Energy Harvesting in Future IoT Devices

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University of Southampton and
Arm-ECS Research Centre

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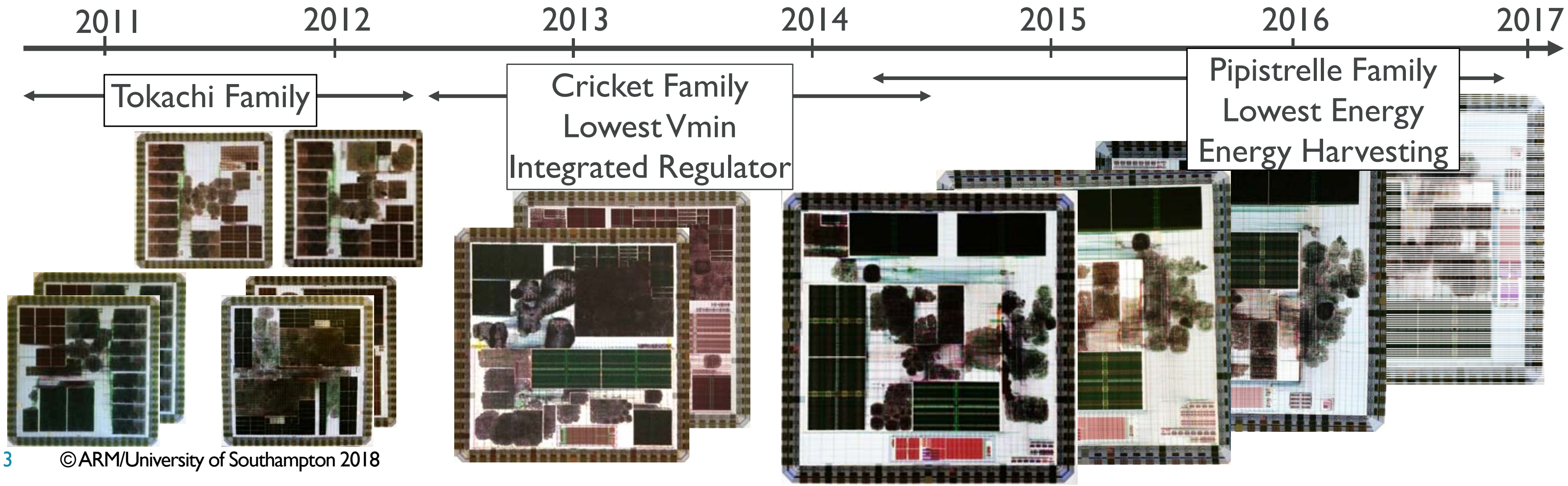
Arm and the University of Southampton

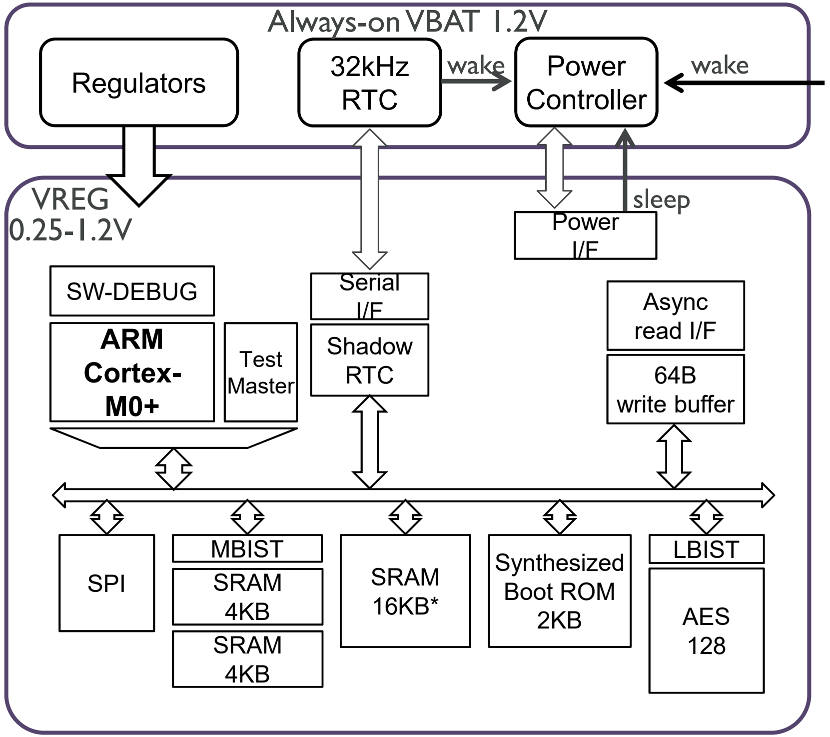
- Arm-ECS Research Centre (est. 2008)
  - Eight Southampton academics, Arm colleagues
  - Five jointly-supervised PhD students completed studies and employed at Arm (four more in the pipeline!)
- Centred around power-efficient computing
  - Mix of priority and ‘blue-sky’ research projects
  - Clock/power gating, energy-efficient IP watermarking, energy harvesting, run-time power modelling, system-level modelling and optimisation
  - 20+ jointly-authored publications
- Collaborative design and regular tape-outs
  - Ten research test chips taped-out over six years

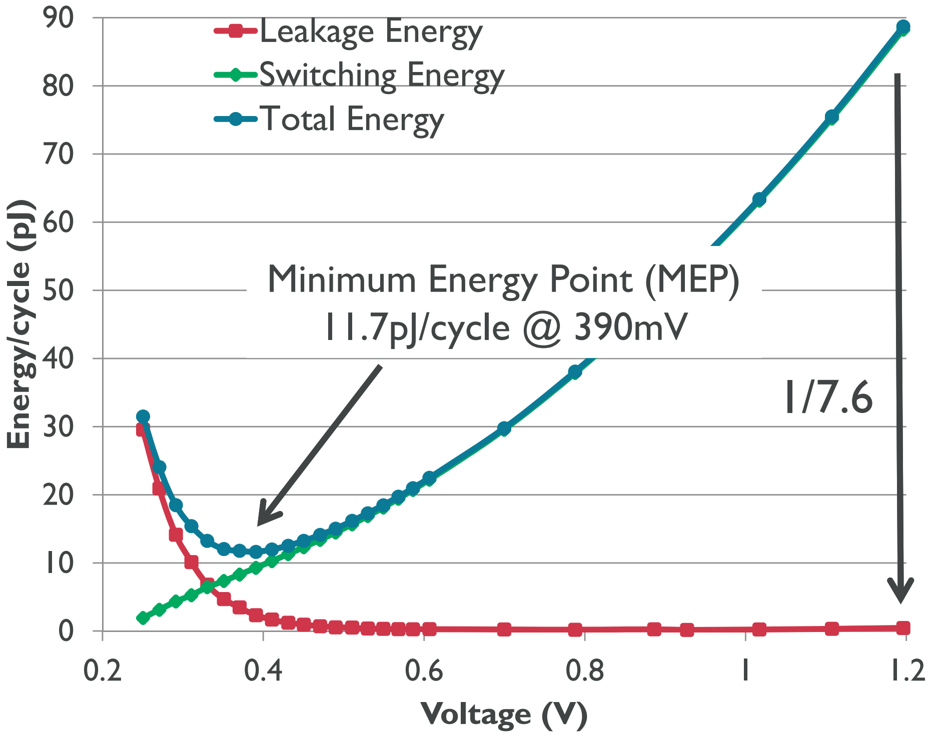
Collaborative Test Chip Program

- TSMC 65nm LP multi-project wafers through Europractice
- Not all projects need silicon – but many do benefit
- And being on a real tapeout is a great learning experience!



