Towards a Taxonomy of Energy Scavenging Applications, **Architectures, and Execution Models**

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Human Camera Perception Perception







What's in a name?

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 - Weakness: Some confusion between intermittent and energy-neutral systems. This needs defining, but I would have interpreted "slow and low" charging for periodic operation to be more of an energy-neutral approach than intermittent.

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- True, batteryless devices
 - "Capacitors only"
 - E.g. Monjolo + derivatives



Figure 3: Vibration sensor.





Figure 4: Airflow sensor.

- Secondary-cell only
 - "Capacitor + Rechargeable"
 - E.g. DoubleDip



- 'Backup' primary cell
 - "Cap + Secondary + Emergency/Exceptional Non-Rechargable"
 - E.g. Permamote



- Parasitic (?) batteryless (?) devices
 - "Capacitors only"
 - E.g. Corrosion cells



- 'Primary' primary cell
 - "Battery powered, duty-cycled devices"
 - E.g. Wireless sensor networking from ~2000-present



 Systems that rely on non-renewable components

Battery-Free Cycle Computer

Traditional bicycle computers (or trip counters) measure the rotation of the wheel by sensing when a magnet mounted on the wheel passes a reed switch (or similar) mounted on the fork. The sensor is wired (or has its own battery to transmit the data wirelessly) to a battery-powered embedded computer which records and displays statistics on the journey.



In this case study, we present a transiently-powered wireless cycle computer which measures distance, speed and active cycling time, and transmits data wirelessly. The system sustains operation by harvesting energy from the rotation of the wheel, operating from minimum speeds of 6kph.

• The "Solar Computer"?





Solar Powered PC & Solar Panel

£950.00

Our Unique 12V Solar Powered Computer

A SolarPC includes;

- Intel Celeron 7th Gen (NUC7CJYH) PC (4GB Ram, 64GB SSD, Windows10), 19" LED Screen, 40W plastic solar panel & 120W lithium-ion battery storage to provide a reliable, consistent power supply.NUC7CJYH product sheet
- Inspire a green generation of Eco Heroes!

• Off-grid home?



Lochside House, Scotland, by Haysom Ward Millar Architects

This rural cottage sits on the edge of a lake in the Scottish Highlands and is crafted from natural materials that complement its scenic location.

It functions entirely off-grid by producing its own electricity from solar panels, and sourcing clean water from a borehole.



The Off-Grid Guest House, USA, by Anacapa Architecture

This house on an isolated site in a Californian nature reserve was designed by Anacapa Architecture to function completely off the grid.

Power is provided by a photovoltaic system, with a propane generator available as a backup, and it also has a private well and water treatment system.

• All of Google's datacenters?

Google Sustainability

Google The Keyword Latest stories Product updates V Company news

Q :

Operating the cleanest in the industry

We've eliminated all of our carbon emissions since our founding i company our size. We've matched 100% of our electricity consum energy purchases since 2017, which includes the electricity to po And we recently committed to fully decarbonize our electricity su operate on clean energy, every hour and in every region.

DATA CENTERS AND INFRASTRUCTURE

Our data centers now work harder when the sun shines anc wind blows



Why do we care about "energy neutral" anyway?

- Deployability
 - (and maintainability and longevity...)
- Sustainability?

"Energy Neutral" → Deployable?

- "One of the remaining issues with wireless water monitoring in residences and offices is that current solutions require installing sensor nodes with access to electrical wiring or replacing batteries frequently"
- "Freedom from a battery or tethered power supply enables developers to deploy applications that require little maintenance, even in harsh, remote environments, like glaciers and in Earth's orbit."
- "However, as we strive towards ubiquitous sensor deployments aimed at supporting applications such as building automation and industrial monitoring, the human cost of frequent battery replacement may become untenable."
- However, large-scale deployments with such devices suffer from high cost (tens to hundreds of USD per device), overhead of maintenance for replacing depleted batteries, and deployment inconvenience due to bulky form factor of devices. Thus, battery-powered sensor devices present a significant challenge to the vision of ubiquitous sensing [16]. As a result, there has been a growing interest in battery-free sensor tags

Energy Neutral \rightarrow **Sustainable**?

- To make this vision feasible energy harvesting must be leveraged and batteries must be left behind, allowing near permanent sensing at low cost and size with **reduced environmental impact**.
- ... batteryless devices with minimal energy storage that run solely off ambient scavenged energy, **promise a more scalable and sustainable alternative.**
- Batteries are large, heavy, expensive and shortlived—even rechargeables wear out after a few years—and the maintenance and environmental costs of replacing trillions of batteries every few years are prohibitive.

How do others define "energy neutral"?

