A simple DR optimization model for a single consumer with different appliances and a solar integration

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Bilevel games
Energy and environmental modeling
Alexandrov geometry in optimization

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Demand response

A definition

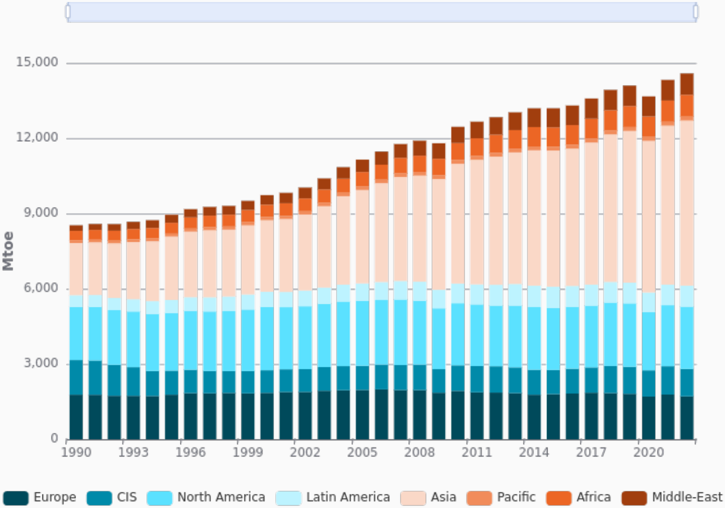
Demand Response or **Demand Side Management** refers to the manipulation and controlling of the demand to fulfill some requirements.

DR through the lens of Resource Management.

This is DR from the supplier point of view.

DR can be helpful when the demand is too high and it becomes expensive to level the supply with the demand.

Consumption trend.



The energy demand is increasing each year.

Note that the significant rise is from Asia. This is particularly due to China and India. However the alarming increase rate in 2023 belongs to India (7.3%, twice the 2010–2019 avg.) and Saudi Arabia.

However, the overall global consumption has slowed down during the past 2–3 years. In particular, we see a decrease (-3.3%) in Europe.

DR through the lens of Engery Transition.

This is more like DR from the consumer point of view.

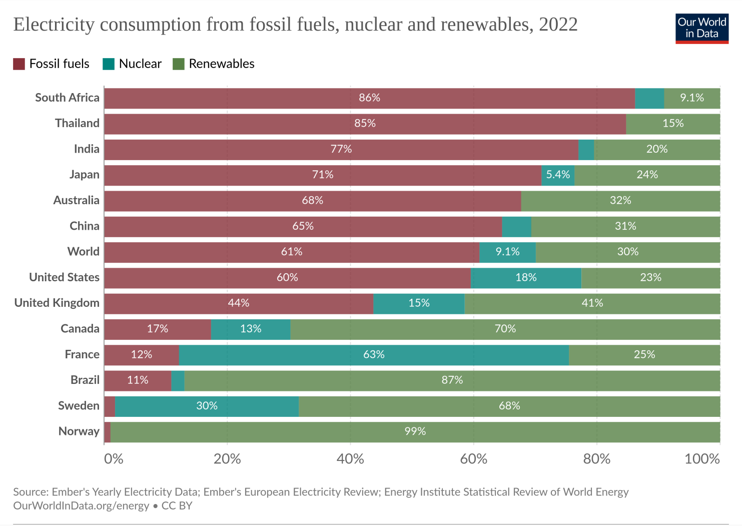
Renewables are highly uncertain. So we need to be more flexible and be able to freely schedule our loads.

What is flexibility?

We need to have options to...

- monitor consumption,
- choose energy sources at will (at any times!),
- produce and store energy when possible,
- schedule the use of each loads,
- etc.

Current energy mix.



