# Speed Planning for Solar-Powered EVs

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# CONTENT.

- Motivation
- Problem
- Solution
- Experimental Results
- Conclusion
- Discussion

# ELECTRIC VEHICLES - FUTURE TRANSPORTATION.


**Less CO2 emission**
**Less noise**
**Higher energy conversion efficiency**
**Smooth operation**

# WHY SOLAR-POWERED ELECTRIC VEHICLES?

**PEV is not enough**
- Battery energy density is low
- Charge time is long
- Lack of a charging infrastructure

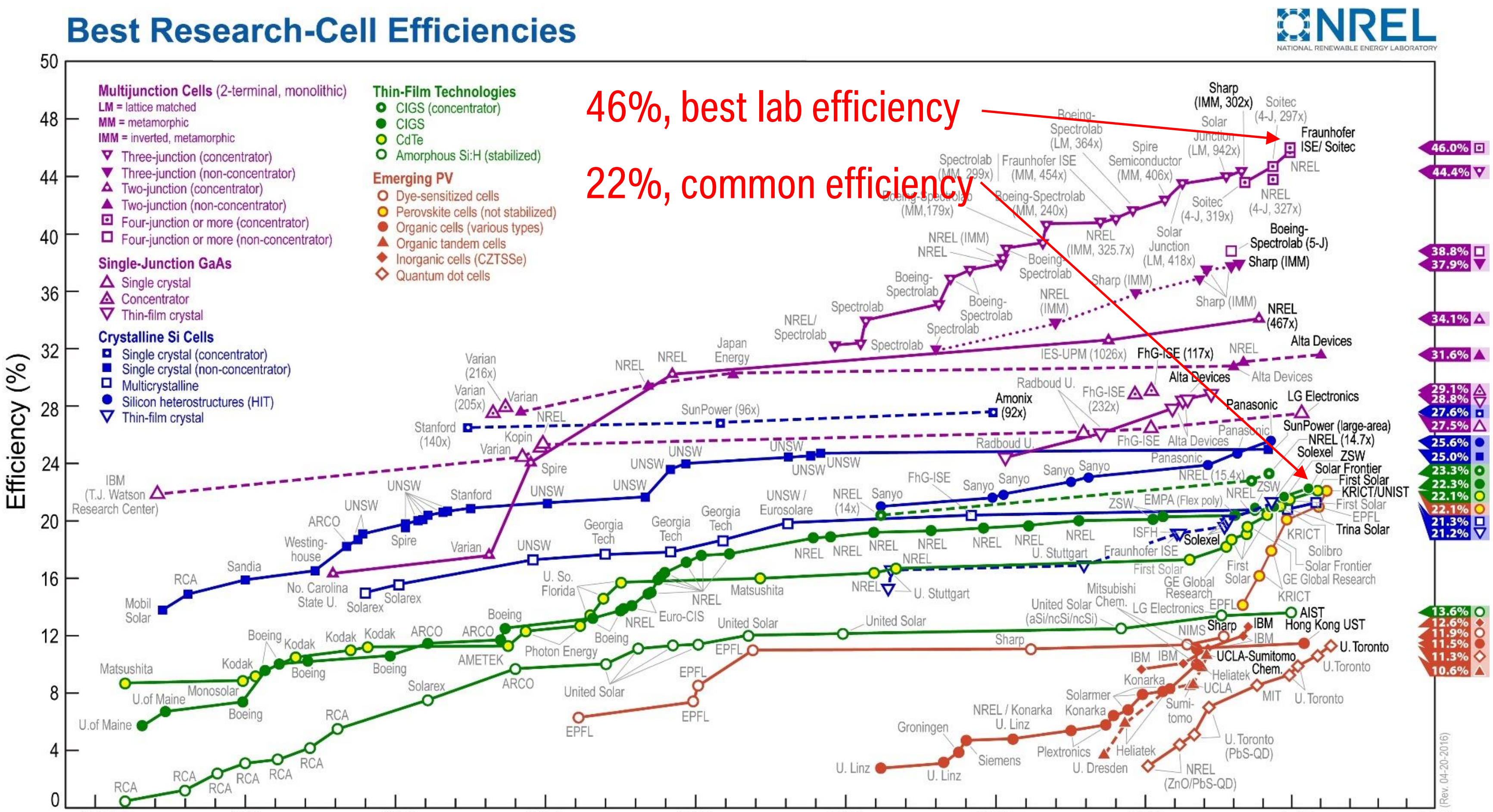
**Solar-powered EVs**
- Truly green energy used
- Abundant solar energy
- Be charged when running

