Physically based modeling for predictive simulation of a net-zero home

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Abstract

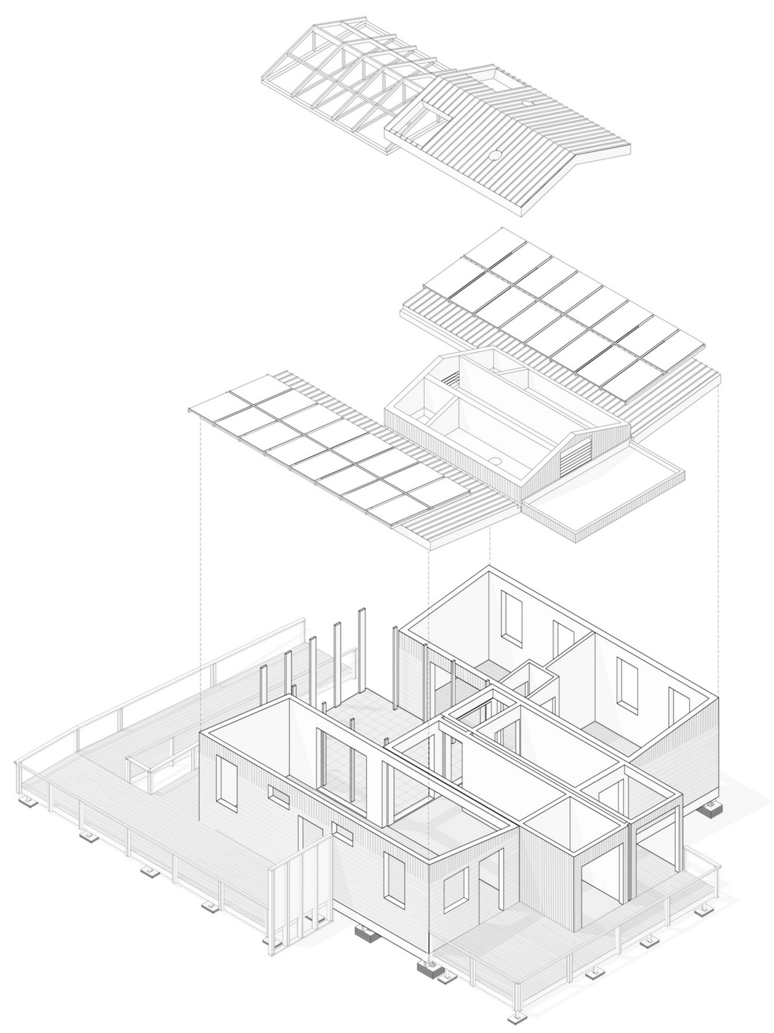
"The U.S. Department of Energy Solar Decathlon is a collegiate competition made up of 10 contests that challenge student teams to design and build full-size, solar-powered houses. The winner of the competition is the team that best blends design excellence and smart energy production with innovation, market potential, and energy and water efficiency." *solardecathlon.gov*

Figure 1: 9 October 2017, Denver, CO

Project overview

re*ACT*: **r**esilient **A**daptive **C**limate **T**echnology

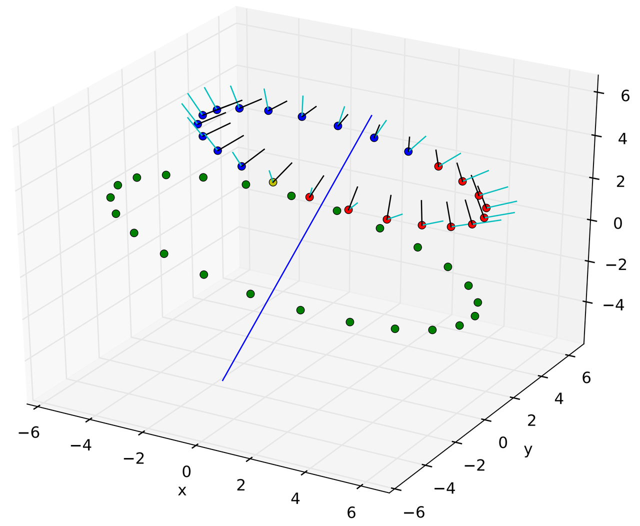
- An objective of re*ACT*'s design is the ability to adapt to both the location in which it is constructed as well as its environment that will change continuously over multiple timescales.
- To maximize our measures of sustainability, re*ACT* must be able to use or recycle low-value resources that would otherwise go to waste. Adaptability means self-awareness, and so re*ACT* must be able to predict its state over a reasonable time horizon so that it can work with the homeowners on the best use of resources over the upcoming day, or to carry out those tasks autonomously.



