THE IMPORTANCE OF ACCURATE BATTERY MODELS FOR THE POWER ASSESSMENT IN SMART ENERGY SYSTEM

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Presenter Introduction

Yukai Chen received the M.Sc. Degree and Ph.D. degree in Computer Engineering from the Department of Control and Computer Engineering at Politecnico di Torino, Turin, Italy, in 2014 and 2018, where he is currently a Postdoctoral Research Fellow.

His main research interest is computer-aided design for integrated circuits and cyber-physical systems, emphasizing the modeling, simulation, and optimization of the extra-functional properties.

He is currently involved in several funded projects focusing on the cyber-physical energy systems, especially for power modeling, simulation, and optimization, from the micro-scale electronic embedded system (System on Chip) to the large-scale electrical energy system (Drone, EV, Smart Grid).

Research Group Introduction

EDA (Electronic Design Automation) Group is an interdepartmental research group including researchers from the Department of Control and Computer Engineering (DAUIN) and the Interuniversity Department of Regional and Urban Studies and Planning (DIST) of Politecnico di Torino. Our research is aimed at the design and development of automated techniques for complex systems. Benefiting from tight interdisciplinary collaborations with other research institutions and with industry experts, our research activities span three main application domains:

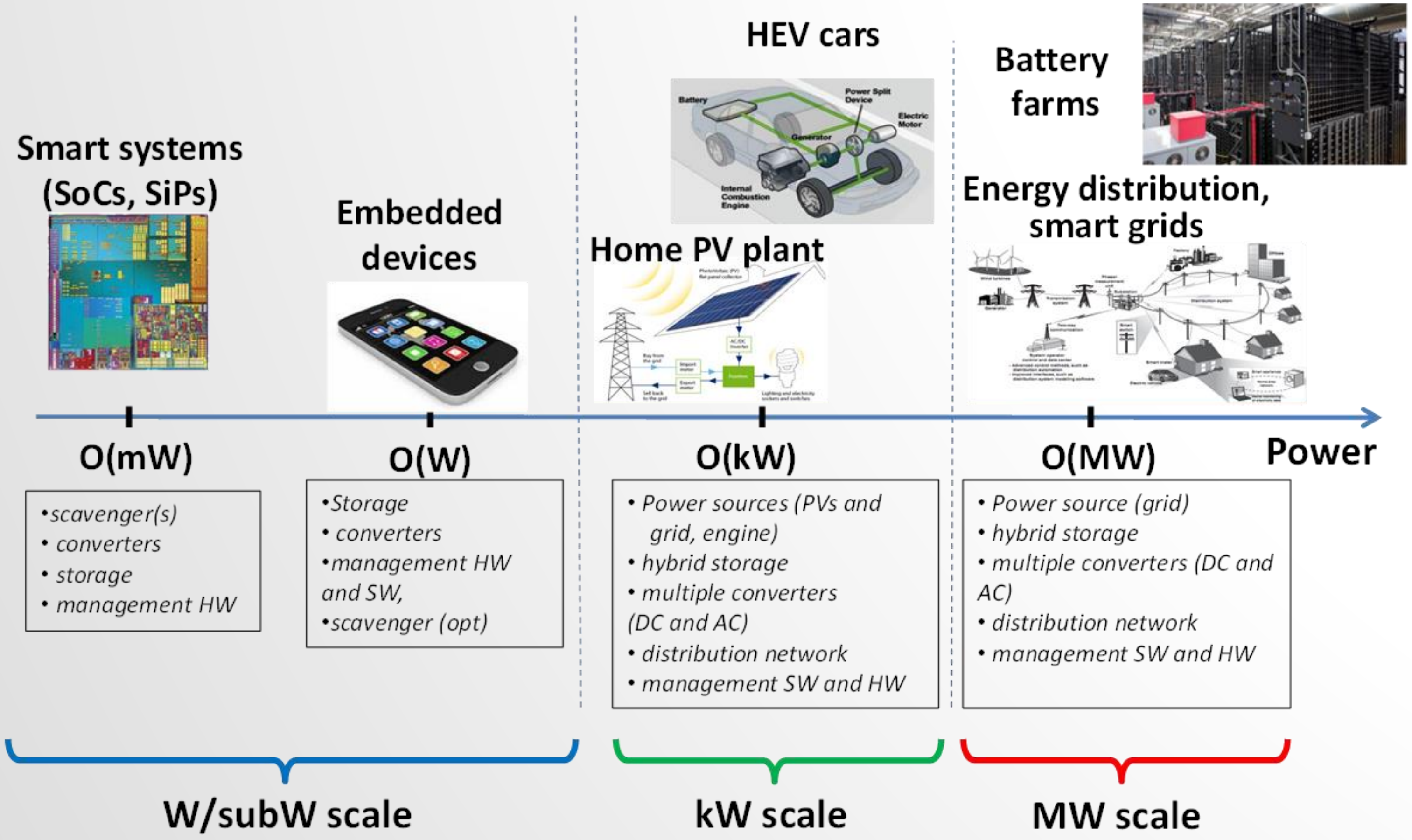
- **VLSI-CAD**: Design Automation for standard digital CMOS ICs, Beyond-CMOS circuits and Electrical Energy Systems.
- **Smart City**: Design and development of novel software solutions for Smart City.
- **Industry 4.0 and Smart Manufacturing**: Combine IOT technologies, cyber-physical systems, wireless sensor networks and machine learning for more efficient manufacturing.