Cricket Sub-threshold MCU

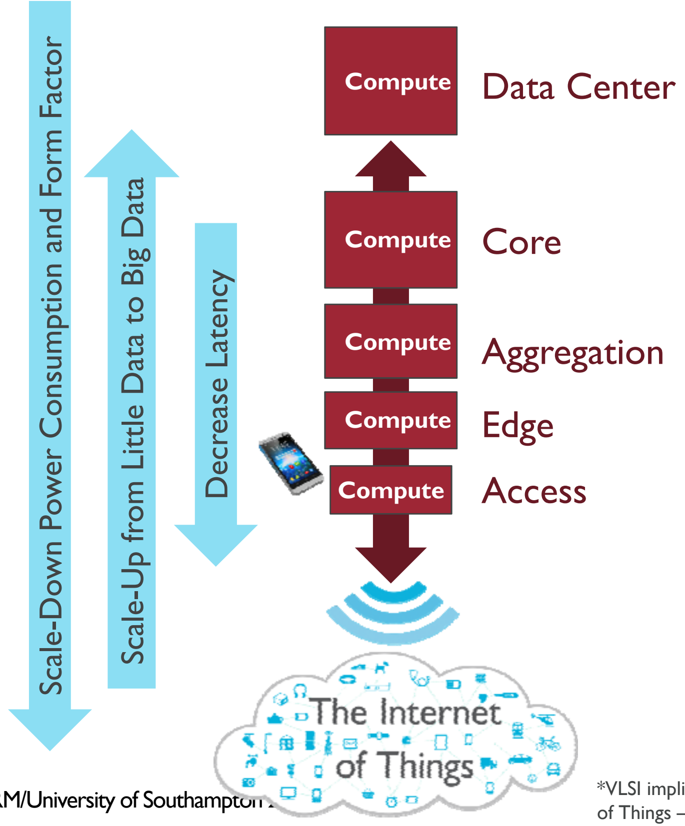


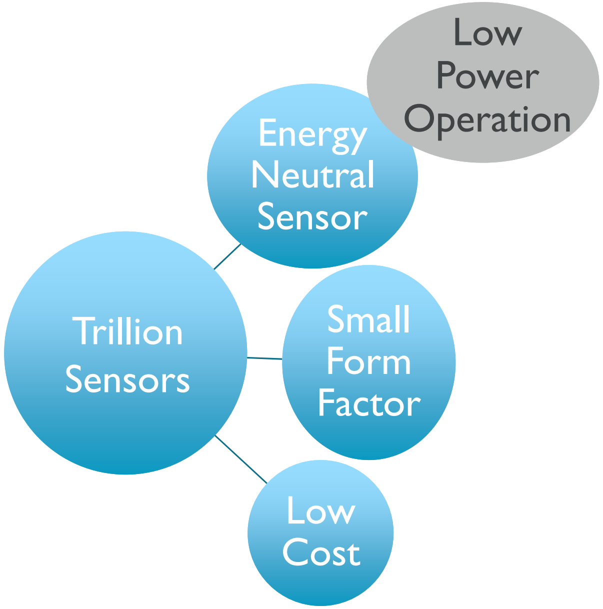


An 80nW Retention 11.7pJ/Cycle Active Subthreshold ARM Cortex-M0+ Subsystem in 65nm CMOS for WSN Applications, Myers et al, ISSCC 2015

Towards a Trillion Devices

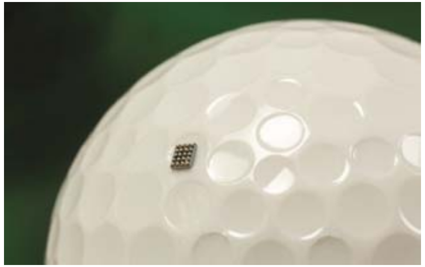
Sensors and Compute in IoT





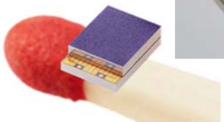
*VLSI implications of the Internet of Things – Greg Y, 2015

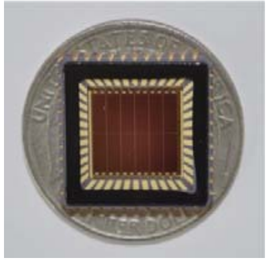
How small is small?

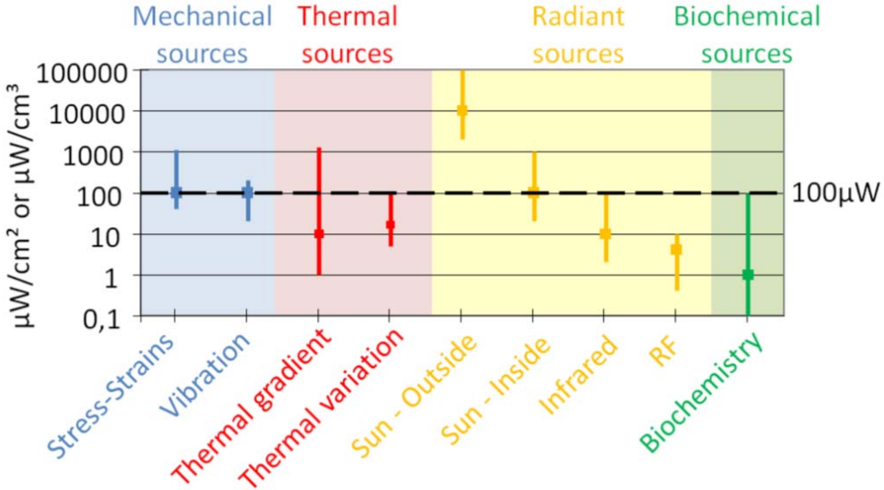


Freescale KL03
- Cortex-M0+
- 32KB Flash
- 2KB RAM
- 8KB ROM
- 12-bit ADC
- High speed comparator

University of Michigan
- Cortex-M
- Custom memory
- Custom Radio
- Custom Battery
- Energy Harvesting



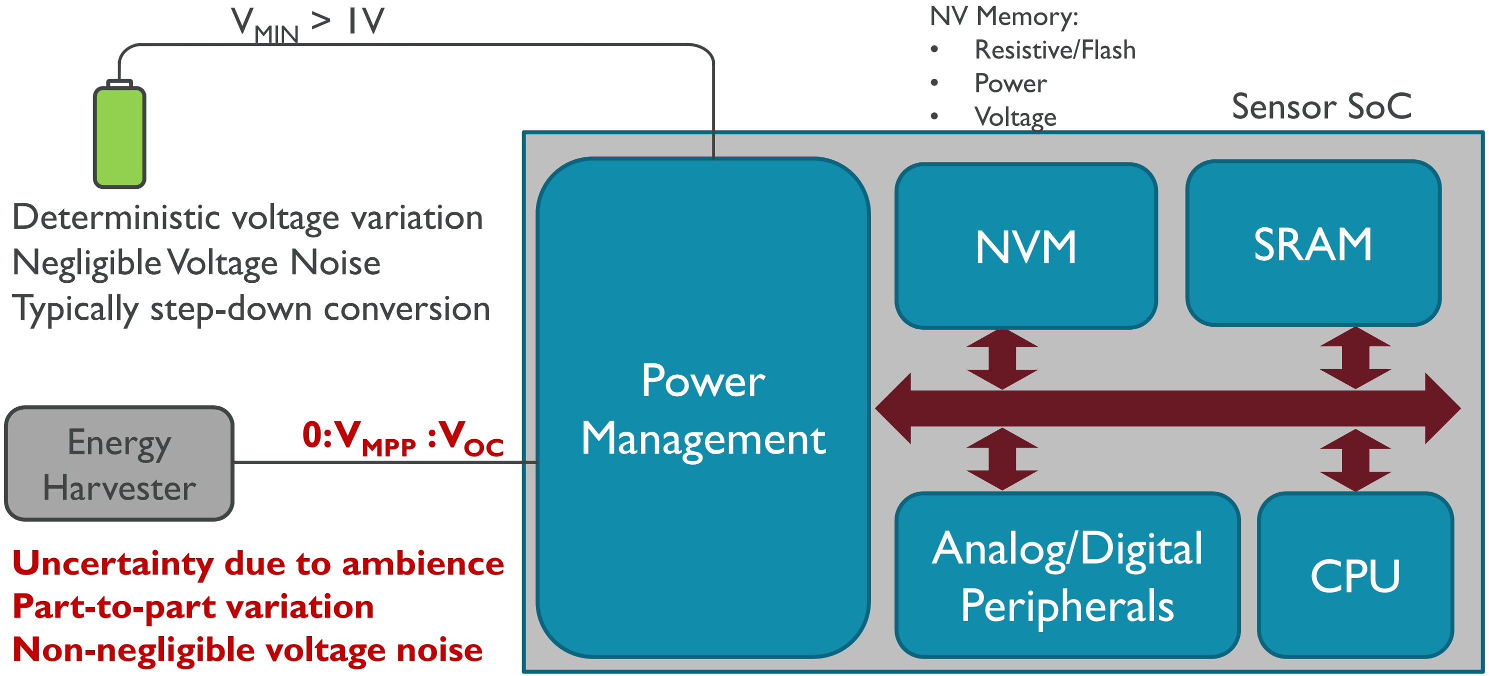




Boisseau, S., G. Despesse, and B. Ahmed Seddik. "Electrostatic conversion for vibration energy harvesting." *arXiv preprint arXiv:1210.5191* (2012)

