AALBORG UNIVERSITY
STUDENTS STUDYREPORT

# Optimizing a wind power supply for green building at the most effective cost

Energy Department, Aalborg University, Denmark

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Master Thesis • Spring 2012

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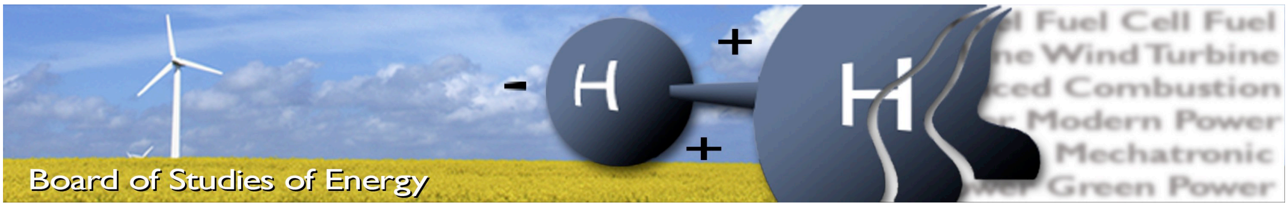
STUDENTS STUDYREPORT

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| **Title:** | **Optimizing a wind power supply for green building at the most effective cost** |
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| **Semester theme:** | |
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| **Supervisor:** | **Cartsen Bojensen and Christoph Milan** |
| **Project group:** | **1008** |


**Synopsis:**

For a net zero building it is essential to have well dimension energy facilities. In this optic we will examine a system with a heat pump, a photovoltaic module and a wind turbine. How will the different energy facilities work together?

For this purpose we will create a program which will enable for every situation to determine how much of each energy it is the most effective in a cost directed constraint to work together.

After writing this program, we will test it on a system determined with average values from Denmark and check if it works.



_______________________________
Lucile Koch-Schlund


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By signing this document, each member of the group confirms that all group members have participated in the project work, and thereby all members are collectively liable for the contents of the report. Furthermore, all group members confirm that the report does not include plagiarism.

# 1. Introduction

The main challenge of the twenty first century will be double: reducing the energy needed to live and finding enough renewable energy for the world remaining demand. Thus reducing the energy input for a house will be one of the solution.

As the world depends more and more on energy, with less and less fossil energy available, a huge challenge is to change of source of energy. The International Agency of Energy have estimated that all together, fossil energies are able to produce 8.2 billion of tep (tons equivalent of oil) in 2007[1]. As for the production of renewable energy, the same agency estimate that it is possible to provide enough renewable energy for the earth if the earth decrease part of his production (around one third).

Hence the difficulty of production all day long with energies which are influenced by the weather. Moreover as oil and gas were cheap energies, developed countries used fossil energies without second thought, thus increasing their dependance and consummation. It is necessary to go back to a more serene use of energy with less spoilage and renewable energies for our essential needs.

The net zero building concept is an option as the production of heat and electricity around the year is equal to the demand in heat and electricity. The conception of a net zero house is a known method[2] but how to optimize different sources of energy in a unique house? Some studies have already been made about a net zero building with just a wind power supply[3] but what about several sources of energy, a wind power supply, a photovoltaic installation and a heat pomp, the combination of the three supplying all the needs in electricity and heat over a year at the most effective cost?

This project will focus on a net zero house connected to the grid with a wind turbine, a photovoltaic installation and a heat pump for the heat production. The main interest of the project will be optimizing the size of the wind power supply to offset the consumption profile of the house also looking at the cost of the installation.

The consumption in electricity and heat of the house is not fixed. It evolves during the year and the day according to the needs in heating and in appliances. The wind supply also does not have a fixed income as it follows the weather so does the photovoltaic installation. How to scale a wind power supply according to the needs of the house at the lowest price? This thesis will answer to that question.

This leeds to questions about the wind supply. How should the wind supply be dimensioned? Should it be in hight or width? A horizontal or a vertical axis wind power supply? What should be the turbine? Should it be a wind turbine sold in a kit or chose each part? It could be also interesting to have some

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[1] International Agency of Energy

2 Zero Energy Building – A review of definitions and calculation methodologies, A.J. Marszala, , , P. Heiselberga, J.S. Bourrelleb, E. Musallc, K. Vossc, I. Sartorid, A. Napolitanoe, Accepted 14 December 2010

[3] Wind power systems for zero net energy housing in the United States, Melissa R. Elkinton, Jon G. McGowan*, James F. Manwell, Accepted 1 October 2008

focus about the place where to install the wind supply. Should their be a minimal distance from the neighbors? Should the noise be a restrain for the choice of the wind supply? And how to balance the cost of the wind supply? A bigger wind supply would mean more energy, but it would be expensive even though it is possible to resell the electricity? The aim should be the lest cost to reach the needs of the house.

This problem having several undetermined variables and many datas for the consumption and the weather, it is impossible to solve it by hand or using a simple excel sheet. I will be using GAMS, a program to solve mathematical problems. In this type of problem we want to maximize the energy and to minimize the price of the whole system. Having several conditions, matrices must be used to theorize the problem. A only solution is needed, as we only want one size for the wind power supply. Knowing all that, I will use a linear optimizing model to solve the problem.

# 2. Thesis statement

The core of this project will be creating a code fog GAMS which will permit for a net zero house given (and its energy consummation) to find the right combination of a photovoltaic installation, a heat pump and a wind turbine. This code will also use the weather profile to enter the parameters for the study.

