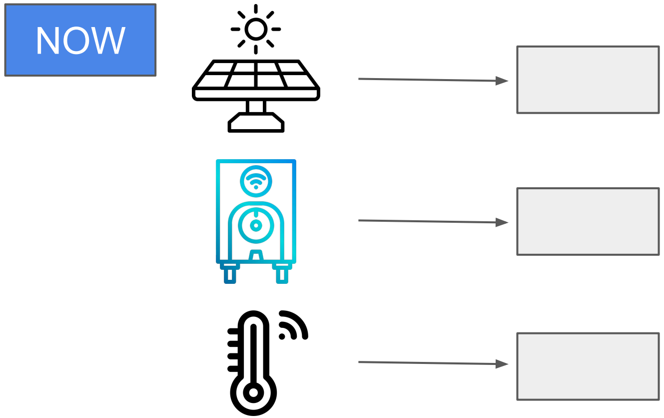
# Smart Homiez: Home DER Optimization

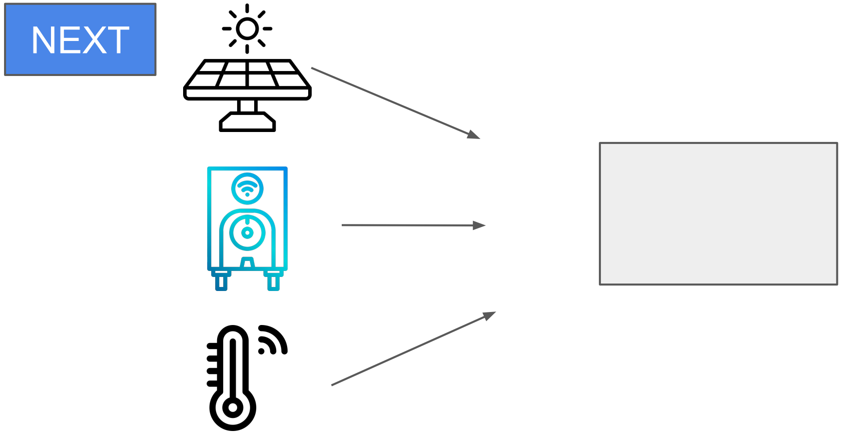
Talia Arauzo, Chitra Dangwal, Weixin Li, Dimitris Vlachogiannis, Karl Walter

Berkeley
UNIVERSITY OF CALIFORNIA

# Motivation & Background

- How can we optimize the energy consumption of in-home energy devices?
- What are the opportunities and benefits of co-optimization?



# PV - Modeling

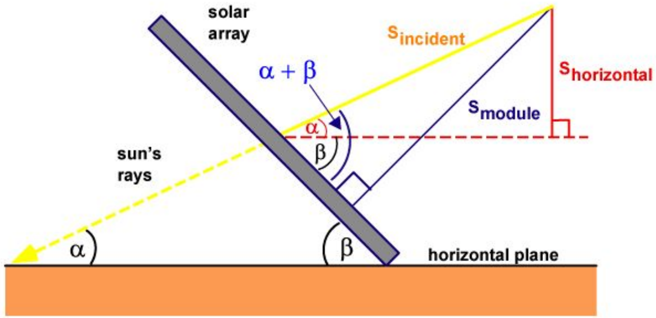
$$PV_{kw} = A_{panels} * S_{module} * \eta_{panels}$$

$$A_{panels} = n_{panels} * A_{panel}$$

$$S_{module} = GHI * \sin\left(\frac{\alpha + \beta}{\alpha}\right)$$

$$\alpha = 90 - \phi + \delta$$

$$\delta = 23.45 * \sin\left(\frac{360}{365} * (284 + d)\right)$$




$PV_{kw}$: power produced by solar photovoltaic (PV) array [kW]

$A_{panels}$: area of PV panels [$m^2$]

$S_{module}$: irradiant normal to surface of PV modules [kW / $m^2$]

$\eta_{panels}$: efficiency of PV

$n_{panels}$: number of PV panels

$A_{panel}$: area of single PV panel

$GHI$: global horizontal irradiance [kW / $m^2$]

$\alpha$: elevation angle [radians]

$\beta$: tilt of module [radians]

