EnerHarv 2024
PSMA International Workshop | 26-28 June, 2024 | Perugia, Italy

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EnerHarv 2024 Workshop:

Unlocking the Potential of EH-based IoT Systems through Intermittent Computing and Cutting-edge Energy and Time Management

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OVERVIEW

Research Vision

- IoT Nightmare: Power Availability
- Energy Harvesting
- Towards Intermittent Computing…

Intermittent Computing

- Hibernus
- However, Challenges Persist…

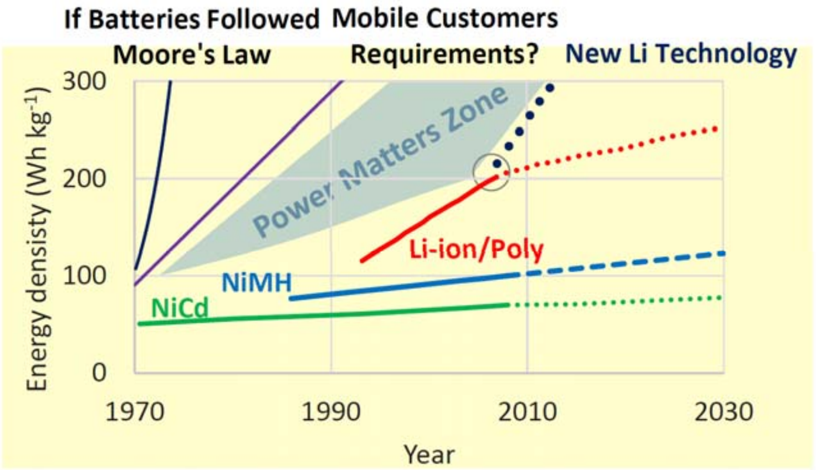
Energy and Time Management

- What do we need?
- Energy and Control Flow
- Systems Execution Flow
- System Design

Results and Discussion

IoT NIGHTMARE: POWER AVAILABILITY

The ubiquitous computing dream of IoT everywhere is accompanied by the nightmare of battery replacement



Source: Avicenne

Battery Technology is Stuck

No Moore's Law in batteries:

2-3%/year growth

IoT systems lifetime depends on battery life!

Solution: Design IoT systems that harvest limited energy from ambient or scavenge power from human activity

ENERGY HARVESTING: CHALLENGES

Different **energy harvesting methods**, such as solar, wind, and thermal, all face a common challenge…

Heat

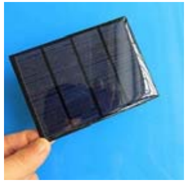
Motion and vibration

Airflow

Ambient EM Energy

Light

Thermal

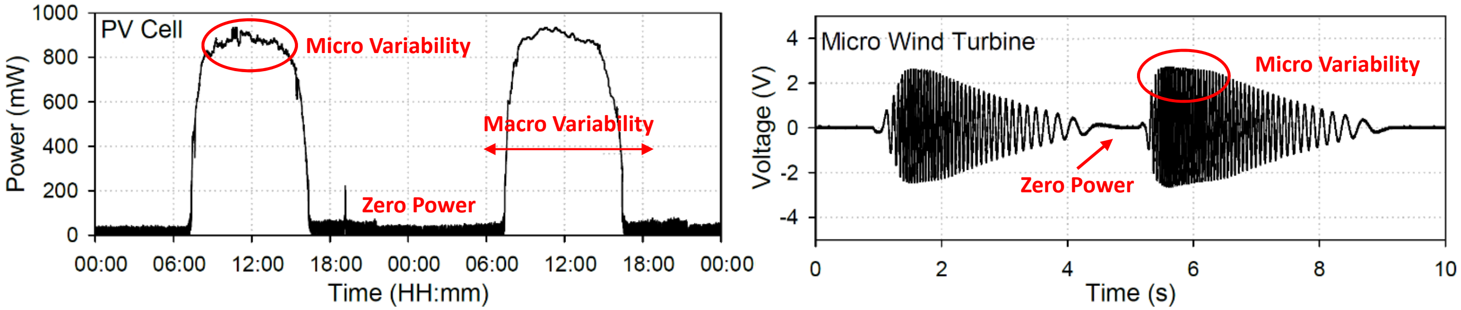


Photovoltaics

Electromagnetic

…energy can be potentially limitless, but **instantaneous power is often uncontrollable** as it relies on the source and environment.

TOWARDS INTERMITTENT COMPUTING...



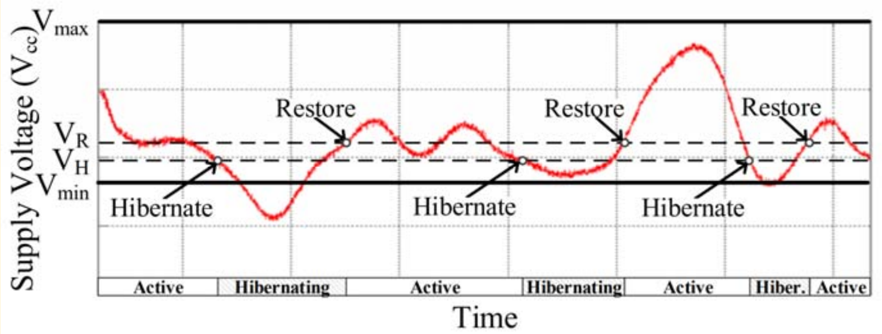
Dynamic and uncontrollable <u>power generation with periods of</u>

<u>**ZERO POWER**</u>

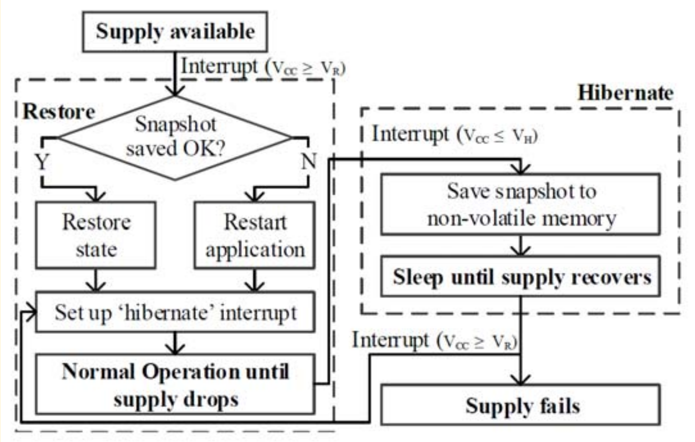
Intermittent computing, utilising non-volatile memory (NVM) to maintain system state during periods of zero power, addresses the unpredictability of energy harvesting (EH) in IoT systems