# WHY SOLAR-POWERED ELECTRIC VEHICLES?


**Tour vehicles in an ancient city**

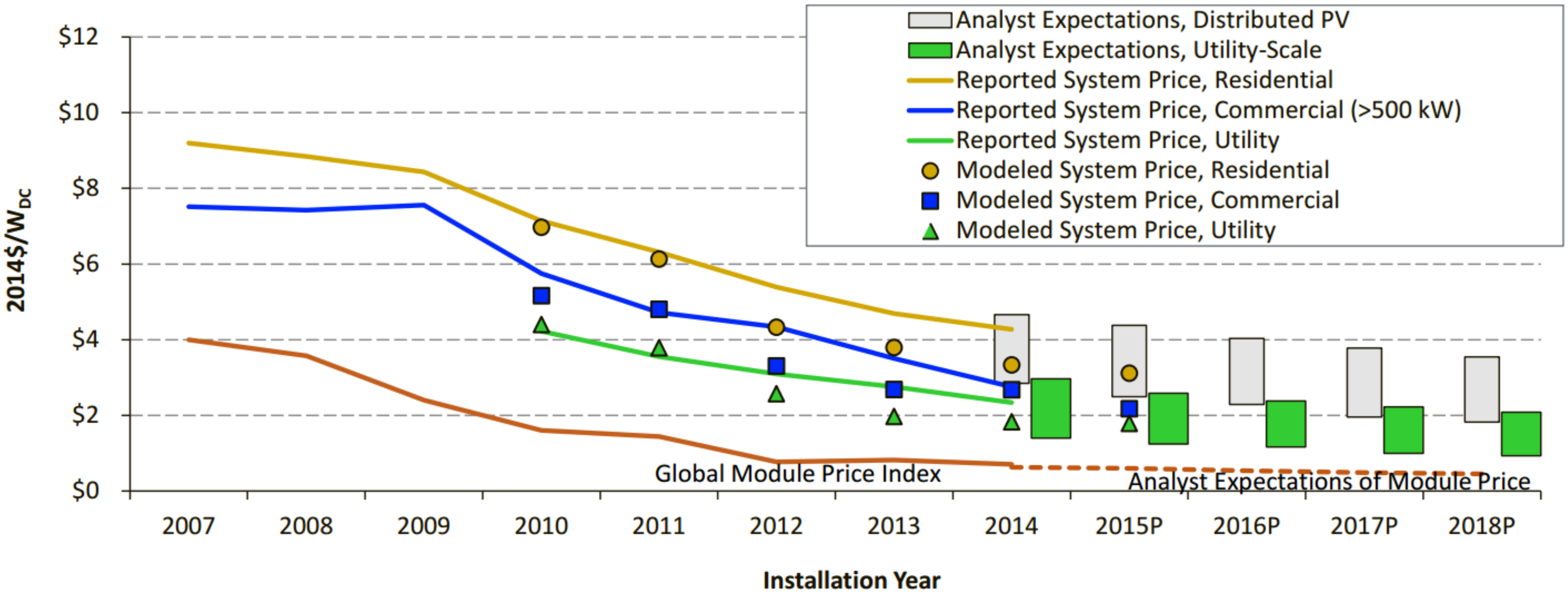
- Insufficient charging piles due to protection requirements.
- Charging is too time consuming

