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Energy Harvesting Framework for Network Simulator 3 (ns-3)

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Introduction

- Battery operated wireless devices
  - Efficiently managing the energy consumptions of the different elements is a major requirement for an efficient design of wireless networks
- Energy harvesting wireless networks
  - The objectives of the communication protocols are fundamentally different than those of using a traditional energy source
- Simulation of communication systems and network protocols over realistic device operations is seen as a necessary task before implementation
  - Flexible and fast, but still accurate, testing of the system evolution

Motivations

- Need for a simulation framework for evaluating the performance of energy aware wireless networks with energy harvesting capabilities
- Several network simulator have been proposed in the literature
- However, most of them don't natively provide models for energy source and energy harvester

Related Work

- Energy aware network simulators have been proposed in the literature
- Broadly classified according to the support for energy harvesting

Related Work - Without Energy Harvesting

- WSNsim [1] (Jun. 2009)
  - One of the first simulators to include a set of flexible and extensible hardware and environment models for energy-aware simulations
  - Not available to the research community
- Energy model for OMNeT++ [2] (Jul. 2009)
  - Evaluation of the energy consumption and network lifetime of sensor networks
  - Energy consumption of the radio transceiver and the CPU
- ns-3 Energy Framework [3] (Mar. 2011)
  - Adds support to ns-3 to devise simulations that include the energy consumption of the communication network
  - Defines the concepts of energy source and device energy model

Related Work - With Energy Harvesting

- PASES [5] (Sep. 2013)
  - Standalone, flexible and extensible design space exploration framework
  - Accurate analysis of the performance and energy consumption of WSNs
  - Requires detailed power models of the node architecture
- GreenCastalia [4] (Oct. 2013)
  - Energy harvesting framework for the Castalia simulator
  - Heterogeneous harvesting and energy source capabilities
- SensEH [6] (May 2014)
  - Complete framework for the simulation and emulation of WSNs with energy harvesting capabilities
  - Relies heavily on the architecture of wireless sensor nodes, thus not being suitable for generic network simulations

Related Work - Summary

- Do not include a model for an energy harvester
- Standalone and proprietary solutions
- Target a specific network architecture (WSN)

Design Goals

- Generic simulation framework
- Extensive and easy to use set of tools
- Modular structure that is easy to extend with new implementations

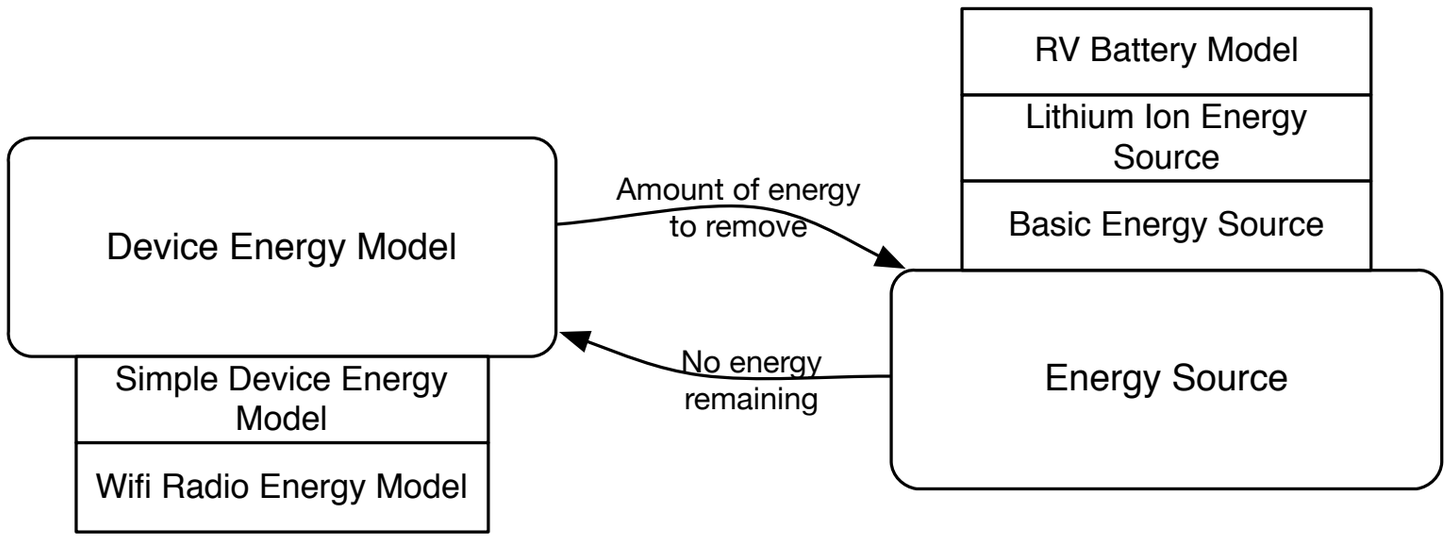
Network Simulator 3 (ns-3)

- Discrete event network simulator
- Open source (GNU GPLv2 license)
- Modular structure
  - Solid simulation core
  - Wide range of models of real world objects, protocols and devices
- Large community of users and developers
- Website: http://www.nsnam.org/

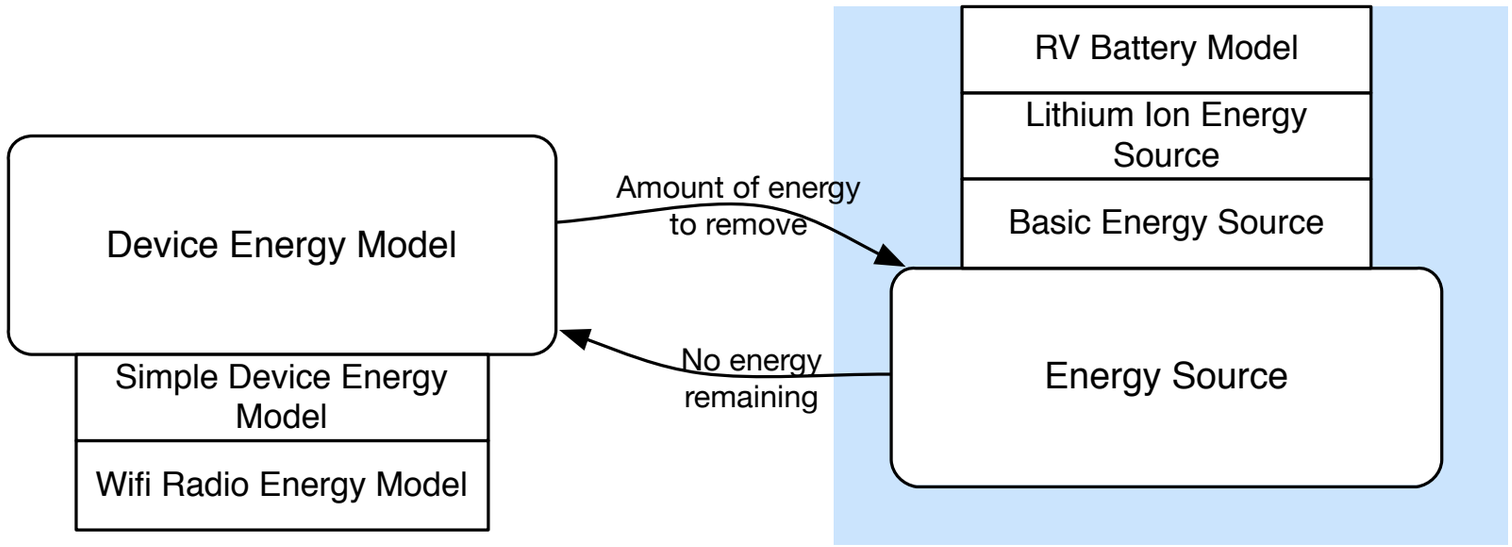
ns-3 Energy Framework

- Included in ns-3.9 released in Aug. 2010
- Allows users to
  - Simulate the energy consumption at a node
  - Determine the overall network lifetime under specific conditions
- The framework defines
  - The concepts of
    - Energy source
    - Device energy model
  - Several methods that provide different types of energy information (e.g., residual energy, current load, etc.) to other ns-3 objects

