Overview of the talk

- **Energy harvesting, where and why**
- Energy autonomous systems (EAS), a challenge for next years
  - Energy from vibrations
  - Energy from light
  - Energy from temperature
  - Energy from radio-frequency
- Industrial applications & some market perspective
- Other applications
- Conclusions
Environmental Energy as an Exploitable Source

- The environment is a source of available energy in many different forms
- Man pursued its exploitation since centuries

![Windmills](image1.png)
![Water wheels](image2.png)
![Sails](image3.png)
![Dynamo](image4.png)

...then came electricity

![Electrochemical cells](image5.png)

Where Energy?

- Environment as a source of highly-available low-density energy
  - Mechanical
  - Thermal
  - Electromagnetic
  - Solar
  - etc.

- Promising sources the research at Ing2 is focusing on
  - Vibrations
  - Electromagnetic radiation

![Em radiation](image6.png)
![Mechanical vibrations](image7.png)

Temperature gradients

![Solar radiation](image8.png)
Why Energy?

- Growing integration of electronics into human lives and environments
  - Paradigm of pervasivity

- Micro-/Nano-electronics allow for ultra-low power designs

- Sustainability and energy autonomy
  - Longer-lifes
  - Bulky batteries
  - Unprecedented applications

Why Energy Harvesting Now?

From concepts

Why Energy Harvesting Now?

To products

Overview of the talk

- Energy harvesting, where and why
- Energy autonomous systems (EAS), a challenge for next years
  - Energy from vibrations
  - Energy from light
  - Energy from temperature
  - Energy from radio-frequency
- Industrial applications & some market perspective
- Other applications
- Conclusions
Energy Autonomous Systems: Definition

Systems designed to operate and/or communicate in known/unknown environments over their all lifetime

Ability to operate less than hundreds of $\mu$W of power in some cm$^3$

A common target for harvesters: $< 100$ mW/cm$^3$ on average, indefinitely

Example [Mitcheson, 2007]

- STLM20 temperature sensor from STM draws typically 12 $\mu$W quiescent power at 2.4 V supply voltage.
- ADC: An ADC reported by Sauerbrey et al. has power dissipation below 1 $\mu$W for 8 bit sampling at 4 kS/s.
- Transmitter: IMEC recently announced an IEEE 802.15.4a standard-compliant ultra-wide-band transmitter with a power consumption of only 0.65 nJ per 16 chip burst operating at a low duty cycle.

The required data rates for biomonitoring applications tend to be quite low due to the relatively low rates of change of the variables. One of the highest rates required is for heartbeat monitoring, at around 100 samples/s. If this is combined with a resolution of 10 bits, then the data rate is 1 kbps, which, if the transmitter power quoted can be scaled to such low data rates, requires only 0.65 uW. This suggests a total power consumption for the sensor node of 10–20 uW, or even 1–2 uW or less if the other components are also duty cycled.
### Problems
- Already proven:
  - Harvesters with $> 100\mu W/cm^3$
  - Systems operating $< 100\mu W/cm^3$

**BUT**
- The environment condition is critical. When? On which conditions?

### Objectives & Challenges
- Focus on the energy instead of power domain
  - By increasing conversion efficiency
  - By using governance of resources
- Harvesting limited by two hard boundaries
  - Storage capabilities of temporary resources
  - Power requirements of the application

---

#### Energy Autonomous Systems: Functional Blocks

**Energy Generation:**
- **Energy Harvesting**: Devices or systems harvesting energy from correlated or uncorrelated sources of energy.
- **Energy Sources & Storage**: Any kind of energy storage element that could be used to accumulate energy in excess from the harvester and provide it to the system in its place whenever the energy is insufficient.
- **Energy Conversion and Optimization**: Any energy conversion system that trades and optimizes the energy stored/harvested in the Energy Generation block to the Energy Consumption block.