INTERMITTENT COMPUTING: HIBERNUS

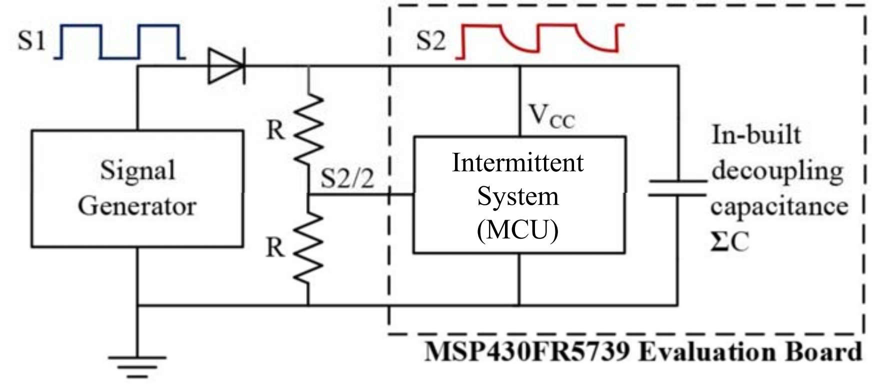
Operation



Flowchart



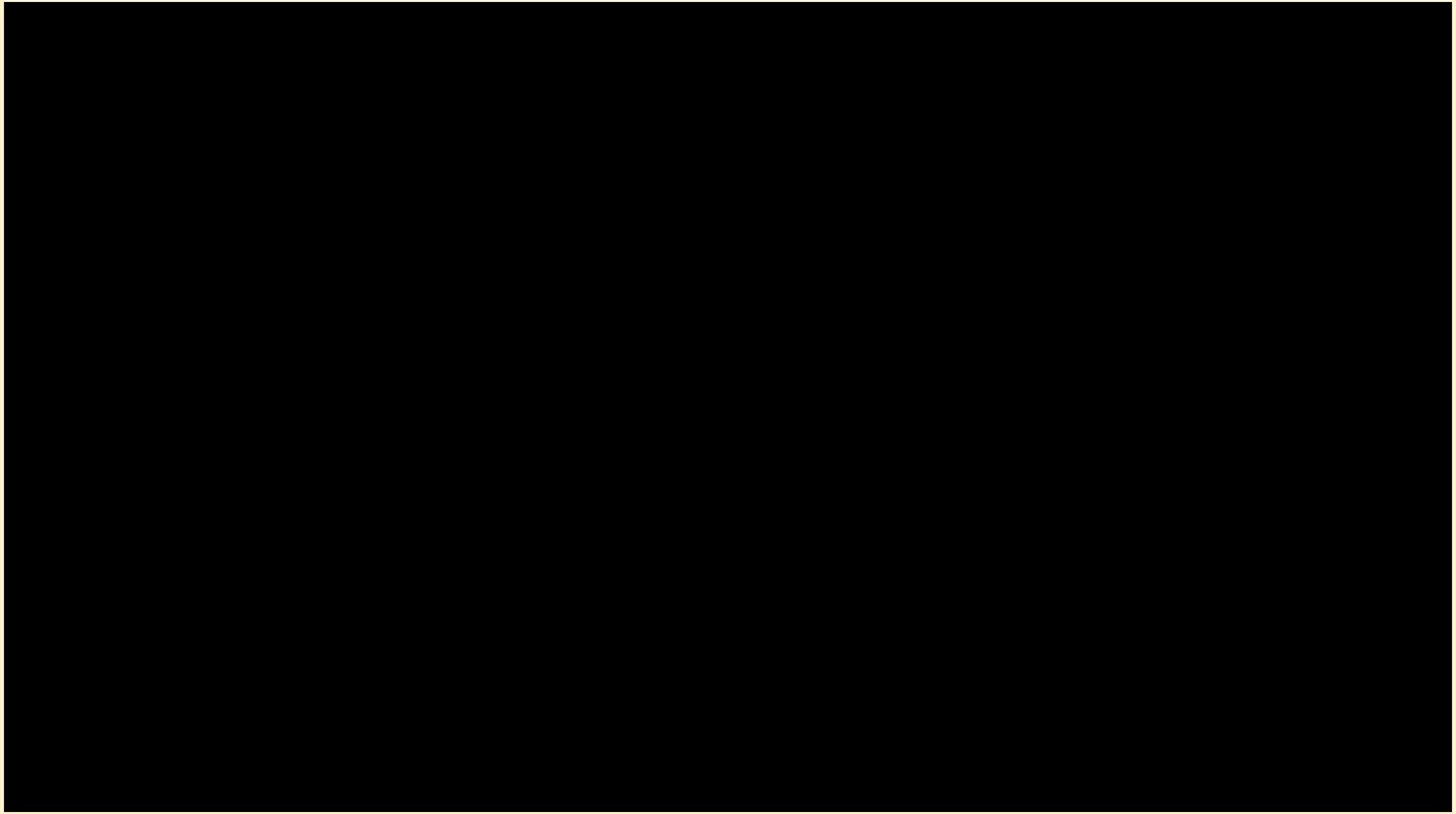
Test Platform



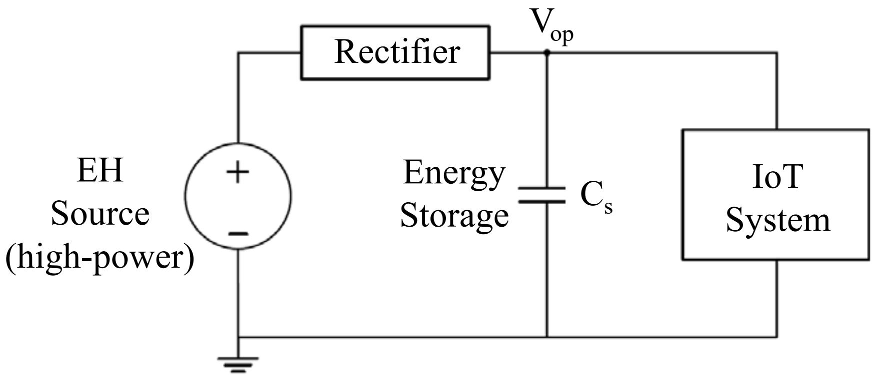
Library

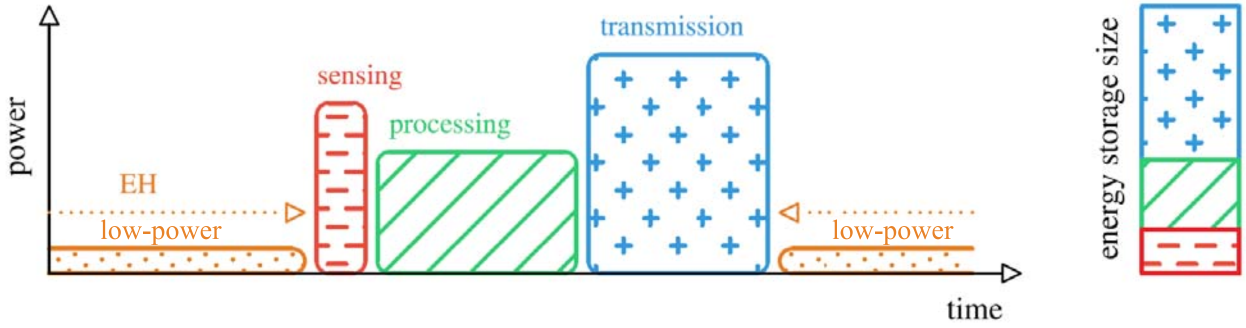
```
#include "hibernus.h"

int main (void) {
  if (flag) restore(); //restore system state
    else initialise(); //initialise hibernus
  // application code goes here
}

__interrupt void COMP_D_ISR(void) {
  hibernate(); //save system state & sleep
}
```

INTERMITTENT COMPUTING: HIBERNUS



HOWEVER, CHALLENGES PERSIST...