# SOLAR ENERGY FEASIBILITY – EFFICIENCY TRENDS.




National Renewable Energy Laboratory http://www.nrel.gov/

# SOLAR ENERGY FEASIBILITY – PRICE TRENDS.




Average U.S. PV System Prices over Time by SunShot, U.S. Department of Energy

# SOLAR-POWERED EV FEASIBILITY – INDUSTRIAL DEMOS.

**Ford C-MAX Solar Energi Concept demonstrated at CES 2014**

Daily range: 60km


**Hanergy SolarPower Concept unveiled in 2015**

Daily range: 40km

# INTRODUCING SOLAR POWER INTO EVS.

Electric vehicles will be the future means of transportation

However, charging limitations are still a major obstacle

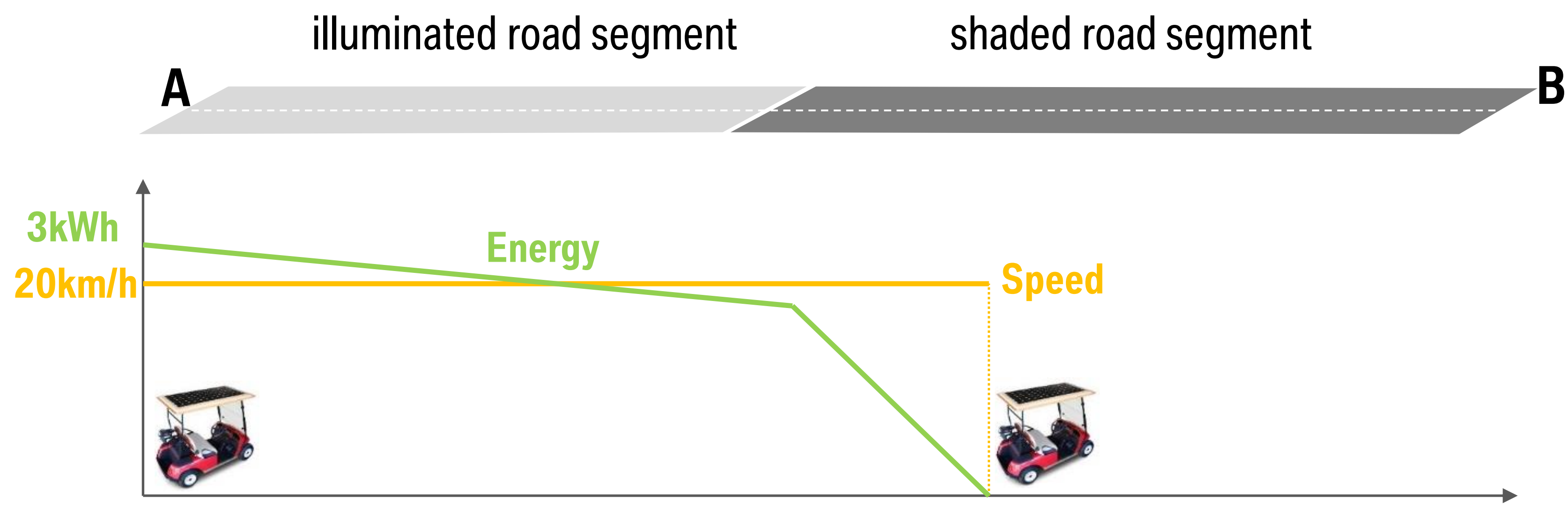
We consider solar-powered EVs as a solution, with

- Increasing solar panel efficiency
- Decreasing prices

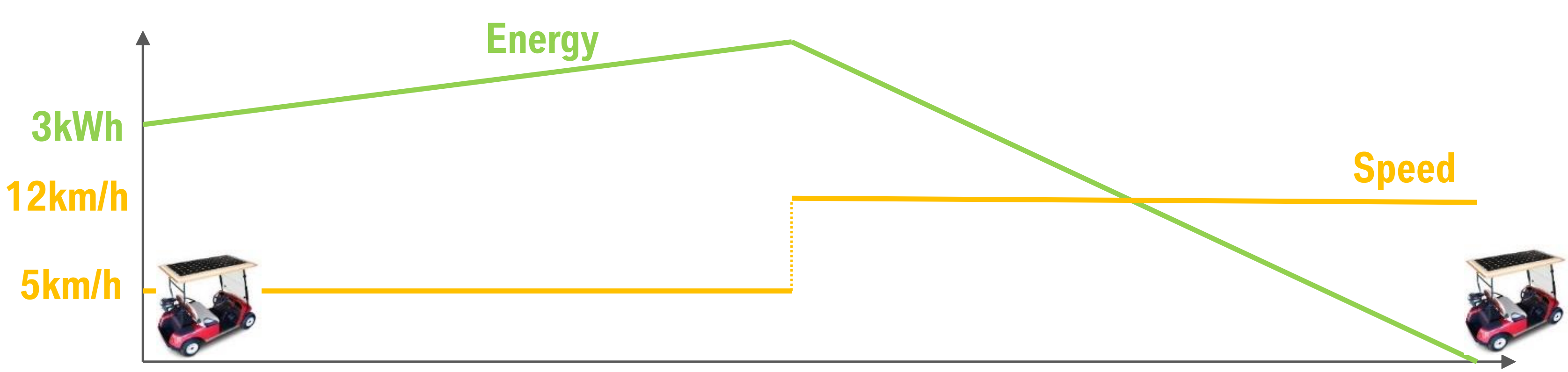
# THE IMPACT OF SHADINGS.

