# Dynamic Management of Integrated Residential Energy Systems

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THE OHIO STATE UNIVERSITY
CAR
College of Engineering
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# OUTLINE

- Introduction
- Proposed Research
- Residential Energy Eco-System Model
    - Household Energy Consumption
    - Personal Transportation Energy Consumption
- Dynamic Energy Management Framework
- Summary and Impact of the Research

# MATTEO MURATORI: PRESENTATION

Born and raised in
Milan (Italy)

B.S. & M.S.
Energy Engineering

POLITECNICO
DI MILANO

Visiting Student

NTNU
Norwegian University of
Science and Technology

# MATTEO MURATORI: PRESENTATION (Con't)

M.S. & Ph.D.
Mechanical Engineering

The Ohio State University
Center for Automotive Research

<u>Research Areas</u>:

- ✓ Thermodynamics
- ✓ Demand Response
- ✓ Statistical Analysis
- ✓ Modeling and Simulations
- ✓ Dynamic Energy Management
- ✓ Plug-in Electric Vehicles
- ✓ Smart Grid
- ✓ Energy Policy

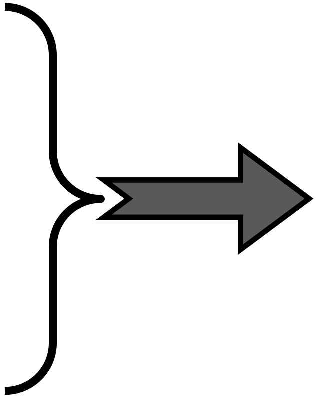
# U.S. ENERGY CONSUMPTION AT A GLANCE

- The U.S. is responsible for about 20% of the world primary energy consumption (4.5% of the world population, 2010)

- **Each American consumes the equivalent of 6 Gallons of gasoline per day !!!**

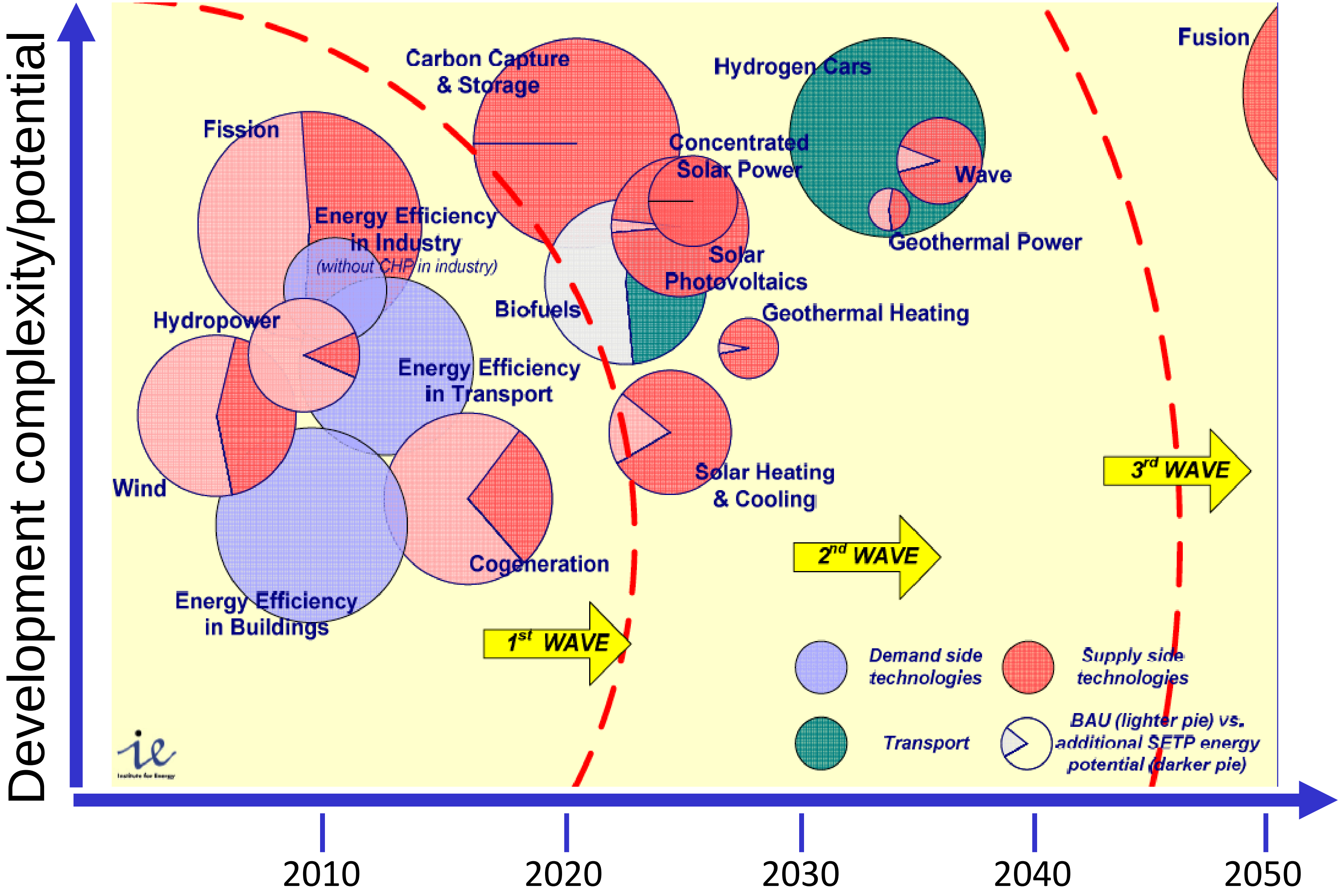
- Implications:

1. Cost
2. Environmental impact
3. Fossil fuel dependency & energy security issue



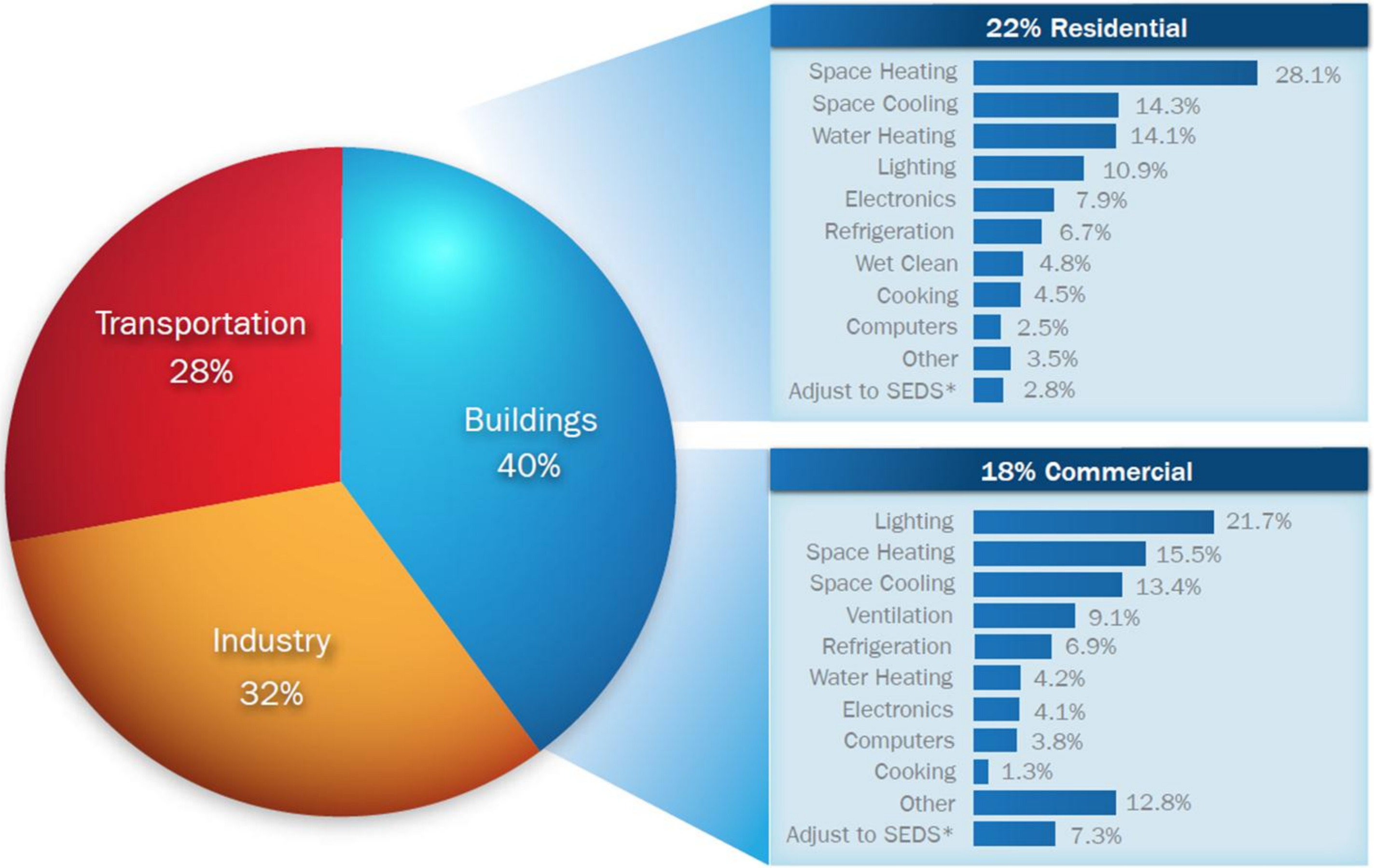
**PARADIGM SHIFT**
IN THE ENERGY INDUSTRY