Variability in Energy Harvesting

Trillion Sensor Nodes: Designer's Perspective



Deterministic voltage variation
Negligible Voltage Noise
Typically step-down conversion

Uncertainty due to ambience
Part-to-part variation
Non-negligible voltage noise
Reverse-current and over-voltage
Buck-Boost Conversion

NV Memory:
- Resistive/Flash
- Power
- Voltage

V Memory:
- 6T/8T/10T
- Banking
- Write-opt/Read-opt
- Power Gating

CPU:
- 8/16/32 bit
- Instructions
- Pipelining

Peripherals:
- Type, Power, Duty cycling

Energy Harvesting in Everyday Life

http://www.harrybishop.ca/?p=437
http://www.vintagecalculators.com/html/teal_photon.html

Challenges of Energy Harvesting

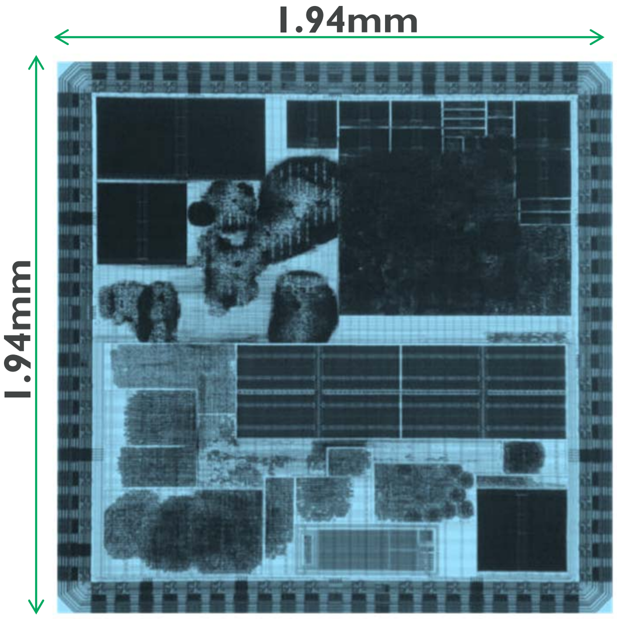
Objectives for Energy Harvesting Systems

- Possible design objectives:
  - Works when I need it to!
  - Maintenance-free
  - Compact
  - Low-cost
  - Highly functional
  - Easy to deploy
  - Energy-aware
  - Able to cold-start
  - Able to work in most environments
  - Aesthetically pleasing
  - Wearable

How can we assess (and design for) variation in energy availability?

Coping with Variation

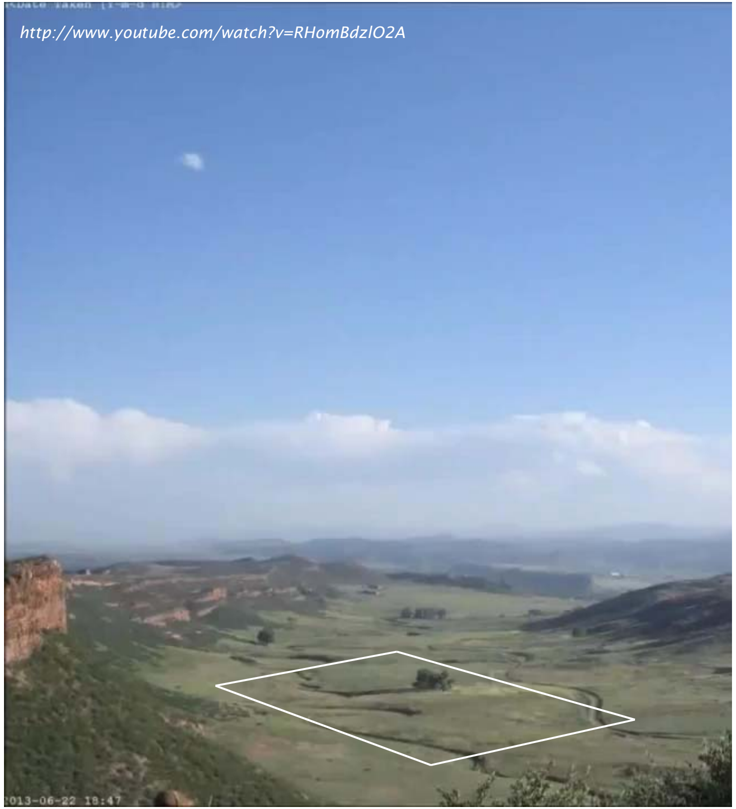
- Well-understood for conventional (battery-powered) systems
  - Process (fast, slow, typical)
  - Supply Voltage (±10%)
  - Temperature (0 to 85°C)
- Not defined for energy-harvesting systems
  - How to accommodate energy source variability? Spatial/temporal?
  - What are reasonable bounds for this?
- We *aim* for energy neutrality: harvesting at least as much as we use



Coping with Variation

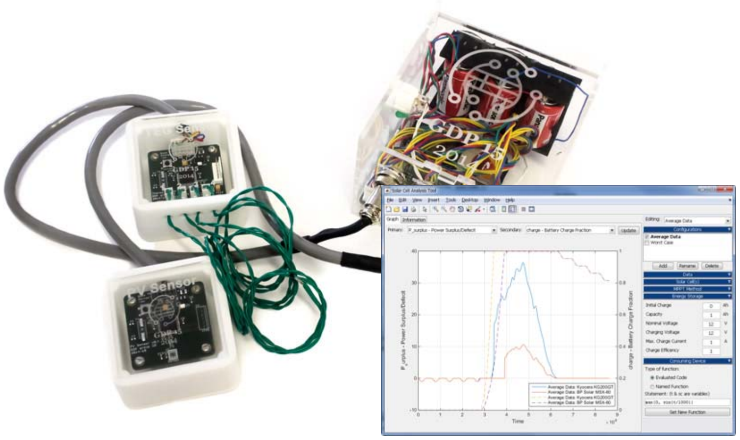
- **Temporal** variation
  - Use a larger energy buffer
  - Energy-aware behaviour: adjust duty-cycle, adapt to changing energy status
- **Spatial** variation
  - Balance sensing and routing tasks across network?

- Have to define these processes at design-time, within certain bounds
- How to estimate those bounds?

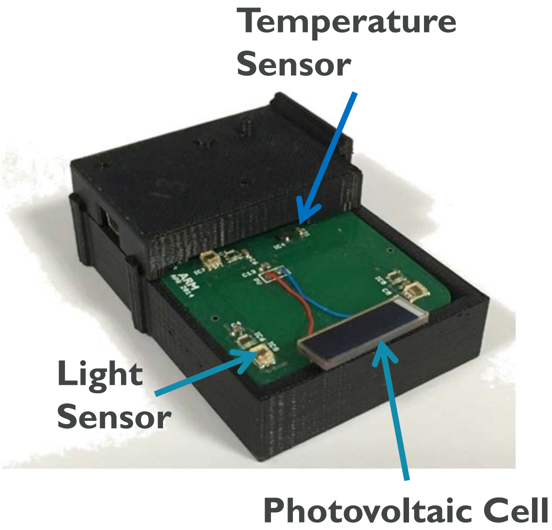


Ground Truth: Energy Availability Assessment

- How much energy is actually available?
- Enspect
  - A general tool, looks at environmental energy availability and models systems



