Co-Simulating Brightway Life Cycle Assessments with the Functional Mockup Interface

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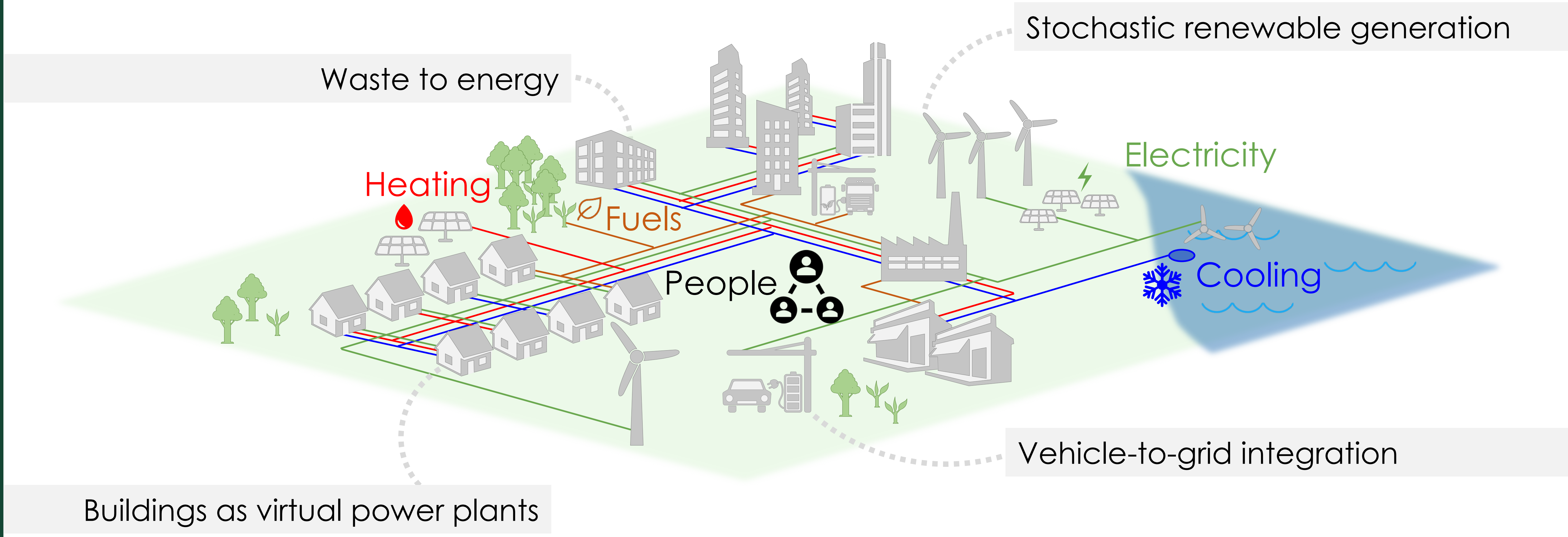
Current Evolution

The built environment is transitioning from **static efficiency** to **dynamic, integrated** systems.