# POTENTIAL ACCORDING TO INSTITUTE FOR ENERGY



# U.S. ENERGY CONSUMPTION BY SECTOR

- **The focus:** residential sector and personal transportation



*Source: US DOE Quadrennial Technology Review - 2011*

# PROBLEM STATEMENT

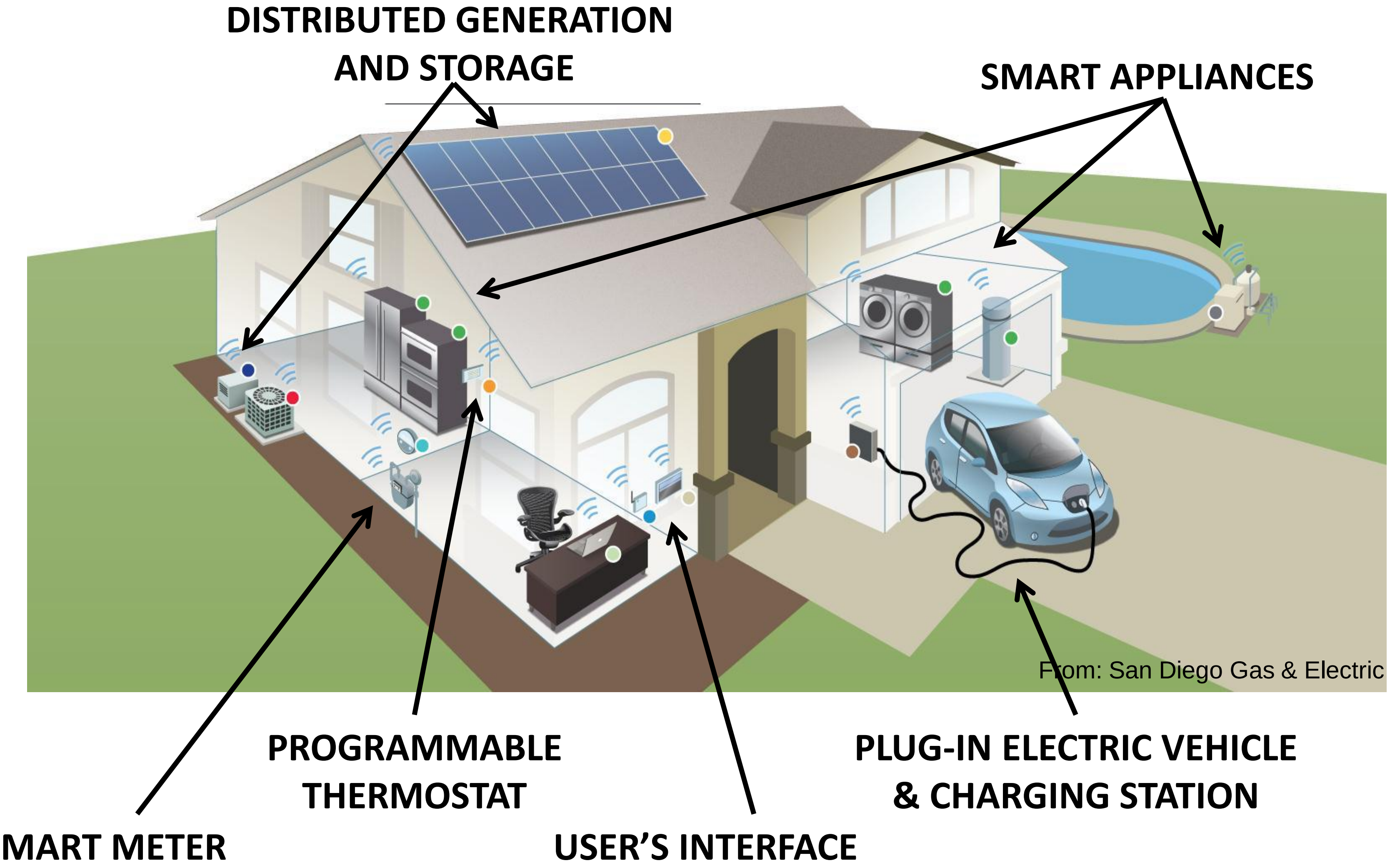
- A centralized system based on fossil fuels is being replaced by a diversified system including renewables, energy storage, distributed generation, and “**efficient demand**”.

- To understand and realize this transformation a comprehensive and accurate **model** of the next-generation power system is needed.

➢ **Research proposal:**

1. Develop a ***Residential Energy Eco-System (REES)*** **model** able to capture all the energy consumption of an individual.
2. Apply **Dynamic Energy Management** techniques to the *REES* in order to intelligently manage energy consumption.

# RESIDENTIAL ENERGY ECO-SYSTEM: DEFINITION



DISTRIBUTED GENERATION AND STORAGE

SMART APPLIANCES

From: San Diego Gas & Electric

PROGRAMMABLE THERMOSTAT

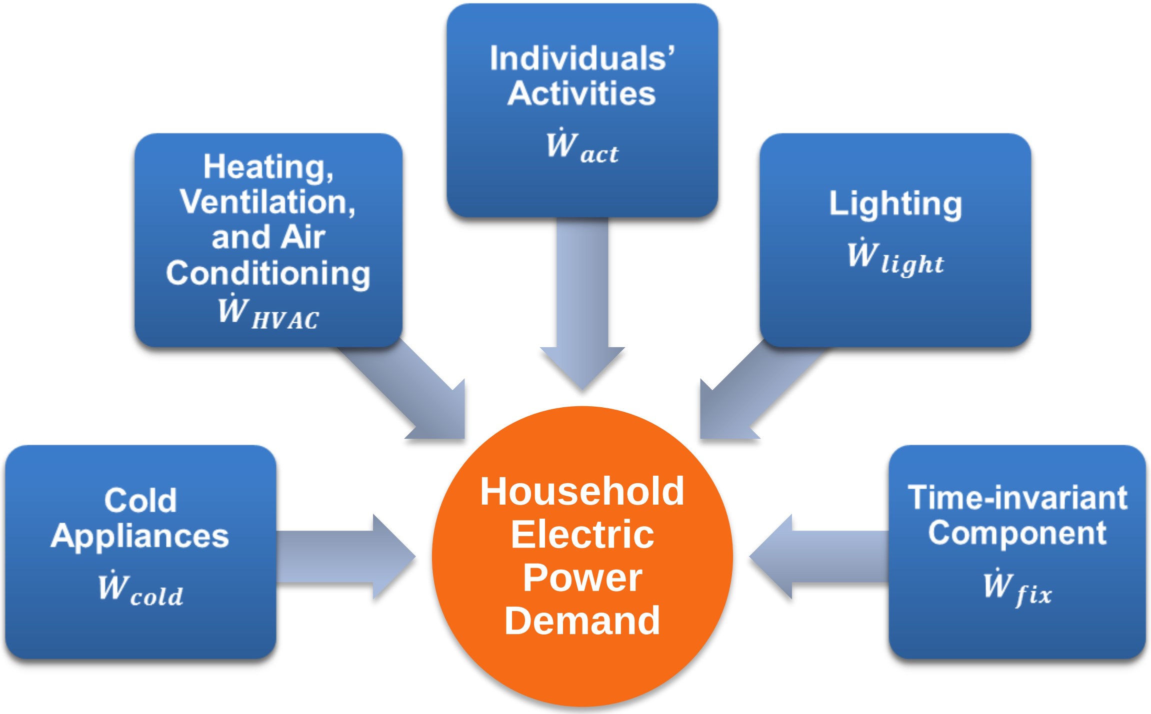
PLUG-IN ELECTRIC VEHICLE & CHARGING STATION

SMART METER

USER'S INTERFACE

# RESIDENTIAL POWER DEMAND MODELING

Estimation of **highly-resolved electricity demand profiles** of a residential household consisting of multiple individuals.



Individuals' Activities $\dot{W}_{act}$

Heating, Ventilation, and Air Conditioning $\dot{W}_{HVAC}$

Lighting $\dot{W}_{light}$

Cold Appliances $\dot{W}_{cold}$

Household Electric Power Demand

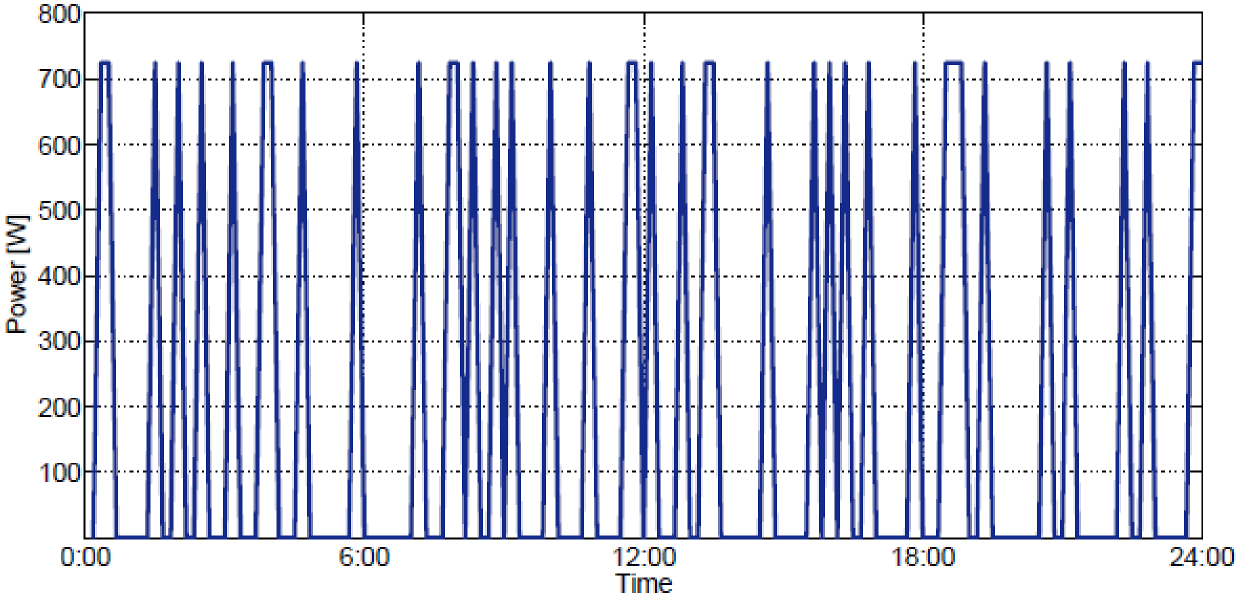
Time-invariant Component $\dot{W}_{fix}$

*M. Muratori, M. Roberts, V. Marano, R. Sioshansi, G. Rizzoni, "Residential Power Demand: A Modeling Technique ".* ***Applied Energy****, Forthcoming.*

# POWER CONSUMPTION OF **COLD APPLIANCES**

Cold appliance consumption, $\dot{W}_{cold}$, is simulated using a **Bernoulli distribution**, with the success probability fixed so that the average on-time of the appliance reflects the national average expected value.

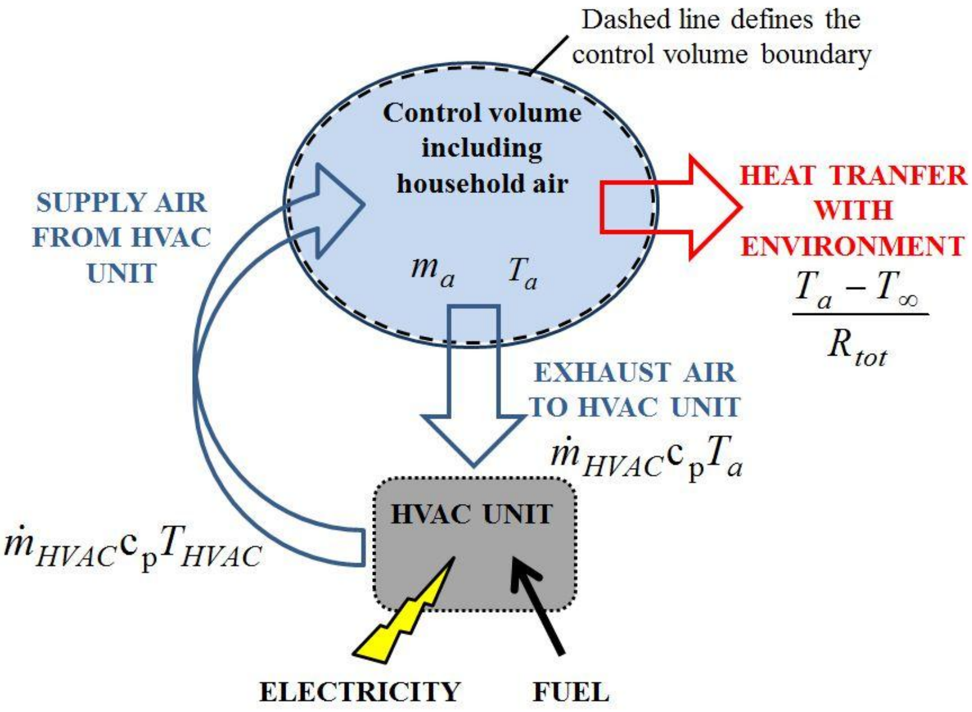
Refrigerators are assumed to be *on/off* devices that always operates at their nominal power when *on*.



