Simple model for the energy supply of a house using hybrid wind-solar power system

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Research project for secondary school students

- The problem to be solved is whether and how a typical house can be supplied with energy off-grid, based entirely on renewable energy sources.
- To this end our students carried out a long term measurement series in order to assess typical energy consumption of houses.

1. Introduction

- Renewable energy sources are becoming increasingly important in energy supply.
- Their contribution covered an estimated 19% of the global final energy consumption in 2011 [1].
- They may not completely substitute fossil fuels and atomic energy in the near future, yet they offer an attractive alternative in the long term.

Solar and wind energy

- Among renewables, solar and wind power are widely available on the Earth.
- The locally available solar energy and wind power substantially depend on meteorological conditions and are highly variable in time.

- Due to their significance and perspective, it is desirable to give renewable energy sources an appropriate share in physics teaching.
- In this lecture a related research project designed for and accomplished by secondary school students is presented.

1st stage

- Our '*Renewable energy sources: stand-alone house with hybrid wind-solar power generator*' project has been carried out in three stages.
- For the first stage the daily energy consumption of an average house was investigated.

2nd and 3rd stage

- For the second stage a mathematical model for an off-grid house with hybrid wind-solar power generator and accumulator system was developed.
- For the third stage a computer simulation program was developed, based on the mathematical model and the data collected by students.

- Wind power has significant variation over shorter time scales therefore it is used generally in conjunction with other sources to give a reliable supply.

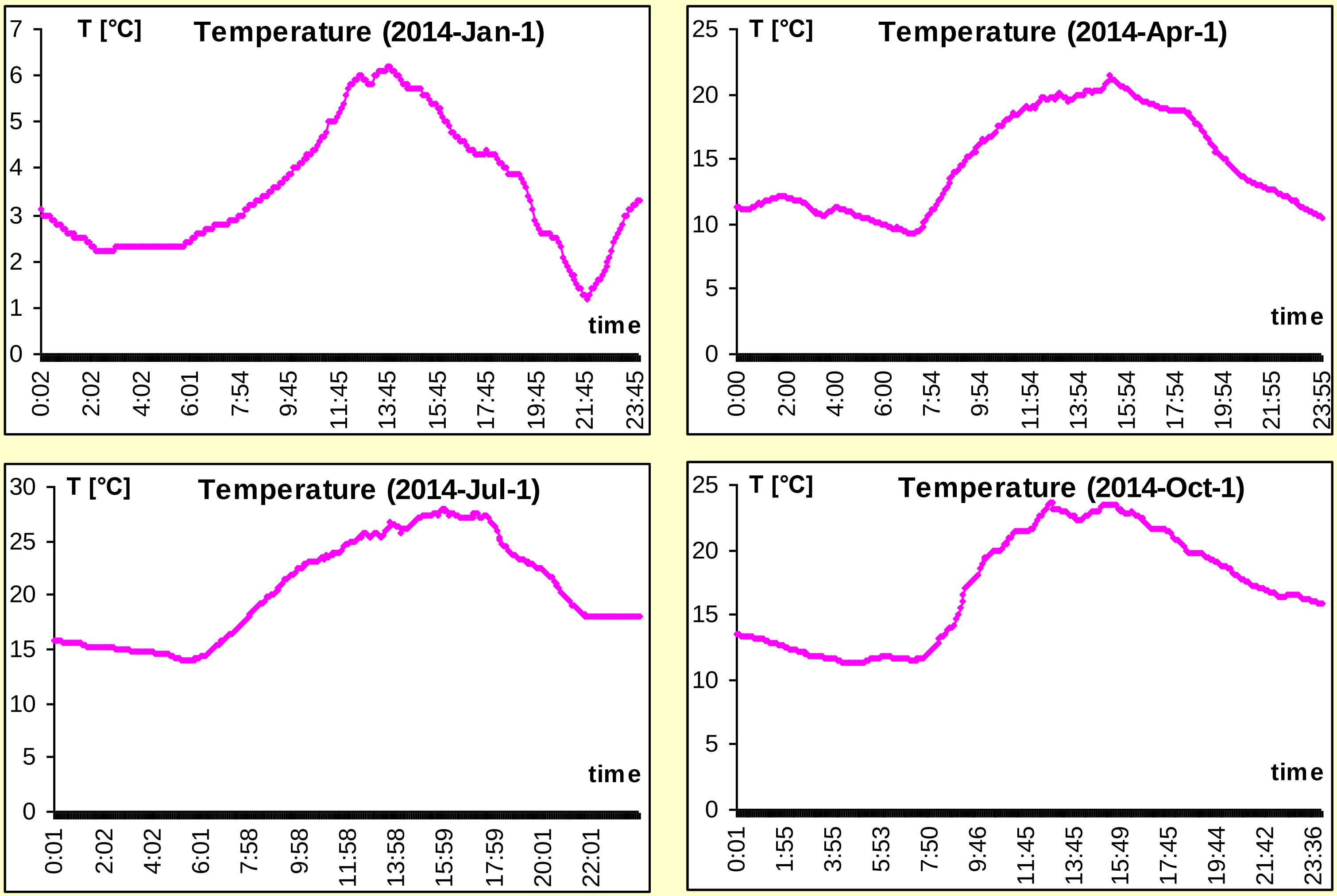
2. Gathering data

- All the students taking part in this project live in the same town, Kalocsa, in self-contained detached houses with insulated walls and central heating systems.
- The number of student houses was N=31.

- We monitored the temperatures on every day during the project.
- I have chosen 4 days from 4 different seasons to present the data:
  - the ‘winter day’ is 2014-Jan-1,
  - the ‘spring day’ is 2014-Apr-1,
  - the ‘summer day’ is 2014-Jul-1,
  - the ‘autumn day’ is 2014-Oct-1.

Outside temperatures

- We can see in figure 1 the outside temperatures on the days chosen.