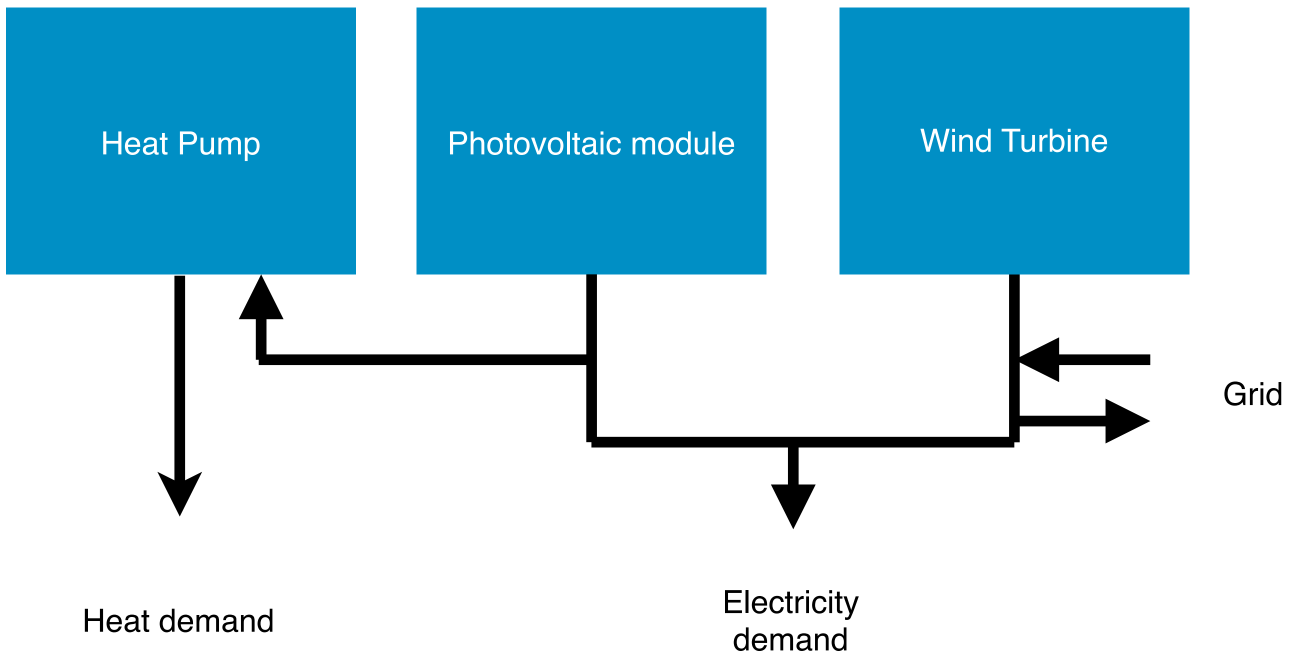
The main question that will be answered during this project is the following:
«How to optimized several energies, incorporating a wind turbine, in a net zero building?»

During this project, I will use some informations already research by Christian MILAN during his PhD project «An optimization methodology for the design of renewable energy systems for residential net zero energy buildings with on-site heat production».

# 3. Description of the system

## 1. Interaction of the system

There are three different technology in action in this project. The heat pump will provide heat to the building, but will demand some electricity. The photovoltaic installation will produce electricity for the




building and the grid during sunny weather. The wind turbine will provide electricity to the house and the grid during windy weather.

*3.1.1 Figure of the system*

## 2. Wind turbine

A wind turbine is a machine which use the kinetic energy of the wind to produce mechanical energy, often transformed in electrical energy. It is composed of 3 components:

- A structural support component which maintain the two other components
- A nacelle which contains the turbine transforming the mechanical energy into electrical energy
- A rotor compose of several blades (mainly 3) rotating around the nacelle taking the wind speed and transforming it into mechanical energy

The energy of the wind has been used for thousand of years, as windmills used to grind corn into flour as early as 600 A.D. [4]. The recent technology of using wind to create electricity has been constructed in the end of the XIXs century. The first wind turbine created to produce electricity and to be sold for this purpose was created by Poul La Cour, a dans. He developed the theory that a wind turbine with less blades will produce more power, thus could create a 25 kW wind turbine with an horizontal axis. G.J.M. Darrieus invited the vertical axis wind turbine.

[4] Mireille Mousnier, Moulins et meuniers dans les campagnes européennes, IXe-XVIIIe siècle, Presses Univ. du Mirail, 2002, p. 231

The total world wide install capacity was 200,457 MW in 2010, with China, USA, Germany, Spain and Italy the top 5 countries[5]. Denmark only comes 9th with 3,802 MW installed capacity of wind turbine, nevertheless, it arrives first when considering the number of wind turbine per inhabitant.

## Vertical axis

The vertical axis wind turbine is called so because the blades rotate around the axis which is vertical. The generator and the gearbox will be placed on the ground near the axis, which help for the maintenance. The main interest in this disposition is that the wind turbine does not need a gyroscope to be oriented in the way the wind flow, but will use the force of the wind whatever it comes from. This is way the vertical axis is often recommended for a urban use. Moreover it will produce less noise as a horizontal axis, due to less vibration and a reduce speed of the blades.

*3.2.1 Image of a Darrieus wind turbine*

There is different types of vertical axis:

- Darrieus wind turbine

Several blades are connected on the upper and lower side to the axis. «They have good efficiency, but produce large torque ripple and cyclical stress on the tower, which contributes to poor reliability. They also generally require some external power source, or an additional Savonius rotor to start turning, because the starting torque is very low. The torque ripple is reduced by using three or more blades which results in greater solidity of the rotor. Solidity is measured by blade area divided by the rotor area. Newer Darrieus type turbines are not held up by guy wires but have an external superstructure connected to the top bearing.» (Gurmit Singh)[6]

- Savonius wind turbine

The Savonius wind turbine is made of half cylinder slightly unbalanced. The wind can easily start them without high speed. There are also used as anemometer. This type of wind turbine is low efficiency but is highly reliable and produce low noise.