Modeling elements

- Irradiance, projection modeling for PV power and outside-wall heat transfer:

$$E_G = \left[E_{sc} \times 0.73^{(AM^{0.678})}\right](0.11 + \cos\zeta_{tilt})$$



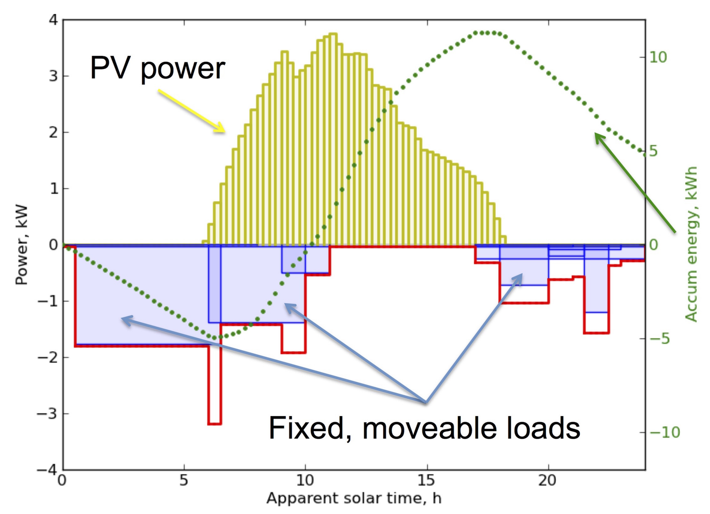
- PV cell I versus V:

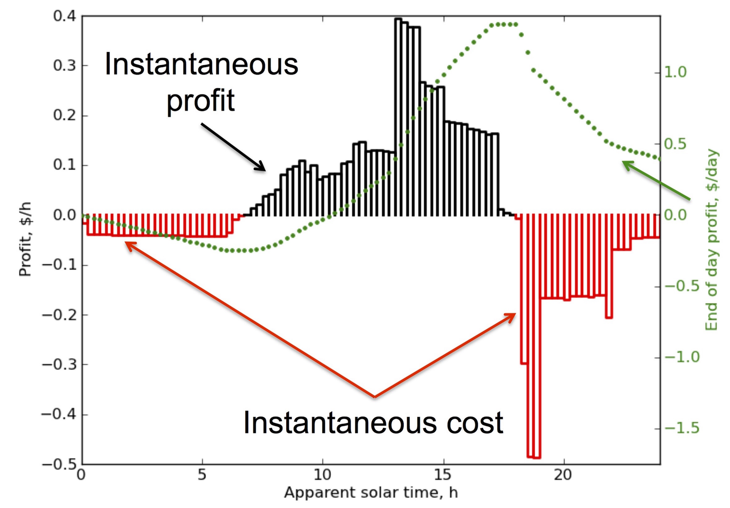
$$I = -I_{ph}X(t) + I_o\left[\exp\left(q\frac{V - IR_s}{\beta kT}\right) - 1\right] + \frac{V - IR_s}{R_{sh}}$$

with parameters estimated using a regularization procedure

- Scheduled-load XML tree structure:

```
<nominalDayEvents>
  <event>
    <title>Refrigerator/freezer</title>
    <startHour>0</startHour>
    <startMinute>00</startMinute>
    <duration units = 'min'>1440</duration>
    <load units = 'W'>47.6</load>
    <wasteHeat units = 'W'>47.6</wasteHeat>
    <CO2 units = 'mol/s'>0</CO2>
    <potableUse units = 'gal/min'>0</potableUse>
    <greywaterUse units = 'gal/min'>0</greywaterUse>
    <greywaterProd units = 'gal/min'>0</greywaterProd>
    <comment>'Manufacturer data'</comment>
  </event>
    ...
```





- Room level thermal modeling, HVAC model elements, water, CO_2 balances, etc. $\Longrightarrow \approx$ 10,000 lines of Python code.

Sustainability metrics

Electrical energy

A traditional measure of sustainability defined by the difference between the PV power production integrated over the day and the energy consumption of fixed and variable loads. House primary battery storage charge/discharge is not included in this calculation, even if the battery is being charged from the grid.

Thermal energy

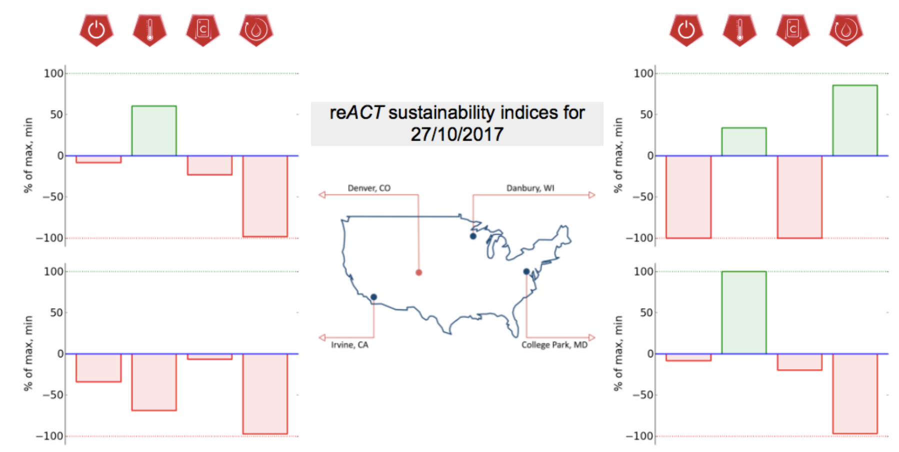
re*ACT*'s greenhouse-enclosed courtyard can be actively controlled to transform it into a thermal energy source or sink for the outdoor units of our heat-pump water heater and HVAC systems. Useable thermal energy stored in the thermal mass of the courtyard is a function of the temperature difference between the outdoor air and the courtyard; the utility of this thermal energy defines our thermal energy sustainability metric.