ns-3 Energy Framework

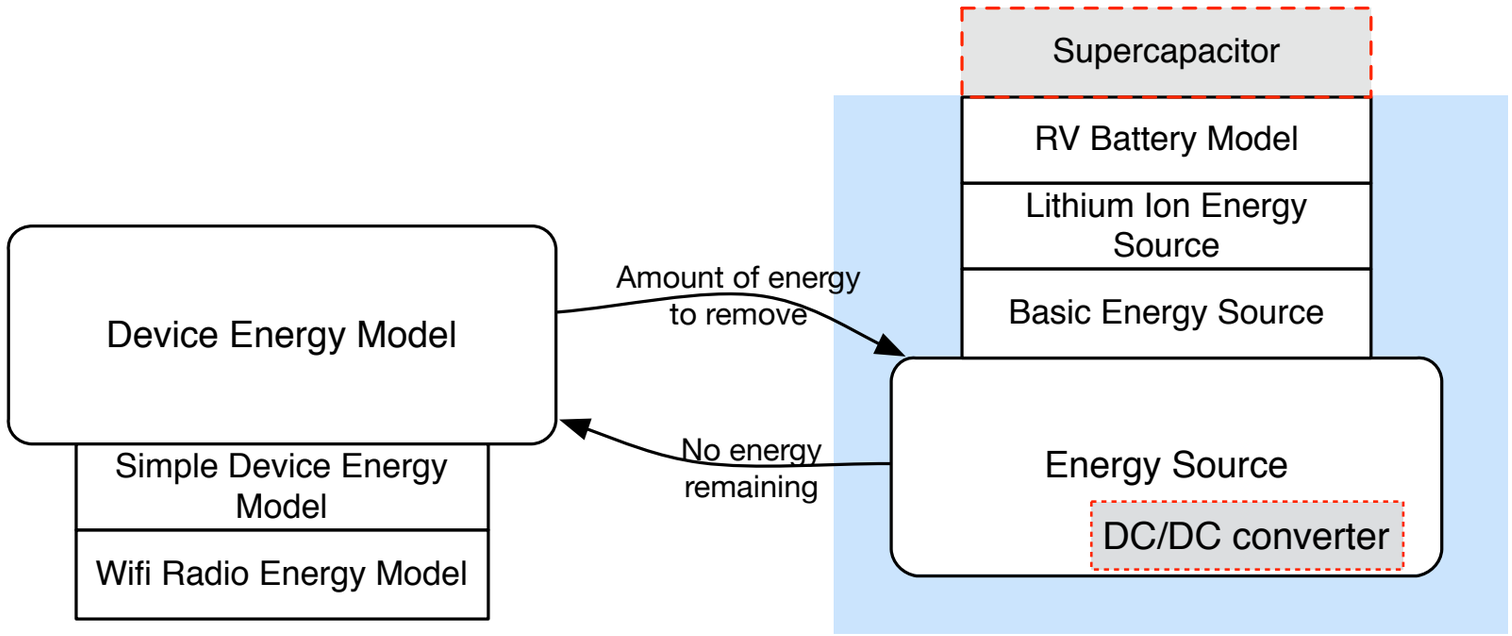


Energy Source



- Stores, and provide to the node, the energy required to perform the different operations
- Different characteristics
  - Maximum energy, voltage, charge-discharge patterns, lifetime, etc…

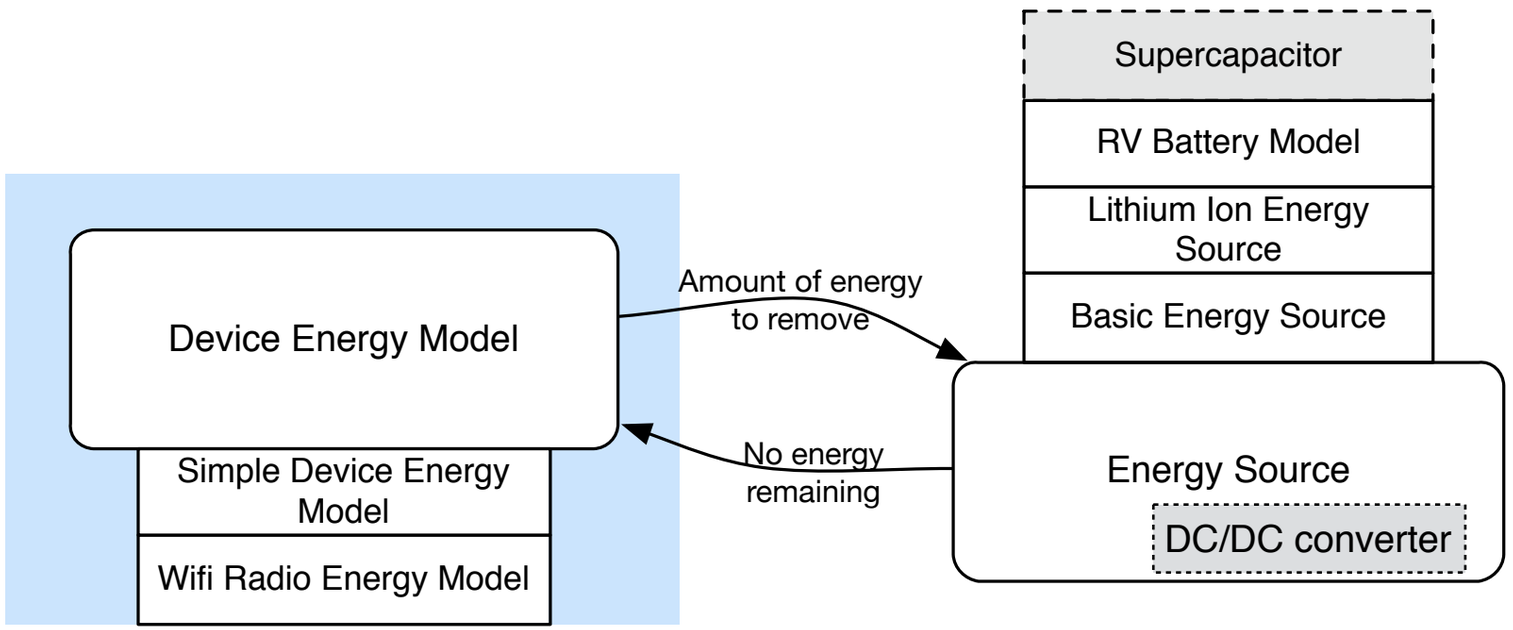
Energy Source



- Our contributions:
  - **Supercapacitor**: models the supercapacitor as an RC network
  - **DC-DC converter**: simple model with a user customizable efficiency

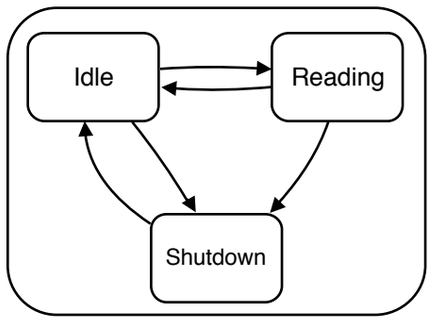
$$I_{\mathrm{s}} = \frac{V_{\mathrm{o}}}{V_{\mathrm{s}}} \frac{I_{\mathrm{load}}}{\eta}$$

Device Energy Model

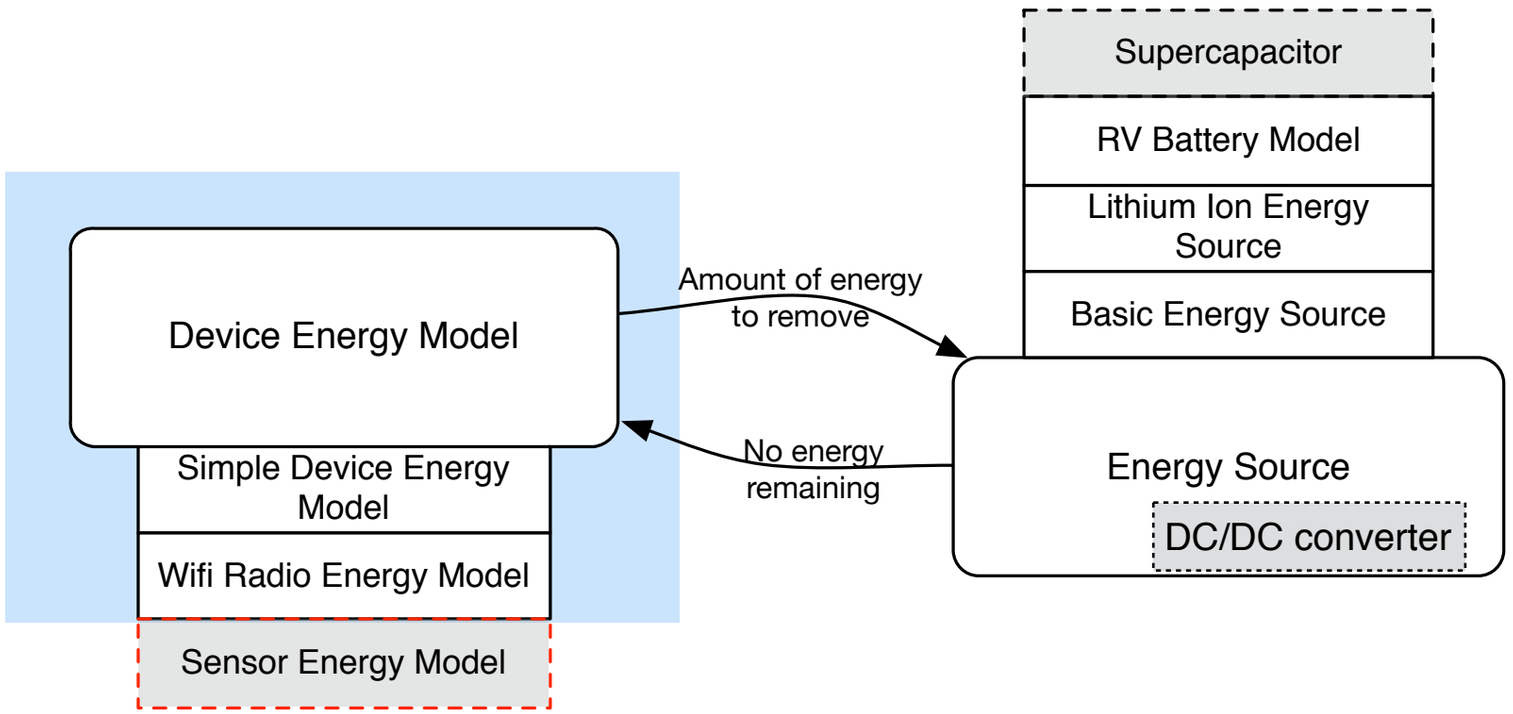


- Describes the amount of energy required to power a certain device connected to the node
- Each device energy model is connected to
  - The actual device → determines the energy consumption according to a state-based model
  - The energy source → decreases its residual energy and notifies the device in case of energy depletion