Shadings by buildings, trees, tunnels, etc. make solar input unstable

# THE SPEED PLANNING PROBLEM.




**Plan A: Constant high speed, stop on the shaded road**




**Plan B: lower and variable speeds, successfully finish the whole trip**

# THE SPEED PLANNING PROBLEM.

**A solar EV driver must carefully plan his speed**

- To reach the destination
- To minimize overall travel time

# THE SPEED PLANNING PROBLEM – FORMULATION.

A constraint non-linear programming problem

**Objective** $$T_{min} = minimize \sum_{i=1}^{n}\left(\frac{S_i^I}{V_i^I} + \frac{S_i^S}{V_i^S}\right)$$

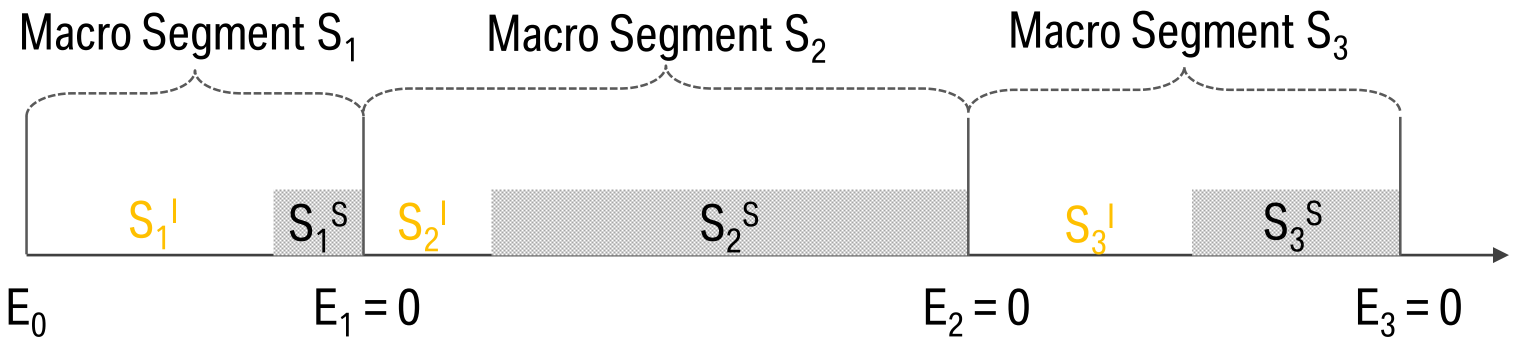
**Constraints** At the end of each road segment: $E_i^* \geq 0$

The problem will be very complex
if there are many interleaving illuminated and shaded road segments

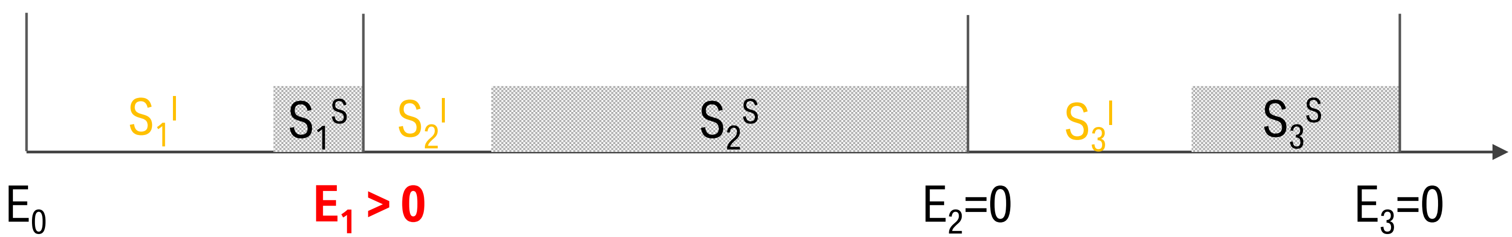
Energy output
(Energy Usage)