Water

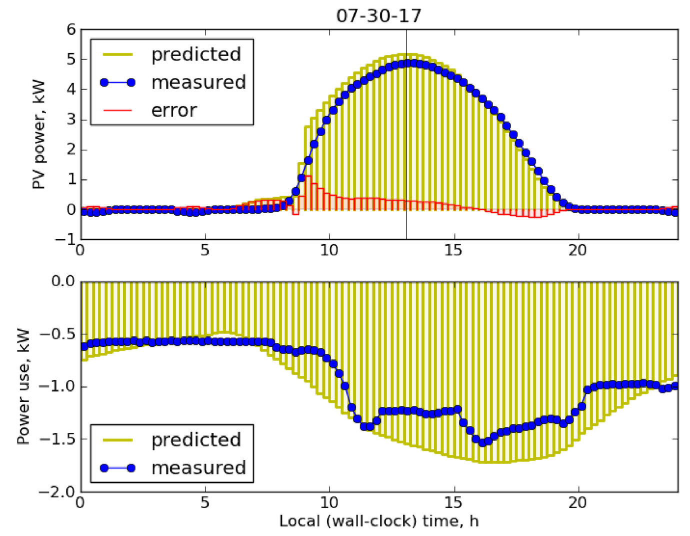
re*ACT* features rainwater harvesting and a sophisticated greywater filtration and disinfection system to reduce the need for purchasing potable water. Using our model-based estimation of house water resources and automated collection of precipitation forecast data, a water sustainability metric was developed based on a normalized ratio of reclaimed to total water daily use,

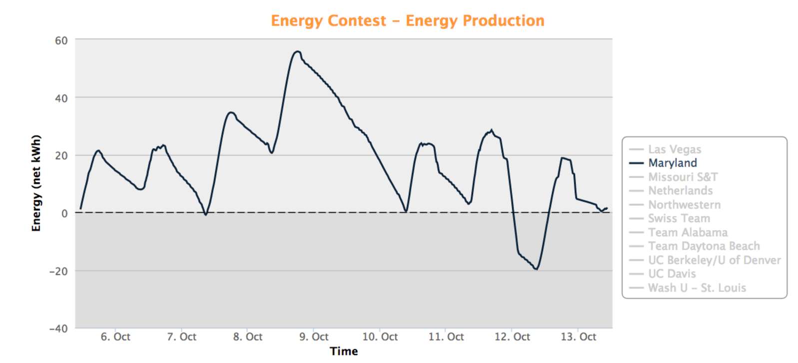
Reduced carbon

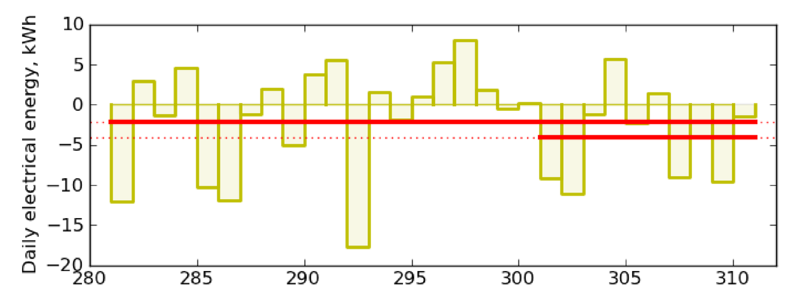
To quantify the rate of energy embodied as food in our green walls, hydroponic garden and planter boxes, we created a carbon sustainability metric based on the production of energy-rich (reduced) carbon compounds by the indoor and outdoor gardens relative to the house occupants' production of CO_2.



Model predictions and validation







Conclusion

We have developed a predictive physically based model of our Solar Decathlon house and demonstrated its utility in scheduling house resources.

Final Scores

Rank	Team	Score
1.	Swiss Team	872.910
2.	Maryland	822.683
3.	UC Berkeley/U of Denver	807.875
4.	Missouri S&T	758.315
5.	Team Alabama	757.873
6.	Northwestern	750.758
7.	Netherlands	750.275