Device Energy Model

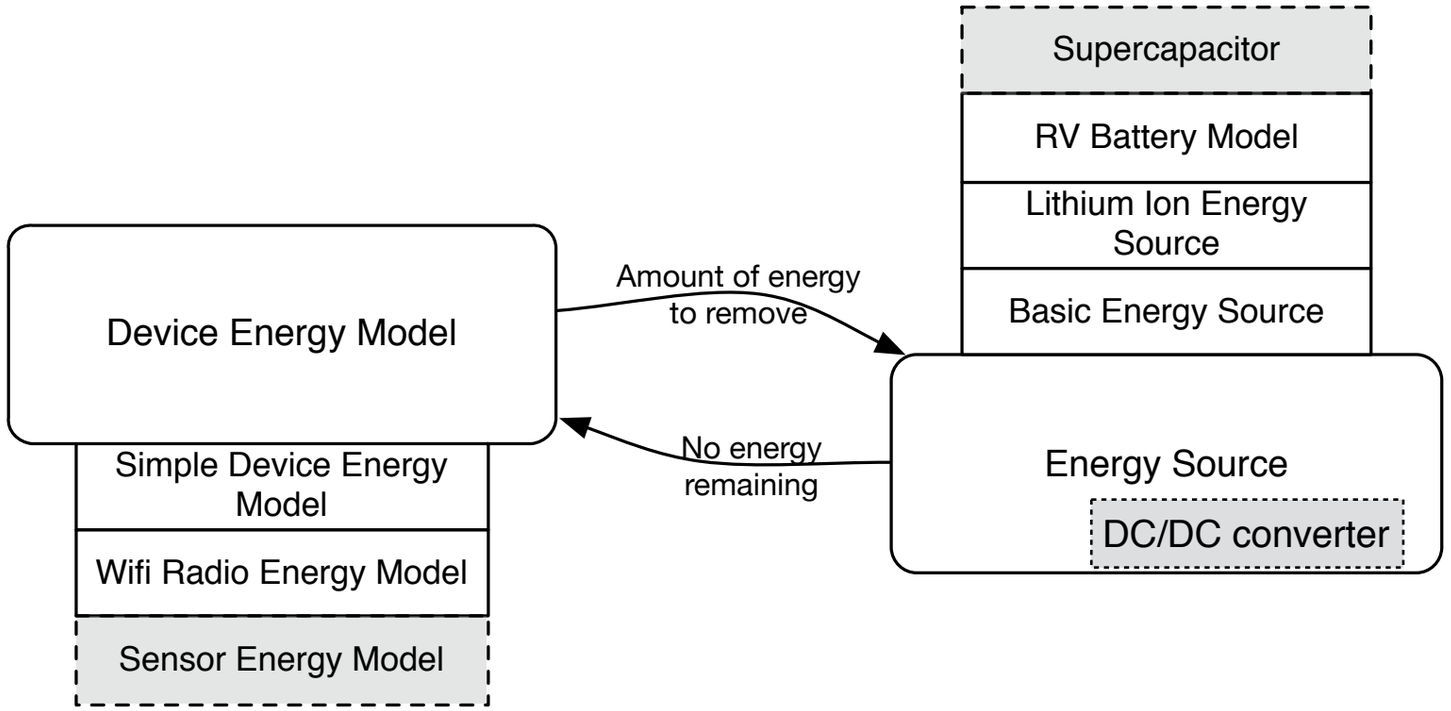


Sensor

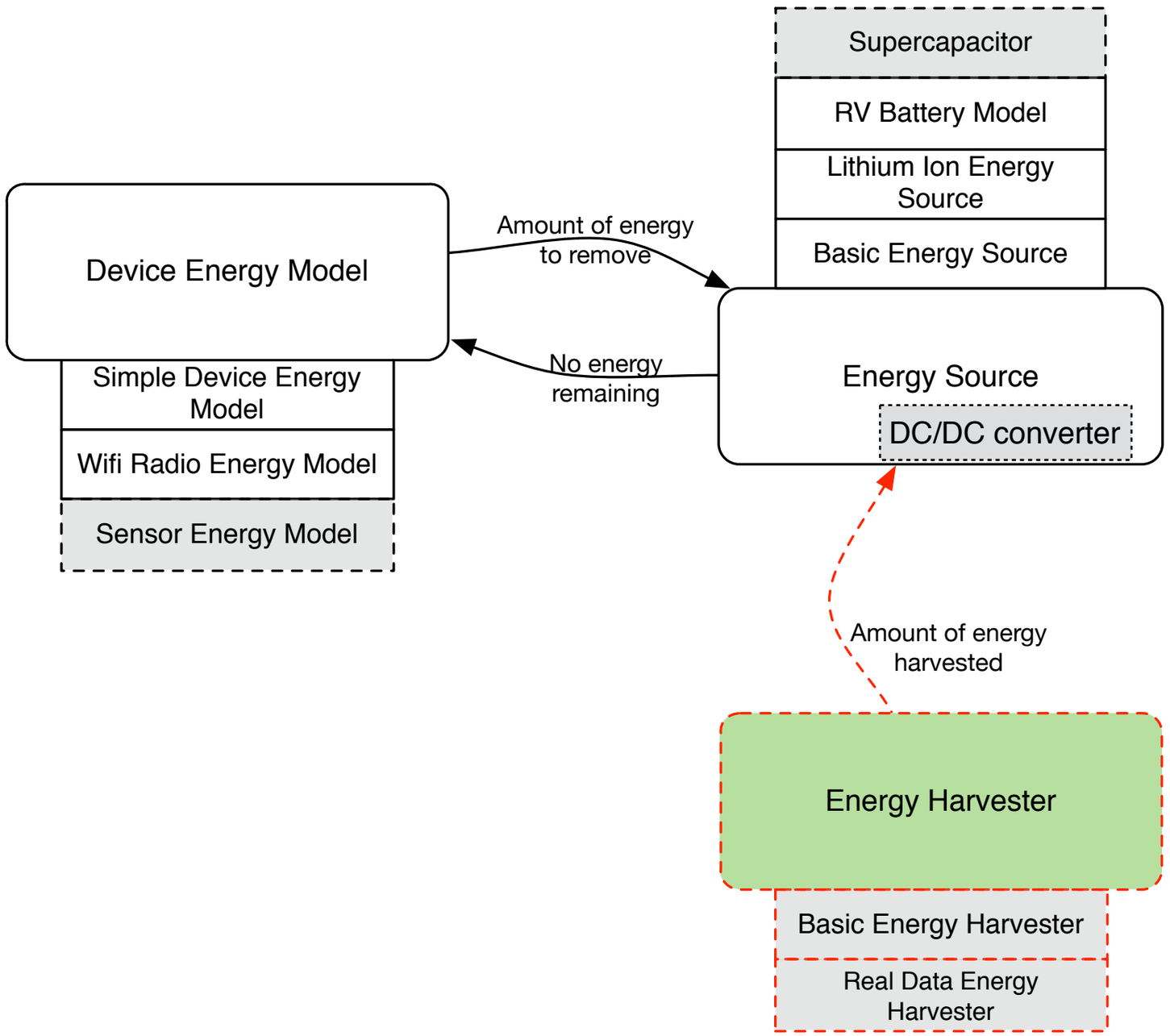


- Our contributions:
  - Sensor Energy Model
    - Generic sensor with 3 states defined as shutdown, idle and reading

