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Algorithms for Radio Networks

WSN: Energy Harvesting

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Literature Energy Harvesting

- **Kansal, Hsu, Zahedi, Srivastava**
  - *Power management in energy harvesting sensor networks*. ACM Trans. Embed. Comput. Syst. 6, 4, Sep. 2007

Motivation

- **Energy harvesting**
  - can remove batteries from WSNs
  - potentially infinite lifetime
  - active time can be increased (or reduced)
- **Example**
  - solar energy only available at daylight
- **Energy concept**
  - necessary for the entire period
  - regulates interplay of sleep phase, data rate and short term energy source

Harvesting Paradigma

- **Typical task in battery operated WSN**
  - minimize energy consumption
  - maximize lifetime
- **Task in harvesting-WSN**
  - continuous operation
    - i.e. infinite lifetime
  - term: energy-neutraler operation

Possible Sources

- **Piezoelectric effect**
  - mechanicyl presures produces voltage
- **Thermoelectric effect**
  - temperature difference of conductors with differen thermal coefficient
- **Kinetic energy**
  - e.g. self-rewinding watches
- **Micro wind turbines**
- **Antennas**
- **Chemical sources,...**

Differences Compared to Batteries

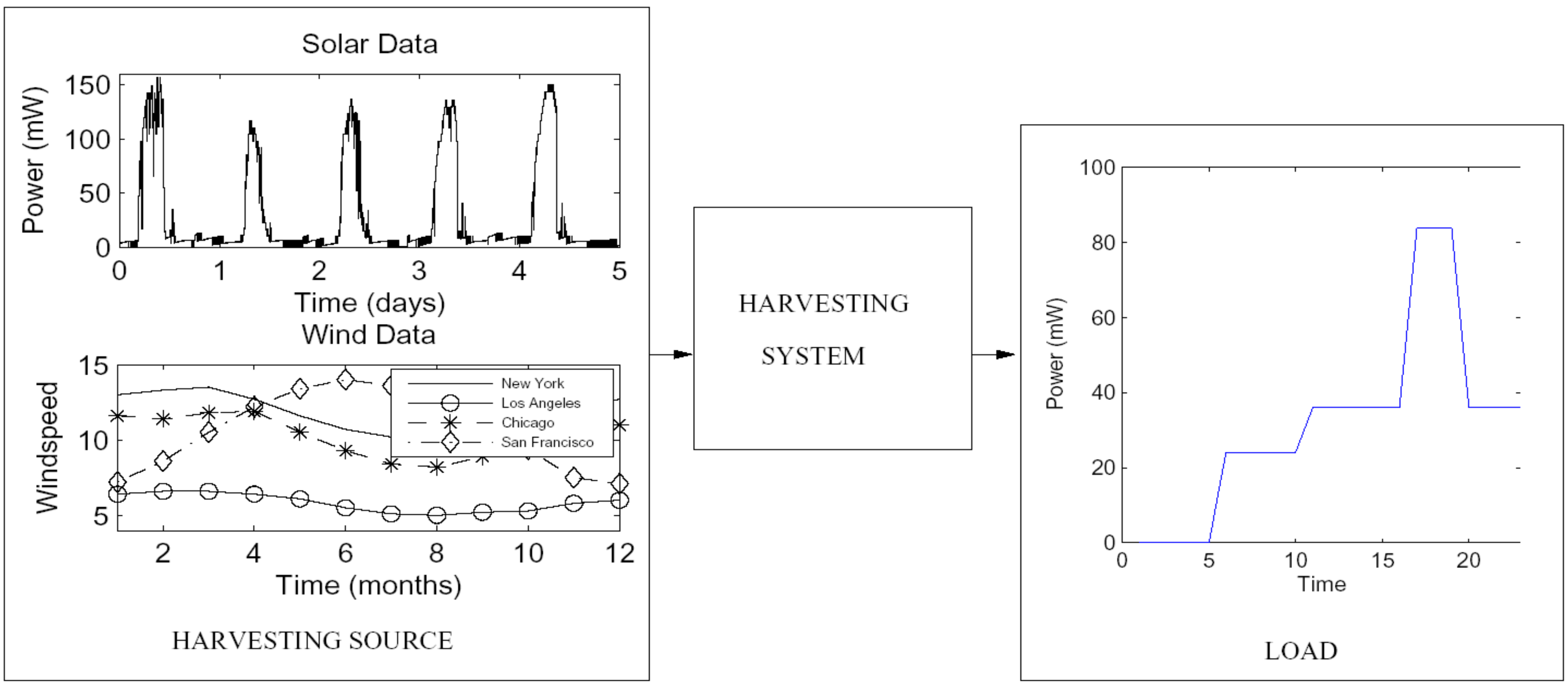
- **Time dependent**
  - form of operation has to be adapted over time
  - sometimes not predictable
- **Location dependent**
  - different nodes have have different energy
    - load balancing necessary
- **Never ending supply**
- **New efficiency paradigm**
  - utilization of energy for maximum performance
  - energy saving may result in unnecessary opportunity costs