**Energy Consumption**: Data acquisition, elaboration, storage and transmission.
Not a Really New Concept…

Power from typing
US 5,911,529 1999

ETA AutoQuartz mechanism, '90s

Thermoelectric generators for wristwatches, C. Piguet et al.
US 4,106,279 1978

Source: C. Piguet

The ZENITH Space
Command, 1956

The Good

DSP Power Trend

The energy per bit per computation decreases according to the technology trend (Gene’s law: energy/bit \(~1.6\)x/year)
**The Bad**

![Energy Storage Sources Projections](image1)

The trend is about 1.5 times per decade for Li-Ion

![Energy Storage Capability](image2)

In this scenario, caps could not substitute chemical storing, but just support it

**The Truth**

- **Energy**
  - Energy storage density trend: ~1.5 times per decade
  - Energy scavenging density trend: depends on efficiency up to physical limits

- **Digital bits**: Gene’s law
  - 1.6 x year

- **Sensing bits**: decrease < Gene’s law

- **Systems**
  - Partially autonomous
  - Totally autonomous

- **Transmission bit**: energy per transmitted bit

H. Tartagni

DEIS/ARCES Ph.D. Course – 2010
### EAS Scenarios

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Characteristics</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Sensing, elaboration and physical collection of data</td>
<td>Smart-dust, in-vivo diagnostics systems</td>
</tr>
<tr>
<td></td>
<td>Senses until energy sources can support it. Data is recovered by physical recollection</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Sensing, elaboration and collection of data by proximity energization</td>
<td>Active RFID, in-vivo diagnostic systems, etc</td>
</tr>
<tr>
<td></td>
<td>Senses until energy sources can support it. Data is recovered by providing external artificial burst energy</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Sensing, Elaboration and RF data transmission</td>
<td>Wireless sensor networks</td>
</tr>
<tr>
<td></td>
<td>Senses, elaborate and transmit data. The energy should be provided to the system lifelong</td>
<td></td>
</tr>
</tbody>
</table>

### Energy Storage

<table>
<thead>
<tr>
<th>Energy Generation</th>
<th>Energy Conversion &amp; Optimization</th>
<th>Energy Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Harvesting</td>
<td>Power Management</td>
<td>Ultra-Low-Power Systems</td>
</tr>
<tr>
<td>Energy Sources &amp; Storage</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Energy-Autonomous System
Energy Storage Sources & Capabilities

Chemical energy has by far the largest performance

Fuel Cells vs Primary Batteries

Conversion efficiency

Source: R, Hahn, FhG

H. Tartagni
Energy Storage: TRLs

- Chemical energy store sources are still unsurpassed but new technologies are competing if harvesting is efficient
- Micro fuel cells is a promising approach but not in a near future
- Advantages of fuel cells over batteries is less pronounced if the constraint is on volume and not on weight

<table>
<thead>
<tr>
<th>Micro batteries</th>
<th>Technology Readiness Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>This film battery</td>
<td>5 years</td>
</tr>
<tr>
<td>Si integrated micro battery</td>
<td></td>
</tr>
<tr>
<td>3D micro-structure electrodes</td>
<td>10 years</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Micro fuel cells</th>
<th>Technology Readiness Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro fuel cell with integrated fuel storage</td>
<td>Basic principle</td>
</tr>
<tr>
<td>3D MEMS based fuel cells</td>
<td>Lab prototype</td>
</tr>
<tr>
<td>Bio fuel cells</td>
<td>Ready for production</td>
</tr>
<tr>
<td>Ambient fuel generator for micro fuel cells</td>
<td></td>
</tr>
</tbody>
</table>

Energy Harvesting

Energy Generation → Energy Conversion & Optimization → Energy Consumption

Ultra-Low-Power Systems

Energy-Autonomous System
Power and Applications

Requirements:
- Small, light energy sources for mobility
- Energy source exceed lifetime for autonomy
- Low cost

Primary batteries: ~1Wh/cm³
Secondary batteries: ~0.3Wh/cm³

Example: At an average power consumption of 100 mW, you need more than 1 cm³ of lithium battery volume for weeks of operation.