Source: Ember's Yearly Electricity Data; Ember's European Electricity Review; Energy Institute Statistical Review of World Energy
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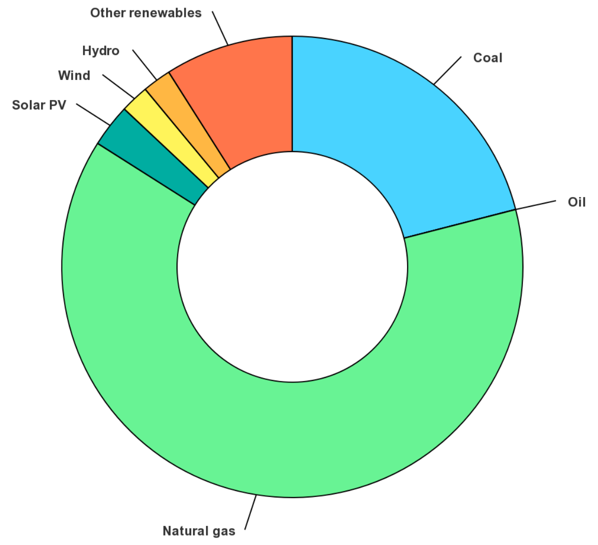
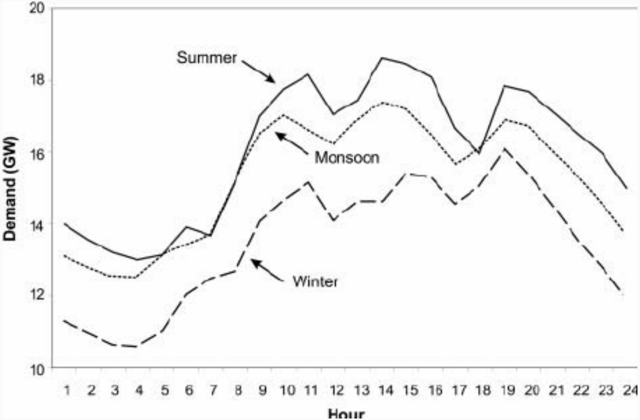
Current energy mix in Thailand.



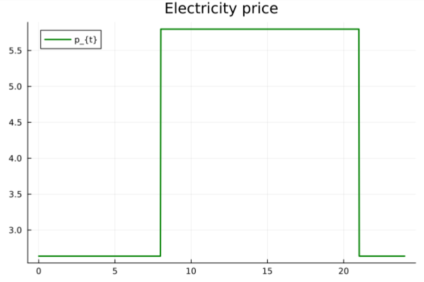
Daily demand (in Thailand) and what we can do.



In Thailand, the intensive use of electricity occurs during 9AM – 9PM (on-peak period).

Can we shift these needs to other time (off-peak period) ? **How ?**

Incentives to decrease the demand.



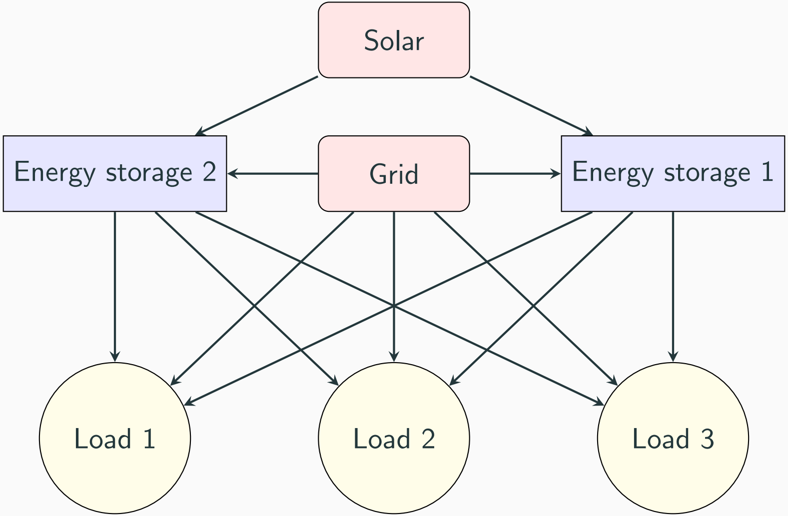
To control the demand, a higher price is put on the on-peak period for large consumers.