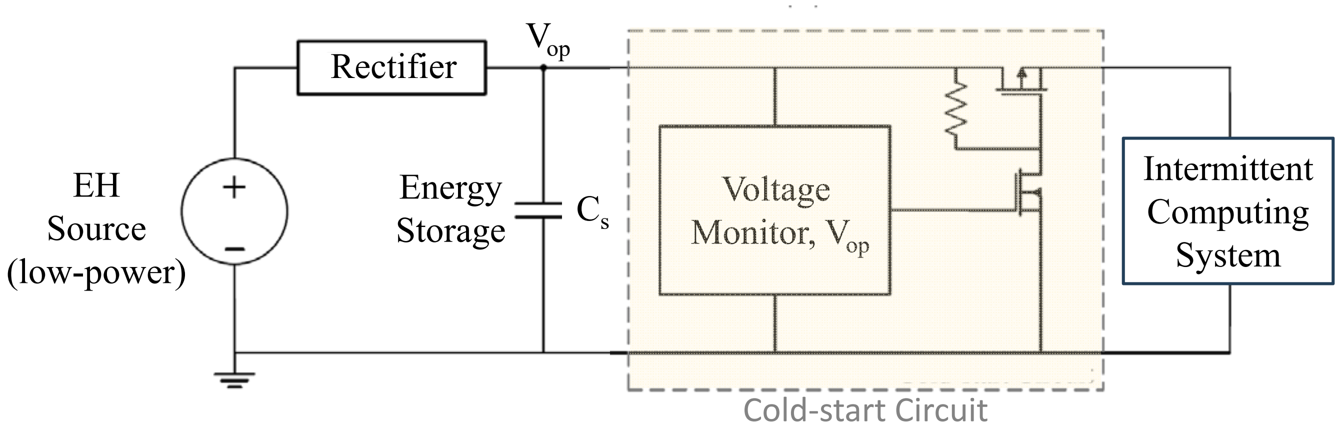


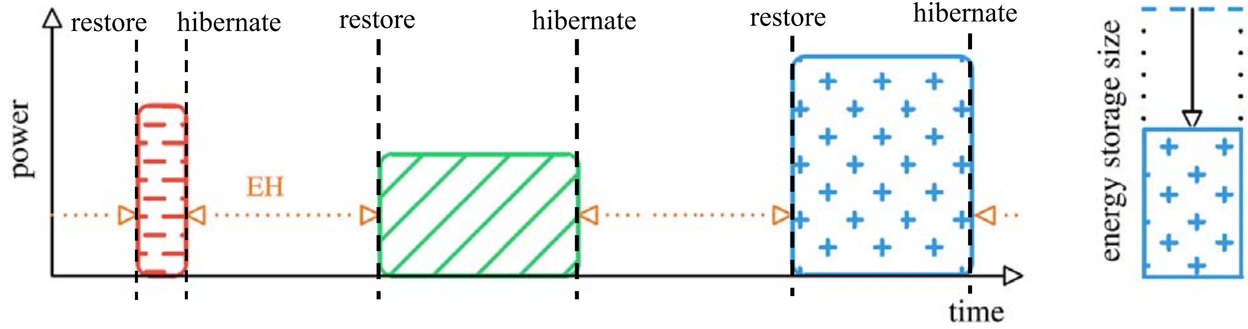


Bad:

- large energy storage tailored for the entire application.
- long charging times and delayed start-up
- a portion of the energy is wasted in low-power mode.

HOWEVER, CHALLENGES PERSIST...





Good:

- reduced energy storage size

Bad:

- energy storage is tailored to the task with the highest energy consumption.

Tasks have **different energy needs**, requiring **different energy storage sizes, C_s**, and/or **operating voltages, V_{op}**.

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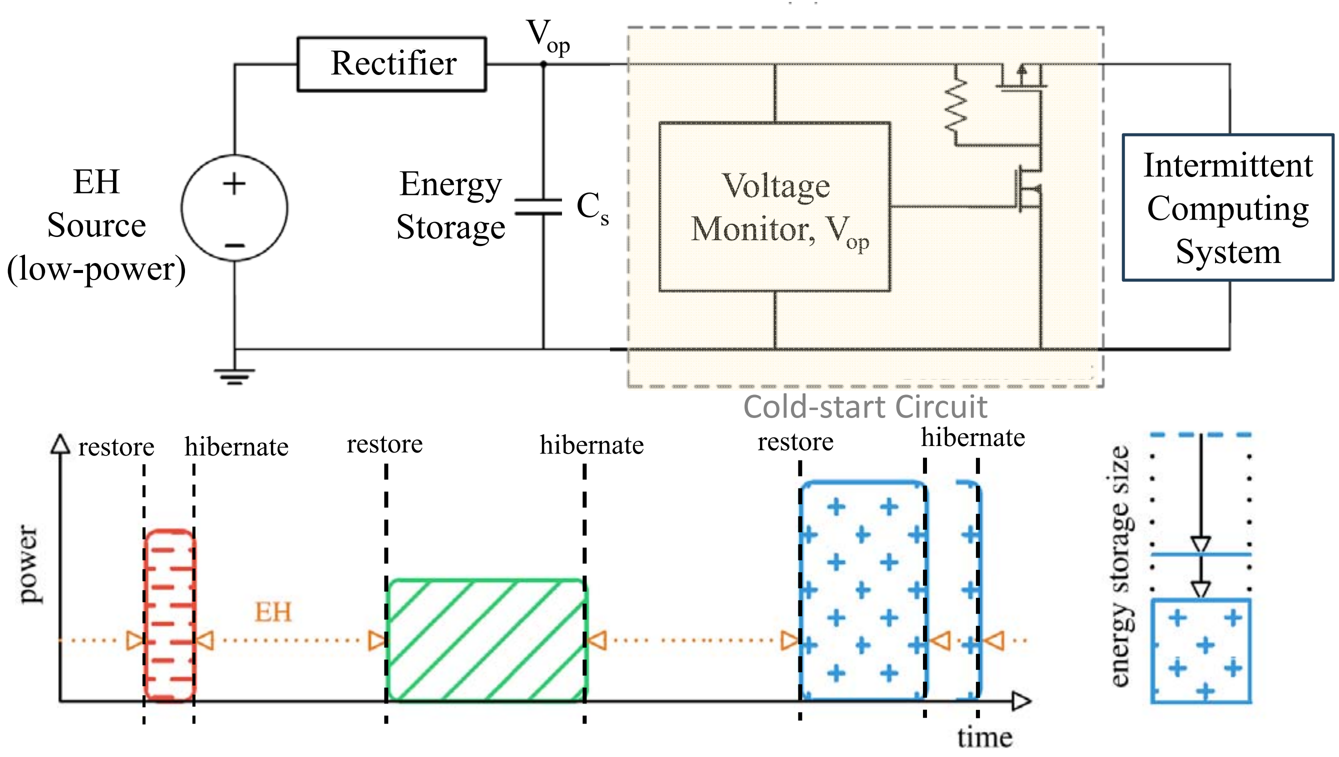
HOWEVER, CHALLENGES PERSIST...



Good:

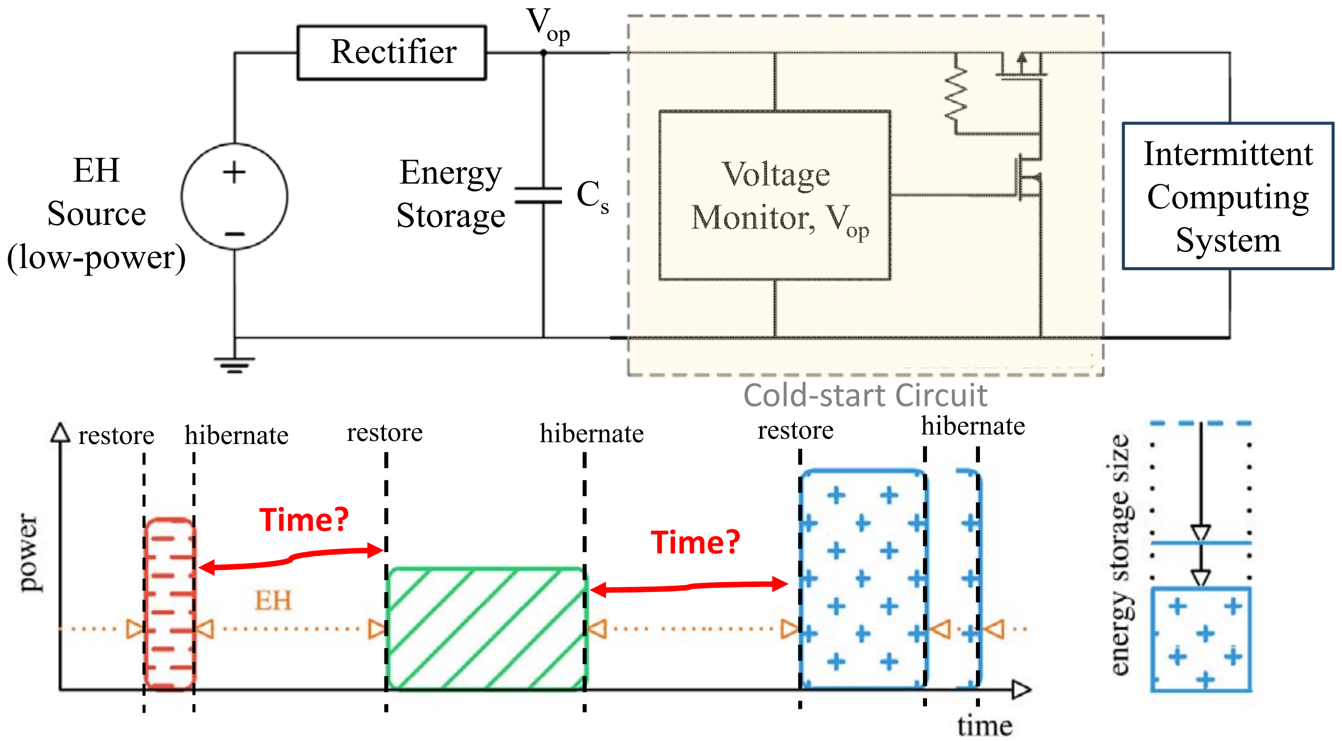
- reduced energy storage size

Bad:

- energy storage is tailored to the task with the highest energy consumption.