# POWER CONSUMPTION OF **HVAC** SYSTEM

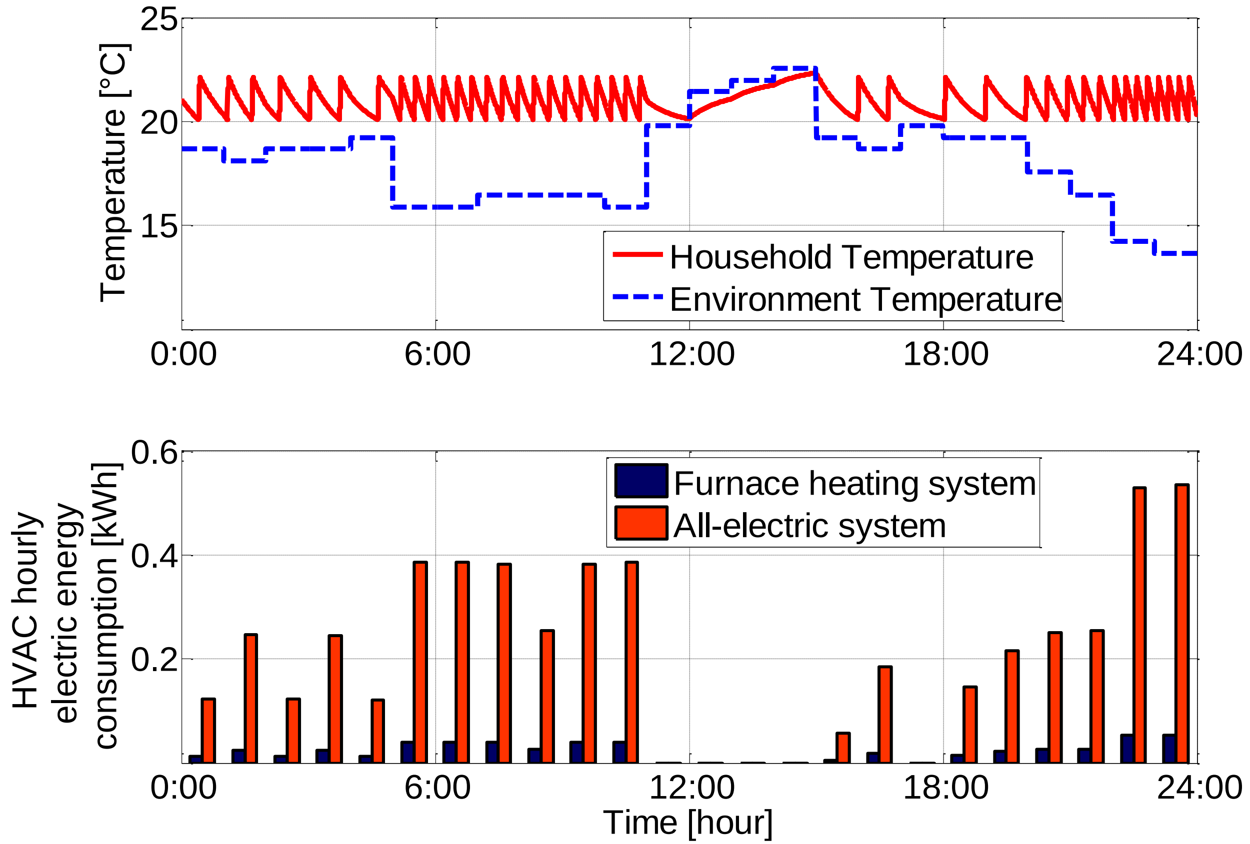
**Heating, Ventilation, and Air Conditioning** energy consumption, $\dot{W}_{HVAC}$, is computed using an engineering model.

The proposed model relies on **fundamental principles** of heat transfer and thermodynamics applied to a control volume including solely the air present in the household.



*M. Muratori, V. Marano, R. Sioshansi, G. Rizzoni, "Energy consumption of residential HVAC systems: a simple physically-based model", 2012 IEEE Power and Energy Society General Meeting, 22-26 July, 2012, San Diego, CA, USA.*

# POWER CONSUMPTION OF **HVAC** SYSTEM

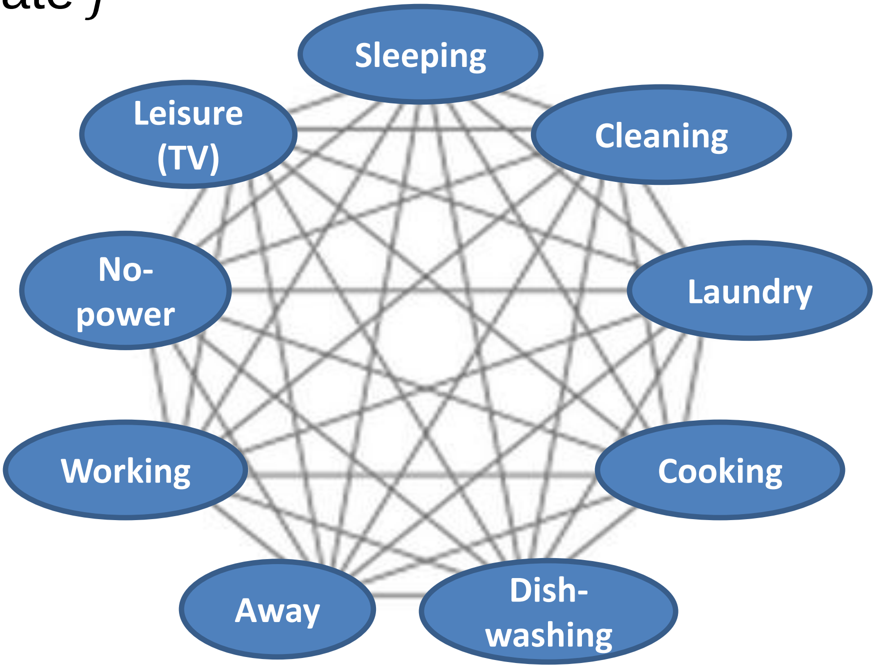


***Simulated temperature evolution and resulting HVAC electricity consumption in a typical household for May 9th 2010 in Indiana -Michigan***

# POWER FOR **INDIVIDUALS' ACTIVITIES**

A **stochastic heterogeneous Markov-chain model** is used to simulate each household member activity profile.

- Each household member is in one of the nine available states in every discrete time step.
- As time proceeds, there is a transition probability $P_{i,j}$ of going from state $i$ to state $j$



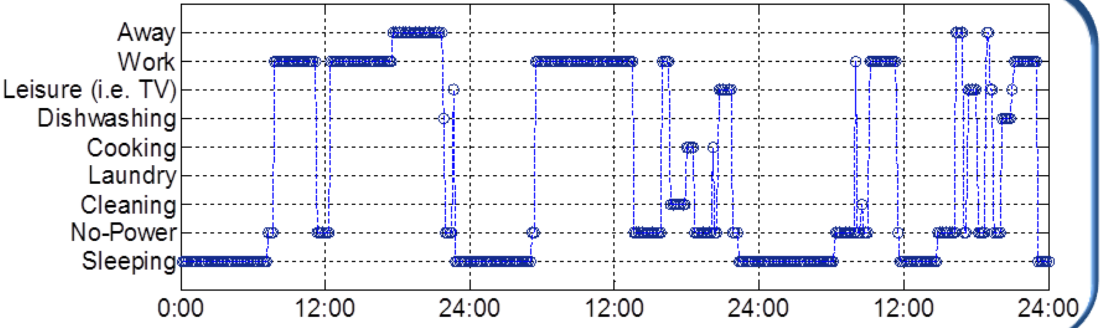
*M. Muratori, V. Marano, R. Sioshansi, and M. Roberts, "Residential Power Demand Prediction and Modelling," in Proceedings of the 24th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (**ECOS 2011**).*

# BEHAVIORAL MODEL

The stochastic process generates high-resolved synthetic activity sequences …

Markov-chain transition probabilities →

*First step*:
Generation of synthetic activity patterns for each household member

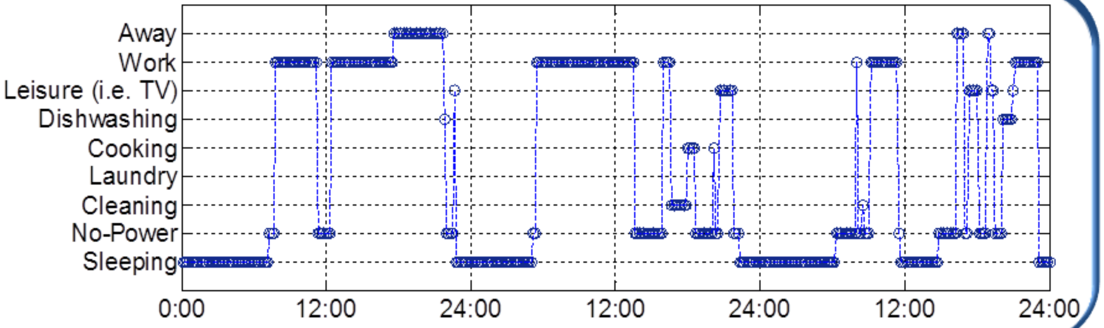


# POWER FOR INDIVIDUALS' ACTIVITIES

**…** that are converted into electric power consumption using the wattage of the appliance associated with each activity.

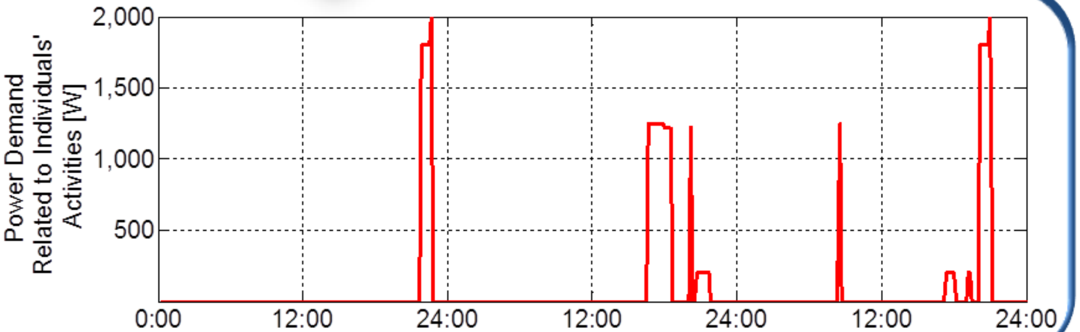
Markov-chain transition probabilities →

*First step*: Generation of synthetic activity patterns for each household member