As a result, some of the loads are shifted (if allowed) to the off-peak period for cheaper operations. **How to do this optimally?**

This is our objective: **to propose a DR model that optimally schedule loads exploiting the grid price and a renewable integration (solar).**

Our Optimal Load Scheduling Model

Energy topology



Indices

T	The number of time slots in a day.
S	The number of all storages available in the system.
$\bar{S}$	The energy source index set $\{1, \cdots, S\} \cup \{grid\}$ comprising of grid and storages.
A^I	The set of all interruptable appliances.
A^U	The set of all uninterruptable appliances.
t	The time index which is an integer ranging from 1 to T.
s	The storage index which is either an integer ranging from 1 to S or $s = grid$.
a	The appliance index taken either from the set A_I or A_U.

Parameters

p_t	The energy purchasing price from the national grid at the time t.
$r_{a,t}$	The energy required to operate the appliance a during the time slot t.
d_a	The daily demand required from the operation of appliance a. For interruptable loads, d_a is the required number operation time slots. For uninterruptable loads, d_a is the required number of starts of operations.
ℓ_a	The duration (number of time slots) that is required to complete an operation of $a \in A_U$.
κ^s	The energy capacity of a storage s.
ρ^s	The maximum charging rate of a storage s.
σ_t	The availability of the solar generated energy at the time t.
$q_{a,t}$	The monetary inconvenience cost to opearate the appliance a at the time t.

Variables

$z_{a,t}^{grid}$	The binary decision to operate the appliance a at the time t using the energy from the grid.
$z_{a,t}^{s}$	The binary decision to operate the appliance a at the time t using the energy from the storage s at time t.
$y_{a,t}$	The binary decision to start the operation of an uninterruptable appliance $a \in A^U$ at the time t.
$e_t^{s,grid}$	The decided amount of energy from the grid that is used for charging the storage s at time t.
$e_t^{s,solar}$	The decided amount of energy from the solar generator that is used for charging the storage s at time t.
e_t^{s}	The state variable describing the available energy in the storage s at time t.

Storage model

Charge-discharge dynamics:

$$e^s_{t+1} = e^s_t - \sum_{a \in A^I \cup A^U} r_{a,t} z^s_{a,t} + e^{s,grid}_t + e^{s,solar}_t,$$

Capacity constraint: $e^s_t \leq \kappa^s$,

Discharge constraint: $\sum_{a \in A^I \cup A^U} r_{a,t} z^s_{a,t} \leq e^s_t$,

Solar availability constraint: $\sum_{s \in S} e^{s,solar}_t \leq \sigma_t$,

Charging rate constraing: $e^{s,grid}_t, e^{s,solar}_t \leq \rho^s$.

Interruptable load model

Required operating hours constraints: $\sum_{s\in\bar{S}}\sum_{t=1}^{T} z_{a,t}^{s} \geq d_a$

Single active source constraint: $\sum_{s\in\bar{S}} z_{a,t}^{s} \leq 1$,

Sufficient charge constraint: $r_{a,t} z_{a,t}^{s} \leq e_t^{s}$.

Uninterruptable load model

The constraints from the previous page are still required, with the following additional ones.