Harvesting Devices

- Photovoltaic
- Vibration
- Thermal
- RF
Scavenging vibrations

- How can research in Electronics contribute to energy autonomous systems? How can vibrations supply systems?

1. Investigation of oscillating piezoelectric materials and devices
   - mechanical-to-electrical transducers
   - modelling required for more accurate predictions and design

2. Experimental validation
   - development of prototypes
   - Realistic targets: wearable systems, transportations, etc
   - dissemination of results
   - cooperation with industry, technological transfer

Source: [http://www.miei.group/zhon_files/](http://www.miei.group/zhon_files/)
Vibrations Harvesting

**Piezoelectric**

Strain in piezoelectric material causes a charge separation (voltage across capacitor).

**Capacitive**

Change in capacitance causes either voltage or charge increase.

**Electromagnetic**

Coil moves through magnetic field causing current in wire.

State-of-the-art Piezoelectric

- Glyne-Jones et al., 2001
  - University of Southampton
  - 3 µW, 1 g @ 800Hz

- Sang-Gook Kim, Rajendra Sood, MIT, 2004
  - 1 µW @ 2.36 V (0.74 mW-h/cm²)

- Efronk et al., 2008: IMEC
  - 60 µW, 2 g @ 572Hz, 0.2 cm²

- Shad Roundy et al, Berkeley, 2003
  - 70 µW, 2.25 mV @ 100Hz, 0.1 cm²

- M. Marzec et al, Tima Labs, 2007
  - 2 µW, 2 g @ 840Hz, 25mm²
State-of-the-art Capacitive

T. Sterken et al., 2003
IMEC, K.U. Leuven
12 mW, 1 g @ 1 kHz, 2 mm²

G. Despese et al., 2007
LETI - MINATEC
12 µW, 0.3 g @ 50 Hz, 1 cm²

M. Kiziroglou et al., 2008
Imperial College London

E. Yeatman et al., 2006
Imperial College London
2.4 mW, 40 g @ 20 Hz, 2 cm³

U. Bartsch et al., 2007
IMTEK

State-of-the-art Electromagnetic

Wen J. Li et al., 2000
Chinese univ. of Hong Kong
680 µW, 9.5 g @ 110 Hz, 1 cm³

T. Sterken et al., 2005
IMEC, K.U. Leuven
300 µW, 50 g @ 5 Hz, 5 cm³

S. Bidoit et al., 2007
University of Southampton
58 µW, 8 mm @ 20 Hz, 2 cm³

Glynne-Jones et al., 2004
University of Southampton
600 µW at 4.3 m/s² @ 100 Hz

D. Spreemann et al., 2006
HSG-IMIT
200 µW, 4 m/s² @ 25 Hz, 1.5 cm³

PMG Perpetuum
40 mW, 1 g @ 100 Hz, 110 cm³
The Origin: Shoe Mounted PiezoElectrics, 2001


- Low-frequency piezo source
  - Mainly capacitive
  - High-voltage, low-energy, low-duty cycle current pulses
  - Linear regulator not very suitable
  - Forward-switching converter (normal components)

- PZT dimorph: 8.4 mW w/500kW-load at walking pace (1Hz)
- $V_{pp} > 100V$, $V_{avg} = 40V$
- Powering RFID tag system

Application Reality
From Our Research: Dealing with Realistic Operating Conditions

- **Accelerations measured in realistic conditions**
  - MCU + accelerometer IC + data logger
- **Analyzed scenarios**
  - railway transports
  - Automotive
  - accelerations range in $a_{\text{rms}} = 0.05g – 0.25g$
- **An equalized mechanical shaker was implemented**
  - for reproducing recorded vibrations
  - Signal processing and equalization