The energy required **even for the same task, can change over time**, which is not ideal when a fixed storage is used.

HOWEVER, CHALLENGES PERSIST...



Good:

- reduced energy storage size

Bad:

- energy storage is tailored to the task with the highest energy consumption.

Intermittent computing **hinders timekeeping during shutdowns**, impeding real-time data collection and processing.

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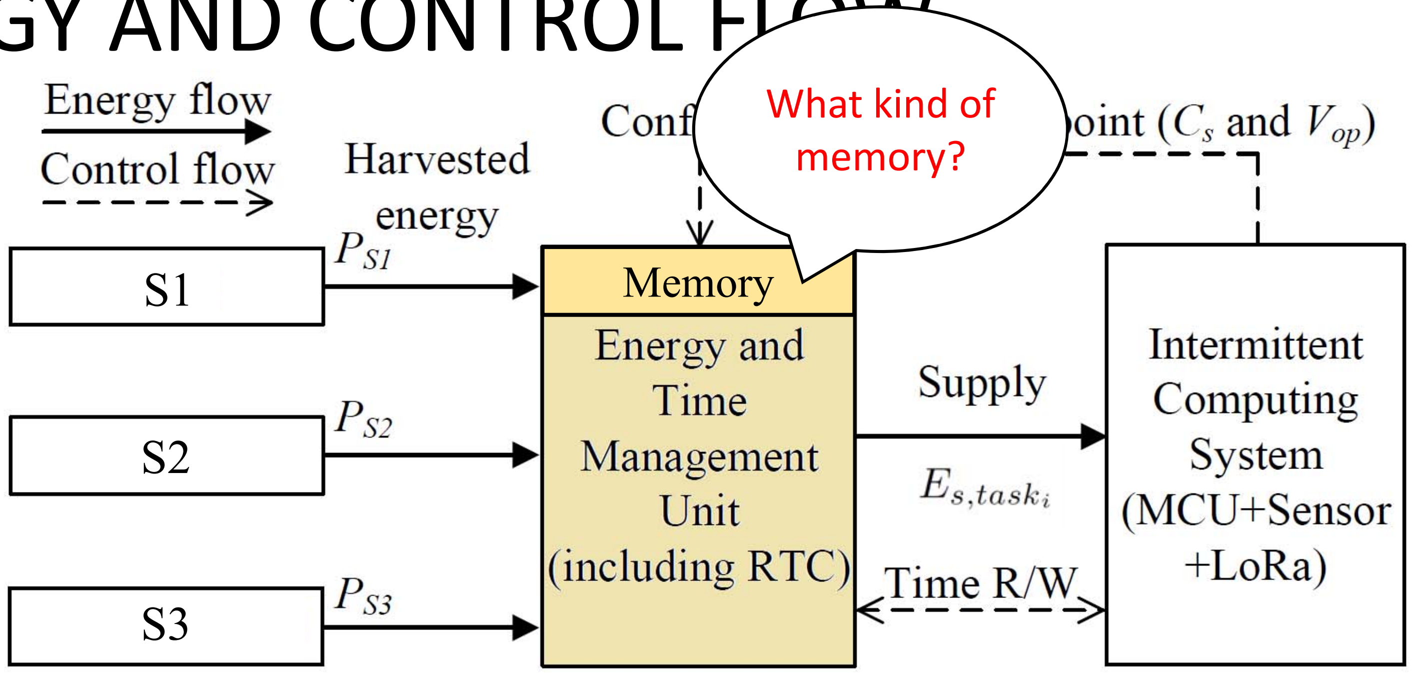
WHAT DO WE NEED?

An energy and time management unit (ETMU) for intermittent computing systems, which facilitates energy-aware task operations and timekeeping capabilities using multi-harvest energy sources.

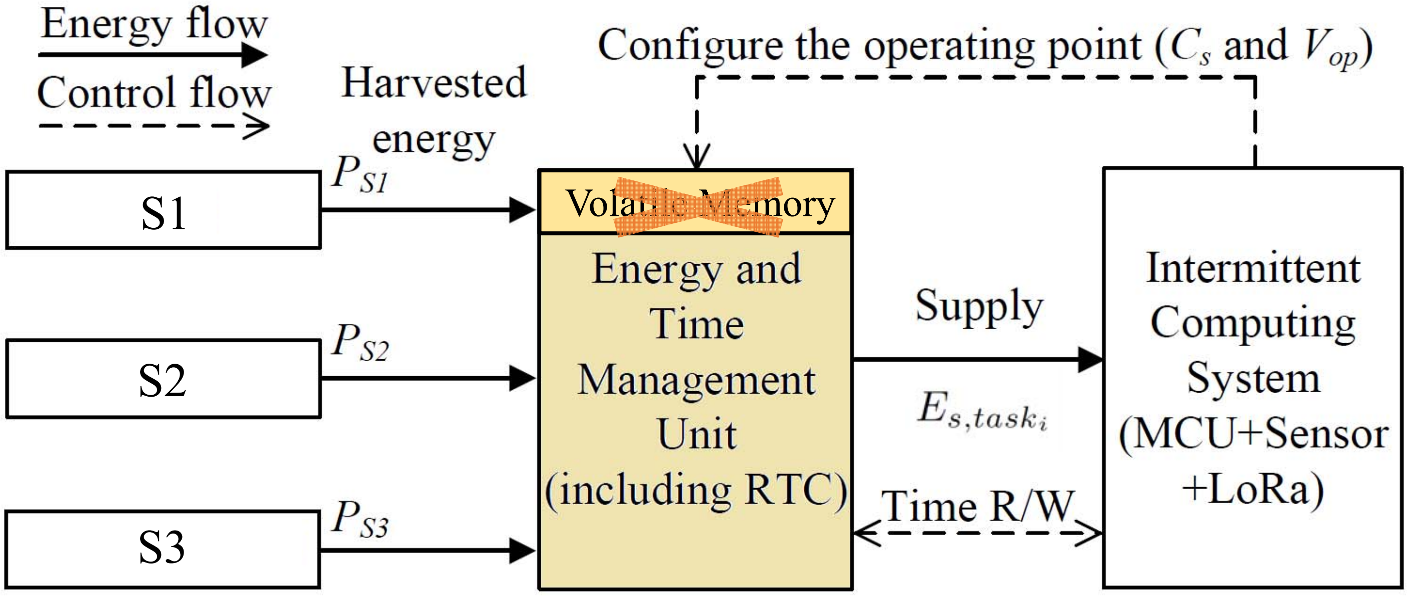
ENERGY AND CONTROL FLOW



$$E_{s,task_i} = C_s(V_{op}^2 - V_{sys,min}^2)/2$$

This ETMU enables **adjusting C_s and V_{op} (operating point)** to provide the required energy for the next task, $E_{s,task_i}$, and incorporates a **low power RTC to ensure timekeeping** while system is powered off.