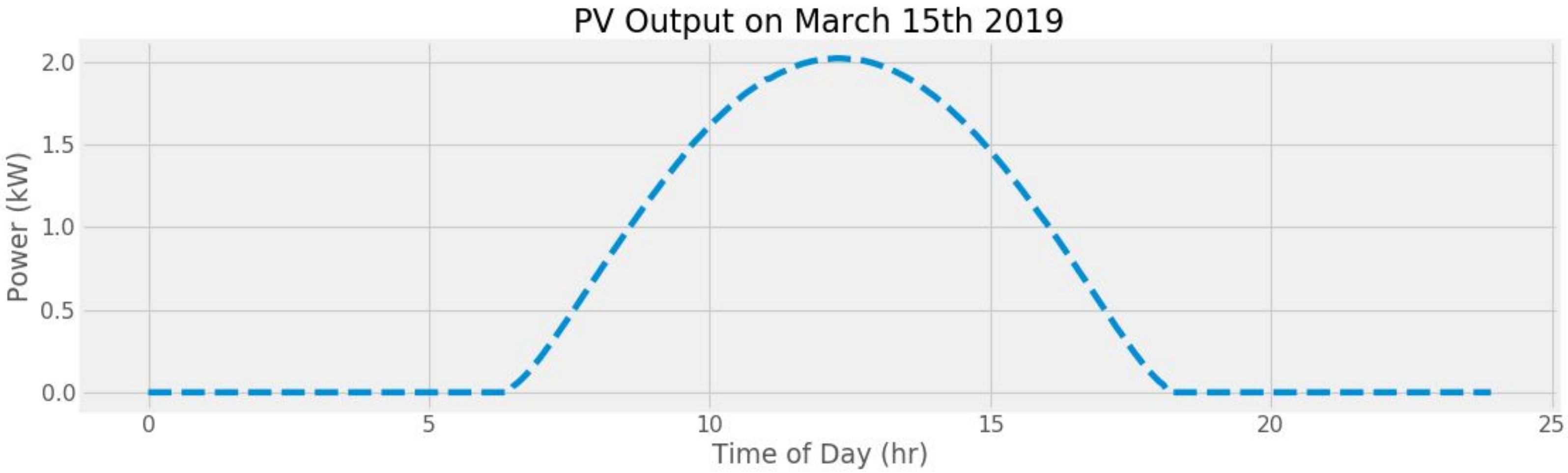
$d$: day of year [ ]

$\phi$: latitude of Berkeley [radians]

$\delta$: declination angle [radians]

Berkeley
UNIVERSITY OF CALIFORNIA

# PV - Results

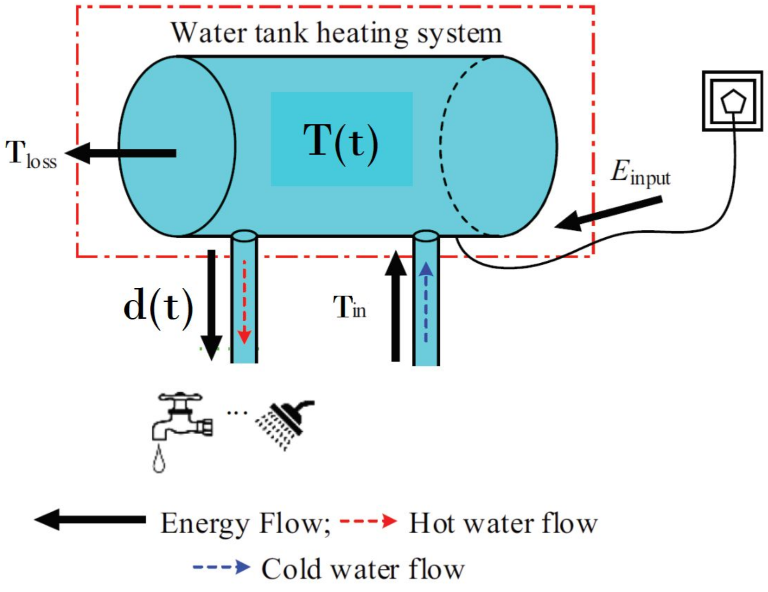

PV Output on March 15th 2019
Power (kW)
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
25
Time of Day (hr)

# Water Heater - Modeling

- Model water temperature in water heater
    - Based on “Appliance Commitment for Household Load Scheduling” by Du & Lu
    - 50 gal heater
    - Thermal dynamics incorporated
    - Exogenous household hot water demands

- Simplifying assumptions
    - Output water temperature is satisfactory for user
    - Water demands are constant
    - Heat transferring process is instantaneous

| | |
|---|---|
| $T(t)$ | Temperature inside the water heater |
| $T_{loss}$ | Temperature loss caused by temperature difference |
| $T_{in}$ | Temperature of cold water flowing into the tank |
| $d(t)$ | Volume of water usage |
| $E_{input}$ | Energy change used to heat water |