Power conversion factors associated with each activity (Appliances wattage) →

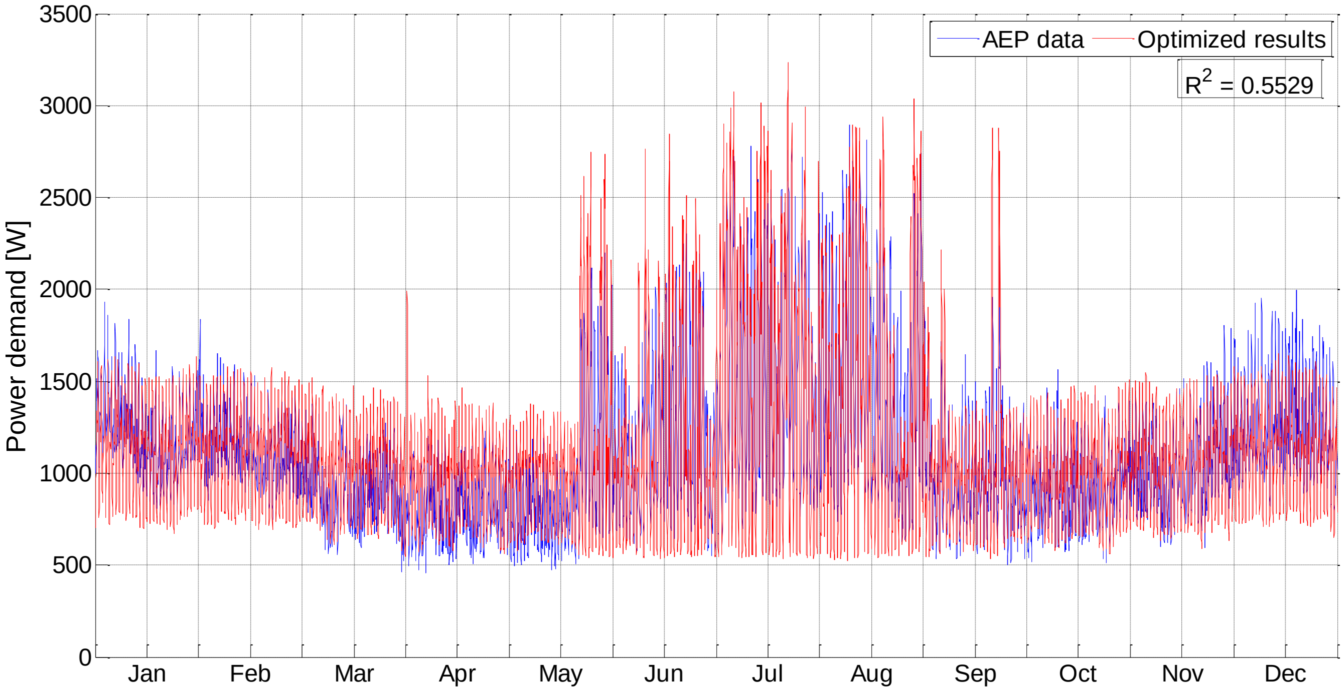
*Second step:* Activity patterns are converted into $\dot{W}_{act}$ by using power conversion factors



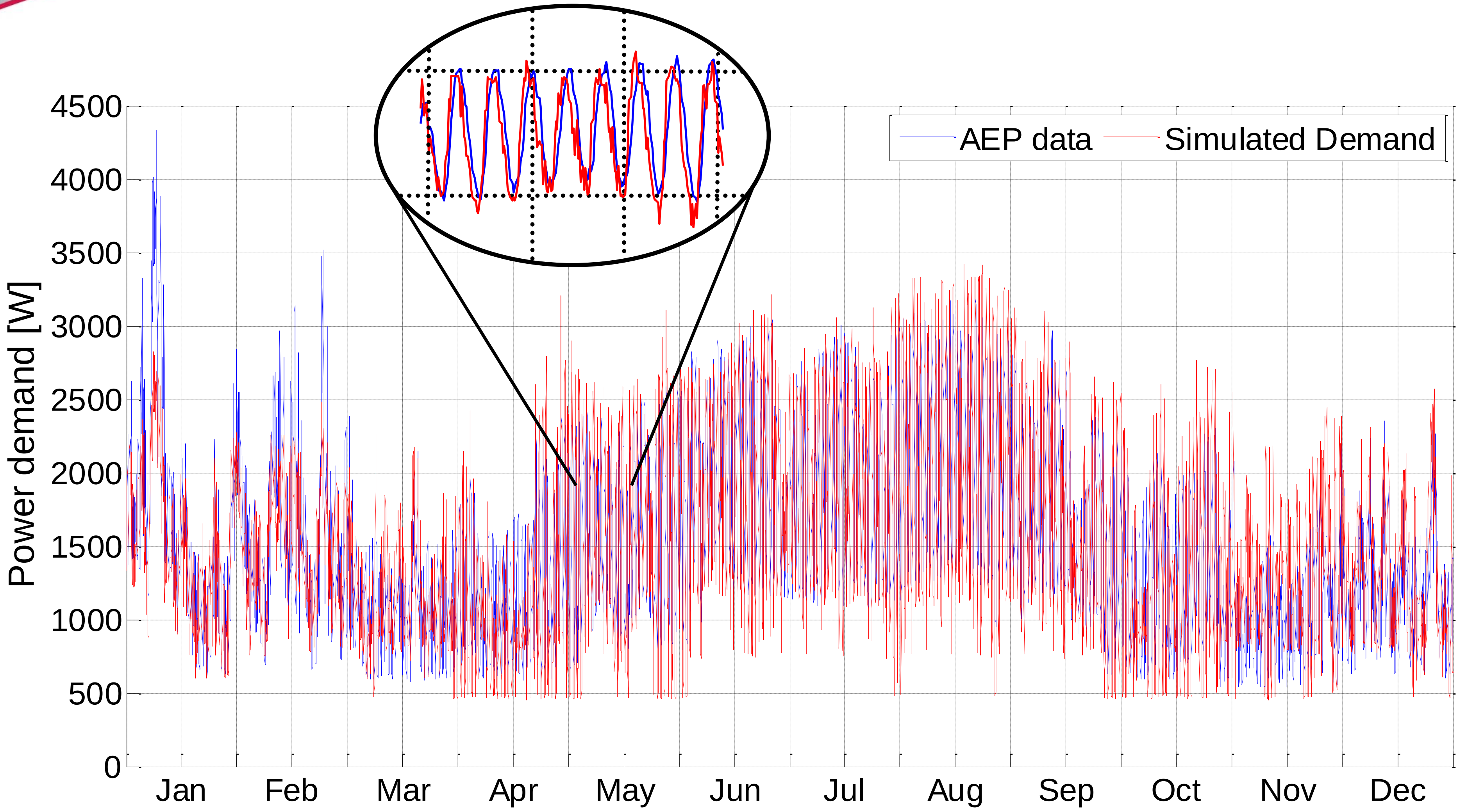
# LIGHTING & TIME-INVARIANT POWER CONSUMPTION

**Lighting** demand depends on the amount of natural lighting available and building occupancy.

The lighting power conversion parameters and $\dot{W}_{fix}$ are computed using a linear regression model against **actual metered data** provided by American Electric Power (AEP).



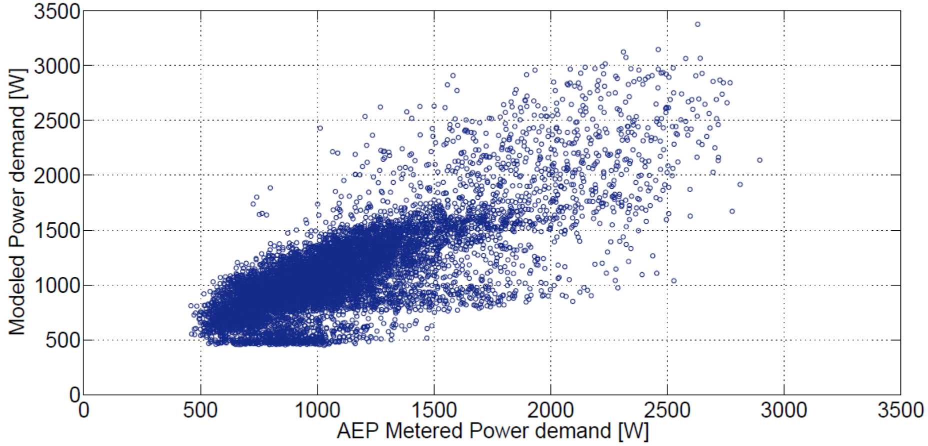
# RESULTS & VALIDATION



# RESULTS & VALIDATION

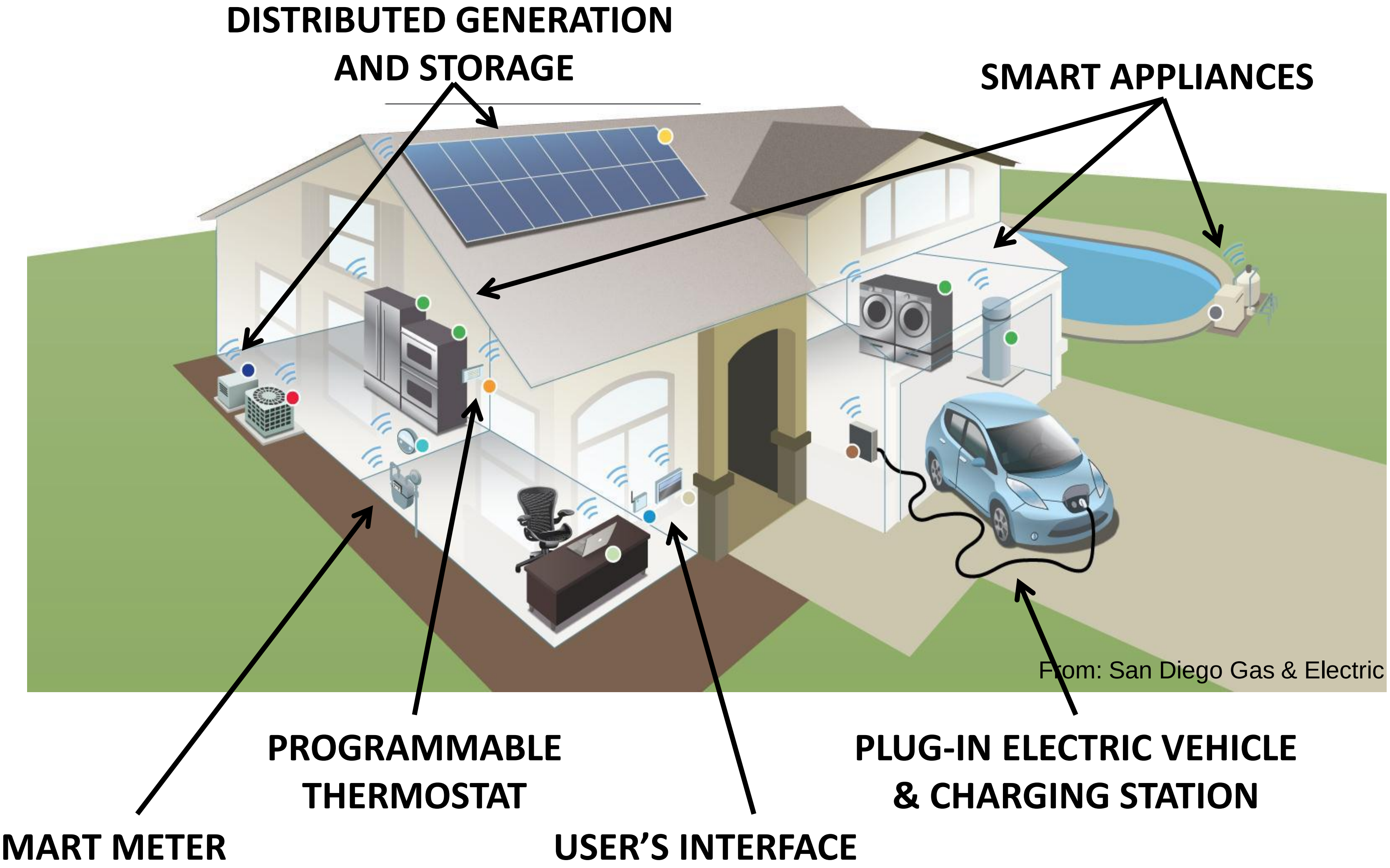
**Two-step validation methodology:**

1. The model is compared against the dataset used for the calibration to verify that the simulated results have the same statistical features as the metered data.
2. The model output is compared against metered data for a different region



| | In-sample | Out-of-sample |
|---|---|---|
| **Means difference** | $< 1\%$ | $\approx 1\%$ |
| **Standard deviations difference** | $\approx 5\%$ | $< 3\%$ |
| **Mann-Whitney U Test (i.e. same distribution)** | $\text{p-value} = 0.097$<br>$\alpha = 0.01$ | $\text{p-value} = 0.138$<br>$\alpha = 0.01$ |
| **Levene/Brown-Forsythe Test (i.e. same variance)** | $\text{p-value} = 0.024$<br>$\alpha = 0.01$ | $\text{p-value} = 0.003$<br>$\alpha = 0.01$ |