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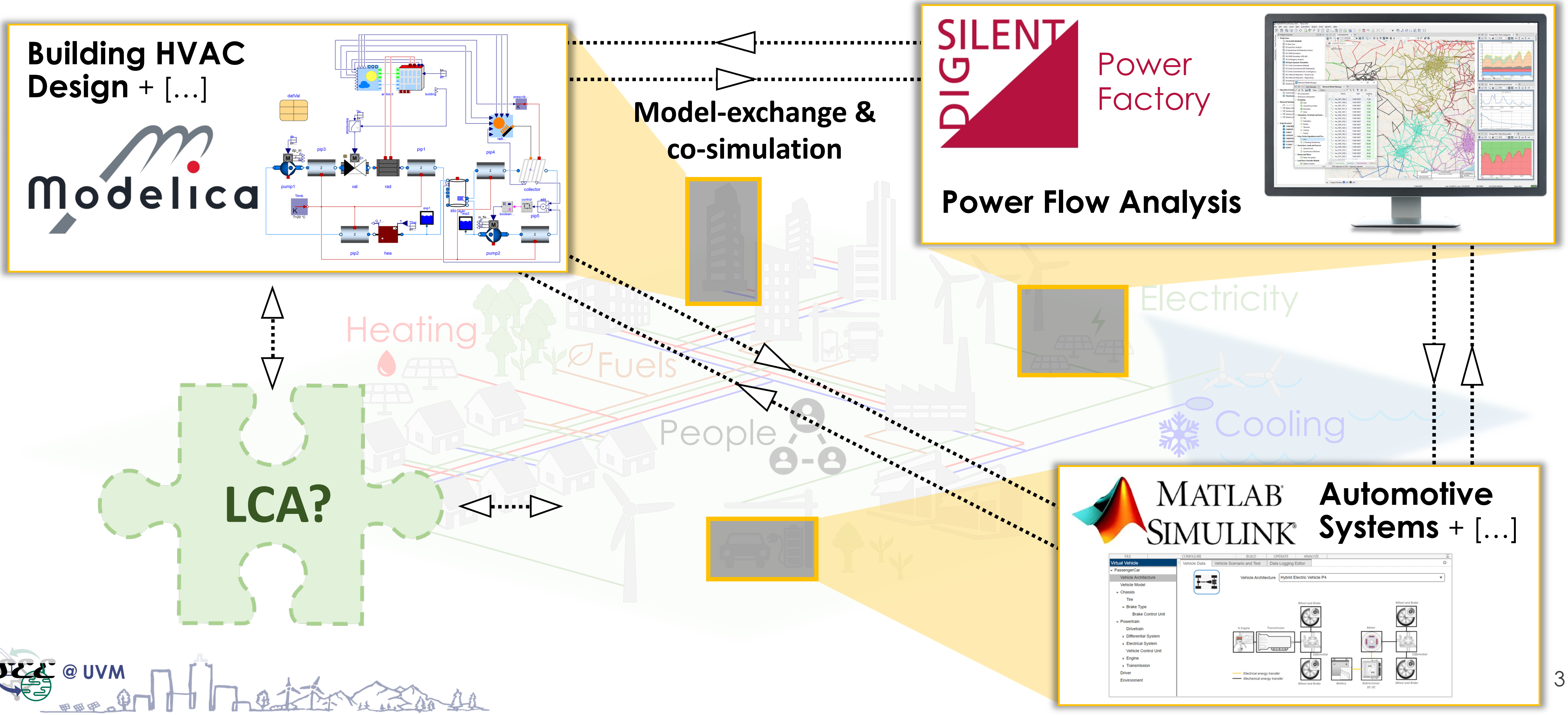
Current Evolution

