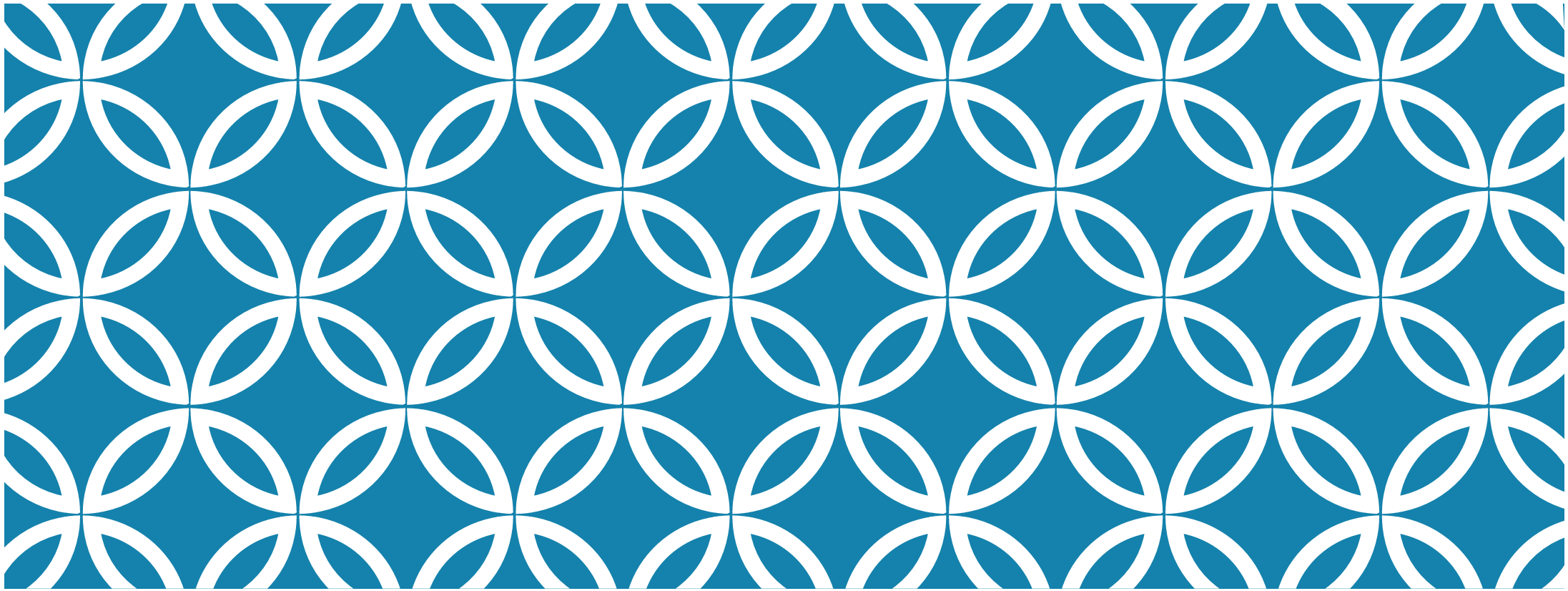
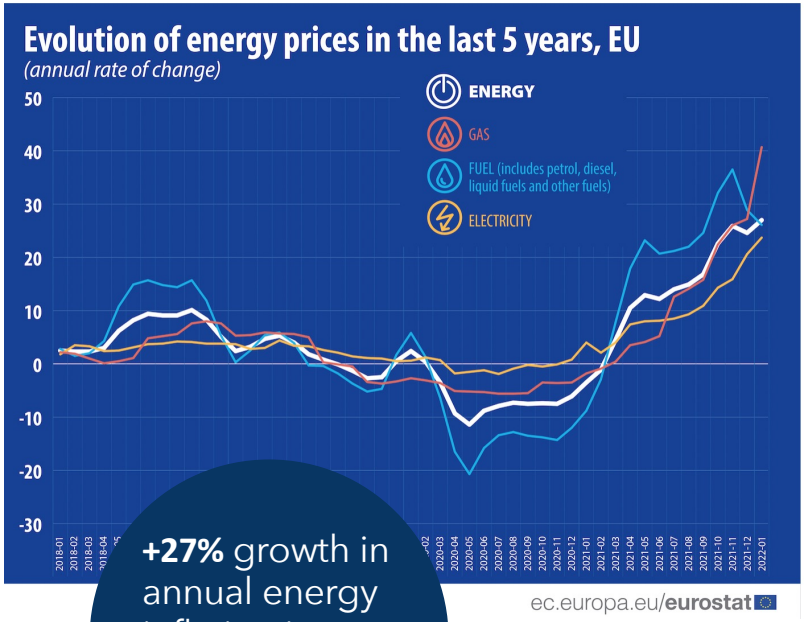


# DESIGNING PV-EV INTEGRATED RESIDENTIAL MICROGRIDS

Prof. Srinivasan Keshav
Department of Computer Science and Technology
University of Cambridge
November 9, 2023

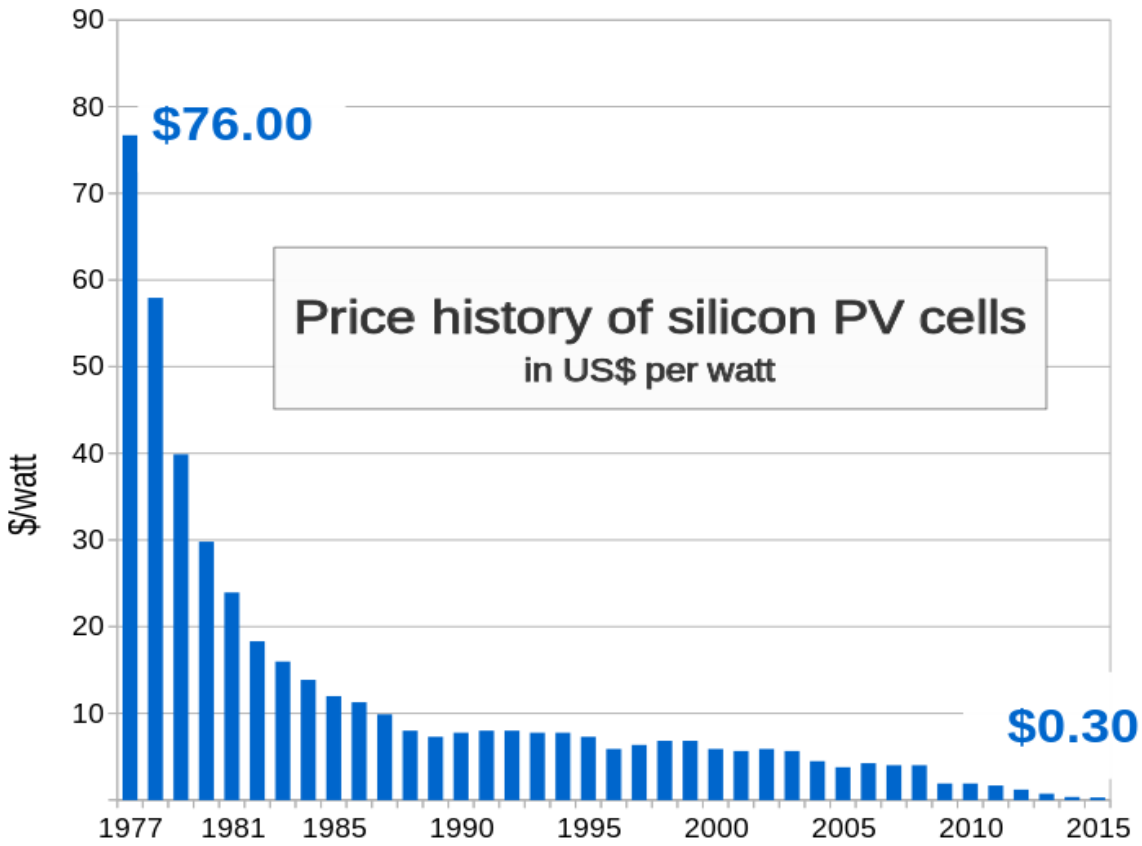
In collaboration with Fiodar Kazhamika, Brad Huang, Anais Berkes, and Benediktas Tarasovas

