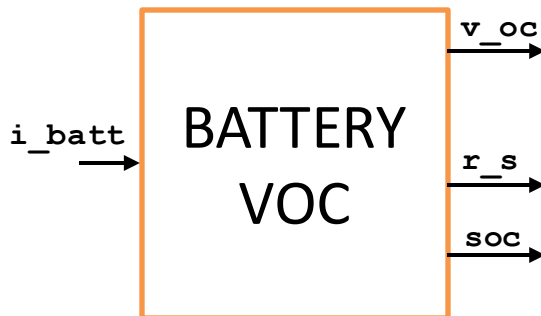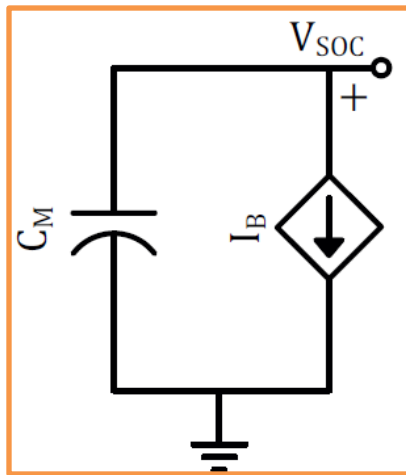
```cpp
void battery_voc::processing()
{
    double tmpcurrent; // Battery current, if negative, the battery is charged
    tmpcurrent = i.read(); // Battery current, if negative, the battery is charged

    // Compute actual state-of-charge solving the integral:
    C_nom = TO-BE-FILLED
    tmpsoc -= (((tmpcurrent + prev_i_batt) * SIM_STEP) /
              (2 * 3600 * C_nom)); // 3600 * Cnom, mAh to mA, cause [sim step] = [s]
    prev_i_batt = tmpcurrent; // Update

    // Output the battery SOC
    if(tmpsoc >= 1) // Not let the SOC overflow
    {
        soc.write(1);
        tmpsoc = 1;
    }
    else
    {
        soc.write(tmpsoc);
    }

    // SOC and battery Voc relationship
    v_oc.write(TO-BE-FILLED); // Place interpolated funct here

    // SOC and battery internal resistance relationship
    r_s.write(TO-BE-FILLED); // Place interpolated funct here

    // When the battery SOC decreases under 1%, the simulation stops.
    if(tmpsoc <= 0.01)
    {
        cout << "SOC is less than or equal to 1%:" << " @" << sc_time_stamp() << endl;
        sc_stop();
    }
}
```

**TO-BE-FILLED**

**TO-BE-FILLED**

**TO-BE-FILLED**

# SystemC implementation (cont'd)

- **inc/battery_char.h** → Implement right part of circuit

**inc/battery_char.h**



Implemented as a circuit netlist!
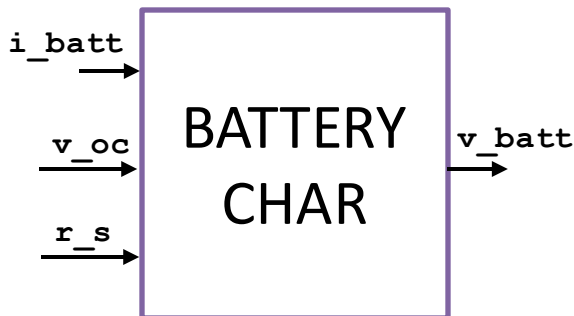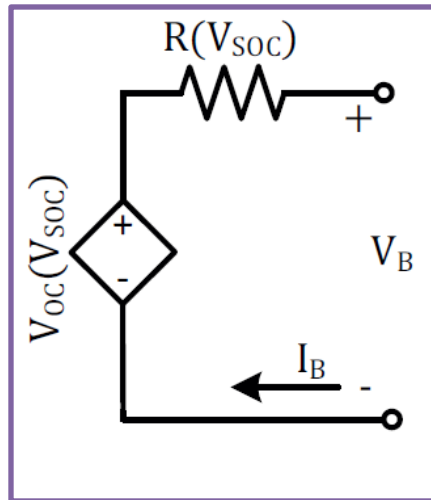
```cpp
SC_CTOR(battery_char)
{
    // V_oc voltage instantiation
    V_oc = new sca_eln::sca_tdf_vsource("V_oc");
    V_oc->inp(v_oc);
    V_oc->p(n1);
    V_oc->n(gnd);
    // Internal resistance instantiation
    R_s = new sca_eln::sca_tdf::sca_r("R_s");
    R_s->p(n1);
    R_s->n(n2);
    R_s->scale=1.0;
    R_s->inp(r_s);
    //Load current instantiation
    I_batt = new sca_eln::sca_tdf::sca_isource("I_batt");
    I_batt->inp(i);
    I_batt->p(n2);
    I_batt->n(gnd);
    //Output voltage of the battery
    V_batt = new sca_eln::sca_tdf::sca_vsink("V_batt");
    V_batt->p(n2);
    V_batt->n(gnd);
    V_batt->outp(v);
}
};
```