Outline

- **Introduction to Smart Energy Systems**
- **Motivation – Power Assessment in Smart Energy Systems**
- **Battery Modelling – Adopted Battery Model**
- **Modeling and Simulation Infrastructure for Smart Energy Systems**
- **Two Case Studies**
  - **Multi-Sensor IoT Nodes Application**
  - **Smart Grid Application**
- **Conclusion**

Smart Energy Systems

- Energy systems incorporate various energy sources and energy storage devices with smart control management.
  - From small-scale System-on-Chip application to large-scale smart grid application.

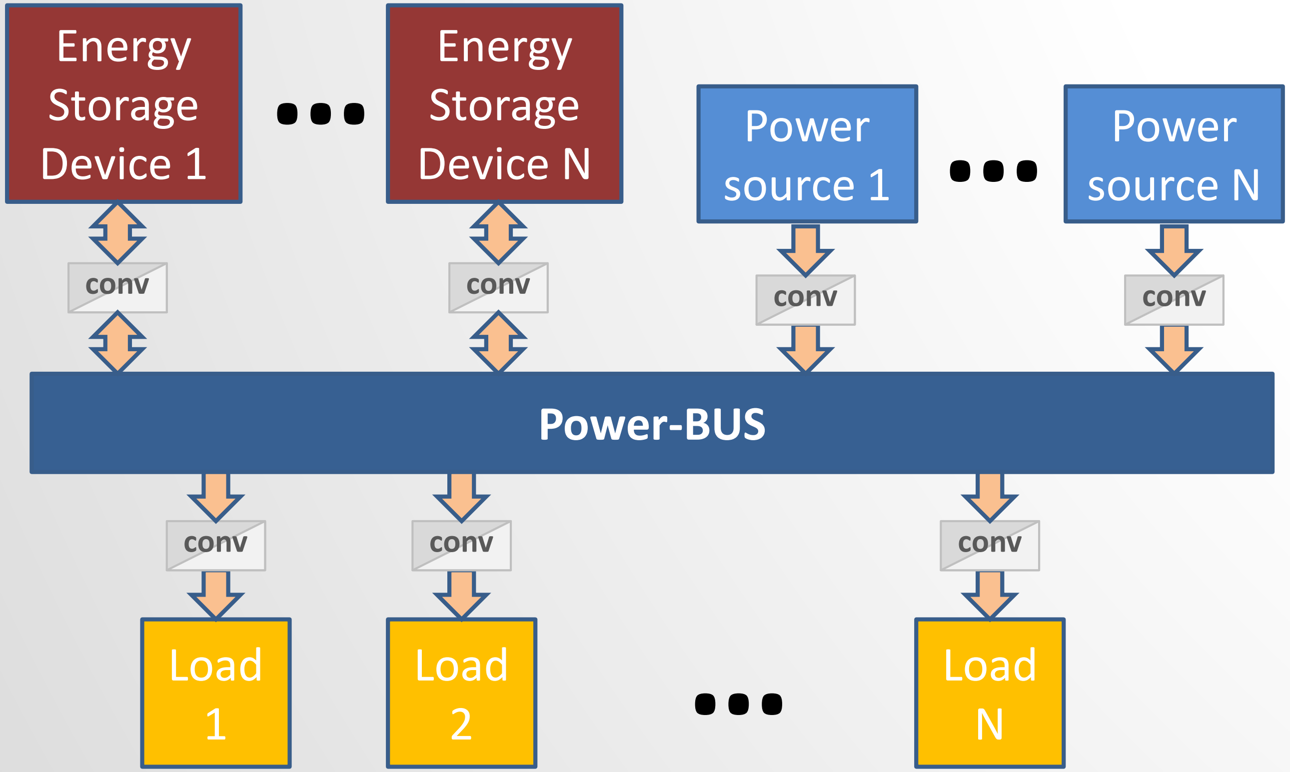


***Challenges in Design Phase*:**

- **Energy is the main feature to be analyzed -> Power as quantity explicitly tracked during the simulation.**
- **Smart energy systems have a significant amount of smartness -> Optimization issues.**
- **Simulation accuracy plays a critical role in the early design phase -> Need accurate models.**

Power Assessment in Smart Energy System

- Observe smart energy system in the perspective of power:
  - Components in the smart energy system can be classified: **Power Source, Energy Storage, Load, Converter**.
- **Smart control management policy** coordinates the different "power components" to achieve high energy efficiency.