# CURRENT TRENDS




**+27%** growth in annual energy inflation in Europe (Jan 2022)

Src: eurostat

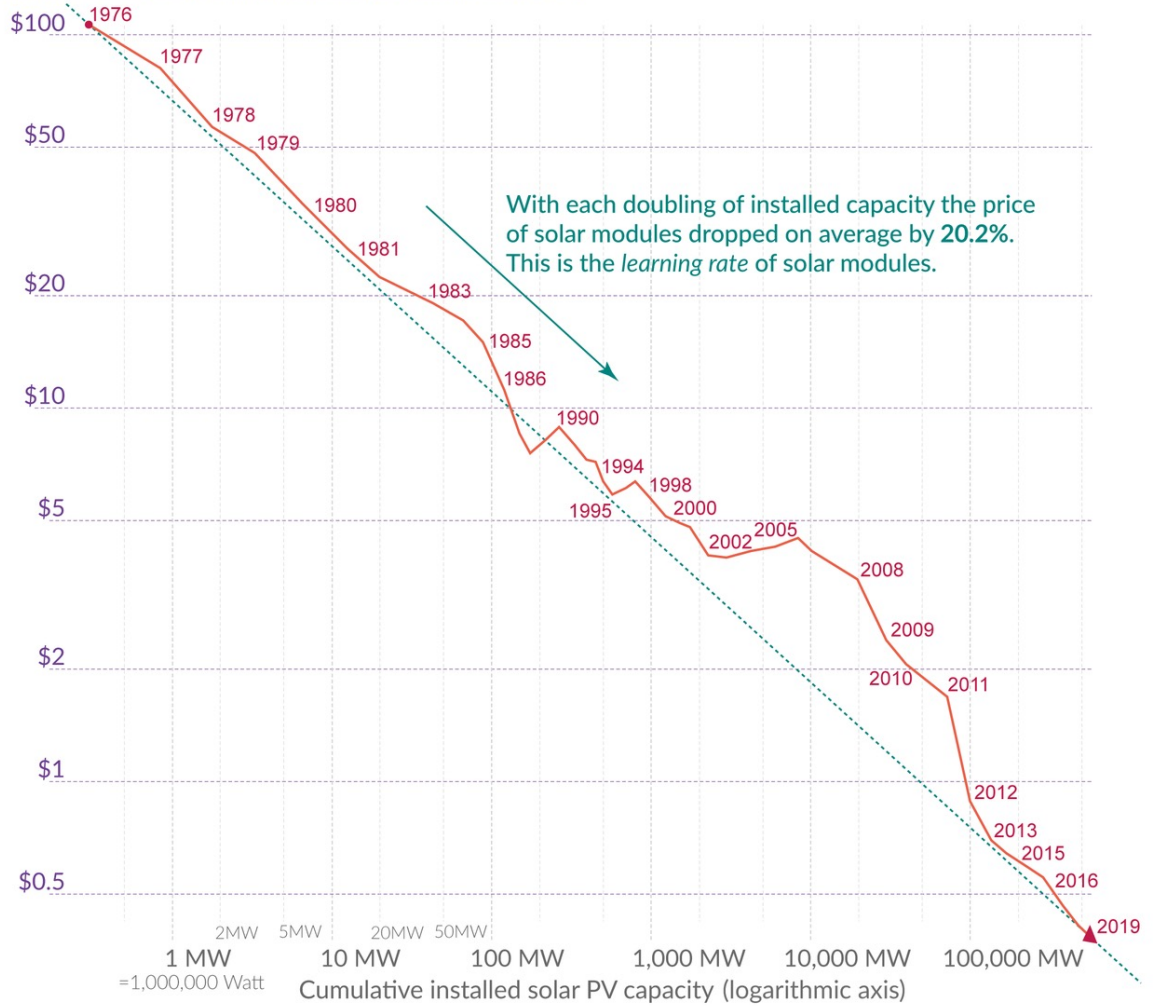



Source: Bloomberg New Energy Finance & pv.energytrend.com

# The price of solar modules declined by 99.6% since 1976

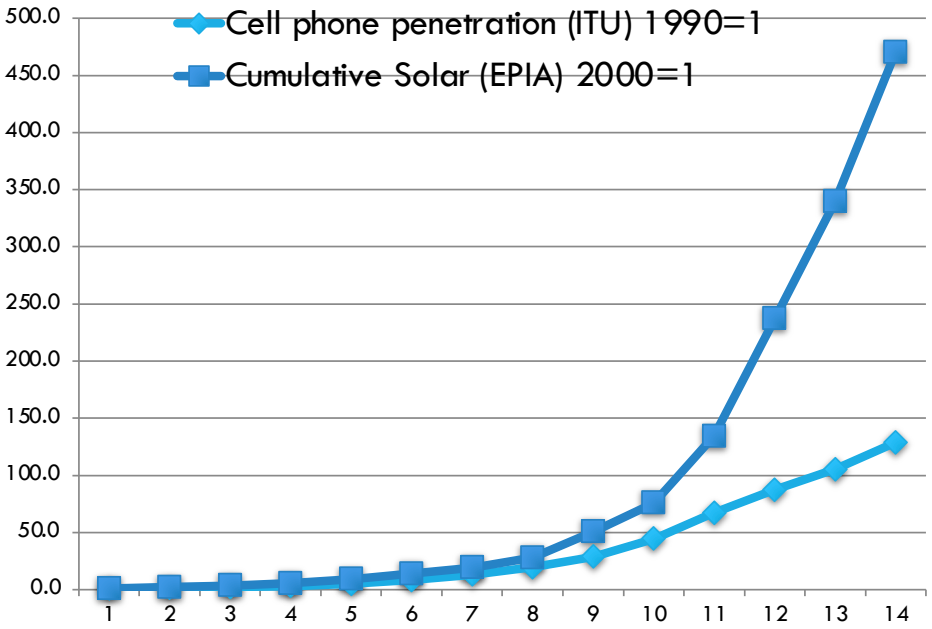
Our World in Data

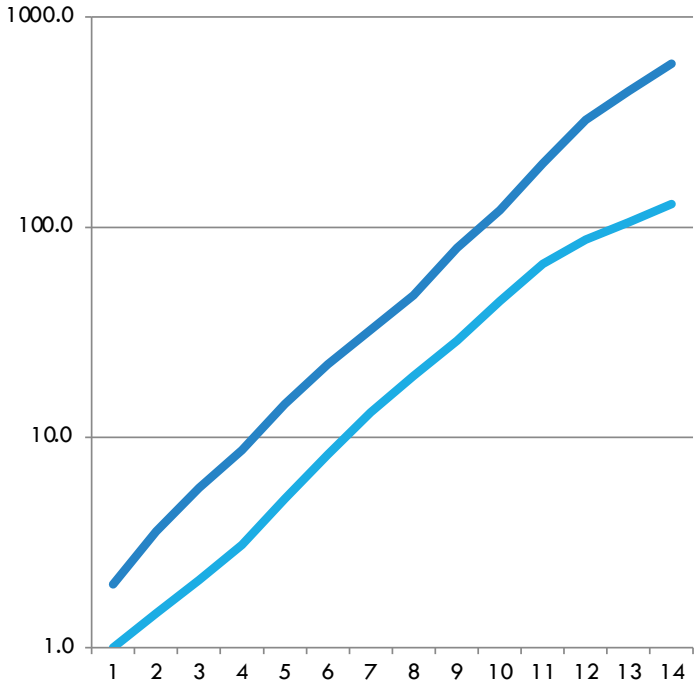
Price per Watt of solar photovoltaics (PV) modules (logarithmic axis)
The prices are adjusted for inflation and presented in 2019 US-$.




Data: Lafond et al. (2017) and IRENA Database; the reported learning rate is an average over several studies reported by de La Tour et al (2013) in Energy. The rate has remained very similar since then.
OurWorldinData.org – Research and data to make progress against the world's largest problems.

# Solar PV is growing as fast as cell phones

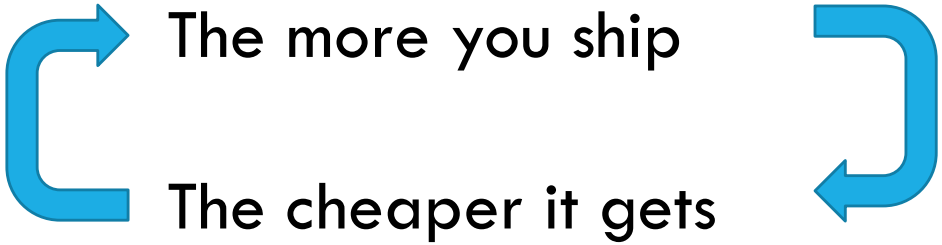


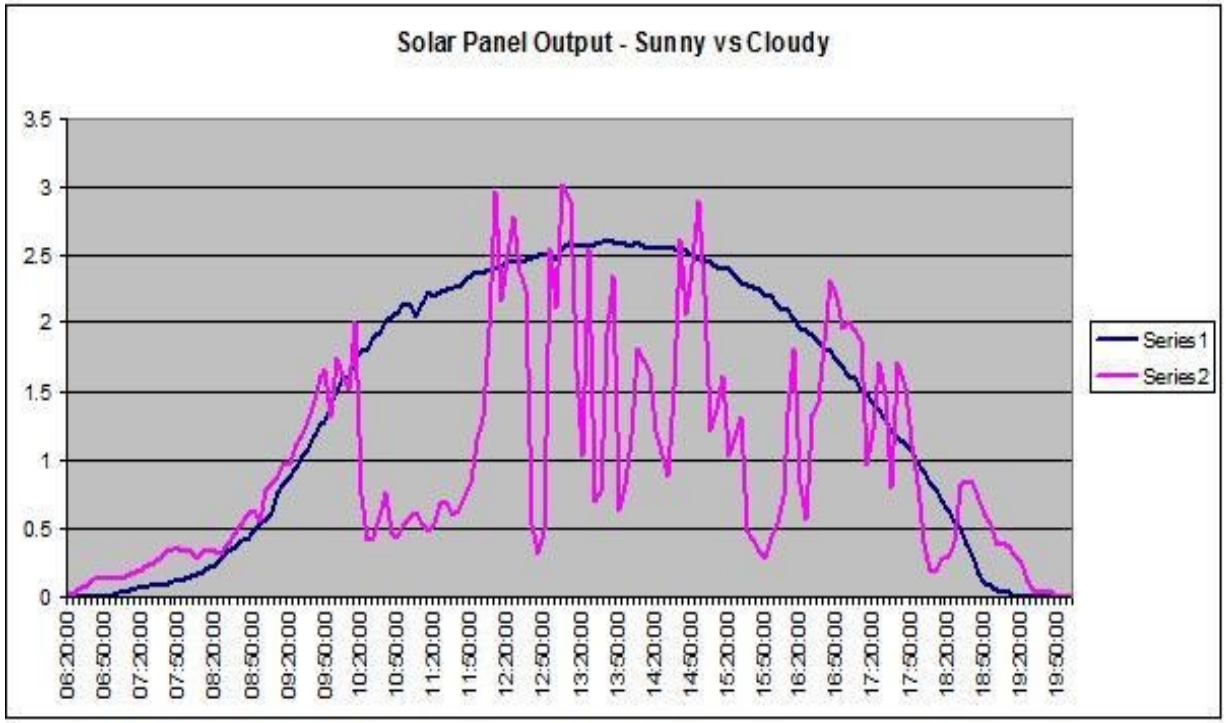

http://www.epia.org/fileadmin/user_upload/Publications/EPIA_Global_Market_Outlook_for_Photovoltaics_2014-2018_-_Medium_Res.pdf