*3.2.2 Image of a Savonius wind turbine*

[5] IEAWind, *2010 Annual Report*, July 2011

[6] Gurmit Singh, *Exploit Nature-Renewable Energy Technologies,* Aditya Books, pp 378

## Horizontal axis

The horizontal axis are the mainly used wind turbines for big installations. As they produce a less disturbed impact on the wind, it is easier to define the behavior of several turbines altogether. Nevertheless, there is other problems with horizontal axis:

- The rotor must be pointed in the wind to produce. Small turbines are equipped with a gyroscope to move easily in the wind direction, larger turbines need to have an electrical system to move them in the wind direction. Altogether the main winds must be studied carefully as each hour without production will be very expensive.
- As the rotor is at the top of the axis, the maintenance is harder and could be very difficult in case of need of a very important change of material.
- The rotation of heavily structure have an impact on the audible and non audible noise. Studies recommend to place at a security distance these types of wind turbines from houses as not to disturb human beings.

*3.2.3 Image of a horizonal wind turbine*

## Choice of the type of wind turbine

During this project, the type of wind turbine will be a vertical axis. This type of wind turbine is less noisy and is easier to implant in a neighborhood. Specifically I will choose a Savonius type as the maintenance is easier to archive.

## Power equation

In all case of turbine, the possible power that can be attain is in function of the wind speed:

$$P = \frac{1}{2}\rho S V^3$$

With: P the power; ρ the air massic volume, S the surface touched by the blades; V the wind speed.

The energy which can be recovered is lower than the kinetic energy of the air located upstream of the wind mill, since the air must preserve a residual kinetic energy so that there is a remaining flow. Albert Bertz showed that the maximum power is equal to the 16/27 of the incidental power.

$$P = \frac{16}{27}\frac{1}{2}\rho S V^3 = 0{,}37 S V^3 = 0{,}37 \Pi \frac{D^2}{4} V^3 = 0{,}291 D^2 V^3$$

## 3. Heat pump

The basic principle of a heat pump is to transfer the calories from a source in order to heat a house and/or to provide warm water. The source of heat can be the surrounding air, the water of a lake, a river or the ground.

Certain heat pumps are reversible and can offer the possibility of refreshing the house during warm temperatures in the summer. It is thus a question of bringing "the cold" to the house, by extracting it from outside.

*3.3.1 Image of the installation of a heat pump in France*

In order to bring energy necessary to the extraction of the calories, the heat pump is connected to the grid. To make the compressor function, which is also used as circulator for the fluid, it is necessary to have a source of electricity. Nevertheless in the event of great cold or heat the electricity needed to cool or heat be very important.
The coefficient of performance, COP, is used to measure the contribution in electricity compared to the energy given to heat the house. This COP is without unit and a kind of "output" of the heat pump.

$$COP = \frac{Q_{sc}}{W}$$

With: $Q_{sc}$ = Power given to the house ; W = the compressor's work

## 4. Photovoltaic installation

A photovoltaic installation is a combination of several objects:

- Several photovoltaics panels, attached on a roof or on the ground, which produce electricity with light
- A converter to change continuous current into alternative current to provide to the grid or for use in the habitation

The photovoltaics panels are based on the photoelectric principal: in a silicium material a photon will transform in a electron thus producing a current. Most of the installation have efficiency of about 15%. The electricity produced can be used directly in the habitation or can be resold to the grid.

The main advantage of this technic is that the energy source is free, as it sun. That is also the main disadvantage as when the sun is not showing the production will be very rare or non existent (for example during the night).

The production for the photovoltaic panels is, at the standard test conditions (STC, 1000 W/m$^2$ , 25°C, ATM of 1,5):

$$P^{PV} = A^{PV} \eta^{PV} I_{STC}^{30°}$$

with $P^{PV}$= the production; $A^{PV}$= the array of photovoltaic, $I^{30}$= the irradiation at the STC

## 5. Net zero house

The principle of a net zero house is that with the production of energy (heat and electricity) the house will not need any energy from the grid or another source of energy. The overall calculation is made over the year, thus in winter the habitation will demand more energy from the grid and will give it back during the summer. In the middle seasons (spring and autumn) the building can be autonomous depending on the weather.

Most of the net zero house will a several energy source from renewable energy, since most of them are only intermittent. The mix will also contain some electricity production (wind, hydraulic, solar) and some heat production (biogaz, biomass, heat pump, solar thermic). A good net zero building will be sufficient in heat production during the winter without having to add an electrical power heating system, but will not also have to many production of electricity as electricity cannot be stocked.

In our case, the net zero building will be habitation for two persons with

- A Wind turbine, that is our main concern
- A photovoltaic installation on the roof
- A heat pump that will provide for all the heating in winter