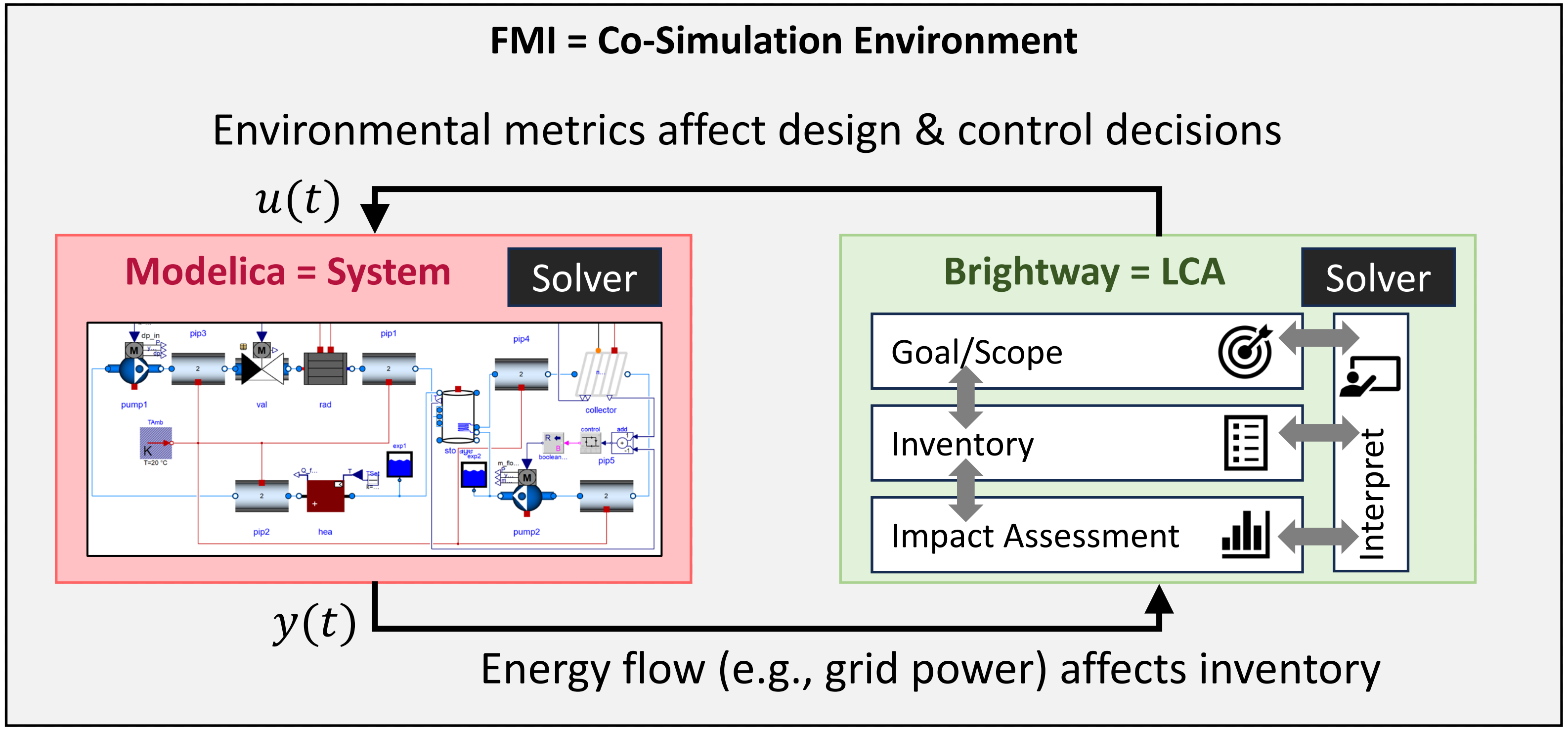
A rich suite of **coupled digital design tools** enable this transition.



Enabling Plug & Play LCAs in System Simulation

Provide a **co-simulation interface and computationally fast models** to couple LCA with dynamic simulation environments.

- Integration pathways through **three open standards**:
  1. Functional Mockup Interface (FMI)
  2. Modelica
  3. Brightway
- Dynamic exchanges



Specific Contribution

A python package

fmlca (v1.0.0)

that links Brightway LCA with the FMI ecosystem.

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What is the Functional Mockup Interface (FMI)?

A **tool-independent**, **free** and **open** standard for **exchanging models** between different simulation tools.

280+ tools

Source: Modelica Association, Project FMI, 2025

Multiple domains

= one FMU (functional mockup unit)