http://stats.areppim.com/stats/stats_mobile.htm

# POSITIVE FEEDBACK LOOP



# BUT…




Makes it challenging to meet demand

# STORAGE

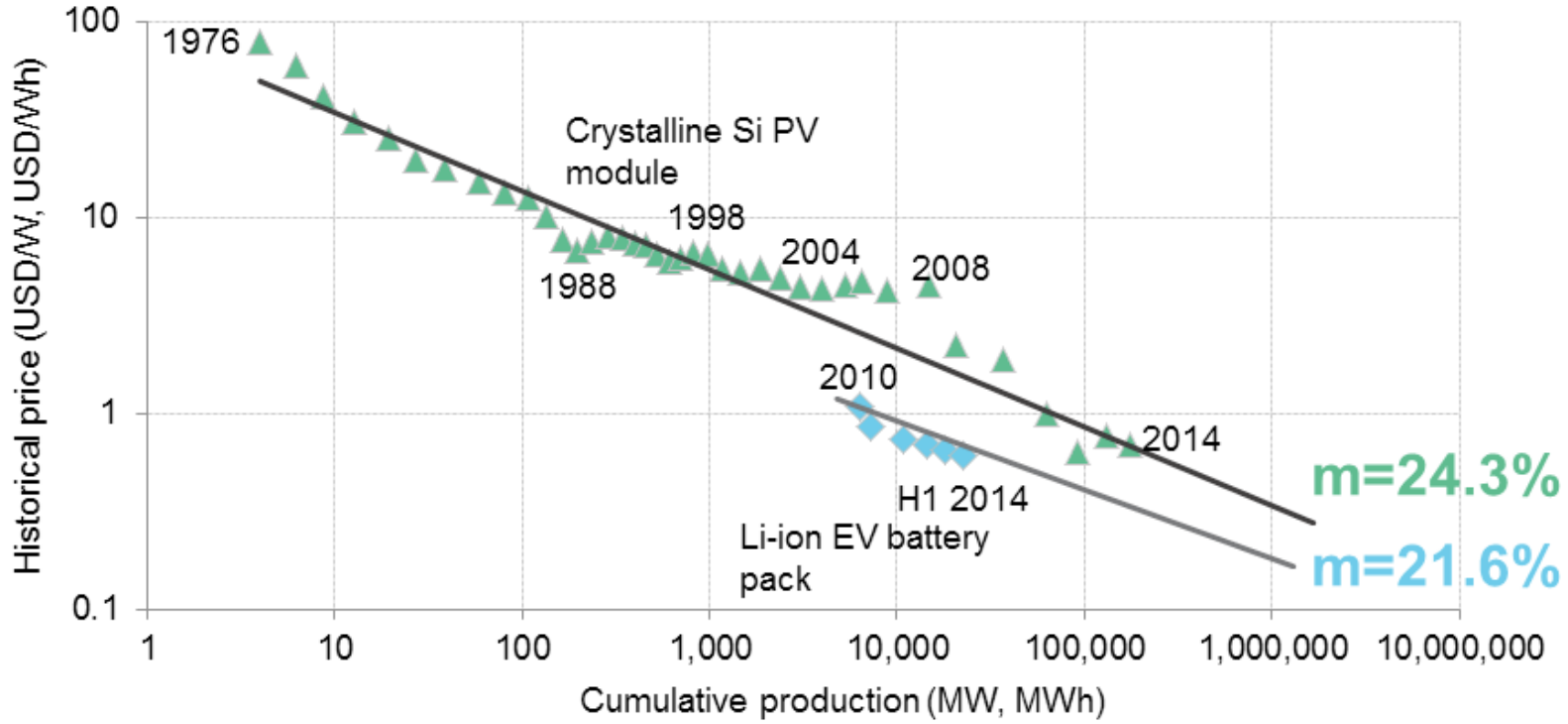
Decouples supply and demand

Allows

- Reliability
- Flexibility

# LITHIUM-ION EV BATTERY EXPERIENCE CURVE COMPARED WITH SOLAR PV EXPERIENCE CURVE

Bloomberg NEW ENERGY FINANCE

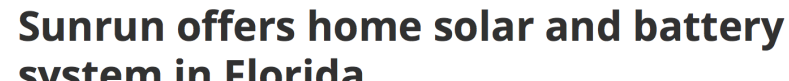



Note: Prices are in real (2014) USD.

Source: Bloomberg New Energy Finance, Maycock, Battery University, MIT

# SOLAR AND STORAGE ARE IN THE NEWS…



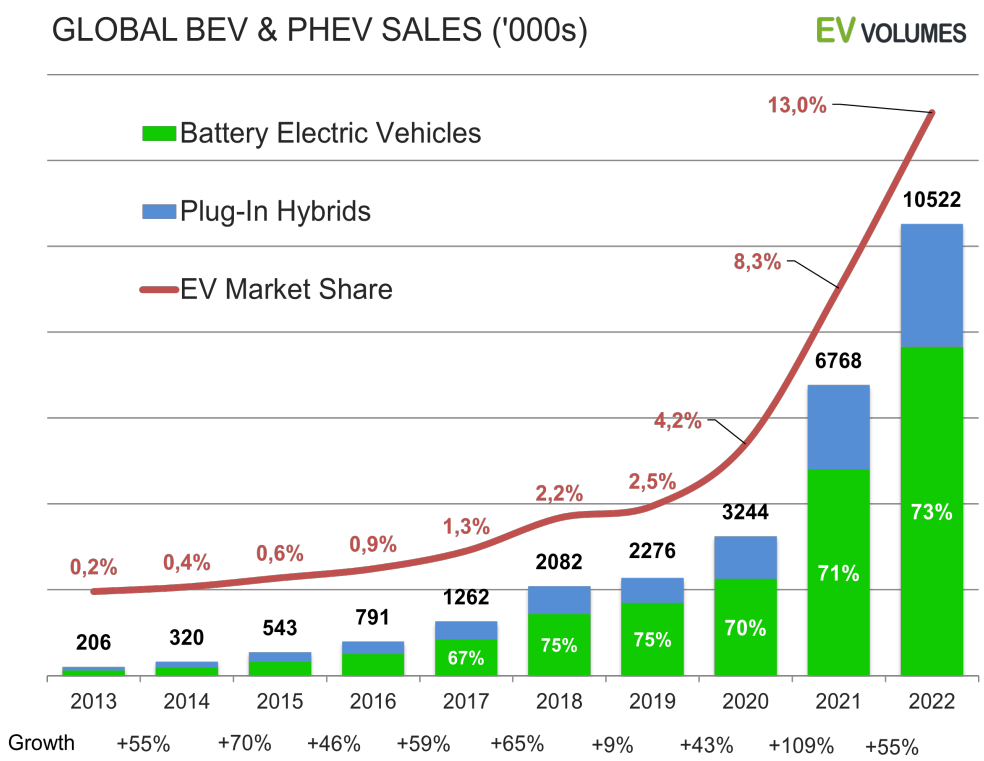









# BUT THERE IS MORE…




https://www.ev-volumes.com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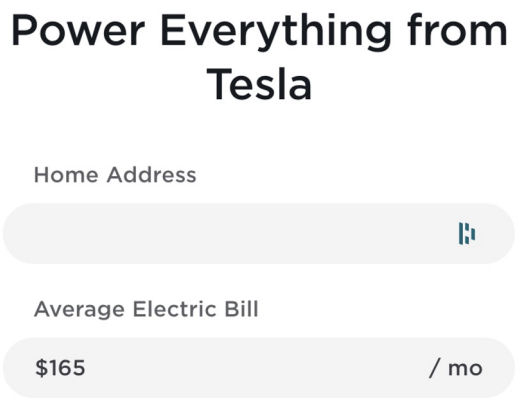
# THREE PRAGMATIC ISSUES

System cost is going down, but still expensive ($10,000's)

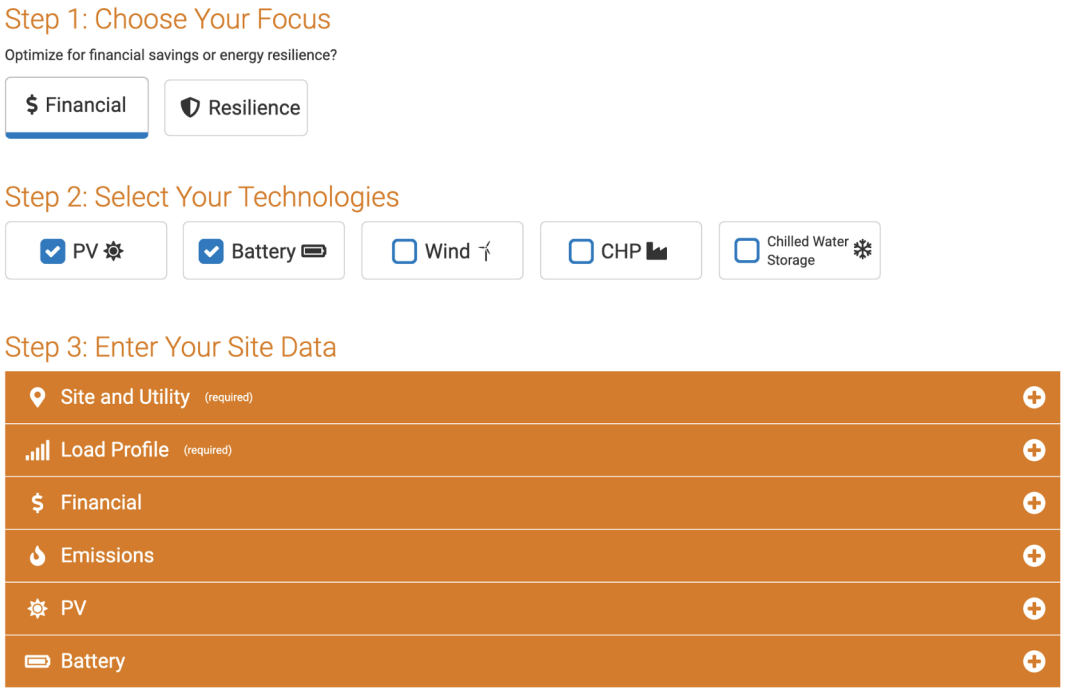
- How much to buy? (Sizing)
- How to place it? (Placement)
- When to charge and discharge the EV/home store? (Operation)

