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DIPLOMARBEIT

# Italiens Energieversorgung mit Schwerpunkt Wasserkraft und die Integration eines hohen Anteils erneuerbarer Energien

Ausgeführt am Atominstitut
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ZUSAMMENFASSUNG

Im 21. Jahrhundert müssen Stromproduktion und Energiebereitstellung im Allgemeinen neue Aspekte berücksichtigen. Zu den bekannten Problemen zählen der CO2-Ausstoß, endliche fossile Brennstoffreserven, insbesondere Öl, und die Endlagerung radioaktiver Stoffe. Mit erneuerbaren Technologien versucht man diese Probleme zu umgehen.

Nach der Wasserkraft sind Wind- und Sonnenenergie die wichtigsten Alternativen. Ihre große Schwachstelle ist die Wetter- bzw. Tageszeitabhängigkeit. Der Schwerpunkt dieser Diplomarbeit liegt auf den Wasserkraftwerken, weil sie mit Speichern und Pumpspeichern die Volatilität der erneuerbaren Technologien kompensieren können.

Nach einer Einführung in die italienische Energieerzeugung werden in einem ausführlichen Überblick aktuelle Kraftwerkstechnologien und deren Eigenschaften vorgestellt. Ein eigenes Kapitel über Speichertechnologien zeigt Vor- und Nachteile betreffend Kosten, Einsatzbereiche und Lebensdauer auf.

Der Hauptteil besteht aus der Beschreibung des linearen Optimierungsmodells und der aufwendigen Datensuche mit darauffolgender Besprechung der Simulationen sowie der Anpassungsmöglichkeiten der Wasserkraft. Hier wird mit einem Modell wird die korrekte Arbeitsweise der Simulationen getestet, ein zweites Modell erforscht einen möglichen Ausbau der vorhandenen Pump- und Turbinierleistung.

ABSTRACT

In the 21$^{st}$ century electricity production and power generation in general have to consider new aspects. Common problems are CO2 emission, finite fossil fuels, especially oil, and final storage of radioactive waste. Renewable energies can help to avoid these problems.

After hydropower, wind and solar power are the most common renewable energy sources. A crucial weak spot is their weather and daytime dependence. In this diploma thesis emphasis is placed on hydro power, since storage and pumped storage facilities can compensate other intermittent power sources.

An introduction into the Italian energy production will be followed by an extensive overview of existing power generation methods and their properties. A separate chapter will be dealing with advantages, disadvantages, costs, range of application and lifecycles of energy storage technologies.

The main section describes the linear optimization model and the intricate data mining, subsequently simulations and modification potentials of hydro power will be discussed. In particular, one model tests the simulations mode of operation, a second model investigates the potential for a capacity extension of existing pumping and turbining.

Table of contents

# 1. Italy’s power grid

GRTN (“Gestore della Rete di Trasmissione Nazionale“) was founded 1999 as part of Enel („**E**nte **n**azionale per l'**e**nergia e**l**ettrica“). Continuing as **Terna** (Trasmissione Elettricità Rete Nazionale S.p.A, since 2005) it controls more than 90 percent of Italy’s powergrid. The net consists of 45 649 km 120-150kV lines, 10 327 km 220 kV lines and 10 254 km 380 kV lines. [34]

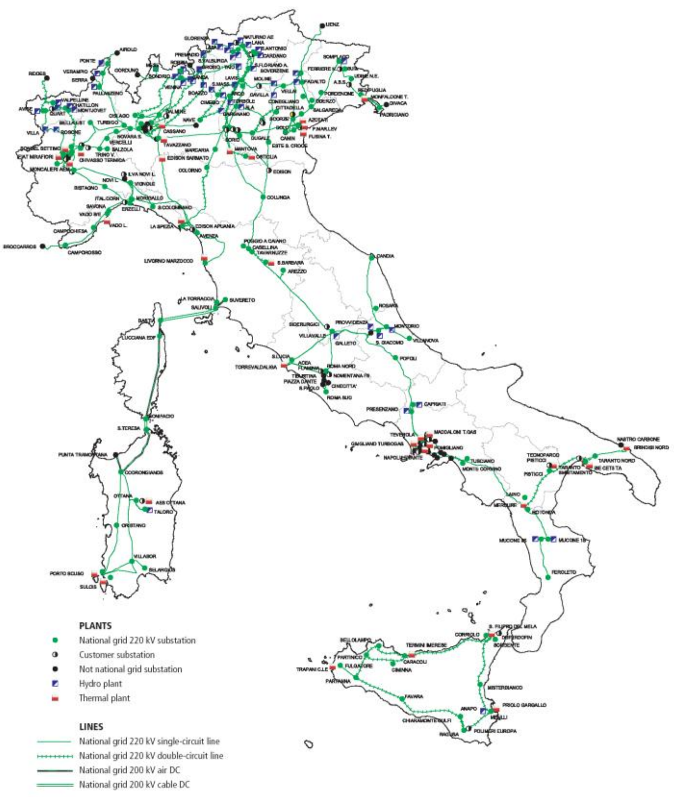



**Figure 1.1.: Italy’s 220 kV Grid [33]**


**Figure 1.2.: Italy’s 380 kV Grid [33]**

## 1.1. Bottlenecks

Bottlenecks are lines of the network that cannot carry the load at peak times. Overload can cause the breakdown of the local network or even initiate a cascade effect, as described in chapter 1.3. In figure 1.3 weak spots, in respect of security, quality and continuity of electricity supply, are specified:

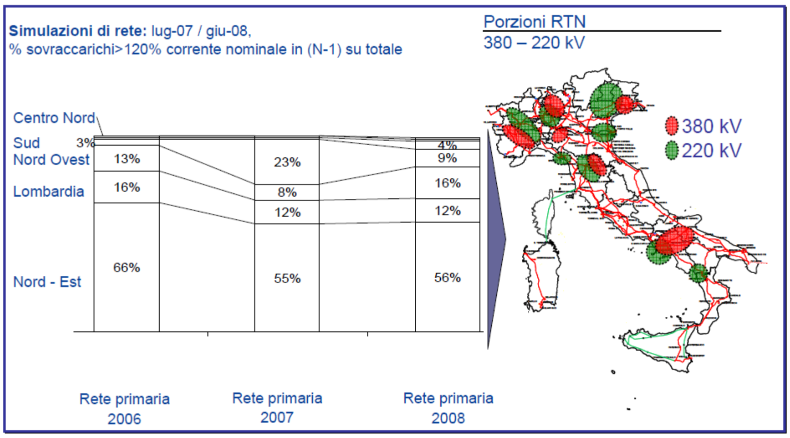



**Figure 1.3: weak spots [22]**

Increase in power flow can cause bottlenecks, for example due to new power plants or new industries. Natural geographic conditions can be a problem as well. One of this kind was improved in 2002 by completing the construction of a 163-kilometer, 400-kilovolt underwater cable to link Italy and Greece. [33]

## 1.2. Pricing

The price development in Italy compared to Germany and France is illustrated in figure 1.3.

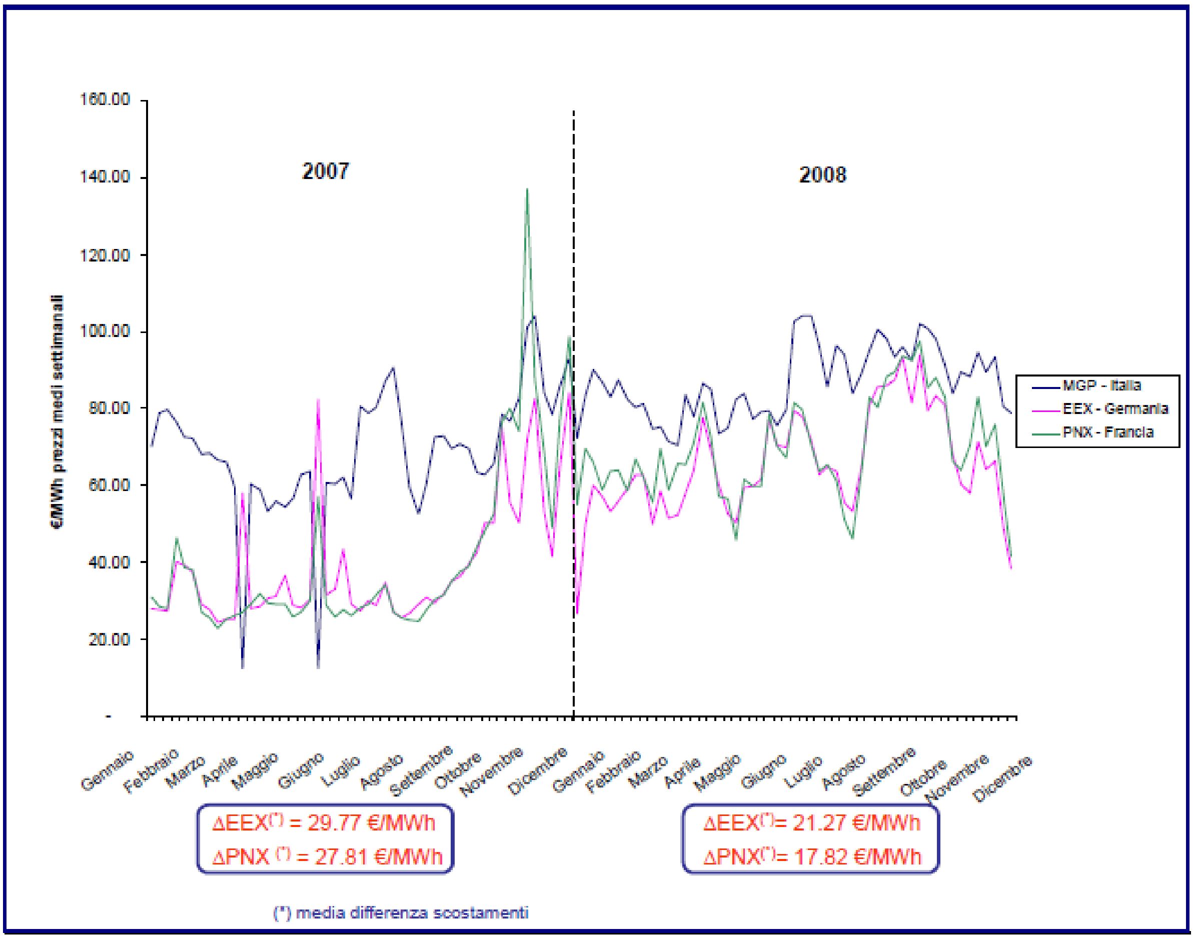



**Figure 1.3: Price development [22]**

Obviously electricity prices in Italy are quite high, while variations correspond to prices in Germany and France. Causes for high electricity prices are:

- Outdated power plant fleet
- Weak power grid
- No lignite fired power plants, no nuclear power plants
- Oligopoly, regional monopoly
- Almost all pumped storage plants belong to ENEL
- Probably too frequent servicing to hold back capacities
- Possibly price fixing

[44]

Prices vary strongly from north to south, originating from saturation transit limits of market areas:

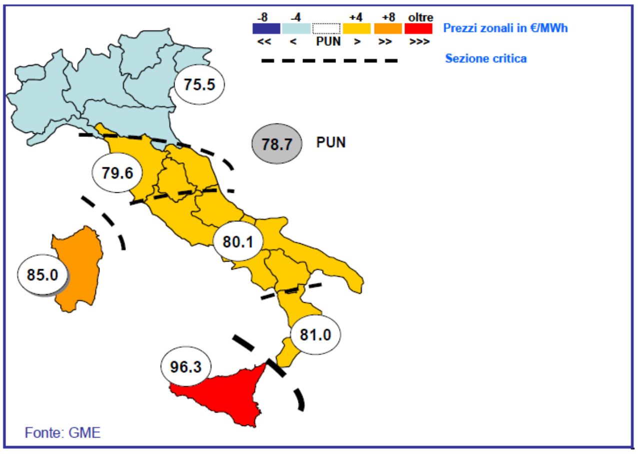



**Figure 1.4: Price variation, Euro/MWh**

This fact and the sunny weather conditions make Sicily a perfect location for solar installations. Photovoltaic modules in this region reach nearly grid parity.

## 1.3. Electroblackout 2003

On the 28th of September 2003, a series of events caused an electric blackout. A supply line from Switzerland was damaged by storms, the cascading effect disrupted also two supply lines from France. More and more lines tripped and Enel lost control of the whole power grid. 56 million people were affected, all of Italy except Sardinia and Elba. Parts of Italy were offline for 12 hours, a part of Switzerland for 3 hours. [36]

## 1.4. Energy production, demand and losses

Figure 1.5 shows the electricity generation in Italy for the years 2010 and 2011. Italy is a net importer of electricity: consuming 334 TWh per year, only 289 TWh are produced.

Domestic electricity generation and demand

Millions of kWh

| | 2011 | 2010 | Change | |
|---|---|---|---|---|
| **Net electricity generation:** | | | | |
| - thermal | 217,369 | 220,984 | (3,615) | -1.6% |
| - hydroelectric | 47,672 | 53,795 | (6,123) | -11.4% |
| - wind | 9,560 | 9,048 | 512 | 5.7% |
| - geothermal | 5,307 | 5,047 | 260 | 5.2% |
| - photovoltaic | 9,258 | 1,874 | 7,384 | - |
| **Total net electricity generation** | **289,166** | **290,748** | **(1,582)** | -0.5% |
| Net electricity imports | 45,626 | 44,160 | 1,466 | 3.3% |
| **Electricity delivered to the network** | **334,792** | **334,908** | **(116)** | - |
| Consumption for pumping | (2,518) | (4,453) | 1,935 | 43.5% |
| **Electricity demand** | **332,274** | **330,455** | **1,819** | 0.6% |

Source: Terna – Rete Elettrica Nazionale (monthly report on electric system – December 2011).

**Figure 1.5: Electricity generation and demand, [29]**

Italy's electricity production covers about 87 % of its demand, the rest is imported. For the year 2007 this means 28.8 TWh from Switzerland, 2.8 TWh from France, 3.2 TWh from Slovenia, 0.2 TWh from Greece and 1.4 TWh from Austria. Italy's exports are about 2.5 TWh. [23]

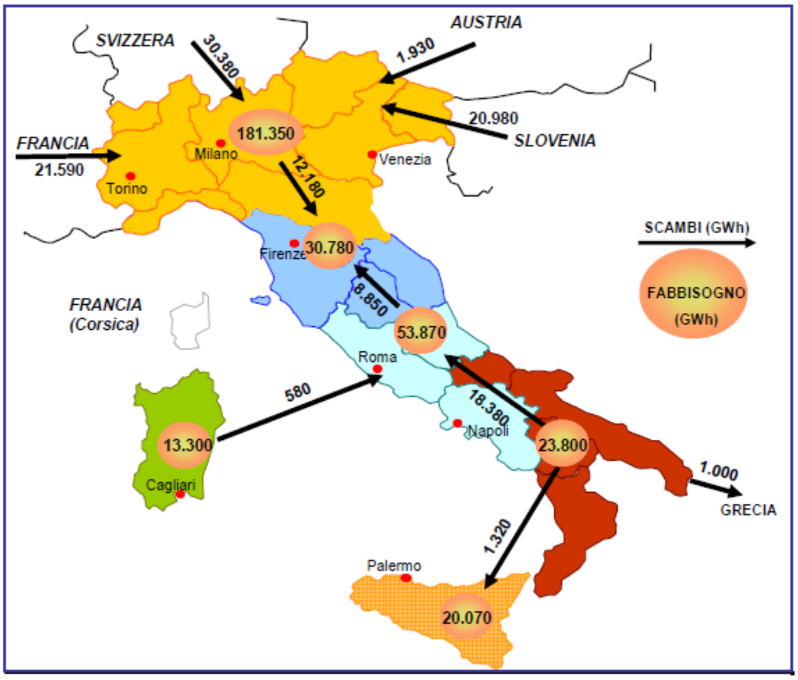



**Figure 1.9: Estimated electricity flows**

In some regions of northern Italy, the power production is adequate for local demand.
For example, in the region of Trentino Alto Adige (i.e. the provinces of Bolzano and Trento) in 2007 the electricity demand was 6.7 TWh, 41% industrial, 37% tertiary, 19% domestic and the rest for agricultural use. In 2007 production in this region was 7.6 TWh.