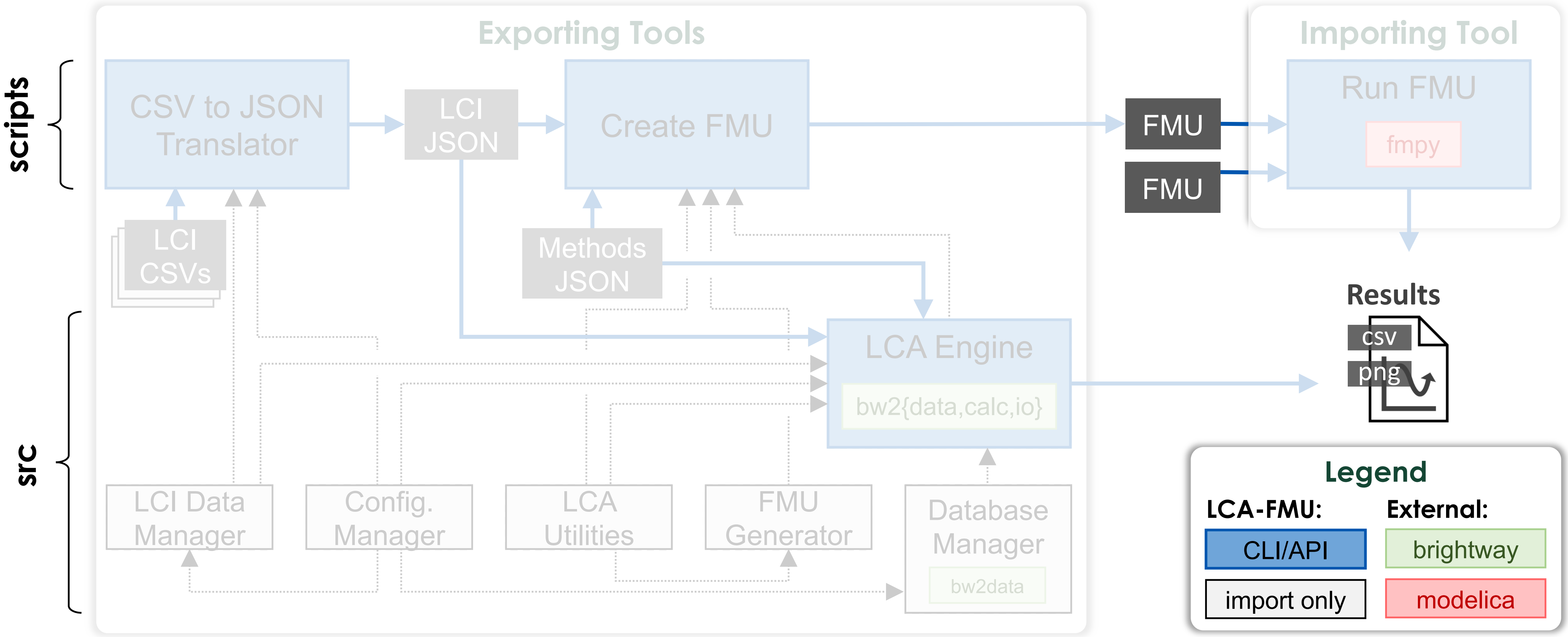
Key features:

- **Containerized** format.
- **Re-use** of models.
- **IP protection** (black box).

FMI is developed by: Modelica Association

fmLCA Workflow Overview

Open-source package for **exporting** LCA-based FMUs and **importing** FMUs for co-simulation.



Focus is on dynamic use-phase energy flows.

Core Features

- **Parameterized single-input single-output** FMUs given as first-order affine surrogate around p_0.
- Two primary export options:
  - **Black-box** (IP protection)
  - **Source code** (internal use)
- Couple **2+ FMUs** in Python/tool of Choice.
- Built around **Ecoinvent** database.

Energy flow rate → LCA FMU → Cumulative impacts (single score)

$$u(t) \rightarrow \boxed{\text{LCA FMU}} \rightarrow y(t)$$

$$y(t) = I_{\text{pro}}(\boldsymbol{p}) + I_{\text{tra}}(\boldsymbol{p}) + \int r_{\text{use}}(\boldsymbol{p})u(t)dt + I_{\text{eol}}(\boldsymbol{p})$$

Parameters: $\boldsymbol{p} = [p_1, \dots, p_n]$ with n unique **LCI.csv** files

Impacts: $I(\boldsymbol{p}) \approx I(\boldsymbol{p}_0) + \sum_{i=1}^{n} s_i \left(p_i - p_{i,0}\right)$

Sensitivities: $s_i = \partial I / \partial p_i | p_0$ (finite difference approx.)