Solutions without Power Management

- **Without energy buffer**
  - harvesting hardware has to supply maximal necessary energy level at minimum energy input
  - only in special situation possiblee
    - e.g. light switch
- **With energy buffer**
  - power management system necessary

Power Management System

- **Target**
  - Providing the necessary energy from external energy source and energy buffer



Energy Sources

- **Uncontrolled but predictable**
  - e.g. daylight
- **Uncontrolled and unpredictable**
  - e.g. wind
- **Controllable**
  - energy is produced if necessary
  - e.g. light switch, dynamo on bike
- **Partially controllable**
  - energy is not always available
  - e.g. radio source in the room with changing reception

Harvesting Theory

- **$P_s(t)$: Power output from energy source a time t**
- **$P_c(t)$: Energy demand at time t**
- **Without energy buffer**
  - $P_s(t) \geq P_c(t)$: node is active
- **Ideal energy buffer**
  - Continuous operation if

$$\int_0^T P_c(t)dt \leq \int_0^T P_s(t)dt + B_0 \quad \forall \quad T \in [0, \infty)$$

  - where B_0 is the initial energy
  - energy buffer is lossless, store any amount of energy

Harvesting Theory

- **$P_s(t)$: Power output from energy source a time t**
- **$P_c(t)$: Energy consumed at time t**
- **Let**

$$[x]^+ = \begin{cases} x & x \geq 0 \\ 0 & x < 0 \end{cases}$$

- **Non-ideal energy buffer**
  - Continuous operation if

$$B_0 + \eta \int_0^T [P_s(t) - P_c(t)]^+ dt - \int_0^T [P_c(t) - P_s(t)]^+ dt - \int_0^T P_{leak}(t) dt \geq 0$$

  - B_0 is the initial energy
  - η: efficiency of energy buffer
  - $P_{leak}(t)$: energy loss of the memory

Harvesting Theory

- **$P_s(t)$: Power output from energy source a time t**
- **$P_c(t)$: Energy consumed at time t**
- **Let** $$[x]^+ = \begin{cases} x & x \geq 0 \\ 0 & x < 0 \end{cases}$$
- **Non-ideal energy buffer with limited reception B**
  - Continuous operation if

$$B_0 + \eta \int_0^T [P_s(t) - P_c(t)]^+ dt - \int_0^T [P_c(t) - P_s(t)]^+ dt - \int_0^T P_{leak}(t) dt \geq 0$$

  - B_0 is the initial energy of the buffer
  - η: efficiency of energy buffer
  - $P_{leak}(t)$: leakage power of the energy buffer

$$B_0 + \eta \int_0^T [P_s(t) - P_c(t)]^+ dt - \int_0^T [P_c(t) - P_s(t)]^+ dt - \int_0^T P_{leak}(t) dt \leq B$$

Model of Benign Energy Behavior

- **If the power source $P_s(t)$ occurs regularly, then it satisfies the following equations**