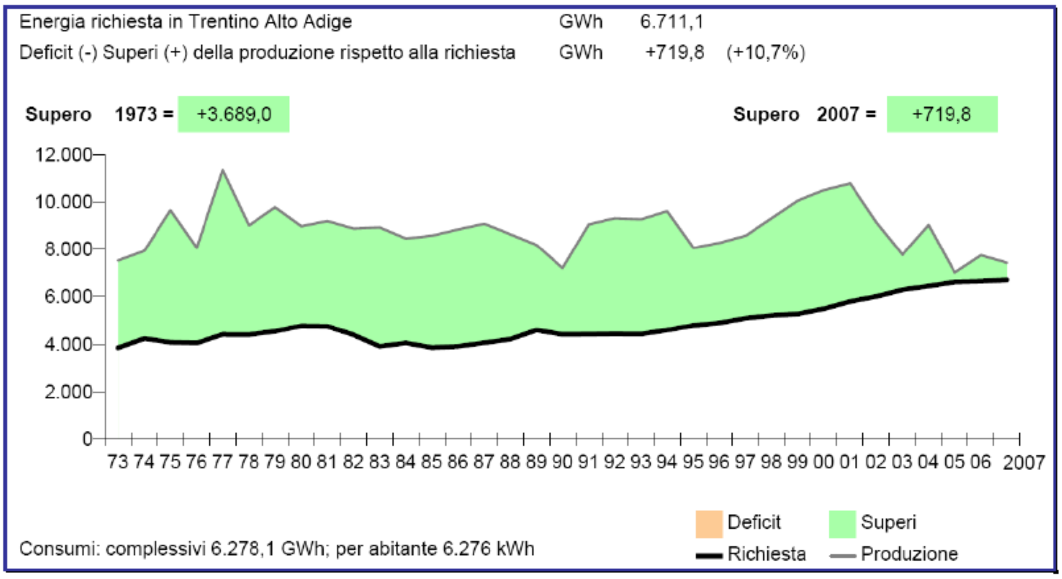



**Figure 1.8: Energy demand and production 1**

# 2. Power plants

In 1987 Italy decided to shut down all three of their nuclear power plants, due to a referendum after the Tschernobyl accident in 1986. During his prime ministry Berlusconi promoted the construction of new nuclear power plants, to compete in the foreign electricity market. 13 plants, satisfying 25% of Italy's electricity demand were scheduled up to the year 2030. In June 2011 a national referendum voted against the reintroduction of nuclear power plants.

<u>Energy providers and their contribution to electricity production in 2011:</u>

<u>A2A:</u>
Thermoelectric production 8.2 TWh, hydroelectric production 3.5 TWh [27]
<u>Edison:</u>
Thermoelectric production 27.1 TWh, hydroelectric production 5.3 TWh [28]
<u>Enel:</u>
Thermoelectric production 50.7 TWh, hydroelectric production 16.5 TWh [29]
<u>Alpiq</u>
Thermoelectric production 15.6 TWh, hydroelectric production 2.6 TWh [30]
<u>Hera</u>
Thermoelectric production 1.13 TWh, thermal energy 0.7 TWh [31]
<u>Saras</u>
Thermoelectric production 4 TWh, windpower 0.175 TWh [32]

Approachable efficiencies for the power plants are listed in table 2.1.:

| | |
|---|---|
| Hydro power | 90 % |
| Gas | 60 % |
| Wind | 50 % |
| Coal | 40 % |
| Nuclear power | 35 % |

**Table 2.1.: Efficiencies of various power plant types [12]**

## 2.1. Thermal power plants

Heat, i.e. the temperature difference between two reservoirs, can be transferred into mechanical work and subsequently into electric power. The theoretical efficiency limit can be described by the Carnot cycle, figure 2.1.

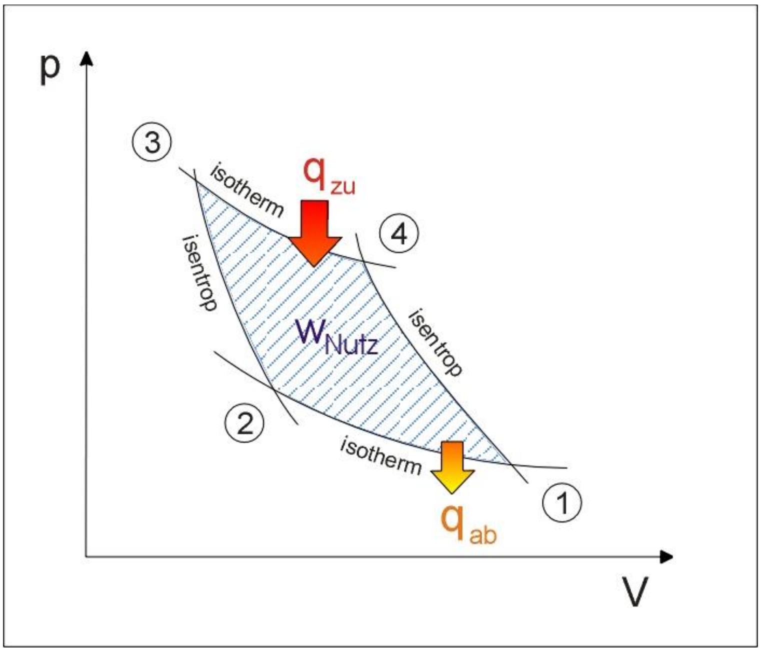



**Figure 2.1.: Carnot cycle [16]**

## 2.1.1 Steam Power Plants

The scheme and the theoretical limit for steam power engines is determined by the Rankine cycle

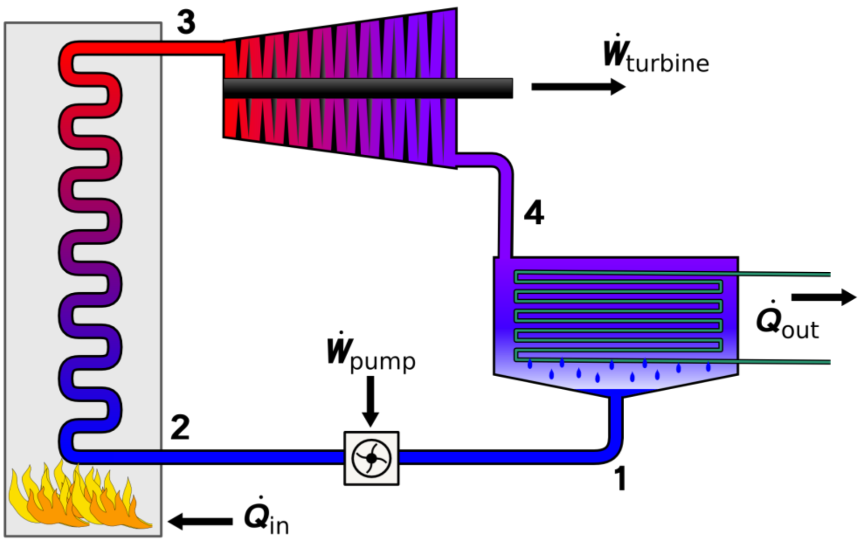



**Figure 2.2: Rankine cycle [25]**

$W_{pump}$=feeding pump
2=boiler
4=condenser
$W_{turbine}$=turbine

Possible heat sources for steam power plants are fossil fuels (gas, oil and coal), nuclear, waste, biomass, solar and geothermal energy.

## 2.1.2. Combined Cycle Gas Turbine Plants

The concept of gas power plants is, regardless of the fuel, the same: combustion heats up and consequently expands a gas. The rising pressure drives a turbine. The Carnot cycle is not exactly applicable in this case, but the Brayton cycle describes the energy conversion best:

1) Isentropic process: Air is pressurized in a compressor
2) Isobaric process: compressed air is heated in an open combustion chamber by burning fuel
3) Isentropic process: heated and pressurized air expands and drives a turbine
4) Isobaric process: heat is released into atmosphere

In reality (not ideal) processes 1 and 2 have to be considered as adiabatic. [18]

All of the commonly used technologies produce (environmentally precarious) CO2, but the amount differs, as shown in table 2.2. Non fossil technologies are not per se responsible for CO2 emissions, but their fabrication, with respect to the current energy mix. Therefore these CO2 balances strongly depend on locality and life time of the plants.

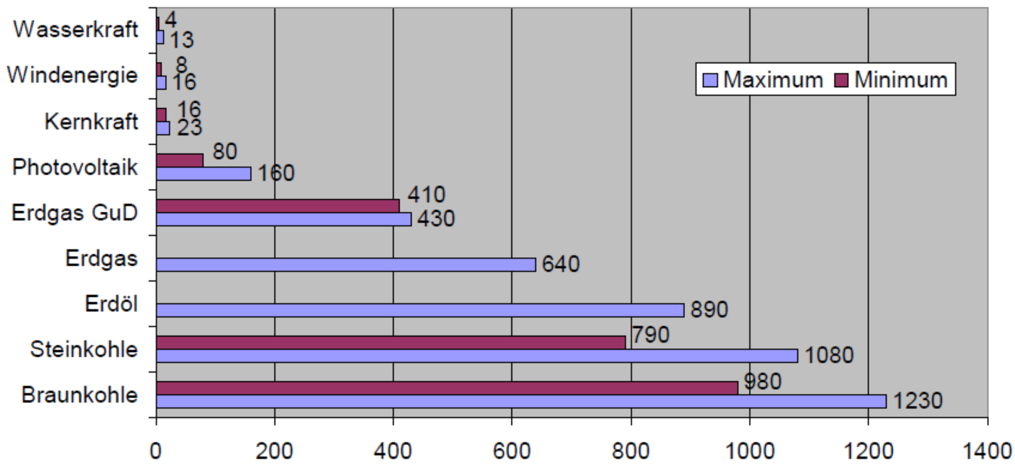



**Table 2.2.: CO2 Emissions g/kWh [17]**

## 2.2. Hydro power plants

Waterwheels have been used since ancient times, the first electricity producing power plant was started in 1878. Hydro power plants use the kinetic and the potential energy of water. There are three main types: run of river-, storage- and pumped storage power plants, details are given below. For different heights and water pressure, respectively, different turbine types are used as shown in figure 2.1. Kaplan turbines can be used up to a height of 80 metres, Francis turbines up to 600 metres and Pelton turbines up to 2000 metres. The maximal flow rates for Francis and Kaplan turbines reach more than 1000 m³/s, while Pelton turbines are limited at about 50 m³/s. An advantage of the Pelton turbine is that the efficiency is high even if the ratio of inflow to inflow maximum is low. On the other hand Francis and Kaplan turbines can be used as pumping facilities, too. [3]

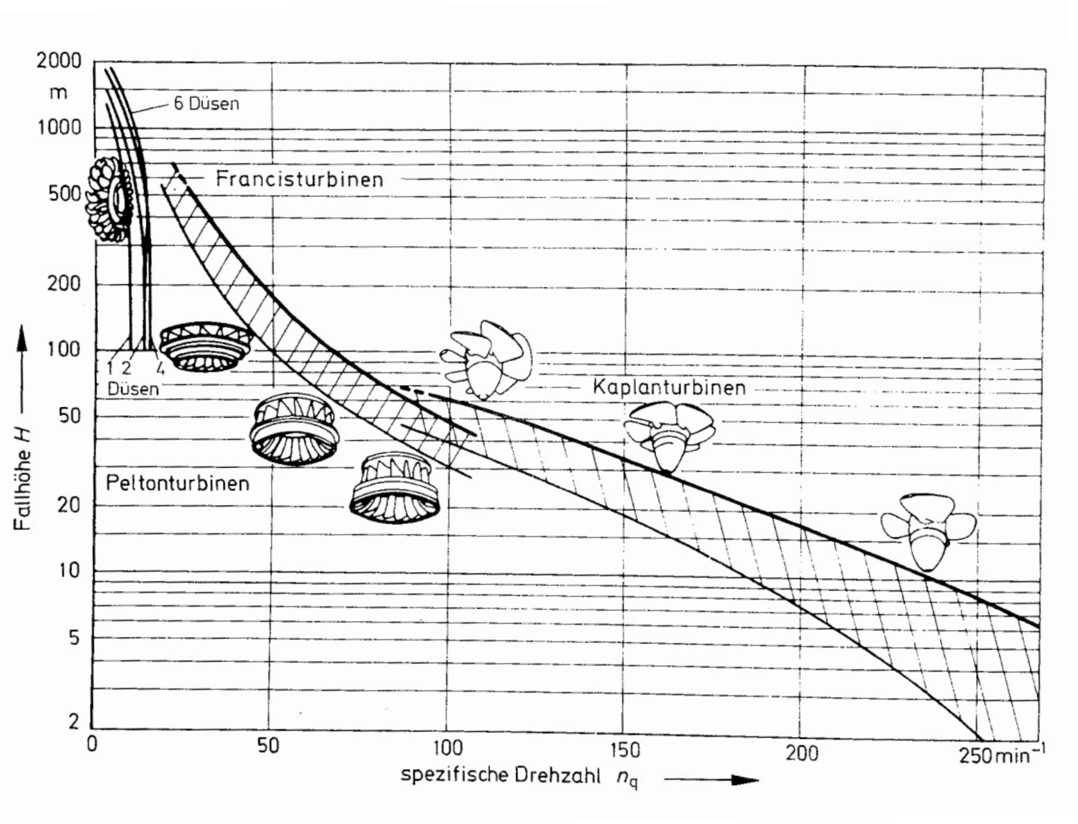



**Figure 2.1: Field of applications for turbine types [3]**

Catchment areas determine when and how much water will be available. Natural inflows can be described by measurements and help to predict the electricity production throughout the year. A typical inflow history is shown in figure 2.2.

Hydropower nowadays provides 16 percent of global electricity consumption [4].
Compared to other means of electricity production, hydro power has the highest value of availability per year:

| | |
|---|---|
| Hydro power plants | 8000 h |
| Geothermal power plants | 7700 h |
| Nuclear power plants | 7000 h |
| Coal power plants | 7000 h |
| Wind power plants | 3800 h |
| Solar power plants | 1500 h |
| 365 days | 8760 h |

**Table 2.2: Working hours per year [9], [51]**

Moreover the theoretical efficiency maximum is virtually 100% in hydro power generation, since the movement of the water can almost be stopped completely.

Hydropower causes very little CO2 emission, namely 40 g CO2 per kWh [6]. Technical problems are cavitation and (dam) silting. Ecological aspects are the suppression of fish movement and the destruction of habitats by flooding areas or drainage of formerly irrigated areas.

## 2.2.1. Run of river power plants

Run of river power plants use the natural flow of a river. Electricity production is limited by the nominal power of the turbine and the seasonal flow capacity of the river concerned: in a small range the river's flow can be controlled by accumulating water or by the operation of upstream situated power plants.

The heights between head waters and turbine are rather low and the incoming amount of water can be high. Therefore Kaplan turbines are used. Number and shape of the blades can vary, a typical form is shown in figure 2.3.1. In Kaplan turbines cavitation can occur very easily, which slowly erodes the petals of the turbine. By modifying the turbine's shape, the cavitations can be forced to occur after the water stream passed the turbine, where they cannot cause damage [5].