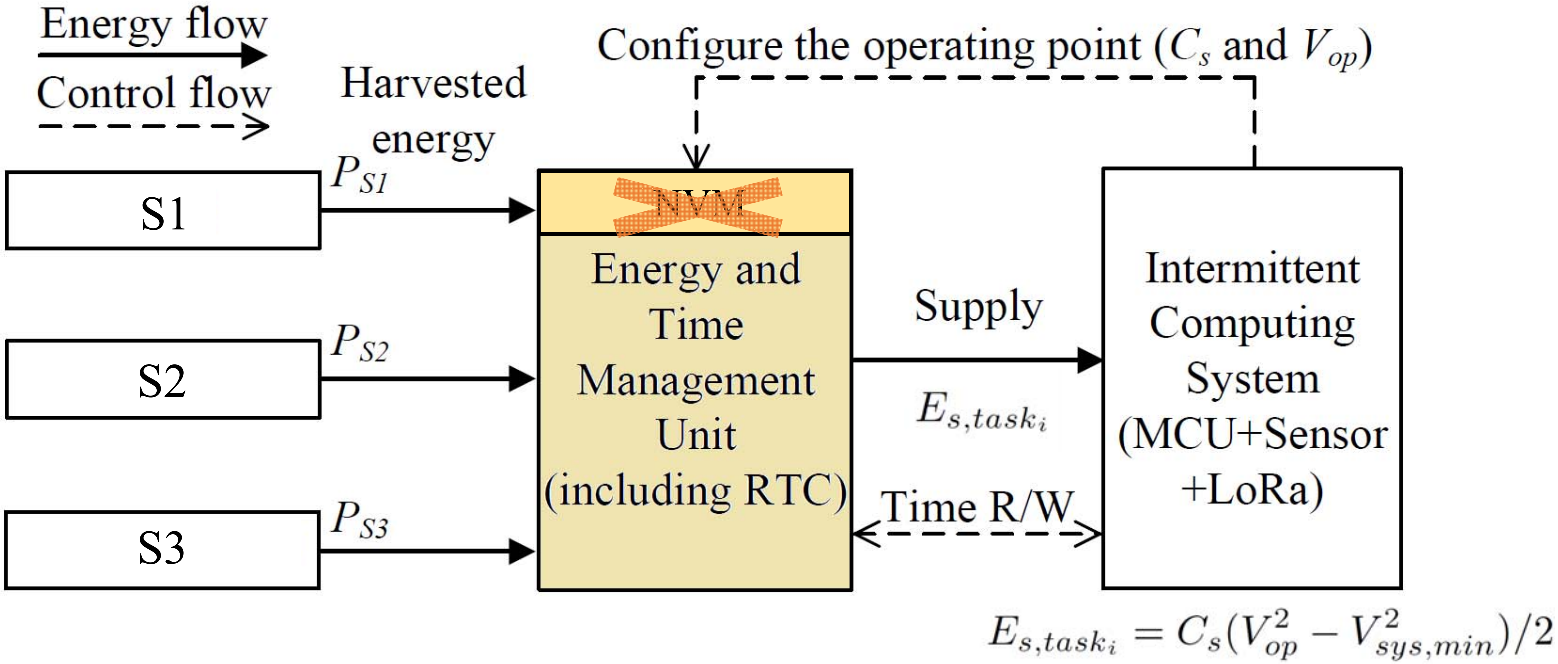
ENERGY AND CONTROL FLOW



$$E_{s,task_i} = C_s(V_{op}^2 - V_{sys,min}^2)/2$$

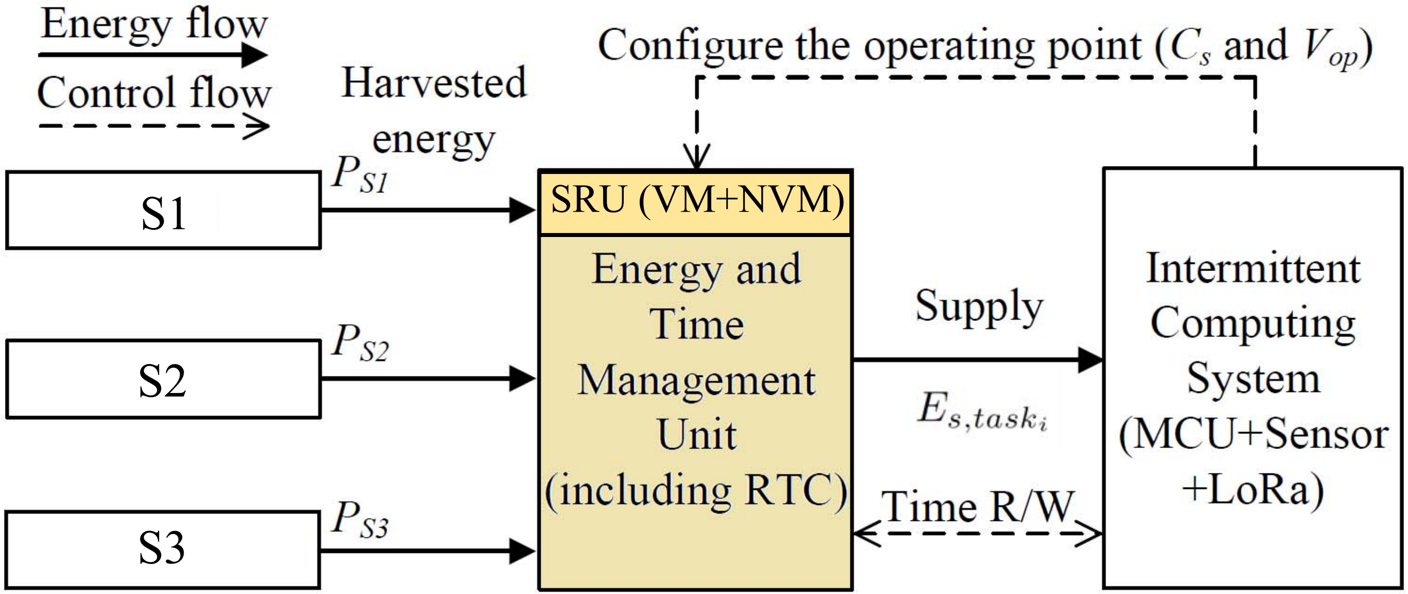
During power outages, **Volatile Memory (VM)** **cannot preserve this operating point** (Cs and Vop).

ENERGY AND CONTROL FLOW



Non-Volatile Memory (NVM) elements consume **too much energy** that is **unaffordable** for low-power systems.

