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Storage-less and converter-less maximum power tracking of photovoltaic cells for a nonvolatile microprocessor

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Outline

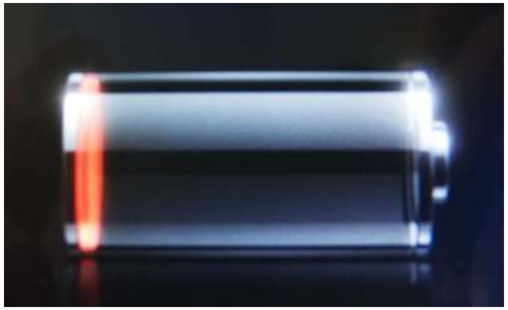
- Background
  - Energy harvesting for IoT applications
  - Maximum power point tracking (MPPT) of a photovoltaic module
  - Conventional system architecture and problems
- Storage-less and converter-less MPPT
  - With a nonvolatile microprocessor
- System evaluation
- Conclusion

Developing IoT applications

- Internet of things (IoT) on the way
  - Structural health monitoring
  - Smart agriculture
  - Smart transportation
  - Etc…

Energy & maintenance is a big problem

- Battery powered devices
  - Most widely used
  - Limited capacity
  - Need regular maintenance
  - Volume/weight overheads
  - Potential high cost



Energy harvesting

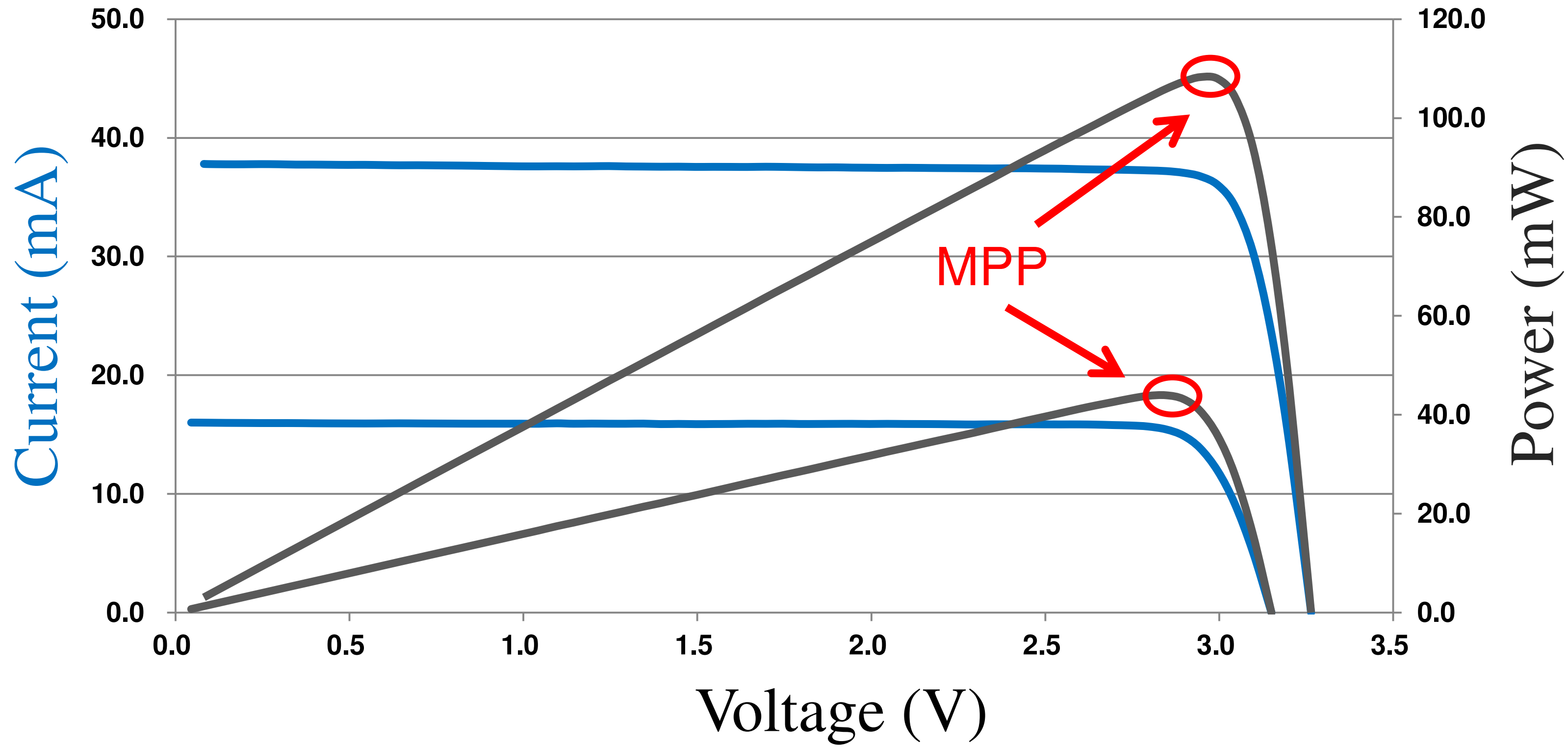
- Power density estimates of different sources

Energy Source	Harvested Power
Vibration/Motion	
Human	4 μW/cm^2
Industry	100 μW/cm^2
Temperature Difference	
Human	25 μW/cm^2
Industry	1–10 mW/cm^2
Light	
Indoor	10 μW/cm^2
Outdoor	10 mW/cm^2
RF	
GSM	0.1 μW/cm^2
WiFi	0.001 μW/cm^2

Source: Texas Instruments White Paper - ULP meets energy harvesting: A game-changing combination for design engineers

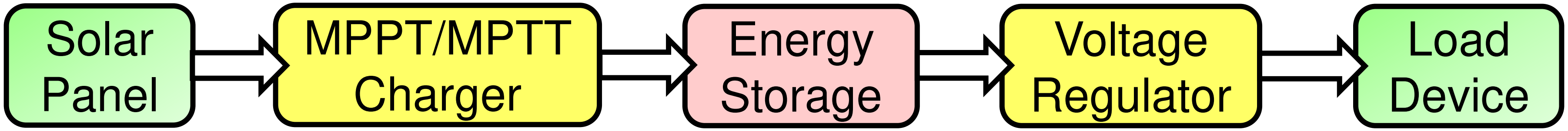
Harvesting solar energy

- Maximum Power Point Tracking (MPPT)
  - Try to extract as much power as possible from the solar panel