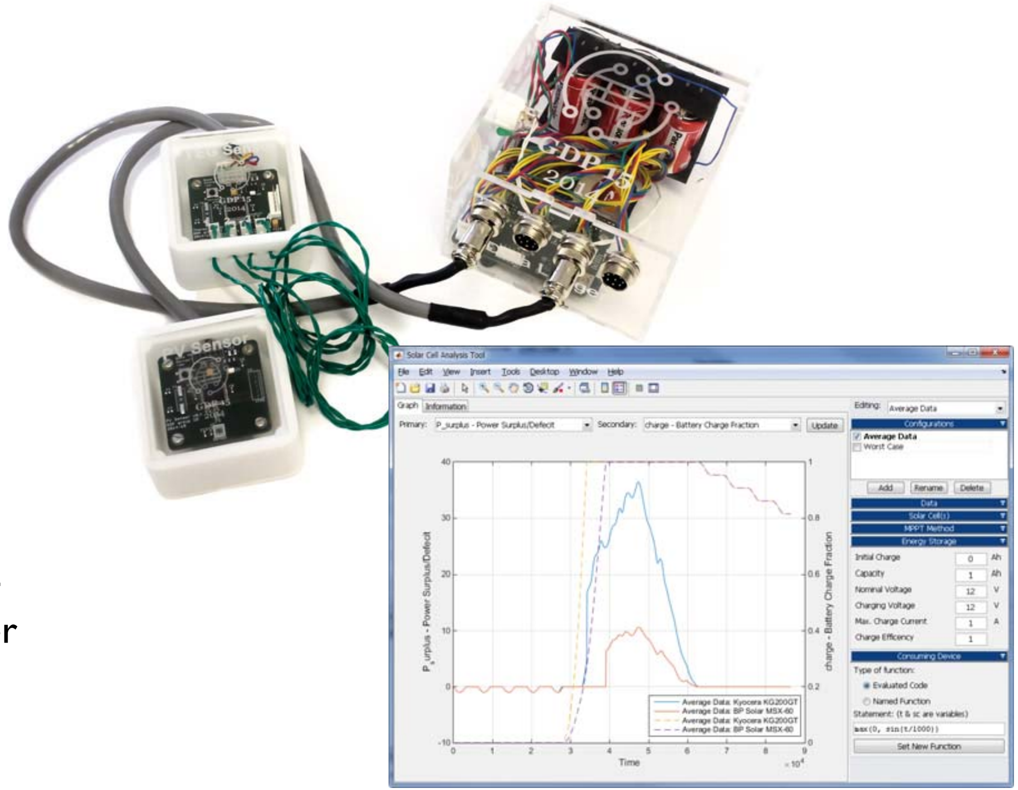
- Micro Solar Evaluation
  - A specialised tool for micro PV cells, <1% error (current and voltage)