# Battery model

- Derive $V_{OC}$ and $R$ as a function of $V$ (SOC)
  - 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
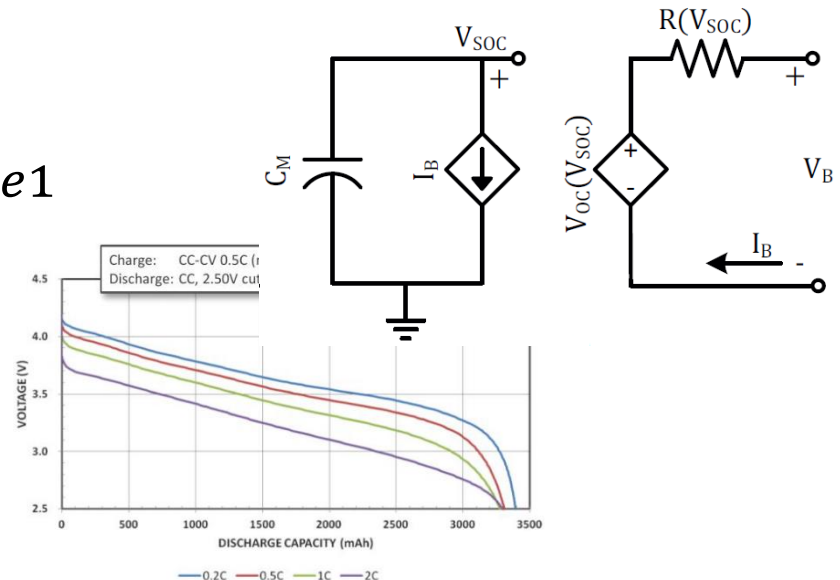
# **Battery model**

- In case you were wondering how we got here…

  - Equation solving the system:
    - $V_{OC} = R\,I + V$
  - Applied for both currents:
    - $\begin{cases} V_{OC} = RI_{curve1} + V_{curve1} \\ V_{OC} = RI_{curve2} + V_{curve2} \end{cases}$

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

# Battery model

- How do we populate the equations?

# Battery model

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

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



Charge: CC-CV 0.5C (max) 4.20V, 65mA cut-off at 25°C
Discharge: CC, 2.50V cut-off at 25°C

curve2 = 0.5C

curve1 = 1C

VOLTAGE (V)

DISCHARGE CAPACITY (mAh)