# RESIDENTIAL ENERGY ECO-SYSTEM: DEFINITION



**DISTRIBUTED GENERATION AND STORAGE**

**SMART APPLIANCES**

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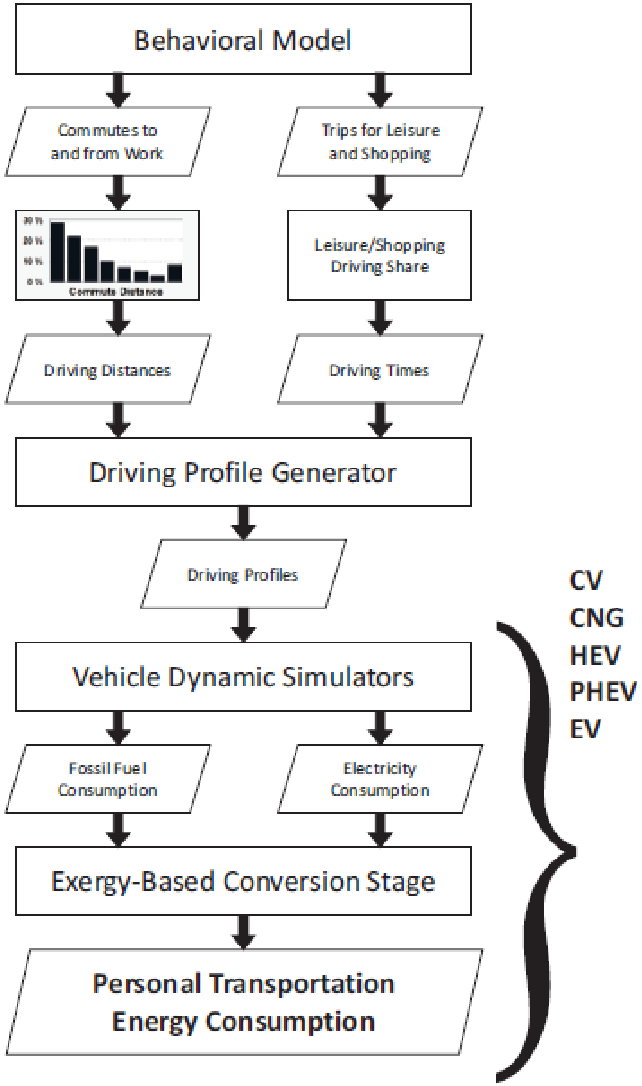
**SMART METER**

**USER'S INTERFACE**

# PERSONAL TRANSPORTATION ENERGY CONSUMPTION

- Estimation of **highly-resolved consumption patterns** for personal transportation, including fossil fuel and/or electricity consumption, depending on vehicle type.

1. Modeling the **behavior of drivers** in order to establish when driving events occur and the length of each event.
2. Generation of **realistic driving profiles** for each driving event.
3. Simulation of **different kind of vehicles** in order to compute energy consumption starting from velocity profile.



Behavioral Model

Commutes to and from Work

Trips for Leisure and Shopping

Commute Distance

Leisure/Shopping Driving Share

Driving Distances

Driving Times

Driving Profile Generator

Driving Profiles

Vehicle Dynamic Simulators

Fossil Fuel Consumption

Electricity Consumption

Exergy-Based Conversion Stage

Personal Transportation Energy Consumption

CV
CNG
HEV
PHEV
EV

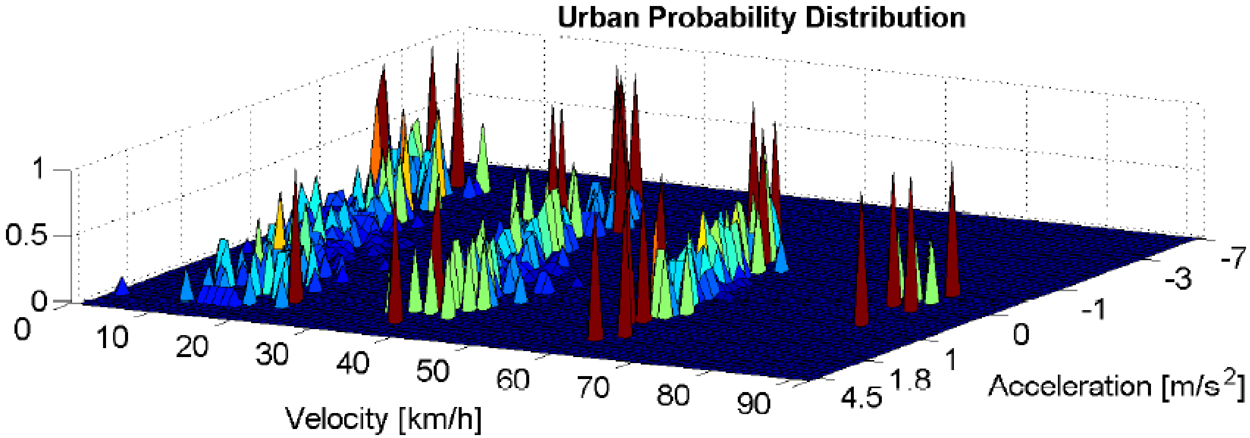
*M. Muratori, M. Moran, E. Serra, G. Rizzoni, "Highly-Resolved Modeling of Personal Transportation Energy Consumption in the United States", **Energy**, invited Paper, 2012.*

# REAL-WORLD DRIVING PROFILE GENERATOR

The ***Driving Profile Generator*** is a Markovian stochastic tool based on historical data that takes as input either a driving duration or a driving distance and generates as output a driving profile.

The data used for the calibration were collected as part of the **SMART@CAR research program.**

These data capture the driving styles of different drivers for several alternative situations, including **over 100˙000 miles of real driving profiles.**



Q. Gong, S. Midlam-Mohler, V. Marano, G. Rizzoni, *An Iterative Markov Chain Approach for Generating Vehicle Drive Cycles*, SAE International Journal on Engines 4 (1) (2011) 1035–1045.

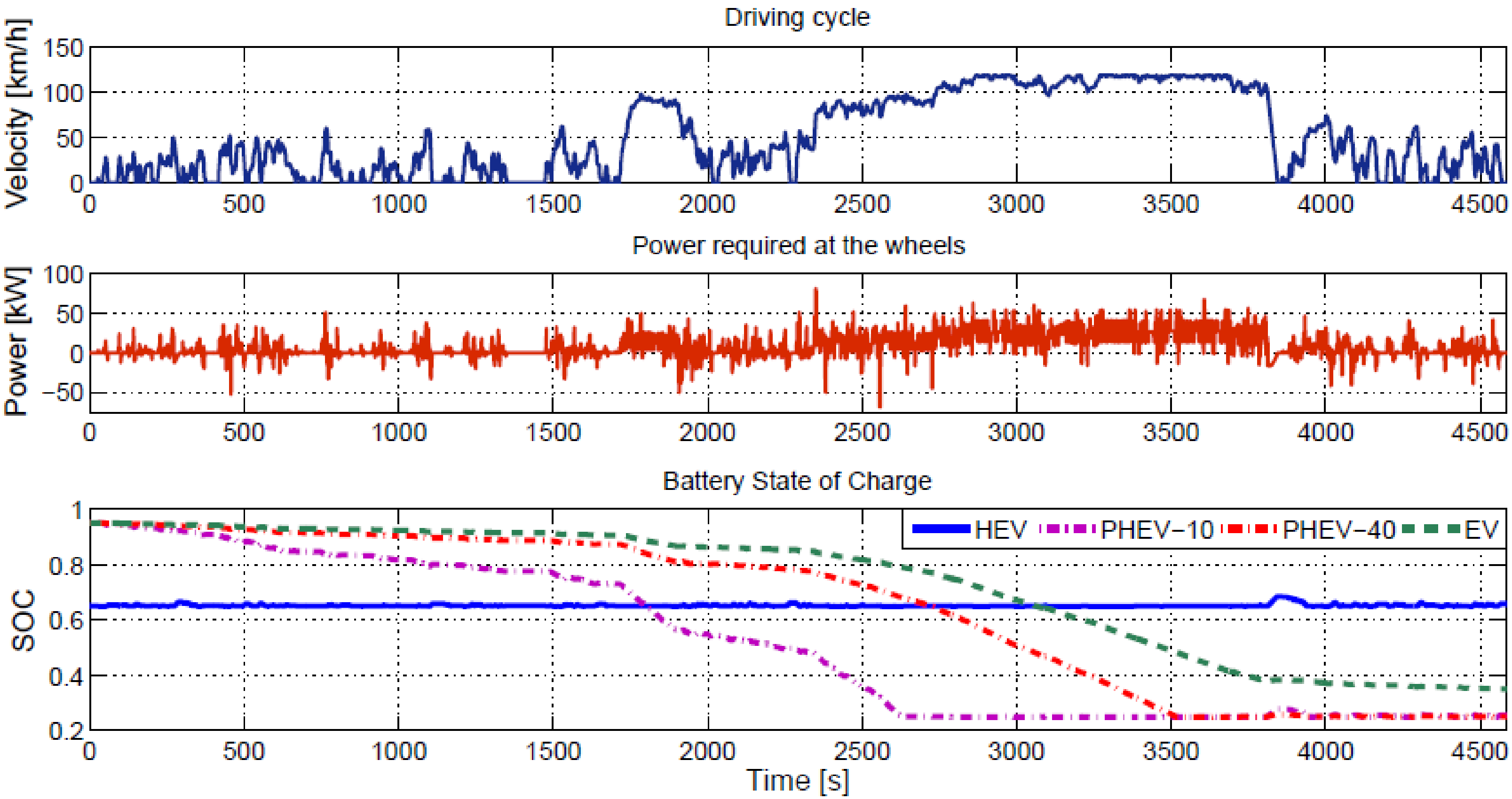
# VEHICLE DYNAMIC SIMULATOR

Vehicle dynamic simulators for a set of different vehicles:

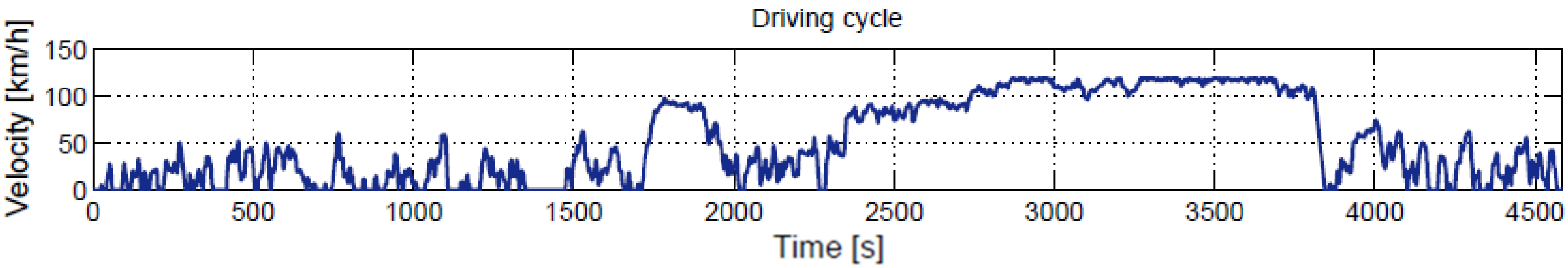
| Vehicle | Curb Weight [kg] | Battery Capacity [kWh] | Electric Range [Miles] | Energy Carriers |
|---|---|---|---|---|
| **Conventional Gasoline Vehicle (CV)** | 1450 | - | - | Gasoline |
| **Hybrid Electric Vehicle (HEV)** | 1550 | 1.3 | 0 | Gasoline |
| **Plug-in Hybrid Electric Vehicle (PHEV-10[1])** | 1600 | 4 | 10 | Gasoline & Electricity |
| **Plug-in Hybrid Electric Vehicle (PHEV-40[2])** | 1700 | 16 | 40 | Gasoline & Electricity |
| **Electric Vehicle (EV[3])** | 1500 | 24 | 100 | Electricity |
| **Compressed Natural Gas Vehicle (CNG)** | 1450 | - | - | Natural Gas |