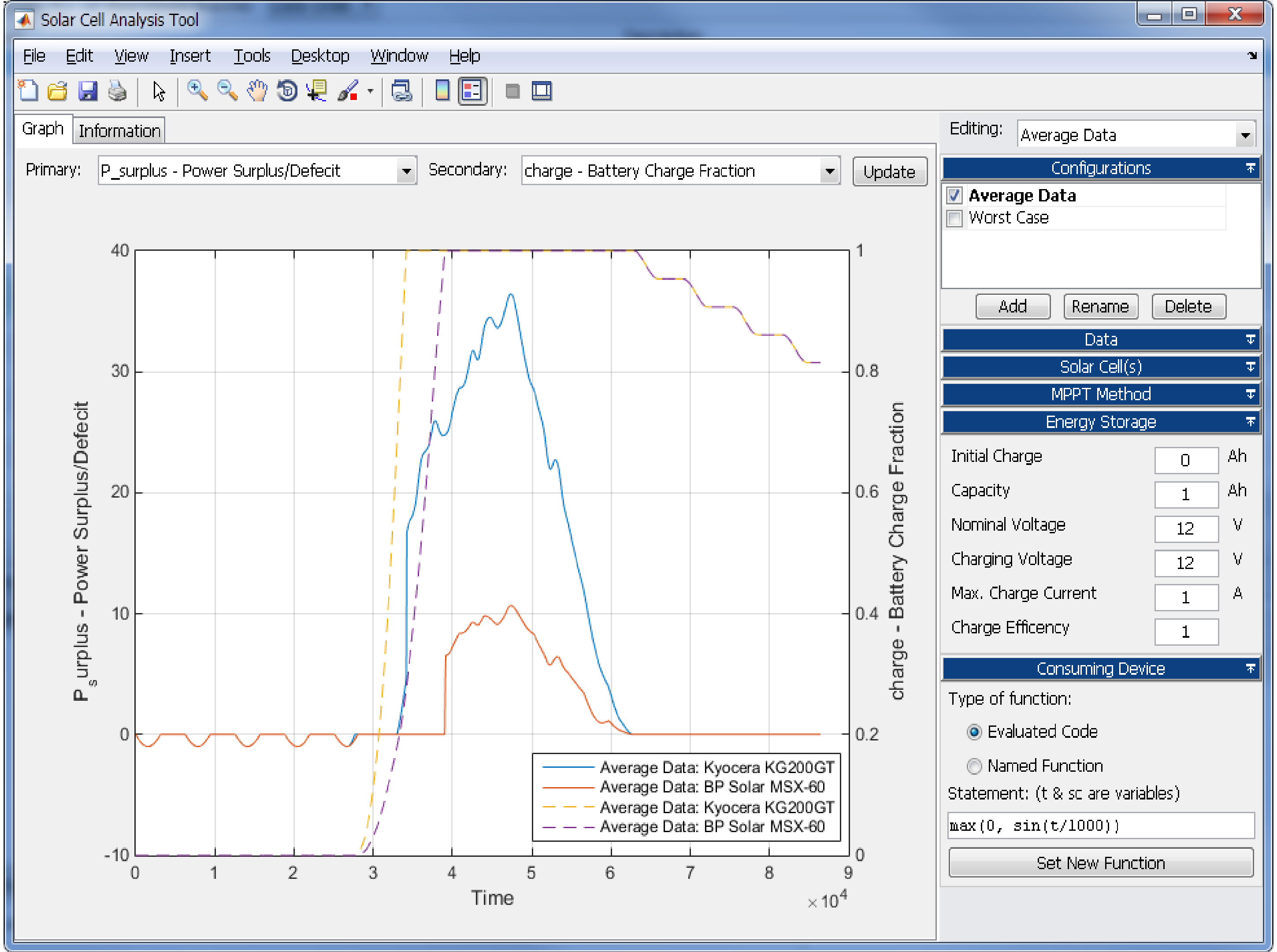


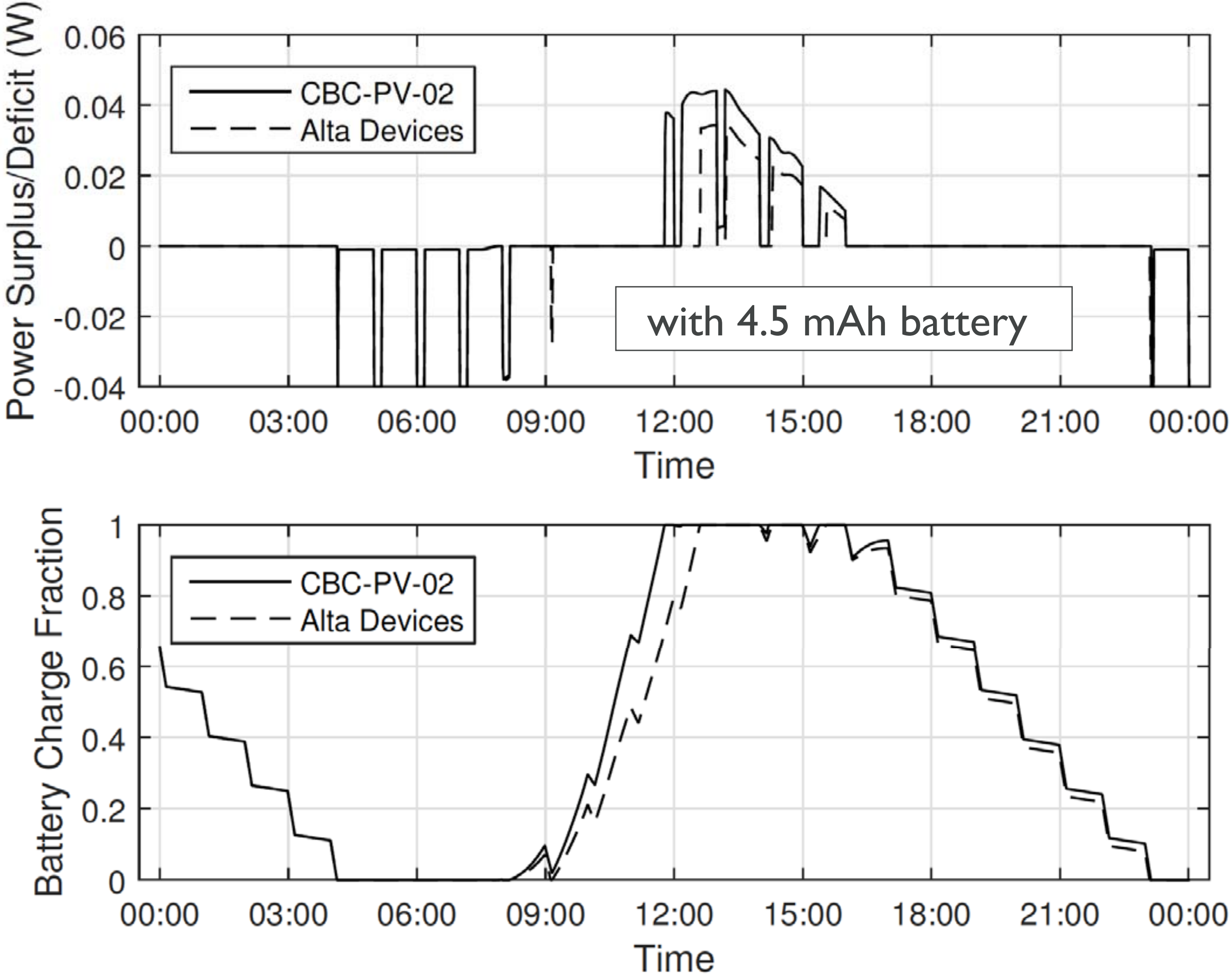
Enspect

- Logger and analysis software
- Models performance of harvester and rest of system
- Evaluate main design choices – flexible and fast

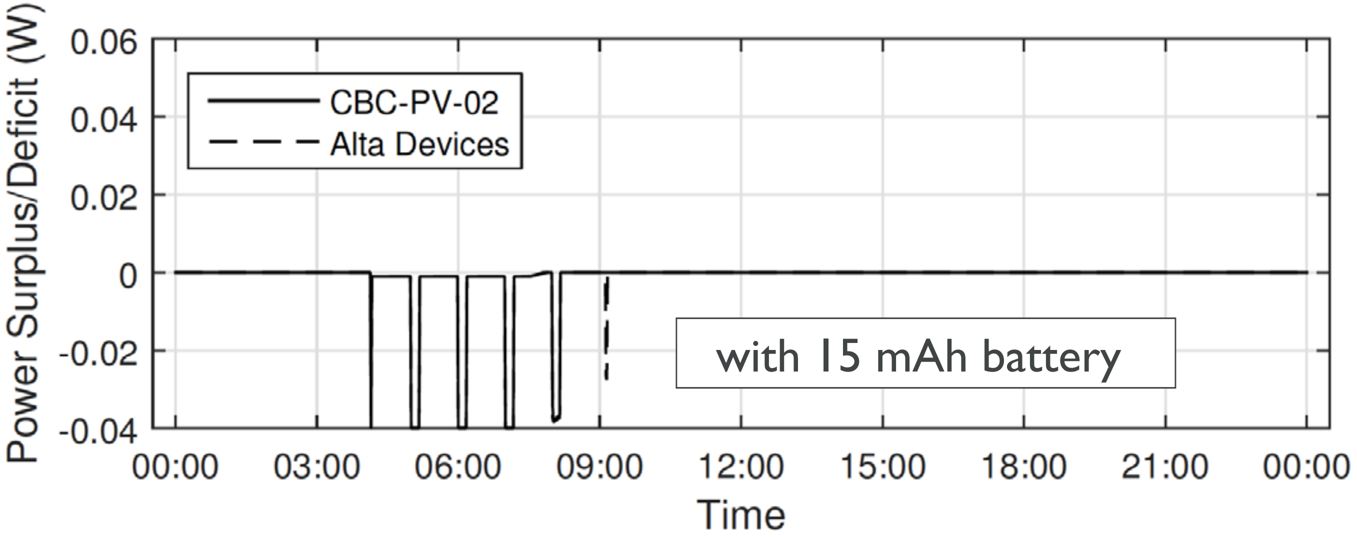
- New concept: energy *surplus* and *deficit* – assists with sizing
  - Storage: enlarge if in surplus and deficit
  - Harvester: enlarge if in deficit, but never in surplus
- Design recursively

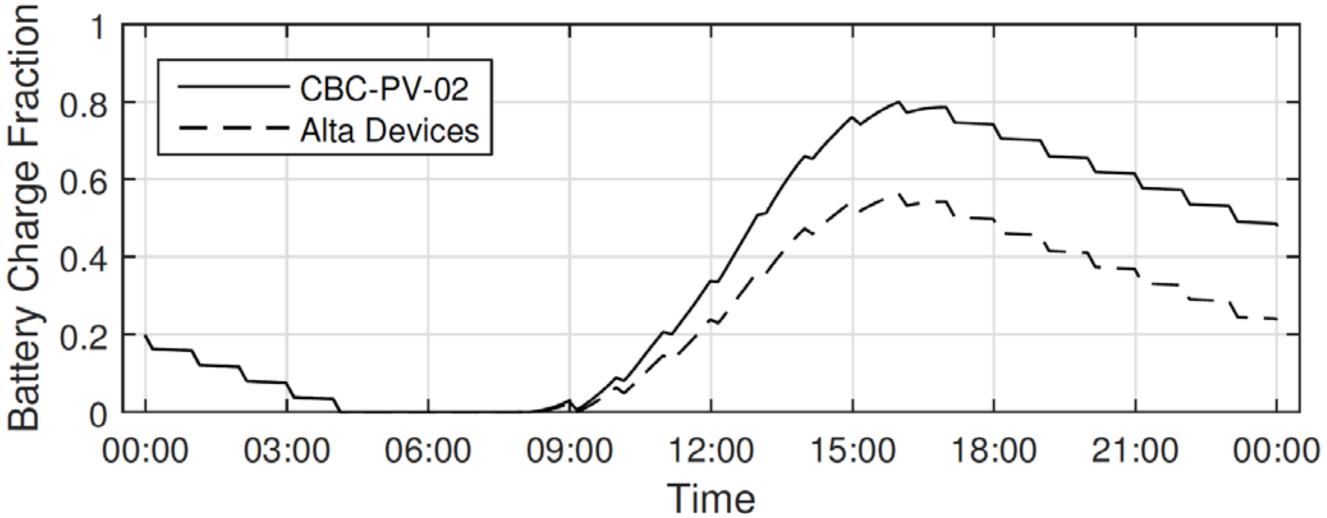



Solar Cell Analysis Tool
File Edit View Insert Tools Desktop Window Help
Graph Information
Primary: P_surplus - Power Surplus/Defecit
Secondary: charge - Battery Charge Fraction
Update
P_surplus - Power Surplus/Defecit
charge - Battery Charge Fraction
Time
× 10^4
Average Data: Kyocera KG200GT
Average Data: BP Solar MSX-60
Average Data: Kyocera KG200GT
Average Data: BP Solar MSX-60
Editing: Average Data
Configurations
Average Data
Worst Case
Add
Rename
Delete
Data
Solar Cell(s)
MPPT Method
Energy Storage
Initial Charge 0 Ah
Capacity 1 Ah
Nominal Voltage 12 V
Charging Voltage 12 V
Max. Charge Current 1 A
Charge Efficency 1
Consuming Device
Type of function:
Evaluated Code
Named Function
Statement: (t & sc are variables)
max(0, sin(t/1000))
Set New Function



Power Surplus/Deficit (W)
0.06
0.04
0.02
0
-0.02
-0.04
CBC-PV-02
Alta Devices
with 4.5 mAh battery
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00
Time
Battery Charge Fraction
1
0.8
0.6
0.4
0.2
0
CBC-PV-02
Alta Devices
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00
Time


Power Surplus/Deficit (W)
0.06
0.04
0.02
0
-0.02
-0.04
CBC-PV-02
Alta Devices
with 15 mAh battery
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00
Time


Battery Charge Fraction
1
0.8
0.6
0.4
0.2
0
CBC-PV-02
Alta Devices
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00
Time

Enspect - Tool for predicti ×

www.enspect.ecs.soton.ac.uk

Enspect

About | Download | Documentation | Contact

Enspect is a complete package for predicting the output of energy harvesting systems

Software last updated
6th Aug 2015

Download

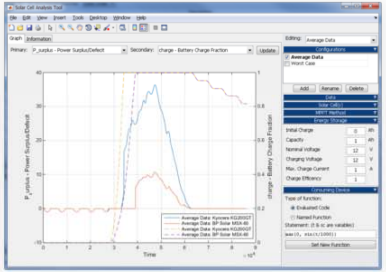
Developed as a project of the School of Electronics and Computer Science at the University of Southampton, Enspect aims to predict the power output of an energy harvesting system. It features a data colleciton unit which logs environmental data, and an analysis tool which processes this data to make predictions. Currently, an advanced photovoltaic cell model and simple thermoelectric generator model are provided.