—0.2C  —0.5C  —1C  —2C
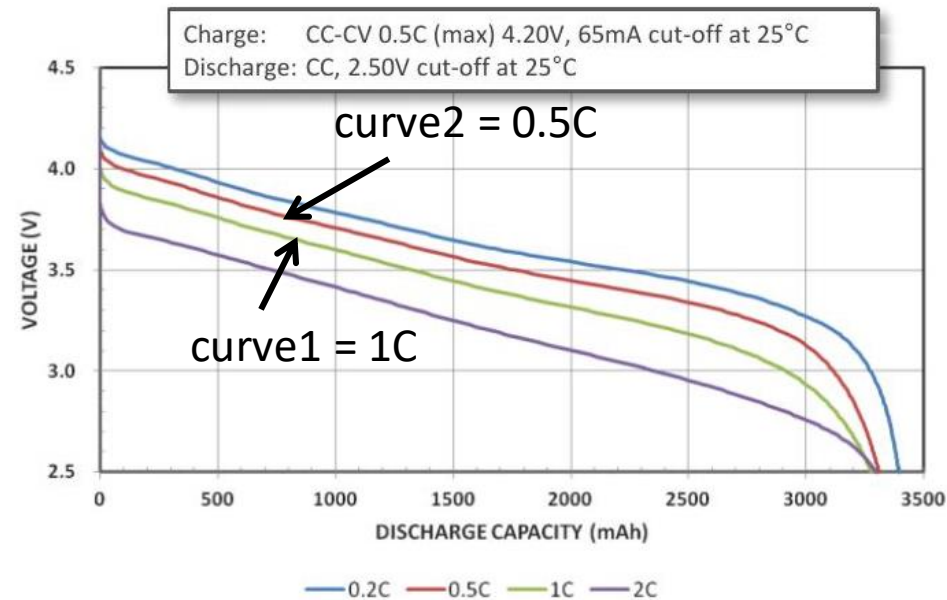
# Battery model

- Your Task:
    1. Download the datasheet figure (course website)
    2. Determine SOC axis
        - Fix the origin where the lower curve ends
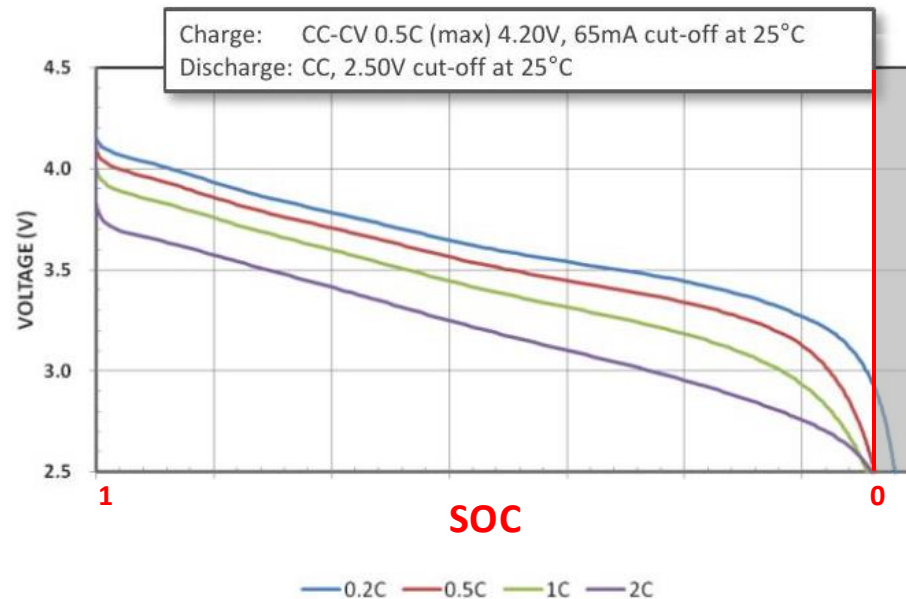
# Battery model

- Your Task:
  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
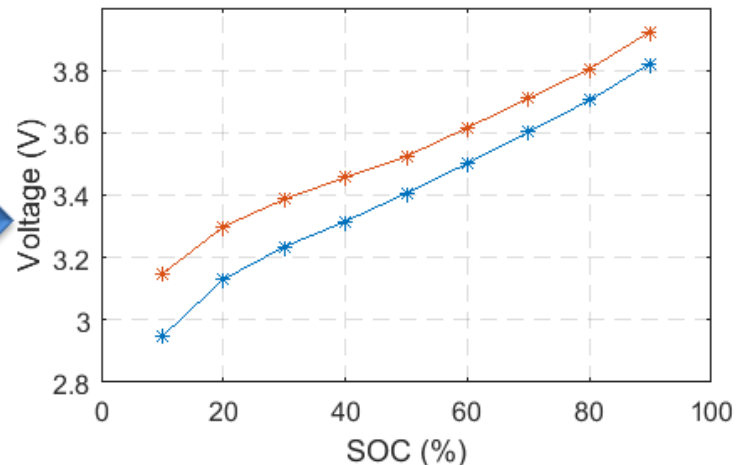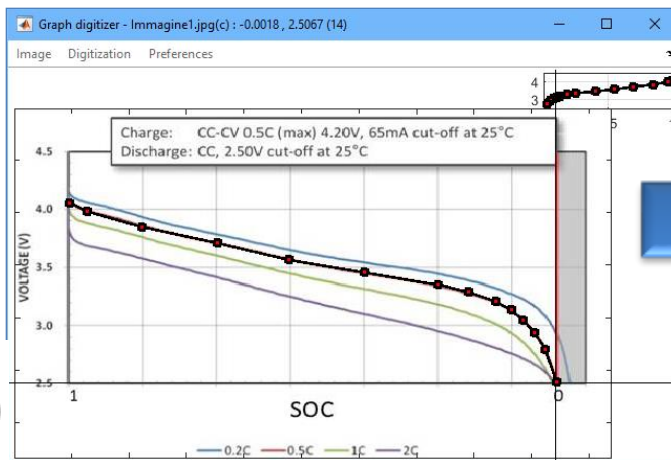
# Battery model