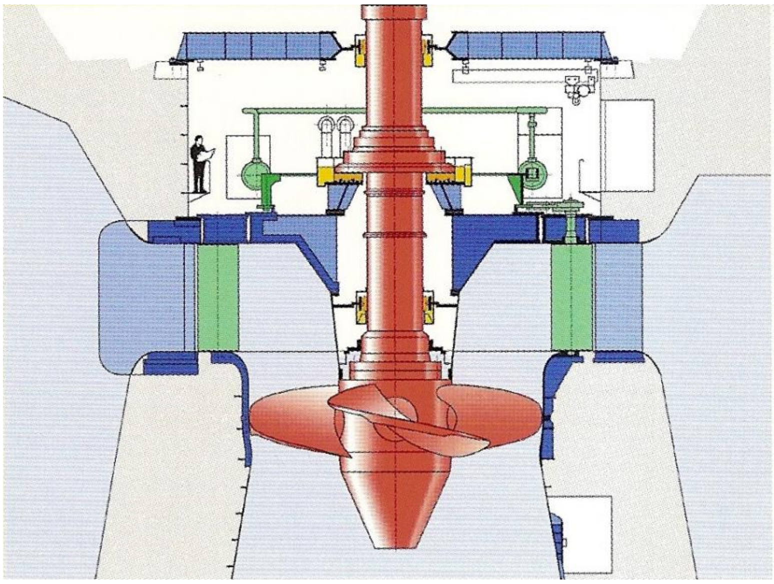


**Figure2.3.1: Kaplan turbine [2]**

## 2.2.2. Storage power plants

Hydro power plants can be combined with water basins, so that the natural inflow can be collected and turbined at times of high electricity demand. Moreover times of strong inflows can be buffered in order to avoid high overflow rates. Depending on the size of the basins, they can serve as daily, weekly or even seasonal storage. Further discussion of the basins is given in chapter 3.1. The energy content can be easily calculated:

$$E = m * g * h,$$

assuming that the detailed structure of the reservoir is known. This energy content multiplied by efficiency factors for turbine, generator and friction in the pipes connecting the reservoirs to the power plant, yields the actual electric power that can be produced:

$$P_{\mathrm{el}} = \eta_{\mathrm{Ges}} * m * g * h$$

$$\eta_{\mathrm{Ges}} = \eta_{\mathrm{G}}\eta_{\mathrm{T}}\eta_{\mathrm{L}} \qquad [10]$$

General values for large power plants:

| | |
|---|---|
| Turbine | $\eta_T$=0,85-0,95 |
| Generator and transformer | $\eta_{GT}$=0,95-0,99 |
| Pipes and valve losses | $\eta_L$=0,9-0,99 |
| Total efficiency | $\eta_{Ges}$ =0,75-0,93 |

**Table 2.3.: Efficiency of hydro power plants [8]**

## 2.2.3. Pumped storage stations

Pumped storage power plants have upper and lower reservoirs. It is possible to pump water from the lower reservoir to the upper reservoir, consuming electricity, or producing electricity by the reverse process. Though there are losses, very good pumped storage plants reach up to 70 percent efficiency. [11]

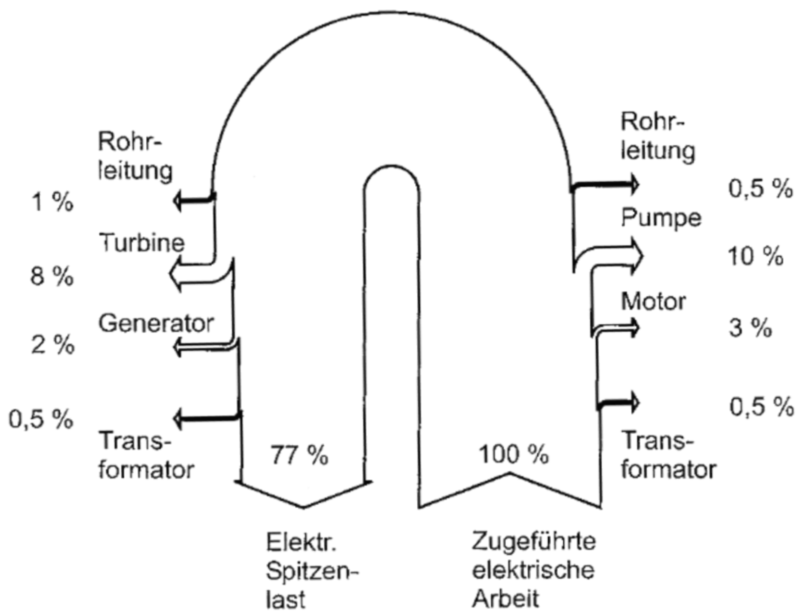



**Figure 2.3.2: Energy balance, hydro storage station [11]**

They can be operated exclusively as pumping stations, or can also have a natural inflow to the upper reservoir and thus produce electricity on their own.

Filling the reservoirs during low demand times can help to provide electricity at high demand. Furthermore, the costs can be regulated and the volatility compensated, if the pumping capacities are high enough.

Large storage facilities are located in Norway, Sweden and France, due to geological predestination. Investigating further potentials is a crucial point for the establishment of renewable energies.

## 2.3. Wind power

Wind power has been used since ancient times, for example as driving force for mills, sawmills or pumping stations. For electricity production the first patent was granted in 1891. [7]
The available wind power can be calculated by

$$P=0.5*\rho*A*c^3$$

with $\rho$=air density, A=cross sectional area, c=wind velocity;
or, considering the Betz factor $C_P$=0.59 for ideal flows:

$$P_{WEK}=0.5*C_P*\rho*A*c^3$$

The maximally extractable power is a function of the speed difference between incoming and outgoing wind speed:

$$P_W=0.5*\rho*A*c*\Delta c^2$$

The maximum energy can be extracted if the wind velocity after the turbine is one third of the incoming wind velocity. The overall efficiency of modern wind power plants can reach about 50%.

[13]

Relevant designs for electricity production use the uplift of specially shaped blades. This principle works for the commonly seen wind turbines, but also for the Darrieus rotor:

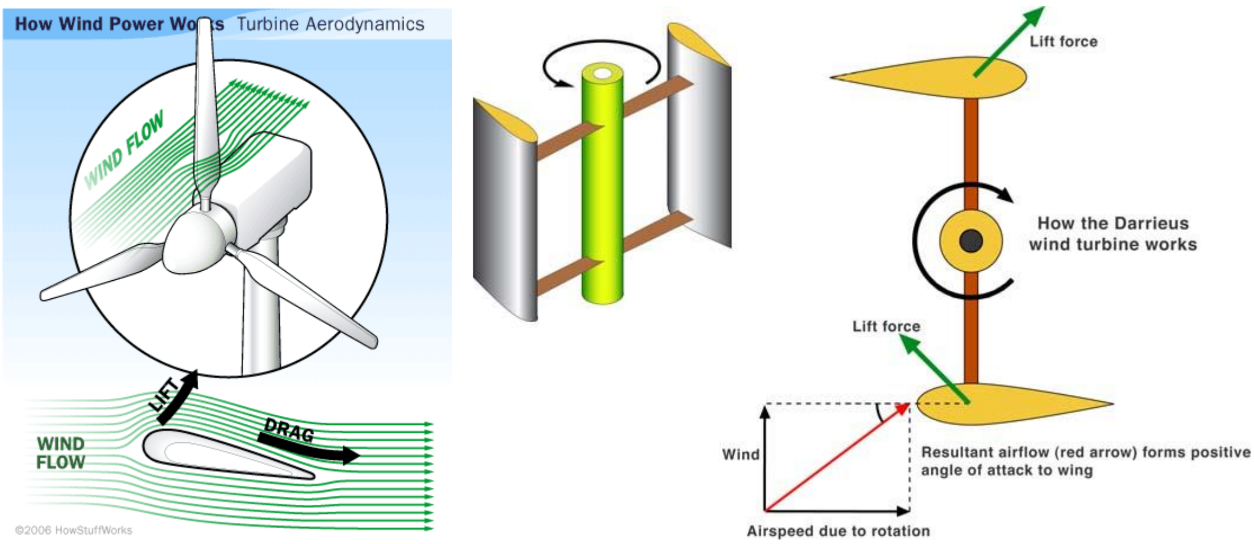



**Figure 2.2.: Wind turbine and Darrieus rotor [14]**

The advantage of the Darrieus rotor is, that it doesn't matter which direction the wind is coming from. Wind turbines on the other hand reach high efficiencies through adjustable blade angles, furthermore they can rotate to face the wind.

Two types of mechanisms can adjust the power of the turbine: stall and pitch regulation. Stall regulated turbines have fixed blades, power is limited by stall, which means aerodynamic uplift decreases drastically at a certain wind velocity. Pitch controlled turbines have adjustable blades to regulate power production. In any case too high wind velocities will result in an interruption of power production. So there is an upper and a lower limit for usable wind velocities.

## 2.4. Photovoltaics

Throughout one year, the sun's radiation at the earth's surface delivers more than a thousand times the energy that mankind uses in one year, all energy forms included. Since 17 % of human energy demand is of electric nature, photovoltaics is a very practical choice.

Based on the photovoltaic effect, a photon creates in a semiconductor an electron-hole pair that, if separated, results in an electric current. Due to its low price, silicon is the most important semiconductor for photovoltaic use. The energy of the photon has to be at least 1.12 eV (at 300 K) to overcome the band gap of the silicon, while exceeding 1.12 eV will not be of any use. This means that not the whole energy of the spectrum of the sun's radiation can be used. Even for an ideal silicon cell 56.5 % of the incoming power are lost. The efficiencies of real solar cells made of silicon are between 5 % (amorphous silicon) and 22 % (monocrystalline silicon). [39]

Single cells are connected to form modules. In Italy the output per installed kW peak (kWp) of photovoltaic modules ranges from 1100 kWh to 2000 kWh per year [40]. A kWp represents the power a module can achieve under ideal conditions.

Rising production numbers and the related decline in prices are illustrated in figures 2.5 and 2.6:

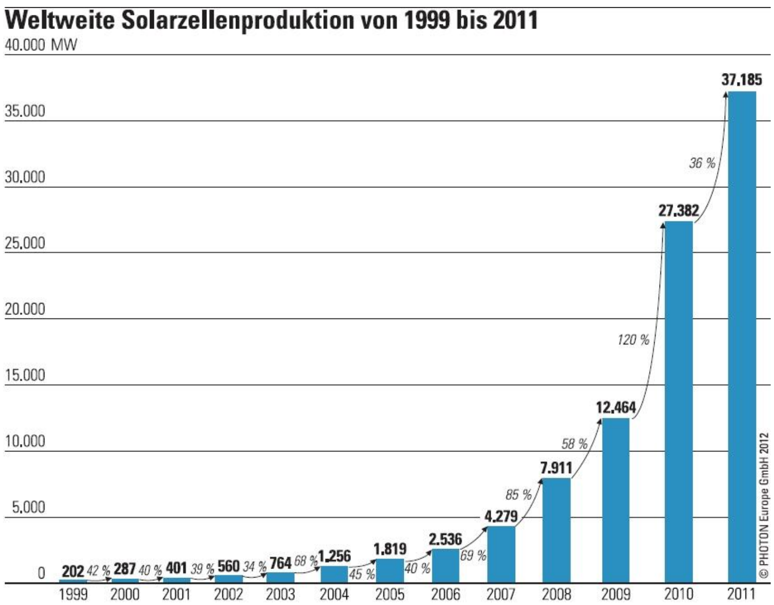
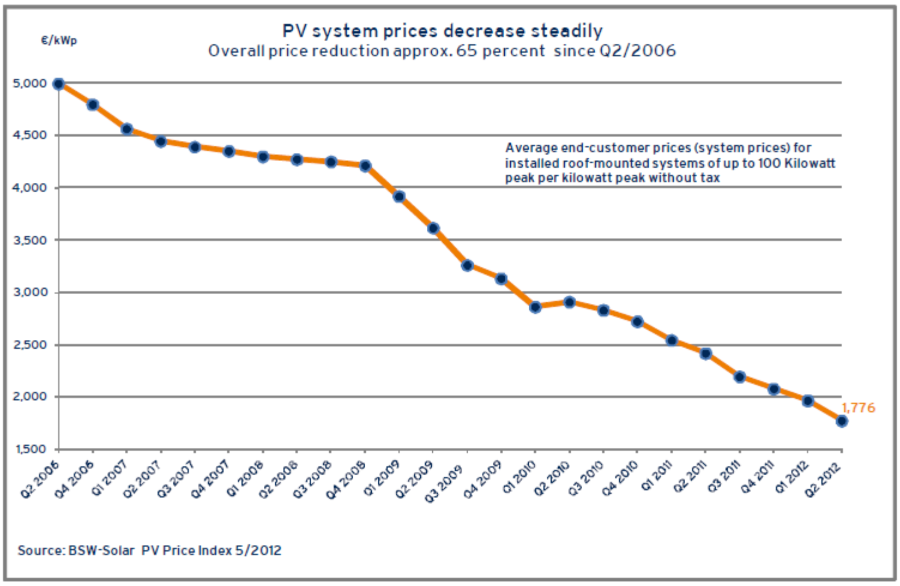



**Figure 2.5: Worldwide solar cell production [41]**




| | System prices [€/kWp] |
|---|---|
| Q2 2006 | 5,000 |
| Q4 2006 | 4,800 |
| Q1 2007 | 4,568 |
| Q2 2007 | 4,448 |
| Q3 2007 | 4,395 |
| Q4 2007 | 4,354 |
| Q1 2008 | 4,303 |
| Q2 2008 | 4,275 |
| Q3 2008 | 4,254 |
| Q4 2008 | 4,216 |
| Q1 2009 | 3,922 |
| Q2 2009 | 3,620 |
| Q3 2009 | 3,263 |
| Q4 2009 | 3,135 |
| Q1 2010 | 2,864 |
| Q2 2010 | 2,912 |
| Q3 2010 | 2,834 |
| Q4 2010 | 2,724 |
| Q1 2011 | 2,546 |
| Q2 2011 | 2,422 |
| Q3 2011 | 2,199 |
| Q4 2011 | 2,082 |
| Q1 2012 | 1,969 |
| Q2 2012 | 1,776 |

**Figure 2.6: price per kWp [42]**

Nevertheless, grid parity is not achieved until today, but state subsidy allows economic operation.

## 2.5. Geothermal

Geothermal power plants use the heat difference between an underground reservoir and the surrounding atmosphere. The earth shows an average gradient of 25°C per km. 80% of the heat is caused by nuclear decay. At particular places the heat can reach the surface more efficiently, because of tectonic gaps or volcanic activities. The function principle is the same as for other steam power plants: the heated working fluid evaporates and runs a turbine, producing electricity. To transport the heat from the reservoir to the surface, different initial situations are possible. Either the reservoir already contains water, which can get to the surface as steam or hot water, or it is dry. The dry rock situation requires man-made water input, to create the energy flow to the surface.

The first geothermal power plant was built in 1904 in Larderello, Italy. It uses steam and water from hot springs, which are called soffioni.

Possible risks are pollutants like methane, ammonia, hydrogen sulphide or carbon dioxide that may escape from the underground reservoirs. Also triggering of earthquakes was reported. [47], [48]

## 2.6. Other power generating systems

A great variety of technologies are used for electricity production. Many of them are just prototypes for which economic operation is not achieved or proved yet. Preconditions are crucial for each type, for example osmosis power plants which have to be located at the inflow of a river into the sea, where the salinity gradient is high.

### 2.6.1. Solar updraft tower

An example for the non photovoltaic use of sun power, the solar updraft tower will be discussed. Prototypes are already operating while broad application is still missing. Installations in deserts seem conceivable. The problem, like in the Desertec project [46], is the transportation of the energy to the users.

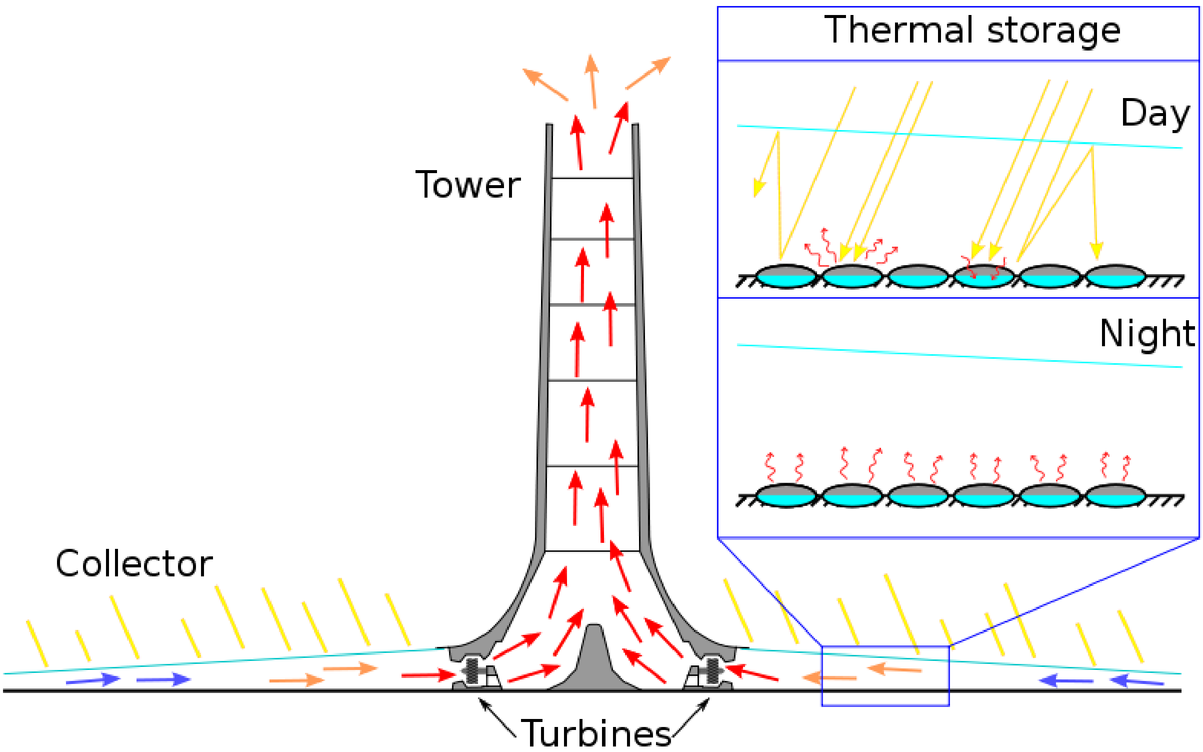



**Figure 2.3. Solar updraft tower**

The solar updraft tower uses the rise of warmer air. It consists roughly of a collector, a turbine and a chimney. Its very low efficiency (around 0.5 percent) is compensated by the low construction costs and its simple construction. [15]

With thermal storage, i.e. water filled tubes, the efficiency can be increased and electricity production during night time is possible.