# SIZING

## Tesla Preliminary Calculator




## NREL ReOpt



# OUR APPROACH

## Data-driven

Finds most economical combination to achieve a quality of service target:

loss-of-load probability (LOLP)

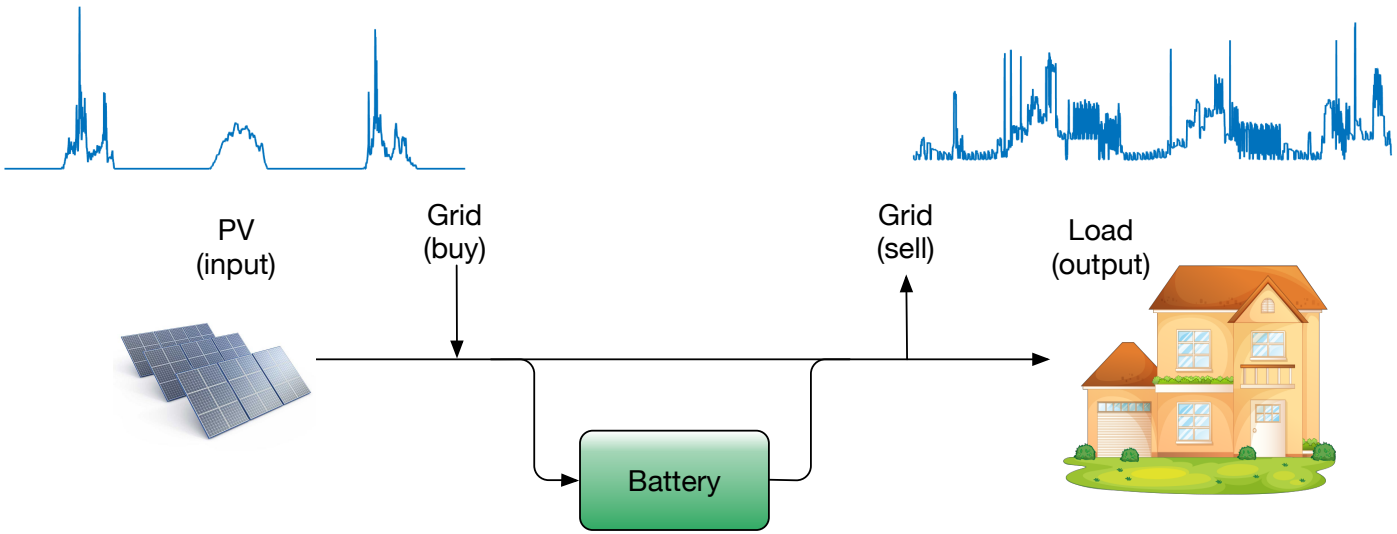
## Practical

Uses limited historical load and solar irradiance data

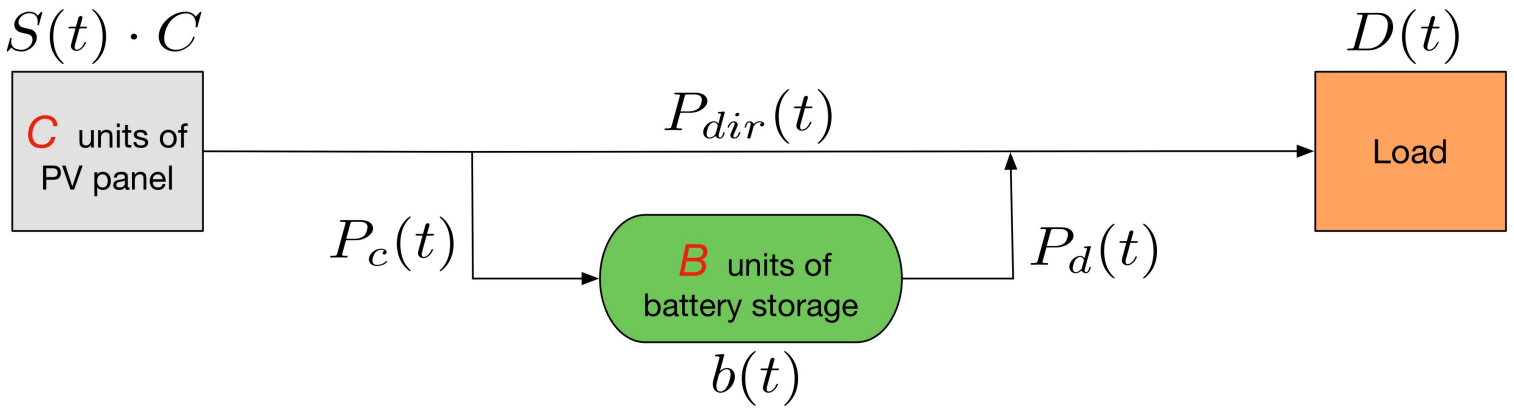
## Robust

Confidence in meeting the loss of load target despite future being unknown

# DATA



# SYSTEM MODEL




LOLP probability that $P_{dir}(t) + P_d(t) < D(t)$

Operating policy Decide $P_c(t), P_d(t)$

# PERFORMANCE TARGET

Target

- The system should meet most of the load, most of the time
- The probability that the system meets over $\theta$ fraction of the load over any fixed length period should be lower bounded by $\gamma$

$$Pr\left(\sum_{t}^{T}(P_{dir}(t)+P_{d}(t)) \geq \sum_{t}^{T} D(t)\theta\right) \geq \gamma$$

# COUPLING

# IDEA: SIMULATION OF OPERATION FOR EACH SIZE

Input: trace pair $<S_i,D_i>$, target, operating policy

Method:

- For a given *B* and C, simulate the process of power flowing through the system
- Search for cheapest *B* and C that meet target LOLP
- Tradeoff between B and C (why?)