No overlapping start constraints:

$$\begin{aligned} y_{a,1} + y_{a,2} + \cdots + y_{a,\ell_a} &\leq 1 \\ y_{a,2} + y_{a,3} + \cdots + y_{a,\ell_a+1} &\leq 1 \\ &\vdots \\ y_{a,T-\ell_a} + y_{a,2} + \cdots + y_{a,T-1} &\leq 1 \\ y_{a,T-\ell_a+1} &\leq 1. \end{aligned}$$

Run-until-completion constraints:

$$\begin{aligned} z^s_{a,1}, \cdots, z^s_{a,\ell_a} &\geq y_{a,1} \\ z^s_{a,2}, \cdots, z^s_{a,\ell_a+1} &\geq y_{a,2} \\ &\vdots \\ z^s_{a,T-\ell_a+1}, \cdots, z^s_{a,T} &\geq y_{a,T-\ell_a+1}. \end{aligned}$$

Disutility function

We model our disutility function as the actual payment together with the monetized inconvenience:

$$C = \underbrace{\sum_{a\in A}\sum_{t=1}^{T} p_t e_{a,t}^{grid}}_{\text{Grid cost for appliances.}} + \underbrace{\sum_{s\in\bar{S}}\sum_{t=1}^{T} p_t e_t^{s,grid}}_{\text{Grid cost for charging.}} + \beta \underbrace{\sum_{a\in A}\sum_{s\in\bar{S}}\sum_{t=1}^{T} q_{a,t} z_{a,t}^{s}}_{\text{Inconvenience cost.}}$$

Putting everything together.

$$\min_{z^{grid}_{a,t},\, z^{s}_{a,t},\, y_{a,t},\, e^{s,grid}_{t},\, e^{s,solar}_{t},\, e^{s}_{t}} \quad \sum_{a\in A}\sum_{t=1}^{T} p_t r_{a,t} z^{grid}_{a,t} + \sum_{s\in\bar{S}}\sum_{t=1}^{T} p_t e^{s,grid}_{t} + \beta \sum_{a\in A}\sum_{s\in\bar{S}}\sum_{t=1}^{T} q_{a,t} z^{s}_{a,t}$$

subject to

For all $s \in \bar{S}$ and $t = 1, \cdots, T$:

$$\left|\begin{array}{l}
e^{s}_{t+1} = e^{s}_{t} - \sum_{a\in A^{I}\cup A^{U}} r_{a,t} z^{s}_{a,t} + e^{s,grid}_{t} + e^{s,solar}_{t} \\
e^{s}_{t} \le \kappa^{s} \\
\sum_{a\in A^{I}\cup A^{U}} r_{a,t} z^{s}_{a,t} \le e^{s}_{t} \\
\sum_{s\in S} e^{s,solar}_{t} \le \sigma_t \\
e^{s,grid}_{t},\, e^{s,solar}_{t} \le \rho^{s}
\end{array}\right.$$

For all $s \in \bar{S}$, $a \in A^{I}$, $t = 1, \cdots, T$:

$$\left|\begin{array}{l}
\sum_{s\in\bar{S}} \sum_{t=1}^{T} z^{s}_{a,t} \ge d_a \\
\sum_{s\in\bar{S}} z^{s}_{a,t} \le 1
\end{array}\right.$$

For all $s \in \bar{S}$, $a \in A^{I} \cup A^{U}$, $t = 1, \cdots, T$:

$$\left|\begin{array}{l}
z^{grid}_{a,t},\, z^{s}_{a,t},\, y_{a,t},\, e^{s,grid}_{t},\, e^{s,solar}_{t},\, e^{s}_{t} \ge 0 \\
z^{grid}_{a,t},\, z^{s}_{a,t},\, y_{a,t} \in \{0,1\}.
\end{array}\right.$$

For all $s \in \bar{S}$, $a \in A^{U}$, $t = 1, \cdots, T$:

$$\left|\begin{array}{l}
y_{a,1} + y_{a,2} + \cdots + y_{a,\ell_a} \le 1 \\
y_{a,2} + y_{a,3} + \cdots + y_{a,\ell_a+1} \le 1 \\
\qquad\qquad \vdots \\
y_{a,T-\ell_a} + y_{a,2} + \cdots + y_{a,T-1} \le 1 \\
y_{a,T-\ell_a+1} \le 1. \\
z^{s}_{a,1}, \cdots, z^{s}_{a,\ell_a} \ge y_{a,1} \\
z^{s}_{a,2}, \cdots, z^{s}_{a,\ell_a+1} \ge y_{a,2} \\
\qquad\qquad \vdots \\
z^{s}_{a,T-\ell_a+1}, \cdots, z^{s}_{a,T} \ge y_{a,T-\ell_a+1} \\
\sum_{t=1}^{T-\ell_a+1} y_{a,t} = d_a \\
\sum_{s\in\bar{S}} z^{s}_{a,t} \le 1
\end{array}\right.$$