Measurements on a prototype in Manzanares, Spain, show good agreement with the theoretical calculations.

For large power plants (1000 m height, 7000 km diameter of the collector and 200 MW rated output) the electricity generation costs are estimated to be 0.10 Euro/kWh [2].

## 2.7. Italy’s power plants

The electricity production in Italy is based on natural gas power plants, which cover more than 55 % of the electricity production.

| 2008 | Number of plants | Power [MW] | Production [GWh] |
|---|---|---|---|
| Hydro power | 2184 | 17632 | 41623 |
| Wind power | 242 | 3537 | 4861.3 |
| Solar power | 32018 | 431.5 | 193 |
| Geothermal power | 31 | 711 | 5520.3 |
| Biomass, waste | 352 | 1555.3 | 5966.4 |
| Coal | 2056 | 76729.6 | 39241.6 |
| Oil | | | 17426 |
| Gas | | | 168000 |
| Other thermal | | | 24554.2 |
| Total | 36883 | 100596.1 | 307385.8 |

**Table 2.4: Number of power plants, installed power and production**

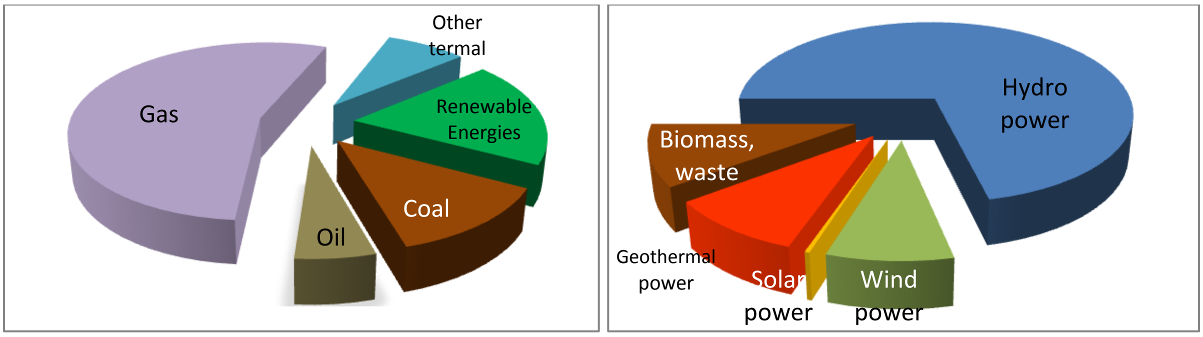



**Figure 2.4: Share of production of power plant types, share of renewables**

All of Italy’s geothermal power plants are located in only three provinces: Pisa, Siena and Grosseto. [49], [50], [52], [53]
In recent years the share of renewable energies is rising. Major contributions to this growth make wind turbines, biomass and waste power plants. Even more remarkable is the increase of solar power: the production in 2012 reached 7 percent of total electricity production in Italy [54].

# 3. Energy storage

Energy storage is a key ingredient to a stable power grid with a high share of renewable energy. Different topics need specific solutions: short time fluctuations have to be compensated by quickly responding buffers, while long term highs and lows need big storage facilities and/or a carefully adjusted energy management. Costs and life spans (e.g. cycles of a battery), but also disposal and environmental compatibility have to be taken into account. In the following, some common storage methods, their advantages and disadvantages, will be presented. In this chapter storage will be used in terms of cycles: energy is used to build up the storage capacity which can later be transformed into a suitable form of energy again (the elementary way of storage would be one directional, for example a storage hydro power plant without the opportunity to pump up the water again).

## 3.1. Water reservoirs

Water reservoirs are potential energy storages. With $g=9.81\ m/s^2$ the applicable equation is $\Delta W=mg\Delta r$. In the process of the global climate circle water is evaporated, rises and thus gains potential energy. Later it precipitates. Ending up above sea level, the remaining potential energy relative to lower grounds can be technically used. Current energy demand can be followed by turning on and off the turbines of a storage hydropower plant. The response time is of the order of minutes, i.e. rather fast compared to other power plants (table 2.4).

Disadvantages can be the vast land requirements of the dams, as their creation changes and/or destroys habitats. An example is the Alta dam in Norway, where the indigenous people of the Sami lost residents and land (though the initially planned project was even bigger).
If there are two reservoirs, electrical energy can be transformed into potential energy again (chapter 2.2.3) [1]

Figure 3.1 shows the distribution of Europe’s hydro power stations. Obviously they are well established in the alpine regions, for high elevations are an undeniable advantage. In Scandinavia geological features, as canyons, provide a large scope of application. Since in Norway many hydro power plants have upper and lower reservoirs, there is still much potential. Nevertheless, there is need for a power grid enhancement if the other European countries are to benefit from this upgrading.

**Storage Hydro Power in Europe:**

*Rated Power, Storage Capacity and Annual Energy Production*

| Data of UCTE 1998 | Rated Power of Reservoir and mixed pumped Storage [GW] | Storage Capacity of Reservoir and mixed pumped Storage [TWh] | Annual Energy Prod. of Reservoir and mixed pumped Storage [TWh] |
|---|---|---|---|
| Slovenia/Croatia | 1,4 | 1,8 | ? |
| Swizerland | 8,2 | 8,4 | 18,0 |
| Serbia and Montenegro | 2,0 | 2,0 | ? |
| Portugal | 2,1 | 2,6 | 4,2 |
| Austria | 5,6 | 3,2 | 7,0 |
| Luxemburg | 0,0 | 0,0 | 0,0 |
| Italy | 7,5 | 7,9 | 17,6 |
| Greece | 1,9 | 2,4 | 2,8 |
| France | 11,6 | 9,8 | 18,2 |
| Germany | 1,4 | 0,3 | 1,1 |
| Belgium | 0,0 | 0,0 | 0,0 |
| Spain | 7,7 | 18,4 | 16,7 |
| **Sum of UCTE** | **49** | **57** | **86** |
| Data of NORDEL | | | |
| Norway | 27,3 | 84,1 | 112,6 |
| Finland | 2,9 | 4,9 | 12,6 |
| Sweden | 16,2 | 33,7 | 63,6 |
| **Sum of NORDEL** | **46** | **123** | **189** |
| **Sum of NORDEL + UCTE** | **96** | **180** | **275** |

G. Czisch, ISET, Vtrg. Mgdb. 2001

**Figure 3.1: Europe's storage hydro power [45]**

## 3.2. Chemical

A variety of chemical reactions can be utilised to store and retrieve energy. Essential is a reversible reaction. In the following chapters some methods are described.

### 3.2.1. Hydrogen

Hydrogen storage is not as trivial as storage of methane, due to its small atoms. Hydrogen readily diffuses through many materials. A cycle for energy storage via hydrogen requires the production of hydrogen (most conveniently by electrolysis) and a process to release the energy again. This process can be simple combustion or, more efficiently, a reaction in fuel cells.

### 3.2.2. Methane

Another power to gas technology involves methane. Including an electrolysis of hydrogen, a reaction with carbon dioxide delivers methane. The advantage of methane, compared to hydrogen, is the easier handling, i.e. storing. Existing gas networks can be used. Large amounts of methane can be stored in depleted gas fields; in Italy the capacity is about 10 billion m³. [21]

## 3.3. Mechanical

Mechanical energy can be stored in springs, movements of a body, the potential energy of higher levels, pressurized gases etc. Exemplarily the principle of flywheels will be described.

### 3.3.1. Flywheel

The concept of a flywheel energy storage device is based on the rotational kinetic energy of a spinning body: $E=I*\omega^2$ ,where I is the moment of inertia and $\omega$ is the angular velocity. The value of I is dependent on the shape (shape factor $K_m$), mass and the location or direction, respectively, of the spinning axis in the object that is rotating. Characteristic parameters of some examples are listed in figure 3.4.1.

Typical applications (in the energy field) are short term storage for grid stabilisation and energy recuperation in braking systems (i.e. in trains).

Longevity (up to $10^7$ cycles [19]) and fast energy release, which means high power, are features of flywheels. On the other hand the material properties have to be considered, since high centrifugal forces can tear the spinning object apart. [20]

| Object | *K*, shape factor | Mass (kg) | Diameter (m) | Angular velocity (rpm) | Energy stored | Energy stored (kWh) |
|---|---|---|---|---|---|---|
| Bicycle wheel | 1 | 1 | 0.7 | 150 | 15 J | $4 \times 10^{-7}$ |
| Flintstone's stone wheel | 0.5 | 245 | 0.5 | 200 | 1,680 J | $4.7 \times 10^{-4}$ |
| Train wheel, 60 km h$^{-1}$ | 0.5 | 942 | 1 | 318 | 65,000 J | $1.8 \times 10^{-2}$ |
| Large truck wheel, 18 mph | 0.5 | 1,000 | 2 | 79 | 17,000 J | $4.8 \times 10^{-3}$ |
| Train braking flywheel | 0.5 | 3,000 | 0.5 | 8,000 | 33 MJ | 9.1 |
| Electrical power backup flywheel | 0.5 | 600 | 0.5 | 30,000 | 92 MJ | 26 |

**Figure 3.4.1: Flywheel parmeters [20]**

## 3.4. Superconductor

Superconducting energy storing devices have the most immediate response of all methods. Furthermore, they deliver high short time power. However, characteristics of superconducting materials provide some difficulties. First of all, they have to be cooled, in the best case to only about 77 K. If critical temperatures or critical fields are exceeded, the materials become normal conducting and consequently can reach very high temperatures through ohmic resistance, destructing the system. Another difficulty of high temperature superconducting materials lies in the fact, that they are brittle and not easy to process. Despite these problems, this method can still financially compete with others. [1]

# 4. Modelling

## 4.1. Model/program

The model, written in Ampl, was developed for the AUTRes100 project. AMPL is an algebraic modelling language for linear and nonlinear optimization problems. Combined with the MOSEK solver and the interior point method, linear optimization manages to handle the large amount of data required for a high resolution. [38]

The AUTRes100 project investigates the implementation of a high share of intermittent renewable energies into the Austrian grid. The high resolution model optimizes investment costs and system stability. Moreover, a 100% renewable energy supply in Austria is analyzed and tested for feasibility. Within the AUTRes100 project surrounding countries and other European countries are taken into account.

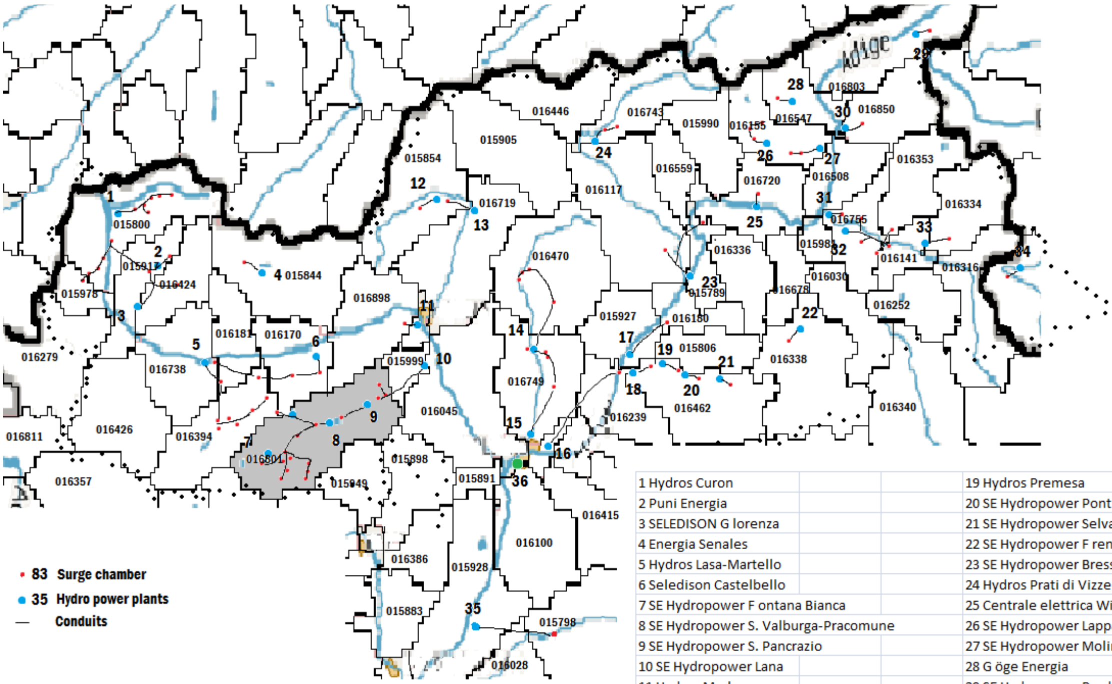
The programming of the model was not part of this diploma thesis and is kept confidential.

## 4.2. Data

A model of current energy production requires the knowledge of existing power plants. Running these power plants involves fuels or in the case of many renewables the exploitation of environmental processes. Focussing on renewable energies, inflows of rivers are most crucial. Energy costs, build up costs, wind and solar radiation will be considered too. Start up costs for thermal power plants will play an important role for the profit optimization by storage power plants, numerous start ups have to be anticipated. In the following chapters the acquired data and the availability will be introduced.

### 4.2.1. Weather/inflows

Inflow data for the model were derived from an open internet source that provided discharge amounts of each hydration area of interest. Figure 4.1 shows an example for the catchment area for the Lana power plant in the Lana valley of the Bolzano province.




| | |
|---|---|
| 1 Hydros Curon | 19 Hydros Premesa |
| 2 Puni Energia | 20 SE Hydropower Pontives |
| 3 SELEDISON G lorenza | 21 SE Hydropower Selva Gardena |
| 4 Energia Senales | 22 SE Hydropower F rena |
| 5 Hydros Lasa-Martello | 23 SE Hydropower Bressanone |
| 6 Seledison Castelbello | 24 Hydros Prati di Vizze |
| 7 SE Hydropower F ontana Bianca | 25 Centrale elettrica Winnebach |
| 8 SE Hydropower S. Valburga-Pracomune | 26 SE Hydropower Lappago |
| 9 SE Hydropower S. Pancrazio | 27 SE Hydropower Molini di Tures |
| 10 SE Hydropower Lana | 28 G öge Energia |
| 11 Hydros Marlengo | 29 SE Hydropower Predoi |
| 12 C entrale elettrica Moso | 30 Azienda elettrica C ampo Tures |
| 13 Enerpass | 31 SE Hydropower Stegona |
| 14 SE Hydropower Sarentino | 32 Hydros Brunico-V aldaora |
| 15 SE Hydropower S. Antonio | 33 Energy Welsperg |
| 16 SE Hydropower Cardano | 34 SE Hydropower V ersciaco |
| 17 Hydros Barbiano-Ponte Gardena | 35 SF Energy S. Floriano |
| 18 SE Hydropower Ponte Gardena | 36 C entrale di teleconduzione Bolzano |

**Figure 4.1: Catchment area of the Lana Valley**

Since the exact amounts of derived water are not available, the water input was calculated by gauging the hourly hydration area data with the yearly energy production of the power plant concerned.

$$V_i = V_{Hi} * V / V_H$$

Standard operating capacities are readily available for all described power plants. This parameter combined with the penstock height yields the yearly inflow into the turbines. This is not to be confused with the amount of water delivered by a river, since overflows are possible. For power plants without any significant storage facilities the maximum inflow rates of the turbines limit the operational capacity. In this case the excess water is lost for energy production.

$$V = [E * f / (H * g * \mu * 1000)]$$

$V$......calculated inflow per year [$m^3/a$]
$V_H$......discharge in hydration area per year [$m^3/a$]
$V_i$......average turbine inflow [$m^3/s$] in the hour "i"
$E$........energy production [GWh/a]
$V_{Hi}$.....discharge in hydration area [$m^3/s$] in the hour "i"
$H$......penstock height [m]
$\mu$.....overall efficiency of the power plant
$g$....earth's gravity
$f$.......conversion coefficient GWh to Joule, $3600 * 10^9$

We obtain cubic metres because of the factor 1/1000 (assuming a water density of $1 g/cm^3$)

Example:

**Hydro power plant Bruneck (inflow per year):**

H=200.75 m
E=144.2 GWh/a

Using the above equation this yields an inflow of about 260 million cubic metres of water. The other parameters stay the same for all hydro power plants. For the overall efficiency this is again an assumption due to the lack of more precise data. Further we ignore variations of the earth's gravity and density variations of the water, since the effects are very small.