[1] 10 miles all-electric range [2] 40 miles all-electric range [3] 100 miles range

# VEHICLE DYNAMIC SIMULATOR – EXAMPLE



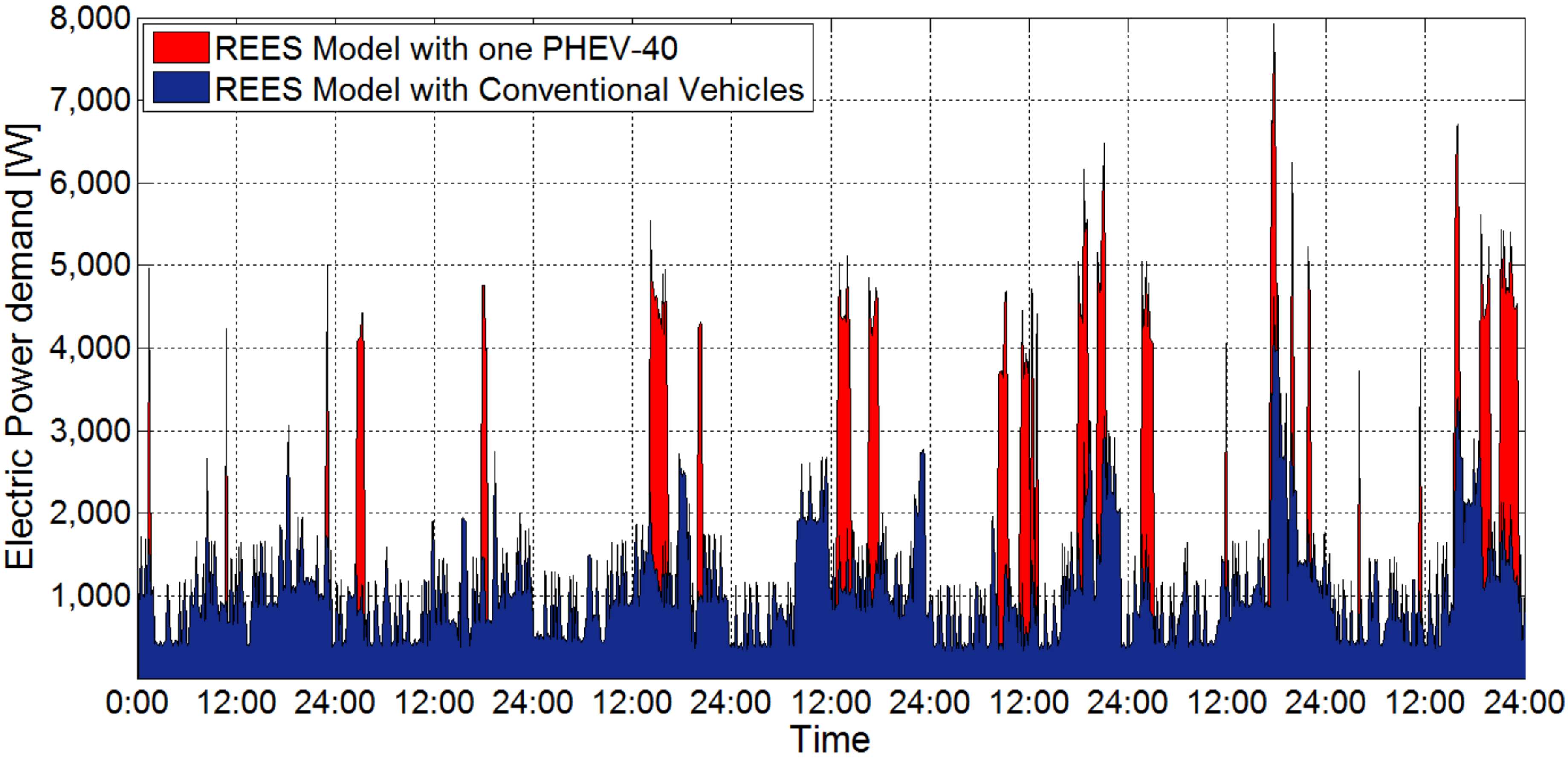
# VEHICLE DYNAMIC SIMULATOR – ENERGY CONS.



| Vehicle | Gasoline Consumption [l] | Electricity Consumption [kWh] | Final SOC |
|---|---|---|---|
| **Conventional Gasoline Vehicle (CV)** | 4.2 | - | - |
| **Hybrid Electric Vehicle (HEV)** | 3.3 | - | 65% |
| **Plug-in Hybrid Electric Vehicle (PHEV-10)** | 1.2 | 2.8 | 25% |
| **Plug-in Hybrid Electric Vehicle (PHEV-40)** | 0.8 | 11.1 | 25% |
| **Electric Vehicle (EV)** | - | 12.2 | 43% |

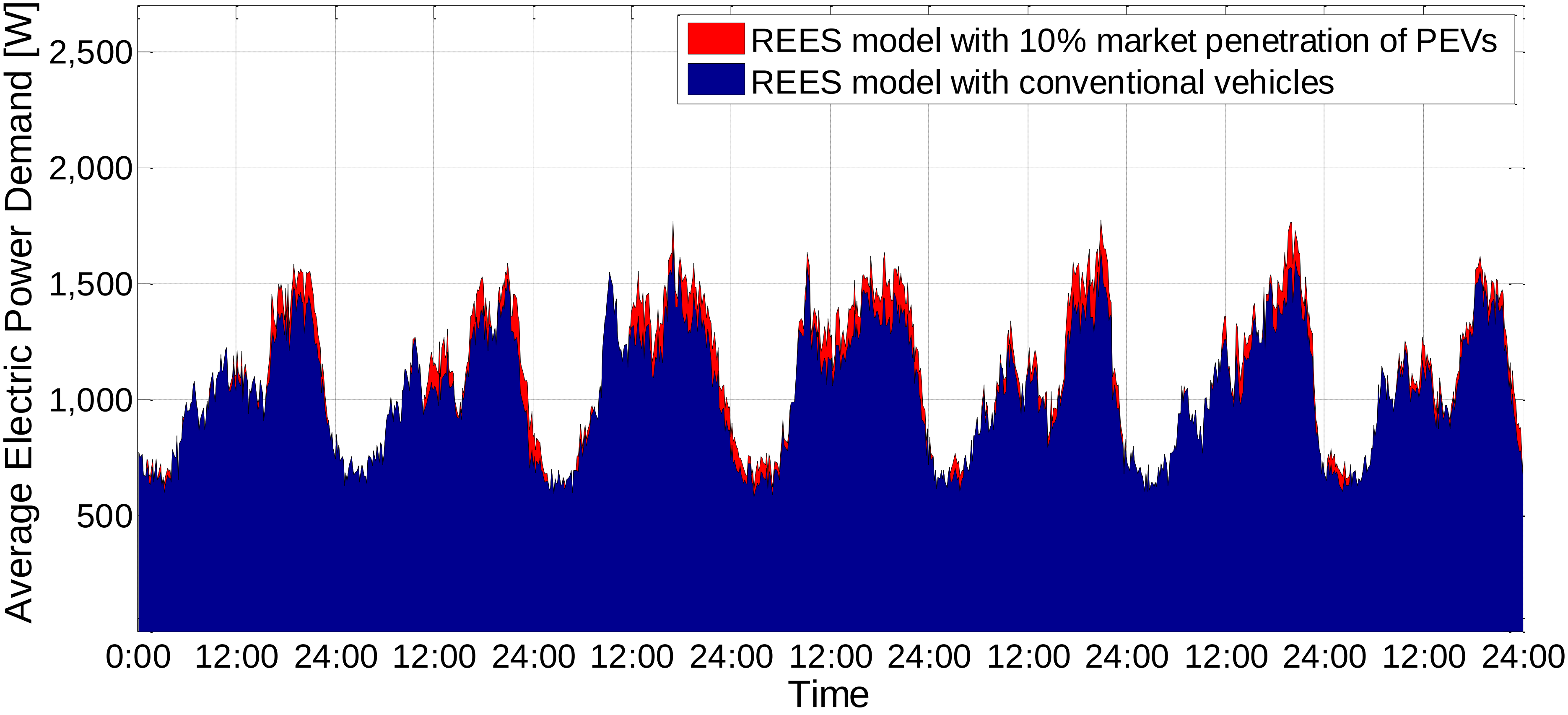
# REES SIMULATIONS – INTEGRATION OF PEVS

Simulation of a **Residential Energy Eco-System** composed by one working couple and two children.



# REES SIMULATIONS – AGGREGATED RESULTS

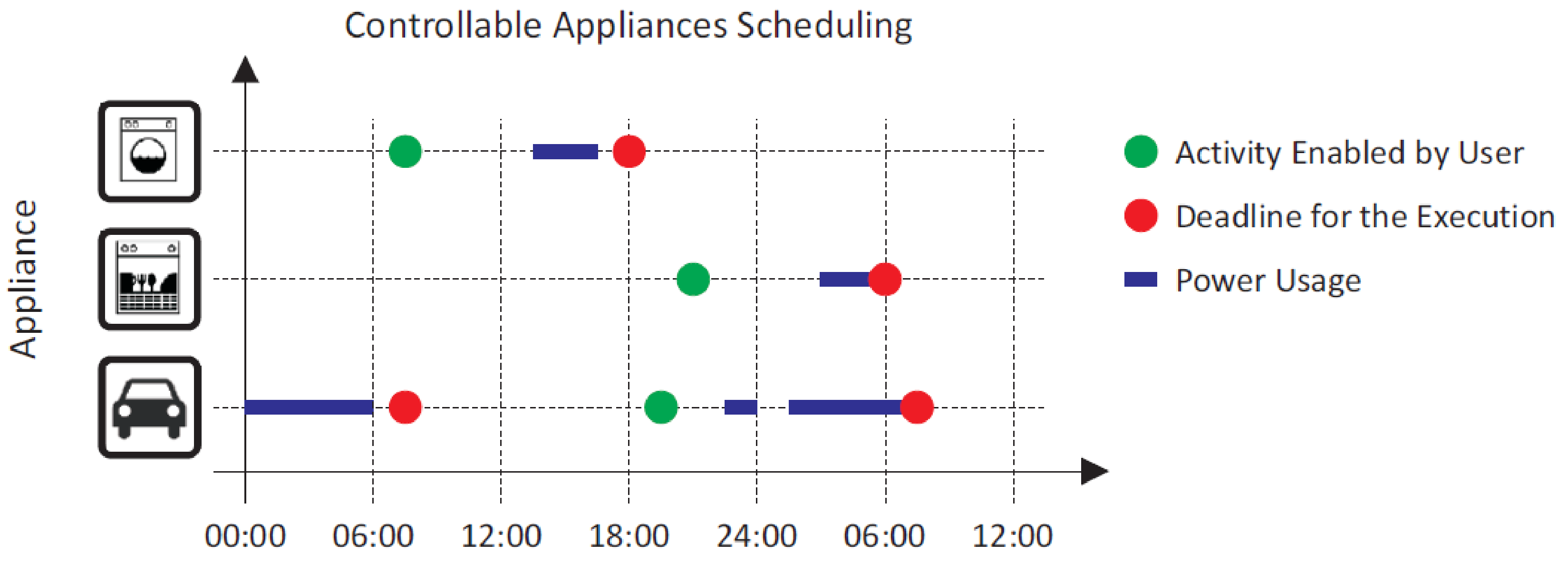
Simulation of 100 **Residential Energy Eco-Systems** representing the U.S. population – First week of January 2010, Midwest region.