***Existing approaches for modeling and simulation of smart energy systems*:**

- **Hardware-in-the-loop approaches mix software simulated models with sensors and actuators.**
- **The model-based methodology that depends on existing models. (MATLAB Simulink)**
- **Equation-based approaches decompose the system into elementary components, modeled with fundamental physics equations. (Modelica)**

Motivation

- The main limitation of the existing power assessment approaches.
  - The adopted built-in classic models are difficult to **extend** their performance.
  - They are not designed for the efficiently simultaneously simulate the **physical portion** (usually continuous-time) and the **cyber part** (usually discrete-time) of the systems (these two portions are the intrinsic features coexist in the smart energy system).
  - They are not supported for the different models of computations (**heterogeneous modeling and simulation support**) in the simulation (the smart energy system is a typical heterogeneous system composed of various components).
- Another one critical point cannot be ignored.
  - The power consumed by the load does not have a perfect 1:1 match with the power provided from the battery because of its non-idealities, consumed power depends on
    - **Current State of Charge (SOC);**
    - **Current magnitude;**
    - **Load current frequency.**

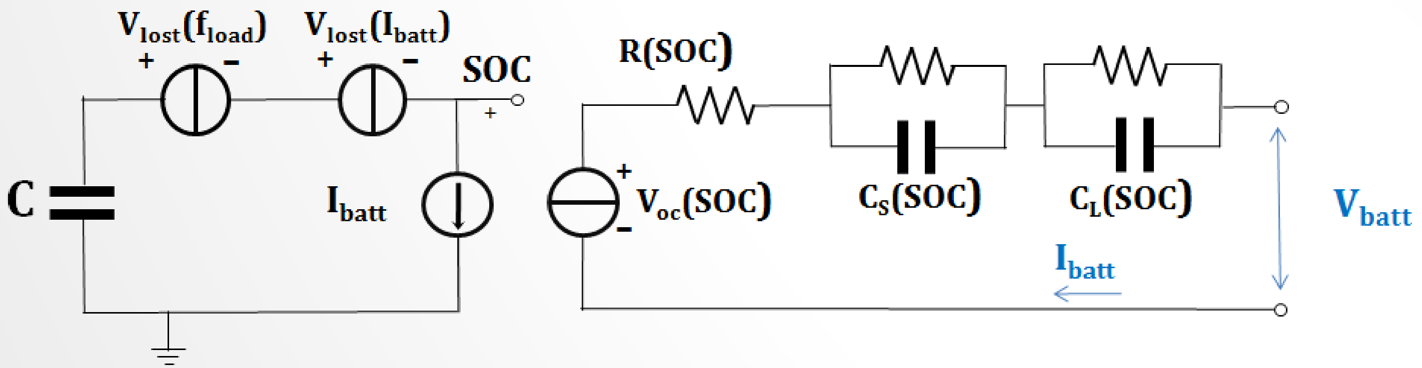
Need one elaborated battery model includes these non-ideal characteristics during the power assessment.

Battery Model

- Three main categories of battery models can be classified in the literature:
  - Mathematical models.
  - Electrochemical models.
  - **Electrical equivalent circuit models.**

Complexity of the parameter identification and heavy computation.

- Adopted circuit equivalent battery model:



  - $\mathbf{V_{lost}(f_{load})}$: modelling the dependence of battery capacity on load frequency;
  - $\mathbf{V_{lost}(I_{load})}$: representing the current dependency (Rated capacity effect);
  - Left-hand side and right-hand side influence mutually to represent the SOC dependency.