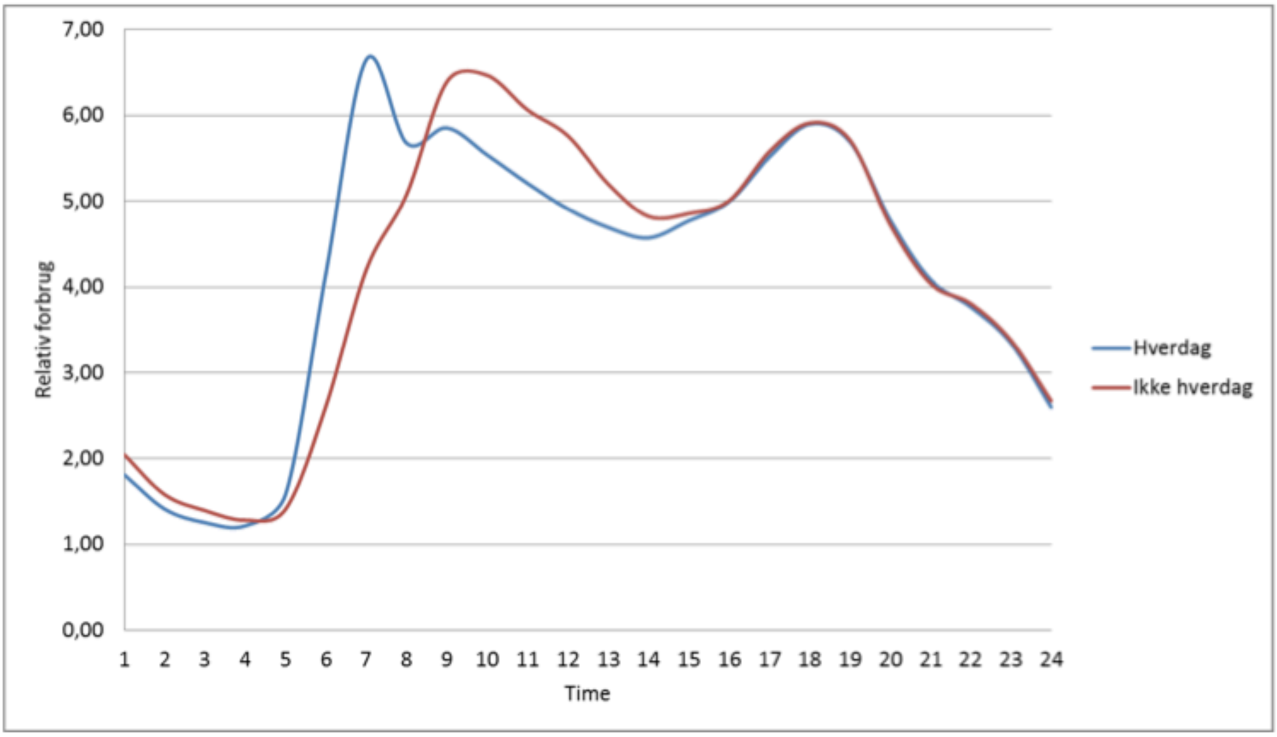
The power consumption profile is very interesting to discuss. Indeed it depends on the weather and on the consumption of heat and electricity. During this project we will assume, to ease the calculation, that the consumption will not change during an hour. This will restraint the number of point to determine:

- 24 hours a day
- 365 days in a year
- that means 8760 points to determine

## 6. The consumption profile

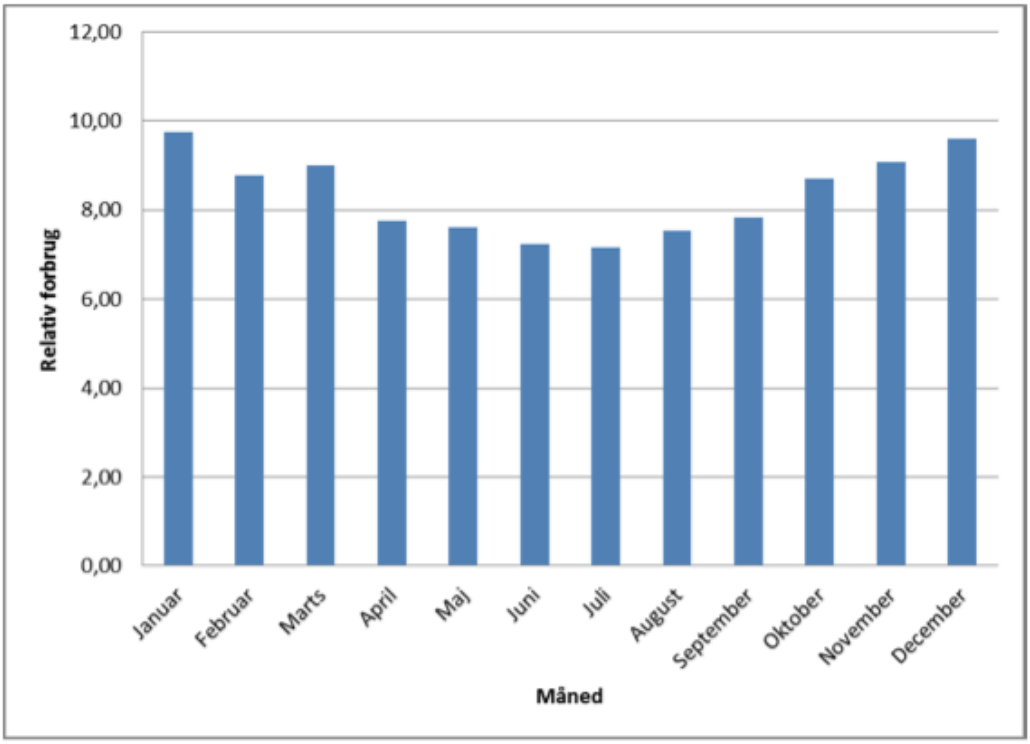
The consumption profile is here extract from another study «Personal and Consumer profiles - Net zero building» from Rasmus L. Jensen, Jesper Nørgaard, Ole Daniels and Rasmus O. Justesen, from Aalborg University (project in danish). The data from this project cannot be given in detail, therefor I will only present some plots to have an idea about the consumption profile used during the program.

Those data about the consumption are an average measure issued of studies about danish consumer. Therefor the hourly distribution of the consumption profile for heat and electricity is pretty representative of any 2 persons family in Denmark.




*3.5.1 Plot of the averge consumption of a couple during a day (extract from the project)*

As shown the plot of the energy consumption («Relativ forbrug») is different if it a week day or a weekend day. On the weekend day, the plot is soften and less early.