Energy consumption

- Students collected the data of the daily energy consumption of their own houses:
  - the energy consumption of the electric appliances was monitored;
  - the natural gas consumption was monitored by gas meter;
  - the wood and coal burned in furnaces were measured in weighing-machines (scales).

$$E_{total,i} = \frac{A_{ave} \cdot N_{ave}}{N} \sum_{j=1}^{N} \frac{E_{total,i,j}}{A_j \cdot N_j},$$

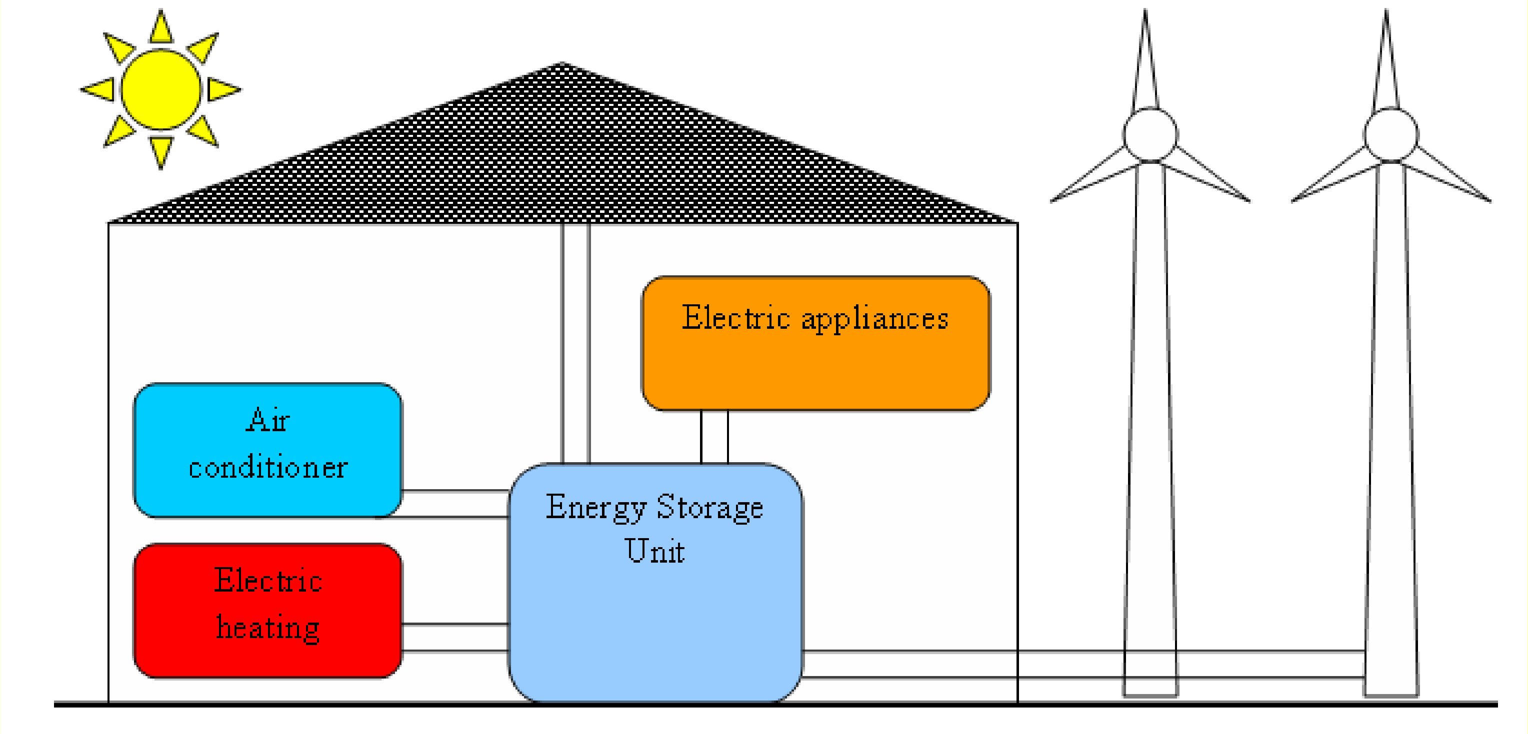
- The ‘heating season’ spans from 1st October to 15th April; between 16th April and 30th September the period was designated as ’non-heating season’.
- The average daily electricity consumption of students’ household was circa:
  - 37 MJ in the heating season
  - and about 35 MJ in the non-heating season.

3. Modelling

- Now a model of an off-grid hybrid wind-solar power generating system is presented.
- In this model we assume that the users cannot (or do not want to) rely on the electric grid system, therefore the energy produced by the hybrid wind-solar system is stored locally in accumulators.

Model setup

- The model setup is depicted schematically in figure 2.
- The parts of the system are the power generating system (photovoltaic modules and wind turbines), the energy storage unit.



PV modules and wind turbines

- This off-grid hybrid wind-solar power generating system consists of N_{photov} pieces of PV modules and N_{windt} pieces of small wind turbines.

PV module

- A photovoltaic (PV or solar) cell converts the energy of light directly into electricity by photovoltaic effect.
- In a PV cell the direct conversion of light to electricity occurs in semi-conducting materials.