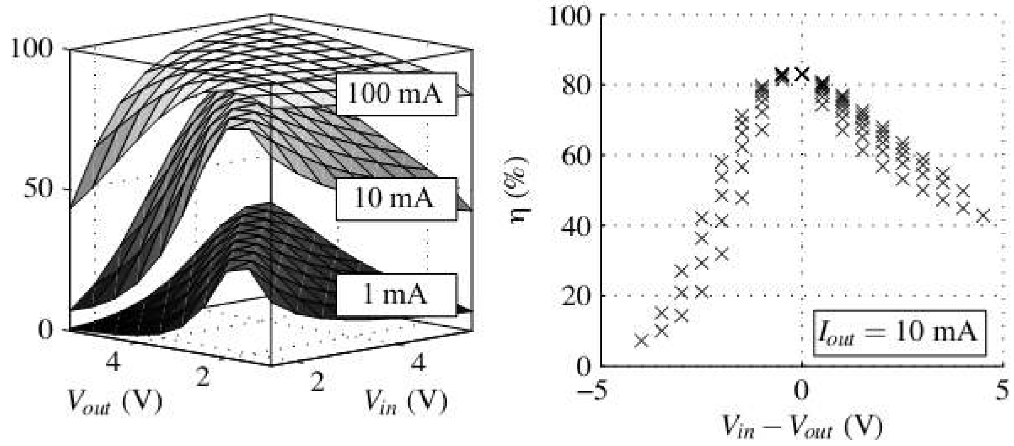
Traditional system architecture

- Solar energy is first charged to a energy storage device (supercapacitor/battery)
- Stored energy is then retrieved and delivered to the load device



Problems in traditional architecture

- 2 stage power converters
  - Expensive
  - Significant conversion loss



Source: Y. Kim, N. Chang, Y. Wang, M. Pedram - Maximum power transfer tracking for a photovoltaic-supercapacitor energy system

- Energy storage
  - Higher cost
  - Weight/volume overhead
  - Limited work cycles (Rechargeable battery)
  - Leakage (Supercapacitor)

Is there an alternate **cheap** and **efficient** way to utilize solar energy?

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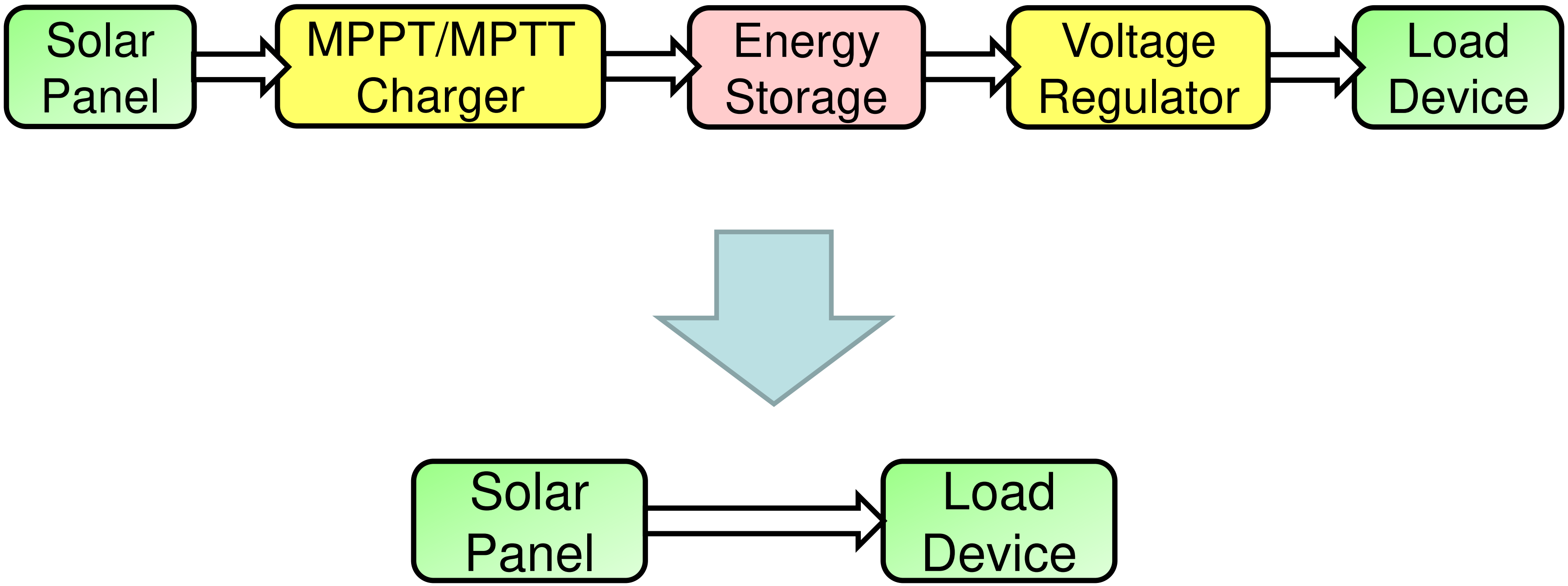
Storage-less and Converter-less