# Water Heater - Optimization

| Factors | |
|---|---|
| Penalty Function | $\alpha = 1$ |
| Input Matrix | $\beta = 10{,}000$ |

| Variables | |
|---|---|
| Temperature [˚C] | T (t) |
| State [0,1] | u(t) |
| TOU Pricing [$/kWh] | p(t) |
| Demand [gal] | d(t) |

| Physical Parameters | |
|---|---|
| Thermal Resistance | R = 1.52 ˚C/kW |
| Thermal Capacitance | C = 863.4 kWh/˚C |
| Heat Capacity | Q = 4 kW |
| Heater Mass | M = 50 gal |
| Initial Temperature | $T_o$ = 60 ˚C |
| Minimum Temperature | $T_{min}$ = 55 ˚C |
| Maximum Temperature | $T_{max}$ = 65 ˚C |
| Input Temperature | $T_{in}$ = 25 ˚C |

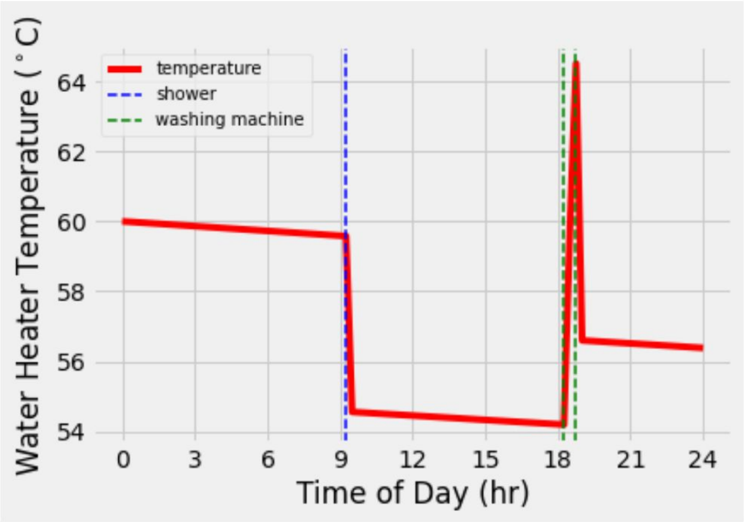
Objective Function:

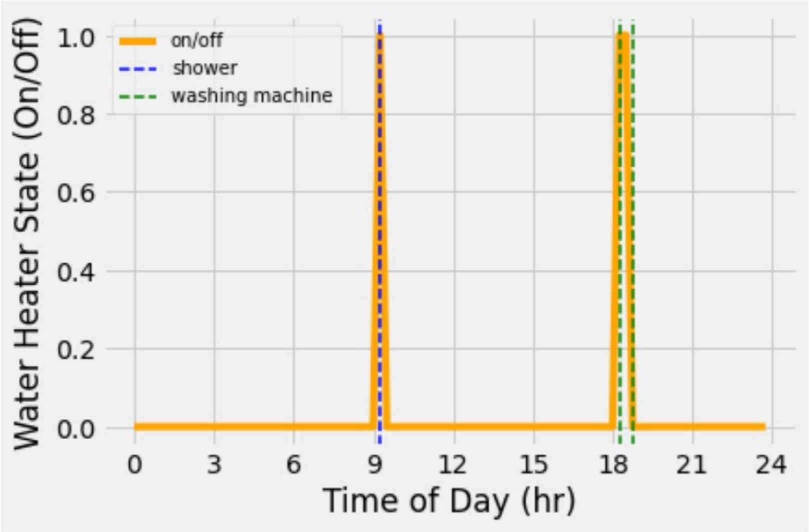
$$\min_{u(t),T(t)} \sum_{t=1}^{n} \underbrace{(p(t)\cdot Q\cdot u(t)\cdot dt)}_{\text{Cost Function}} + \underbrace{\frac{1}{2}\alpha\left[\max_{T(t)}(0, -T(t+1)+T_{min})\right]^2}_{\text{Penalty Function: } T(t+1)\geq T_{min}}$$

Constraints:

1) Initial temp: $T(0) = T_0$
2) Max temp: $T(t+1) \leq T_{max}$
3) Temp + demand: $T(t+1) = \underbrace{e^{\frac{-\Delta t}{RC}}}_{A}\left[\frac{M-d(t)}{M}T(t) + \frac{d(t)}{M}T_{in}\right] + \underbrace{\beta QR\left(1-e^{\frac{-\Delta t}{RC}}\right)}_{B}u(t)$