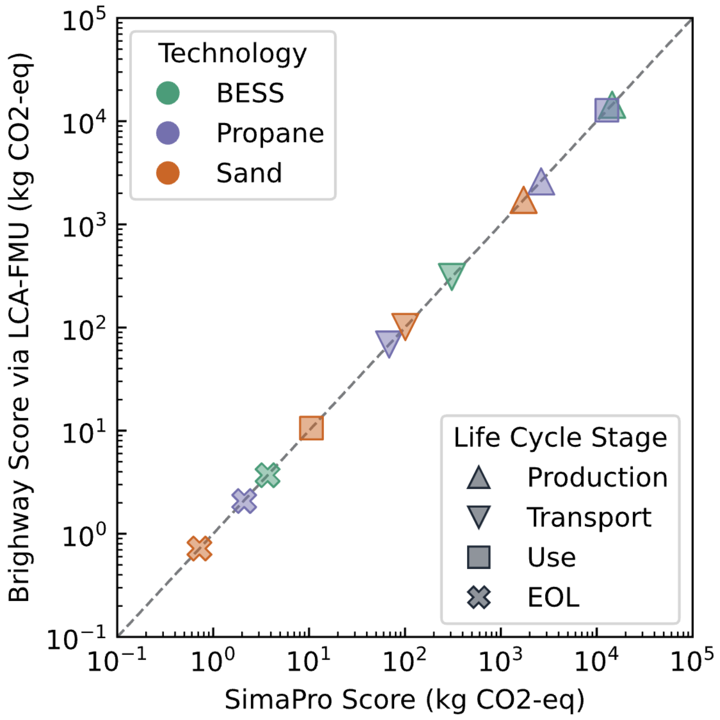
- See fmLCA git repository for more info…
  particularly help **– h** documentation in CLIs:

```
> python scripts/create_fmu.py -h
```

Validation

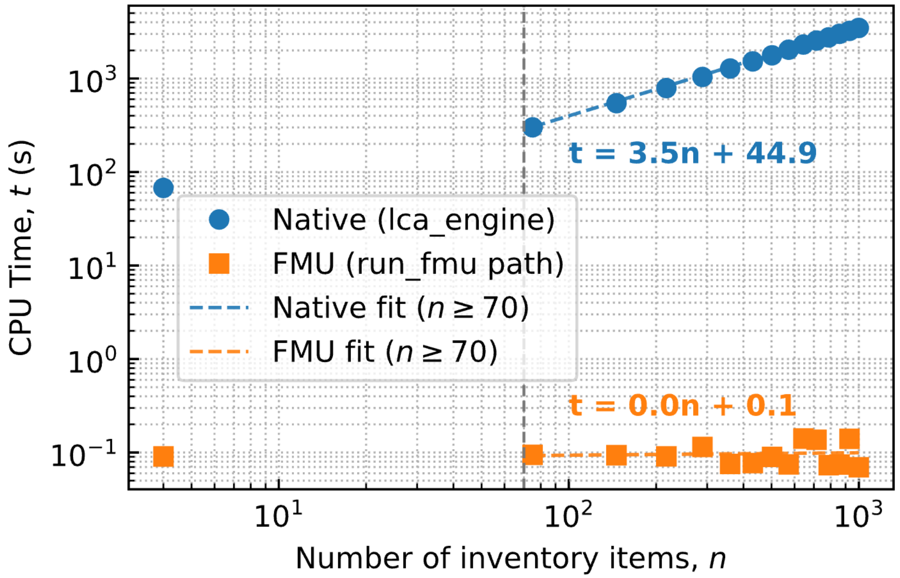
fmLCA Results Match SimaPro

Total **percent difference < 0.14%** for all energy storage systems.



Computing Speed Results

- Creating FMUs: Build time as usual with BW2 with **parameterization $\mathcal{O}(n+1)$**.
- Running FMUs: Pre-compiled FMUs reduce CPU time from **21 minutes to 0.1 seconds** (360 random LCI items).