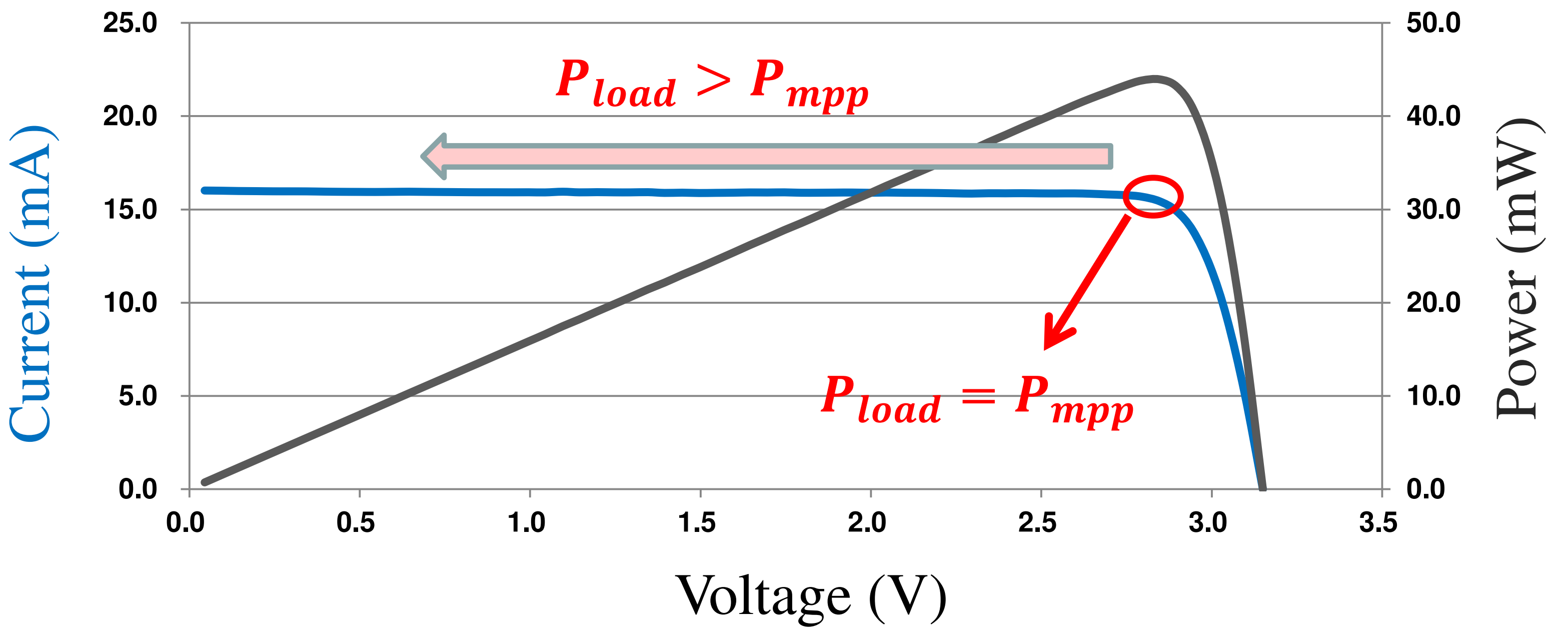
Storage-less and Converter-less

Advantages

- Storage-less
  - No long-term energy storage (battery or super-capacitor)
  - Maintenance free
  - Volume, weight and cost reduction
- Converter-less
  - Higher power transfer efficiency
  - Lower cost

Does it work?

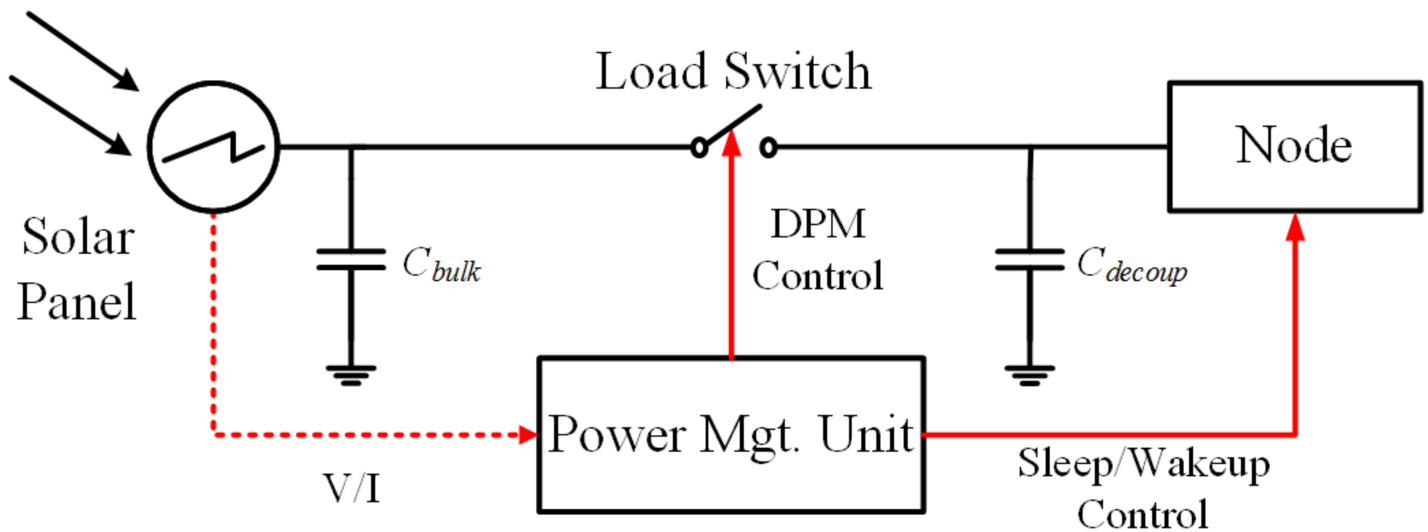
- How to ensure the functionality?
  - V_{solar} collapses if $P_{load} > P_{mpp}$



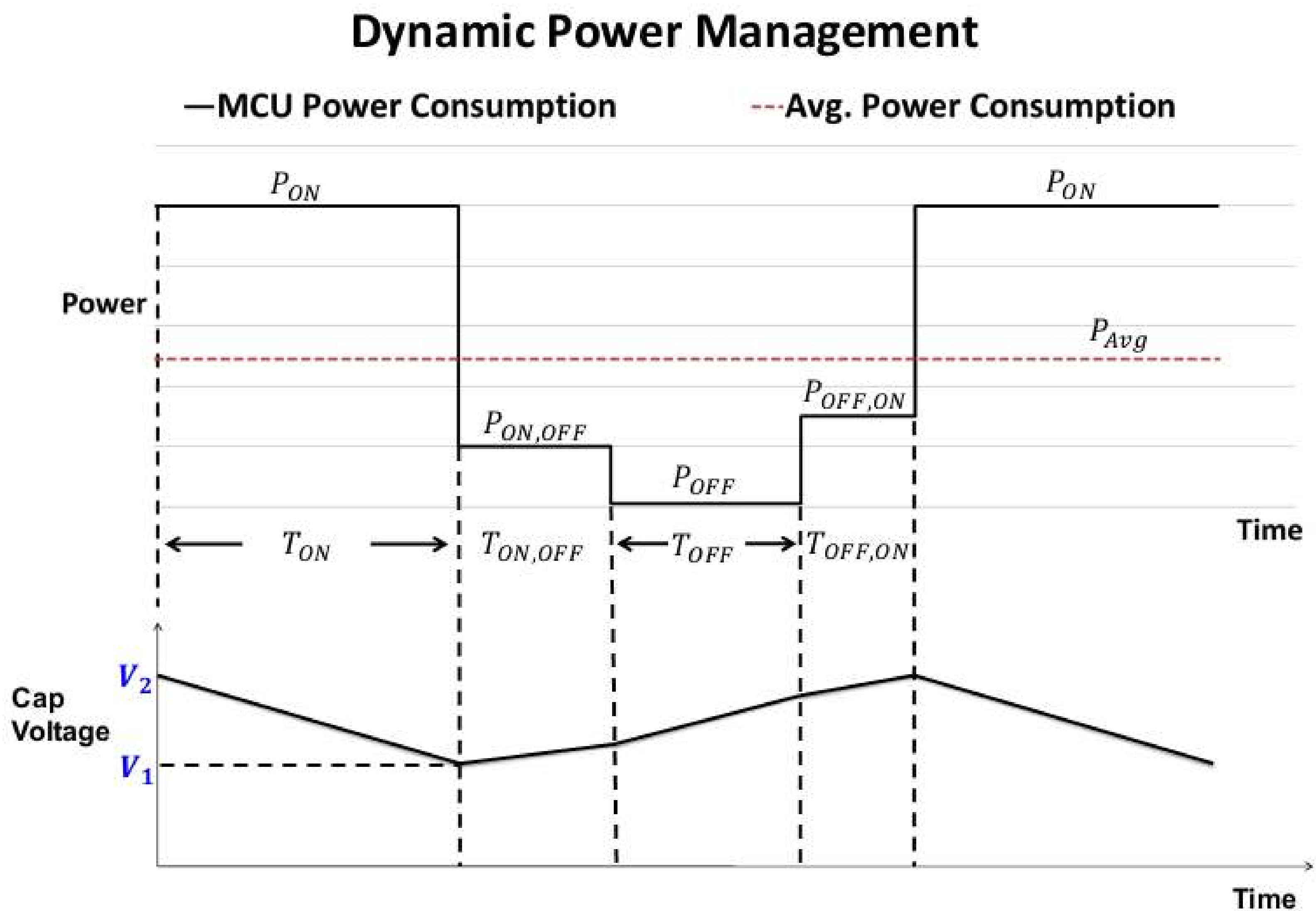
- How to perform MPPT?
  - How to match P_{load} with the varying P_{solar}