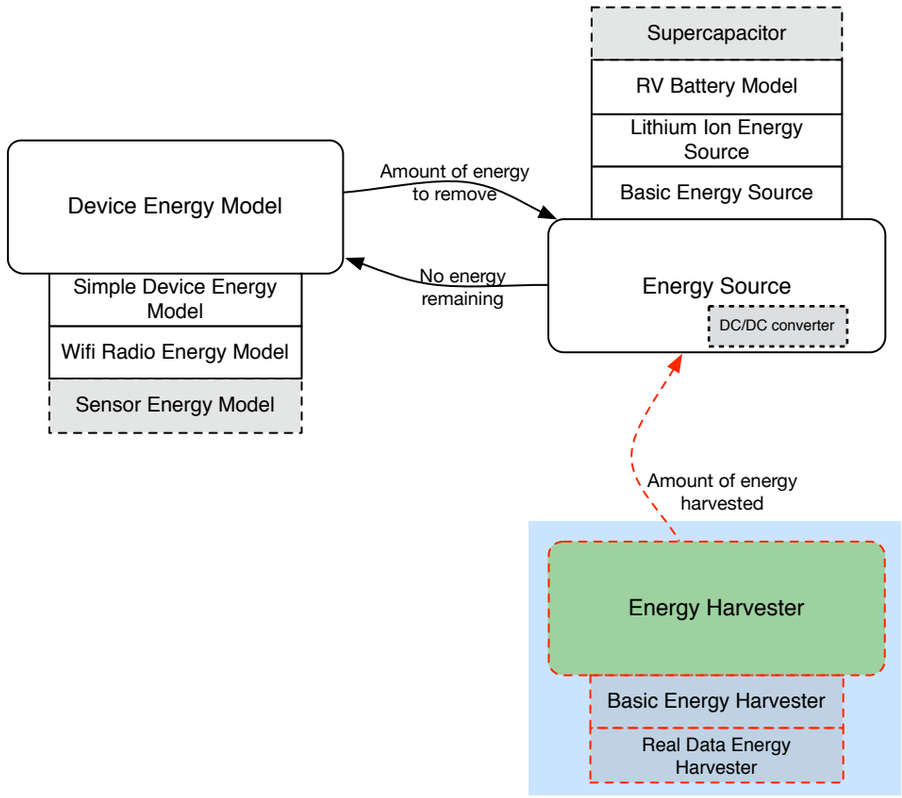
ns-3 Energy Framework



ns-3 Energy Harvesting Framework

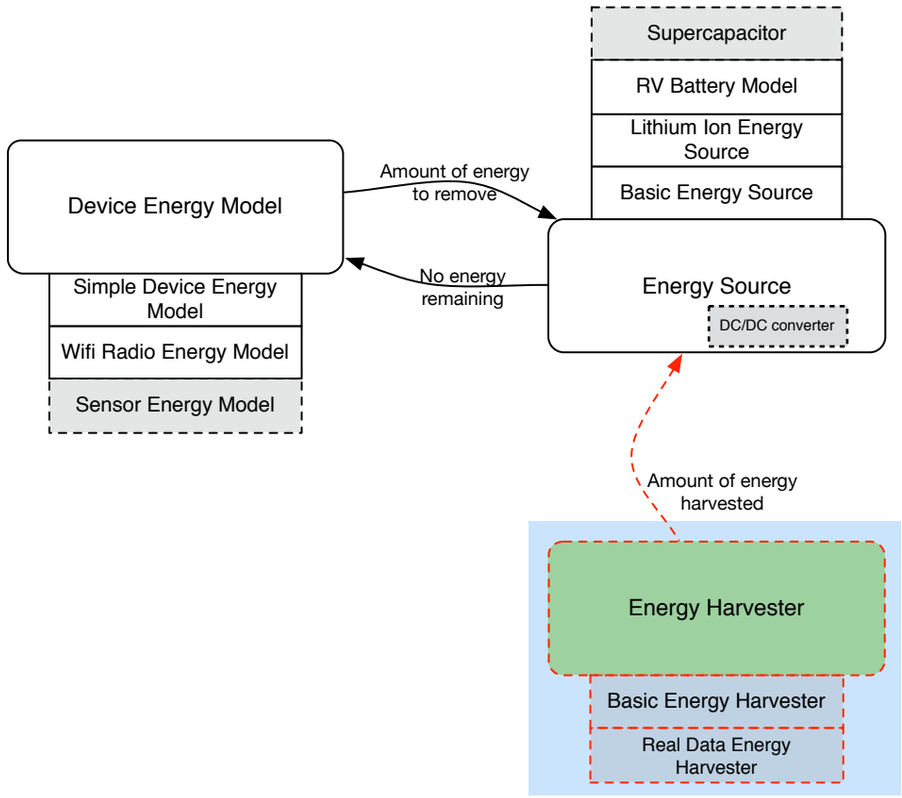


Energy Harvester



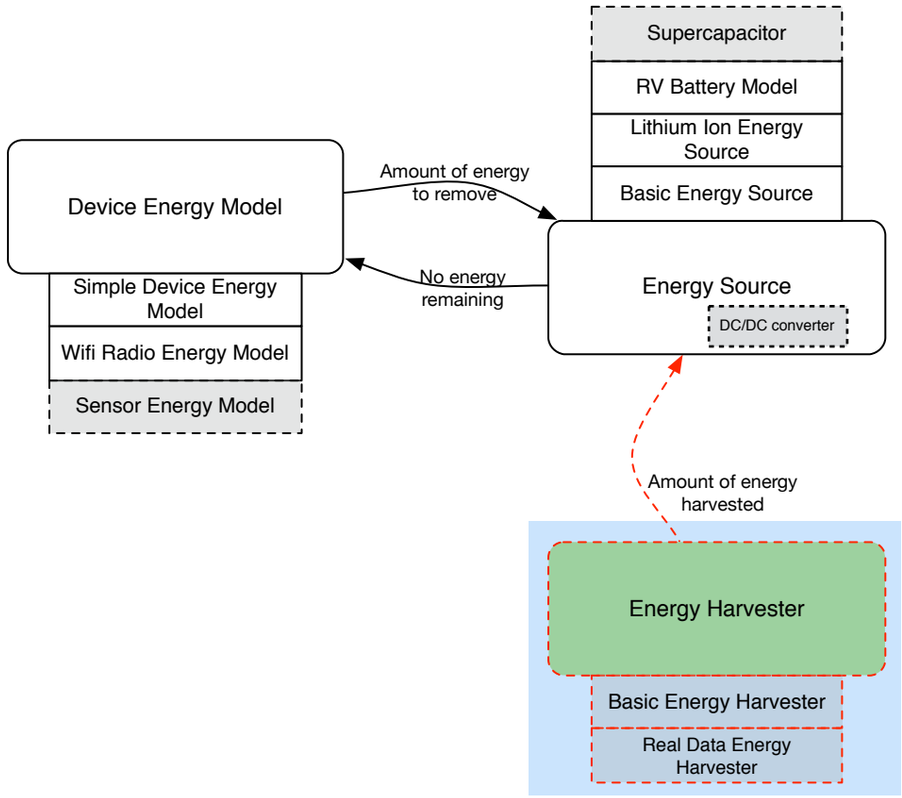
- Harvest energy from the environment and recharge the energy source to which it is connected
  - Includes the complete implementation of the actual energy harvesting device (e.g., a solar panel) and the environment (e.g., the solar radiation)

Energy Harvester



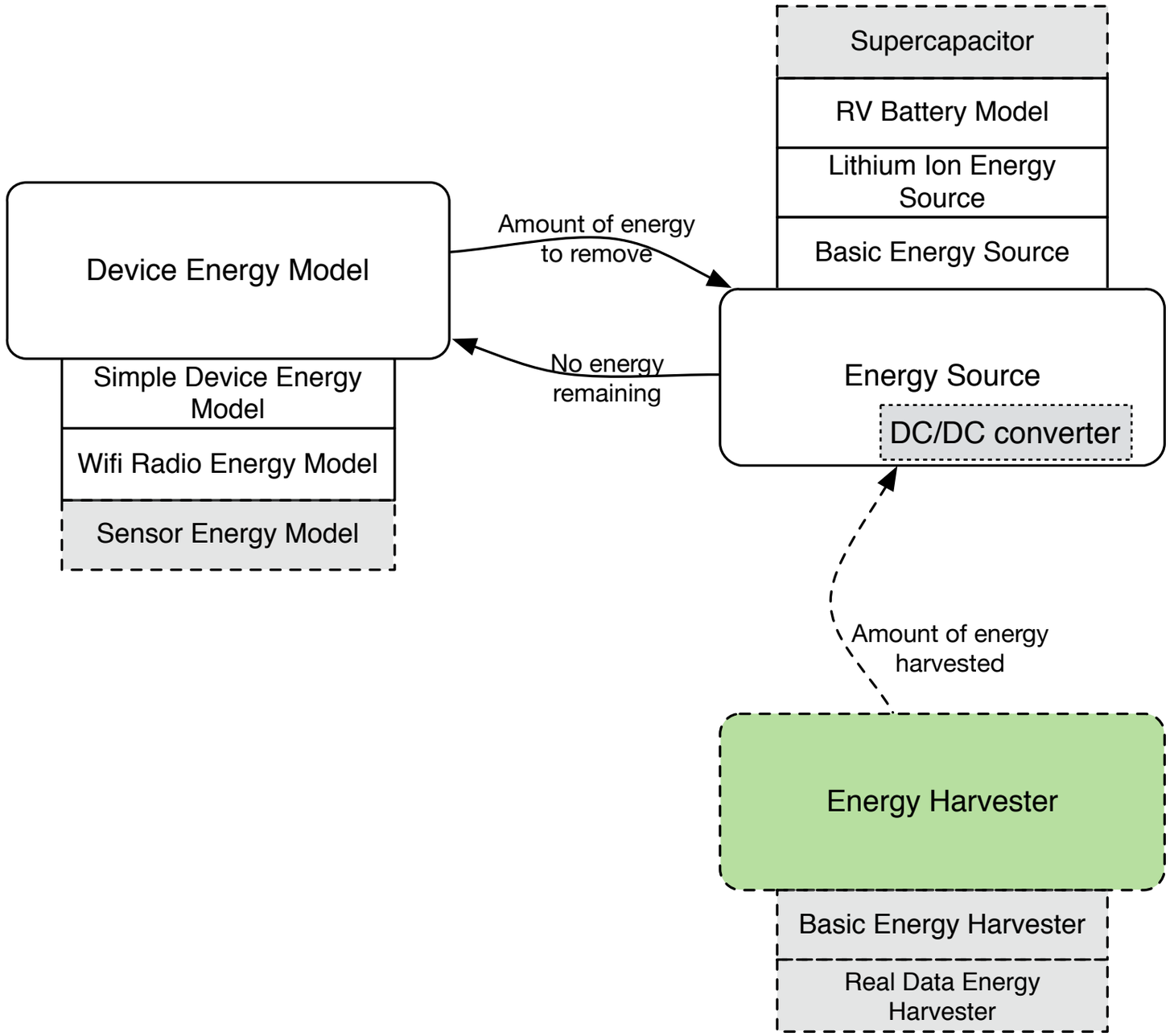
- Default interface
- Implementations
  - **Basic Energy Harvester**: a simple model in which the amount of power provided by the harvester varies over time according to a customizable generic random variable and time update intervals
  - **Real Data Energy Harvester**: the amount of power provided by the harvester is defined in a user customizable dataset of real measurements