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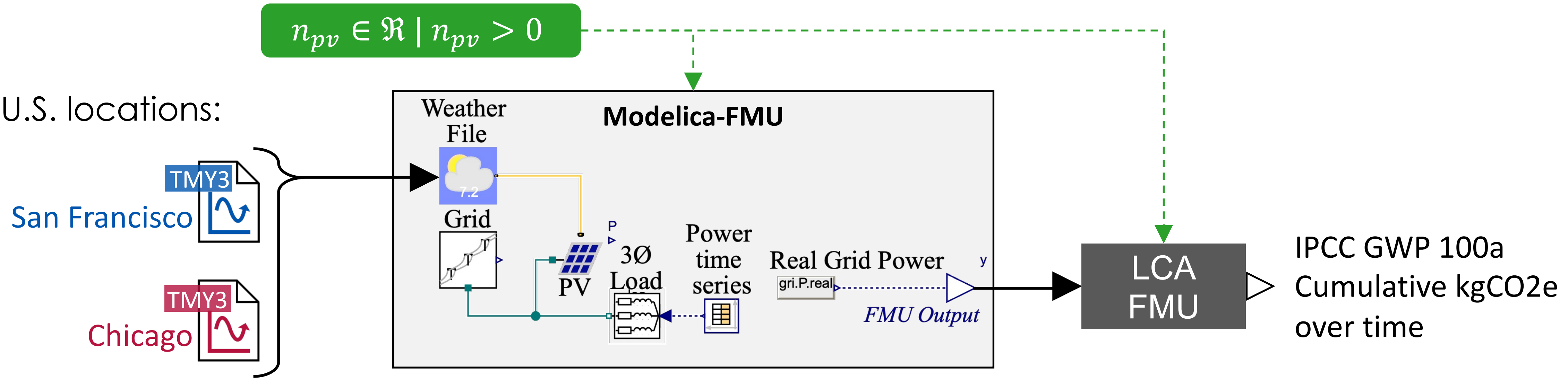
Importing: From FMUs to Co-Simulation Results

Live Jupyter Notebook Demonstration →

Two U.S. locations:



File names in fmu/ directory:

PV_System_WECC.fmu

PvWecc_Ipcc_v1.0.0.fmu

PV_System_MRO.fmu

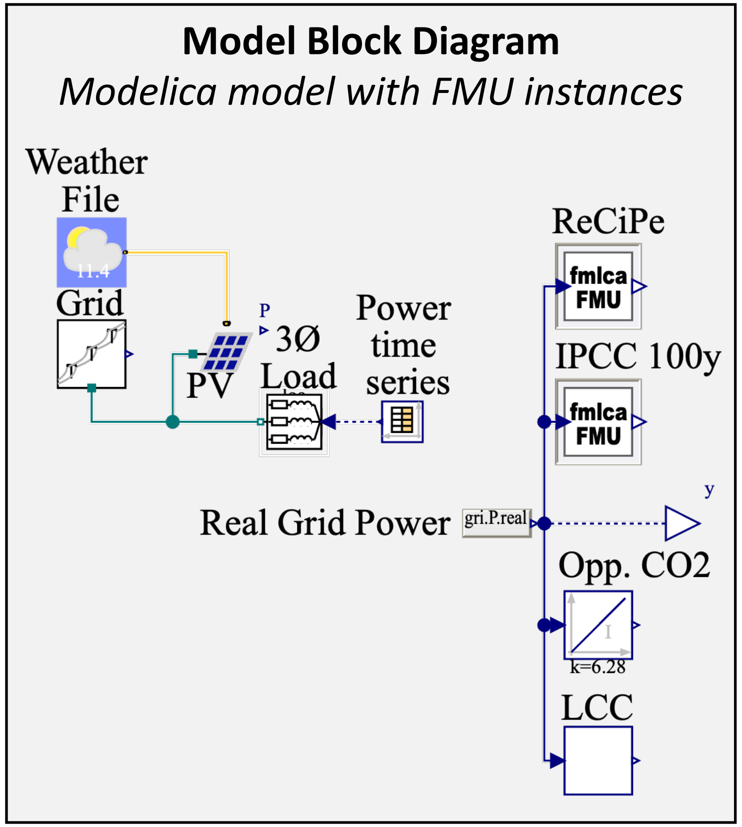
PvMro_Ipcc_v1.0.0.fmu

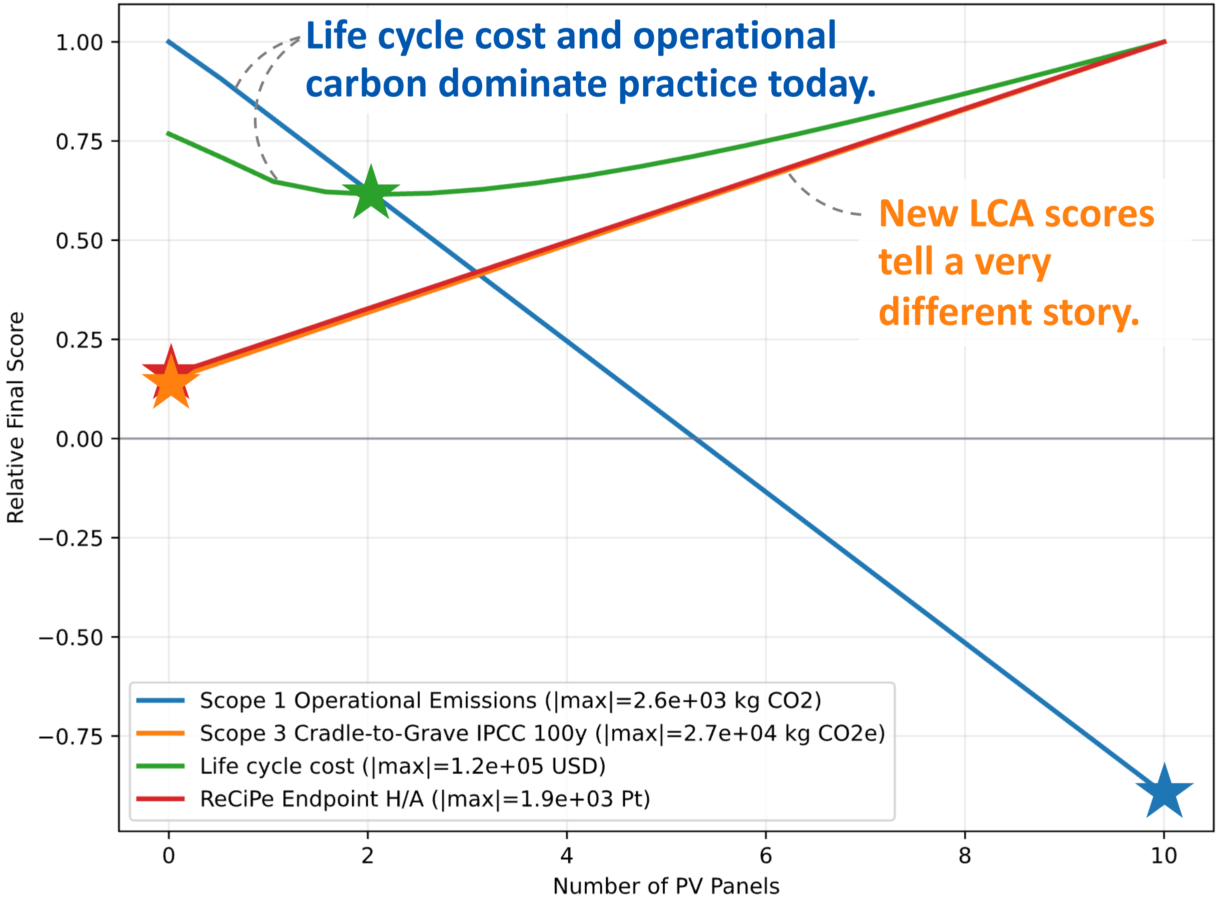
LCI: US-MRO + PV (n_{pv})

LCIA Method: ipcc.json

Expanded Demonstration Case

How does a cradle-to-grave LCA perspective with dynamic energy flows influence system design compared to other performance objectives?