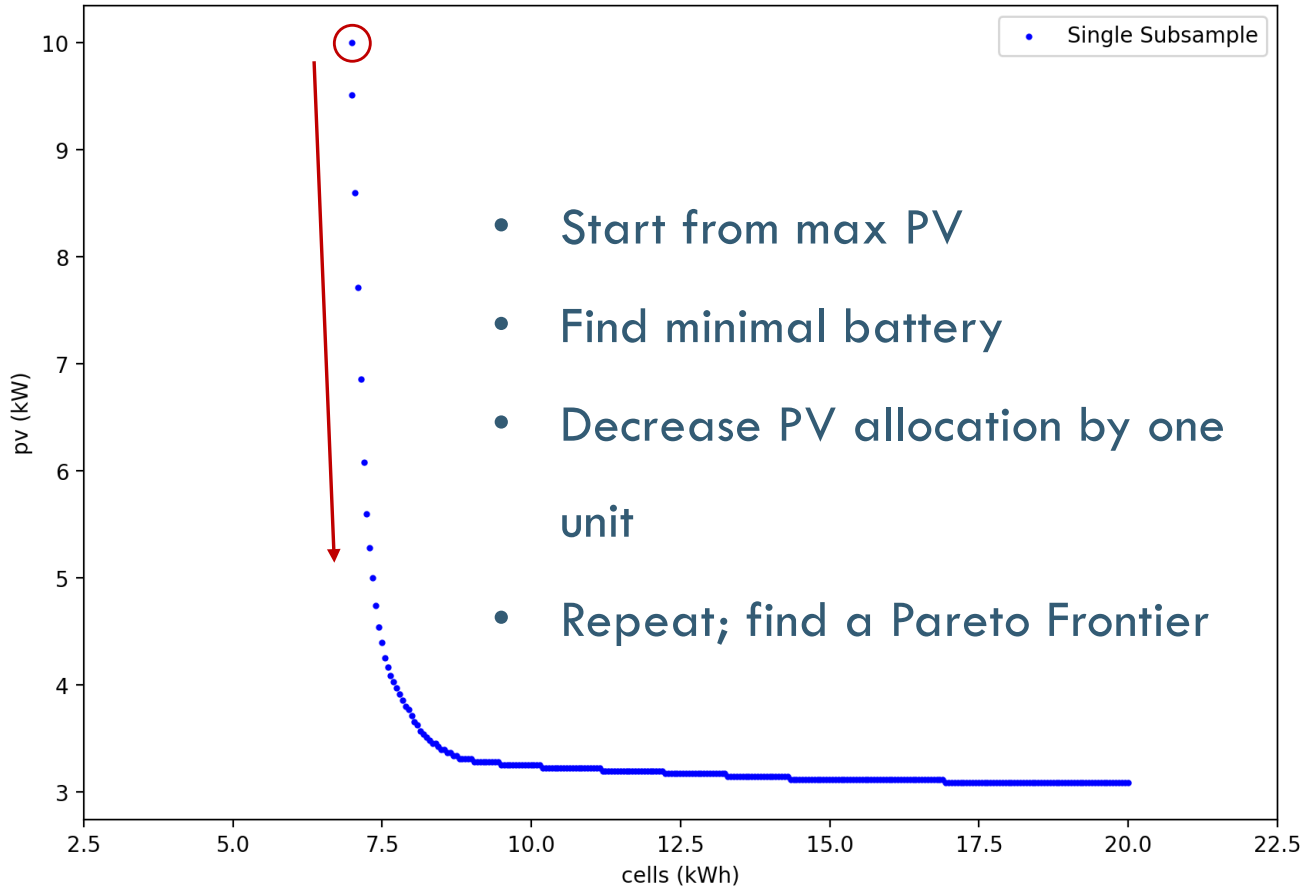
Output: <*B*, C> pair

# ALGORITHM

Subsample PV/load traces of length T

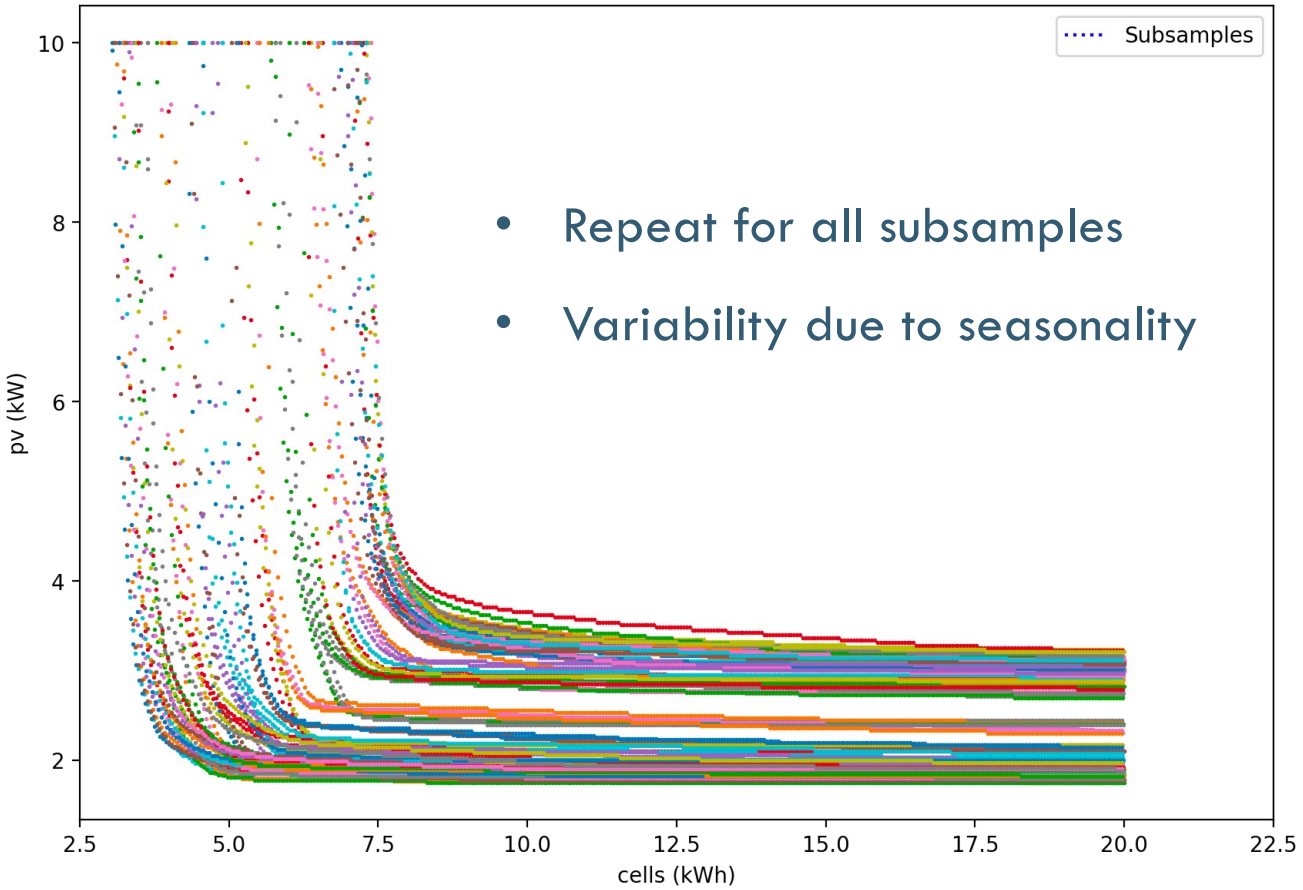
- Computer (B,C) Pareto frontier for each subsample
- Chebyshev bound for robustness

# SINGLE-ROOF SIZING ALGORITHM



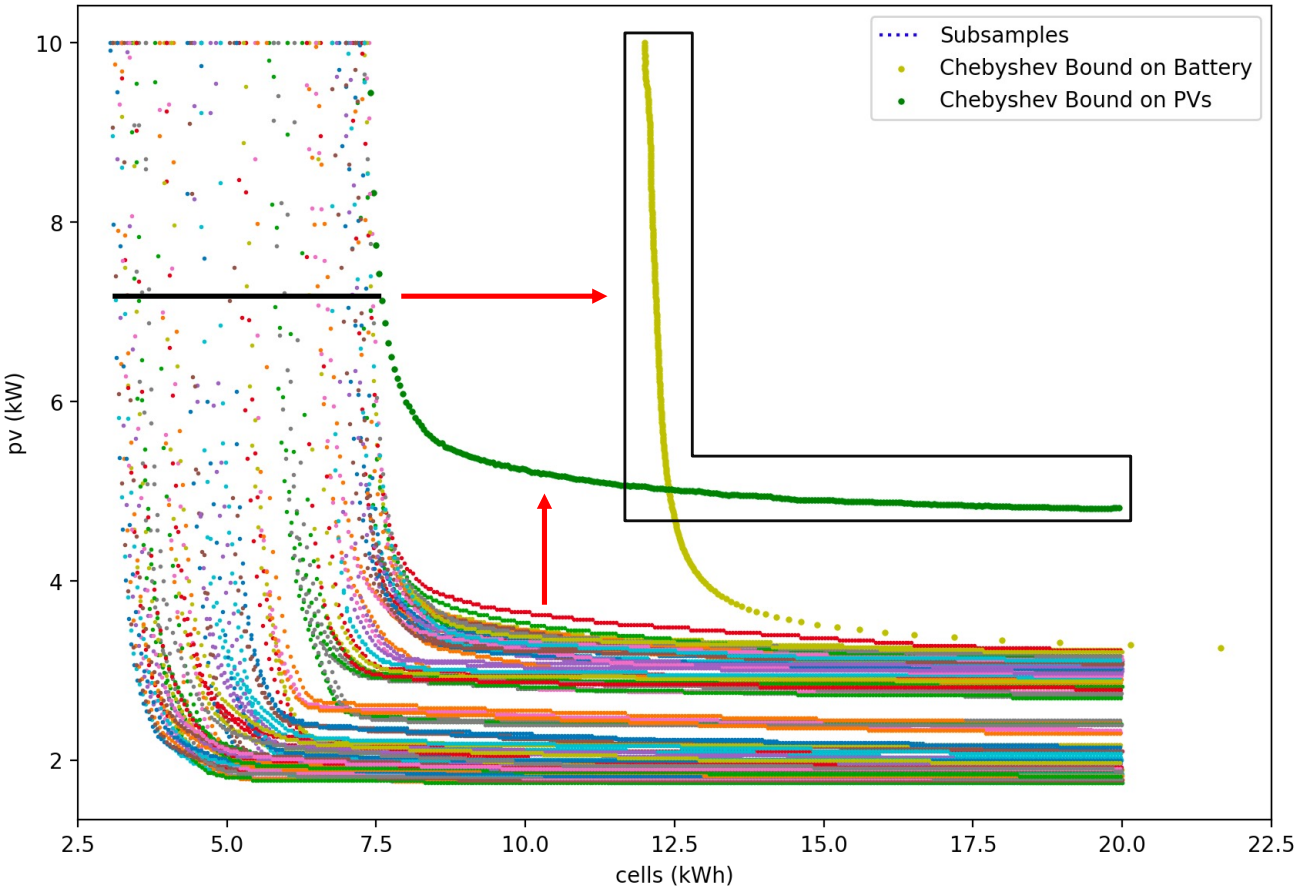

- Start from max PV
- Find minimal battery
- Decrease PV allocation by one unit
- Repeat; find a Pareto Frontier

# SINGLE-ROOF SIZING ALGORITHM




- Repeat for all subsamples
- Variability due to seasonality

# SINGLE-ROOF SIZING ALGORITHM

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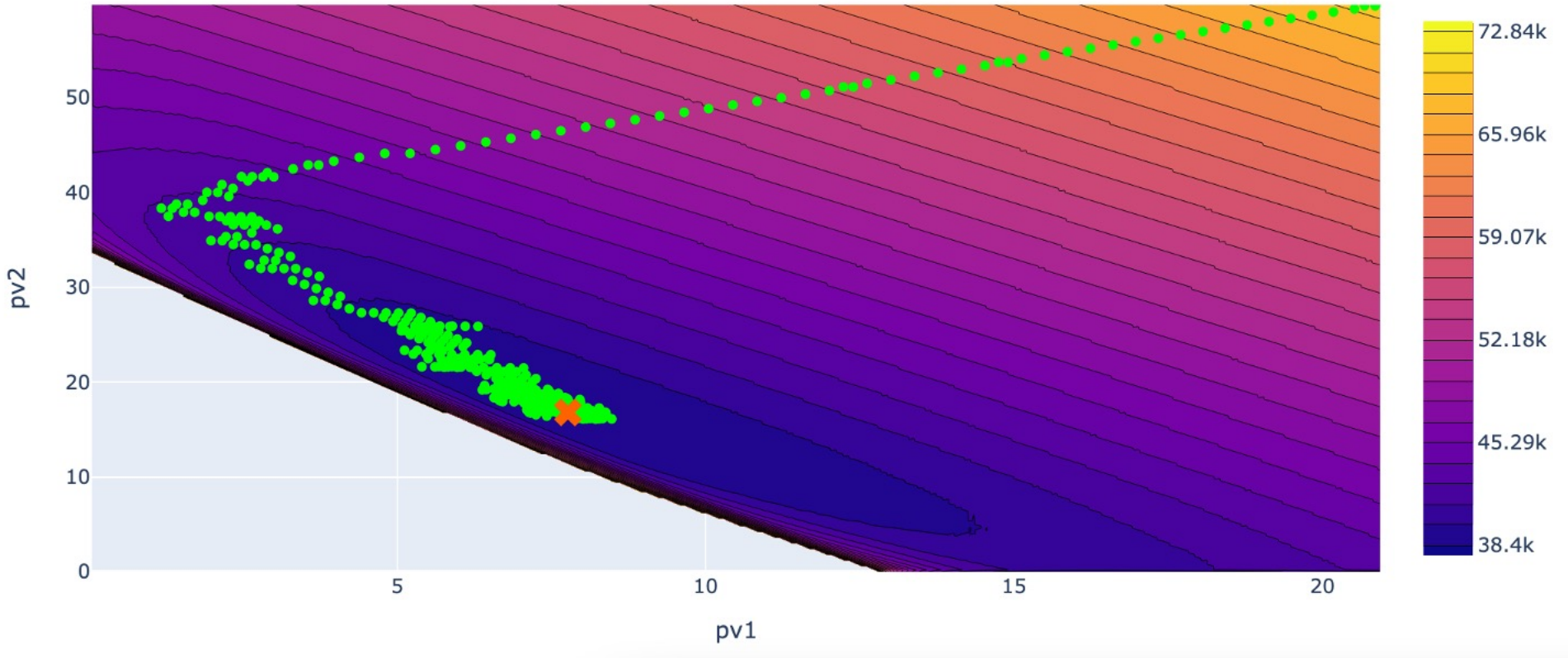
# MULTI-ROOF SIZING ALGORITHM