$$\int_{\tau}^{\tau+T} P_s(t)dt \leq \rho_1 T + \sigma_1$$

$$\int_{\tau}^{\tau+T} P_s(t)dt \geq \rho_1 T - \sigma_2$$

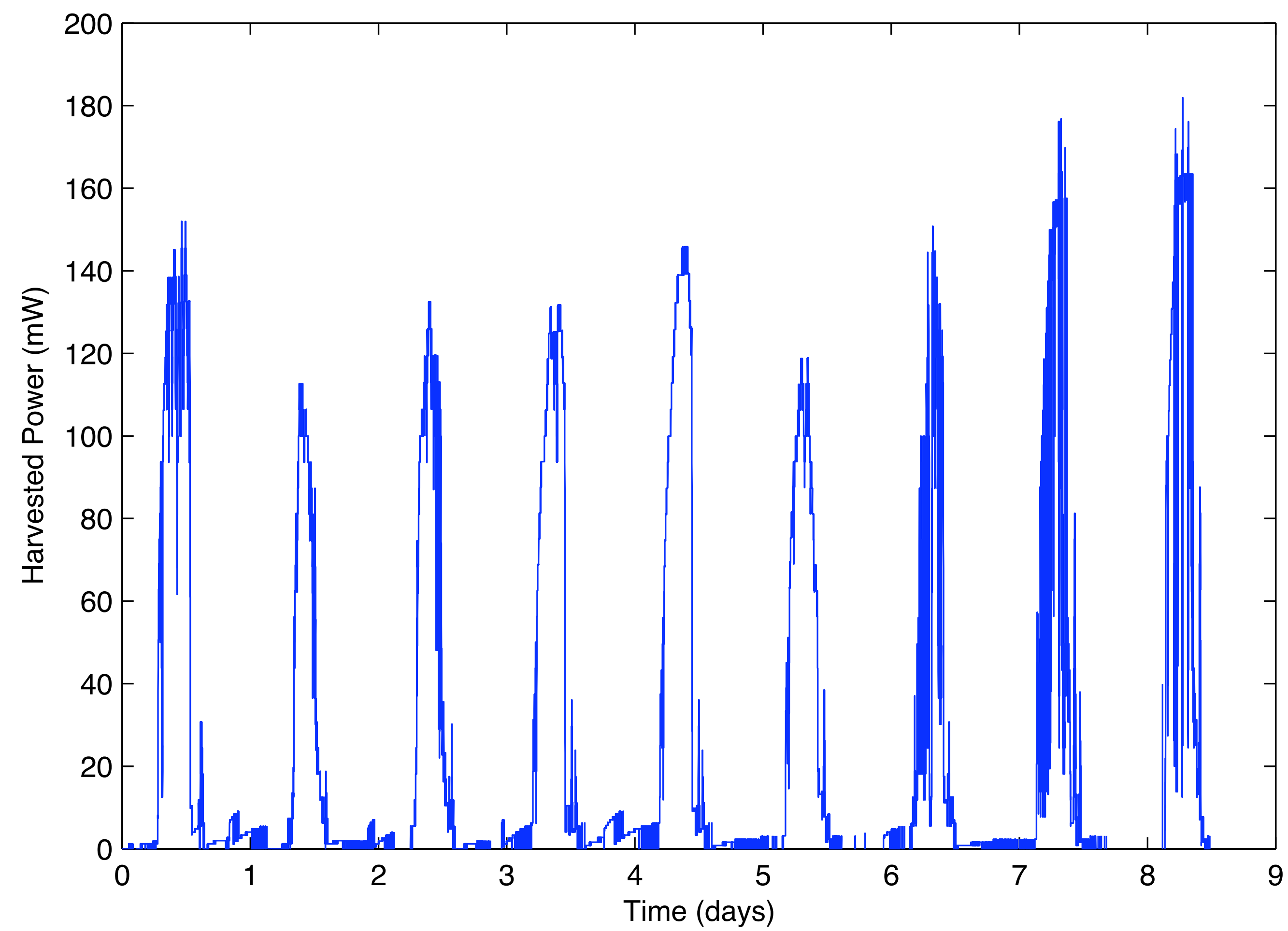


Fig. 2. Solar energy based charging power recorded for 9 days

Model of Benign Energy Behavior

- **Benign energy consumption:**
  - $P_c(t)$ satisfies the following

$$\int_{\tau}^{\tau+T} P_c(t)\,dt \;\leq\; \rho_2 T + \sigma_3$$

$$\int_{\tau}^{\tau+T} P_c(t)\,dt \;\geq\; \rho_2 T - \sigma_4$$

Energy Neutrality for Benign Sources

- **Substitution into the non-ideal energy source inequality:**

$$B_0 + \eta \cdot \min\{\int_T P_s(t)dt\} - \max\{\int_T P_c(t)dt\} - \int_T P_{leak}(t)dt \;\geq\; 0$$
$$\Rightarrow B_0 + \eta(\rho_1 T - \sigma_2) - (\rho_2 T + \sigma_3) - \rho_{leak} T \;\geq\; 0$$

- **This inequality must hold for T=0**

$B_0 \geq \eta\sigma_2 + \sigma_3$

- **This condition must hold for all T**

$\eta\rho_1 - \rho_{leak} \geq \rho_2$

- **If these inequalities hold then continuous operation can be guaranteed**

Necessary Energy Buffer for Benign Energy Sources

- **Substituting in the second equation**

$$B_0 + \eta \cdot \max\{\int_T P_s(t)dt\} - \min\{\int_T P_c(t)dt\} - \int_T P_{leak}(t)dt \ \leq \ B$$

$$\Rightarrow B_0 + \eta(\rho_1 T + \sigma_1) - (\rho_2 T - \sigma_4) - \rho_{leak} T \ \leq \ B$$

- **For T=0 we need**

$$B_0 + \eta(\sigma_1 - \sigma_4) \leq B$$

- **Substitution of** $B_0 \geq \eta\sigma_2 + \sigma_3$ **yields**

$$B \geq \eta(\sigma_1 + \sigma_2) + \sigma_3 - \sigma_4$$

- **For T $\rightarrow \infty$ we have**

$$\eta\rho_1 - \rho_{leak} \leq \rho_2$$

  - This condition may be violated without problems

Energy Neutral Operation

- **Theorem**
  - For benign energy sources the energy neutrality can be satisfied if the following conditions apply
    - $\rho_2 \leq \eta\rho_1 - \rho_{leak}$
    - $B \geq \eta\sigma_1 + \eta\sigma_2 + \sigma_3$
    - $B_0 \geq \eta\sigma_2 + \sigma_3$