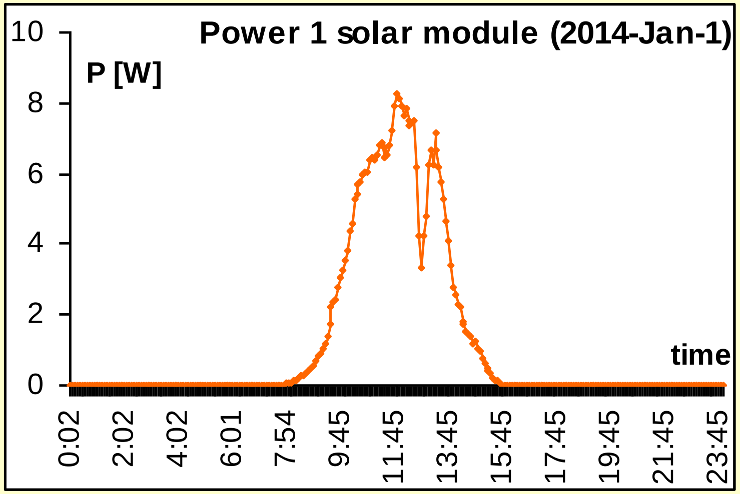
Power of a photovoltaic module

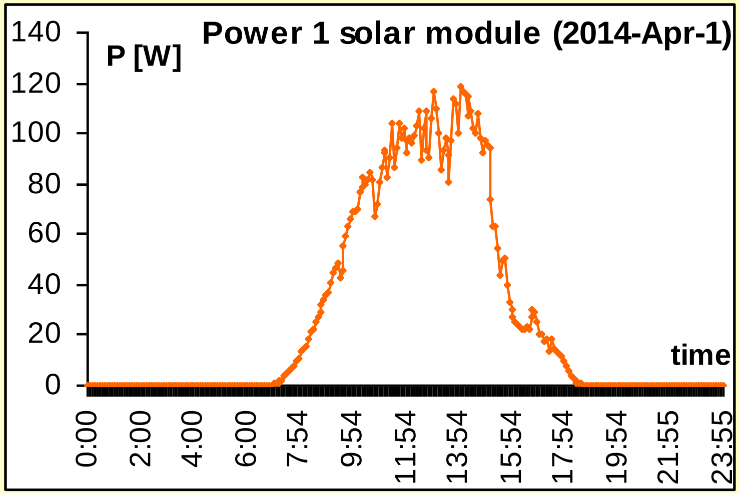
- The power of a photovoltaic module (P_{photov}) is proportional to the incoming light power [2]:

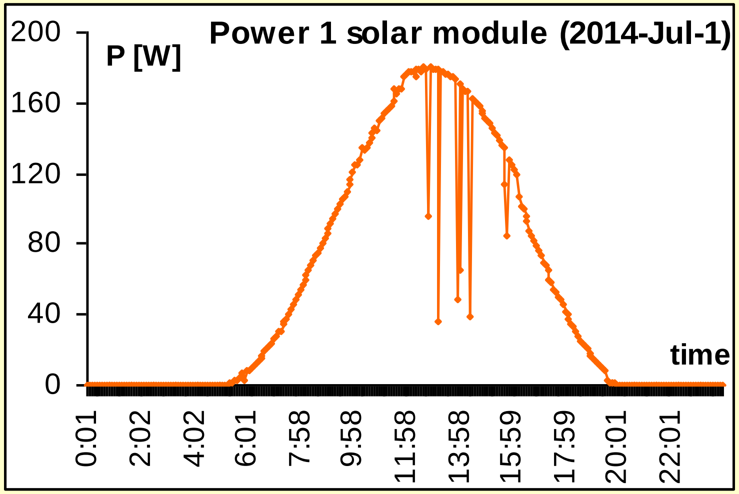
$$P_{photov} = P_{photov}(t) = \eta_{photov} \cdot A_{photov} \cdot I(t),$$

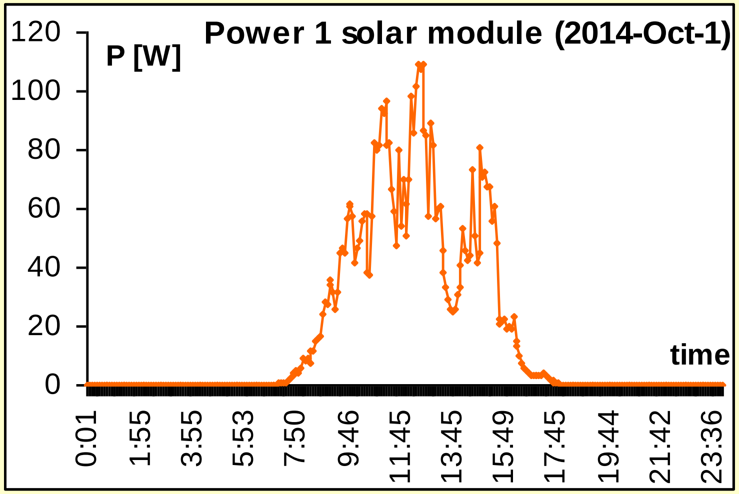
Power of one PV module

- Figure 3 shows the power of one photovoltaic module on the days chosen.