$$E_{\text{out}} = S \times (aV^2 + b)$$

# A KEY PROPERTY.

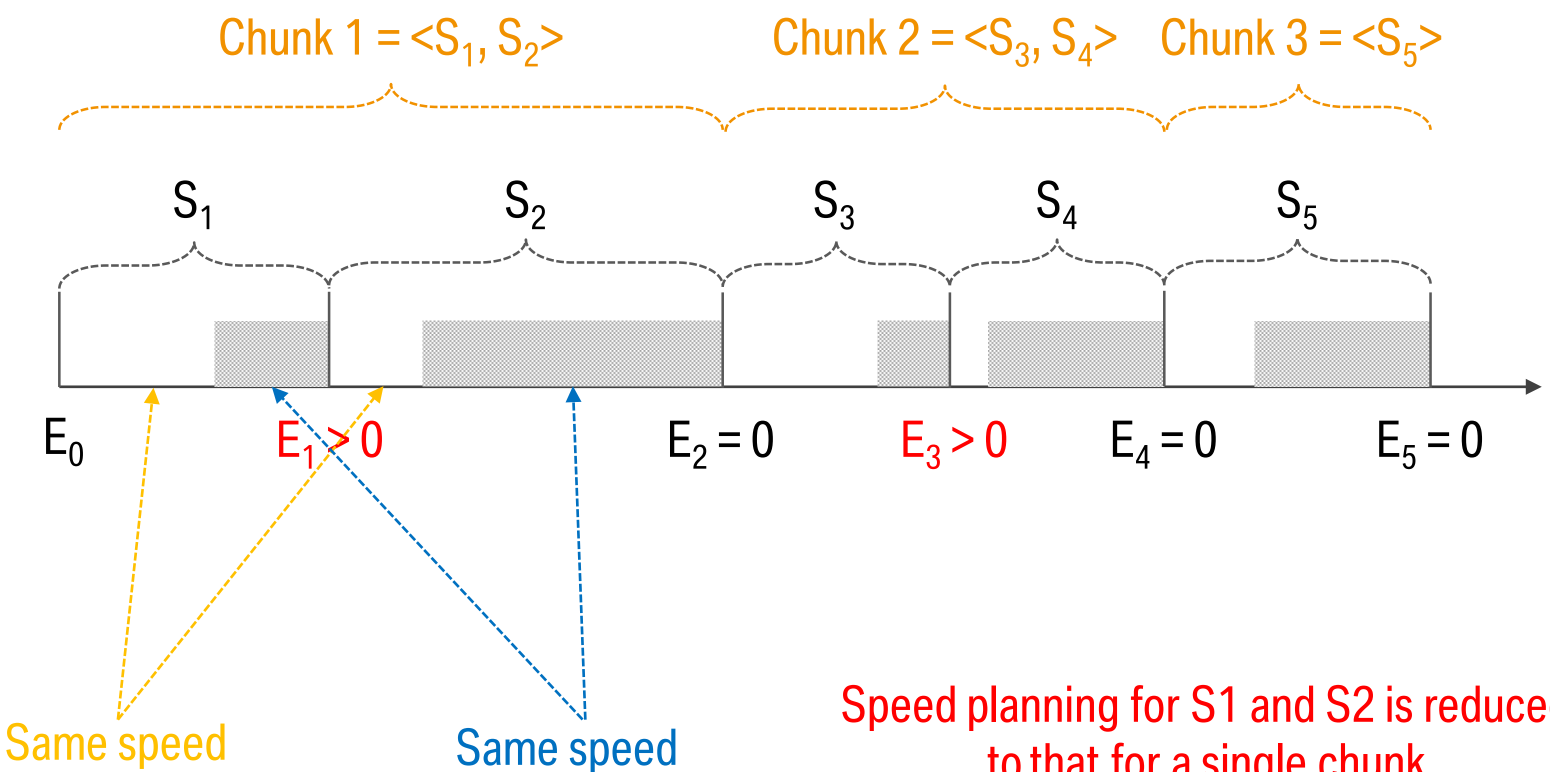



**Intuition** At the end of each shaded segment, the remained energy is zero, to maximize speed for the previous macro segment