Energy Harvester

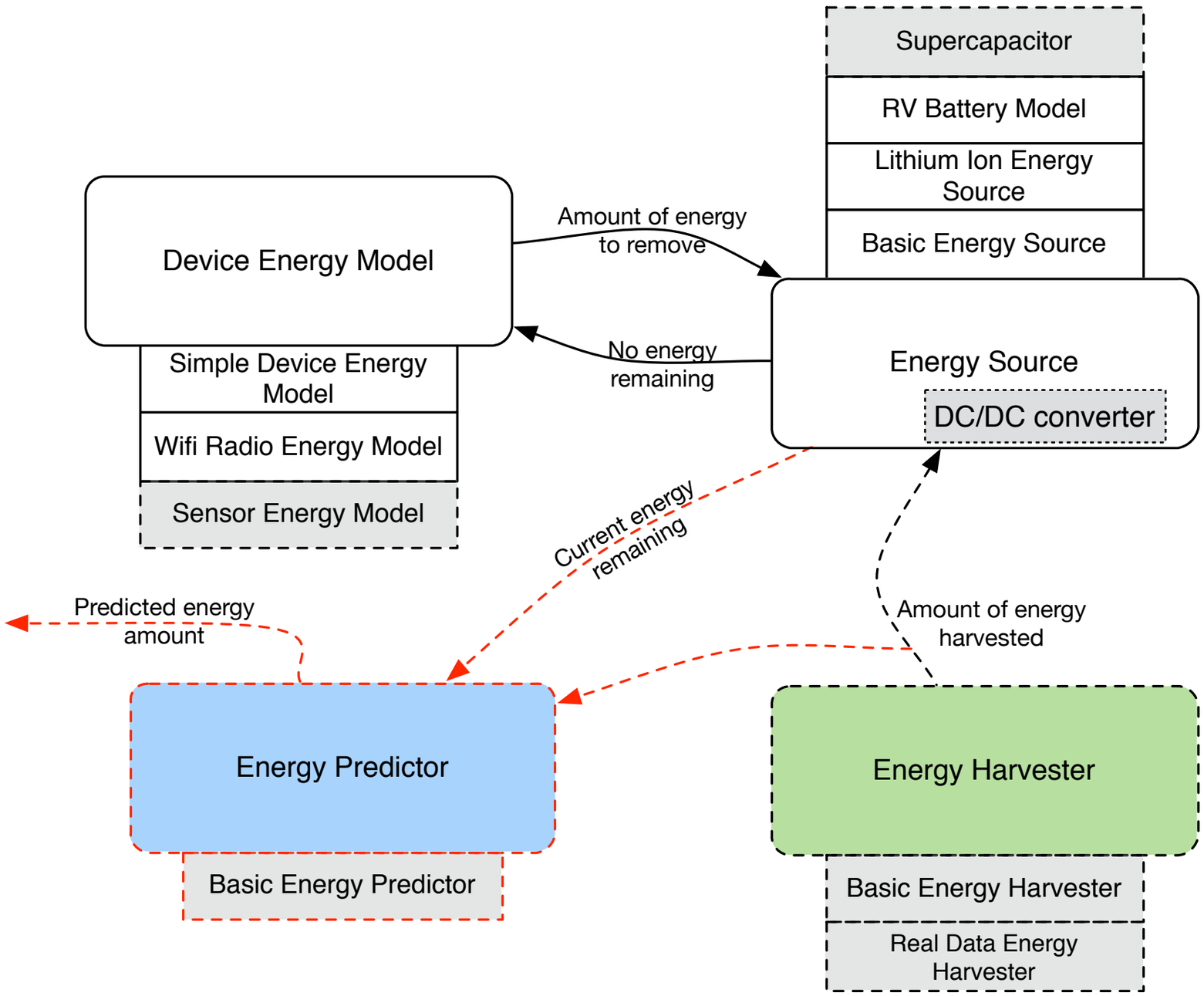


- Included in ns-3.21 (released in Sep. 2014)

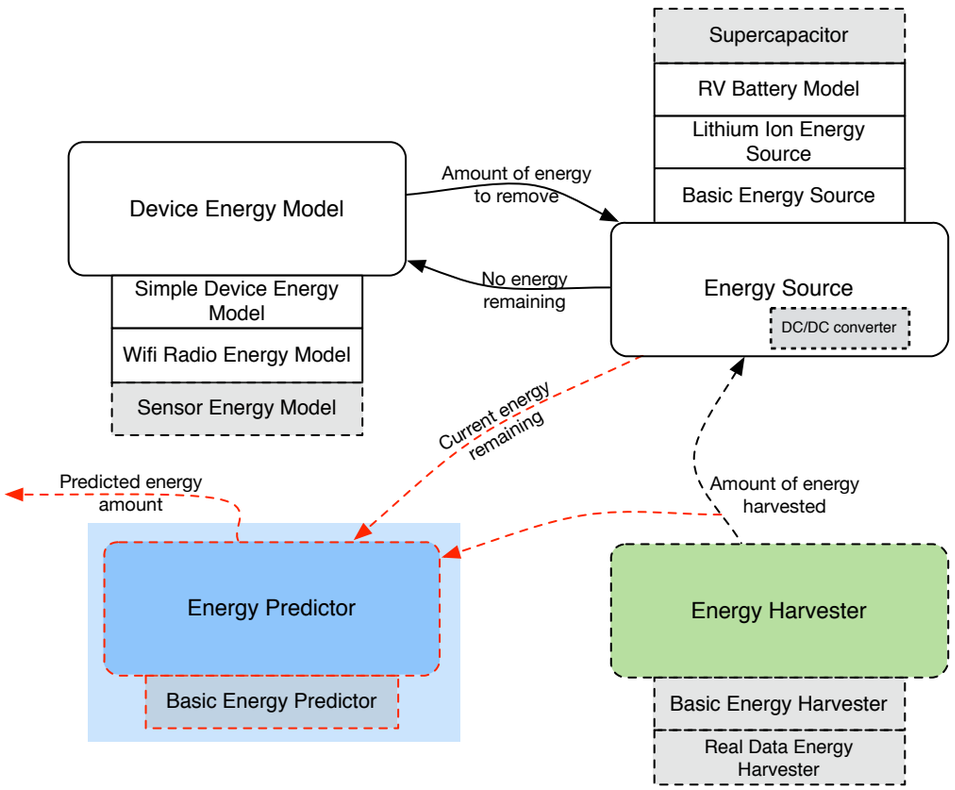
ns-3 Energy Harvesting Framework



ns-3 Energy Harvesting Framework

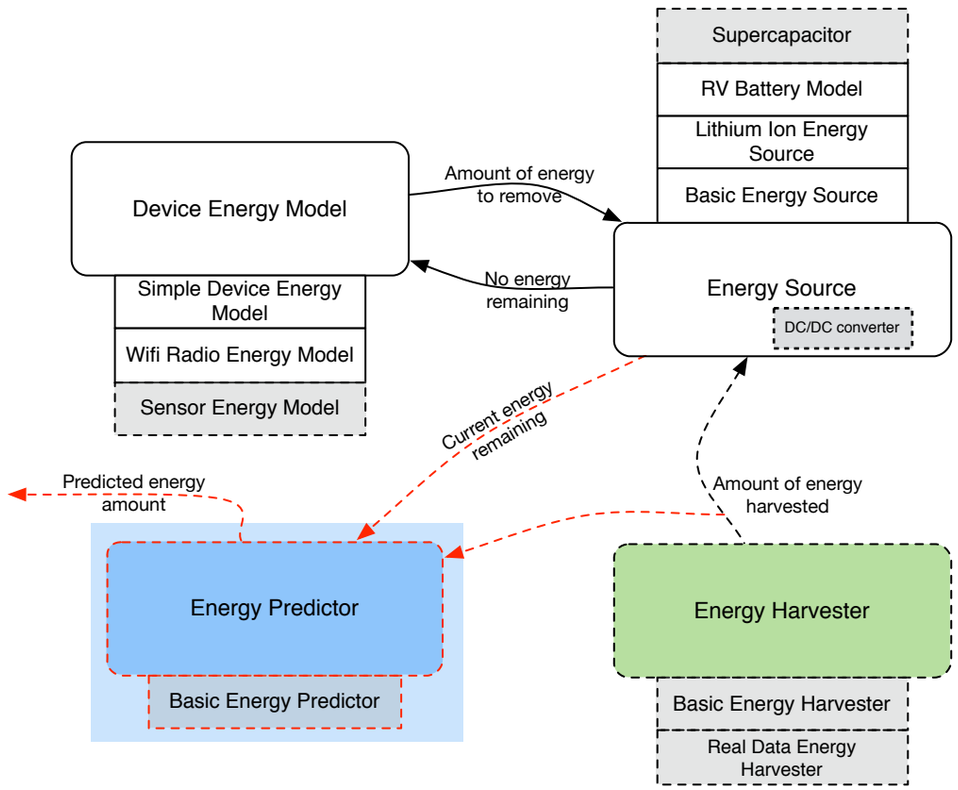


Energy Predictor



- Gathers information from the energy source and harvester and use this information to predict the amount of energy that will be available in the future
- The predicted value can be used at other layers of the protocol stack to better utilize the available energy