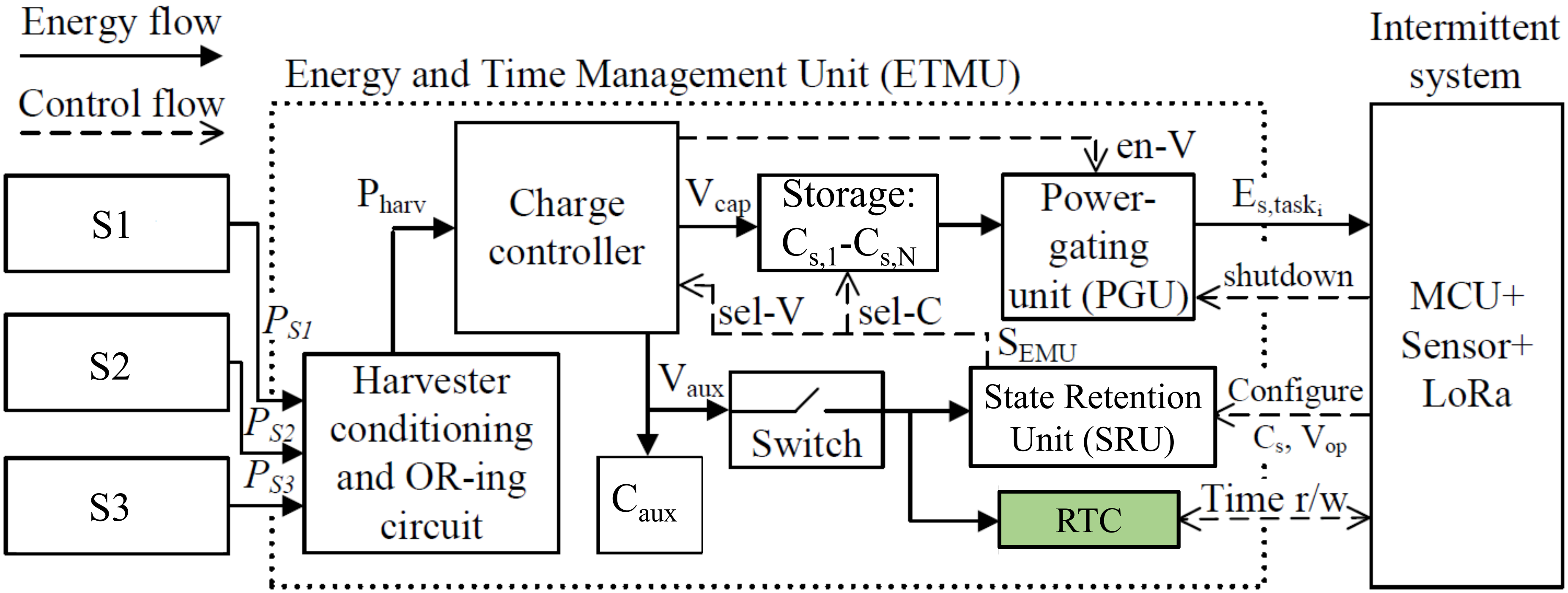
ENERGY AND CONTROL FLOW



Solution: A state retention unit (SRU) incorporates an NVM+VM approach that includes both NVM and VM benefits, avoiding their drawbacks.

How it works: The operating point (Cs and Vop) is primarily maintained on VM elements, whilst the NVM elements are activated sporadically.

SYSTEM DESIGN



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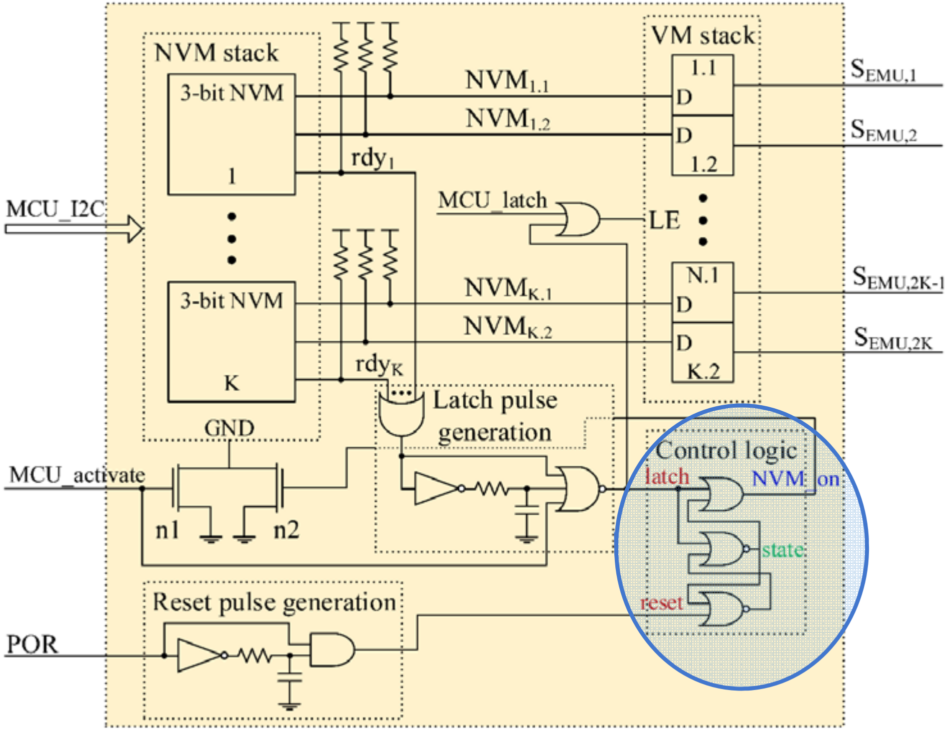
STATE RETENTION UNIT (SRU)



The SRU manages the operating point (C_s and V_{op}) keeping it in VM during normal operation and restoring it from NVM when needed:

- **Operating point update** – write from MCU to NVM + write from NVM to VM.
- **Operating point recovery** – write from NVM to VM.

Control logic activates the NVM when restoring the operating point after a power outage and deactivates it, when This operating point is restored.

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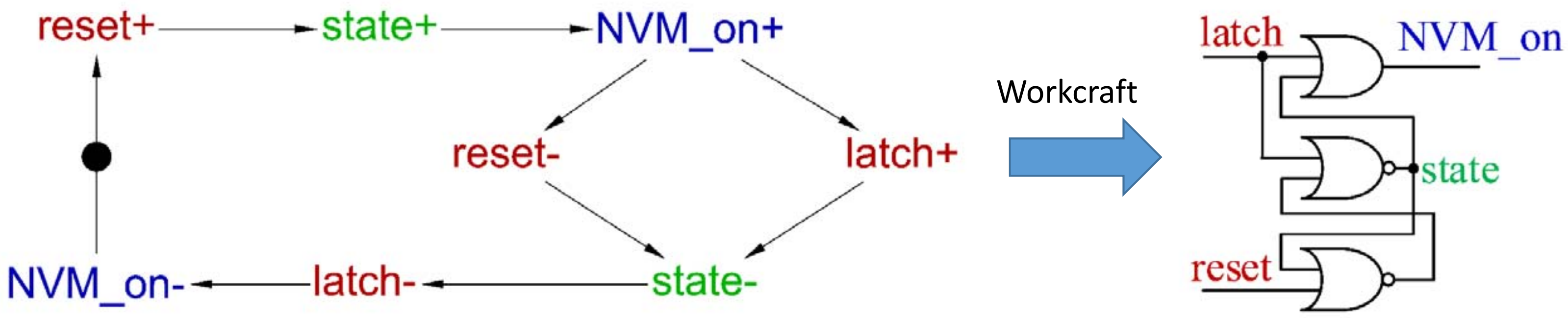
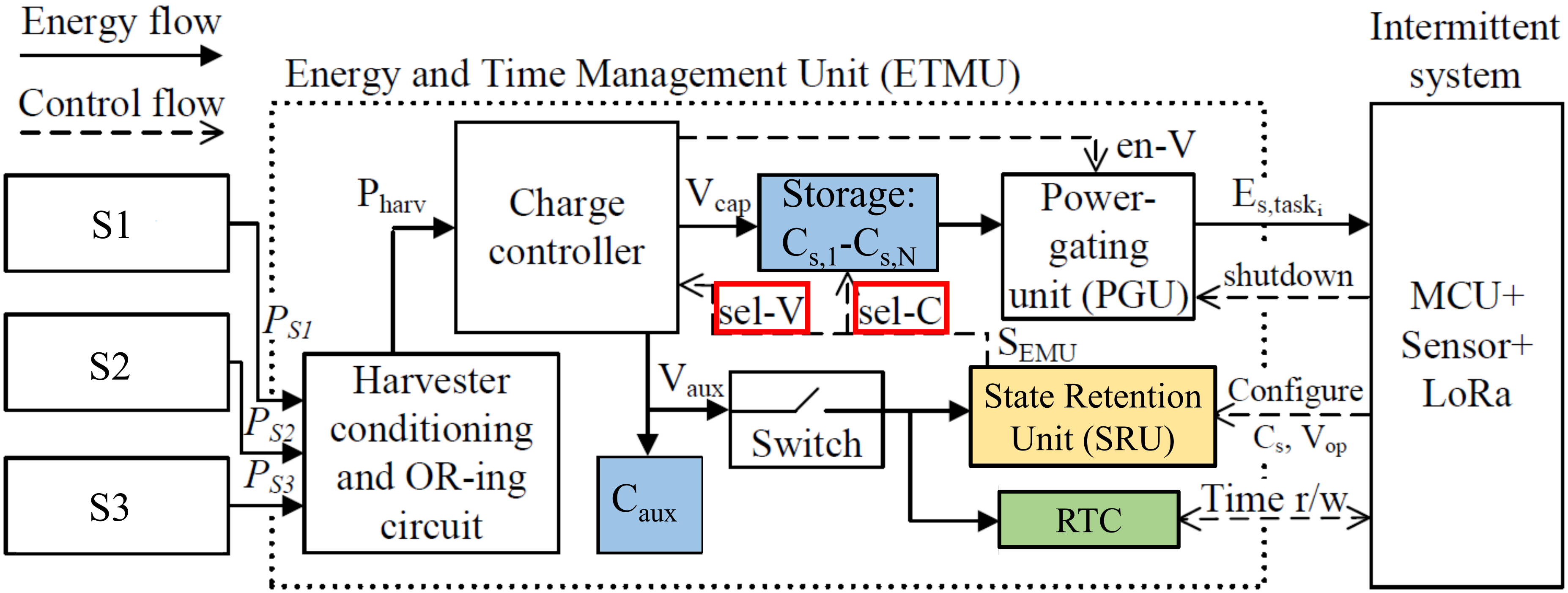
CONTROL LOGIC