In this simple formula the inflow can get greater than the maximum inflow rates of the turbines, so water is lost again. Nevertheless this shortcoming was not eliminated. The reason is that compensating possible overflows is part of the tasks for the related reservoirs. Therefore the electricity production should be below the average production capacity. For the year 2005, however, the simulated production in some cases exceeds the average production by some percent. The reason is the way of calibration: to allow different production capacities for different years, the calibration was done for nine years at once, namely the years 2000 up to and including 2008. 2005 was a year with high precipitation, so high production is plausible. Examples in table 3.2 are derived from a simulation done with the EEX model and data of the PUN, the national single price (Prezzo Unico Nazionale).

| 2005 | Fontana Bianca | Graun | San Antonio |
|---|---|---|---|
| RAV [GWh] | 48.2 | 41.9 | 256 |
| Simulated power production [GWh] | 56.4 (without pumping) | 41.8 | 279 |

**Table 3.2: Power production: average and simulated, examples (EEX model with PUN prices)**

## 4.2.2. Power plants/dams

The search for existing power plants and their respective dams was not an easy task, because complete data sets are not available. Part of this diploma thesis was the collection of data of all power plants in Italy (of all types) with capacities larger than (and equal to) 50 MW. Data include the following:

Hydro power plants:
year of start up, owner, exact location, average electricity generation, elevation of turbine axes, number and type of turbines and respective generation capacity, type of the plant (run of river, storage, pumped storage), maximum water input capacity, drop height and catchment area.

Dams:
maximum/minimum water level, energy content, volume, type, surface, location and hourly inflow.

Thermal power plants:
installed capacity, number of units, type, type of fuel, location, year of construction and owner

The European Network of Transmission System Operators for Electricity (ENTSO-E) provided an overview of the number and size of Italy's power plants. More precise data had to be found on the internet, as written requests to energy providers and other institutions remained unsuccessful (Either no answers or negative answers were given or a financial reward was demanded).

Data procured from the internet are not very precise and differ from the ENTSO-E data:

75 hydro power plants greater than 50 MW with a total capacity of 13921 MW were found, compared to ENTSO-E's 71 hydro power plants with 13656 MW total capacity. 18 of these were identified as pumped storage power plants, 41 as storage power plants and 9 as run of water power plants. For the remaining 7 power plants the data was insufficient to specify their types.

67 thermal power plants greater than 200 MW with a total capacity of 57859 MW were found, compared to ENTSO-E's 144 thermal power plants with 54336 MW total capacity.

The reason for the difference in the power plants' number is that some data sources consider groups of units as one plant while other sources count every single unit apart. The difference in the total power may also result from this effect, given that the limit 50 MW, or 200 MW, respectively, of power plant capacity is no more clearly defined.

Most locations and main characteristics (installed MW, year of construction, standard output capacity) were found. Other essential data, like upper level and lower level of the dams, energy contents, efficiencies and locations of the penstock remained were estimated, or measured, respectively. Measurement of upper and lower levels, surface areas and length of conduits were done with the help of "google earth". Estimations of energy contents were done by a comparison with well known Austrian dams, considering two types: alpine region dams and box shaped artificial dams. According formulas have been deduced. A comparison of estimations and known data proved to be sufficiently  accurate for this approach.

An overview of the identified power plants can be seen in the following figures.

**Figure 4.2: Thermal power plants, greater than 200 MW**

Locating each hydro power plant was very time consuming. Only one data source provided coordinates for five plants. The other plants were found by looking for their reservoirs, penstock lines and transformer stations or transmission lines, respectively. Google earth and Bing maps were the most convenient instruments, since their use is free of charge. Information going beyond basic data like power, standard operating capacity, size of related dams and penstock height, were rare. Yet there were some well documented examples, e.g. the power plant Kastelbell:

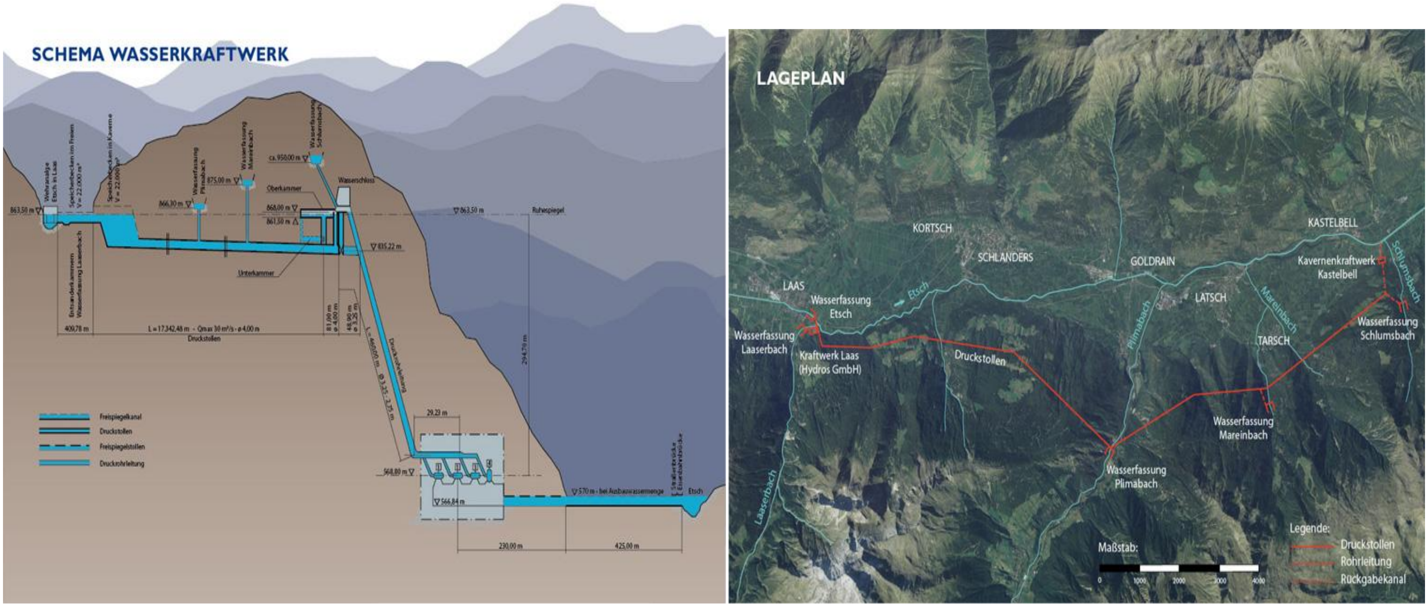



**Figure 4.3.: Scheme of the Kastelbell power plant**


**Figure 4.4: Hydro power plants, greater than 50 MW**

In northern Italy lots of reservoirs are located, because the alpine regions provide many possibilities for dam building. Dams in central or southern Italy are concentrated on the innermost parts, far away from the coast, where elevations are high. The biggest dam is Campotosto, containing 217 million cubic metres of water. About 85 dams or basins have been identified, 40 more were described in the province of Bolzano.


**Figure 4.5: Reservoirs used for hydro power production**

Since data availability was weak, the focus was shifted from Italy to a small region in Italy, for which the data was quite accurate: the province of Bolzano. Bolzano accounts for more than 14 percent of Italy's hydro power production. In spite of producing a surplus of electricity throughout the year, the province is not self sufficient. Even if the energy contents of the reservoirs were sufficient to procure isolated operation, it is more profitable to involve thermal power plants of other provinces. Changing price levels leave a margin for pumped hydro storage plants. Storage plants without pumping save capacities for use at high price times. In this thesis the Bolzano province will be considered as an isolated system. The identified power plants and dams are shown in figure 4.6. Most of the power plants have upper and lower dams, therefore further development of pumped storage facilities seems feasible.

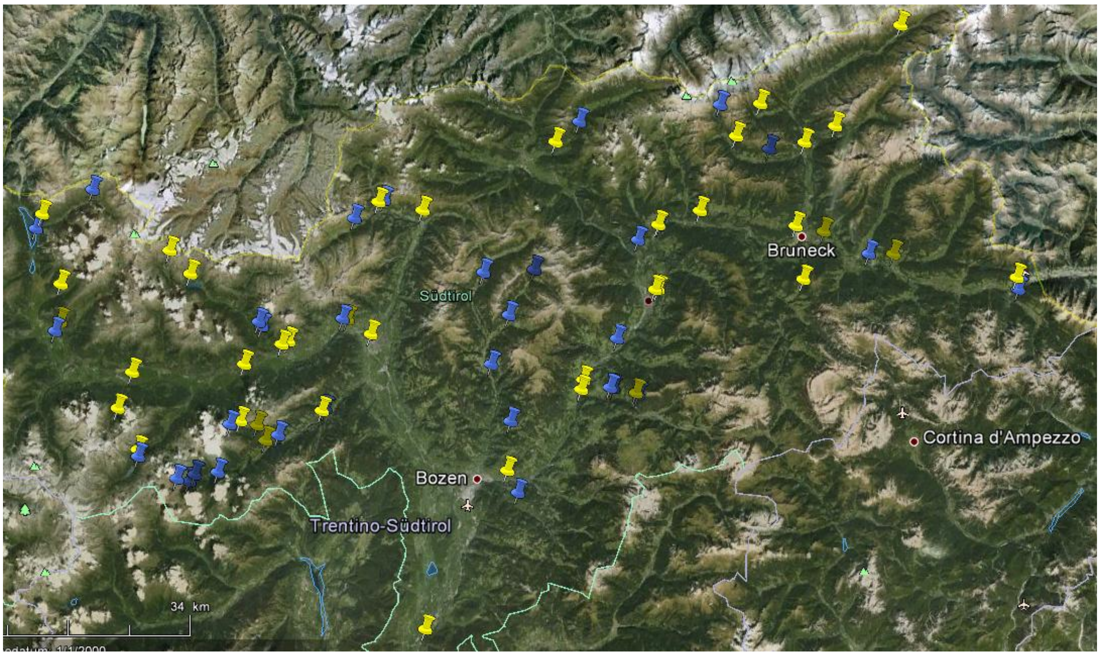


**Figure 4.6: Dams (blue pins) and hydro power plants (yellow pins) of Bolzano**

Bolzano has an installed hydro power capacity of 1517.8 MW (2007, [55]) that accounts for 4.46 TWh net production in the year 2007. In 2007 255 hydro power stations have been operating. Number and capacities are still growing, although this is not obvious if one analyses the production numbers. Variation in precipitation gives the wrong impression of decreasing capacities, looking at the years 2006 and 2007 in table 4.2.

| | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|
| net electricity production [TWh] | 3.99 | 4.52 | 4.46 | 5.56 |
| of which hydropower [TWh] | 3.93 | 4.45 | 4.34 | 5.50 |
| percent of Italy's electricity production | 1.4 | 1.6 | 1.5 | 1.8 |
| percent of Italy's hydro production | 9.3 | 10.6 | 11.4 | 14.3 |

**Table 4.2: Hydro power production of Bolzano [55]**

Other than hydro power plants play an insignificant role: in 2007 only seven biomass power plants with a capacity of 9.5 MW, two wind power plants with a capacity of 3 MW and 226 solar power stations with a capacity of 7.4 MW have been feeding electricity into the public power grid.

In a first step the operation of the model was tested. Especially the Lana valley served as a check point dor comparing the data calculated by the model. In the Lana Valley five hydro power plants produce a yearly average of 451 GWh: Fontana Bianca (10.2 MW, 8.2 MW pumping), Pracupola (42 MW, 35 MW pumping), Valburga (15.5 MW), Pancrazio (17 MW) and Lana (27.8 MW). Except the lowest one, Lana, all of them have upper and lower dams, but only the Fontana Bianca power plant is constructed as a pumped storage plant. Since data were unclear in terms of pumping for the Pracupola power plant, this power plant was implemented as storage power plant.

The first runs of the model showed a strange behaviour in pumping activities: pumping capacity reached values up to 120 MW, although the pumping facility of Fontana Bianca has a capacity of only 8.2 MW. The reason was an excluded line in the model. Furthermore the production of Pracupola exceeded by far the average yearly production. Instead of the real penstock height of 377.5 m the model was using the height difference of the upper and lower reservoir, which is about 1000 m.

Obviously more than 600 m of drop height are not utilised, which is an opportunity for an extension. On the other hand, if Pracupola was a pumped storage plant, an extension has to have two partitions, because a single pumping facility cannot manage this height. The problems were fixed and the other power systems were checked likewise.

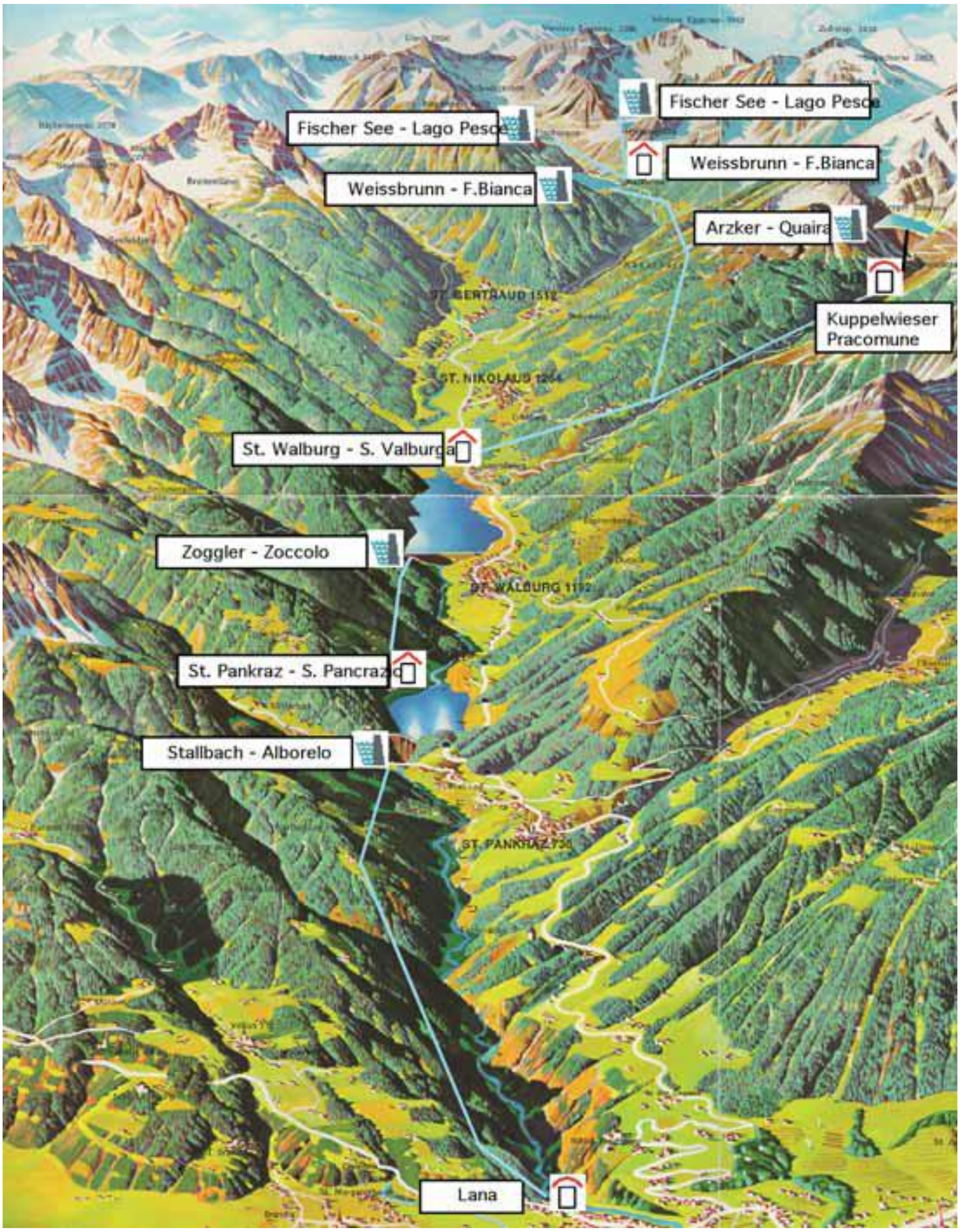


**Figure 4.6: The Lana valley and its hydro power system [37]**

## 4.3. Simulations/Results

First the simulation of the Bolzano region was run with data for the year 2005. Pumping and turbining activities of the only pumped storage plant, Fontana Bianca, reflect changes of the electricity price, as one can see in figure 4.3.1 for the fourth week of January. This simulation was done with EEX prices, Italian electricity prices were simulated later.