# DYNAMIC ENERGY MANAGEMENT – FRAMEWORK

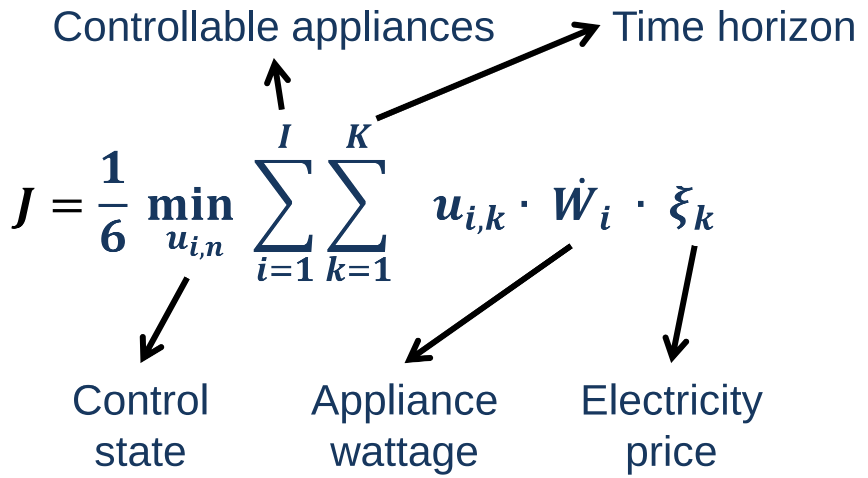
The objective of the proposed **Dynamic Energy Management** framework is to effectively manage energy consumption at the household level.

This is aimed at making intelligent decisions on when operating residential controllable appliances, including HVAC systems and charging of plug-in electric vehicles.



# DYNAMIC ENERGY MANAGEMENT – FORMULATION

An **optimal schedule** for each device (controllable appliances, vehicles charging, and thermostat setting point) over a given period of time is found with the objective of minimizing a cost function.



Controllable appliances

Time horizon

$$J = \frac{1}{6} \min_{u_{i,n}} \sum_{i=1}^{I} \sum_{k=1}^{K} u_{i,k} \cdot \dot{W}_i \cdot \xi_k$$

Control state

Appliance wattage

Electricity price

A number of **operational constraints** need to be satisfied, capturing:

- Technology (interruptible or non-interruptible loads);
- User preferences (appliances’ run-cycles and vehicle charging must be completed within a time limit);
- Comfort effects (temperature range).

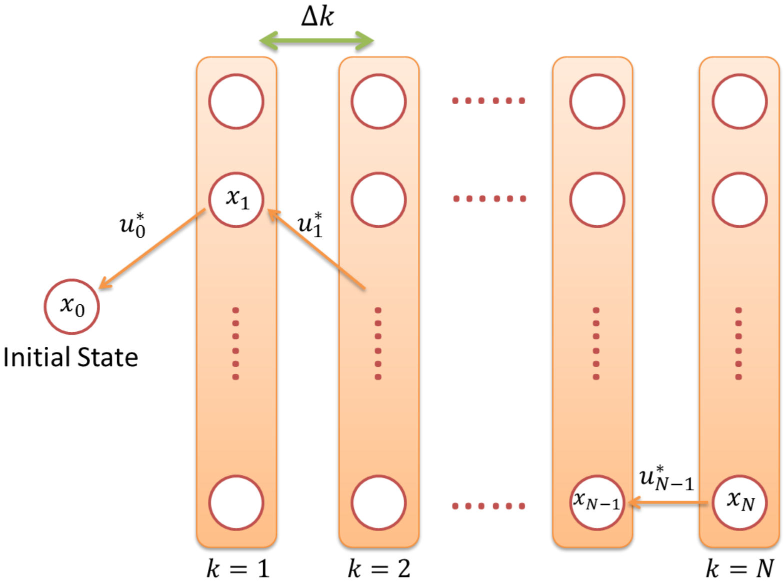
# DYNAMIC ENERGY MANAGEMENT – DP IMPLEMENTATION

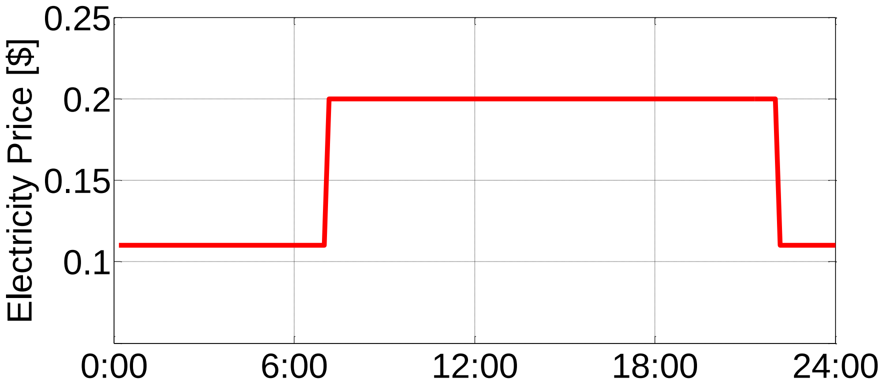
This is a sequential decision making problem (or optimal control problem) → **Dynamic Programming** (DP) can be used as solution algorithm.

Expected cost starting from $x_t(o)$:

$$J_\pi(x_t(0)) = E\left\{ \underset{\big\downarrow}{g_K(x_t(K))} + \sum_{k=0}^{K-1} [g_k(k), u(k))] \right\}$$

Cost of the power consumption of the appliances from $k$ to $k + 1$





# DP IMPLEMENTATION – STATE DYNAMICS

## Non-interruptible controllable appliances timing dynamics:

$$x_t^i(k+1) = \begin{cases} -W^i & \text{if } \big(x_a(k) = i\big) \wedge \big(u^i(k) = 0\big) \wedge \big(x_t^i(k) = -\infty\big) \\ 1 & \text{if } \big(x_t^i(k) < 0\big) \wedge \big(u^i(k) = 1\big) \\ x_t^i(k) + 1 & \text{if } \big(-\infty < x_t^i(k) \leq 0\big) \wedge \big(u^i(k) = 0\big) \\ x_t^i(k) + 1 & \text{if } \big(0 < x_t^i(k) < C^i\big) \\ -\infty & \text{if } \big(x_t^i(k) = C^i\big) \end{cases}$$

Count-down

## Interruptible controllable appliances timing dynamics:

$$x_{t1}^i(k+1) = \begin{cases} x_{t1}^i(k) & \big(u^i(k) = 0\big) \\ x_{t1}^i(k) + 1 & \big(u^i(k) = 1\big) \\ 0 & \text{if } \big(x_{t1}^i(k) = C^i\big) \end{cases}$$

Counter

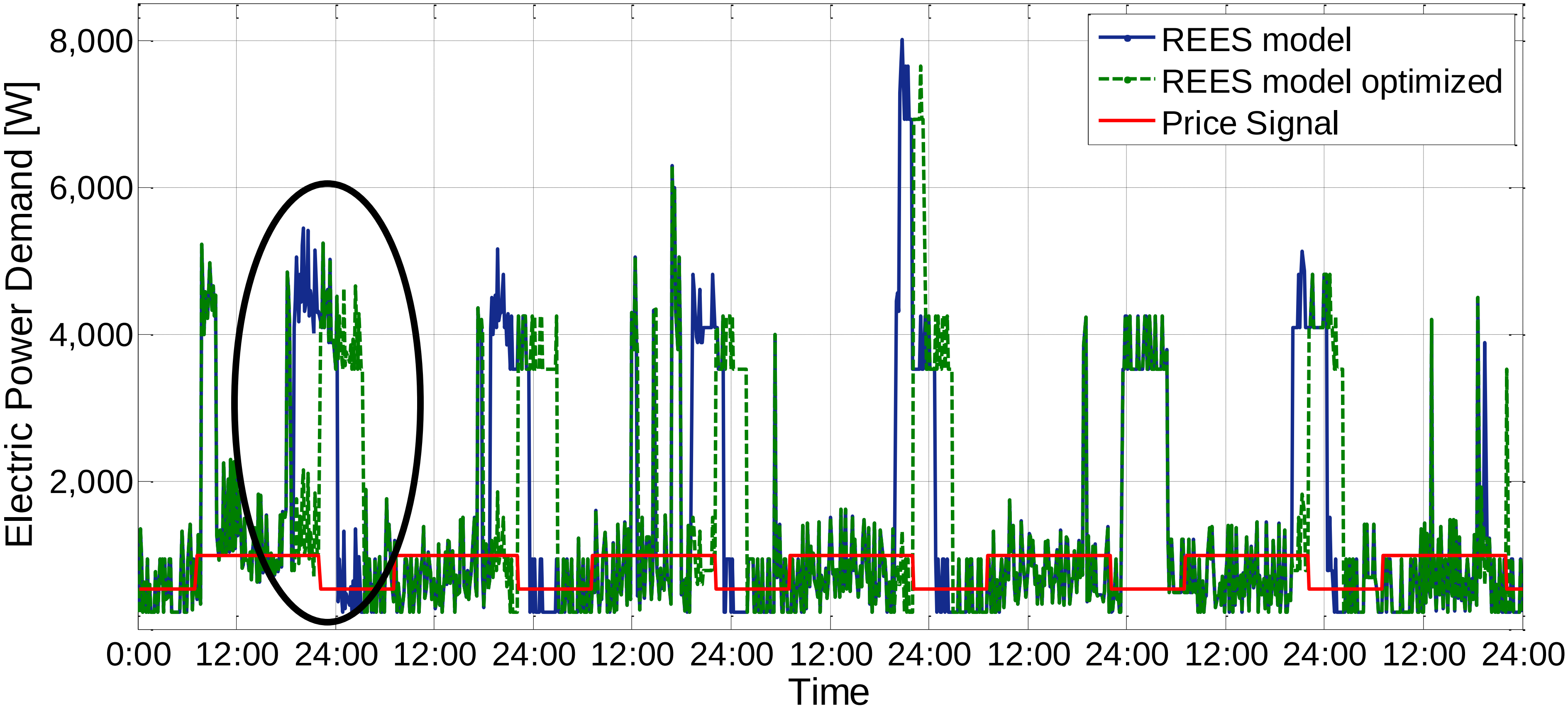
$$x_{t2}^i(k+1) = \begin{cases} -W^i & \text{if } \big(x_a(k) = i\big) \wedge \big(u^i(k) = 0\big) \wedge \big(x_{t2}^i(k) = -\infty\big) \\ -(W^i + 1) & \text{if } \big(x_a(k) = i\big) \wedge \big(u^i(k) = 1\big) \wedge \big(x_{t2}^i(k) = -\infty\big) \\ x_{t2}^i(k) & \text{if } \big(u^i(k) = 1\big) \\ x_{t2}^i(k) + 1 & \text{if } \big(u^i(k) = 0\big) \\ -\infty & \text{if } \big(x_{t1}^i(k) = C^i\big) \end{cases}$$

Count-down

| Name | Value | Time-Step | Description |
|---|---|---|---|
| $W^i$ | 4 | - | Maximum waiting time to start the execution of the $i^{th}$ appliance |
| $C^i$ | 6 | - | Completion time required to run the $i^{th}$ appliance |
| $E^i$ | - | 3 | Enabling time for the $i^{th}$ appliance |
| $D^i$ | - | 13 | Deadline to complete the execution of the $i^{th}$ appliance |