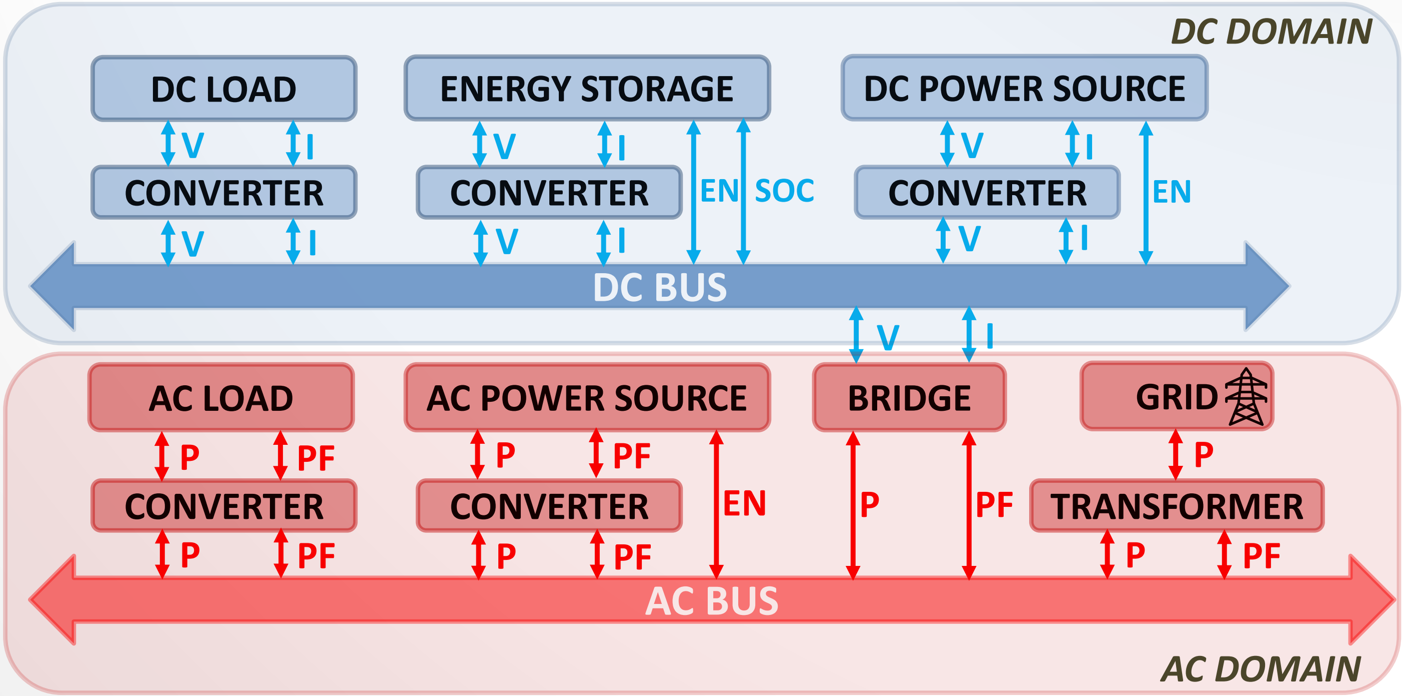
Modeling and Simulation Infrastructure

- To conduct the power assessment, the designer needs to run a smart energy system simulation to track power flow in the systems.
  - Four different components: power source, power load, energy storage, and conversion devices.
  - The system may only operate in the DC domain, or operate in both DC and AC domain.

Simulation framework:

- **Bus-based modular architecture**
- **Bus plays the role of smart control**
- **V and I ports in DC domain**
- **P and PF ports in AC domain**
- **En port represent the enable signal**