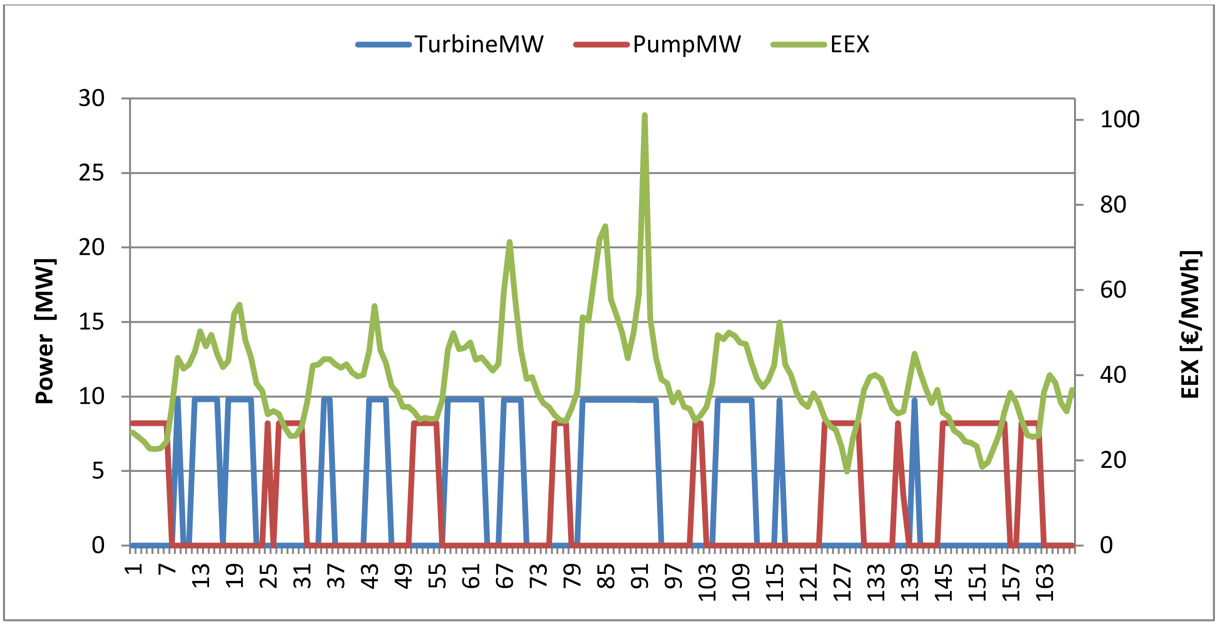



**Figure 4.3.1: Pumping and turbining activity of Fontana Bianca**

### 4.3.1 EEX model with PUN price simulations

In this simulation the national single price PUN (Prezzo Unico Nazionale) was used [43]. Figure 4.3.2 shows the fourth week in January. The graph of the price is smoother than the one for the EEX price, there are fewer small peaks, but the values are clearly higher at practically all times. Monday to Friday seems to show no differences between each other, on the contrast to the EEX price. Nevertheless, this is only true for this specific week. Causes for the high prices were discussed in chapter 1.2. Development of more powerful transmission lines to the neighbouring countries could help adapt prices to European standard.

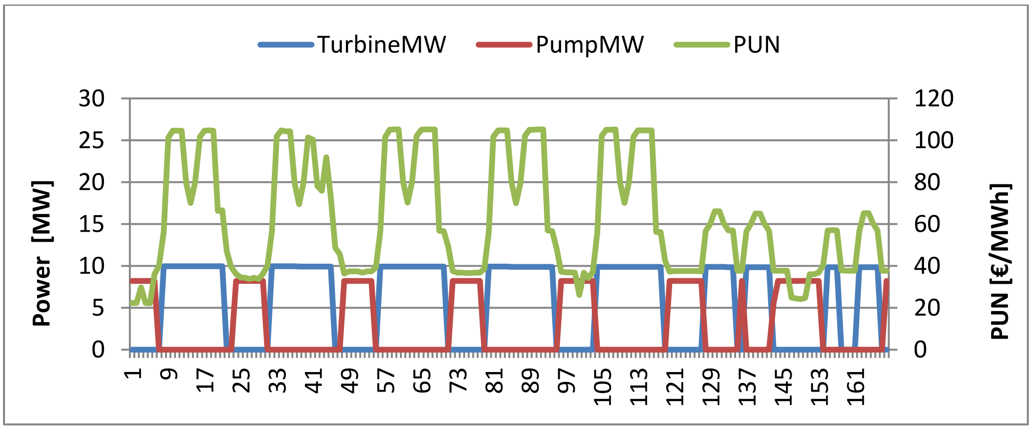



**Figure 4.3.2: Pumping and turbining activity of Fontana Bianca**

In figure 4.3.3 the difference of the energy contents of the individual simulations for the years 2005, 2006, 2007, 2005-2007 and 2005-2006 are compared. The cyclic precondition of the model forces the values to be the same at the beginning and the end of each simulation. That prevents the model from assuming a full reservoir at the beginning and an empty at the end of the simulation, which would create a maximum, but unrealistic, output.

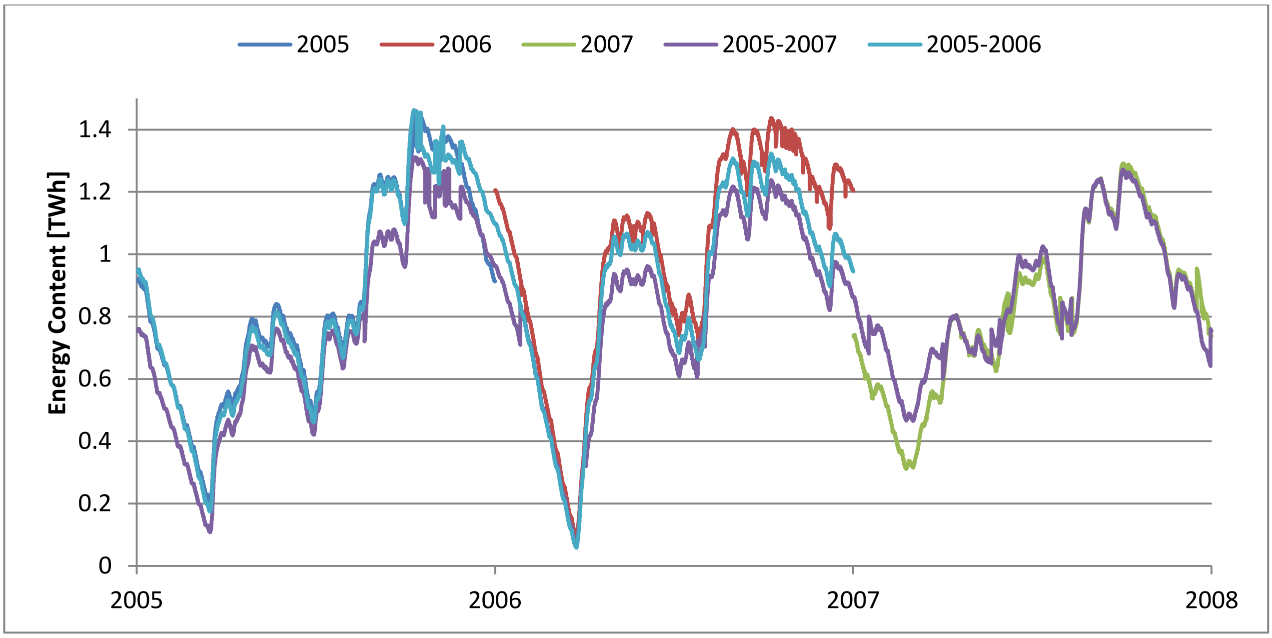



**Figure 4.3.3: Overall energy content for the years 2006 to 2007**

The total energy contents of the previous figures has to be specified in more detail: since in an optimal case water from an elevation is used by several hydro power plants until sea level is reached, it is reasonable to assume the energy content of a full reservoir in the following way:

E=m*g*H,

with H being the center of mass in meters above sea level, g being the earth's acceleration and m the mass of the water filled reservoir volume. To look at the energy content of a single power plant one has to take into account the height of the turbine axis relative to sea level. However, if the lower dam's maximum level is above the turbine's axis, it lessens the energy content of the upper dam. The real energy contents for some important power plants of the focus region, the province of Bolzano, are shown in figure 4.3.4.

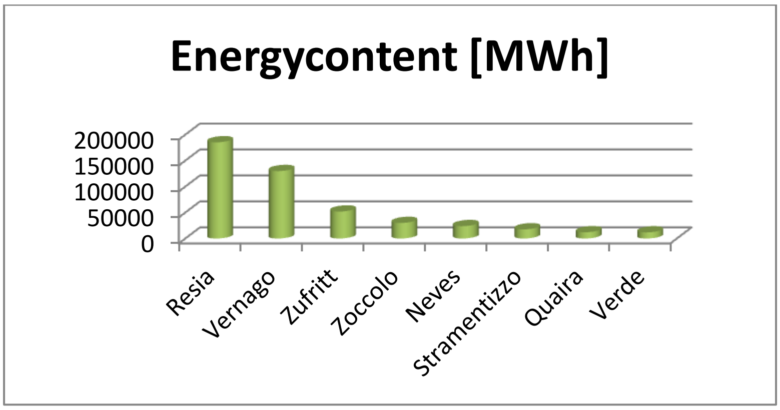



**Figure 4.3.4: Energy contents**

Processes for a single pumped power plant are shown in figure 4.3.5. The pumped storage plant Pracupola, part of the Lana valley system, has an installed power of 10.2 MW. There is no plant upstream, inflows into the reservoir of Quaira are utilized only for the Pracupola plant. The sizes of the reservoirs are 33 million m³ for the lower one, Zoccolo, and 11.7 million m³ for Quaira, the upper one. The upper reservoir clearly shows peaks in a weekly interval, due to price variations during a week. Every little peak indicates a weekend, where prices are low, as can be seen in figure 4.3.1 and 4.3.2. Peaks of Zoccolo are inconspicuous. It is deceiving to assume this is due to the reservoir size, which is about three times the one of Quaira. This creates a shift on the vertical axis, but not a reduction of the peak sizes. The real reason for the smaller peaks are on the one hand a power plant downstream, that uses the Zoccolo waters, on the other hand a further reservoir with a power plant feeding Zoccolo. A closer look at an arbitrary 2 week interval reveals their correlation, demonstrated in figure 4.3.6. Declining energy content in Zoccolo accompanies rising energy content in Quaira on a daily basis.

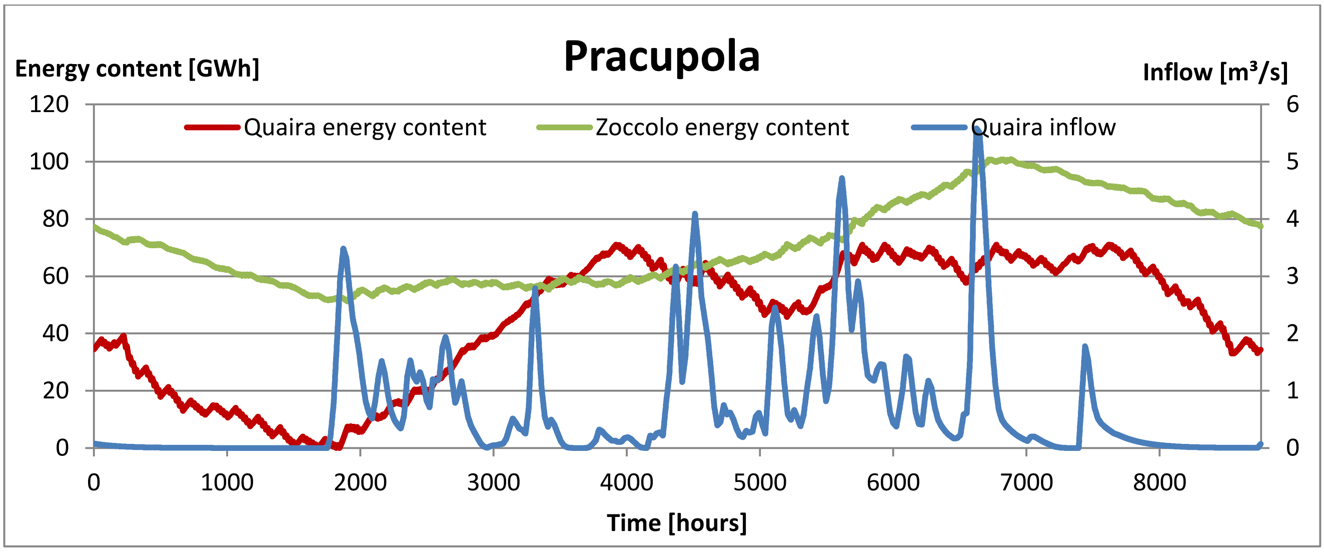



**Figure 4.3.5: Inflow and energy contents of Pracupola**

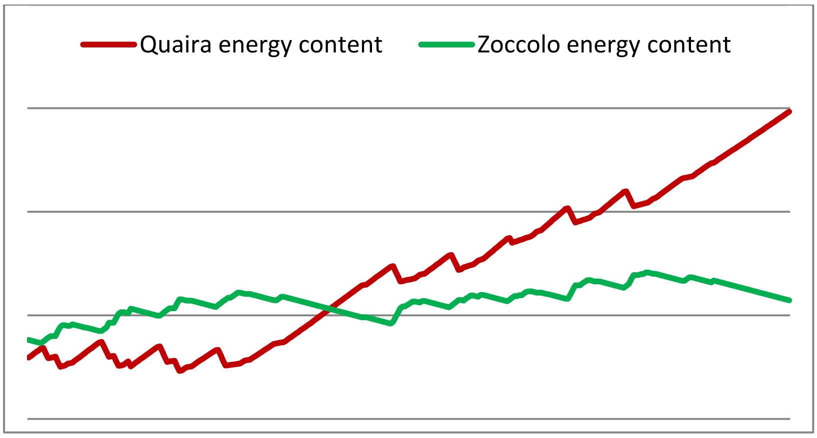



**Figure 4.3.6: Quaira and Zoccolo reservoir trend of energy content**

The province of Bolzano provides enough electricity of hydro power for its own demand at most times, as one can see in figure 4.3.7 for the year 2005. Even though the production of one year from renewable sources is sufficient, in some times non renewable sources have to balance high peaks of demand when hydropower production is low.