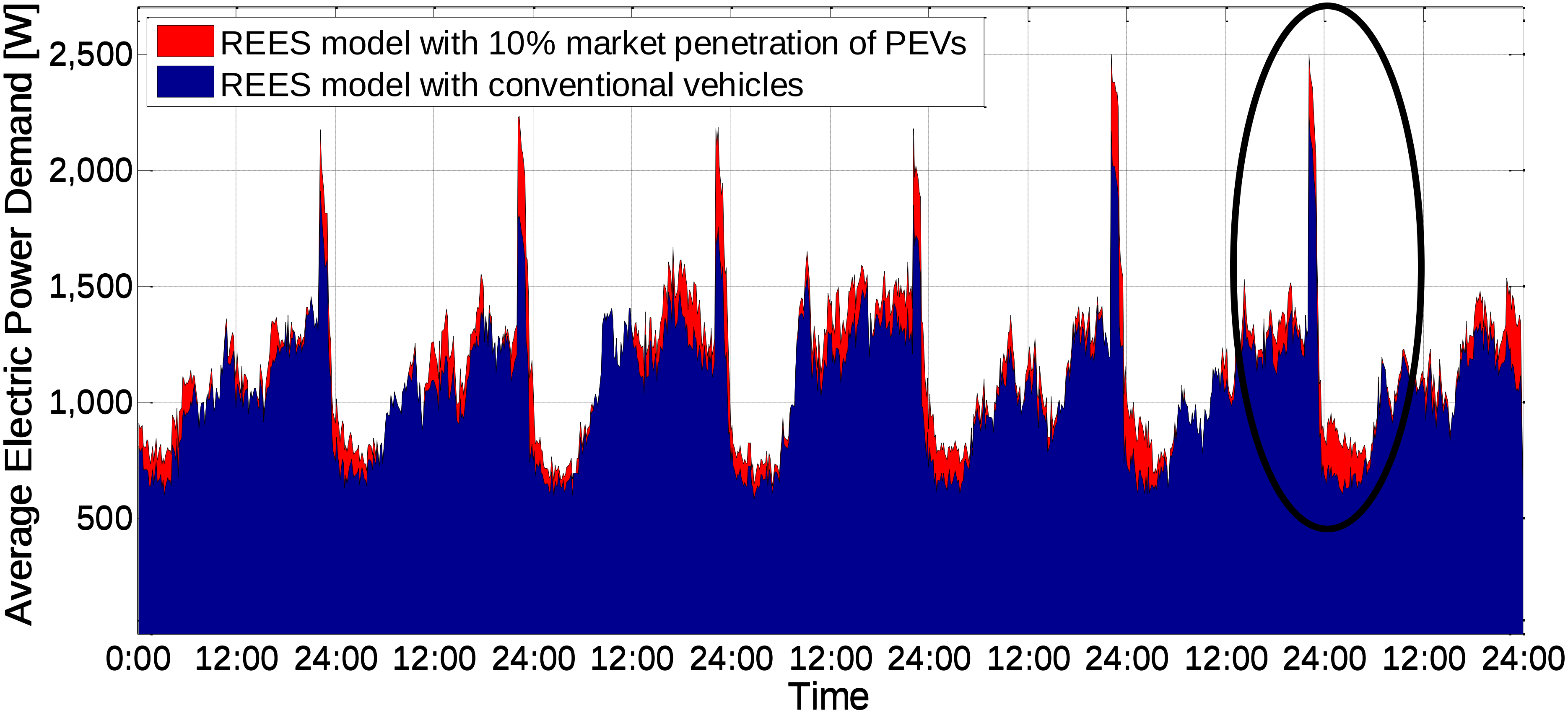
# DYNAMIC ENERGY MANAGEMENT – SIMULATIONS

**Introduction of dynamic energy management** on one Residential Energy Eco-System composed by one working couple, two children, and one PHEV-40



# REES SIMULATIONS – AGGREGATED RESULTS

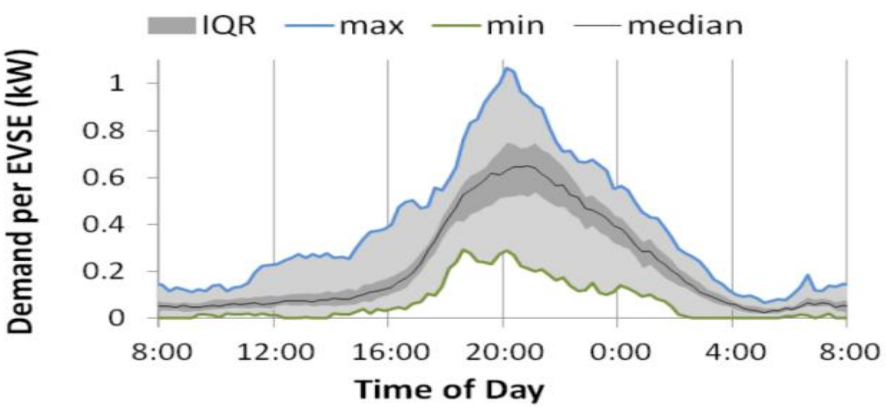
Simulation of 100 **Residential Energy Eco-Systems** representing the U.S. population – First week of January 2010, Midwest region.

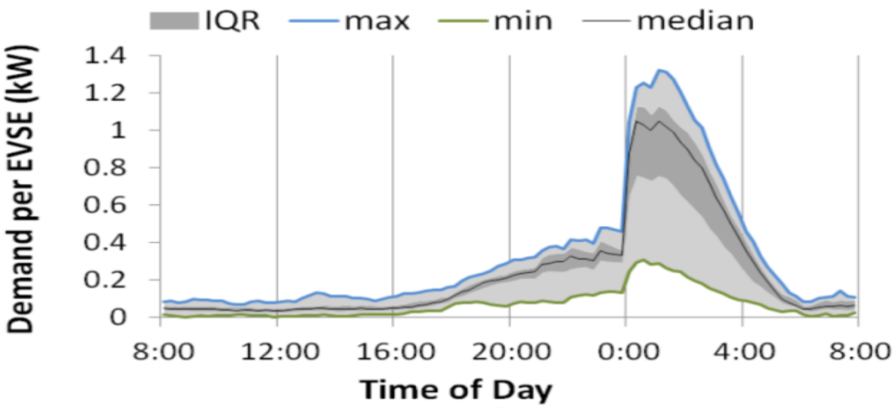


# REAL WORLD DEMAND RESPONSE DATA

These **rebound peaks** are confirmed by actual data:

The EV Project is the largest deployment of electric vehicles and charge infrastructure in history.





**No access to any time-of-use rate.**

The charging demand starts to increase gradually after 4 p.m. and naturally peaks around 8 p.m.

**Time-of-use rate plan.**

The demand peaks exactly when electricity price changes (12 a.m.).
The demand increase is steeper and presents a higher peak value

# FUTURE WORK

- Development of accurate and significant quantitative metrics and taxonomies to evaluate demand response programs other than graphical comparison.

- Study and evaluate the impact of different electricity price structures towards total residential and transportation demand (*i.e*. power-proportional price).

- Extension of the proposed Dynamic Energy Management system to include HVAC systems in the optimization algorithm.

- Extension of the proposed Dynamic Energy Management system towards a stochastic optimization, where future probabilities of users to engage in energy-consuming activities are exploited.

# **PURPOSE** OF THE PROPOSED ENERGY MANAGEMENT

1. **Quantify the impact of distributed “egoistic” residential energy management systems:** *i.e.* evaluation of undesired rebound dynamics, understanding heterogeneous loads dynamics and stochastic end-user behaviors.

2. Set a **threshold for real-time implementation** and effective deployment of demand-side response programs. Understanding of computation issues related to different price structures, like real-time pricing or time-of-use rates.

3. Set a **basis for a higher-level energy management framework** intended to coordinate multiple home energy management systems to achieve effective collective response.
   This can be used to address a variety of **sustainability** issues, such as increase system flexibility via grid-friendly demand response, minimize the total primary energy consumption or the carbon footprint, or minimize energy-related economic expenditures.

# **SUMMARY** OF THE RESEARCH

- ***Residential Energy Eco-System (REES)*** model is able to capture all the energy consumption of an individual, including energy consumed inside the household and energy consumption related to personal transportation.

- ***Dynamic Energy Management*** is an automated system that allows to intelligently manage energy consumption in the *REES*.

- The proposed management framework is non-disruptive, in the sense that it does not require individuals to change their behavior.

- While most of the works available in the literature rely on historical data, here a simultaneous optimization of all the components (including smart appliances, HVAC systems, and PEVs) is proposed based on proper highly-resolved modeling.

# **IMPACT** OF THE RESEARCH

- This set of tools allows for evaluating energy-related costs/benefits for **consumers**, as well as possible advantages for **electric utilities** (load shaping), and positive/ negative externalities for the **society** as a whole (energy policy).

- Develop tools for education outreach on current opportunities for energy savings and **evaluation of different technology adoptions**.

- This tool will serve as a **virtual laboratory** for investigating fundamental economic and policy-related questions regarding the interplay of individual consumers with energy-use aspects.

- Example: evaluating the **impact of PEVs on the electric grid** – especially at the distribution level; evaluating the **effect of different electricity price structures on residential demand response; …**

# PUBLICATIONS

1) *M. Muratori, V. Marano, R. Sioshansi, and M. Roberts, "Residential Power Demand Prediction and Modelling," in Proceedings of the 24th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (**ECOS 2011**), July 4–7, 2011, Novi Sad, Serbia.*
2) *M. Muratori, M. Roberts, R. Sioshansi, V. Marano, G. Rizzoni, "Modeling Residential Power Demand", **UCEAO 6th Annual Conference**, Securing Ohio's Energy and Economic Future, April 2-3, 2012, Columbus,Ohio, U.S.A.*
3) M. Muratori, E. Serra, V. Marano, and M. Moran, "Personal Transportation Energy Consumption," in Proceedings of the 25th International Conference on Efficiency, Cost, Optimization Simulation and Environmental impact of Energy Systems (**ECOS 2012**), June 26–29, 2012, Perugia, Italy.
4) M. Muratori, V. Marano, R. Sioshansi, and G. Rizzoni, "Energy consumption of residential HVAC systems: a simple physically-based model," in **2012 IEEE Power and Energy Society** General Meeting, Institute of Electrical and Electronics Engineers, 22-26 July 2012, San Diego, CA, U.S.A.
5) *M. Muratori, C. Chang, W. Zhang, E. Serra, G. Rizzoni, "Impact of Electricity Price on Residential Demand Response",* Submitted to the 26th International Conference on Efficiency, Cost, Optimization Simulation and Environmental impact of Energy Systems (**ECOS 2013**), Submitted. July 16–19, 2013, Guilin, China.
6) *M. Muratori, M. Roberts, V. Marano, R. Sioshansi, G. Rizzoni, "Residential Power Demand: A Modeling Technique ". **Applied Energy**, Forthcoming.*
7) H. B. Smith, M. Muratori, A. Pielow, B.J. Yurkovich, A. Krishnamurthy, R. Sioshansi, G. Rizzoni, M.C. Roberts, "*A User-Steered Energy Generation and Consumption Multi-Model Simulation for Pricing and Policy Development*", **IEEE CiSE**, Submitted, 2012.
8) *M. Muratori, M. Moran, E. Serra, G. Rizzoni, "Highly-Resolved Modeling of Personal Transportation Energy Consumption in the United States", **Energy**, invited Paper, 2012.*

# Q&A

## Dynamic Management of Integrated Residential Energy Systems

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February, 13th 2013