Features in comparison

Models	**Model type**	**Advantages**	**Disadvatages**
Ours	MILP	Linear, Simple, Flexible.	Not distributed.
TS'12	MINLP	Flexible	Inexactly solved, Not distributed.
NZL'18	MIQP	Community-capable	Nonlinear, Not distributed, Single load type.
SXJ'14	MINLP	Direct baseline comparison.	

Some simulations

Approach

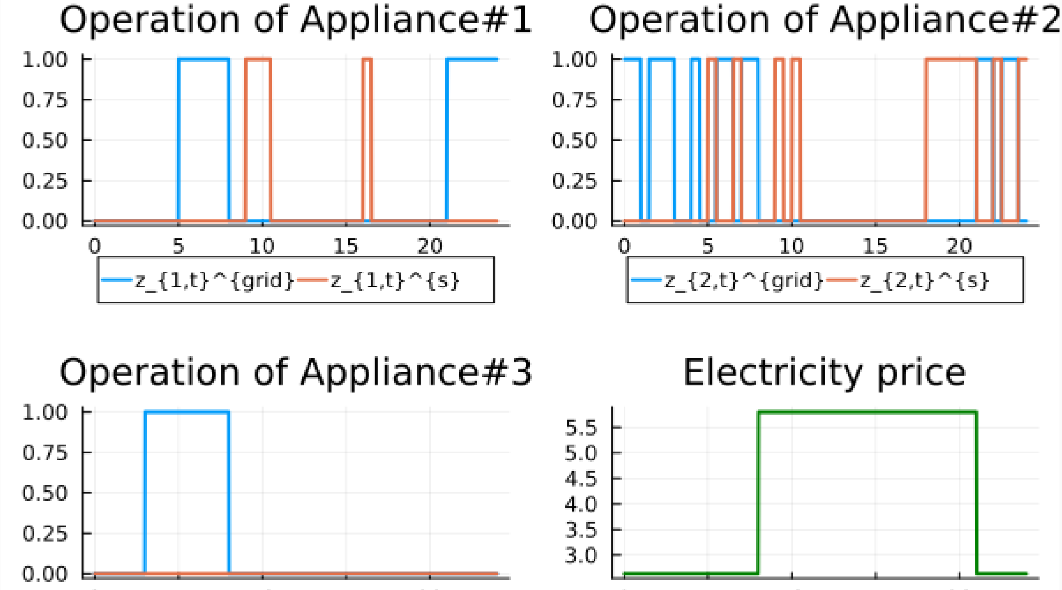
Since our model is a MILP, we can use literally any solver.

In our simulation, we used `Julia` Mahtematical Programming package, `JuMP`, with `Gurobi` solver.

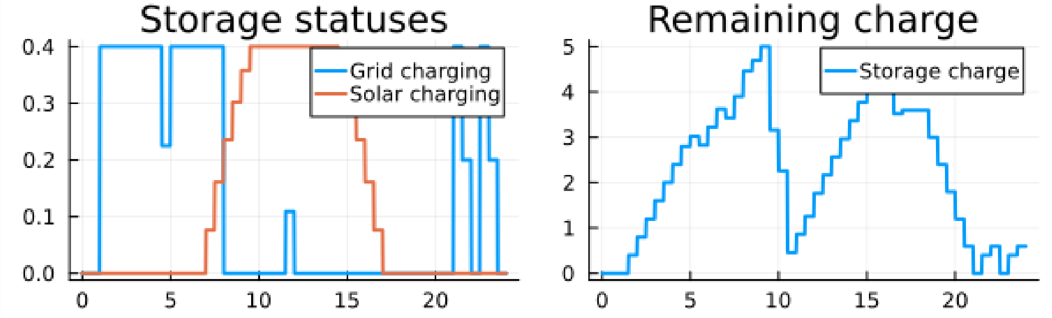
Presented here are some simulations of a topology of