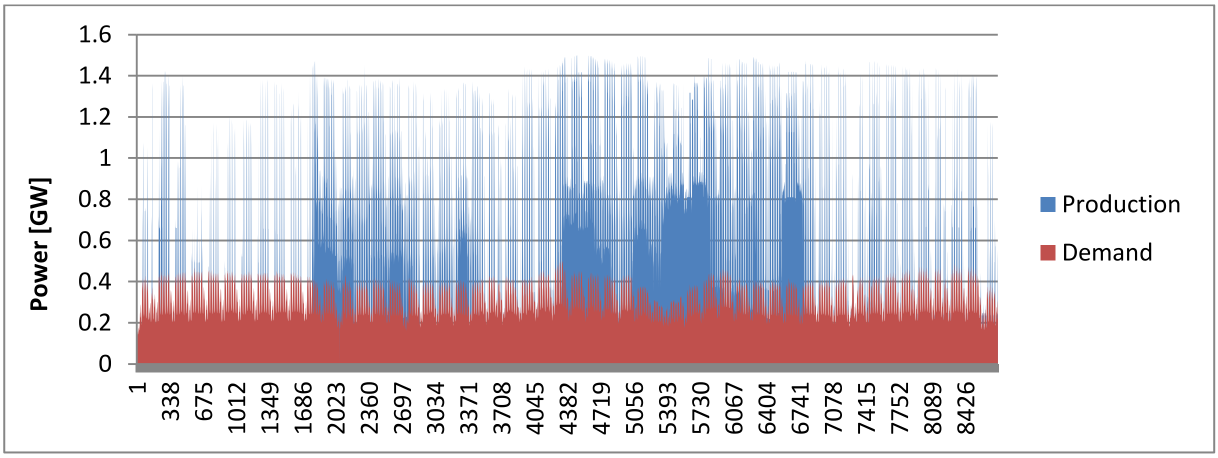



**Figure 4.3.7: Power production and demand of the province of Bolzano**

Looking at the surplus of electricity production by hydro power in comparison to the demand, the domination of positive values is apparent.

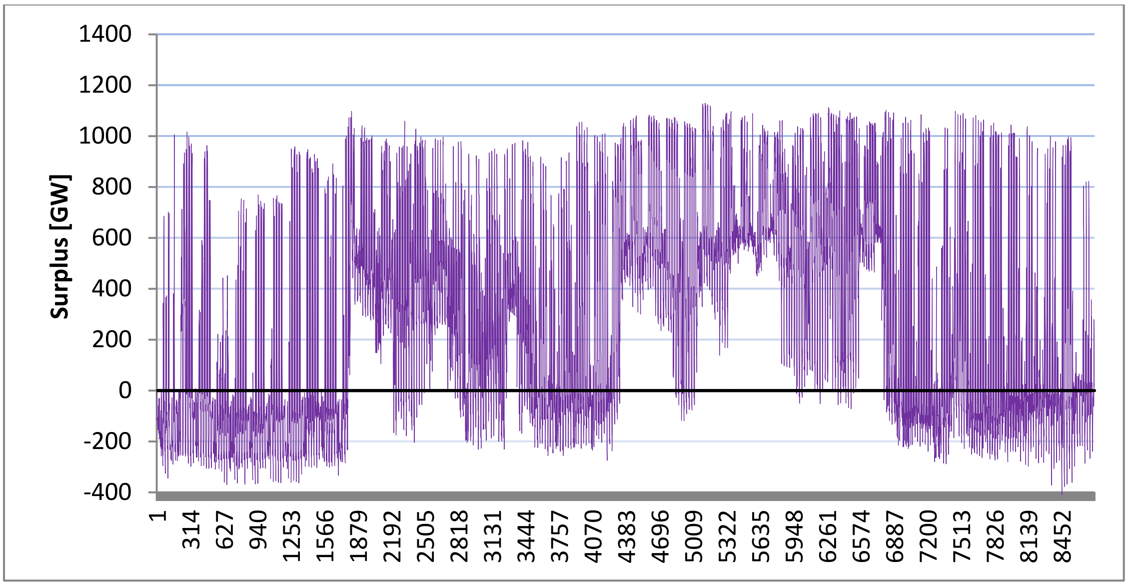



**Figure 4.3.8: Surplus simulated for the year 2005**

### 4.3.1.1 Profits

Run of river power plants can only use water at its current availability. Containment facilities are very small, i.e. can hold back water only for a short time. Power plants without reservoirs show a behaviour like the Moso plant, illustrated in figure 4.3.9. Overflow is inevitable, so 16 percent of the inflows are lost for this power plant. Even higher capacities could overcome this problem, nevertheless, the model calculation in chapter 4.3.2 will show that the resulting plus of the profit does not compensate the construction costs.

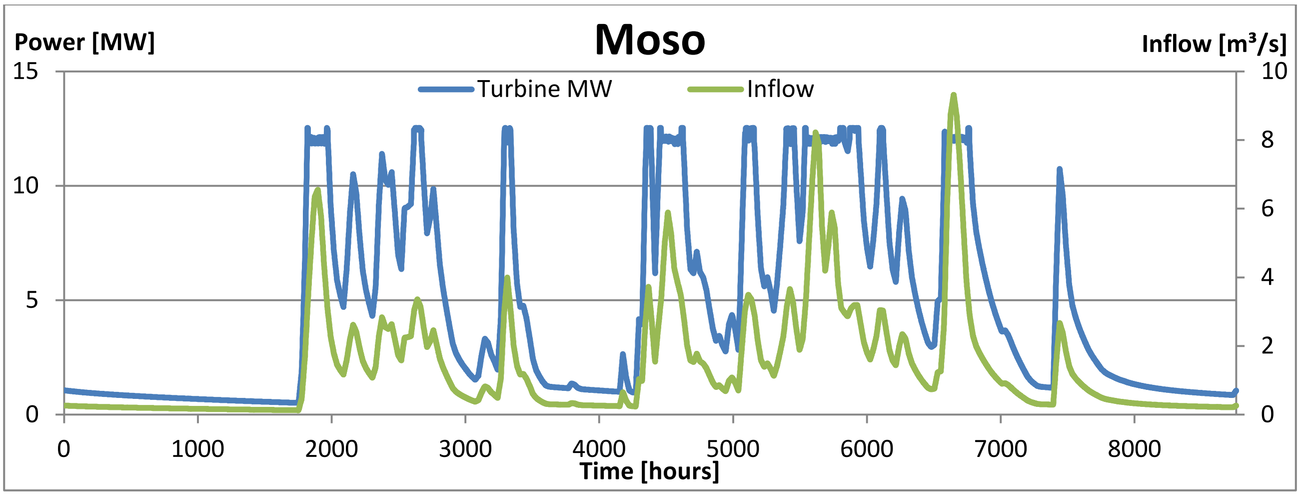


**Figure 4.3.9: Moso power plant, simulation for the year 2005**

For small reservoirs, an adaption to price variation is possible, but only in a small range. Profits for storage power plants and pumped storage plants are higher. For comparison table 4.3 lists the parameters of four power plants: the run of water power plants Kastelbell and Töll, and the storage power plants Bruneck and San Antonio. Most obviously the parameter profit per MWh produced proves the benefit of a big storage facility. Holding back water for later turbining implies the need for a higher installed capacity to handle the accumulated volumes. Downstream power plants profit of the time management of upper power plants with big reservoirs, if they are close enough. On the other hand the opposite is the case if they are too far away. For this consideration, the model describes reality only if upper and lower plants cooperate, i.e. they are owned by the same company.

Simulation of the year 2005:

| | Run of water power plants | | Storage power plants | |
|---|---|---|---|---|
| | Töll | Kastelbell | Bruneck | San Floriano |
| Reservoir Volume [1000m³] | 6 | 44 | 4800 | 11500 |
| MW | 28.6 | 87 | 42 | 135 |
| Profit [million €] | 11.83 | 36.12 | 9.06 | 36.67 |
| GWh produced | 187681.38 | 574860.58 | 133.47 | 501.78 |
| €/MWh | 63.03 | 62.84 | 67.86 | 73.08 |

**Table 4.3: Comparison of run of water and storage power plants**

The ratio of profit to MWh in relation to reservoir size is demonstrated in figure 4.3.10. The blue bars represent the reservoir size and the numbers attached to the bars indicate their related profit per MWh. Pumped storage plants are omitted in this figure. The power plants with no notable catchment show ratios of 56 to 58 €/MWh.

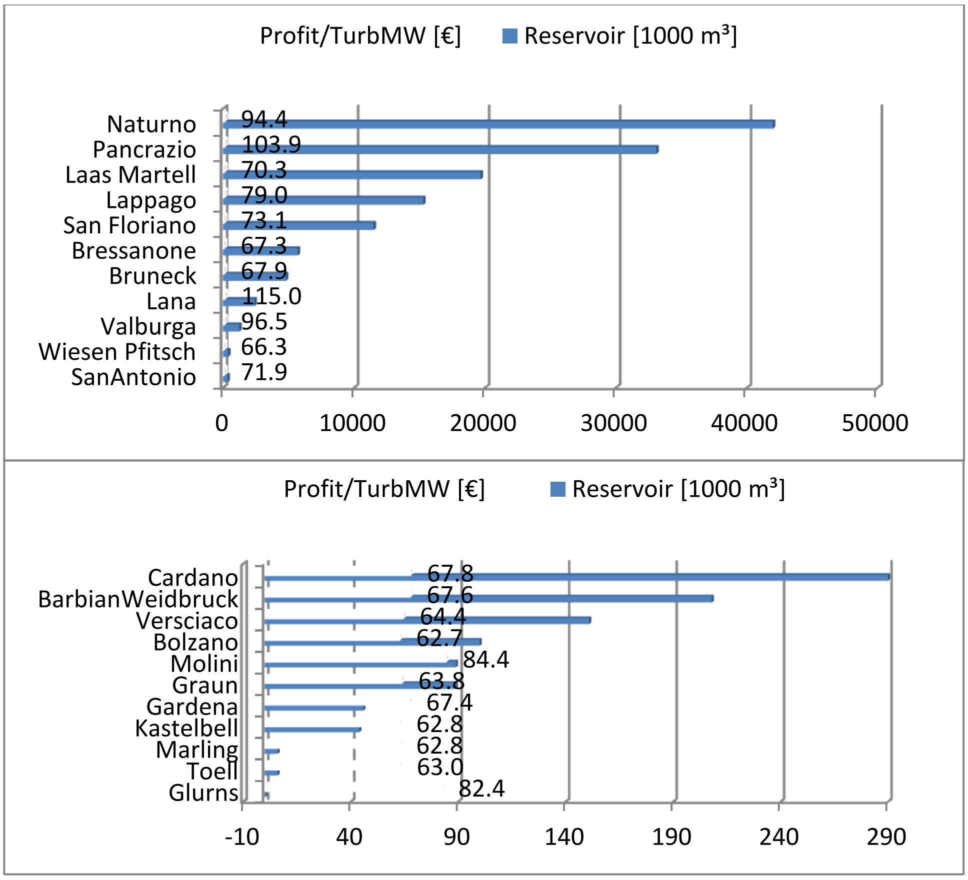



**Figure 4.3.10: Reservoir size and profit/MWh**

Turbining activities are very similar for the simulations of the single year runs and the 2005-2007 run. For the single year runs values of maximal turbining activities reach 1.505 GW, the multi year run from 2005 to 2007 has a maximum of only 1.360 GW. For the 2005 to 2006 simulation, on the other hand, values again go up to 1.505 GW. The electricity produced varies from 5.1 TWh in the year 2005 to 6.1 TWh in the year 2006 to 5.8 TWh in 2007. This is in good agreement with figure 1.8, since the smallest hydro power plants were not included.

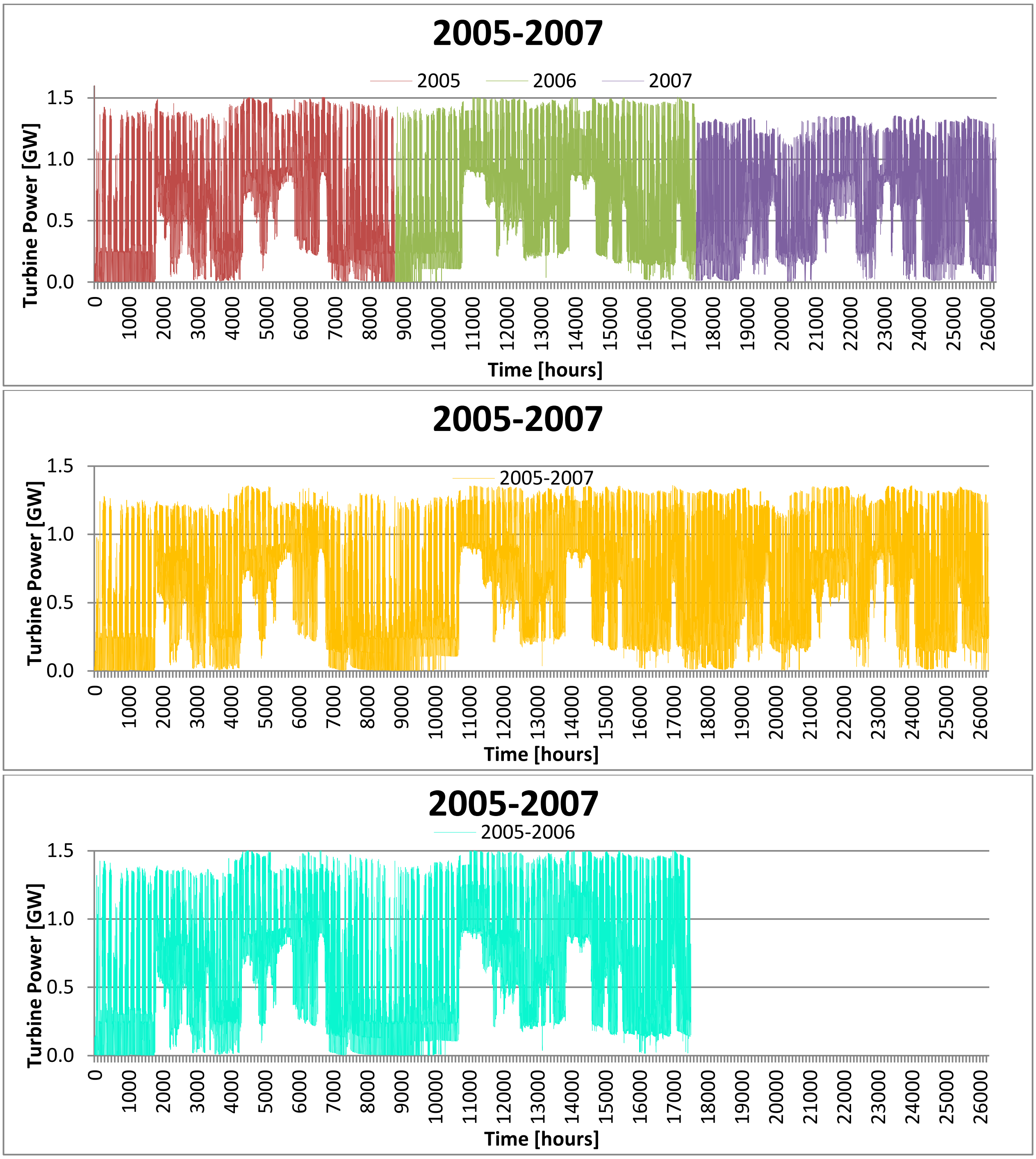



**Figure 4.3.11: Total turbining activity for different simulations**

Profits per year are listed in table 4.3. These values are obtained by simply multiplying the PUN price by the currently active turbine power. Expenses and other economic factors are ignored, so the term profit is only partly correct. Peculiar about these numbers is the fact, that the multi year runs do not yield higher profits. The model should be able to optimise the profit even better if it deals with two or more years at once. After all, multiple year runs should yield at least profits as high as the ones for single year runs, since the model would have the liberty to run them as if they were single years. The only restricting parameter is the energy content. As mentioned before, energy contents of beginning and end of a simulation have to be the same. For every simulation the model chooses different energy contents for the beginning. Nevertheless, the difference of the profits is rather small, i.e. below 4 percent. The difference of single year runs among each other are justified by precipitation variation. The total inflows into all simulated power plants were calculated as mentioned in chapter 4.2.1.

| | Profit [million €/a] | Inflow [million m³/a] | Production [TWh/a] | Profit [€/MWh] | Average price [€/MWh] | Profit/ avg. price |
|---|---|---|---|---|---|---|
| 2005 | 389 | 0.99 | 5.31 | 73.17 | 58.59 | 1.249 |
| 2006 | 552 | 1.16 | 6.13 | 90.11 | 74.75 | 1.205 |
| 2007 | 511 | 1.13 | 5.78 | 88.42 | 70.99 | 1.246 |
| 2005-2007 | 466 | 1.09 | 5.59 | 83.43 | 68.11 | 1.225 |
| 2005+2006+2007 | 484 | 1.09 | 5.74 | 84.31 | 68.11 | 1.238 |
| 2005-2006 | 470 | 1.08 | 5.71 | 82.27 | 66.67 | 1.234 |
| 2005+2006 | 471 | 1.08 | 5.72 | 82.24 | 66.67 | 1.234 |

**Table 4.3: Profits and production for different simulation intervals**

| | Profit [million €/a] | Inflow [million m³/a] | Production [TWh/a] | Profit [€/MWh] | Average price [€/MWh] | Profit/ avg. price |
|---|---|---|---|---|---|---|
| 2005 | 381 | 0.99 | 5.12 | 71.77 | 58.59 | 1.225 |
| 2006 | 543 | 1.16 | 5.95 | 88.67 | 74.75 | 1.186 |
| 2007 | 502 | 1.13 | 5.60 | 86.93 | 70.99 | 1.225 |
| 2005-2007 | 458 | 1.09 | 5.40 | 81.94 | 68.11 | 1.203 |
| 2005+2006+2007 | 476 | 1.09 | 5.56 | 82.87 | 68.11 | 1.217 |
| 2005-2006 | 461 | 1.08 | 5.52 | 80.83 | 66.67 | 1.212 |
| 2005+2006 | 462 | 1.08 | 5.54 | 80.82 | 66.67 | 1.212 |

**Table 4.3.b: Net profits and net production for different simulation intervals, pumping considered**

## 4.3.2. Capacity extension model

In the extension simulations the model is free to upgrade every power plant's turbining and, if existent, pumping capacity. The costs of the amplification are assumed to be 900€ per additional kW of capacity [54]. This estimation does not include site specific conditions, but is rather an average cost. To test possible pumping upgrades, where only turbining was existing, five new pumping facilities were implemented. The locations were choosen by looking for storage power plants whose discharge level is very close to a lower reservoir. Including the two existing, seven pumped storage power plants were implemented: Fontana Bianca, Pracupola, Barbian Weidbruck, Laas Martell, Valburga, Pancrazio and Graun. The remaining 29 unchanged power plants were available for upgrading only in turbine capacity. For the new version of Barbian Weidbruck, pumping and turbining was checked by comparing it to the PUN. The first 10 days of January show the expected behaviour, like in the previous simulations of the already installed and tested Fontana Bianca pumped storage plant.