# Water Heater - Results: $0.91/day




Water Demands:

1. Shower (24 gal): 9-9:15 am
2. Washing machine (30 gal): 6-6:45 pm

Berkeley
UNIVERSITY OF CALIFORNIA

# HVAC - Modeling

Modelling Outlook:

- Thermal Model → Complexity can vary with amount of details being modelled
- Incorporation of no. of sources of heat gain and loss
- Simplified Model: Simplifying assumptions
  - 1 state thermal model chosen
  - Lowers the complexity of the in-depth physical model
  - Maintaining overall accuracy

| Variables | |
|---|---|
| Outdoor temperature [°C] | $T_{out}(t)$ |
| Indoor temperature [°C] | $T_{in}(t)$ |
| Thermal energy flow from the sun [kW] | $\emptyset_{ir}(t)$ |
| Thermal energy flow of the HVAC [kW] | $\emptyset_{H/A}(t)=P_{heat}Z_{heat}$ |
| On/Off state of HVAC [0,1] | $Z_{heat}$ |

**Thermal Model**

HVAC input

$$C\frac{dT_{in}}{dt} = \frac{1}{R_t}(T_{out} - T_{in}) + \emptyset_{H/A} + A(1-p)\emptyset_{ir} + n_{ac}V_{house}\rho_{air}C2(T_{out} - T_{in})/3600$$

Heat lost/gained to ambient

Solar energy gained

Air exchanges with the outside

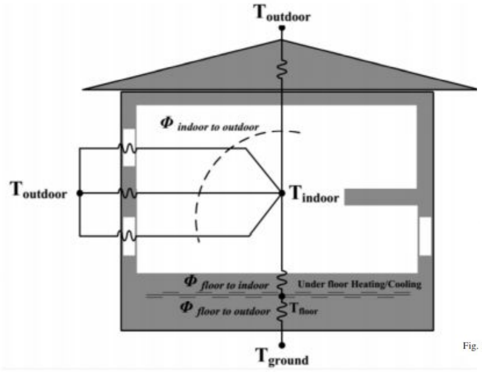



Fig. 1. Thermal modeling of a building.

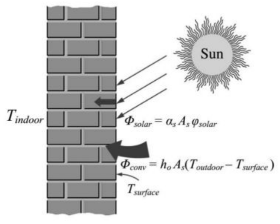



Fig. 2. Solar radiation effect on heating and cooling of a building.

Anvari-Moghaddam, Amjad, Hassan Monsef, and Ashkan Rahimi-Kian. "Optimal smart home energy management considering energy saving and a comfortable lifestyle." *IEEE Transactions on Smart Grid* 6.1 (2014): 324-332.

| |
|---|
| Exogenous input |
| Input to optimize |

# HVAC - Optimization

**Discrete Model:** $T(t_{k+1}) = A_d T(t_k) + B_d u(t_k)$

$$\begin{cases} A_d = e^{A\Delta t} = e^{\left(-\frac{1}{CR}-\frac{n_{ac}V_{house}\rho_{air}C_2}{3600C}\right)\Delta t} \\ B_d = \frac{1}{C}\left[\frac{1}{R}+\frac{n_{ac}V_{house}\rho_{air}C_2}{3600} \quad 1 \quad A(1-p)\right]\frac{1}{\left(-\frac{1}{CR}-\frac{n_{ac}V_{house}\rho_{air}C_2}{3600C}\right)}\left(e^{\left(-\frac{1}{CR}-\frac{n_{ac}V_{house}\rho_{air}C_2}{3600C}\right)\Delta t}-1\right) \end{cases}$$

Model Input:

$$u(t_k) = \begin{bmatrix} T_{out}(t_k) \\ \boxed{\emptyset_{H/A}(t_k)} \\ \emptyset_{ir}(t_k) \end{bmatrix}$$

**Model Optimization:** For specified heating power, optimize the variable "z(t)" i.e. ON/OFF state of HVAC $\emptyset_{H/A}(t_k) = P_{heat} z(t_k)$