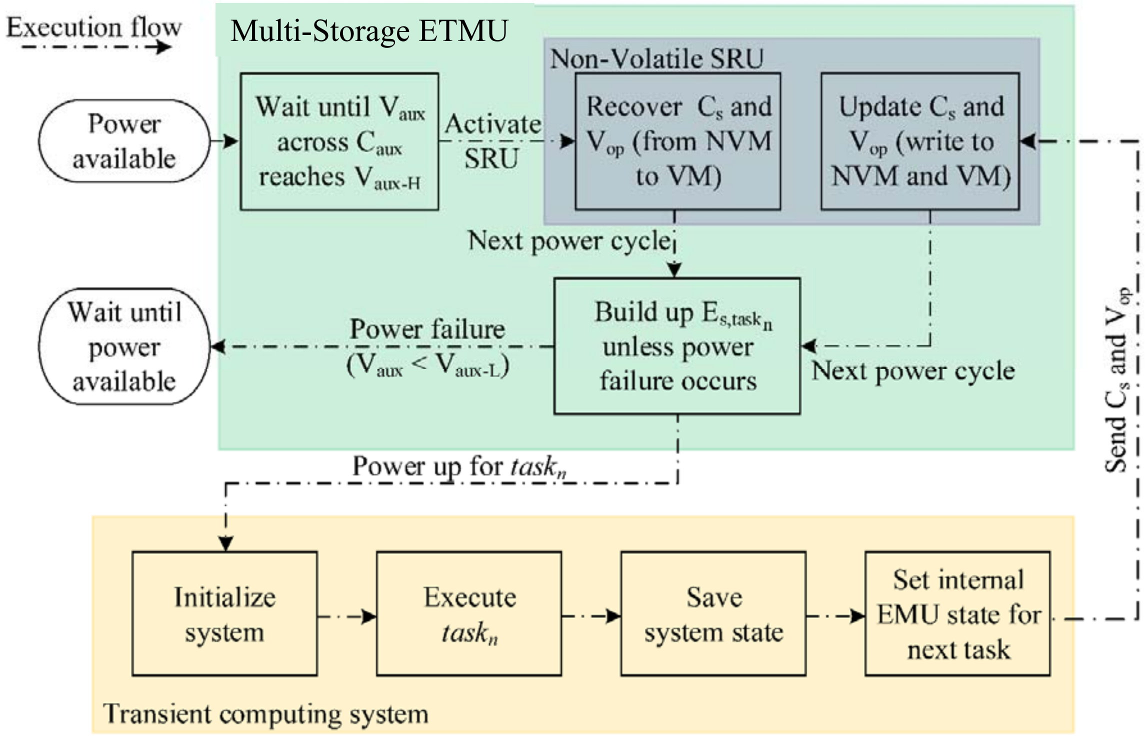


- **Control logic** is a state machine designed using asynchronous design method.
- **Signal Transition Graph (STG)** is a special type of Petri net whose transitions are associated with the rising and falling edges of signals.
- **Workcraft environment** synthesises an asynchronous circuit from the formal (using STG) specification.

SYSTEM DESIGN

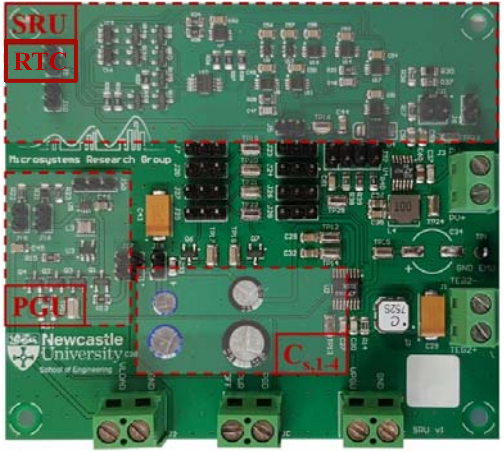


SYSTEM EXECUTION FLOW



- The execution flow involves the **interaction between** the ETMU and the intermittent system.
- The SRU uses an auxiliary storage, C_{aux}, for supply. Its voltage, V_{aux}, is monitored to check if **power is available**.

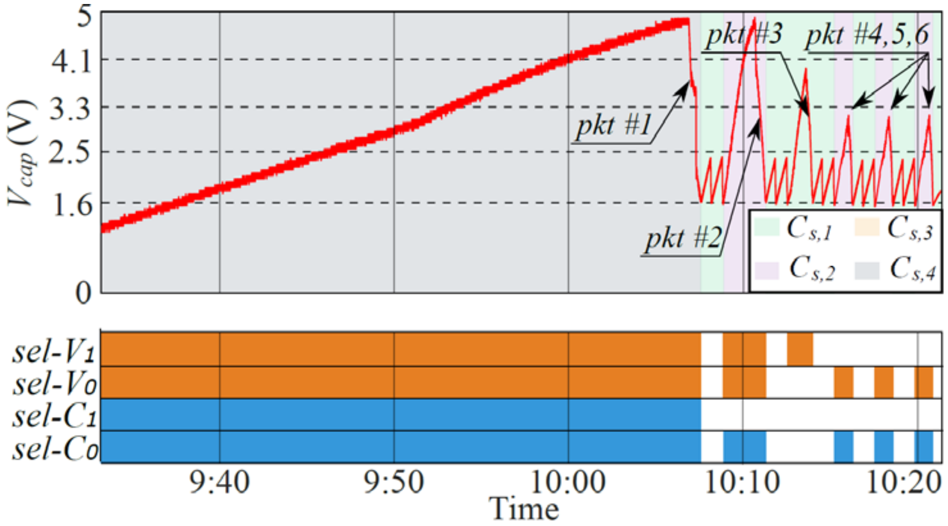
EXPERIMENTAL PROTOTYPE AND EXECUTED TASKS



	Task	E_{task}	C_s	V_{op}	$sel\text{-}C_{1,0}$	$sel\text{-}V_{1,0}$
Ultrasonic sensing		2.1mJ	15mF	2.5V	0 0	0 0
Communication	SF7, Tx=2-9dBm	42.4mJ	15mF	3.3V	0 0	0 1
	SF7, Tx=10-14dBm	51.5mJ	22mF	3.3V	0 1	0 1
	SF8, Tx=14dBm	71.0mJ	15mF	4.1V	0 0	1 0
	SF9, Tx=14dBm	107mJ	22mF	4.1V	0 1	1 0
	SF10, Tx=14dBm	170mJ	22mF	5V	0 1	1 1
	SF11, Tx=14dBm	338mJ	47mF	5V	1 0	1 1
	SF12, Tx=14dBm	595mJ	100mF	5V	1 1	1 1

- The prototype of the ETMU can select between **4 C_s and 4 V_{op}** resulting in **16 possible ETMU internal states**.
- The ultrasonic measurement (**task 1**) requires a fixed amount of energy.
- The LoRa transmission (**task 2**) is executed with different communication parameters, i.e., **Spreading Factor (SF) and transmitting power (Tx),** resulting in varying energy required.