Proposed solution

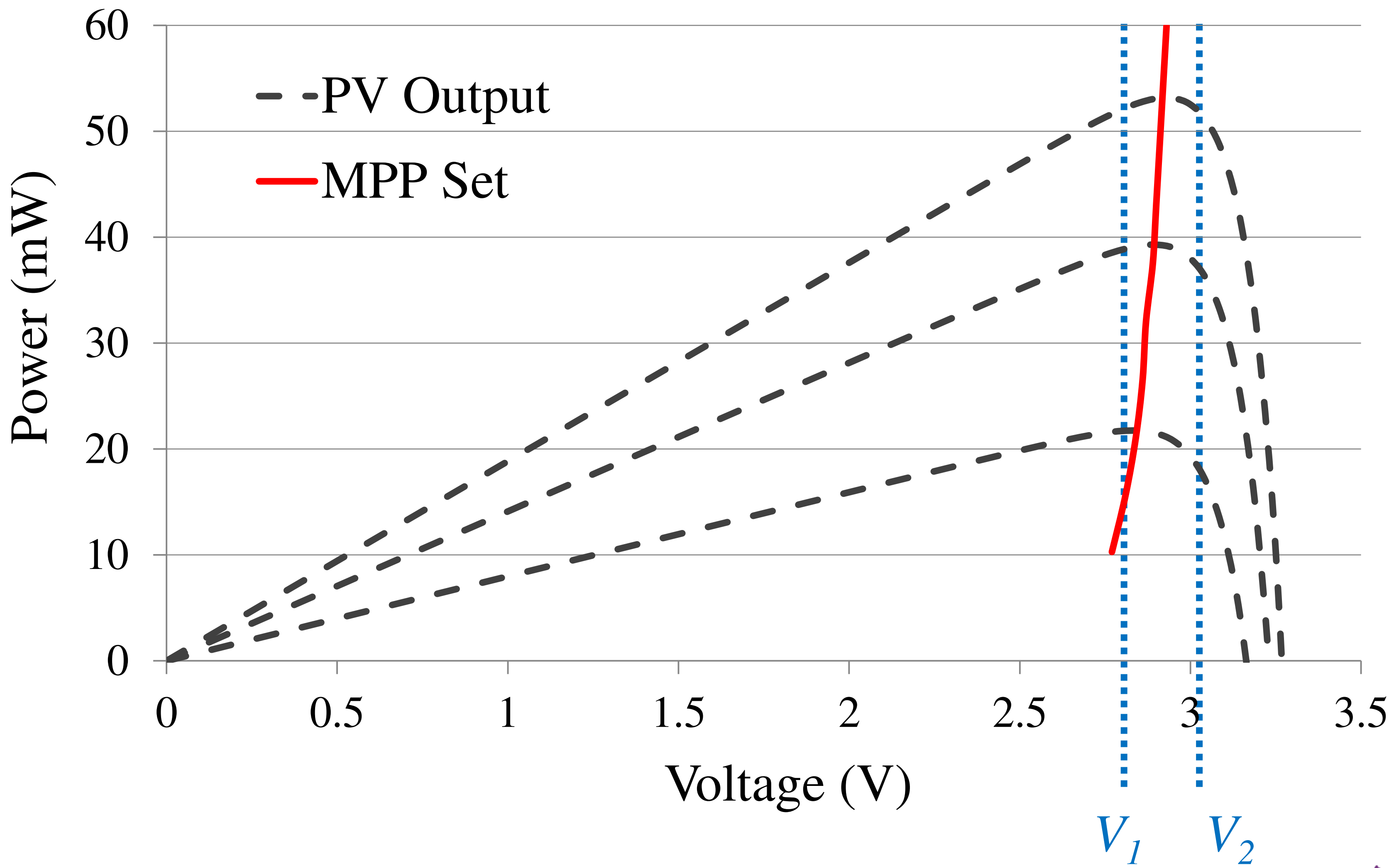
- Connect the PV to the load via a load switch
- Adjust average load current by Dynamic Power Management(DPM)
- Match the average load current with the MPP current of the solar panel