Energy Predictor



- Default interface
- Implementation
  - **Basic Energy Predictor**: implementation of Pro-Energy [7]. The predicted energy is computed as

$$\hat{E}_{t+1} = \alpha C_t + (1-\alpha) E^d_{t+1}$$

Harvested energy

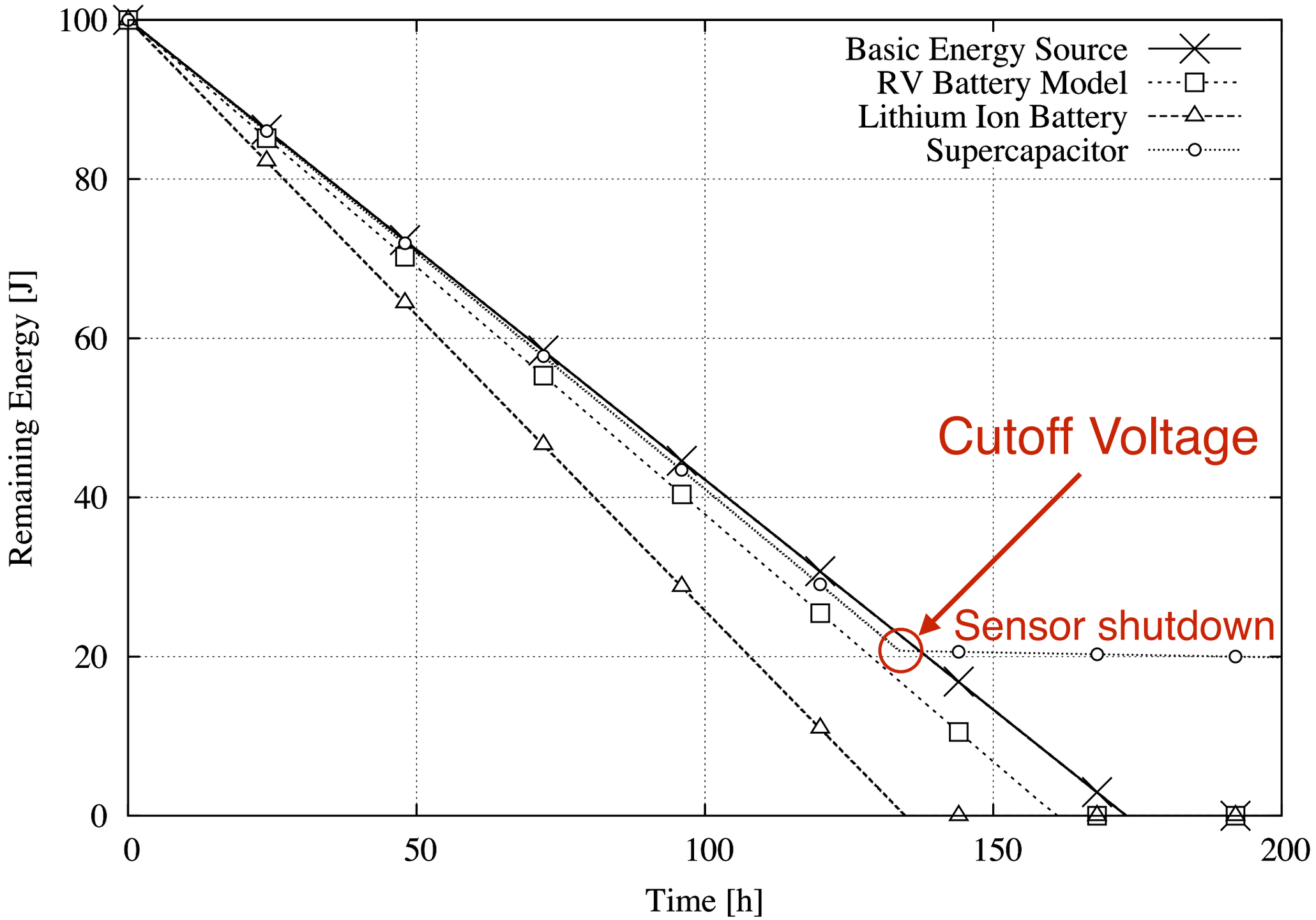
Stored energy profile

weighting parameter

Example of Results

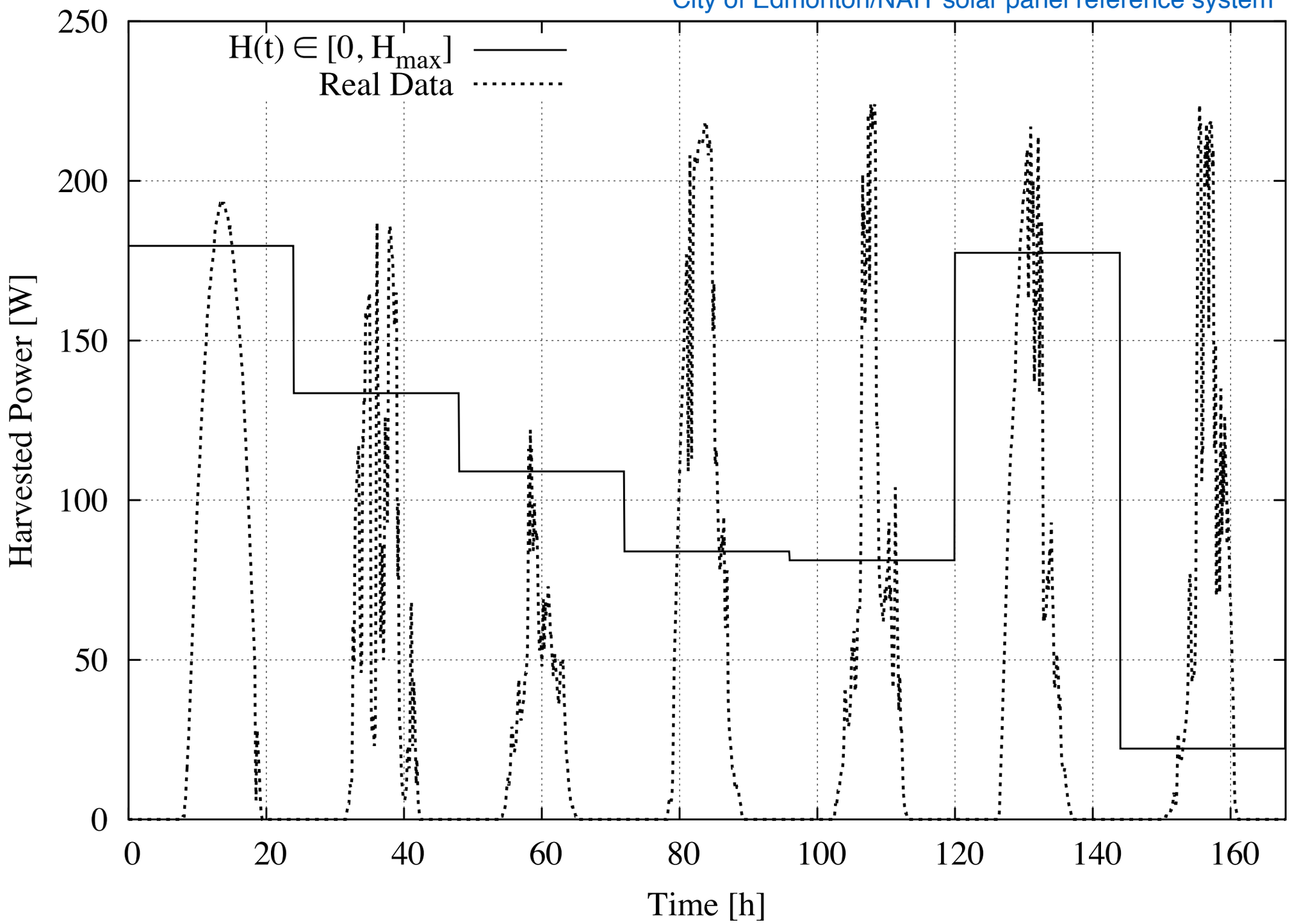
- Operational Voltage 3.3V
- $\eta = 0.9$
- Cutoff Voltage 1.0V
- Sensor Energy Model
  - Reading: 25 mA
  - Idle: 7 µA
  - Shutdown: 1 µA
- The sensor performs periodic readings every 10 minutes