- Interpolation: `scipy.interpolate` function `interp1d` (link)
  - `interp_func = interp1d(x,y, bound_error=False)`
  - `newX = np.linspace(0, 1, 100)`
  - `newY = interp_func(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)
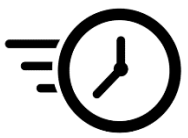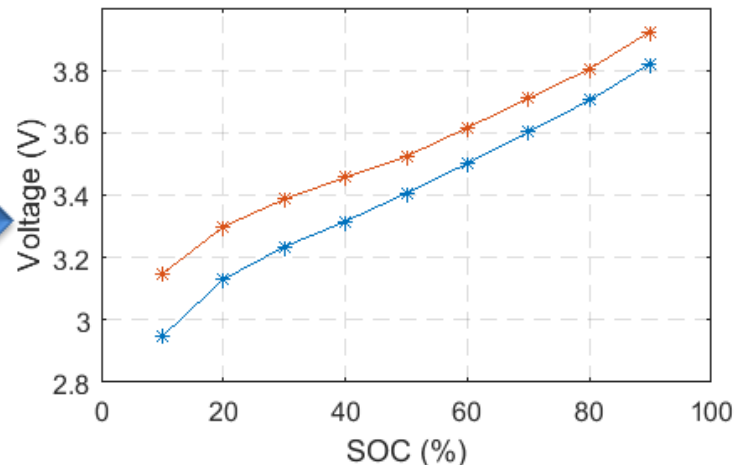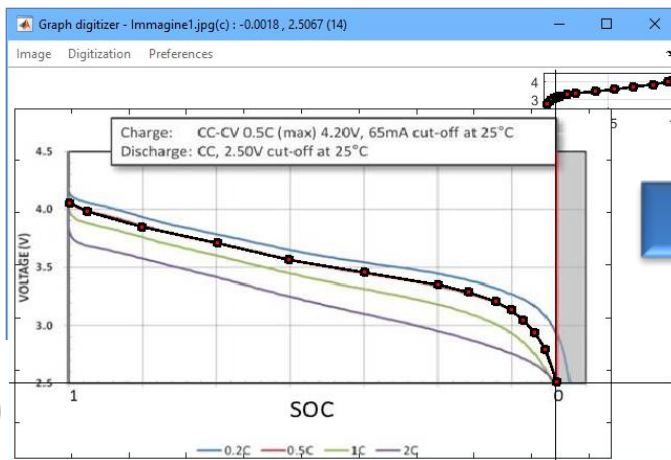
# Battery model

- ## 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!
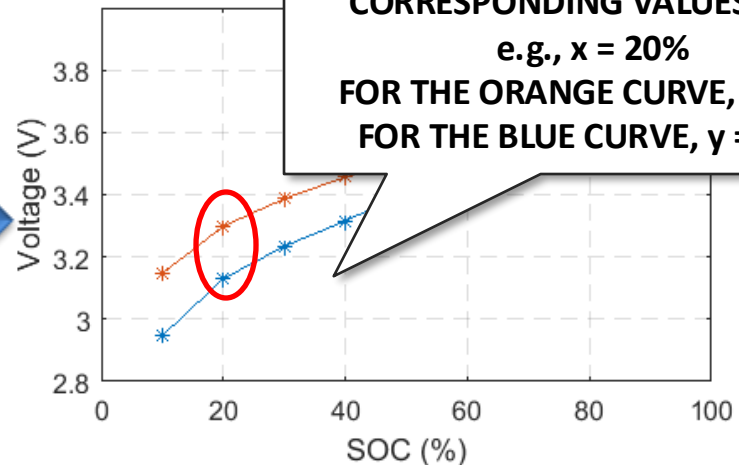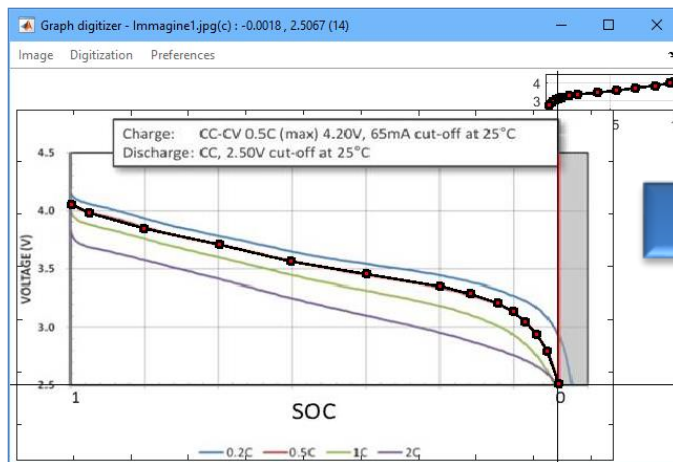


AFTER INTERPOLATION, GIVEN THE SAME x VALUE WE HAVE THE CORRESPONDING VALUES OF y:
e.g., x = 20%
FOR THE ORANGE CURVE, y = 3.3
FOR THE BLUE CURVE, y = 3.12

# 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   WE DERIVE FROM
THE SAMPLES     THE EQUATIONS

# **Battery model**

- **Your Task:** fit the resulting data into functions by using the `curve_fit` function of `scipy.optimize` ([link](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

`src/battery_voc.cpp`

```
// SOC and battery Voc relationship
v_oc.write(TO-BE-FILLED); // Place interpolated funct here

// SOC and battery internal resistance relationship
r_s.write(TO-BE-FILLED); // Place interpolated funct here
```