Data Collection Unit

Envrionmental data is collected via sensor modules collected to a central logger unit. Sensor modules were developed to allow **light irradiance modelling** for solar cells and **temperature sensors for thermoelectric generators**. Data is logged in CSV format to a standard SD card.

- Controlled **wirelessly** via Bluetooth.
- Long **battery life**.
- Modular **plug-and-play** design allows new sensors to be developed.

Analysis Tool



Complementing the data collection unit is an easy to use **graphical simulation tool**, able to predict power outputs from harvesters and take into account the power profile of the **consuming device** and any **battery storage**.

- Developed in **MATLAB**.
- Able to **compare** any number of system configurations.
- Models photovoltaic cells and thermoelectric generators.
- Gives a range of **graphical** and **tabular** outputs.

More details

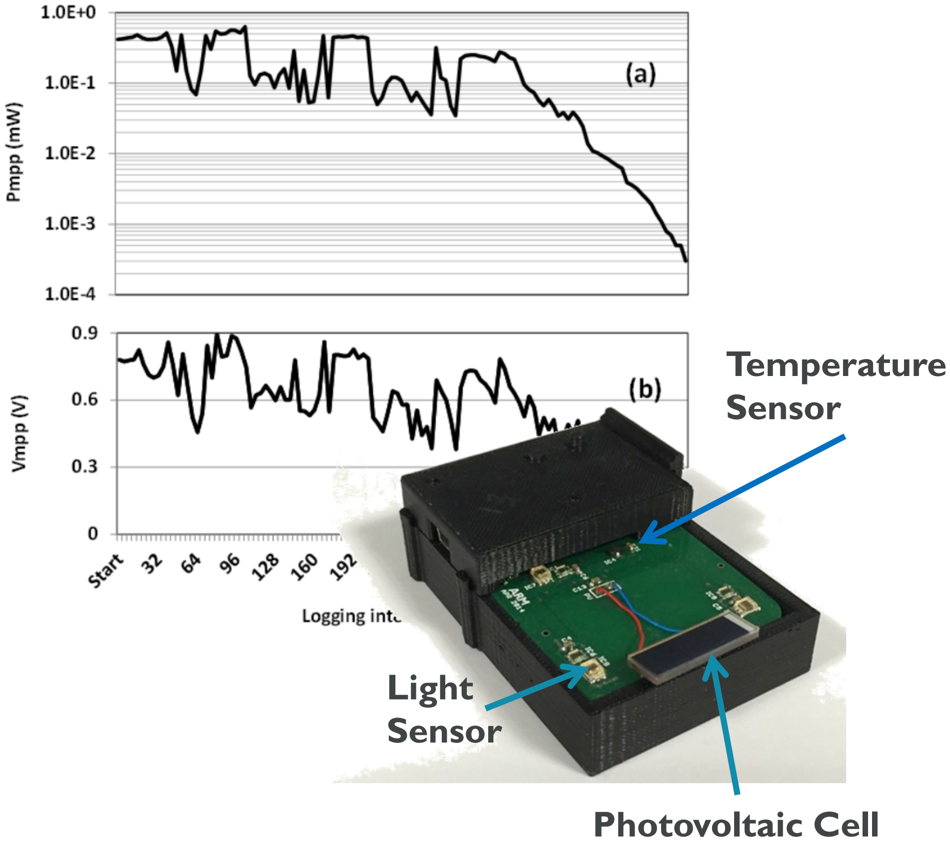
www.enspect.ecs.soton.ac.uk

The software used in the data collection unit and analysis

Find information on getting started with using the analysis

Micro Solar Evaluation

- Specifically for evaluating cm^2-scale cells in real environments (1 week+)
- Performs a full I-V sweep each time
- Better than 1% error
  - V measurement (0.1V…1.5V)
  - I measurement (10uA…5mA)
- Evaluate cell performance, design interface circuits inc. maximum power point tracking techniques



Using in System Design

- SPICE models of system components (inc. harvesters)
  - Variation-aware SPICE model
- Enables Monte-Carlo simulation of system performance

Extract Data from characterisation system

↓

Parse measured data for ‘remarkable points’

↓

Derive fitting functions for each parameter in model

↓

Generate SPICE model using fitted functions

SPICE Description

```
.SUBCKT PVCELL P N lux=200
.param rp_scale = lux>1800?2:1
.param iph='-9e-12*lux*lux+70e-9*lux-5e-6'
.param is='5e9*pwr(lux,-9.5)'
.param is_var=agauss(0,1e-11,3)
.
.
IP N Pint 'iph'
DMAIN Pint N dpv
.
.
.MODEL dpv  D (LEVEL=1 ...)
.ends PVCELL
```

Test Bench

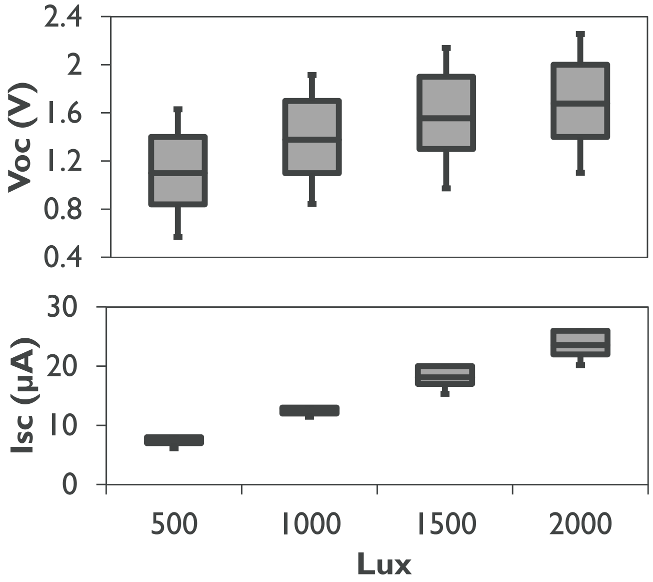
```
RLOAD VP 0 'rload'
X1 Vp 0 PVCELL lux='illum'

.tran 1n 3u sweep monte=30 $$data=iload

.data illum_data
+illum 500 1000 1500 2000 2500
.enddata
```

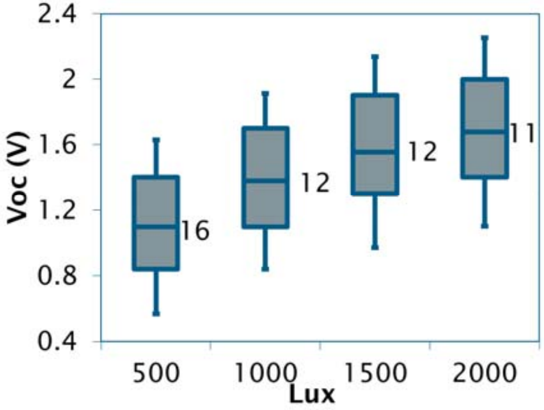
Micro Solar: Unexpected Findings

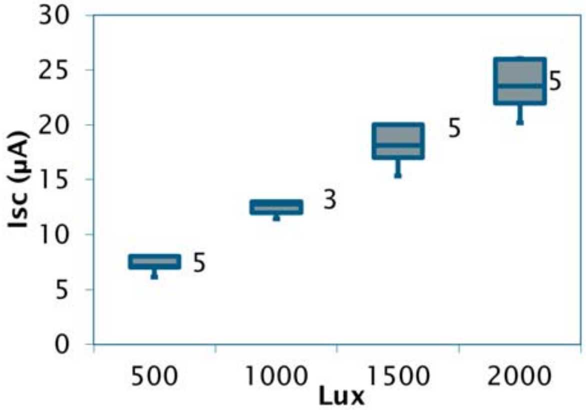
- Variation between cm^2 PV cells
  - Same manufacturer, same batch!