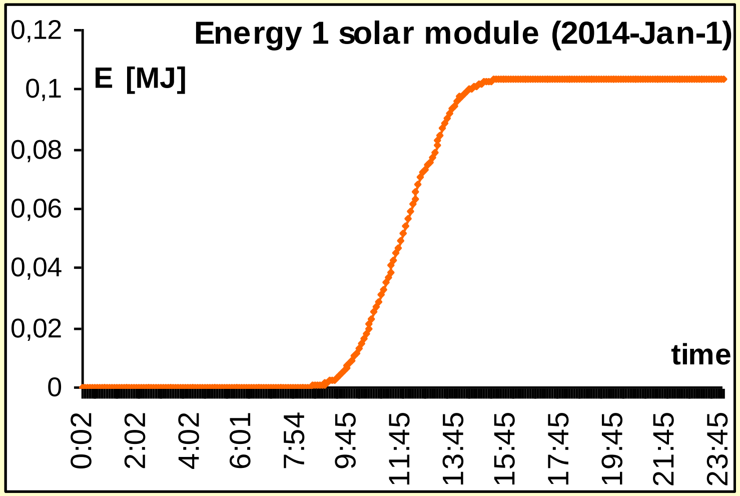


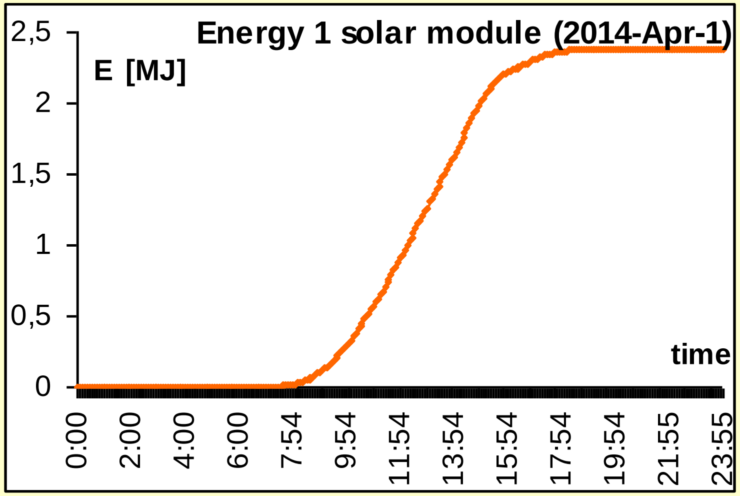


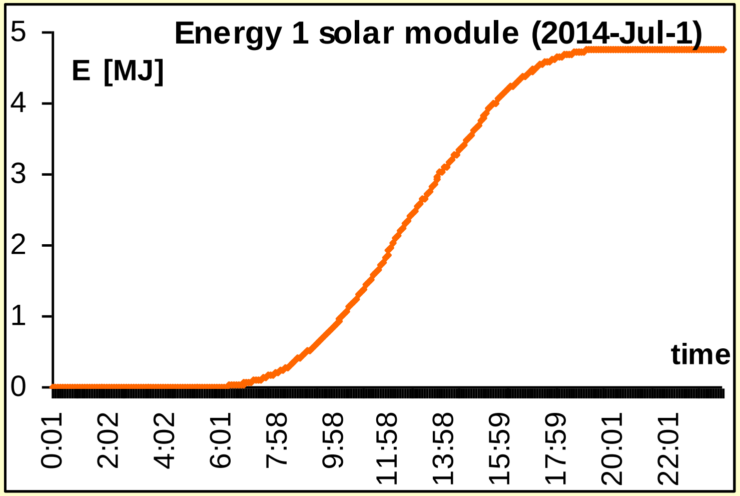
Energy of PV module

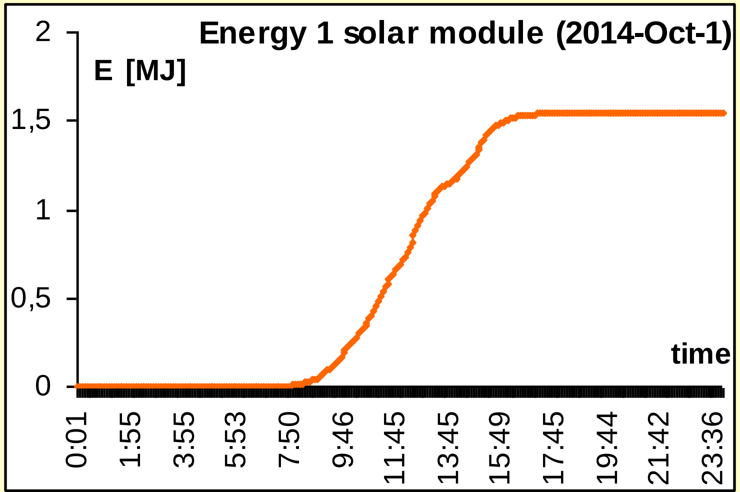
$$E_{photov,i} = \sum_{ith_{day_0}}^{ith_{day_0}+T_{day}} P_{photov}(t) \cdot N_{photov} \cdot \Delta t,$$

- In figure 4 the sum-total electrical energy produced by one photovoltaic module on the days chosen is shown.









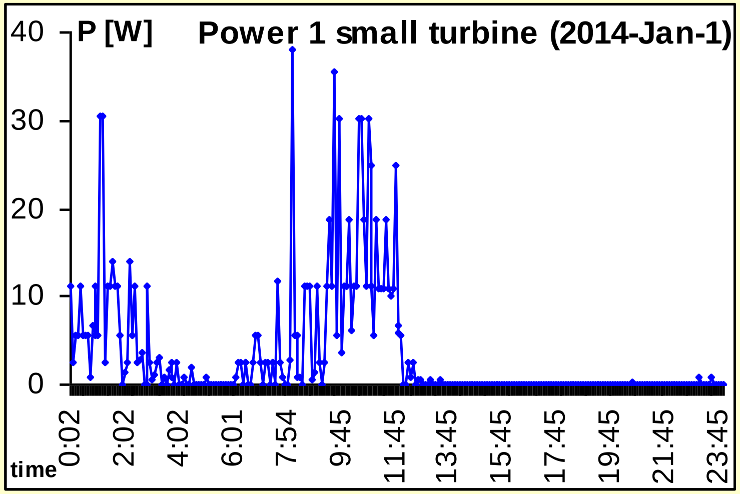
Wind turbines

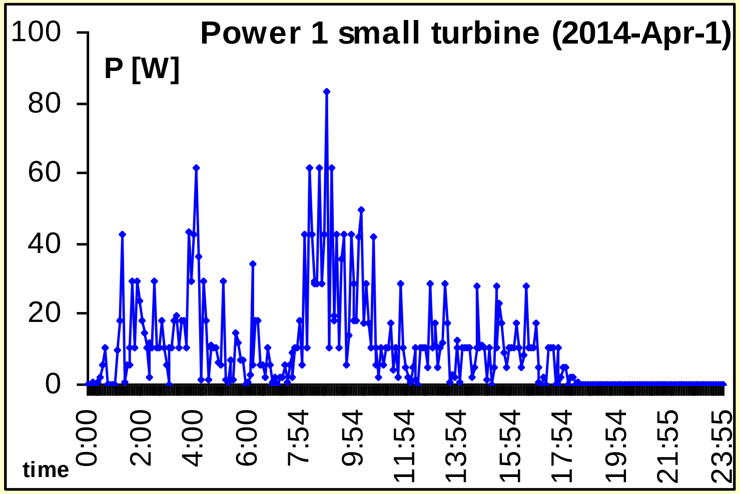
- Wind turbine generates electricity from the kinetic power of the wind.
- The power output of the wind turbine is proportional to the area swept by the blades and to the cube of the wind velocity.
- The power of wind turbine (P_{windt}) is assumed [3]:

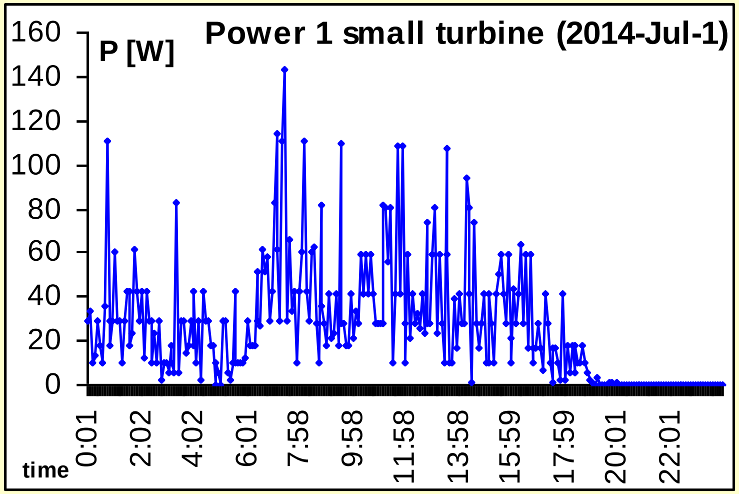
$$P_{windt} = P_{windt}(t) = C_{po} \cdot \frac{\rho_{air}(t)}{2} \cdot A_{rotor} \cdot v_{wind}^{3}(t),$$

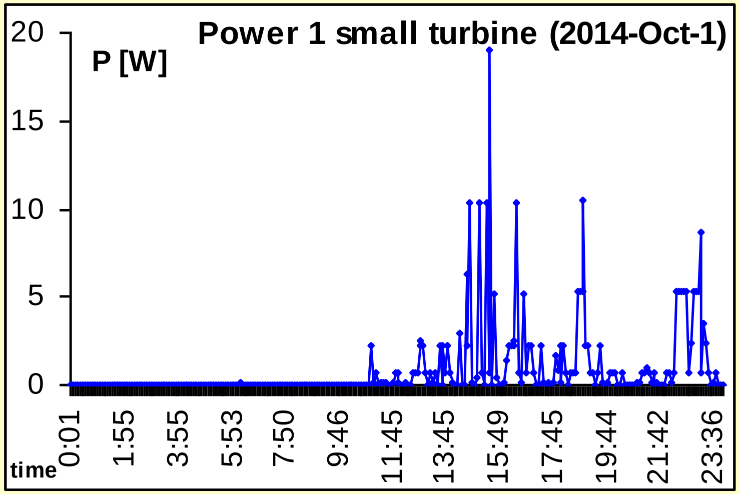
Power of wind turbine

- In figure 5 the power of one small wind turbine can be seen on the days chosen.