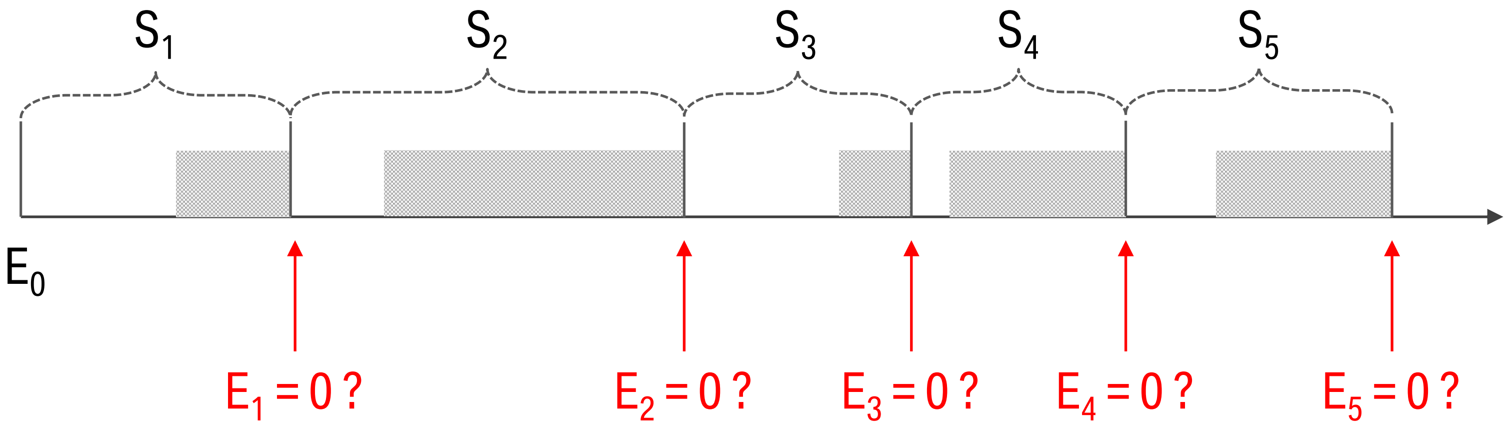

**Global Optimal** Energy transfer from S1 to S2 ($E_1 > 0$), otherwise, the EV has to run very slowly in $S_2^I$ to collect enough energy to survive $S_2^S$

# A KEY PROPERTY.




Speed planning for S1 and S2 is reduced to that for a single chunk

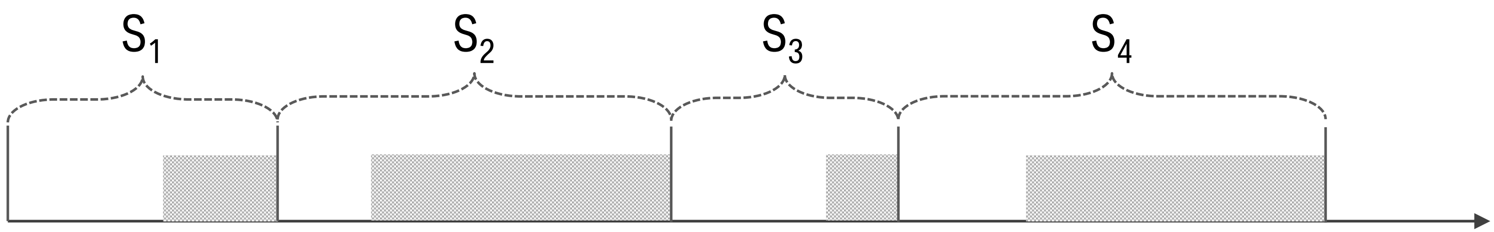
# FINDING THE ZERO-ENERGY POINTS – CHALLENGES.




First, we do not know how many zero-energy points exist;
Second, we do not know where these point locates

**$2^N$ possibilities to try!!**

# FINDING THE ZERO-ENERGY POINTS – DYNAMIC PROGRAMMING.




$$\mathrm{Opt}(4) = C$$

$$\mathrm{Opt}(3) = \min \begin{cases} T(3,3) + \mathrm{Opt}(4) \\ T(3,4) \end{cases}$$

$$\mathrm{Opt}(2) = \min \begin{cases} T(2,2) + \mathrm{Opt}(3) \\ T(2,3) + \mathrm{Opt}(4) \\ T(2,4) \end{cases}$$

$$\mathrm{Opt}(1) = \min \begin{cases} T(1,1) + \mathrm{Opt}(2) \\ T(1,2) + \mathrm{Opt}(3) \\ T(1,3) + \mathrm{Opt}(4) \\ T(1,4) \end{cases}$$

$$\mathbf{Opt}(x) = \min_{\substack{\forall x \le c_x \le N \\ \forall c_x \le c_{x+1} \le N \\ \cdots \\ \forall c_{N-2} \le c_{N-1} \le N}} \{\sum_{k=x}^{N} t_{cs}(c_{k-1}, c_k)\}$$