MPPT achieved by fine-grained DPM



MPPT achieved by fine-grained DPM



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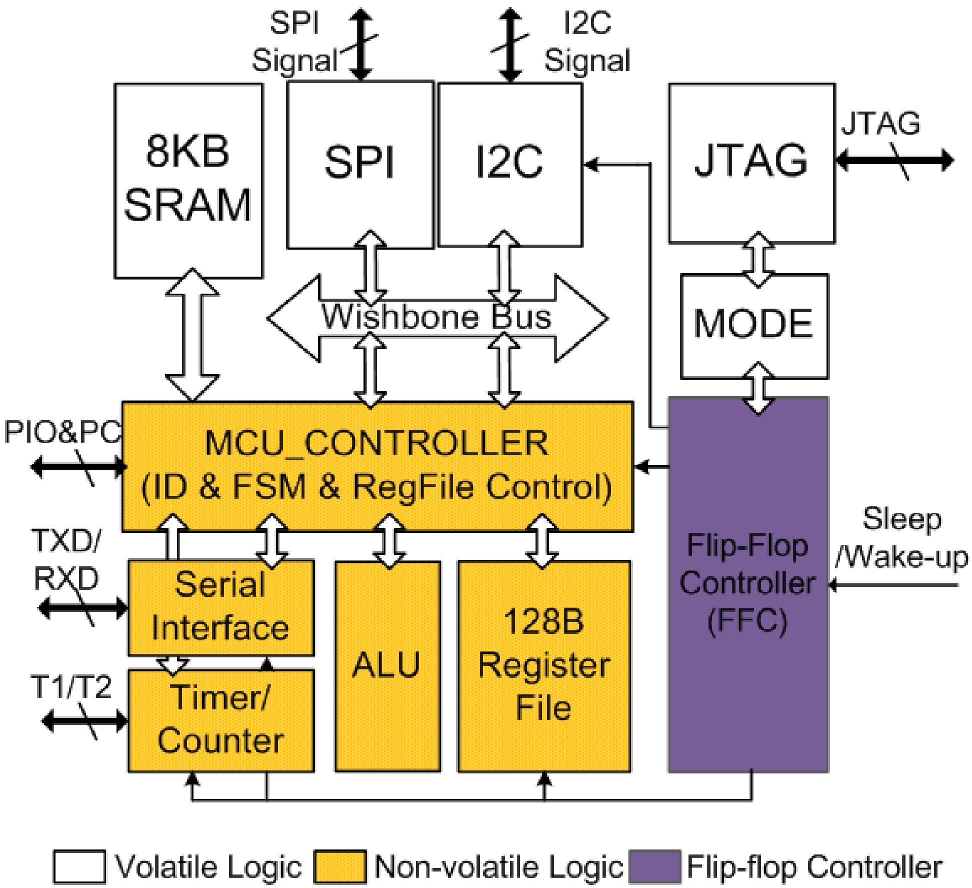
Need for a nonvolatile microprocessor

- Transition overheads are NOT negligible
  - Especially when transitions are frequent (C_{bulk}~$1\mu F$, T_{DPM}~ several ms)
  - Smaller time overhead, more time for task execution
  - Smaller energy overhead, more energy for task execution
- Transition overheads are significant for conventional microprocessor
  - Typical time overhead
    - Several ms
  - Typical energy overhead
    - 20 mA if write to a Flash

THU1010N nonvolatile microprocessor



- Based on standard 8051 micro-controller
- Fully replace original Flip-Flop with Nonvolatile FeFF
- Flip-flip Controller
- Peripherals for embedded applications and online debug

Transition overheads comparison

- NV processor is faster in state transitions

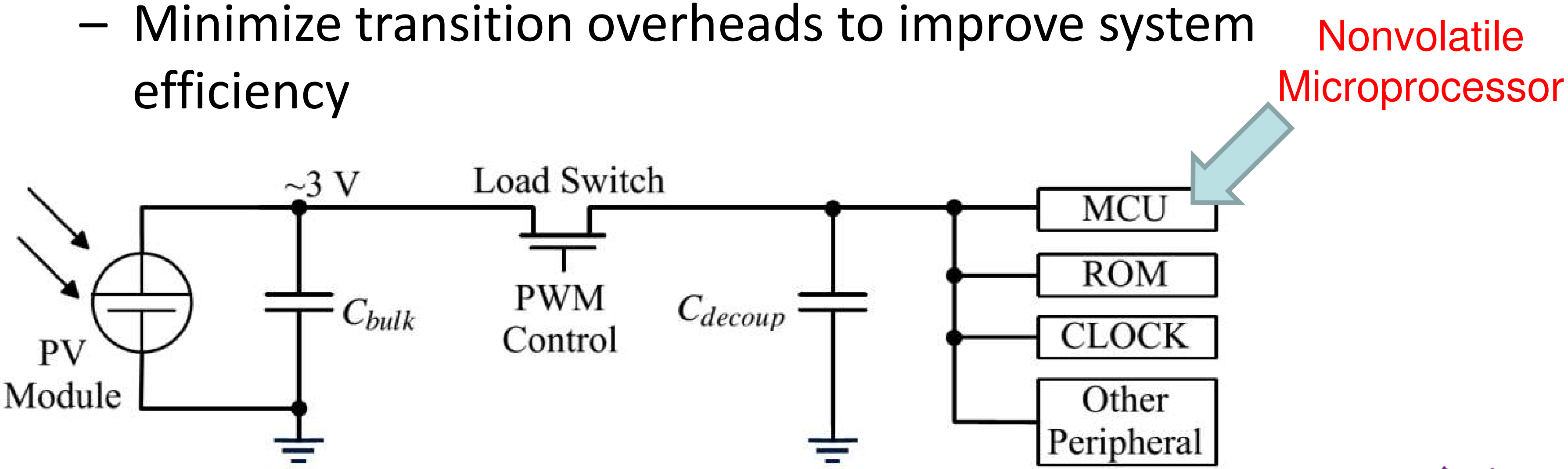
	THU1010N	TI-MSP430 with Flash [1]	TI-MSP430 with FRAM [2]
Backup time	8us	6ms	212us
Recovery time	3us	3ms	310us

- Less energy overhead in state transitions for NV processor

	THU1010N	TI-MSP430 with Flash [1]	Ratio
Backup energy	23.1nJ	445uJ	19000
Recovery energy	8.1nJ	0.6uJ	74

Storage-less and Converter-less MPPT

- MPPT
  - Achieved by Dynamic Power Management (DPM)
  - DPM is fine-grained power gating of the node
  - A buck capacitor is used as energy buffer and extend the time constant
- Nonvolatile microprocessor
  - Minimize transition overheads to improve system efficiency