Subsample PV/load traces of length T

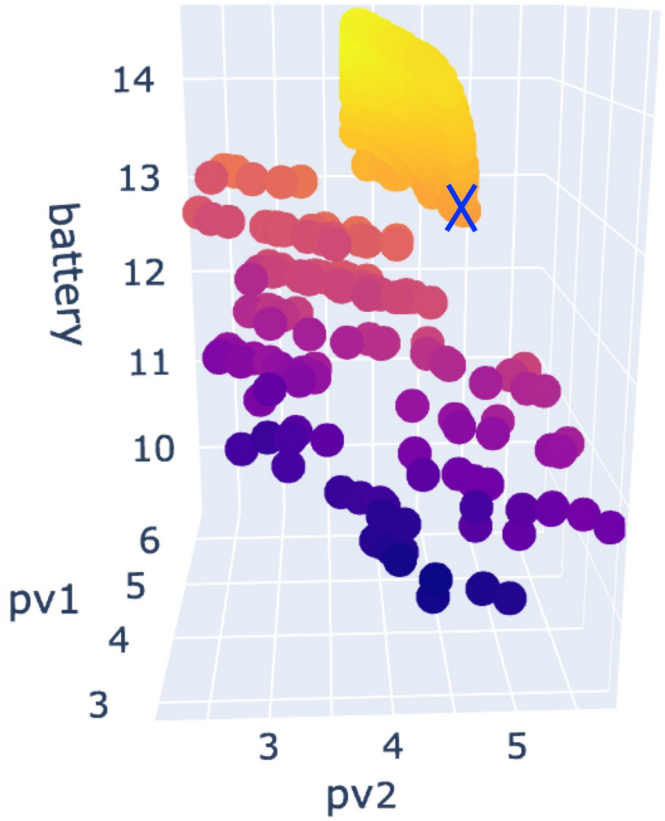
**Minimal cost sizing tuples** for each subsample

**Multivariate** Chebyshev bound for robustness

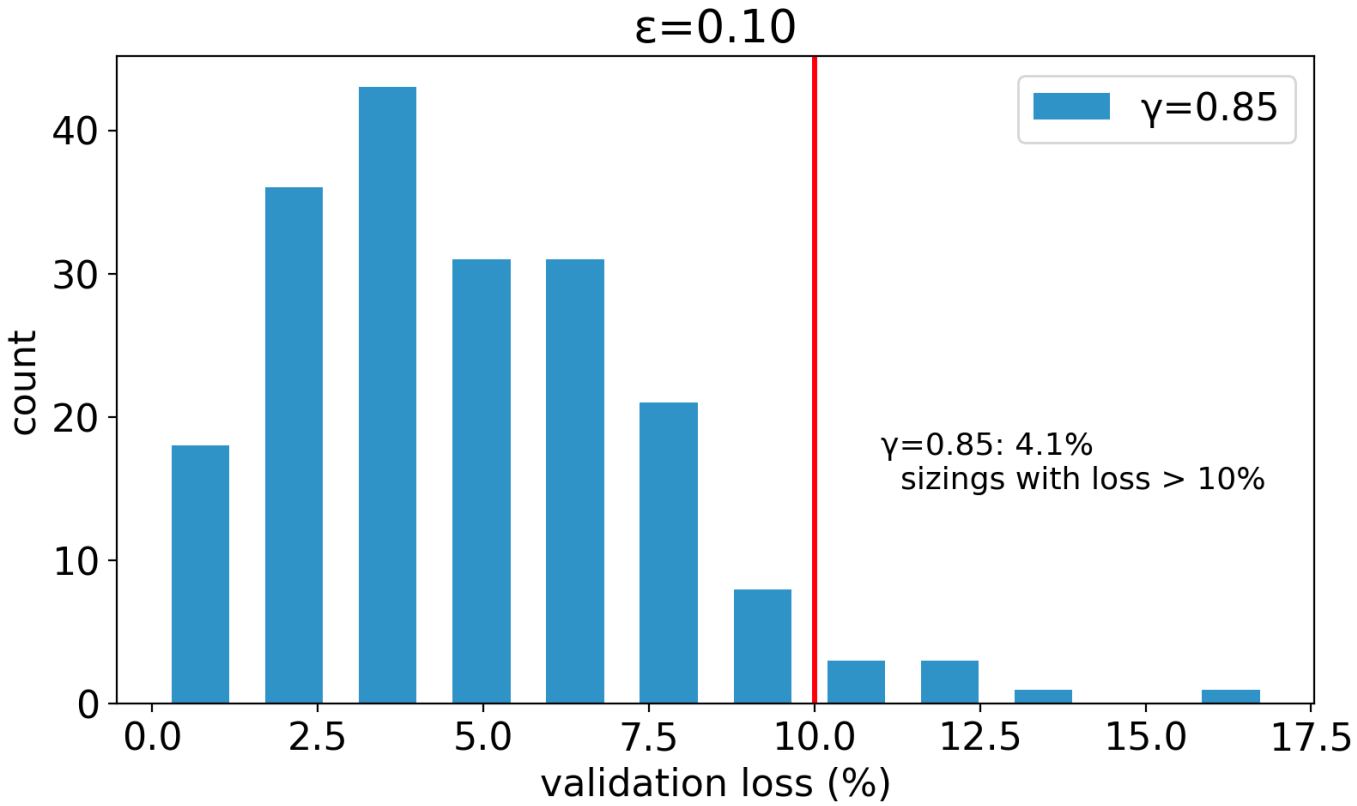
# MIN-COST FINDING



# CHEBYSHEV BOUND



# ROBUSTNESS

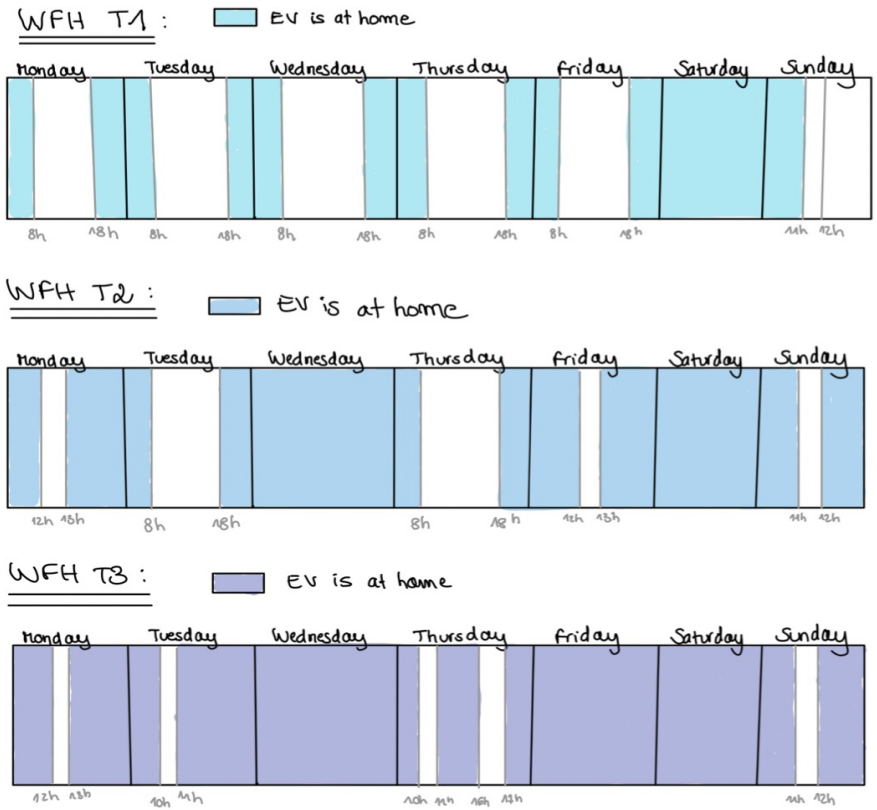

ε=0.10
γ=0.85
γ=0.85: 4.1%
sizings with loss > 10%
count
validation loss (%)
0
10
20
30
40
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5