**TO-BE-FILLED**

**TO-BE-FILLED**

# Lab 3 – Part 3
# Load modeling and scheduling

# Simulator overview
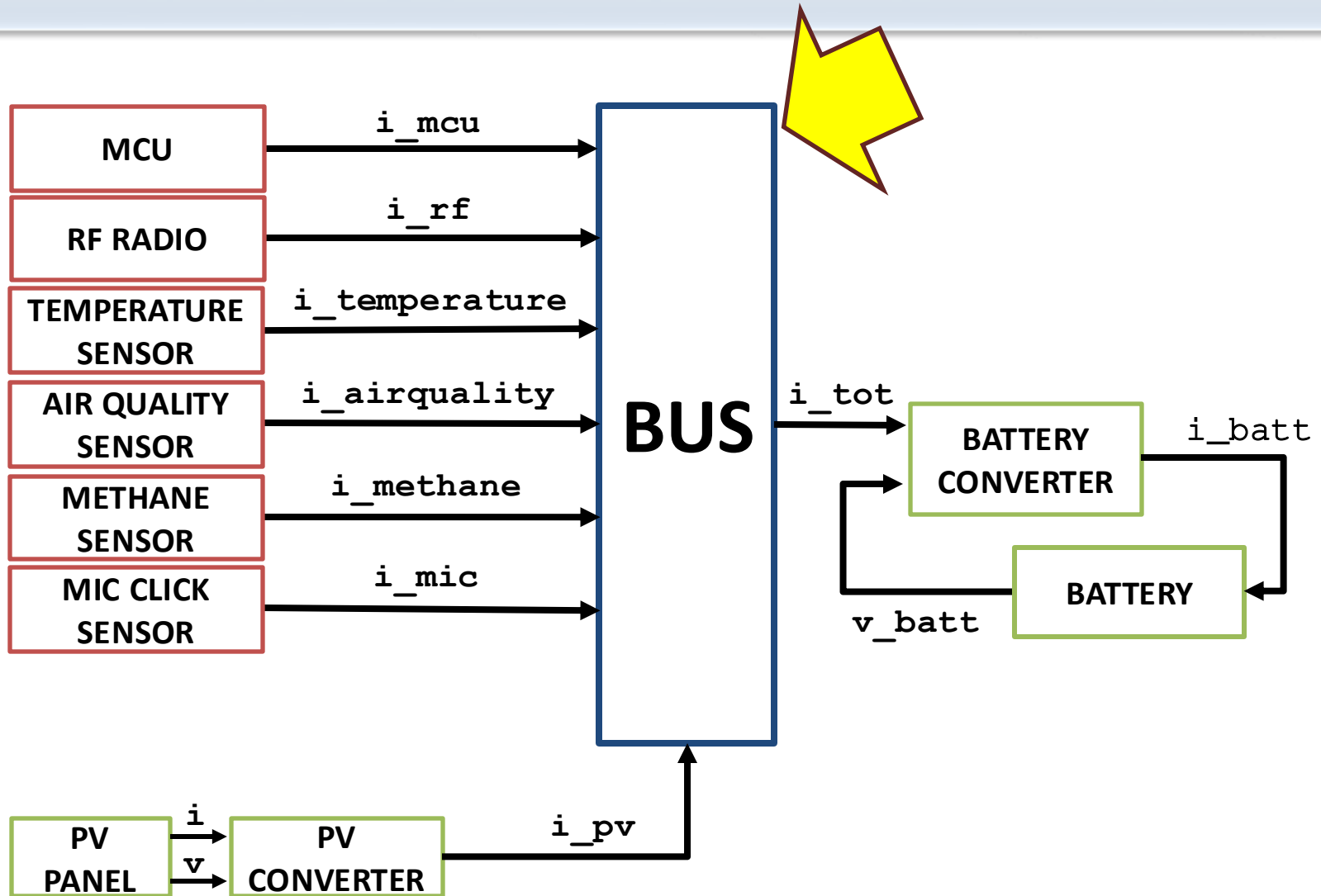
# DC bus

- 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

- 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: $\dfrac{P_{LOAD} - PPV}{3.3V}$