From Our Research: Piezo Scavenging

- **Multi-source / Multi-cap prototype**
  - Power and efficiency evaluation
  - System demonstrator (supervised by ETHLAB)
    - Self-power self-updating E-ink display for railway systems (advertising, communications, etc.)
    - Based on multi-source technology or actively controlled rectification according to power needs
    - Low duty-cycle of operation (1 update/day)
    - Ultra-low power MCU ($P_d \sim 100\text{uW@1MHz}$) compatible with power budget
From Our Research: Main Achievements

- Smart conversion circuits increase harvested energy of a 2x - 3x factor with respect to existing solutions
  - The research group in Electronics at Ing2-Cesena demonstrated the results at national and international conferences
  - Research activities were awarded as one of best contributions at the 2008 Congress of the Italian Association for Sensors and Micro-systems (AISEM2009)

- Research open to Industry
  - Cooperation with Eurotech Group, world leader in high technology for computer miniaturization
  - Joint development of new energy-autonomous prototypal systems for new applications

Thermal Harvesting

Differently doped semiconductors are joined by metal contacts and placed in a temperature gradient making a “thermopile”
RF Scavenging

- Wide diffusion of RF communications devices (cell phones, wi-fi hot-spots, etc.) in humanized environments
  - Electromagnetic waves transfer information and energy at distance
- The idea: to collect energy rather than information
- How: the RECTENNA concept
  - Antenna + rectifying circuit
  - Applicable to many common wireless standards (GSM-900, UMTS, IEEE802.11, …), easy to realize and integrate
RF Harvesting

Concept of “rectenna”: a rectifying antenna harvesting RF emissions from surrounding environment

Source: A. Costanzo, UniBO

Extremely performing antenna array (Gain ~ 12 dB) designed for UMTS uplink band (1.92÷1.98 GHz)

A common watch has been switched on by a simple phone call!

BUT:
- Strictly linearly polarized radiated farfield, not efficient for unpredictable sources
- Too large to be converted into a wearable implementation

From Our Research: Harvesting from Cell Phones
From Our Research: Towards Wearable Implementations

- A challenging technology conversion, which implies:
  - An overview of suitable electrotextile materials
  - A detailed investigation about antenna performances when bent on curved surfaces

- **Electro-textiles**: generally created by incorporating conductive threads into fabrics by means of weaving and knitting

- **Performance during bending must be preserved.** In our design at 0.9 and 2.45 GHz it remains unchanged

---

### Harvesting Technologies Comparison

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>SOURCE CHARACTERISTICS</th>
<th>PHYSICAL EFFICIENCY</th>
<th>HARVESTED POWER</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PHOTOVOLTAIC</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Office</td>
<td>0.1 mW/cm²</td>
<td>10-24%</td>
<td>10 μW/cm²</td>
</tr>
<tr>
<td>Outdoor</td>
<td>100 mW/cm²</td>
<td></td>
<td>10 mW/cm²</td>
</tr>
<tr>
<td><strong>VIBRATION/ MOTION</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human</td>
<td>0.5-1 m/s²@1-50Hz</td>
<td>1-30%</td>
<td>4 μW/cm²</td>
</tr>
<tr>
<td>Industry</td>
<td>1-10 m/s²@5-1kHz</td>
<td></td>
<td>100 μW/cm²</td>
</tr>
<tr>
<td><strong>THERMAL ENERGY</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human</td>
<td>20 mW/cm²</td>
<td>0.10%</td>
<td>25 μW/cm²</td>
</tr>
<tr>
<td>Industry</td>
<td>100 mW/cm²</td>
<td>3%</td>
<td>1-10 mW/cm²</td>
</tr>
<tr>
<td><strong>RF</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GSM 900 MHz</td>
<td>0.3-0.93 μW/cm²</td>
<td>50%</td>
<td>0.1 μW/cm²</td>
</tr>
<tr>
<td>1800 MHz</td>
<td>0.1-0.51 μW/cm²</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: C. van Hoof, IMEC
Electronic technologies for energy harvesting