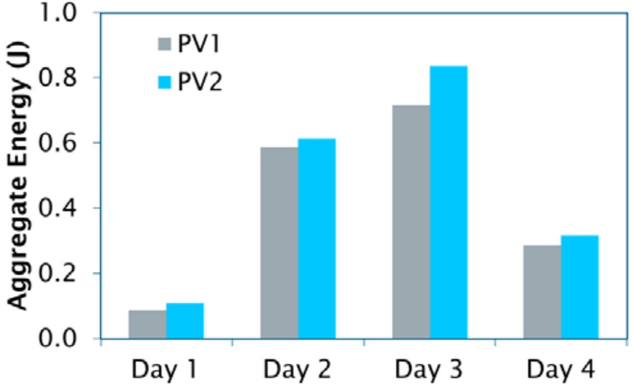


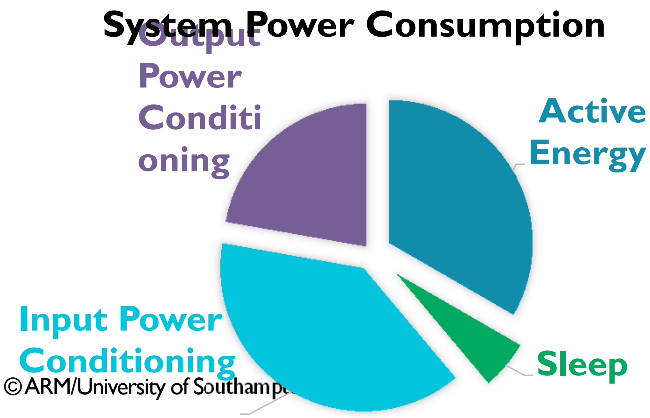
- Datasheets don't show this!
  - Typically state V and I (for light level)
  - No idea of variation
- So part-part variation is *very* significant (and unexpected)
  - Due to variation in doping on small cells?

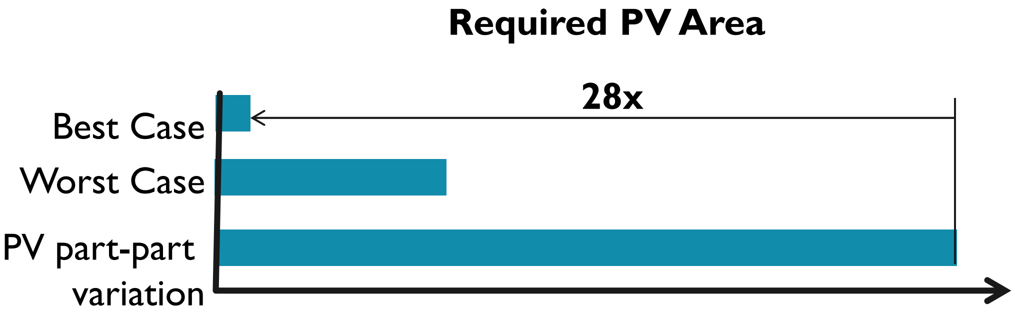
Modeling and Variability











[Savanth EnsSys'15]

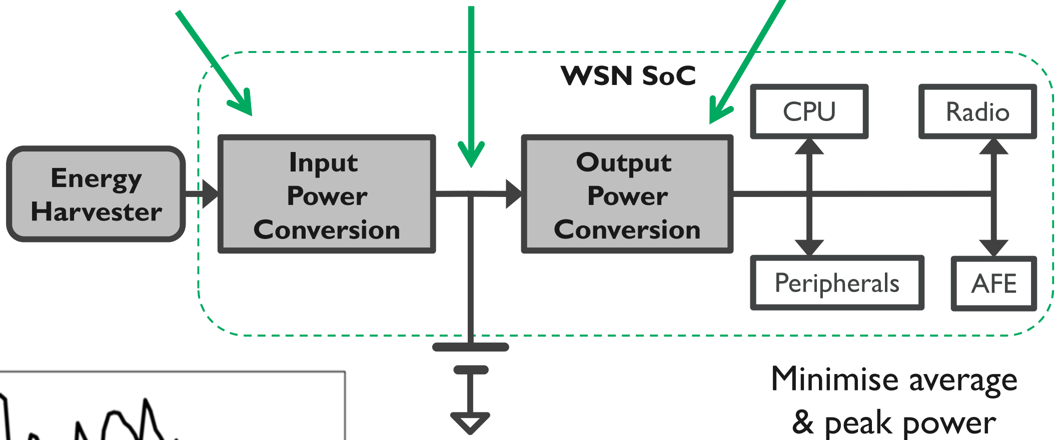
Voltage, Power and Energy

Up to 50% conversion loss: depends on topology & voltage difference

Self-discharge and resistive losses

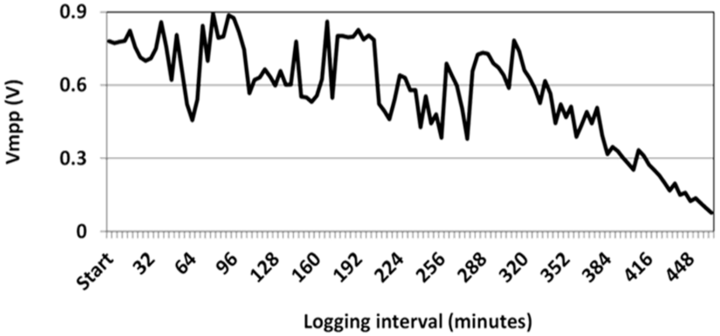
Up to 70% conversion loss: depends on topology & loading

Maximum power point tracking, limit output to safe voltage



Compensate for input/output variations, monitor for brown-out

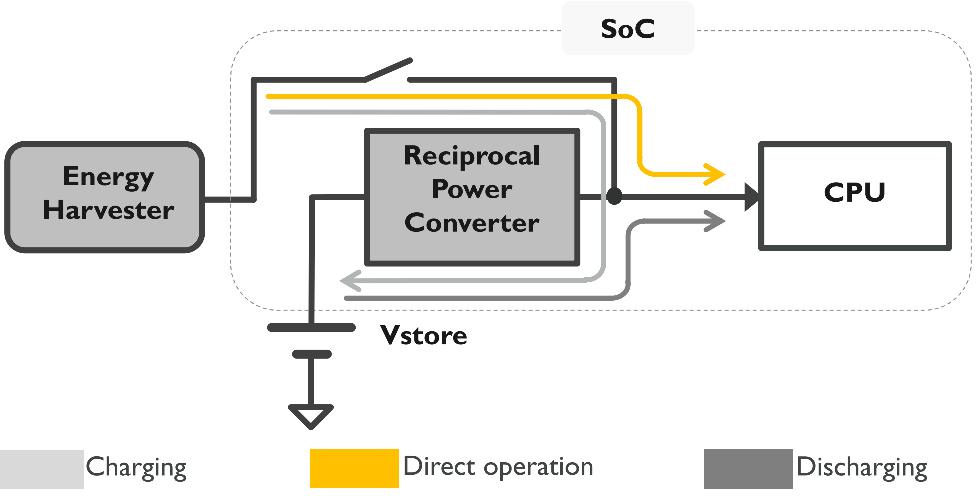
Minimise average & peak power



[Savanth TCAS'17]