Generic Smart Energy System Modular Architecture



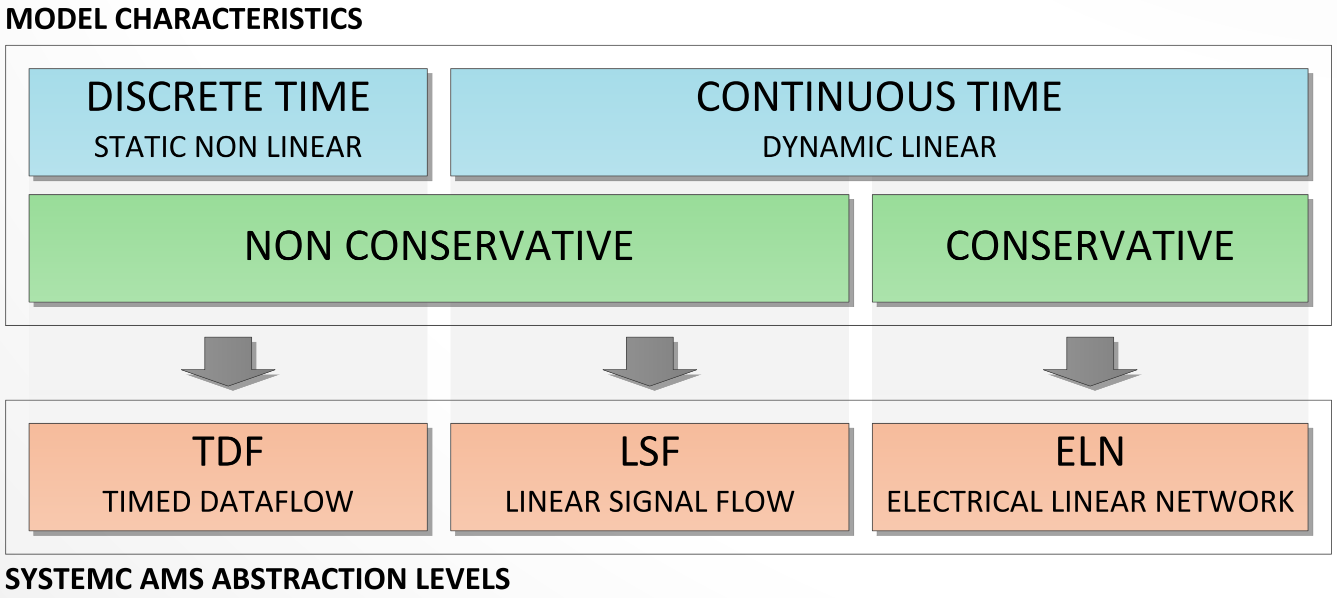
Implementation Simulation Framework

- SystemC-AMS is selected to implement the simulation framework.
  - Heterogeneous is one main feature of the smart energy system.
  - SystemC-AMS supports different model of computations.
  - SystemC-AMS supports different abstraction levels models concurrent simulation.
  - SystemC is an extension of C/C++ language.

SystemC-AMS Model of Computation:

- **Timed Data-Flow(TDF):** Scheduled statically by considering their producer-consumer dependencies in the discrete-time domain.
- **Linear Signal Flow (LSF):** Modeling of continuous-time through a library of pre-defined non-conservative primitive modules.
- **Electrical Linear Network (ELN):** Modeling the electrical network by connecting the instantiation of predefined primitives.

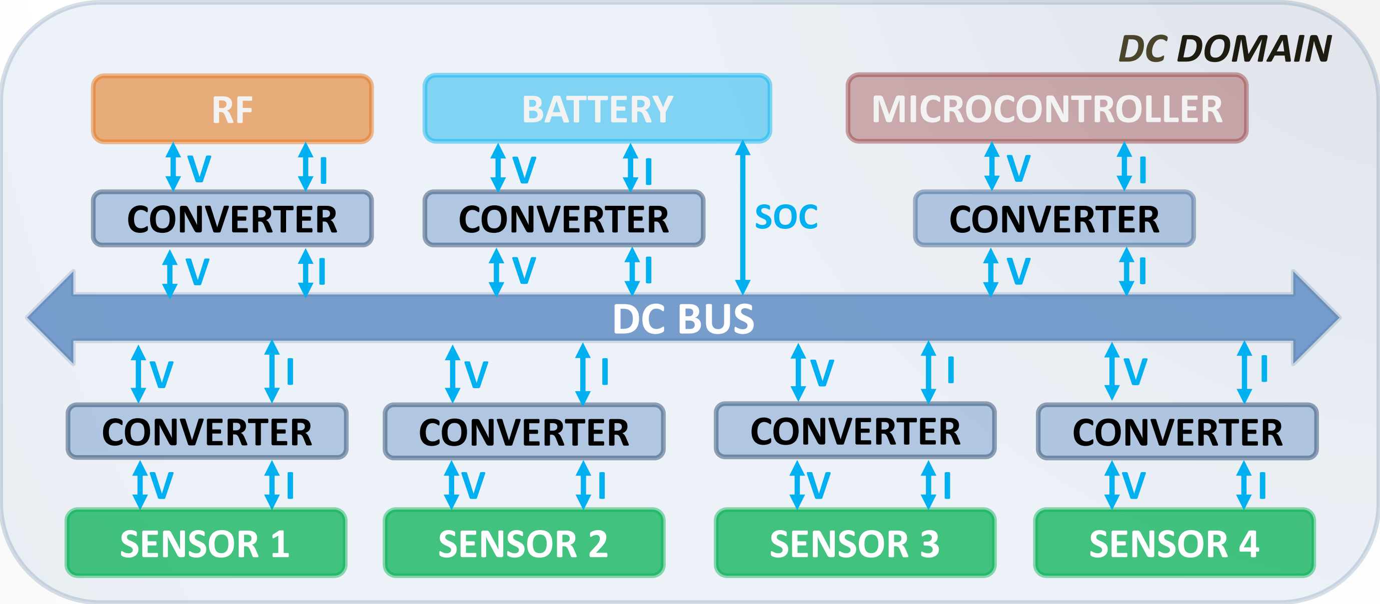
Different Model of Computations from SystemC-AMS



Small-Scale Smart Energy System Case Study

- Multi-sensor IoT device
  - Four different sensors;
  - One lithium-ion battery;
  - One Radio Frequency (RF) transceiver;
  - One Micro controller unit;
  - Several DC/DC converters.