# DC bus

- Defined in **`inc/bus.h`** and implemented in `src/bus.cpp`

```cpp
SCA_TDF_MODULE(bus)
{
    sca_tdf::sca_in<double> i_mcu; // Requested current from MCU
    sca_tdf::sca_in<double> i_rf; // Requested current from RF module
    sca_tdf::sca_in<double> i_air_quality_sensor; // Requested current from air_quality_sensor
    sca_tdf::sca_in<double> i_methane_sensor; // Requested current from methane_sensor
    sca_tdf::sca_in<double> i_temperature_sensor; // Requested current from temperature_sensor
    sca_tdf::sca_in<double> i_mic_click_sensor; // Requested current from mic_click_sensor
    sca_tdf::sca_in<double> real_i_pv; // Provided current from pv panel after conversion

    sca_tdf::sca_out<double> i_tot;

    SCA_CTOR(bus): i_tot("i_tot"),
                    i_mcu("i_mcu"),
                    i_rf("i_rf"),
                    i_air_quality_sensor("i_air_quality_sensor"),
                    i_methane_sensor("i_methane_sensor"),
                    i_temperature_sensor("i_temperature_sensor"),
                    i_mic_click_sensor("i_mic_click_sensor"),
                    real_i_pv("real_i_pv") {};        You, last week • massive refactoring to comp

    void set_attributes();
    void initialize();
    void processing();
};
```
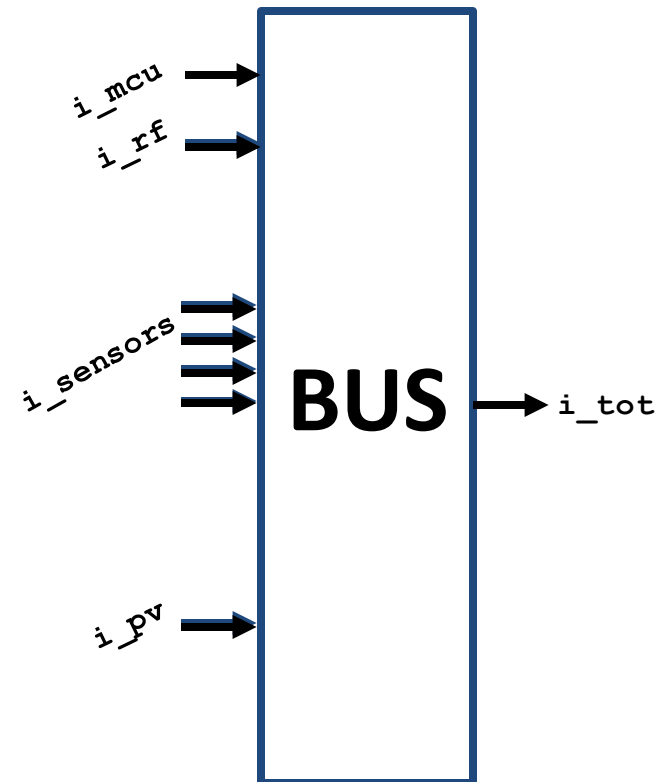
# DC bus

- Defined in `inc/bus.h` and implemented in **src/bus.cpp**

```cpp
void bus::processing()
{
    // Compute total current consumption
    double tot_consumed = i_mcu.read() + i_rf.read()
                        + i_air_quality_sensor.read()
                        + i_methane_sensor.read()
                        + i_temperature_sensor.read()
                        + i_mic_click_sensor.read()
                        ;

    double tot_scavenged = real_i_pv.read();

    double tot_requested = tot_consumed - tot_scavenged;

    i_tot.write(tot_requested); // tot_requested >= 0 ? pow_from_battery : pow_to_battery
}
```