- Wikipedia:
 - "An Energy Neutral Design is a Design of any type (Website, Multi-media, Architecture, Art, Music, Entertainment, etc.) that has the environment and low energy consumption practices in mind during all stages of planning and production."

DEFINITION OF ENERGY NEUTRALITY

- A WRRF that generates 100% or more of the energy it needs for its operation solely from the energy embedded in the water and wastes it treats
- On the road to energy neutrality, the metrics can be:

Site electrical energy: kWh/MG

The "Closed System" Model

Primary energy; MJ/MG

At 100% energy neutrality, the metrics are equivalent. On the road to energy neutrality, they are not.

Delft municipal authority aims to be energy-neutral by 2050. This aspiration comes on top of several other targets, including 50% CO2 emissions reduction by 2030 relative to a 1990 baseline. While municipal energy neutrality means energy demand is met entirely by renewables, this does not mean all that energy is necessarily generated within municipal bc generated The "All Renewable" Model ff

example) it still satisfies the de

How does the International Workshop on Energy Harvesting & Energy-Neutral Sensing Systems define energy-neutral?

• ...this workshop will bring researchers together to explore the challenges, issues and opportunities in the research, design, and engineering of energy-harvesting, energy-neutral and intermittent sensing systems. These are enabling technologies for future applications in smart energy, transportation, environmental monitoring and smart cities. Innovative solutions in hardware for energy scavenging, adaptive algorithms, and power management policies are needed to enable either uninterrupted or intermittent operation.

How does the International Workshop on Energy Harvesting & Energy-Neutral Sensing Systems define energy-neutral?

Topics of interest include, but are not limited to, the following:

- Power management concepts, algorithms and circuits for energy-harvesting sensing systems
- Hardware and software concepts, algorithms and circuits for intermittent computing
- Middleware and services supporting interoperability between zero-energy networks
- Resource management and operating system support for energy-harvesting sensing systems
- Network-wide distributed energy management (e.g. routing, adaptive duty cycling, etc.)
- Communication in intermittent-power domain
- Online measurement of energy intake and consumption
- Predicting energy intake and consumption
- Ensuring reliable operation in energy-harvesting sensor systems
- Modelling, simulation and tools for effective design of future energy harvesting sensing systems
- Architectures and standards for **energy-neutral**, **power-neutral** or intermittent sensing systems
- Internet of (battery-less) things
- Experience with real-world deployments and innovative applications

Defining "energy neutral" as used by our community?

- What the definition seems to be today:
 - An energy neutral *device* is one that harvests as much energy as it uses.
- Questions:
 - Can a device harvest from anything, or must the source be renewable?
 - Must it be 100% scavenged energy? ("The permamote question")
 - Does this allow rechargeable batteries should it?
 - ...?
- Notice: Energy neutral \Rightarrow intermittent!

What about "intermittent"?

- The dictionary:
 - "coming and going at intervals : not continuous"
 - "occurring at irregular intervals; not continuous or steady"
 - "not happening regularly or continuously; stopping and starting repeatedly or with periods in between"
- Does duty cycled operation qualify as intermittent?
- Suggestion:
 - Intermittency arises when a system is resource constrained

How did intermittency get mixed in with energy neutrality?

- Many traditional "energy neutral sources" are intermittent
 - E.g. Solar / photovoltaics, impulse sources
- Instantaneous power mismatch
 - Requires the ability to time-shift energy income or outflow
- Unpredictable sources limits capability of practical income time-shifting
 - This unpredictability is then transferred to the outflow

A black box view of energy scavenging systems



Newer energy sources are not intermittent, but still demand (now-predictable!) intermittent operation



If all ducks are birds..

- How to differentiate **duty cycled** and **intermittent** operation?
- Suggestion:
 - Duty cycled is a choice
 - A system could power-on on-demand <u>at any time</u>
 - Intermittent operation is a necessity
 - A system has times is <u>incapable of operation</u>

Towards a taxonomy then

- Energy Neutral Operation is ... [no steady-state non-renewable use?]
- Intermittent Operation and Duty Cycling are techniques that can help achieve Energy Neutral Operation
- Duty Cycling is always **Reliable**
- Intermittent Operation can be **Reliable** or **Unpredictable**

Did we all agree on all of that?

• Great, here are some things that are completely different to talk about

Energy Neutral & Intermittent Opportunities in the Large NSF/VMw Actual net-load and 3-hour ramps are approximately

Digital Inf four years ahead of ISO's original estimate



What do Emergy Neutral/Conscious Systems look like?

- *emergy* the amount of energy that was consumed in direct and indirect transformations to make a product or service.
 - "Embodied energy"
- If sustainability is our goal, need more sustainability-oriented metrics