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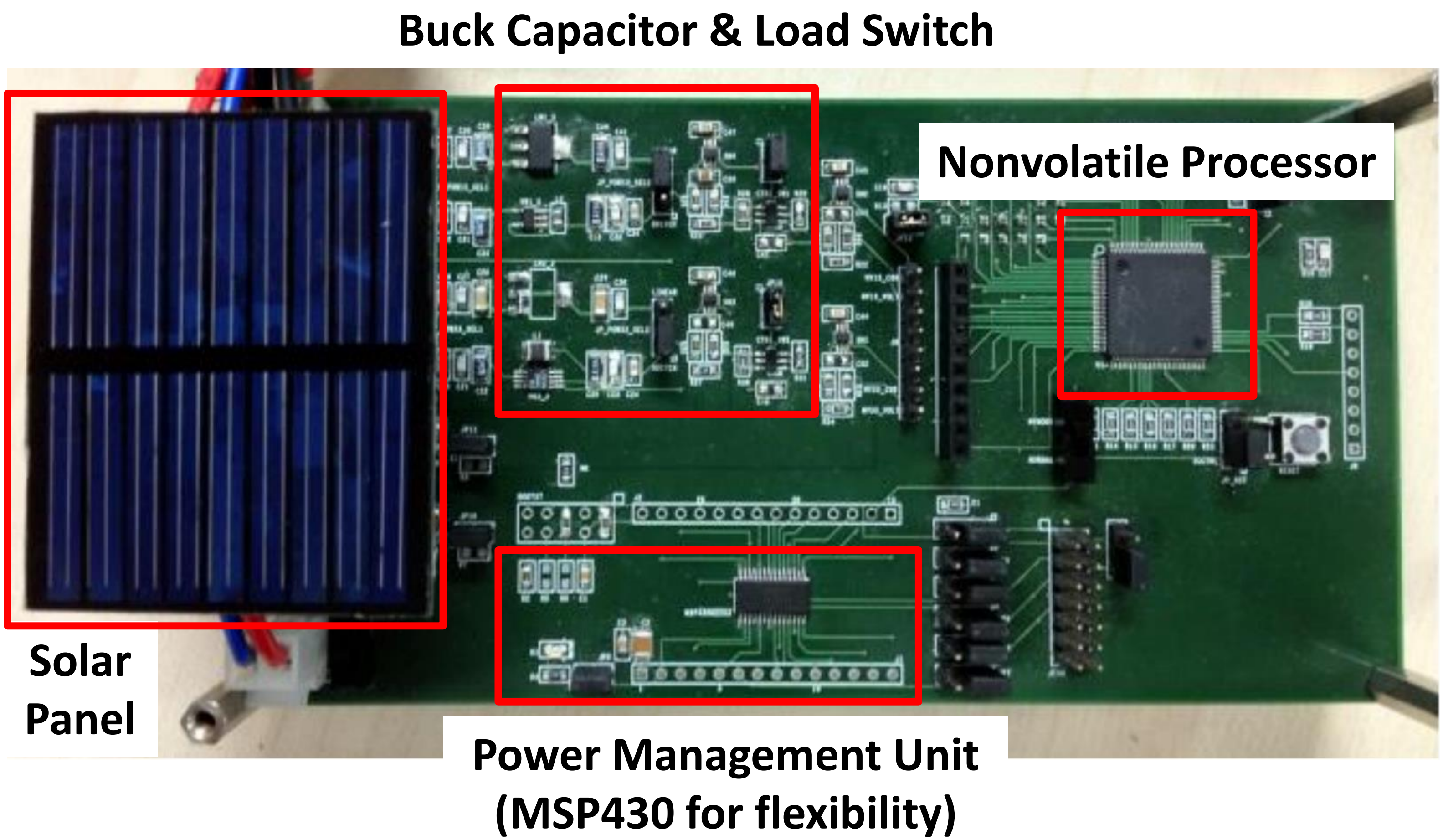
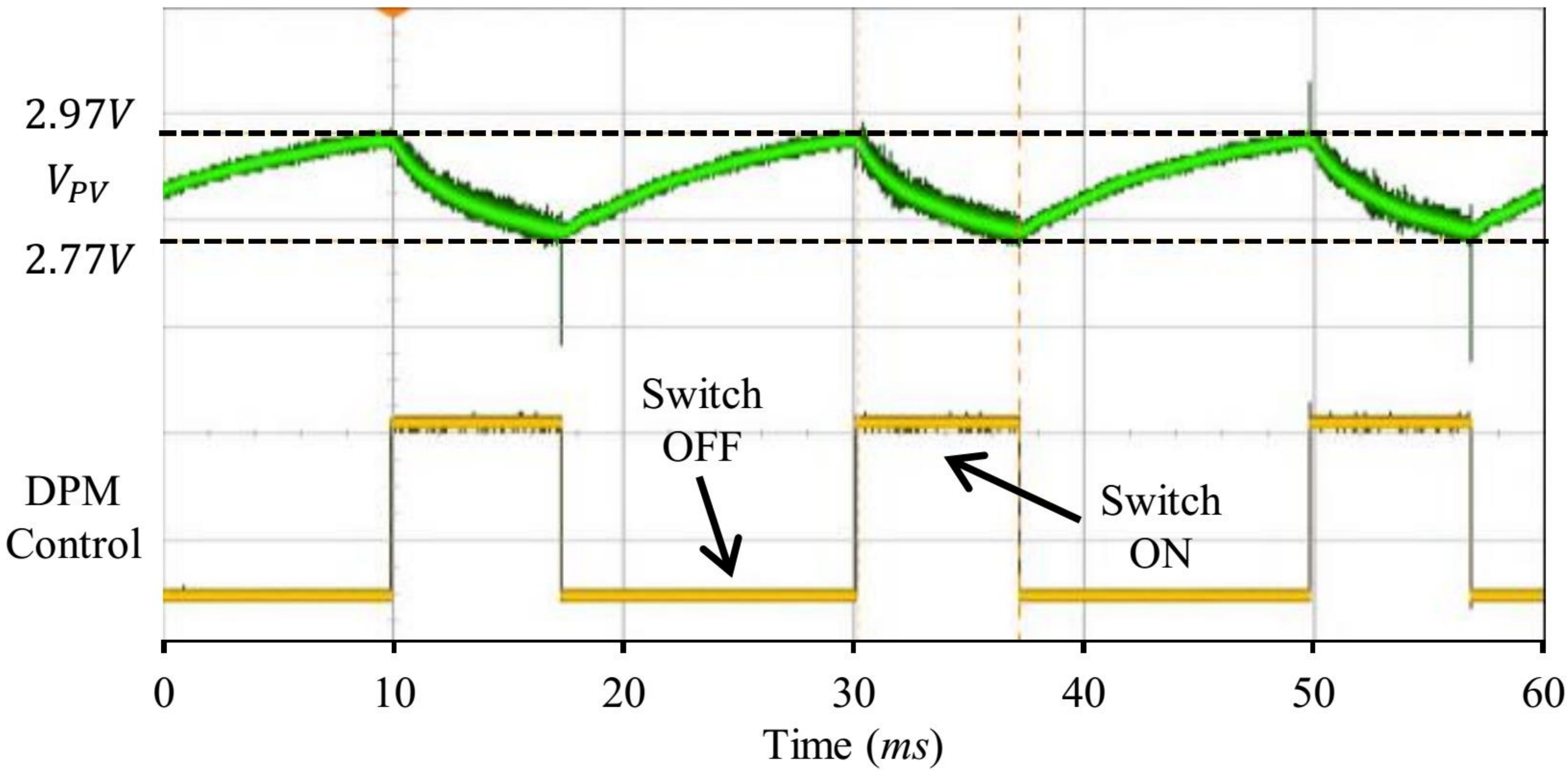
Evaluation board