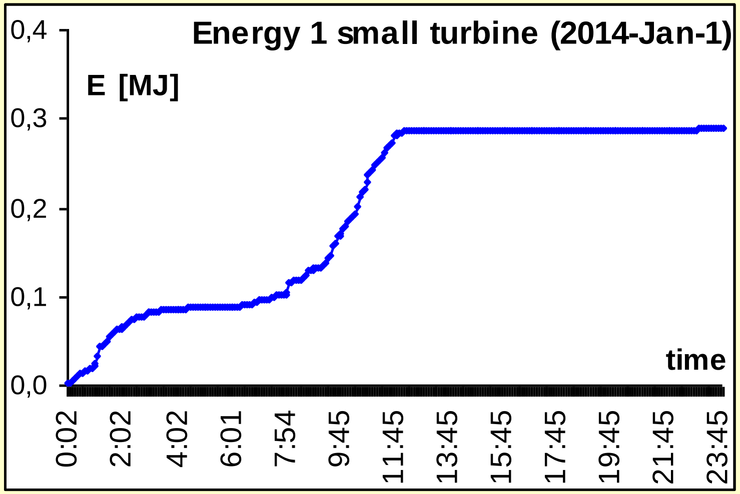


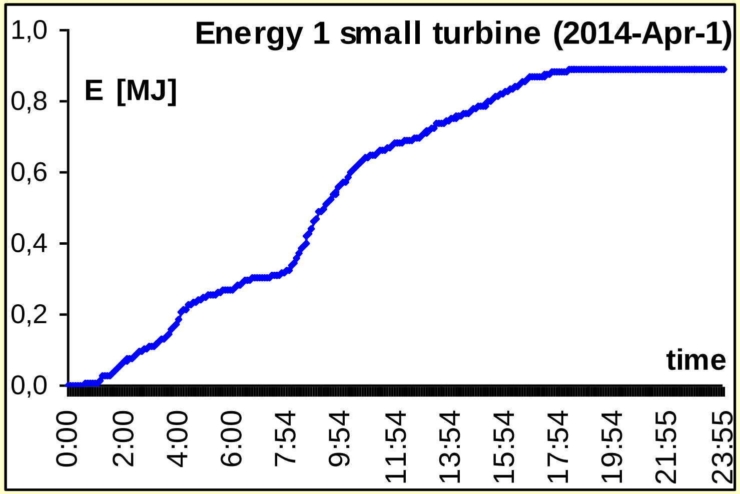


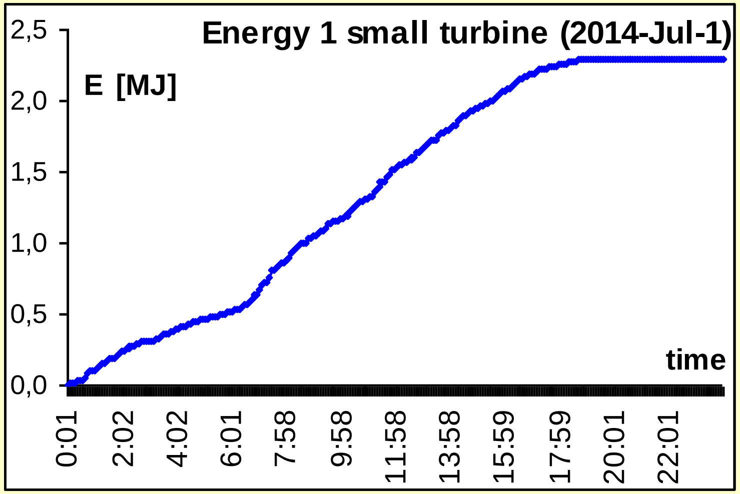
Energy of wind turbine

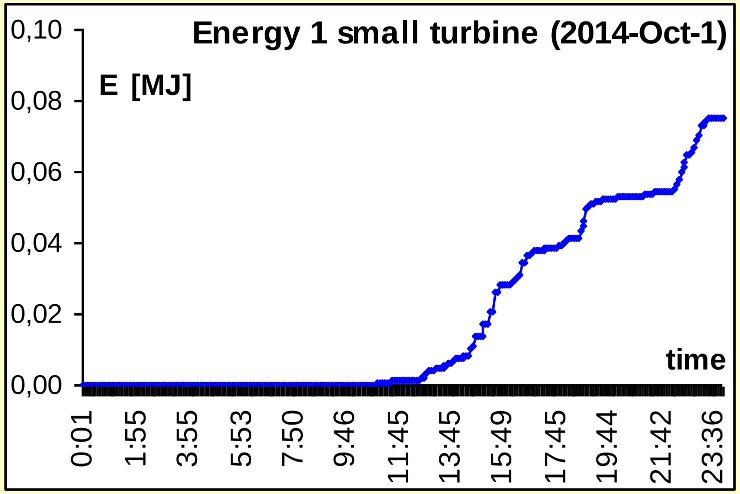
$$E_{windt,i} = \sum_{ith_{day_0}}^{ith_{day_0}+T_{day}} P_{windt}(t) \cdot N_{windt} \cdot \Delta t$$

- In figure 6 the sum-total electrical energy produced by one small wind turbine on the days chosen is shown.









Produced energy

- During the period of the project the wind speed, the pressure of air, the temperature of air and the sunlight is monitored in every Δt=5 minutes automatically by a local weather station, so it is available for us.
- The total daily production of electrical energy in our hybrid system on *i*th day can be determined by knowing, separately, the daily energy production of the solar modules and the daily energy production of the wind turbines:

$$E_{ee,i} = E_{photov,i} + E_{windt,i},$$

Accumulators

- When electrical energy is generated in solar modules and/or in wind turbines it is stored instantly in accumulators according to the model assumption.
- I would like to discuss what size of accumulator capacity (E_{acc_max}) is suitable for the parameters given in our off-grid system.

4. Energy input and output and energy storage

- In order to determine the necessary storage capacity of batteries, we study the energy inputs (produced energy) and outputs (dissipated energy) of the system in details.

Heat transmission

- The rate of heat transmission (transfer) is directly proportional to the temperature difference between the surroundings and the body.
- The heat transmission power from the environment to the building through the walls (and roof) can be estimated by the expression [4]:

$$P_{heattr} = P_{heattr}(t) = U \cdot A_f \cdot (T_{out}(t) - T_{in}(t)),$$

Heat radiation

- We tried to construct only an approximate model accounting for thermal radiation.
- Heat transfer power from the environment to the building due to thermal radiation can be estimated by the expression [5]:

$$P_{rad} = P_{rad}(t) = \varepsilon \cdot \sigma \cdot A_f \cdot \left(T_{out}^4(t) - T_{in}^4(t)\right),$$

Heating of the house

- In this simple model our building is an off-grid system and has electric heating; that is, electric current through a resistor releases heat.
- The electric heating power released is proportional to the square of the current (I_c) and the resistance (R):

$$P_{heating} = P_{heating}(t) = R \cdot I_c^2(t).$$

- The total electrical energy consumption of resistance heating on *i*th day:

$$E_{heating,i} = \sum_{ith_{day_0}}^{ith_{day_0} + T_{day}} P_{heating}(t) \cdot \Delta t.$$

Cooling of the house

- The total electrical energy consumption of air conditioner on *i*th day:

$$E_{cooling,i} = \sum_{ith_{day_0}}^{ith_{day_0} + T_{day}} P_{aircond}(t) \cdot \Delta t,$$

Energy storage

- **Internal energy**
- Our building can store energy as internal energy.

Internal energy

- The internal energy of a macroscopic system at a given temperature is proportional to its heat capacity.

$$E_{internal,i} = C_{air} \cdot T_{in,i} + C_{wall} \cdot \frac{T_{in,i} + T_{out,i}}{2},$$

Accumulator system

- The energy $E_{acc}(t)$ available in the accumulators over time t can be neither negative nor can it surpass the storage capacity of the system:

$$0 \leq E_{acc}(t) \leq E_{acc\_max},$$

5. Energy balance

Heating season

- It is supposed for simplicity that in the ‘heating season’ the internal energy of the model house on *i*th day:

$$E_{internal,i} = E_{internal,i-1} + \eta_{heating} \cdot E_{heating,i} + E_{heattr,i} + E_{rad,i}.$$

Energy stored in accumulators

- In the ‘heating season’ the energy stored in accumulators at the end of *i*th day:

$$E_{acc,i} = E_{acc,i-1} + E_{photov,i} + E_{windt,i} - E_{heating,i} - E_{eapp,i}.$$

Non heating season

- In the 'non heating season' the internal energy of model house on *i*th day:

$$E_{internal,i} = E_{internal,i-1} - C_{cooling} \cdot E_{cooling,i} + E_{heattr,i} + E_{rad,i} \cdot$$

Energy stored in accumulators

- In the ‘non heating season’ the energy stored in accumulators at the end of *i*th day:

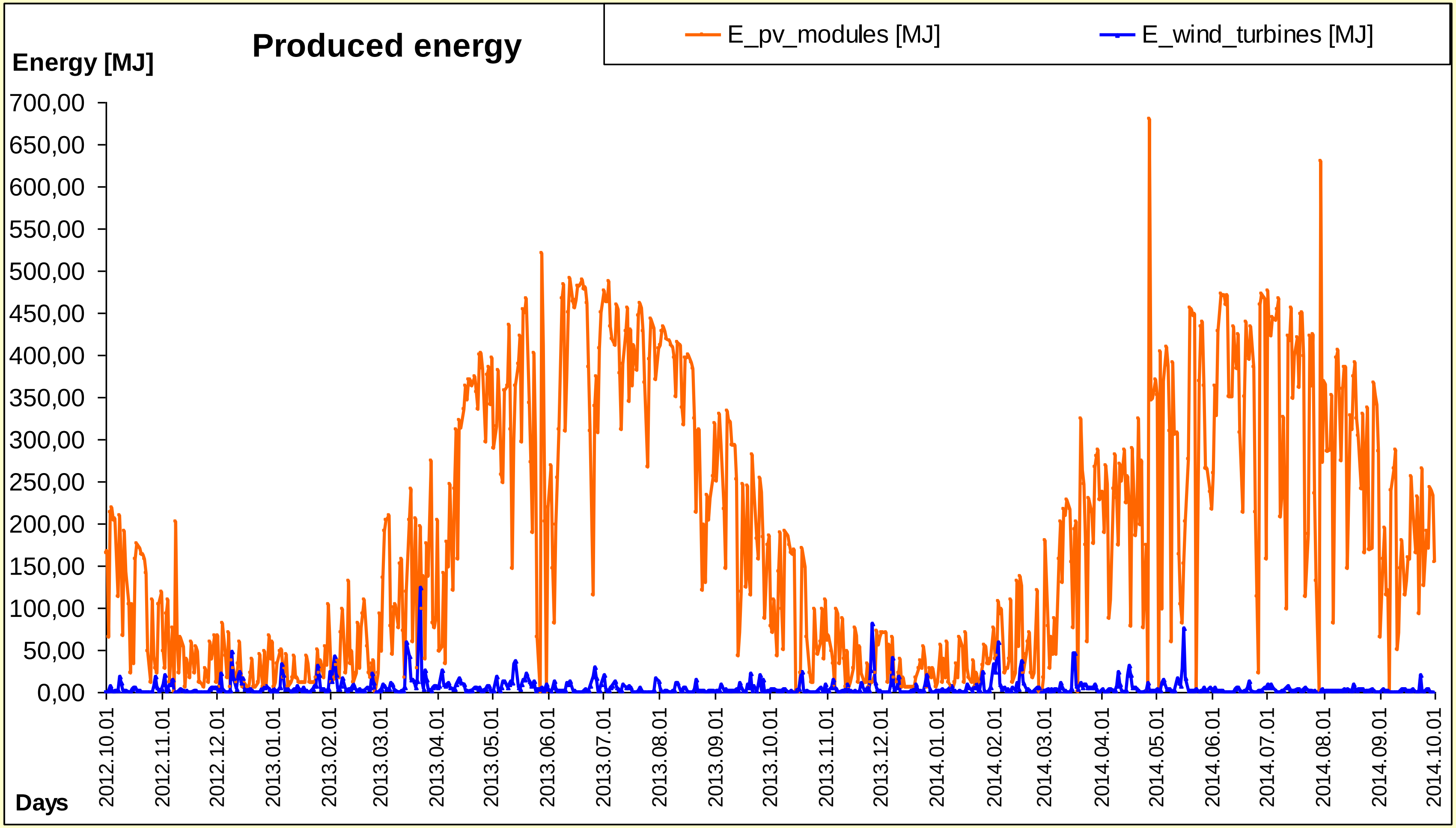
$$E_{acc,i} = E_{acc,i-1} + E_{photov,i} + E_{windt,i} - E_{cooling,i} - E_{eapp,i}.$$

6. Simulations

- In the simulations we ‘estimated’ the energy consumption of a typical house with 4 inhabitants.

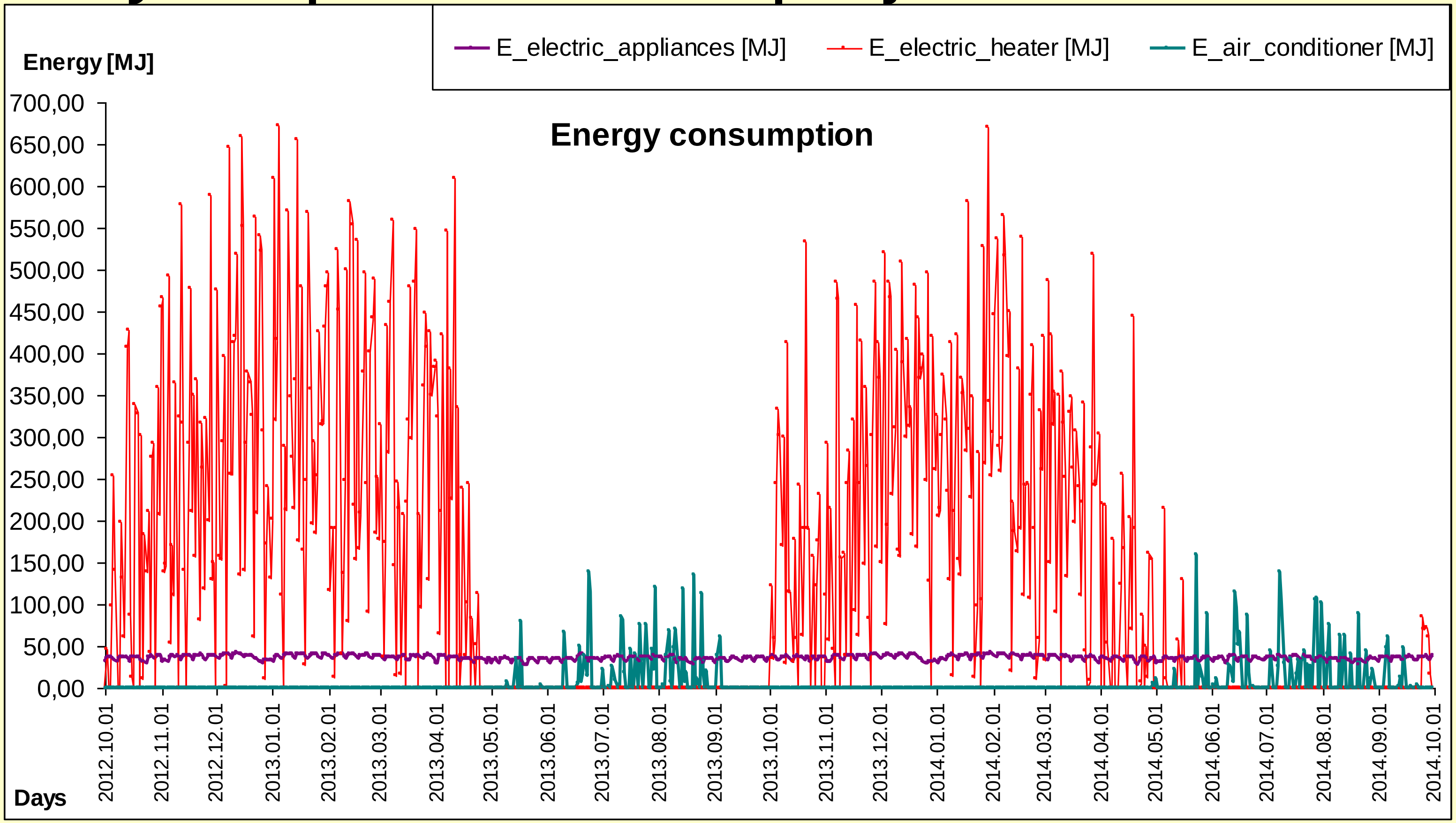
Produced energy

- In figure 7 the electrical energy produced by photovoltaic modules and wind turbines can be seen in the 2 years period of project.