This smart energy system only works in the DC domain.

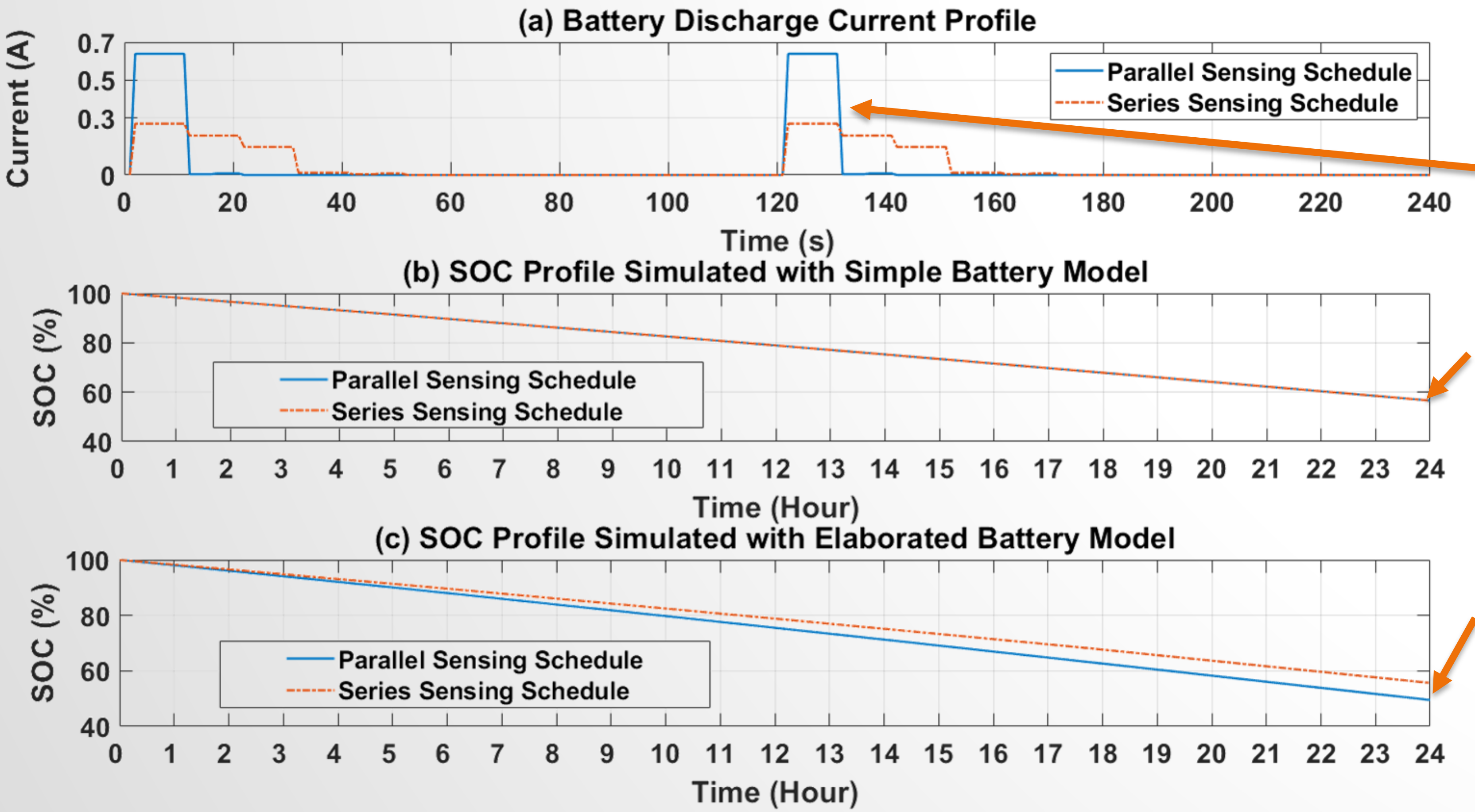


This smart energy system's operating scenario:

- A periodic sequence of the following tasks: sensing, computation, and transmission.
- When the system executes these tasks, it is the active period (T_{active}), then the system enters a longer idle period (T_{idle}) after these operations.
- Different scheduling of sensors in the period T_{active} generate different load current profiles, finally affecting the available SOC of battery, which determines **the lifetime of the system**.