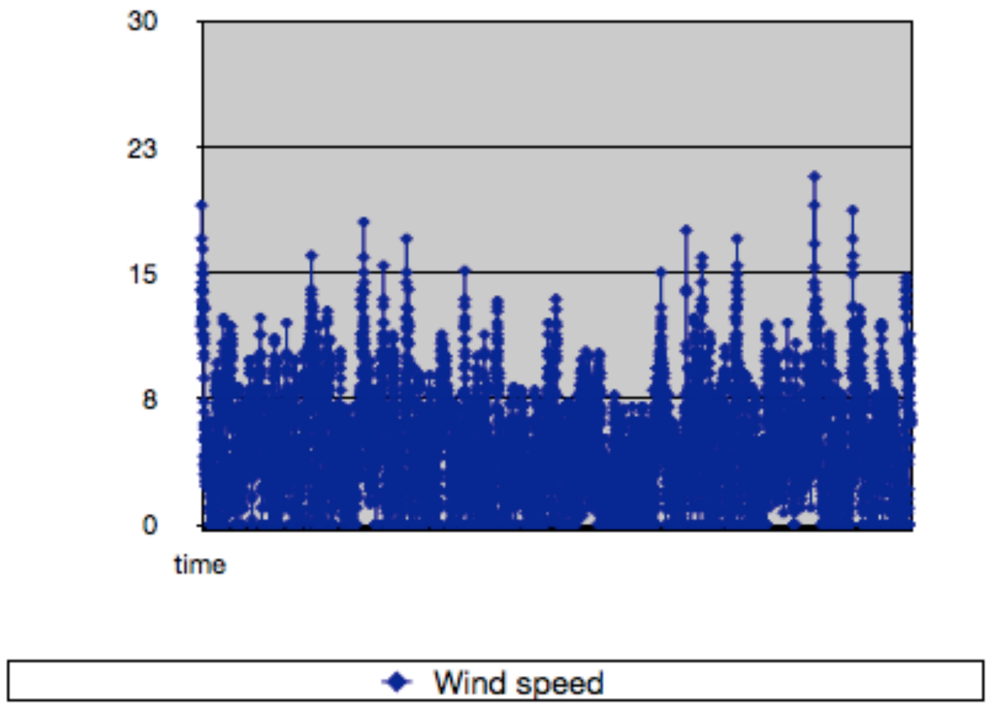



*3.6.2 Plot of the consumption during the year (extract from the project)*

As expected the consumption is higher in the winter month. The difference from a winter month to a summer month is not that huge (almost 10 to 7) because most of the energy used is to run electronic machines as dishwasher and lamps. So the difference between to opposed month are due to heat production and lights (we use more light in the winter than in the summer).

## 7. Weather profile

The weather profile is extract from danish reference year (DRY). To bring to life our model we need information each hour about the ground temperature, the wind speed and the sun irradiation. The y are therefore standardize. The sun irradiation as been measured at 30° inclined from a horizontal surface. The ground temperature has been obtained at 1 m of depth in Germany with measurement from 1894 to 2006. We will applied a coefficient as to obtain a temperature valid for Denmark (with a limit of obtaining a COP of 4).
As we are focusing on the wind turbine, here is a profile of the wind speed during the year.




*3.7.1 Plot of the variation of the wind speed during the year*

As you can see, the wind speed is pretty much around 8 m/s, which is superior from the recommendation by experts to have a rentability (the minimum is 5 m/s). There is 13 days during the year were the wind speed is above 15 m/s. As we are using a vertical axis wind turbine, there is no max speed where we should stop the wind turbine. As we choose a savonius type, there are not minimal limite for the wind speed and the wind turbine will begin producing under 5m/s, even though it will not be a huge amount.

During this chapter we have described the system as it will be modeled. We will now go further into the details for the model.

# 4. Equations of the system

For us to now how to model the system we need to set some constant and some variables. What will we now from the beginning and what will we need to study, that is the question.

## 1. Choice of the constant

The choice of the constant are easy to choose: they are the values that we have at our disposition. For example it is the values for the investments, for the maintenance or the datas of the weather (ground temperature and wind speed). It is also the efficiency of the different systems and the specificities of the building.

I will be studying the same case study as Christian Milan, here are the main assumption one the building and the system.

| Description | Value | Unit |
|---|---|---|
| Size of south facing roof space | 80 | $m^2$ |
| Number of occupants | 2 | |
| Supply temperature | 328 | K |
| Return temperature | 293 | K |
| Discount rate | 0.03 | % |
| Operational life span | 20 | years |

*4.1.1 Table about the characteristics on the building*

An other question is the insvestments and maintenance costs. For the 3 energies the costs depends on part of the capacity installed and on some fixed costs which represents the costs of installation. For example for the wind turbine, the cost of a wind turbine depends on its capacity but also on the preparation of ground which is necessary to install the wind turbine.

| Technology | Efficiency | Investment costs (€) | Maintenance costs (€/year) |
|---|---|---|---|
| PV | 0,12 | 3661* $cap^{PV}$+2027 | 1% of the total investment |
| Heat Pump | 3,3 | 696* $cap^{HP}$+12406 | 200 |
| Wind Turbine | 0,291 | 6750*$cap^{WT}$ +5000 | 1,5% of the total investment |

[7]

[7] www.les_energies_renouvelables.eu

## 2. Choice of the variables and mathematical representation of the energy system

The problem is a problem of reduction of cost. We want to minimize the investment thus it is important to know the best balance between the several energies. For those reason this is a linear programming problem. We are looking to minimize a fonction which depends on the capacity of the heat pump, the PV modules and the wind turbine, that can be formulated in this way:

$$\begin{aligned}
&\min f(x) = (cap^{HP}, cap^{WT}, cap^{PV}) \\
&s.t. \\
&h_i(x) = 0 \\
&g_j(x) \le 0
\end{aligned}$$

with

- x being the vector of the design variables.
- $cap^{HP}$, $cap^{WT}$, $cap^{PV}$, representing the installed capacity of the heat pump, the wind turbine and PV
- $h_i$ and $g_j$ stating the equality and inequality design constraints on the energy system

We will now look furthermore in the different equation that are necessary to resolve the problem.