Simulation Results - Energy Source

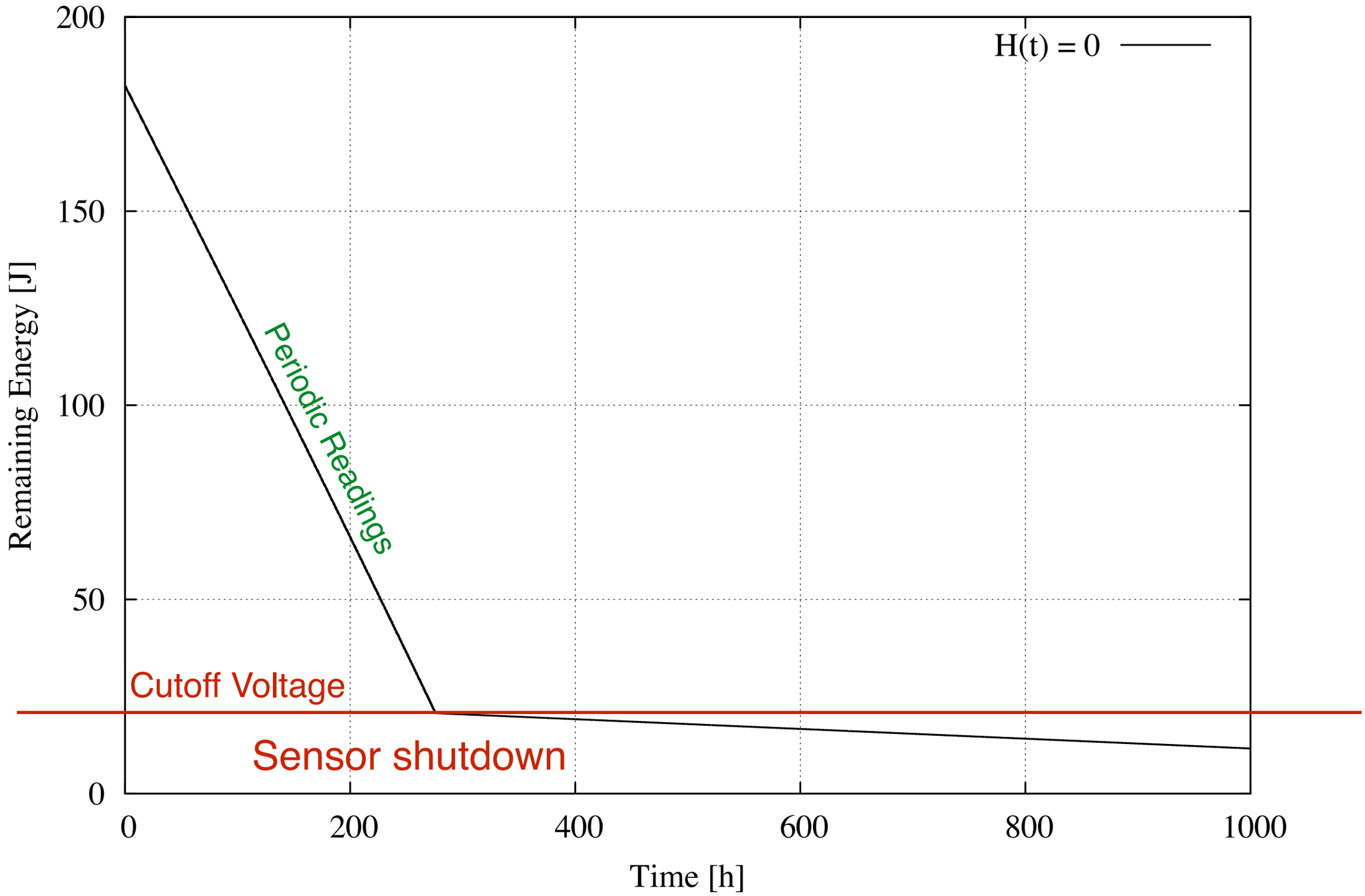


Simulation Results - Energy Harvester

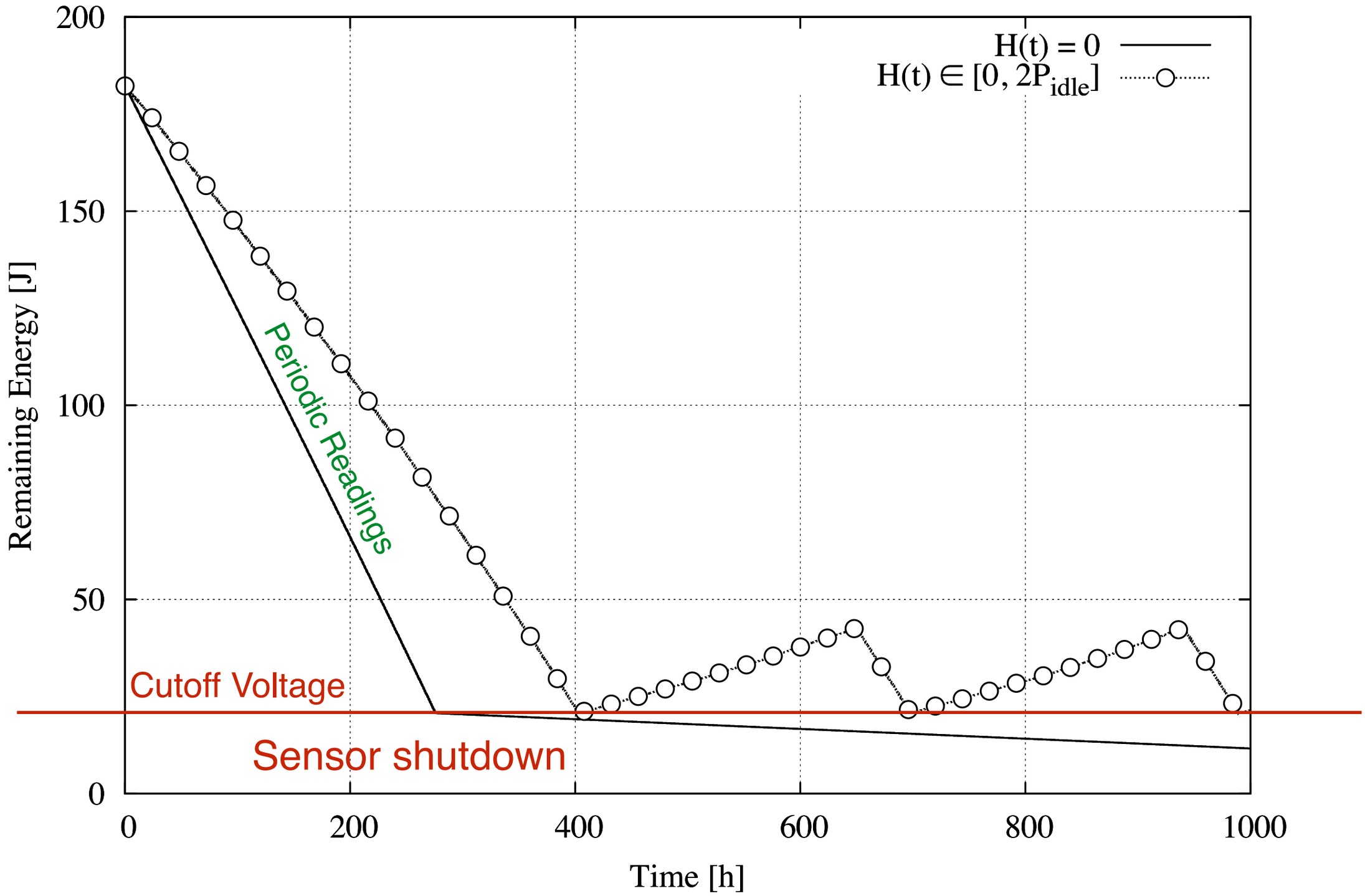
City of Edmonton/NAIT solar panel reference system