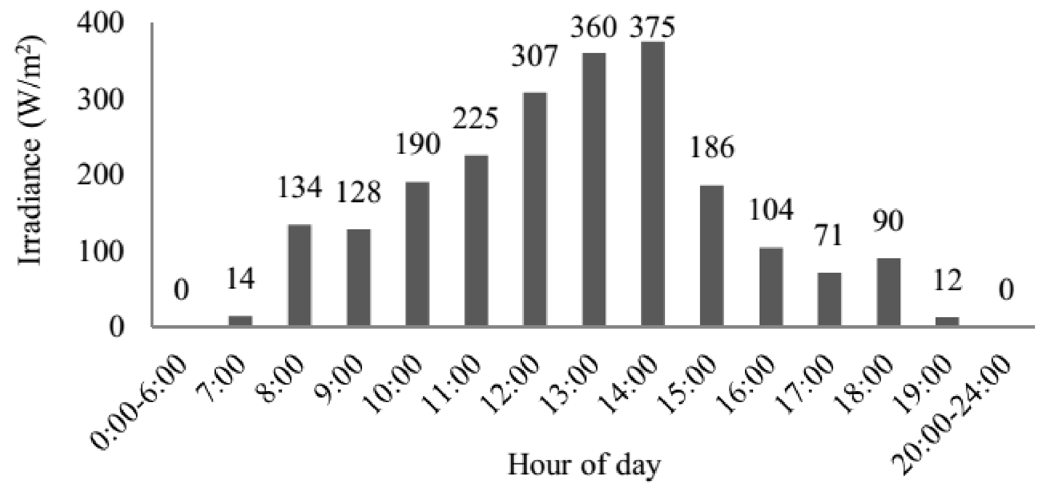
Evaluation board

- Captured waveform



Efficiency evaluation

- Simulation Setup
  - $P_{ON} = 25mW, P_{mpp} = 14.7mW@200W/m^2$
  - $C_{bulk} = 4.7\mu F, C_{decoup} = 20nF$
  - $[V_1, V_2] = [2.75V, 2.90V]$
  - Assume $P_{ON} = P_{ON,OFF} = P_{OFF,ON}$
  - Transition Time Overhead
    - $T_{ON,OFF} = 8\mu s, T_{OFF,ON} = 3\mu s$ (Proposed system with NVMCU)
    - $T_{ON,OFF} = 0.3ms, T_{OFF,ON} = 0.2ms$ (Proposed system with conv. MCU)
  - Omit the power consumption of the power management unit

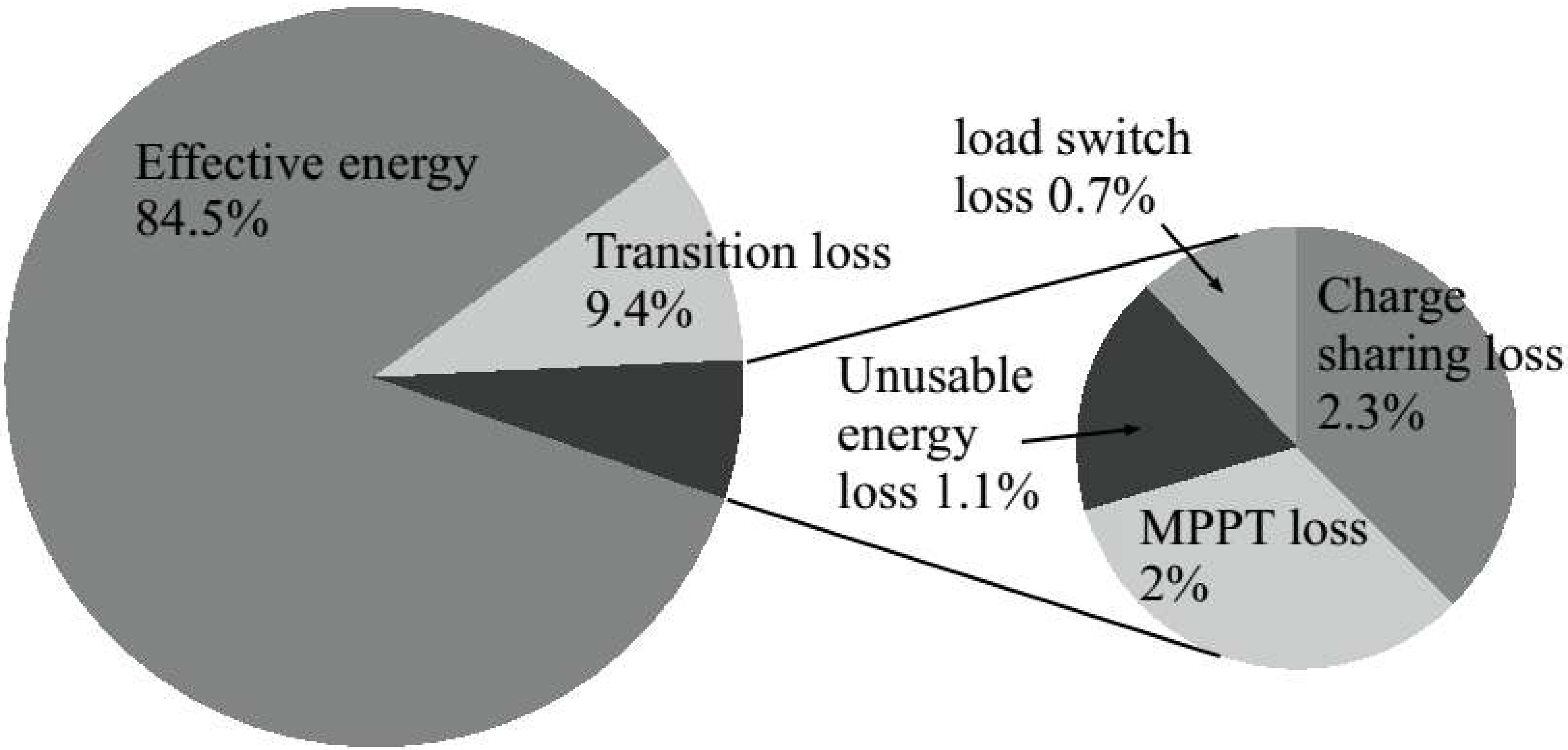


Efficiency evaluation

TABLE IV
DYNAMIC POWER MANAGEMENT RESULTS.