**Objective function:**

$$\min_{z(t)} \sum_{t=1}^{n} p(t) \cdot P_{heat} \cdot z(t)$$

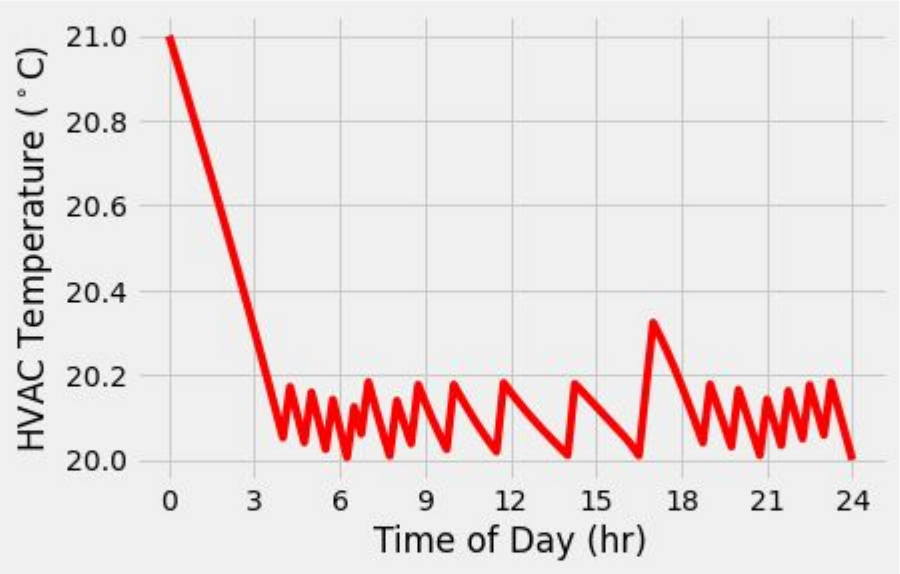
**Constraints :**

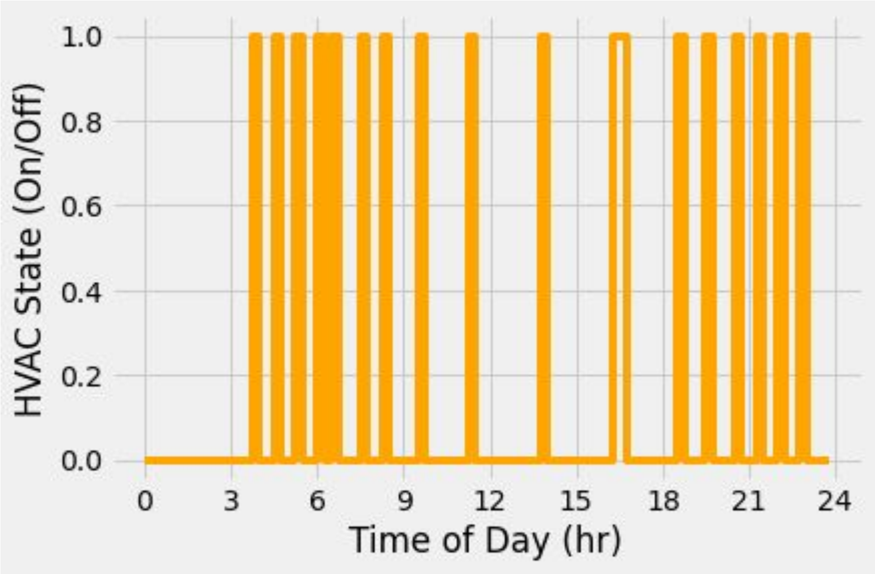
1. Initial condition $T(0) = T_0$
2. Max temp. $T(t_k) \le T_{max}$
3. Minimum temp. $T(t_k) \ge T_{min}$

| Physical Parameters | |
|---|---|
| Capacity of the total indoor air's heat | C=8.12 [kWh/°C]<br>C2=1214.4/$\rho_{air}$ [J/(kg*°C)] |
| Heating power of the HVAC [kW] | $P_{heat}$=60*$A_{floor}$/1000 |
| Total resistance against heat flow [°C/kW] | $R_t$=8.02 |
| Area of the floor/window [m²] | $A_{window}$=4<br>$A_{floor}$=100 |
| Volume of the house [m3] | $V_{house}$=300 |
| Part of the irradiation of sun directly observed by window | P=0.995 |
| Air density [kg/m3] | $\rho_{air}$=1.2 |
| Number of air change of the house [1/hr] | $n_{air}$=0.35 |
| Minimum temperature | $T_{min}$=20 |
| Maximum temperature | $T_{max}$=24 |
| Initial temperature | $T_o$=21 |

Berkeley
UNIVERSITY OF CALIFORNIA

# HVAC - Results: $7.99/day



# Next Steps

1

**Co-Optimize:** Limit consumption to solar production, i.e., $E_{WH} + E_{HVAC} \leq \beta E_{solar}$

2

**Explore Robust Optimization:** Investigate using uncertain demand scenarios

Berkeley
UNIVERSITY OF CALIFORNIA

# Thank you!

# Questions?