INTERMITTENT SYSTEM OPERATION FOR SCENARIO 1

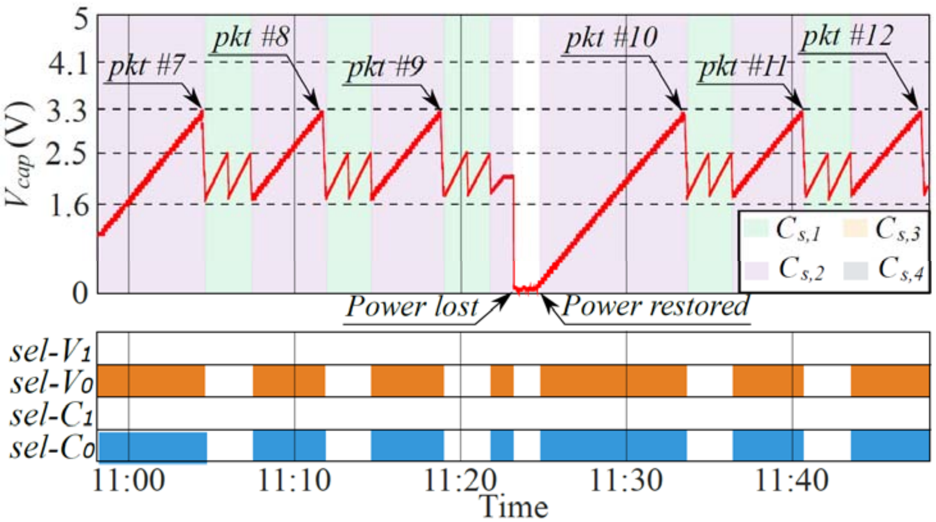


System powered by an outdoor PV cell while moving towards the gateway

	Rx Time	Pkt N	SF	Tx (dBm)	SNR	RSSI (dB)	Data			
							Time1	Q1	Time2	Q2
Scenario 1	10:07:04	1	12	14	1	-114	0	0	0	0
	10:10:50	2	10	14	2.2	-112	10:07:56	9.5	10:08:30	9.5
	10:13:44	3	8	14	10.8	-101	10:11:42	9.6	10:12:16	9.5
	10:16:03	4	7	14	7.5	-97	10:14:36	9.5	10:15:10	9.4
	10:18:22	5	7	14	8	-97	10:16:55	9.6	10:17:30	9.4
	10:20:41	6	7	14	8.8	-96	10:19:14	9.4	10:19:48	9.5

Received LoRAWAN data at the gateway in Scenario 1

INTERMITTENT SYSTEM OPERATION FOR SCENARIO 2



System powered by an indoor PV cell and is located close to the gateway

	Rx Time	Pkt N	SF	Tx (dBm)	SNR	RSSI (dB)	Data			
							Time1	Q1	Time2	Q2
Scenario 2	11:05:15	7	7	14	9.2	-98	10:21:33	9.6	10:22:07	9.4
	11:12:13	8	7	14	8.5	-100	11:06:42	9.4	11:08:09	9.6
	11:19:10	9	7	14	7.5	-98	11:13:40	9.4	11:15:07	9.5
	11:33:39	10	7	14	8	-97	11:20:37	9.7	11:22:40	9.6
	11:40:37	11	7	14	7.2	-97	11:35:06	9.5	11:36:33	9.6
	11:47:35	12	7	14	6.8	-98	11:42:04	9.5	11:43:31	9.3

Received LoRAWAN data at the gateway in Scenario 2

	C_s (mF)	V_{op} (V)	Start-up time (s)	Charging time (s)
Case 1	100	5	2604	114
Case 2	22	3.3	308	62

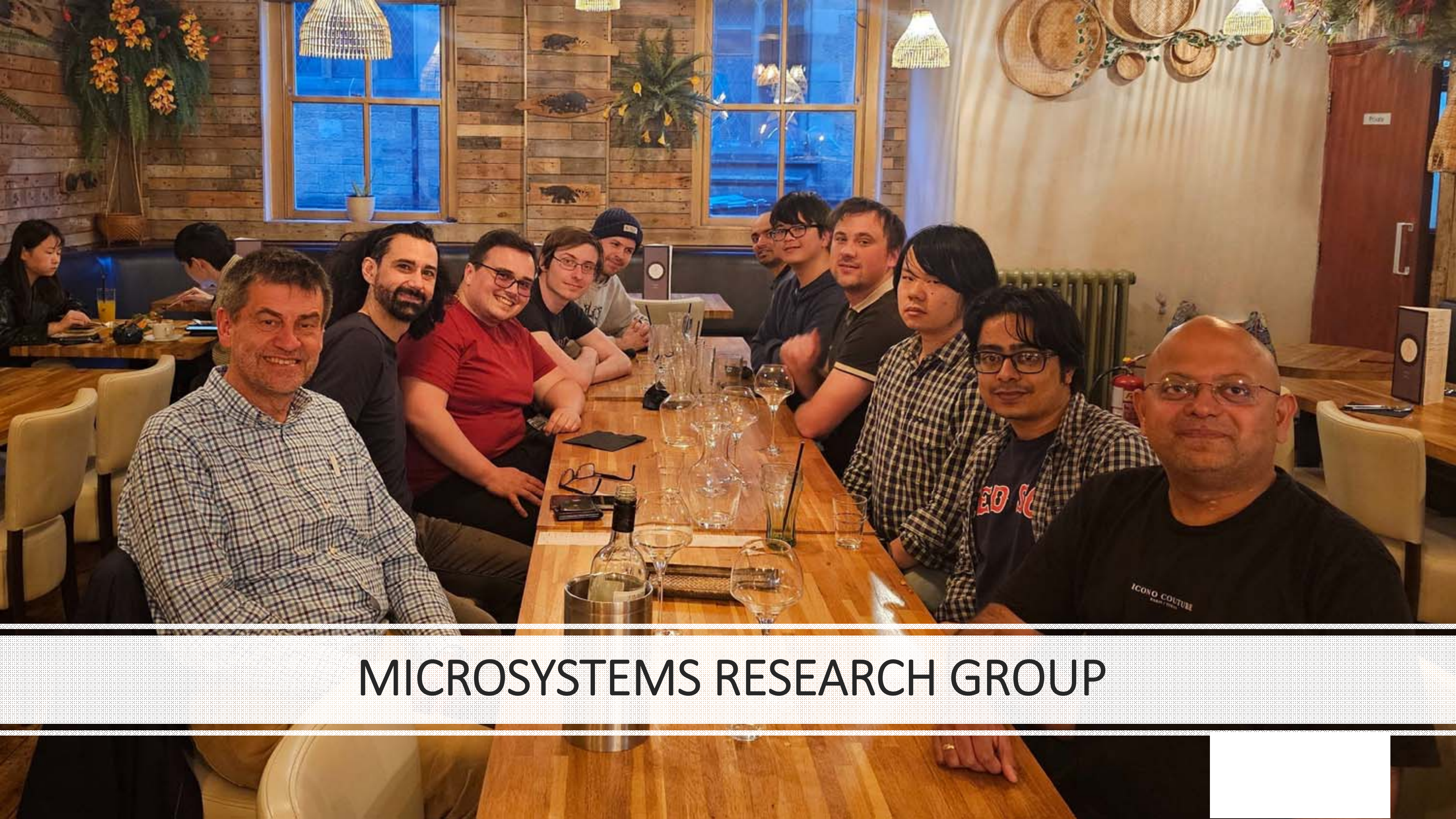
Start-up and charging times for the system powered by TEG with fixed PS1 = 5mW, and SF7 and Tx = 14dBm

CONCLUSIONS

- A multi-storage ETMU incorporating a non-volatile SRU for task-based intermittent systems. The ETMU allows selecting the operating voltage and energy storage size for the next task, i.e., the internal EMU state, at run-time and keeping track of time.

- Thanks to the hybrid NVM+VM approach adopted, the ETMU can reliably maintain its internal state during a power outage and recover it once power is available.

- Future studies will investigate how to determine the energy requirements of each task automatically, without knowing them in advance, using various learning mechanisms, e.g., reinforcement learning.



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Q & A

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Questions/comments???

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