**Energy supply**

The maximal amount of energy which can be provided to the supply system at a certain hour is directly influenced by the installed capacity of the wind turbine, which is directly influenced by the diameter of the pales, as presented in the chapter 3.

$$cap^{WT} = \frac{16}{27}\rho^{air}\pi R^2 \left(V^{wind}\right)^3$$

For a PV module the maximum of energy that could be provided is a function of the efficiency of the panel, the sun irradiation at his maximum (1000 W/m$^2$ ) and the surface of roof covered by PV panels.

$$cap^{PV} = \eta^{PV} A^{PV} 1000$$

The coefficient of performance (COP) of the heat pump is useful to deduct the capacity of the heat pump when you also take in account the capacity of the compressor.

$$cap^{HP} = cap^{compr} COP^{average}$$

For the COP a yearly average value is used. The compressor needs to work even when the demand is very high, so the capacity of the compressor should be superior than the demand, therefor we use this inequality to represent it.

$$cap^{compr} \ge \dot{e}_{d,h}^{HP,demand}$$

The yearly average COP is calculated based on monthly COPs.

$$COP^{Average} = \frac{\sum_m COP_m}{12}$$

Due to weather condition, the heat and the electricity will change each hour. We can than calculate each hour what is the production and then deduct the capacity. This is the same for the PV panels and the wind turbine as both are function of the weather.

$$\dot{e}_{d,h}^{WT} = \frac{16}{27}\rho^{air}\pi R^2 \left(V_{d,h}^{W}\right)^3$$
$$\dot{e}_{d,h}^{PV} = A^{PV}\eta^{PV}G_{d,h}^{30}$$

We should put a constraint on the surface of PV module so it does not exceed the roof space available in the south.

$$A^{roof} \geq A^{PV}$$

The COP monthly is used to determinate the production of the heat pump:

$$\dot{q}_{d,h}^{HP} = COP_m \cdot \dot{e}_{d,h}^{HP,demand}$$

And it can be calculated knowing the temperature necessary for the house and the temperature of the house.

$$COP_m = \eta^{HP} \cdot \frac{T^{\sup ply}}{T^{\sup ply} - \overline{T}_{d,h}^{ground,1m}}$$

The supply temperature $T^{supply}$ and heat pump efficiency $\eta^{HP}$ are kept as constant values.

**Electricity consumption**

The energy overall should be balance between the demand of electricity by the house and the heat pump and the production of heat and electricity and what could give the grid.

$$\dot{e}_{d,h}^{demand} + \dot{e}_{d,h}^{HP,demand} - \dot{e}_{d,h}^{WT} - \dot{e}_{d,h}^{PV} = \dot{e}_{d,h}^{grid}$$

The balance should work all the time. If there is to much electric production from the PV module and the wind turbine, it can be given back to the grid. In the contrary, if there is note enough electricity for the demand, it can be purchased. But this balance should be over looked during the year. This means that at the end of the year, there shouldn't be more electricity purchased than produced, thus this formula.

$$\sum_d \sum_h \dot{e}_{d,h}^{grid} + \frac{e_{\Pr od}^{WT} \cdot cap^{WT}}{n} + \frac{e_{\Pr od}^{HP} \cdot cap^{HP}}{n} + \frac{e_{\Pr od}^{PV} \cdot cap^{PV}}{n} \leq 0$$

**Heat consumption**

The heat consumption is modeled in a different way as the electric consumption as there is only one thing consuming the heat and it his the house, without any storage.

$$\dot{q}_{d,h}^{demand} - \dot{q}_{d,h}^{HP} = 0$$

**Economical performance**

The investment cost is the sum of all the individual investment cost for each energy. The investment in a energy is depended of the installed capacity.

$$inv = (inv^{WT} \cdot cap^{WT}) + (inv^{HP} \cdot cap^{HP}) + (inv^{PV} \cdot cap^{PV})$$

Each year it is necessary to have some maintenance operations on the system, those cost also count in the overall total. A simplification can be made by assuming that it will be the same cost every year. Those cost also depends of the installed capacity.

$$OM = (om^{WT} \cdot cap^{WT}) + (om^{HP} \cdot cap^{HP}) + (om^{PV} \cdot cap^{PV})$$

The net present value (NPV), the total cost of the project, is obtain by counting the maintenance costs for each year, a year being i, for the lasting of the project, n.

$$Uspwf = \frac{1}{i} \cdot \left(1 - (1+i)^{-n}\right)$$

$$f(x) = NPV = inv + (OM \cdot Uspwf)$$

# 5. Resolution of the problem on GAMS

## 1. Explanation of the code

GAMS is a program based on a very simple language of programming, so it is easy to understand both by humans and the machine. Therefore except a few specific commands, the code is only declaration of variable and of the equations. It is a program used to resolve scientific problems with several types of models from linear model to non-linear model.

The structure of the code should follow a very specific structure for the program to understand the code:

- First you must declare the sets, which are the variable, like the x from f(x). It is possible to give them directly a value (using to / /) but it can also be given later
- Secondly, you declare the data. That means that every value that will need for the rest of the program should be declare. In my case, I did not have any table as my values were in a excell files and were to important to enter in this part.
- Variables are known then: they are what you are looking for.
- Initial values: the values that will enable the program to begin with
- First you declare the equation, then you can describe them
- After declaring your variables and your equation, it is time to call the model you want to use, so the program knows which model to use to solve the equations and the function to obtain
- When you ask to solve, you should list your equations in the order the program should solve them
- The final state is to precise the display statement and to be sure to have everything you want to know. It is also possible to specify how you want the display (in a other type of file or a plot...)

My code respect those several steps. Some of my equations are very close to Christian Milan's. This is due to the nature of this project which very close to his.

Determining the heat production and then the capacity of the heat pump is not the most difficult part of the code, it is determining the ratio of PV and wind turbine. Indeed as both participate to the production of electricity, and not at the same time, it is the hardest part of the code.

Why choosing a linear model? As explained in the chapter 4, we are trying to minimize the cost function

$$\min f(x) = (cap^{HP}, cap^{WT}, cap^{PV})$$

This function can be decline in a matrix where each row is an hour of the year and to resolve that we need a linear optimization model.