# IMPACT OF EVS

Depends on how long they're present at home and charging style

- If working from home, they're present longer

# OUR SOLUTION FOR POST COVID EV TRACES




Typical commuter

Hybrid

Typical WFH

***Figure 5.5.:*** *The T1,T2 and T3 profiles.*

# EV CHARGING APPROACHES

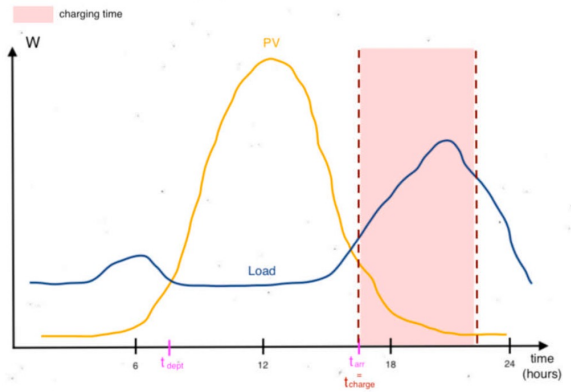



***Figure 3.3.:*** *Naive EV Charging Control.*

$$t_{charge} = t_{arr}$$

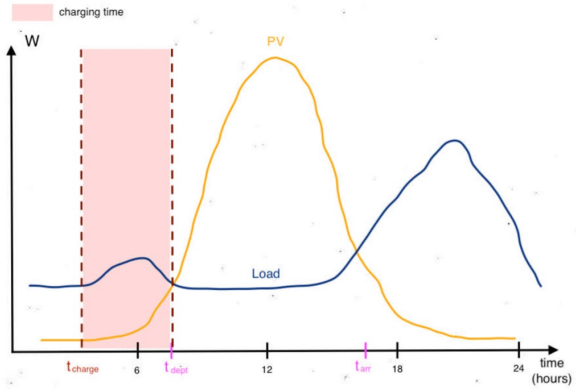



***Figure 3.4.:*** *Last Period EV Charging Control.*

$$t_{charge} = t_{dep} - K$$

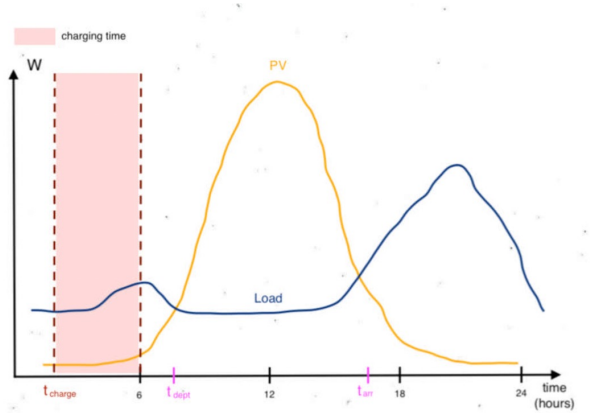



***Figure 3.5.:*** *Minimise Cost EV Charging Control.*

$$t_{charge} = t_{ch}$$

# Impact of **WFH** on the design

- Essential to consider commuting patterns
- Increase in WFH leads to cheaper and more efficient systems (approx. 30% cost decrease)

# Potential of **bidirectional** EVs

- With 2 WFH days per week, storage is not needed in some cases
- Adding more WFH days does not significantly change the microgrid design requirements
- Heavily depends on location, individual consumption patterns,…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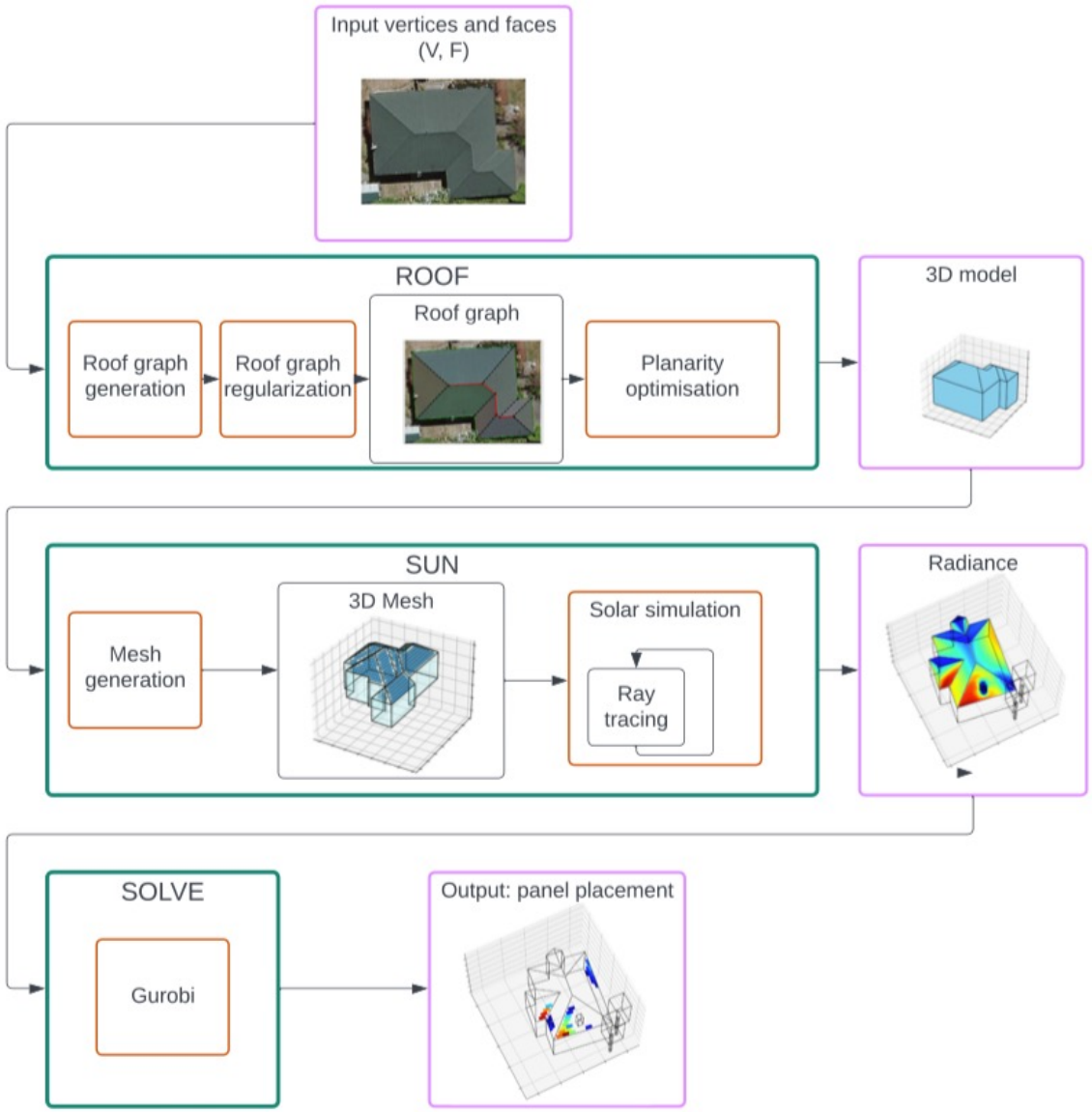
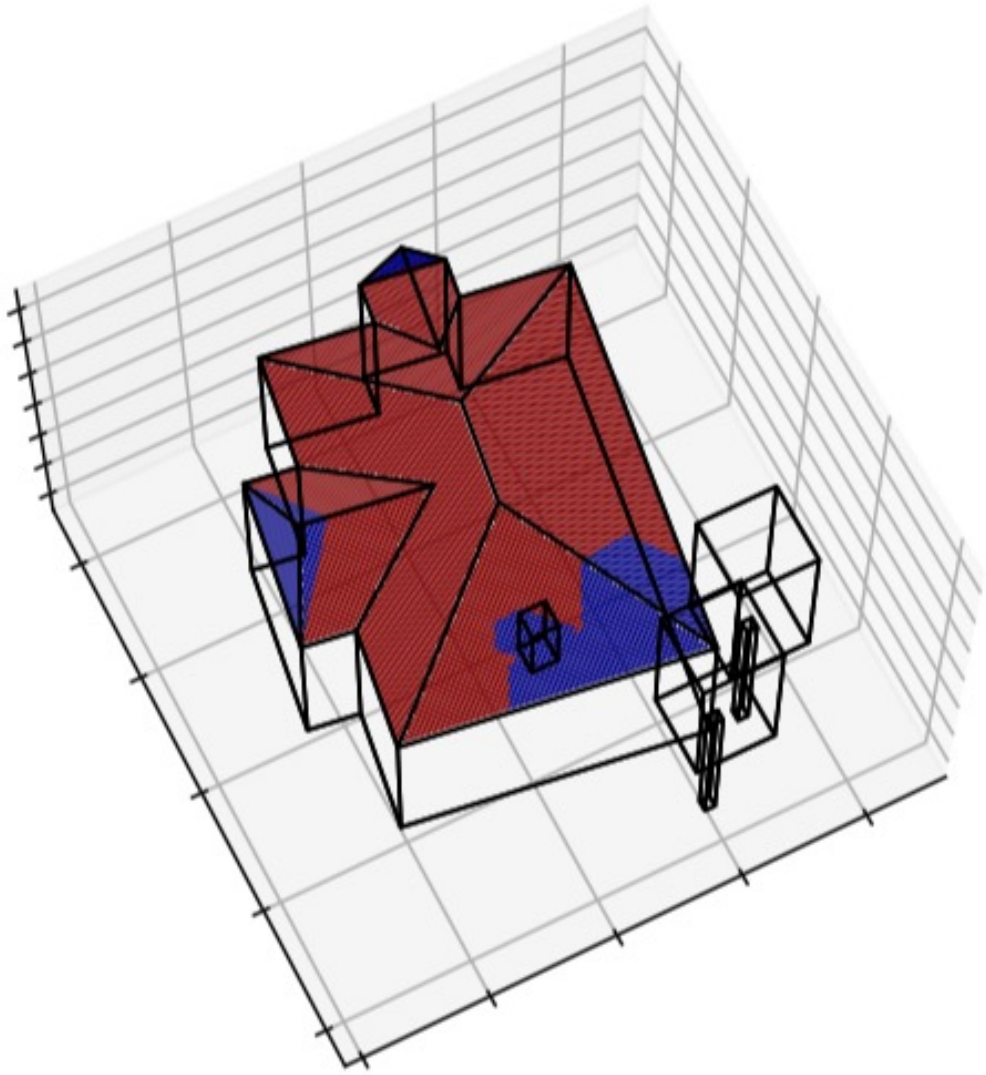
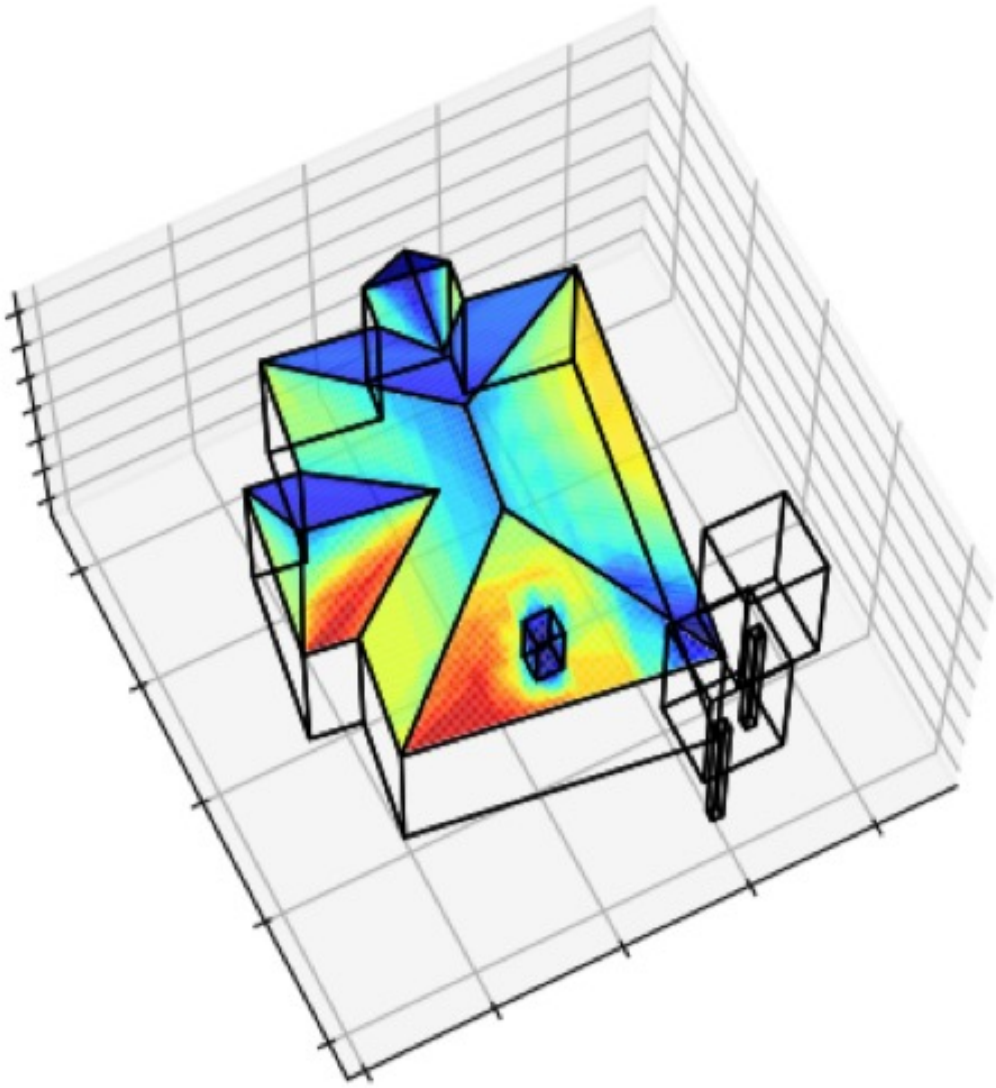
# PLACEMENT