Note! This case is for demonstration only and does not include the necessary scope for energy system design decisions.

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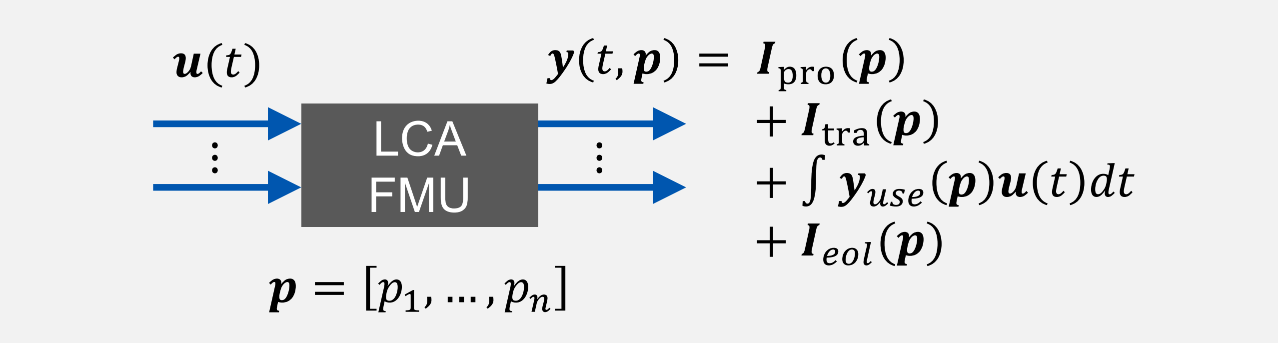
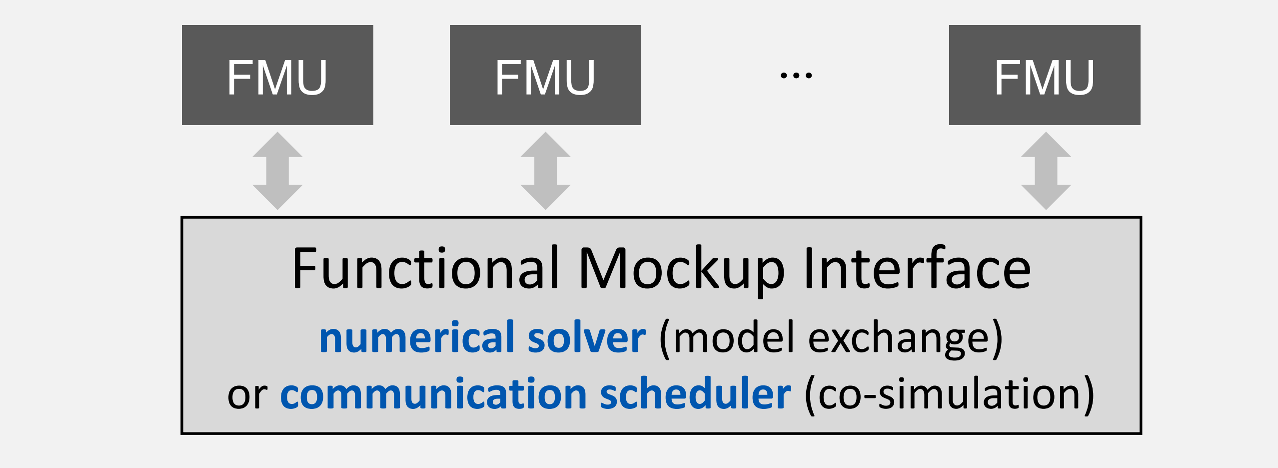
Project Vision

Anticipated Future Additions

- Multi-input, multi-output FMUs.
- Use-phase flow dynamics beyond energy.
  - Water consumption
  - Thermal fluids
  - Contaminants
- Dynamic characterization of impacts.
- Alternative communication protocols suitable for a larger set of FMUs.
- Focus on multi-energy systems with future extension to other applications.





We welcome your input and suggestions!

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Thank you!

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Access fmLCA

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