Small-Scale Smart Energy System Case Study

- In order to show the influence of the battery model accuracy:
  - Two different battery models: simple circuit equivalent battery model vs. adopted battery model.
  - Two different sensing schedules: all sensors work concurrently vs. all sensors work in series.



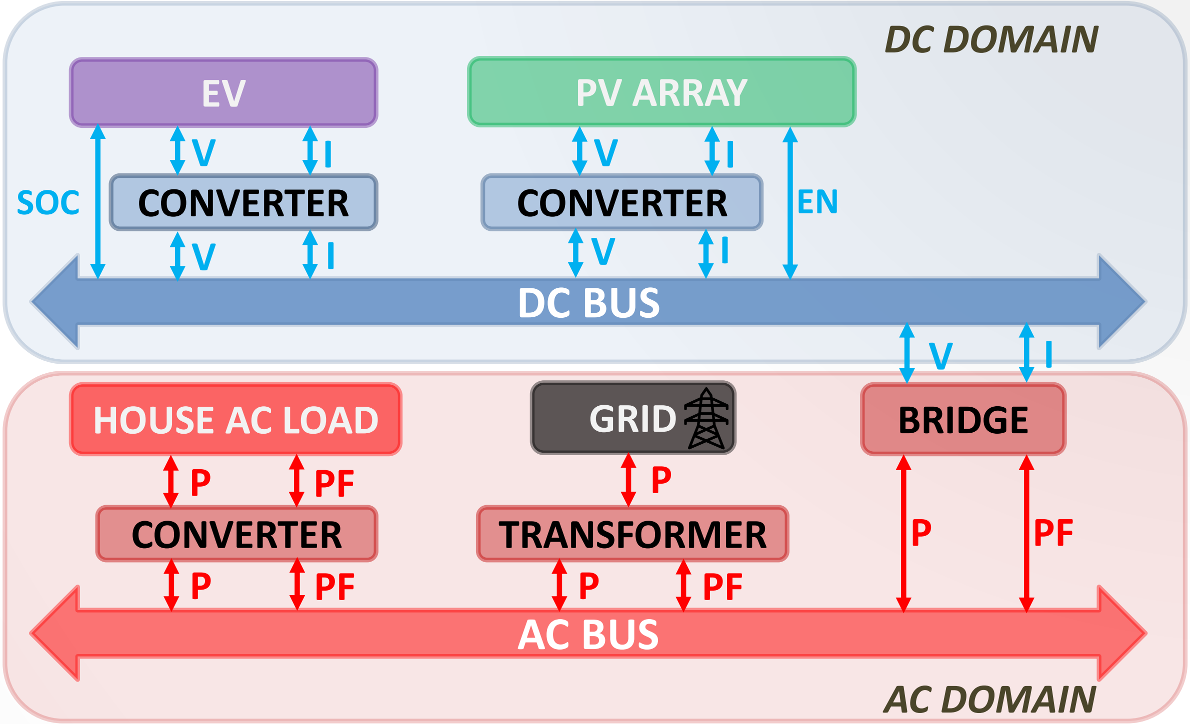
Simulation results:

- Parallel schedule has higher peak currents -> More rated capacity effect.
- Simple battery model cannot show the difference between two schedules.
- The adopted battery model tell the parallel schedule consumes **6.14%** more than the series sensing schedule.

Large-Scale Smart Energy System Case Study

- Smart Home with EV
  - An EV;
  - A PV Array;
  - Grid Utility;
  - A House;
  - Several DC/DC converters, transformers.

This smart energy system works in the DC and AC domains.