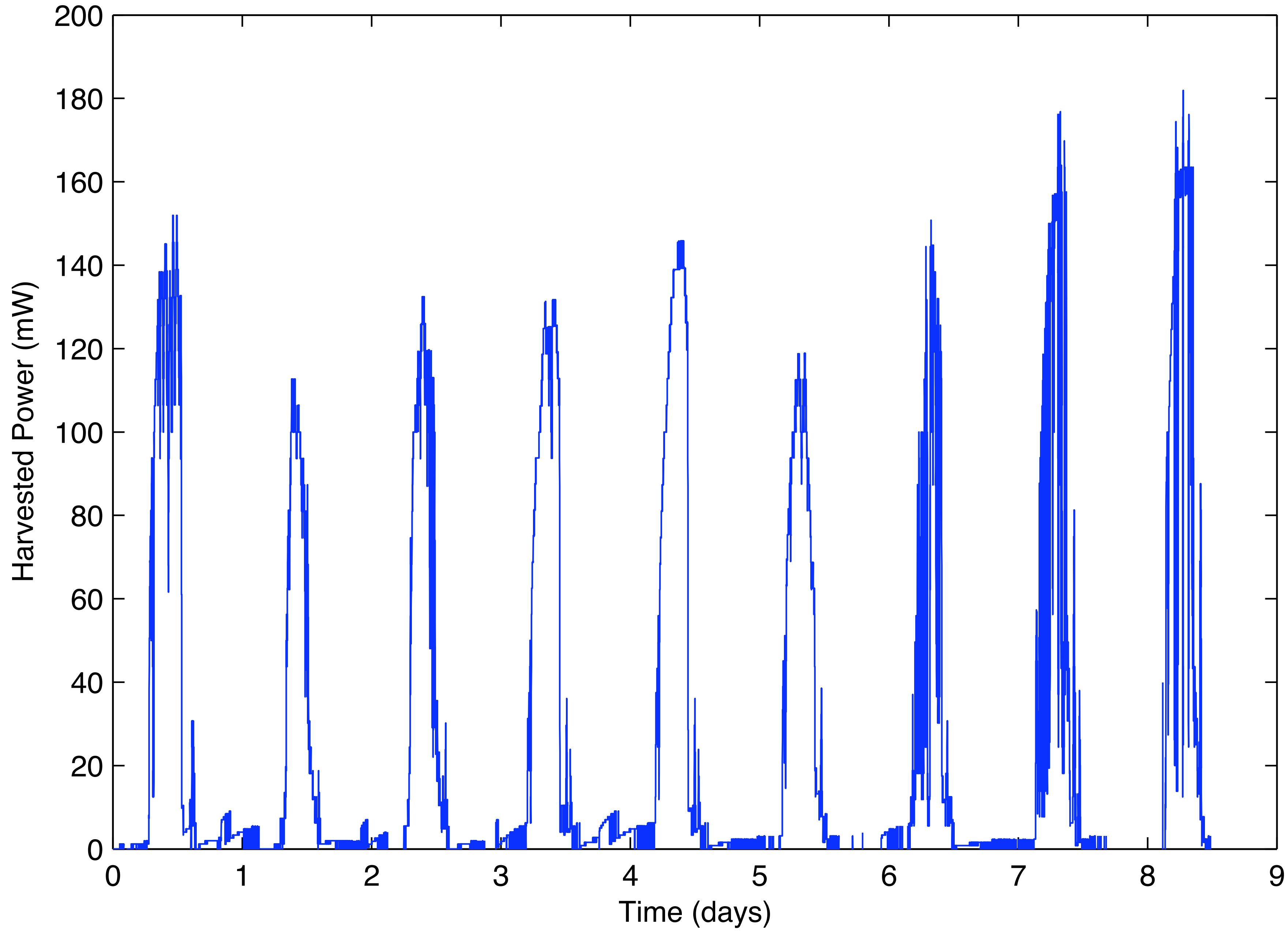


Fig. 2. Solar energy based charging power recorded for 9 days

Parameter	Value	Units
ρ_1	23.6	mW
σ_1	1.4639×10^3	J
σ_2	1.8566×10^3	J

Further Considerations

- **The behavior of energy sources can be learned**
  - As a result, the available energy can be calculated
  - The task can be adapted to the energy supply
- **Thereby**
  - Nodes with better energy situation can take over routing
  - Measurements can occur seldomer, but will never stop

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