Input vertices and faces
(V, F)
ROOF
Roof graph
generation
Roof graph
regularization
Roof graph
Planarity
optimisation
3D model
SUN
Mesh
generation
3D Mesh
Solar simulation
Ray
tracing
Radiance
SOLVE
Gurobi
Output: panel placement





# CONCLUSIONS

Solar, storage, and EVs are here to stay

Sizing, operation, and placement are challenging research problems

Our algorithms provide data-driven, robust solutions

# Solar Panel and Battery Size Calculator

1 My Location — 2 Solar Panel Parameters — 3 Electricity Load Estimation — 4 Estimation Parameters — 5 Results

## Welcome!

This calculator is intended for homeowners and small to medium businesses to determine how many solar panels and how large a storage battery to buy to achieve a certain level of grid independence, based on your location, solar panel parameters, and electricity usages. The algorithm accounts for **multiple roof segments**.

This calculator uses machine learning to estimate your hourly electricity usage and a robust statistical algorithm to optimize the amount of solar panels and battery storage needed to fulfill a certain portion of your electricity needs with minimum cost.

To use this calculator, please prepare the following:

- **Your location**, in terms of longitude and latitude. Later this page you can also detect your location with your IP address or enter your city.
- **Solar panel parameters**, including the tilt and azimuth of your solar panel, and what types of panels you intend to install. See detailed instruction at page 2. The parameters and instructions are provided by PVWatts.
- **Your electricity statements**, up to a year for each month. We are interested in how much electricity (in kWh) you used for each month during the past year, as well as (optionally) the electricity cost for the last entire year.
- **Your local system costs** for solar panels and batteries. We listed out some sample prices per unit in the US but different region has different costs. EnergySage provides great instructions and example prices.

## Your Location

**Location**: Your location is needed to compute how much electricity your solar panels can generate. Enter your locations using one of the following ways:

**Autofill location using your IP address:** Detect Location

OR

**Enter your city:** your city

OR

**Enter your latitude and longitude:** latitude longitude

OR

Manually Input PV Generation Parameters Instead

Next

# Solar Panel and Battery Size Calculator

✓ My Location — 2 Solar Panel Parameters — 3 Electricity Load Estimation — 4 Estimation Parameters — 5 Results

**Enter parameters of your solar panel.**

## Solar Panel Position

**Tilt** ⓘ: The tilt angle is the angle from horizontal of the solar panel. The optimal angle, if possible, is the absolute value of the latitude of your location. See below for detailed instruction.

**Azimuth** ⓘ: For a fixed array, the azimuth angle is the **angle clockwise from true north** describing the direction that the array faces. An azimuth angle of 180° is for a south-facing array, and an azimuth angle of zero degrees is for a north-facing array. See below for detailed instruction.

**Enter your number of roof segments:**

**Enter your Tilt and Azimuth:** Tilt in degrees Azimuth in degrees

## Solar Panel System Losses

**System Losses** ⓘ: The system losses account for performance losses you would expect in a real system that are not explicitly calculated by the PVWatts® model equations. The system losses account for performance losses you would expect in a real system that are not explicitly calculated by the PVWatts® model equations. Click on the info icon for detailed instruction.

**System Losses (%)*** %, [0,99]

## Solar Panel Type

**Module Type** ⓘ: The module type describes the type of photovoltaic film used in the solar panel. See below for detailed instruction.

**Array Type** ⓘ: The array type describes whether the solar panel in the array are fixed, or whether they move to track the movement of the sun across the sky with one or two axes of rotation. See below for detailed instruction.

**Module Type *** Button

**Array Type *** Button

Next Previous

# TESLA BLINKED!

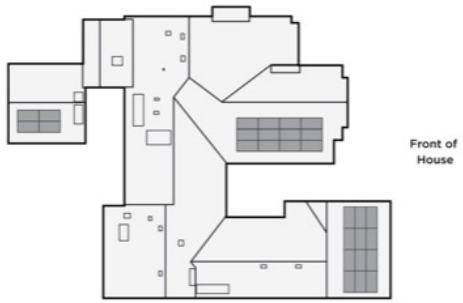
## Power Everything from Tesla

Home Address

Average Electric Bill

$165 / mo

## How to use the Interactive Layout Experience




For eligible solar panel layouts, select 'Review' under 'Your System Design,' then 'Request a Layout Change' to be taken to the Interactive Layout tool in your Tesla Account.

- De-select a numbered roof area to remove solar (the roof area will turn red) or select a roof area to add solar (the roof area will populate with solar panels).
- You can toggle between the layout and your roof's sunlight exposure and your energy consumption versus system production using the tab under the layout.
- A notification will be sent once your redesign is ready for review in your Tesla Account.

# REFERENCES


B.G. Huang, F. Kazhamiaka, and S. Keshav, Sizing Solar Panels and Storage for Multiple Roofs, *Proc. ACM eEnergy*, June 2021.

F. Kazhamiaka, Y. Ghiassi-Farokhfal, S. Keshav, and C. Rosenberg, Comparison of Different Approaches for Solar PV and Storage Sizing, *Proc. IEEE Transactions on Sustainable Computing*,September 2019.

S. Sun, F. Kazhamiaka, S. Keshav, and C. Rosenberg, Using Synthetic Traces for Robust Energy System Sizing, *Proc. ACM eEnergy 2019*, June 2019.

F. Kazhamiaka, C. Rosenberg, and S. Keshav, Tractable Lithium-Ion Storage Models for Optimizing Energy Systems, *Energy Informatics,* 2:1, 2019.

F. Kazhamiaka, S. Keshav, and C. Rosenberg, Robust and Practical Approaches for Solar PV and Storage Sizing, *Proc. ACM eEnergy 2018*, June 2018.

F. Kazhamiaka, C. Rosenberg and S. Keshav, "Practical Strategies for Storage Operation in Energy Systems: Design and Evaluation," *IEEE Transactions on Sustainable Energy,* vol. 7, no. 4, pp. 1602-1610, Oct. 2016.