- Micro-/Nano-electronics open new scenarios
  - Reduced size and extreme integration level
  - Ultra-low power consumption
- Our group is investigating "smart" self-powered circuits and systems for efficiently harvesting low-density ambient energy
  - On-board intelligence increase energy efficiency, but require power for running
  - The key point is that the required power must be lower than the increase in collected energy
  - Challenging energy budget required for sustainability
  - Design of full-custom CMOS silicon chips
  - Suitable also for RF and other power sources
DC-DC converters concepts

Boost converter

- Efficient if L large, R small
- OK for discrete
- Integrated solution: Small L, large R
- Efficiency decreases

Dickson charge pump

- Charge pump with switching capacitors
- Losses due to parasitics (u)
  (dis)charging
- Optimize n and C-f

Intelligent Conversion

Strategy to increase the output power of a piezoelectric cantilever

Schematic of a full-wave rectifier for multi-phase piezoelectric energy harvester. It uses a rectifier without voltage drop across the diodes
Energy Consumption

Energy Cost Trends for Bandwidth
Bandwidth and Resolution

Energy demanded by various applications. The more precision and amount of data required, the more energy spent per time. Data are based on 5pJ/conversion.

Three directions for EAS:
• Interfaces
• Computing
• Wireless

A/D Interfaces


ADC architectures:
• SAR
• Sigma-Delta
• Asynchronous ADC
• Time-domain converters

Tentative Roadmap

Source: M. Belleville
### Computing

<table>
<thead>
<tr>
<th>Chip</th>
<th>MOPS/mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional microprocessor</td>
<td>1</td>
</tr>
<tr>
<td>Conventional DSP core</td>
<td>45</td>
</tr>
<tr>
<td>Low-power DSP core</td>
<td>65</td>
</tr>
<tr>
<td>CSEM MACGIC core 180 nm</td>
<td>100</td>
</tr>
<tr>
<td>DSP + hardware accelerators</td>
<td>190</td>
</tr>
<tr>
<td>Dedicated hardware (no flexibility)</td>
<td>1900</td>
</tr>
<tr>
<td>Upper bond (not reachable)</td>
<td>2500</td>
</tr>
</tbody>
</table>

Specialization reduces power

### Technologies
- Optimized memory access
- Multi-Vt
- Power gating

### Architectures:
- Asynchronous logic
- Subthreshold logic
- Error tolerant logic
- Vdd tuning
- Probabilistic CMOS

### Tentative Roadmaps

<table>
<thead>
<tr>
<th>Year of production</th>
<th>2008</th>
<th>2009</th>
<th>2012</th>
<th>2015</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSP Comput.Pwr D0 @ cst. Dyn. Pwr</td>
<td>1</td>
<td>1.5</td>
<td>6</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>LP DSP Dyn. energy (μW/MMACs) @ cst. Comput. Pwr (10 MMACs)</td>
<td>2</td>
<td>1.3</td>
<td>0.3</td>
<td>0.08</td>
<td>0.02</td>
</tr>
<tr>
<td>Stdby Pwr reduction by design techniques 00 @ medium duty cycle</td>
<td>1.3</td>
<td>1.9</td>
<td>2.7</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>Stdby Pwr reduction by design techniques 00 @ low duty cycle</td>
<td>4</td>
<td>10</td>
<td>18</td>
<td>28</td>
<td></td>
</tr>
</tbody>
</table>

Source: M. Belleville

Assumption: ITRS leakage targets met
Overview of the talk

- Energy harvesting, where and why
- Energy autonomous systems (EAS), a challenge for next years
  - Energy from vibrations
  - Energy from light
  - Energy from temperature
  - Energy from radio-frequency
- Industrial applications & some market perspective
- Other applications
- Conclusions
Industrial Application Reality: KCF Technology

Industrial Application Reality: Perpetuum
What About the Future Standards?

EnOcean Alliance with about 150 companies involved with interoperable devices, mainly for use in buildings, and well over 500,000 of them installed.