**Consumed Current**

**—**

**Generated Current**

**=**

**Requested Current**

# 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



MIKROE
be on time

AIR QUALITY SENSOR

MIC CLICK SENSOR

METHANE SENSOR

TEMPERATURE SENSOR

# 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

**AIR QUALITY SENSOR**

SLEEP
2uA
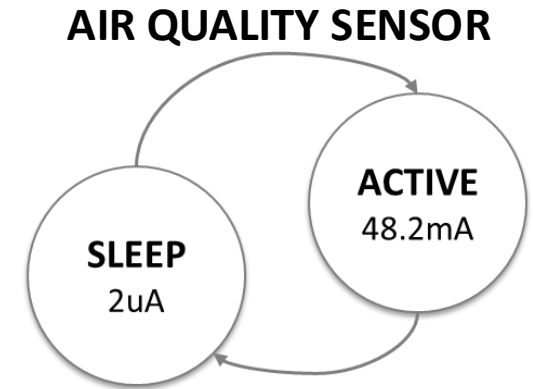
ACTIVE
48.2mA

| 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**
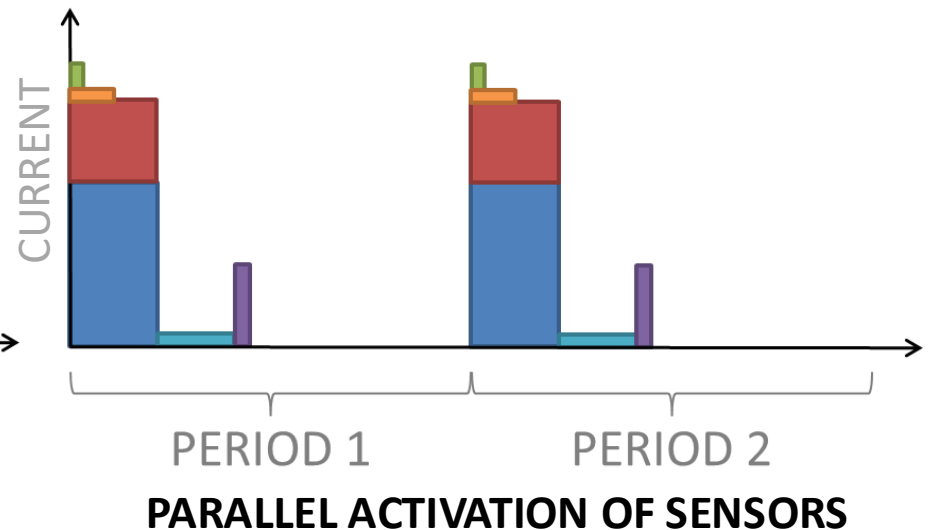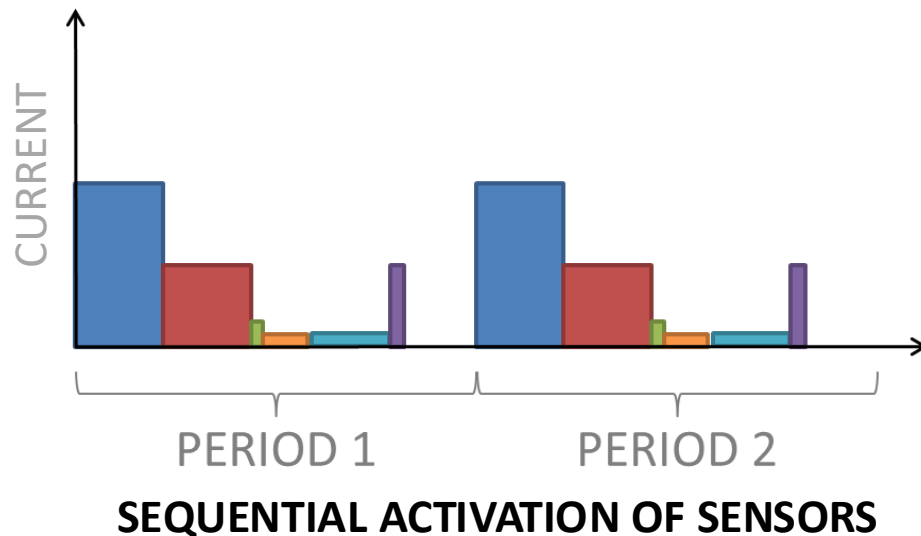
# **Loads**

- Who controls load activation?
  - Defined in the second half of
    `sim_setting/parallel.json`

```json
"sensors" : [
    {
        "name": "air_quality_sensor",
        "current_on": "48.2",
        "current_idle": "0.002",
        "activation_time": "0",
        "time_on": "30"
    },
    {
        "name": "methane_sensor",
        "current_on": "18",
        "current_idle": "0.002",
        "activation_time": "0",
        "time_on": "30"
    },
    {
        ...
```

Same activation time
→ Parallel Execution

N.B., Current values
are in mA !!

# Loads

- Who controls load activation?
  - Defined under `sim_setting/parallel.json`

```
"mcu" : {
    "states":[
        {
        "name": "ON",
        "current": "13",
        "time_on": "6"
        }
    ],
    "current_idle": "0.002"
},
```

Activated after sensors

```
"rf" : {
    "states":[
        {
        "name": "ON",
        "current": "0.1",
        "time_on": "24"
        }
    ],
    "current_idle": "0.001"
}
```

Activated after MCU

# Simulation settings

- Who controls load activation?
  - Defined in the first half of **sim_setting/parallel.json**
- Simulation Step: 1 second

```json
{
"sim_step" : 1,
"sim_len": 7736400,
"period" : 120,
"vref_bus" : 3.3,
"soc_init" : 1.0,
"selfdisch_factor" : 0.0,
"sensors" : [
```

Length of Gmonth.txt file

# **Simulation settings**

- To run the simulation, in a terminal launch the bash script:
  - `$ source simulate.sh sim_setting/parallel.json`

```bash
#!/bin/bash

cd simulator

# Python codegen   1
cd codegen
sim_setup_path=$1
python codegen.py -f ${sim_setup_path}
cd ..

# Compile   2
make clean
make

# launch the simulation   3
.bin/run.x
```

**1** Generate simulation source code using a template-based python script directly from the `sim_setting/parallel.json` file.