**Complexity is $O(n^2)$**

# FINDING THE ZERO-ENERGY POINTS – DYNAMIC PROGRAMMING.

| No. | Macro Segments | Length (km) | Travel Time (min) | OPT (sec) | GS (sec) |
|---|---|---|---|---|---|
| 1 | 2 | 3.9 | 44.56 | 2 | 3 |
| 2 | 2 | 5.3 | 67.14 | 3 | 34 |
| 3 | 3 | 16.3 | 193.24 | 3 | 34 |
| 4 | 4 | 13.2 | 147.94 | 8 | 158 |
| 5 | 5 | 13.3 | 145.62 | 30 | 125 |
| 6 | 6 | 9.8 | 105.25 | 18 | 152 |
| 7 | 7 | 9.5 | 105.10 | 23 | 174 |
| 8 | 8 | 11.5 | 129.83 | 90 | 129 |
| 9 | 9 | 11.7 | 127.56 | 58 | 1076 |
| 10 | 10 | 12.7 | 138.49 | 98 | 937 |
| 11 | 11 | 15.7 | 169.45 | 64 | 1151 |
| 12 | 12 | 19.1 | 218.15 | 78 | 827 |
| 13 | 13 | 20.3 | 227.22 | 122 | 1044 |
| 14 | 14 | 22.9 | 271.81 | 123 | 2430 |
| 15 | 15 | 27.8 | 314.45 | 106 | 2900 |
| 16 | 16 | 20.4 | 235.60 | 150 | 8215 |
| 17 | 17 | 28.0 | 321.48 | 153 | 9441 |
| 18 | 18 | 24.8 | 286.20 | 171 | 4788 |
| 19 | 19 | 28.7 | 330.35 | 200 | 9436 |
| 20 | 20 | 27.5 | 314.46 | 278 | N/A |

20 paths containing 2 ~ 20 macro segments
Path length: 3.9 ~ 27.5km
Travel Time: 44.56 ~ 330.35min

OPT: Our approach
GS: GlobalSearch in Matlab

# SOLUTION OVERVIEW.

At the end of some shaded segments, the remained energy is zero.

The whole path is partitioned into chunks by these zero-energy points.

A dynamic programming approach to find the zero-energy points with complexity $O(n^2)$

# A VALIDATION PLATFORM.

| Component | Specifications |
|---|---|
| Solar Panel | Module: Yingli Solar YL270C-30b<br>Technology: Monocrystaline<br>Power Output (STC): 270W<br>Module Efficiency: 16.6%<br>Dimensions: 1640X990X40 (mm)<br>Weight: 18.5kg |
| MPPT Controller | Module: BlueSolar MPPT 100/50<br>Rated Charge Current: 50A<br>Max. Efficiency: 98% |
| Electric Vehicle | Dimensions: 2050X1220X1570(mm)<br>Kerb Mass: 580kg<br>Drive Type: rear wheel<br>Motor Type: Brushless DC motor<br>Rated Motor Power: 2.2kW<br>Max. Speed: 35km/h |

# EXPERIMENTAL RESULTS – CLEAR DAY.

| Clear Day $P_{max} = 210W$ Experiment Time：10:32:02 ~ 11:15:44 | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Segments** | Distance (km) | Travel Time (min) | | Energy Input (Wh) (Solar energy harvested) | | Energy Output (Wh) (EV energy consumed) | |
| | | **Predicted (our algo.)** | **Real (Measured)** | **Predicted (our algo.)** | **Real (Measured)** | **Predicted (our algo.)** | **Real (Measured)** |
| $S_1^I$ (illuminated) | 1.76 | 23.59 | 23.80 | 82.55 | 78.17 | 58.43 | 66.38 |
| $S_1^S$ (shaded) | 0.54 | 1.48 | 1.55 | 0 | 1.29 | 20.42 | 21.18 |
| $S_2^I$ (illuminated) | 1.22 | 16.35 | 16.82 | 57.22 | 58.01 | 40.50 | 49.60 |
| $S_2^S$ (shaded) | 0.54 | 1.48 | 1.55 | 0 | 1.33 | 20.42 | 22.89 |
| **Total** | 4.06 | 42.90 | 43.72 | 139.77 | 138.80 | 139.77 | 160.05 |