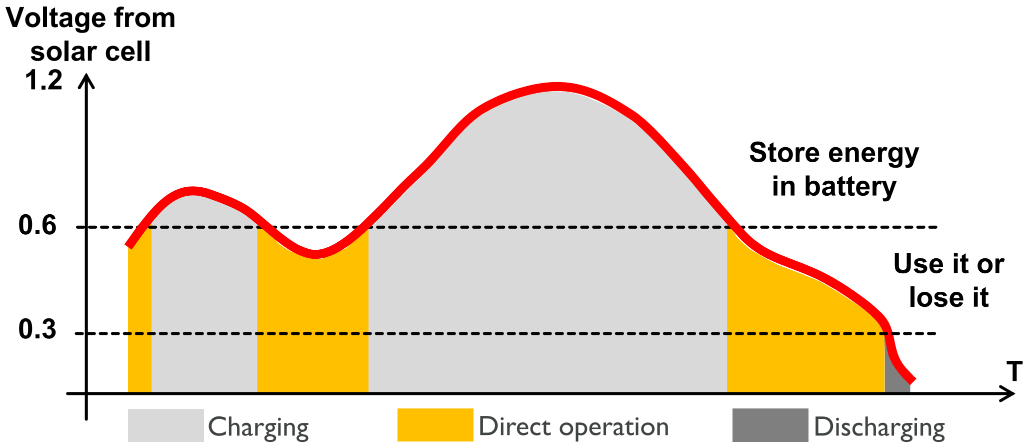
Efficient System Design

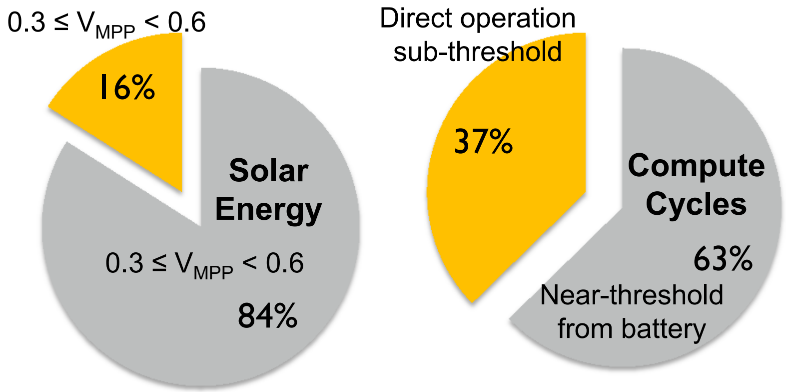
- Reciprocal converter, with direct operation
- Avoid the use of two converter stages
- Enables direct operation when conditions allow



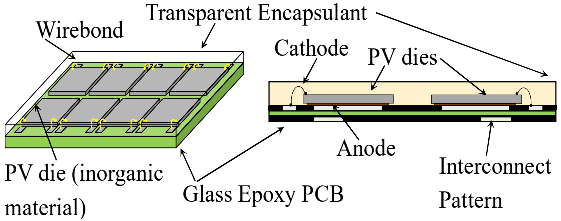
Energy Harvesting: Use it or Lose It!

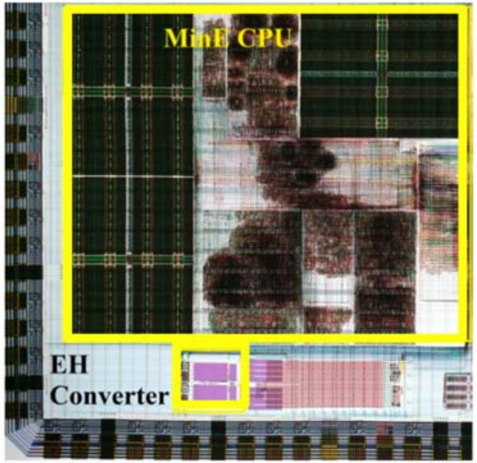
- Energy harvesters have variable output, causing waste of available energy
- Significant gains possible from direct-operation under some conditions



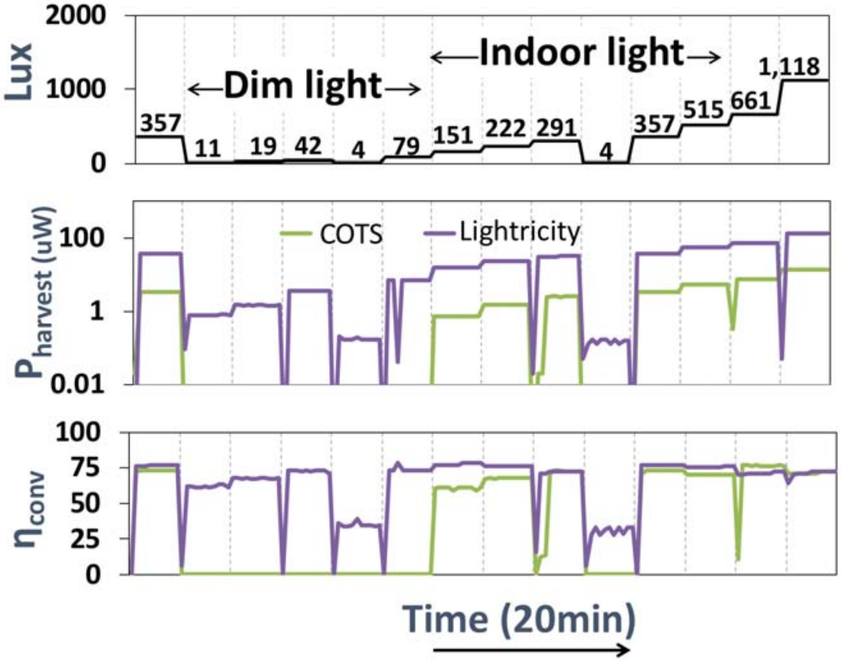


Solution: Co-Design



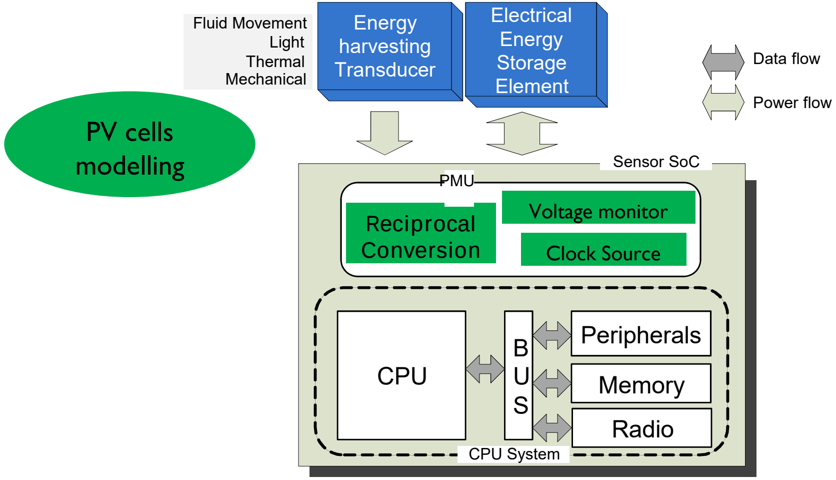


Block	Area (µm)
CHIP	1940 x 1940
LOGIC	1180 x 980
DCDC	175 X 210 (3%)

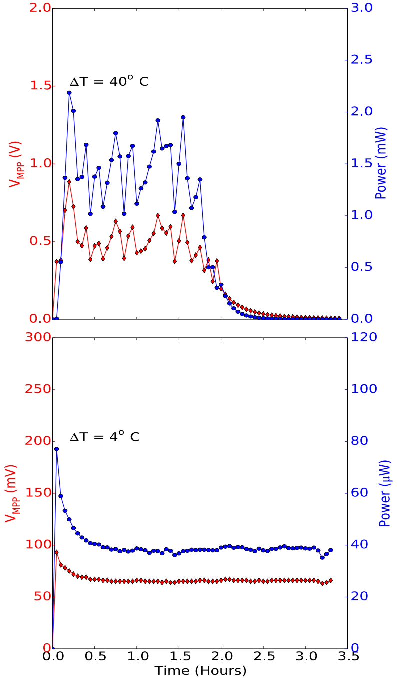


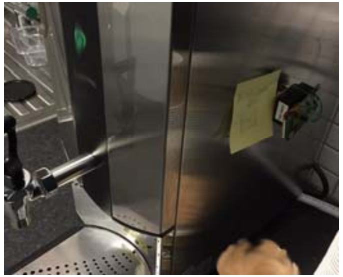
[Savanth PMEMS'17, TCAS'17]

Solution: Holistic System Approach



[Savanth ISSCC'17, VSLID'17]





Energy-neutral system operation with 50 lux continuous light or 200lux for 2hrs/day , 20°C ΔT continuous or 50°C ΔT for <1min/day

Conclusion

- Energy Harvesting and sensor system design for IoT
- Challenges with small scale energy harvesters
- Need for co-design, using real data, and holistic system solution
- Benefits from direct operation

- An open challenge: how to define *applications* to cope with variability

Acknowledgements:

- Arm: A Savanth, J Myers, P Prabhat, S Yang, A Kufel, D Flynn