## 2. First test

The problem was solved within 0,472 seconds on a 1,86 GHz processor. We found the hereby results

| PV | HP | WT |
|---|---|---|
| $Cap^{PV}$ (kW) | $Cap^{HP}$ (kW) | $Cap^{WT}$ (kW) |
| 5,56 (46,3 $m^2$) | 4,97 | 3,71 |

## 3. Results

The repartition of the PV and the wind turbine for the electricity is around 60%/40% as the investment cost for the wind turbine are more expensive.

The total cost of investment is 68,312.69 € and the maintenance cost is 724,22 € per year.

| Cost over 20 years | Total investment costs | maintenance cost per year |
|---|---|---|
| 82 797,09 | 68 312,69 | 724,22 |

The production of electricity is of course more important in summer and during the middle seasons, to catch up the winter period.

Using the results above we can deduct that the program is working as the total consumption of heat and electricity is feed.

# 6. Conclusion

The core idea of this project was to balance different type of production of energy in the same habitation and to look how they would work one with another with another constrain: a cost minimizing effort.

In order to do that, we had to create a program to do so and to compare a heat pump, a photovoltaic facility and a wind turbine. Having two different type of energy (heat and electricity) was also a challenge as we need to fulfill both needs by different ways and that one energy will interact with the other (the heat pump needing electricity, delivered by the PV and the wind turbine).

When trying a example to test the program, we obtain good results. If we compare this situation and the example from Christian Milan's project (with a heat pump, PV modules, solar thermic installation and a heat storage), with the same building and consumption requirement, he obtains a cheaper investments. That is due to the high price of installing a wind turbine. Maybe that in a country where selling the electricity that is produced, having a wind turbine could be more effective on a price range, as you can gain money.

During this project, we did not consider the price of selling electricity to a local electricity provider because it is in the core of the project that their should be a perfect balance between what is given and what is taken from the grid. Nevertheless in countries, like France, it could be a better choice to sell all the production to the electricity provider as the price of selling is much more interesting than buying electricity (around 12 c€/kWh when you buy it, around 45 c€/kWh for the PV up to 3 kWc and 8 c€/kWh for the wind turbine).

# 7. References and bibliography

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Gipe Paul

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Khaligh Alireza

**Wind Energy Engineering,**
Jain Pramod

**Valuing wind generation on integrated power systems,**
Dragoon Ken

**Introduction to optimum design,**
Arora Jasbir S.

***Moulins et meuniers dans les campagnes européennes, IXe-XVIIIe siècle,***
Mireille Mousnier, Presses Univ. du Mirail, 2002, p. 231