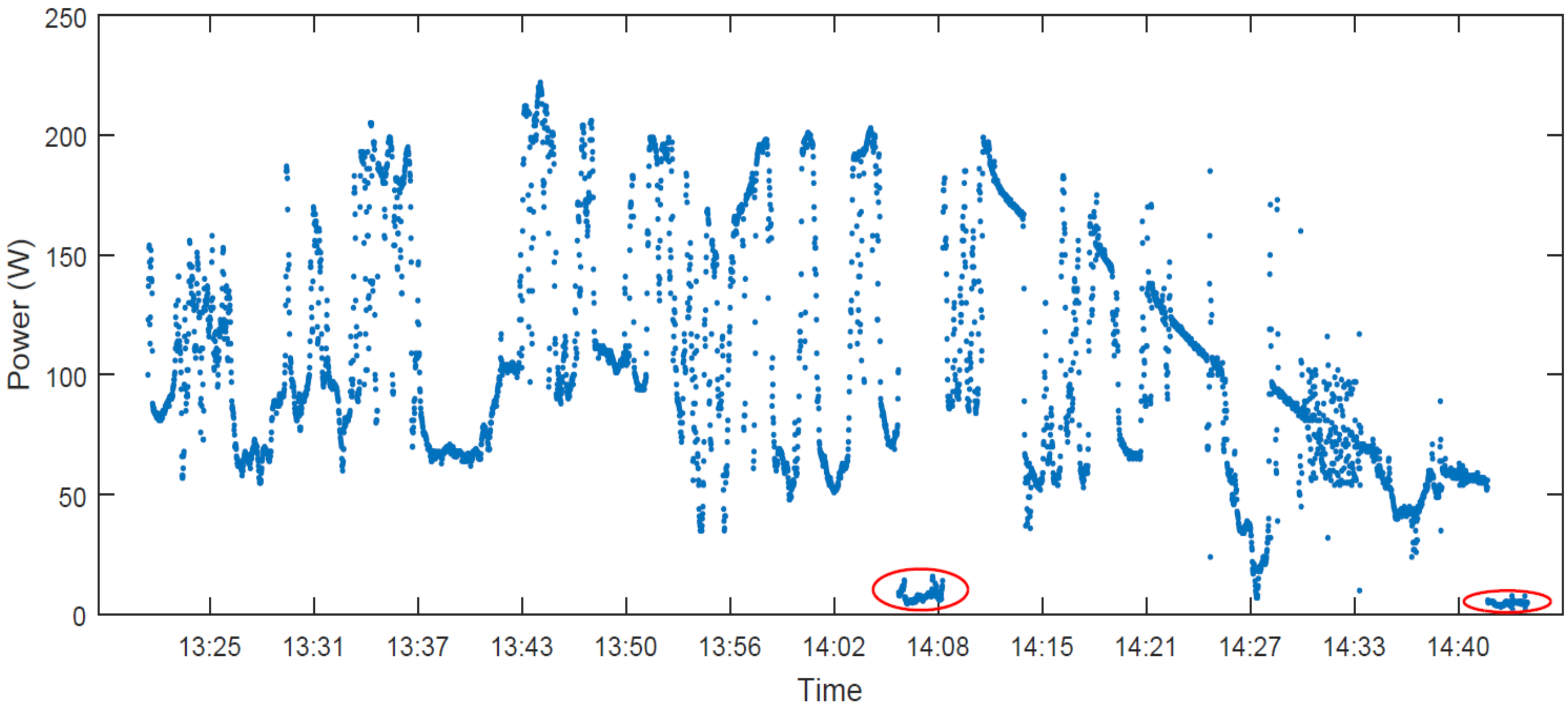
Travel Time, Energy input, and output predicted by our approach is close to those obtained from the solar EV prototype

# EXPERIMENTAL RESULTS – CLOUDY DAY.

| **Cloudy Day** $E_0 = 60Wh \quad P_{max} = 60W$ **Experiment Time: 13:21:26 ~ 14:44:12** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Segments** | Distance (km) | Travel Time (min) | | Energy Input (Wh) (Solar energy harvested) | | Energy Output (Wh) (EV energy consumed) | | |
| | | **Predicted (our algo.)** | **Real (Measured)** | **Predicted (our algo.)** | **Real (Measured)** | **Predicted (our algo.)** | **Real (Measured)** |
| $S_1^I$ **(illuminated)** | 1.76 | 45.12 | 45.05 | 45.12 | 87.12 | 58.18 | 76.75 |
| $S_1^S$ **(shaded)** | 0.54 | 2.24 | 2.65 | 0 | 0.35 | 18.95 | 19.73 |
| $S_2^I$ **(illuminated)** | 1.22 | 31.28 | 32.70 | 31.28 | 48.76 | 40.33 | 54.40 |
| $S_2^S$ **(shaded)** | 0.54 | 2.24 | 2.38 | 0 | 0.19 | 18.94 | 18.64 |
| **Total** | 4.06 | 80.88 | 82.78 | 76.40 | 136.42 | 136.40 | 166.52 |

We witness a difference between our prediction and real solar EV, solar input is very unpredictable with the movement of cloud.

# EXPERIMENTAL RESULTS – CLOUDY DAY. SOLAR ENERGY HARVESTED



# CONCLUSION.

(1) We studied the problem of speed planning for Solar-Powered EVs

– Goal: to successfully finish a trip with minimal travel time by the Solar- Powered EV

(2) We model it as a multi-constraint non-linear programming problem

(3) Solution: an optimal structure + dynamic programming

– Complexity: $O(n^2)$, n is the trip macro segment

(4) Validation with a Real Solar-Powered EV prototype

# DISCUSSION.

## Further extension for practical implementation

- Unpredictable weather, and unpredictable traffic conditions
- Variable solar input due to changing solar angle
- Acceleration energy

# Thank you