ZigBee is already the leading standard for parts of the smart grid and the in-building wireless network market, and it already has the International Electrotechnical Commission (IEC) seal of approval. Almost all ZigBee applications rely on batteries. This is why the ZigBee Alliance will amend its standard to work with more energy-harvesting devices, possibly battery free ones if they can crack the technical problems.

Ocean has one project with 10,000 wireless, battery-less sensors installed on a single building site. The MGM Center in Las Vegas has about 70,000 ZigBee radios installed but they are not solely reliant on energy harvesting.

A Strong Market Application: Tire Pressure Monitoring System (TPMS)

1. The market for wireless energy scavenging for use in tire-pressure monitoring systems (TPMSs) is slowly developing, with potential that should be realized by 2015. A lot of R&D is still necessary, though, before these devices can successfully come to the market. (courtesy of Sappi Corp.)

2. Siemens VDO (now Continental) collaborated with Goodyear Tire and Rubber Co. to develop a TPMS device that can be mounted on the tire rim. (courtesy of Goodyear Tire & Rubber Co.)
Overview of the talk

- Energy harvesting, where and why
- Energy autonomous systems (EAS), a challenge for next years
  - Energy from vibrations
  - Energy from light
  - Energy from temperature
  - Energy from radio-frequency
- Industrial applications & some market perspective
- Other applications
- Conclusions
Applications

First Apple licensed solar charging case for iPod Touch

Source: Novothink

To capture energy from the raindrops the scientists used a 25 micrometer thick PVDF (polyvinylidene fluoride) polymer, a piezoelectric material that converts mechanical energy into electrical energy.

Source: CEA/Leti

Energy Harvesting Luggage

Interactive Telecommunications Program student Ohad Folman has created Pluggage as his final project - an item of carry-on luggage that harvests kinetic energy and solar power to charge small electrical devices.

The Pluggage has a built-in battery/inverter and a solar panel, enabling it to power up mobile devices each time the bag is rolled or exposed to direct sunlight. The kinetic energy from the rolling wheels at the base is converted via a generator/turbine into electrical energy.
Zero Energy Media Wall

**GreenPix** is a groundbreaking project where sustainable and digital media technology is applied to the curtain wall of Xicui entertainment complex in Beijing, near the site of the 2008 Olympic Games. Featuring one of the largest color LED displays worldwide and the first photovoltaic system integrated into a glass curtain wall in China, the building performs as a self-sufficient organic system, harvesting solar energy by day and using it to illuminate the screen after dark, mirroring a day's climatic cycle.

Energy from Dance

Club Surya in London is one of a new generation of "eco-clubs" which encourages its patrons to work towards climate change. The club’s main feature is the piezoelectric dance floor.

The dance floor uses piezoelectricity where crystal and ceramics create a charge to generate electricity. The nightclub has a "bouncing" floor made of springs and a series of power generating blocks which produce a small electrical current when squashed. As dancers move the floor up and down to squeeze the blocks, the current is fed into nearby batteries which are constantly recharged by the movement of the floor. The electricity created in this way is used to power parts of the nightclub such as the sound and lighting.
Insect Cyborgs

Defence Advanced Research Projects Agency (DARPA) is conducting a Hybrid Insect MEMS (HI-MEMS) program which is aimed at developing technology that provides more control over insect locomotion. This is done by developing tightly coupled machine-insect interfaces by placing micro-mechanical systems inside the insects during the early stages of metamorphosis.
Conclusions

• Energy harvesting for industrial application is a new concept just started few years ago

• The energy harvesting paradigm fits perfectly in the energy sustainability today’s vision

• The number of applications is increasing exponentially

Tank you for your attention!

CATRENE Working Group on Energy Autonomous Systems

White Paper
Acknowledgments

R. Codeluppi, A. Costanzo, M. Dini, C. Fiega, A. Golfarelli,
M. Magi, A. Romani, M. Rossi, E. Sangiorgi

Cassa dei Risparmi di Forlì