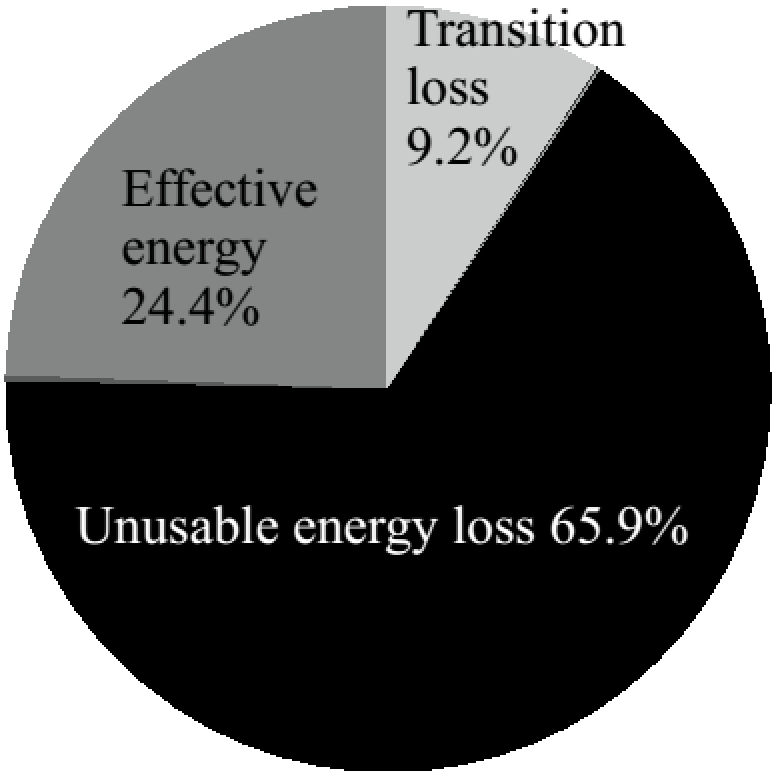
Common DPM statistics					Proposed System			Volatile Microprocessor Baseline		
Time	V_{mpp} (V)	T_{dpm} (μs)	D_{dpm}	E_{mpp} (J)	Work	E_{task} (J)	η_{sys} (%)	Work	E_{task} (J)	η_{sys} (%)
7:00	2.50	N/A	N/A	4.83	No	0	0	No	0	0
8:00	2.73	218	31.6%	50.14	Yes	36.38	72.6	No	0	0
9:00	2.72	224	30.0%	47.81	Yes	34.30	71.7	No	0	0
10:00	2.76	191	46.9%	71.95	Yes	57.07	79.3	No	0	0
11:00	2.78	195	56.5%	85.69	Yes	71.25	83.1	No	0	0
12:00	2.80	301	79.7%	118.14	Yes	108.37	91.7	No	0	0
13:00	2.82	1100	95.1%	139.27	Yes	135.39	97.2	Yes	65.74	47.2
14:00	2.82	1360	99.6%	145.27	Yes	143.72	98.9	Yes	138.34	95.2
15:00	2.76	192	45.8%	70.38	Yes	55.51	78.9	No	0	0
16:00	2.70	260	23.6%	38.57	Yes	26.27	68.1	No	0	0
17:00	2.67	369	14.8%	25.98	Yes	15.90	61.2	No	0	0
18:00	2.69	294	19.9%	33.21	Yes	21.78	65.6	No	0	0
19:00	2.50	N/A	N/A	4.11	No	0	0	No	0	0
Overall				835.34		705.94	84.5		204.08	24.4

Efficiency of the proposed system

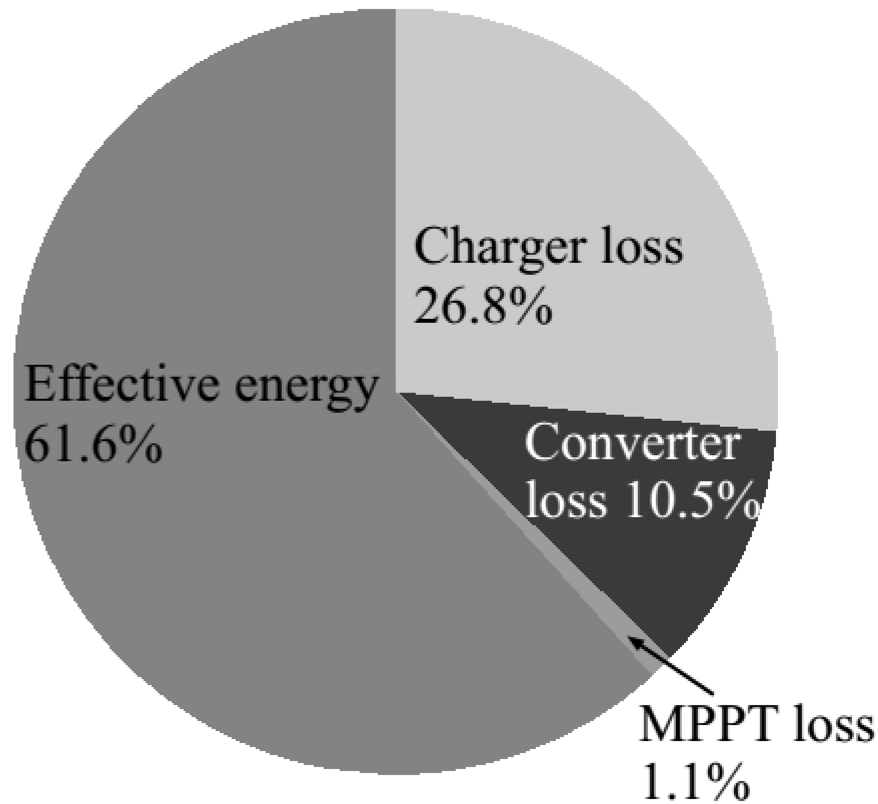


- Efficiency up to 95.4% if $C_{bulk} = 47\mu F$

Efficiency of conventional system



(b) Volatile microprocessor baseline



(c) Conventional MPTT baseline

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Emerging application

- JUNE -- a wearable bracelet with UV sensor
- Sun protection advice
  - SPF, sunglasses
  - Wear a hat

Source: http://www.netatmo.com/en-US/product/june

Conclusion

- Storage-less and Converter-less MPPT
  - Provides a very efficient way to power electronic devices with solar panels
  - Low cost and maintenance-free
  - Demonstrates a promising application for nonvolatile microprocessors
- Extension
  - Combine with traditional system(2 coverters + supercap) to achieve higher efficiency and better QoS simultaneously

Thank You