- 3 scheulable loads. 2 interruptable and 1 uninterruptable.
- 1 storage unit.
- TOU pricing.

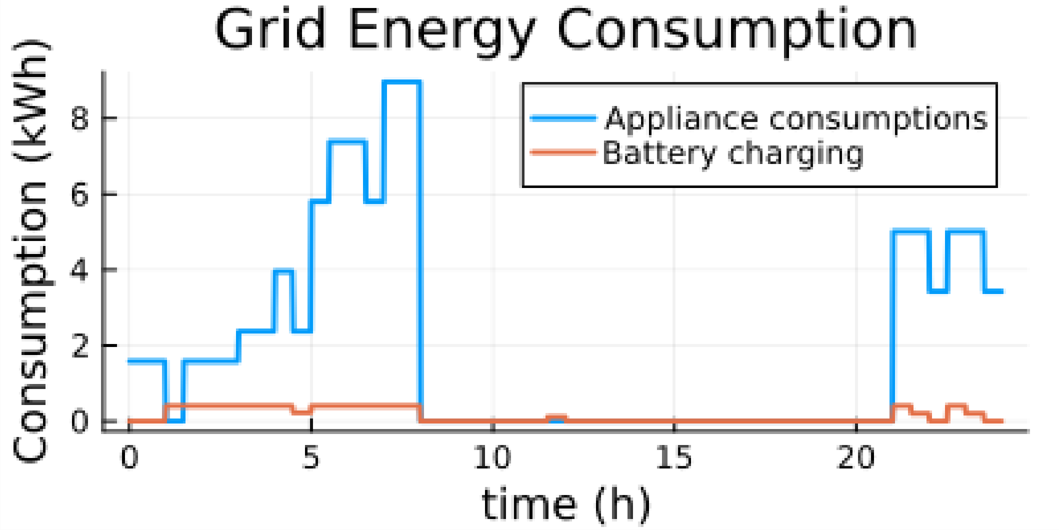
Simulation results (I)



Simulation results (I)



Simulation results (I)



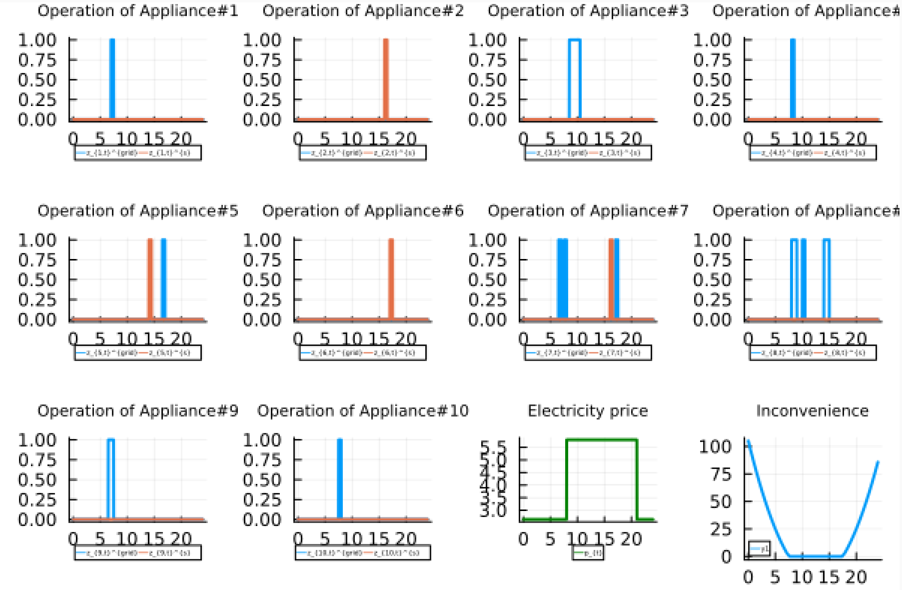
Simulation results (II)

We can play around with our models.