Energy consumption

- In figure 8 the electrical energy consumption of the house (electrical home appliances, electric heater and air conditioner) is shown in the 2 year period of the project.

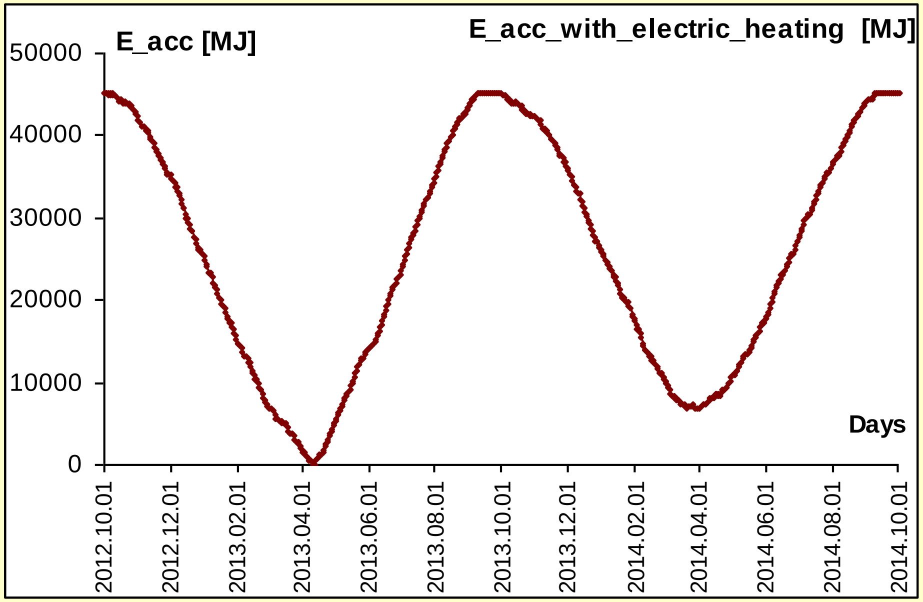


Capacity of the accumulator system

- **Computer simulation** is performed in order to determine the necessary capacity of the storage unit [6].

With electric heating

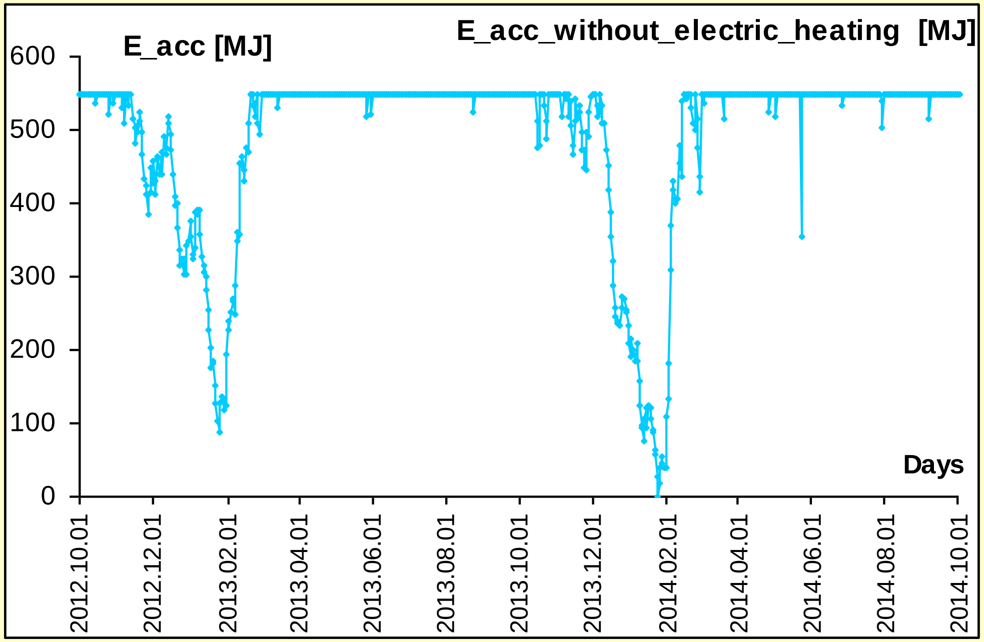
- In the simulation with the given data the necessary capacity of the energy storage unit that must be chosen is approx. **45097 MJ**, in order to prevent blackouts every day in the 2 year period of the project.
- In figure 9 the electrical energy of accumulator system is shown.



- The capacity of the accumulator-system derived from the simulation has a value too large for a real-world storage system.
- It can not be realised in the real world in a house.

Without electric heating

- If the electric heating is rejected and fossil fuel (e.g. wood) heating is applied, then the necessary capacity of storage unit is approx. **547.5 MJ**, according to our simulation. In figure 10 the electrical energy of accumulator system can be seen (without electric heating).



- That storage capacity might be realised, but it would be very expensive: e.g. an automotive battery is usually lead-acid type, and is made of galvanic cells in series to provide 12 V.
- The electrical energy stored in a common automotive accumulator is about 2.5 MJ, that is, 219 pieces of similar car battery could store 547.5 MJ electrical energy, theoretically.

7. Conclusion

- One of the goals of this project was to strengthen our students' internal motivation for learning about the topic of renewables.
- The modern topics of physics can help in raising the interest of the students and motivating them to learn the subject.

- A simple mathematical description of the energy flow of a house with off-grid power generating system was given.

Theory and practice

- We think that this student project helps to strengthen connection between theory and practice, improving practice within the field of physics education.

References

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Thank You