# 8. Appendix

**Code of the gams program**

```
*Project by Lucile Koch-Schlund, in may 2012

$offlisting
$offsymxref
$offsymlist
$offuelxref
$offuellist


Set
t                       "time of the day"                                   /
1*24/
d                       "day of the year"                                   /
1*365/
x                       "index for the binary variables"                    /
1,2,3,4/
;

Parameters

*Parameters needed to dimension the size of the energy

COP(d,t)                "coefficient of performance, changes "
COPAV                   "coefficient of performance over the year"
GroundTemp(d,t)         "ground temperature, Celsius"
DemandTemp              "heat of the temperature required by the housee,
Celsius"
HeatDemandHourly(d,t)   "heat consumption of the building per hour, kWh/h"
ElecDemandHourly(d,t)   "electricity consumption of the building per hour, kWh/h"
EffInv                  "inverter efficiency for electricity fed into the grid, %"
Windspeed(d,t)          "speed of the wind, m/s"
Roofspace               "Maximal space that could be occupied by the PV with a
south orientation, m2"
Irradiation(d,t)        "Irradiation of the sun for the PV, W/m2"
EffPV                   "PV Efficiency"
;

*Economical parameters
HPinv                   "Heat Pump investment costs per kW, euro/kW"
WTinv                   "Wind turbine investment costs per kW, euro/kW"
PVinv                   "PV investment costs per kW, euro/kW"
HPcosttime              "Cost for the maintenance per year and per kW for Heat
Pump, Euro/kW*year"
WTcosttime              "Cost for the maintenance per year and per kW for the
wind turbine, euro/kW*year"
PVcosttime              "Cost for the maintenance per year and per kW for the
PV, euro/kW*year"
i                       "discount rate"
n                       "operational life span"
```

```
;

$CALL 'GDXXRW ZEB-MIP_neu.XLS skipempty=0 trace=2 index=Para!B3:G27'
$gdxin ZEB-MIP_neu.gdx
$load COP COPAV GroundTemp DemandTemp HeatDEmandHourly ElecDemandHourly EffInv
Windspeed PVspace» Irradiation EffPV
$load HPinv WTinv PVinv HPcosttime Wtcosttime PVcosttime

binary variables
y(t,h,x)                    "It is to verify if energy is given to the grid (1) or taken from it (0)"
;

Positive variables
*Variables that need to be calculated for the resolution of the program
InstCpr                     "Heat pump's compressor capacity that could be
installed, kW"
InstHP                      "Heat pump's capacity that could be installed, kW"
InstPV                      "PV capacity that could be installed, kW"
InstWT                      "Wind Turbine capacity that could be installed, kW"
;


*dependent variables
heatHPhourly(d,t)           "heat produced by heat pump, kWh/h"
elecHPhourly(d,t)           "electricity consumption by heart pump, kWh/h"
elecWThourly(d,t)           "electricity production by the wind turbine, kWh/h"
elecPVhourly(d,t)           "electricity production by the PV, kWh/h"
heatHP(d,t)                 "yearly heat production by heat pump, kWh/year"
elecHP(d,t)                 "yearly electricity consumption by heat pump, kWh/year"
elecWT(d,t)                 "yearly electricity production by wind turbine, kWh/year"
elecPV(d,t)                 "yearly electricity production by the PV, kWh/year"
WTdiameter                  "Diameter of the wind turbine"
PVspace                     "Space occupied by the PV, m2"
ElecGridNetout(d,t)         "net electricity taken from the grid, kWh/h"
inv                         "total investment costs of the energy system, euro"
OM                          "yearly O&M costs of the energy system, euro/year"


*Uspwf                      "uniform series present worth factor"
NPV                         "net present value, euro"

Variables
ElecGridGross(d,t)          "gross electricity exchange rate with the grid, kWh/h"
ElecGridNetin(d,t)          "net electricity rate taken from the grid, kWh,h"
obj                         "objective"
;


Equations
*Declaration

*Objective function
ObjMinCost                  "The objective of the program: cost minimization"
```

```
*Energy Supply
EqHPProduction(d,t)                    "Calculation of heat pump
production"
EqWTProduction(d,t)                    "Calculation of wind turbine production"
EqPVProduction(d,t)                    "Calculation of PV production"
Conroof                                        "Constraint on available roof space"


*Electricity consumption
EqElecGridGross(d,t)                   "calculation of consumed electricity from the grid at time
t"
EqElecGridNetPositive(t,h,x)           "calculation of electricity consumed from the grid"
ConElecGridNetPositive(t,h,x)          "condition to assure positive values"
EqElecGridNetNegatives(t,h,x)                  "calculation of electricity feeded into the grid"
ConElecGridNetNegative(t,h,x)                  "condition to assure negative values"
ConElecGridBinary(t,h,x)               "condition to assure max. one binary to be chosen"
ConElecGridl                           "constraint on Grid Exchanged Electricity"

*heat consumption
EqHeatdemand(d,t)                      "calculation of consumed heat "

*coupling installed capacity and array area
EqCapCompr(d,t)                                "calculation of the heat pump's compressor
capacity"
EqCapHP(d,t)                           "calculation of the installed capacity under standard
conditions"
EqCapWT(d,t)                           "calculation of the wind turbine's installed capacity"
EqCapPV(d,t)                           "Calculation of the PV's installed capacity"

system Costs
EqInv                                  "calculation of the total investment costs of the energy
supply system"
EqOM                                   "calculation of the yearly O&M costs of the energy
supply system"
EqUspwf                                        "calculation of the uniform series present worth
factor"
EqNPV                                  "calculation of the net present value"



*Definition of equations

*objective function
objMinCost                             obj=E=NPV ;

*Energy Supply
EqHPProduction(d,t)
          heatHPhourly(d,t)=E=COP(d,t)*elecHPhourly(d,t) ;
EqWTProduction(d,t)
          elecWThourly(d,t)=E=0,291*(Windspeed(d,t)^3)*3600*WTdiameter ;
EqPVProduction(d,t)                    elecPVhourly(d,t)=E=(PVspace*EffPV*Irradiation(d,t)/
1000 ;
Conroof                                Roofspace=G=PVspace ;
```

```
*Electricity consumption
EqElecGridGross(d,t)                ElecDemandhourly(d,t)+elecHPhourly(d,t)-elecWThourly(d,t)-
elecPVhourly(d,t)=E=ElecGridGross(d,t) ;
EqElecGridNetnegative(d,t,x)        y(d,t,'1')*ElecGridGross(d,t)**EffInverter=E=ElecGridNetin(d,t) ;
ConElecGridNetNegative(d,t,x)       y(d,t,'1')*ElecGridGross(d,t)=L=0 ;
EqElecGridNetpositive(d,t,x)              y(d,t,'2')*ElecgridGross(d,t)=E=ElecGridNetout(d,t) ;
ConElecGridNetPositive(d,t,x)             y(d,t,'2')*ElecGridGross(d,t)=G=0 ;
ConElecGridBinary(d,t,x)                  y(d,t,'1')+y(d,t,'2')=E=1 ;
ConElecGridI                              sum((d,t),ElecGridNetin(d,t))
+sum((d,t),ElecGridNetout(d,t))=E=0 ;

*Heat consumption
EqHeatdemand(d,t)                         HeatDemandhourly(d,t)=E=heatHPhourly(d,t) ;


*Coupling installed capacity and array area
EqCapCompr(d,t)                           instCpr=G=elecHPhourly(d,t) ;
EqCapHP(d,t)                              instHP=G=capCpr*COPAV
EqCapWT(d,t)                              instWT=E=elecWThourly(d,t) ;
EqCapPV(d,t)                              instPV=E=PVspace*EffPV ;

*System costs
EqInv                                     inv=E=((27459*instPV+15203)/7.5)+(5219.5*instHP
+93046)/7.5+(50625*instWT+37500)/7.5) ;
EqOM                                      OM=E=(PVcosttime*(27459*instPV+15203)/7.5) +
(HPcosttime) + (WTcosttime* (50625*instWT+37500)/7.5))

*EqUspwf
EqNPV                                     NPV=E=inv+(OM*(1/i)*(1-((1+i)*exp(-n)))) ;

*variable.1=value

Option limrow=0, limcol=0, solprint=off, optcr=0.01, optca=1;;

Model MinCostLP "simplifed linear version"                              /ObjMinCost,
                                                                        EqHPProduction,
                                                                        ConRoofspace,
                                                                        EqElecGridGross,
                                                                        EqCapPV,
                                                                        EqCapCompr,
                                                                        EqCapHP,
                                                                        EqCapWT,
                                                                        EqInv,
                                                                        EqOM,
                                                                        EqNPV,
                                                                        ConElecGridI/

MinCostMINLP                                                                  /
ObjMinCost,
                                                                  EqHPProduction,

                                                                  EqElecPVProduction,
                                                                  ConRoofSpace,
```

```
EqElecGridGross,
EqElecGridNetpositive,
ConElecGridNetPositive,
EqElecGridNetnegative,
ConElecGridNetNegative,
ConElecGridBinary,
ConElecGridNetTotal,
EqCapPV,
EqCapCompr,
EqCapHP,
EqCapWT,
EqInv,
EqOM,
EqNPV/;

solve MinCostLp using LP minimizing obj;

display PVinst.1, HPinst.1, WTinst.1, elecHPhourly.1, elecWThourly.1, PVspace.1,
```