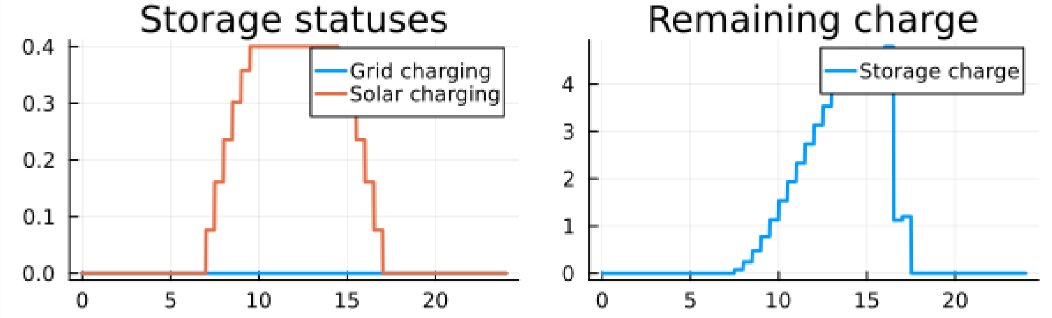
This time, we incorporate

- 10 loads.
- No grid charging.
- At most 2 loads are active at a time.
- Quadratic inconvenience parameters.

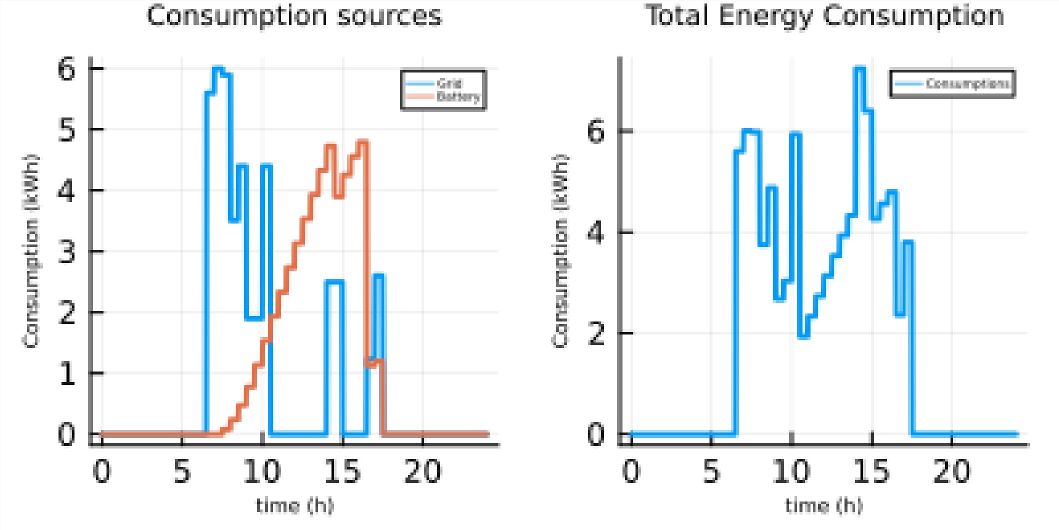
Simulation results (II)



Simulation results (II)



Simulation results (II)



Conclusions

We have developed a DR load scheduling model that is

- very simple
- linear
- flexible with loads
- flexible with consumer type
- flexible with preferences.

Thank you for being here. ;)