**2** Compile.

**3** Run simulation.

# Simulation output

- The simulation outputs are saved in the `sim_trace.txt` file.



```
1   %time soc i_tot i_mcu i_rf i_pv v_pv real_i_pv i_batt v_batt i_air_quality_sensor i_methane_sensor i_temperature_sensor i_mic_click_sensor
2   0 0 66.653 0.002 0.001 0 0 0 0 4.1138 48.2 18 0.3 0.15
3   1 1 66.653 0.002 0.001 0 0 0 58.8435823726 4.11379642475 48.2 18 0.3 0.15
4   2 0.999997446025 66.653 0.002 0.001 0 0 0 58.8436335128 4.11379126317 48.2 18 0.3 0.15
5   3 0.999992338073 66.653 0.002 0.001 0 0 0 58.8437073439 4.1137861016 48.2 18 0.3 0.15
6   4 0.999987230115 66.653 0.002 0.001 0 0 0 58.8437811753 4.11378094003 48.2 18 0.3 0.15
7   5 0.999982122152 66.653 0.002 0.001 0 0 0 58.8438550067 4.11377577846 48.2 18 0.3 0.15
8   6 0.999977014181 66.355 0.002 0.001 0 0 0 58.8439288383 4.1137706169 48.2 18 0.002 0.15
9   7 0.999971906205 66.355 0.002 0.001 0 0 0 58.5903200911 4.11376547075 48.2 18 0.002 0.15
10  8 0.999966809232 66.355 0.002 0.001 0 0 0 58.5903933851 4.11376033145 48.2 18 0.002 0.15
11  9 0.999961723263 66.355 0.002 0.001 0 0 0 58.5904665818 4.11375519215 48.2 18 0.002 0.15
12  10 0.999956637289 66.355 0.002 0.001 0 0 0 58.5905397786 4.11375005286 48.2 18 0.002 0.15
13  11 0.999951551307 66.355 0.002 0.001 0 0 0 58.5906129756 4.11374491357 48.2 18 0.002 0.15
14  12 0.99994646532 66.207 0.002 0.001 0 0 0 58.5906861727 4.11373977429 48.2 18 0.002 0.002
15  13 0.999941379326 66.207 0.002 0.001 0 0 0 58.4647381469 4.11373464266 48.2 18 0.002 0.002
16  14 0.999936298795 66.207 0.002 0.001 0 0 0 58.464811078 4.11372951444 48.2 18 0.002 0.002
17  15 0.999931223728 66.207 0.002 0.001 0 0 0 58.4648839609 4.11372438622 48.2 18 0.002 0.002
18  16 0.999926148655 66.207 0.002 0.001 0 0 0 58.4649568439 4.11371925801 48.2 18 0.002 0.002
19  17 0.999921073575 66.207 0.002 0.001 0 0 0 58.4650297271 4.1137141298 48.2 18 0.002 0.002
20  18 0.999915998489 66.207 0.002 0.001 0 0 0 58.4651026103 4.11370900159 48.2 18 0.002 0.002
21  19 0.999910923396 66.207 0.002 0.001 0 0 0 58.4651754937 4.11370387339 48.2 18 0.002 0.002
```

simulation timestamp

traced signals

# Simulation output

- How to control which signals are traced?
  - Refer to the `src/main.cpp` file:

```cpp
// the following signals will be traced. Comment any signal you don't want to trace
sca_util::sca_trace(atf, soc, "soc" );
sca_util::sca_trace(atf, i_tot, "i_tot" );
sca_util::sca_trace(atf, i_mcu, "i_mcu" );
sca_util::sca_trace(atf, i_rf, "i_rf" );
sca_util::sca_trace(atf, i_pv, "i_pv" );
sca_util::sca_trace(atf, v_pv, "v_pv" );
sca_util::sca_trace(atf, real_i_pv, "real_i_pv" );
sca_util::sca_trace(atf, i_batt, "i_batt" );
sca_util::sca_trace(atf, v_batt, "v_batt" );
sca_util::sca_trace(atf, i_air_quality_sensor, "i_air_quality_sensor" );
sca_util::sca_trace(atf, i_methane_sensor, "i_methane_sensor" );
sca_util::sca_trace(atf, i_temperature_sensor, "i_temperature_sensor" );
sca_util::sca_trace(atf, i_mic_click_sensor, "i_mic_click_sensor" );
```

**N.B., if you comment some lines DO NOT perform the "Python codegen" step of `simulate.sh` script, but perform directly compilation and the run simulation.**

# 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 quantities
     - 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
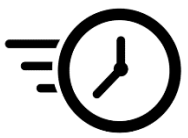
  - Compare:
    - Different scheduling
      - All sensors in parallel
      - Sequential activation of the sensor
    - Does the scheduling impacts on the evolution of battery lifetime?
    - If no impact, why???

**You need to develop a new `json` file in `sim_setting`**

# **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**

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.

By Carlo Canzioni, Keysight Technologies, Inc.

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

# Things to bear in mind:

- Efficiency is a number between 0 and 100 for all converters

- When digitizing, take care of axis prefix (e.g., mA = milli Ampere) – fix the digitization to the correct scale!
  - In the simulation, 1 = 1mA, 1V,…

- Don't forget to set battery capacity