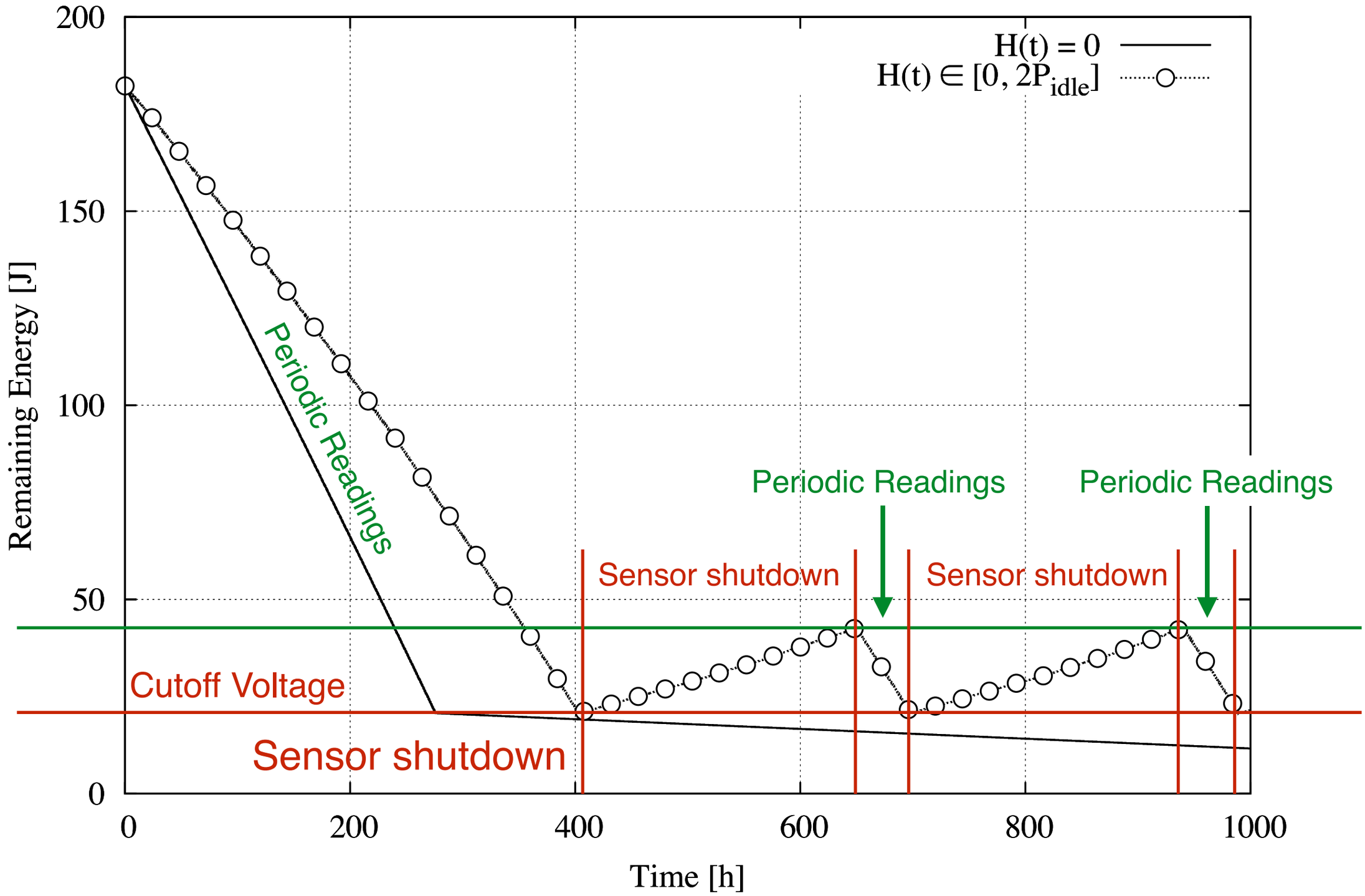
Simulation Results - Sensing



Simulation Results - Sensing



Simulation Results - Sensing



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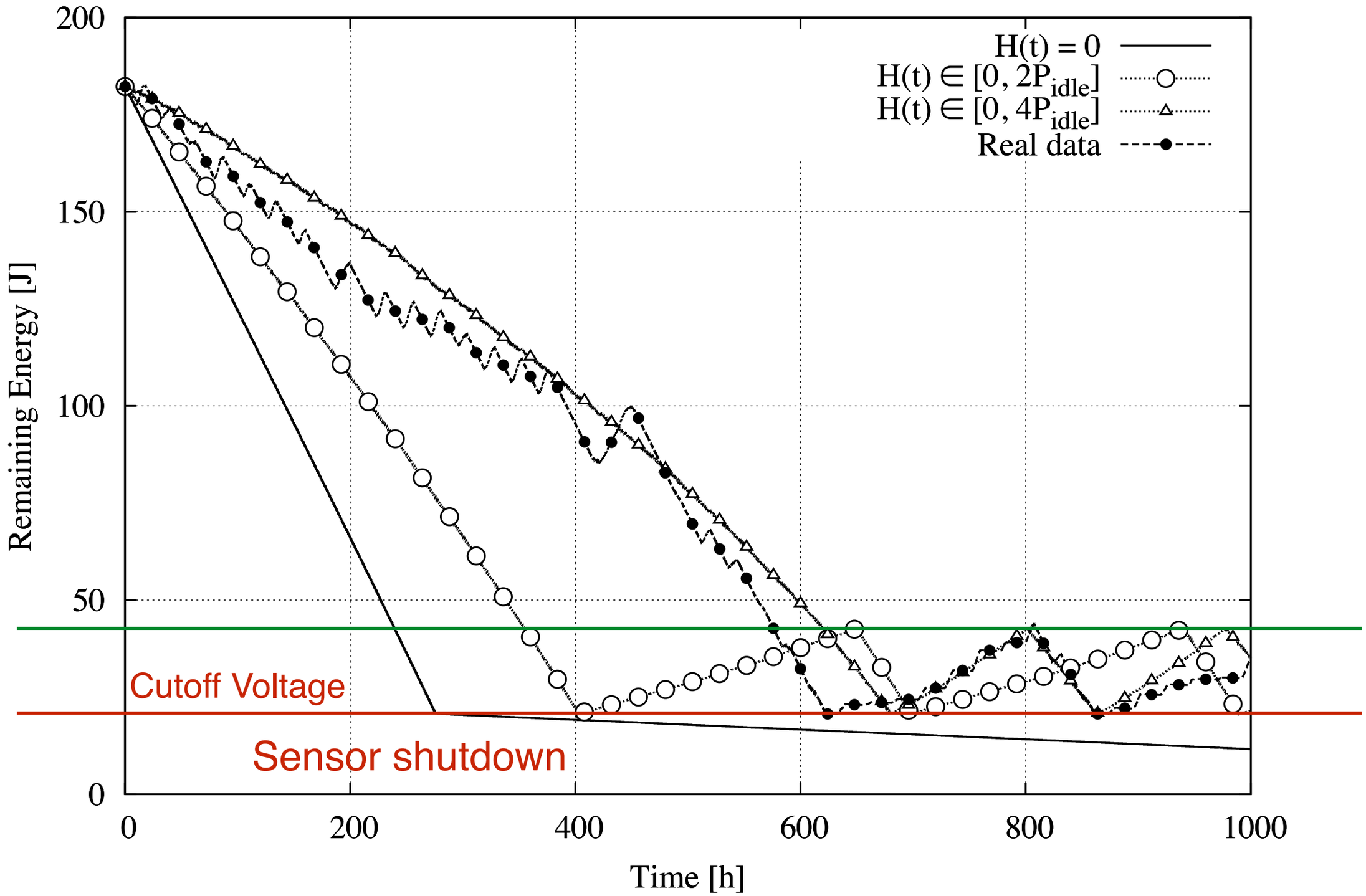
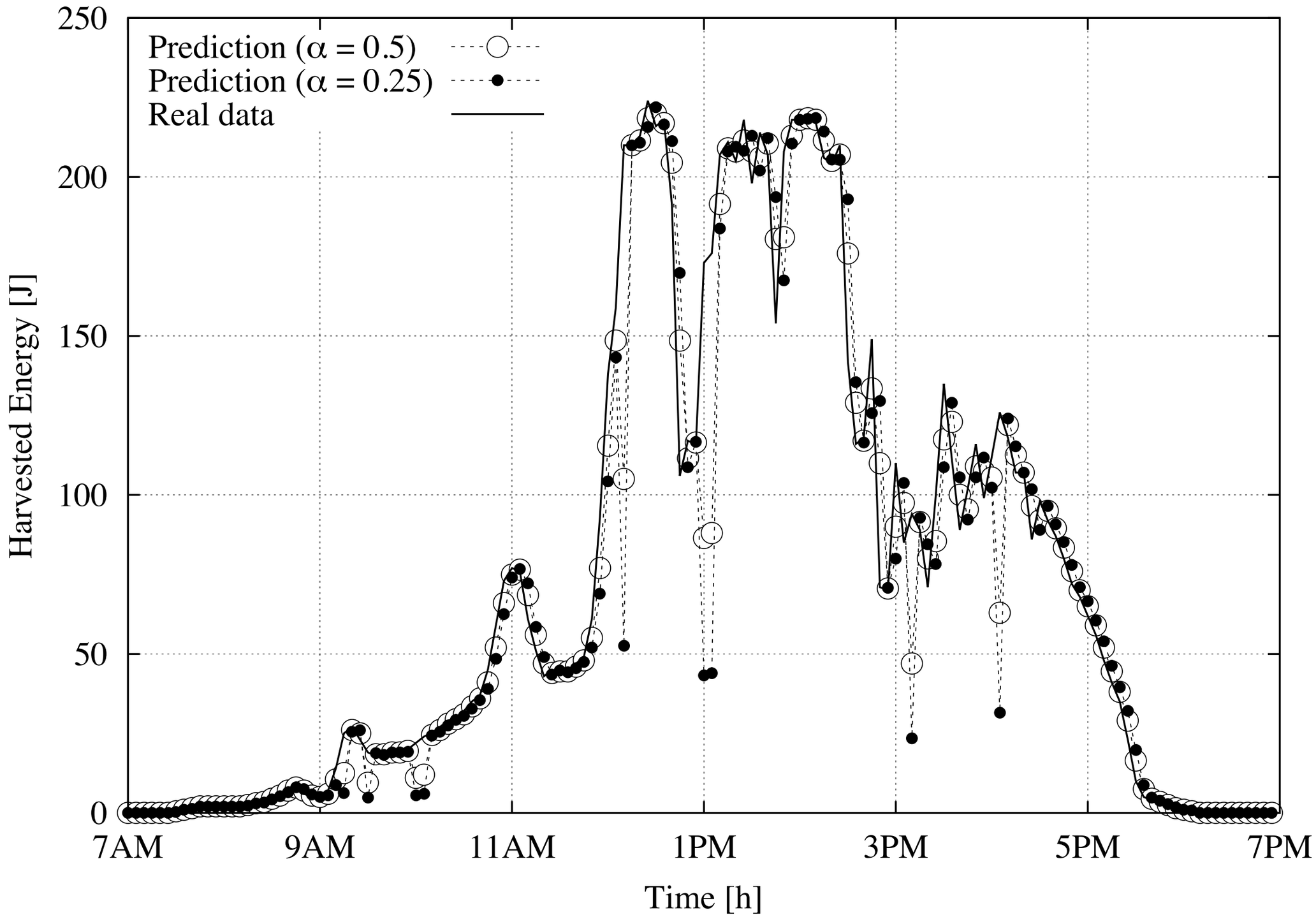


Simulation Results - Energy Predictor



Conclusions

- We proposed an extension to the ns-3 energy framework
  - Added the concept of Energy Harvester and Energy Predictor
  - Implementation of new models
    - Supercapacitor
    - Sensor Energy Model
- We showed the impact of the different components on the system performance through some examples of simulation results
- As a future work, we plan to further extend the set of implementations and to provide an application that links them together

References

- [1] G. V. Merrett, N. M. White, N. R. Harris, and B. M. Al-Hashimi, "*Energy-aware simulation for wireless sensor networks,*" in Proc. of IEEE SECON, Rome, Italy, Jun. 2009.
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- [3] H. Wu, S. Nabar, and R. Poovendran, "*An energy framework for the network simulator 3 (ns-3),*" in Proc. of ACM SIMUTools, Barcelona, Spain, Mar. 2011.
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- [7] A. Cammarano, C. Petrioli, and D. Spenza, "*Pro-Energy: a novel energy prediction model for solar and wind energy harvesting wireless sensor networks,*" in Proc. of IEEE MASS, Las Vegas, Nevada, USA, Oct. 2012.

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