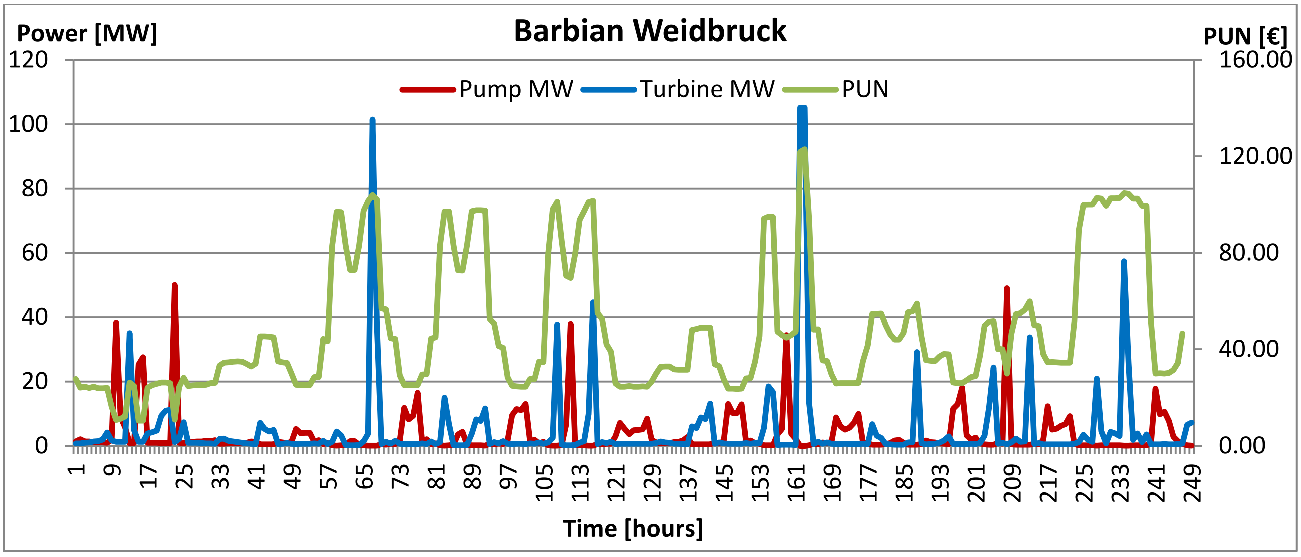



**Figure 4.3.12: Barbian Weidbruck with extended power and pumping, simulation of the year 2005**

Originally, the Bolzano province had 1.5 GW of hydro power capacity (chapter 4.2.2). For the simulation of the year 2005 the model suggests a build up of another 9.4 GW, for the year 2006 12.0 GW, for the year 2007 13.5 GW, for the multi year run 2005-2007 13.5 GW and the multi year run 2005-2006 10.3 GW. The deviations are caused by variable water inflows and electricity prices. Considering the investment costs of 900€/kW, this means total costs of 8.46 to 12.15 billion €. Table 4.4 shows that the profit can compensate this huge investment.

For a more precise analysis of the simulations the overall energy content is depicted in figure 4.3.13. In contrast to the simulation of the original power plants (figure 4.3.3), the extended capacity of pumped storage plants creates an additional high frequency oscillation of the energy contents.

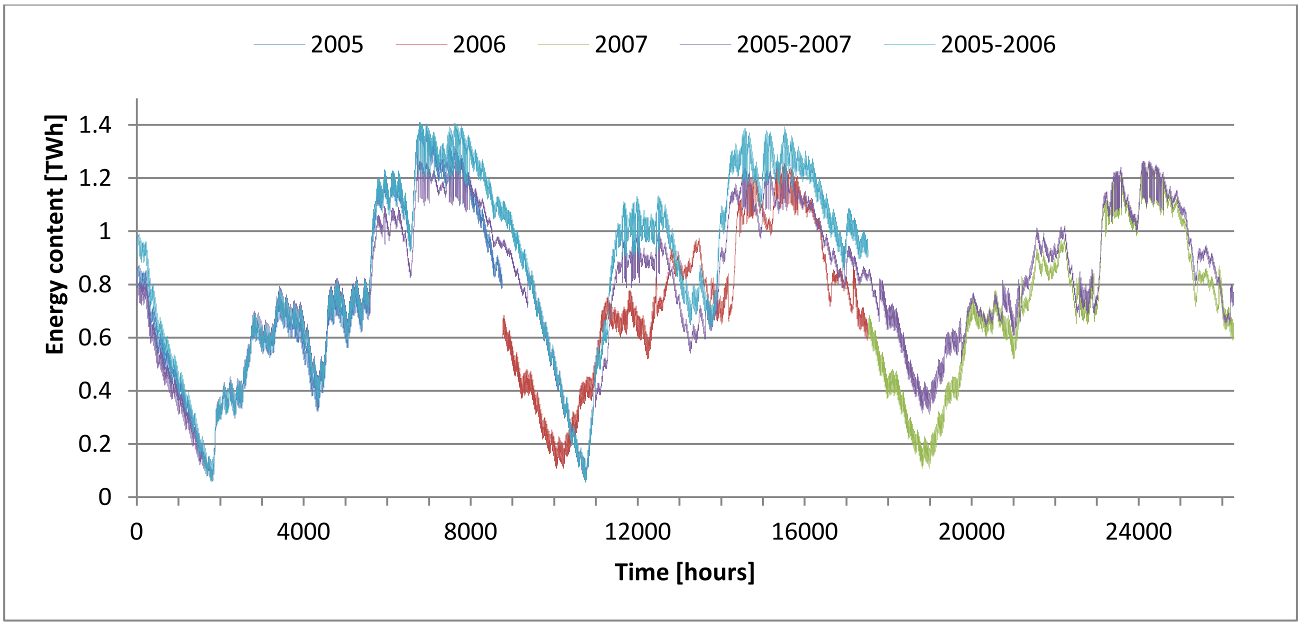



**Figure 4.3.13: Overall energy content for the years 2006 to 2007**

Due to the higher installed power, the switching on and off of the turbines follows price variations more closely. The turbines do not work at medium price levels, but only at the peak of prices. In a delineation (as in figure 4.3.11) high oscillation rates obscure all structures:

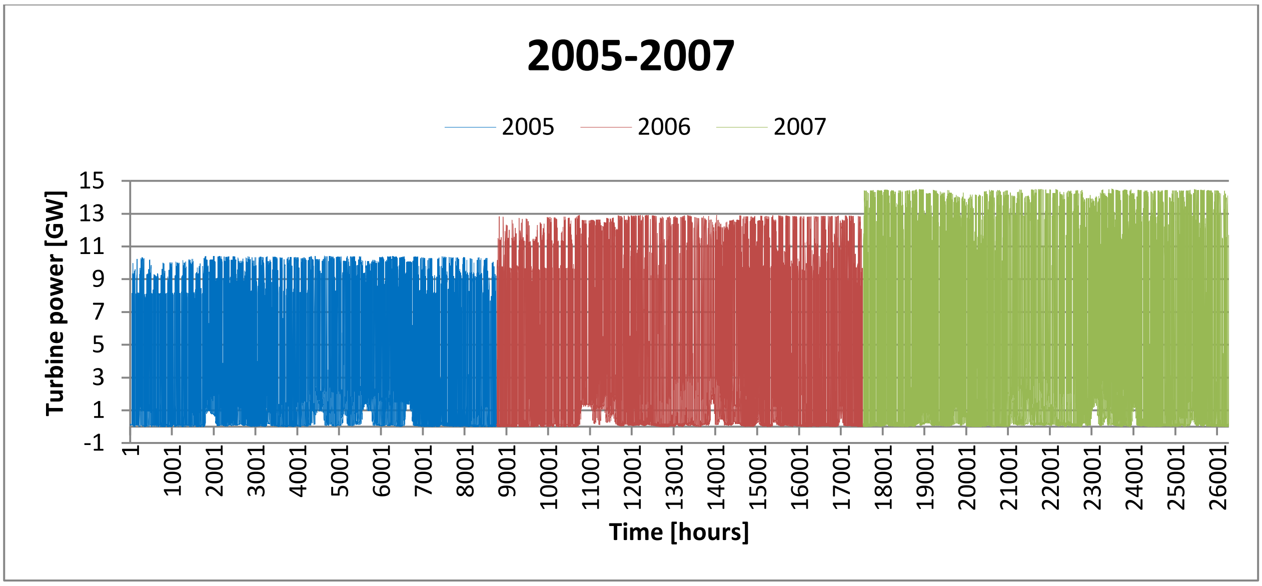



**Figure 4.3.14: Total turbining activity for different simulations**

A closer look at a smaller time interval reveals the distribution. Figure 4.3.15 contrasts turbining with the electricity prices in the first two weeks of January in 2005. Working hours are restricted to small time intervals.

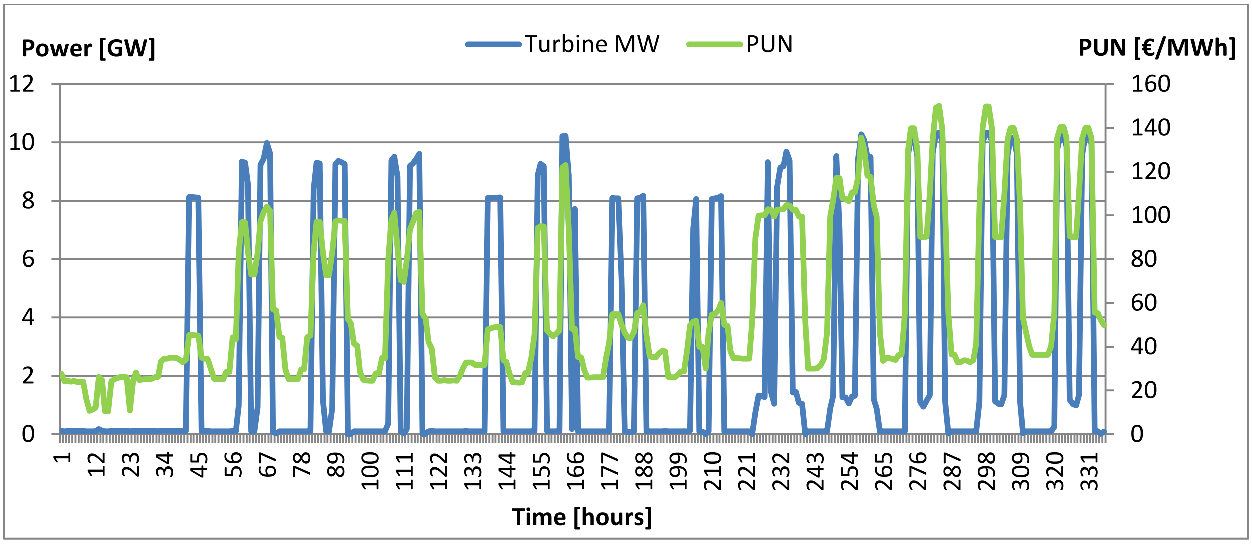



**Figure 4.3.15: Total turbining activity, first two weeks of January in 2005**

The effect of the extension of capacities on net electricity production is rather small. Pumping consumes a lot more than natural production creates by inflows. Nevertheless, the profits rise drastically. In this case the net production of electricity means the total turbining generation reduced by the pumping input.

## 4.3.2. Profits

Annuity for a span of 35 years accounts for 73 € per year per kW. For a 12 GW upgrade this means yearly costs of 876 million €, on the contrast to 1800 million € of profit. Assumptions, however, did not include the strength of the power grid surrounding the power plants. Large flows of electricity due to large capacities of the power plants would push the existing power network to its limits. An installed power of 12 GW represents 20 % of Italy's maximum load (maximum load of the year 2007: 56.82 GW, [56]). Installations this large are very likely to change electricity prices. Therefore the estimations are only an upper limit for the profits. Furthermore, gradients of the electricity prices will change due to growing photovoltaic installations, possibly reducing peak prices.

| | Original capacity | | | Extended capacity | | |
|---|---|---|---|---|---|---|
| | Production [TWh/a] | Net prod. [TWh/a] | Profit [million €/a] | Production [TWh/a] | Net prod. [TWh/a] | Profit [million €/a] |
| 2005 | 5.31 | 5.13 | 381 | 26.17 | -1.08 | 1340 |
| 2006 | 6.13 | 5.96 | 543 | 28.44 | 0.19 | 1958 |
| 2007 | 5.78 | 5.60 | 502 | 30.58 | -1.41 | 2252 |
| 2005-2007 | 5.59 | 5.40 | 458 | 28.46 | -0.59 | 1826 |
| 2005+2006+2007 | 5.74 | 5.56 | 476 | 28.40 | -0.77 | 1850 |
| 2005-2006 | 5.71 | 5.52 | 461 | 27.31 | -0.21 | 1621 |
| 2005+2006 | 5.72 | 5.54 | 462 | 27.31 | -0.45 | 1649 |

**Table 4.4: Comparison of normal capacity and extended capacity model**

## 4.4. Outlook

Model simulations in this thesis were done extensively with data from the province of Bolzano. On the one hand, Bolzano accounts for a large part of Italy's hydro power, namely 14.3 % (2008: 5.5 GWh, [55]), on the other hand, this represents only 1.8 % of the total electricity production in Italy.

Simulations showed the reliability of the model. The simulated production of the power plants was in accordance with historical data, in a quantitative manner as well as related to timed activity.

Work with the "extended capacity model" suggested an upgrade from 1.3 GW to 12 GW installed hydro power in the province of Bolzano. In this scenario the actual production changes insignificantly, but excessive use of pumping allows immense profits. The feasibility of these extensions with respect to the grid capacities was not examined, but the extent of the build-up seems disproportionate.

For a more representative simulation more data for the whole of Italy is needed. The data used in this thesis covers nearly 90 percent of the power plants of Bolzano, but only 75 % of Italy. Implementing the remaining power plants of Italy remained impossible due to the lack of data concerning dams and reservoirs and relations between them.

Proper inflow data for all reservoirs are essential for a more precise simulation.

As a conclusion, it can be said that the models produce reliable data, as far as precise input information is available. In order to procure these data, more time and work or collaborations would be needed. The trend to an increase of renewable power is obvious. Italy's share of renewable energy of the gross primary energy consumption in 2010 was 10.1 percent. Italy's aim is to reach 17 percent by 2020. Italy's model, fed with appropriate data, is able to simulate this high share of intermittent energy production and show extension potentials.

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