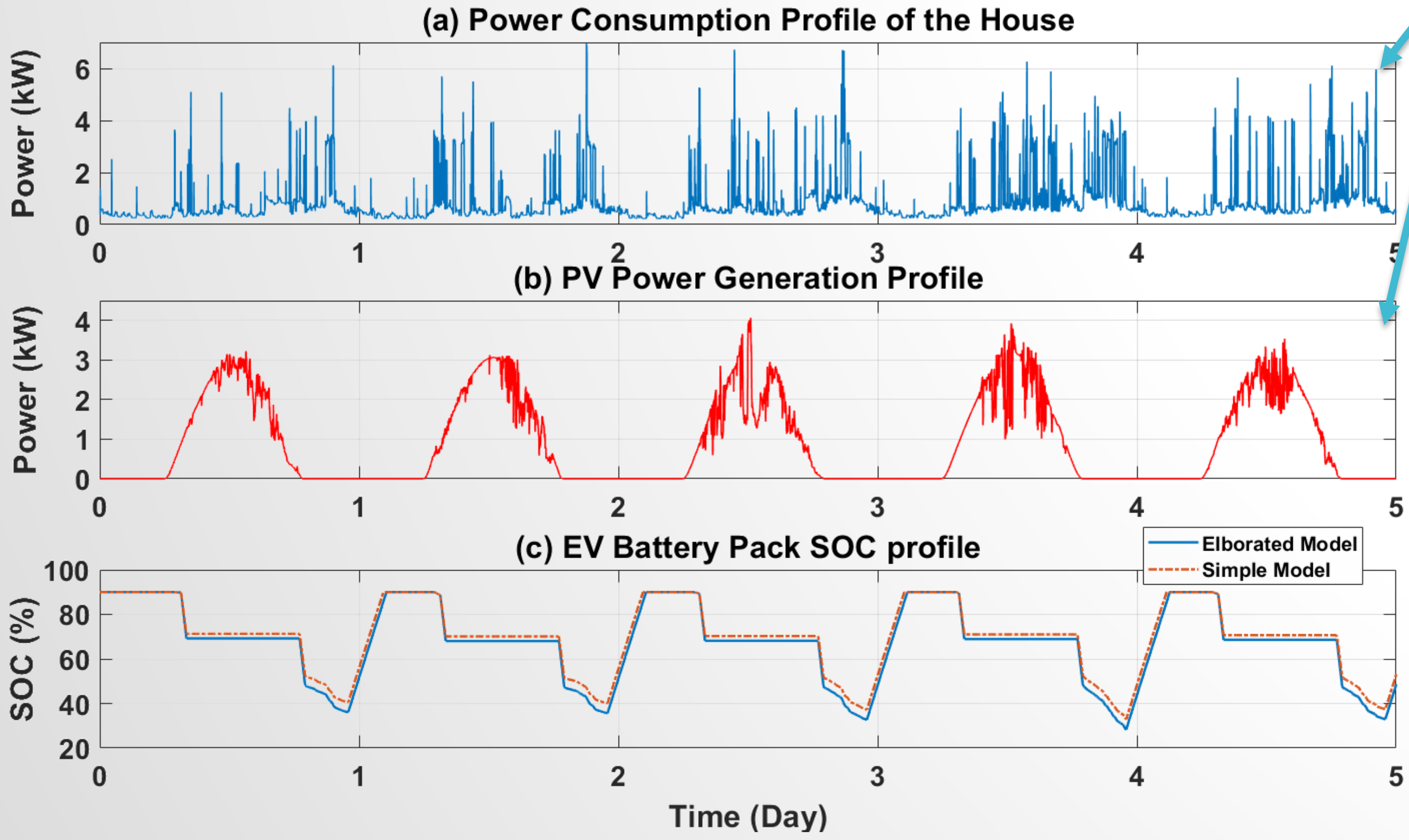


This smart energy system's operating scenario:

- The EV operates the daily commute routine between the house and the working place.
- When the EV is not plugged with the house, the PV array provides the solar power to support the power consumption of the house; additional power will be sold to the grid, and power deficit will be bought from the grid.
- When the EV is connected with the house, the power consumption of the house is provided by the EV first, then the house starts to buy power from utility grid if the battery pack is depleted; finally, the EV and house start to buy the power from the grid during the lowest electricity price period.

Large-Scale Smart Energy System Case Study

- The input traces of solar irradiance used in the simulation is extracted from the dataset provided by the National Renewable Energy Laboratory (NREL) Measurement and Instrumentation Data Centre (MIDC).
- The time-dependent electricity price is adopted in the simulation.
- The EV operates a daily commute routine with constant speed.



Simulation results:

- Power consumption vs. Power generation.
- Battery pack has full charge at the beginning, it starts to discharge power after the EV leave the house to the working place;
- The SOC keeps stable when the EV parked in the working place, then the SOC decreases again when the EV return the house.
- The EV provides the power to the house if needed; finally the battery pack is charged.
- The simple battery model always gives the **underestimated power assessment.**

Conclusion

- **Power assessment** is an essential step in the early design phase of the smart energy system.
- An **accurate power assessment** in the smart energy system simulation requires sophisticated models of different system components.
- The battery model is the critical one due to its **non-ideal properties**.
- Incorporating the **elaborated circuit equivalent battery model** for conducting power assessment of the smart energy system to generate more accurate results.
- Both **small-scale and large-scale** smart energy systems illustrate the importance of the battery model accuracy while conducting power assessment.