TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

DIPLOMARBEIT

Research for a linear optimised power model of Italy with focus on the hydro power system of Veneto

Ausgeführt am Institut für Analysis und Scientific Computing

der Technischen Universität Wien

unter der Anleitung von

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Wien

Wien, Oktober 2014

Abstract

Electricity and power generation are of high interest nowadays. Nevertheless new aspects have to be considered, i.e. sustainability and renewable energies are in the centre of attention. Since the European Union was founded the member states as well as the rest of Europe started to increase their collaboration. Hence there is a need of coordinating the energy policy. First of all it is important to have an overview of the European power network. In 2010 the Vienna University of Technology started the 30 months lasting AutRES100 project which concentrated on the power network of Austria. This project is now extended to whole Europe. The focus of this thesis is on the region Veneto which is located in the northern part of Italy and is an important energy exchange partner of Austria.

The thesis starts with an introduction and overview of the energy market. The current energy markets of the world, the European Union and Italy are described and the goals for the future are discussed. The next section deals with hydroelectric power considering the different plant types, their set-ups and other basic aspects. Then a short presentation of the chosen region Veneto follows.

The most time-consuming part of this thesis is finding the input data for the model. Unfortunately no complete and reliable database of hydroelectric power plants of Italy exists. The model used is the one developed for the AutRES100 project i.e. the data have to be adapted to this model. Finally it is solved using the Simplex and the Interior Point Method which are both algorithms for linear optimisation.

At the end of this thesis some model simulations are presented. Outcomes are beside others the turbine activity, the energy content and the revenue of each power plant. First simulations considering the existing power plants of Veneto are discussed to decide whether the model gives reliable results. Later on the input data are modified by increasing the turbine power or by installing a pump in order to find out whether such a change of the power plant parameters would be economically advisable and which effect it has on the behaviour of the power plants. It is found that the model of the AutRES100 project can be used for the region Veneto because all the results are in good agreement with the expectations and are internally consistent. Moreover it can be concluded that the hydroelectric power production of Veneto has the potential to be improved economically just by installing turbines with higher powers or pumps.

Zusammenfassung

Elektrizität und Energieerzeugug sind heutzutage von großem Interesse. Nichtsdestotrotz müssen neue Aspekte beachtet werden, d.h. Nachhaltigkeit und erneuerbare Energien spielen eine zentrale Rolle. Seit die Europäische Union gegründet wurde, begannen die Mitgliedsstaaten sowie der Rest von Europa ihre Zusammenarbeit zu intensivieren. Daher besteht der Bedarf die Energiepolitik zu koordinieren. Zunächst ist es wichtig, einen Überblick über das europäische Stromnetzwerk zu bekommen. Im Jahr 2010 startete die Technische Universität Wien das 30 Monate dauerende AutRES100 Projekt, welches sich auf das österreichische Stromnetzwerk konzentrierte. Dieses Projekt wird nun auf ganz Europa ausgeweitet. Diese Diplomarbeit beschäftigt sich mit der Region Venetien, welche sich im nördlichen Teil von Italien befindet und ein bedeutender Energieaustauschpartner Österreichs ist.

Die Diplomarbeit beginnt mit einer Einführung und einem Überblick über den Energiemarkt. Die gegenwärtigen Energiemärkte der Welt, der Europäischen Union und Italiens werden beschrieben und die Ziele für die Zukunft diskutiert. Das nächste Kapitel beschäftigt sich mit Wasserkraft und betrachtet die unterschiedlichen Kraftwerkstypen, deren Aufbauten und andere grundlegende Aspekte. Dann folgt eine kurze Präsentation der gewählten Region Venetien.

Der zeitintensivste Teil dieser Arbeit ist die Eingabedaten für das Modell zu finden. Bedauerlicherweise gibt es keine komplette und vertrauenswürdige Datenbank für Wasserkraftwerke in Italien. Das verwendete Modell ist jenes, welches für das AutRES100 Projekt entwickelt wurde, d.h. die Daten müssen diesem Modell angepasst werden. Schlussendlich wird es mit der Simplex und der Interior Point Methode, die beides Algorithmen zur linearen Optimierung sind, gelöst.

Am Ende der Arbeit werden einige Modellsimulationen präsentiert. Berechnet werden unter anderem die Turbinenaktivität, der Energiegehalt und der Erlös der einzelnen Kraftwerke. Zuerst werden Simulationen, welche die existierenden Kraftwerke von Venetien betrachten, diskutiert um zu entscheiden, ob das Model zuverlässige Ergebnisse liefert. Später werden die Eingabedaten modifiziert, indem die Turbinenleistung gesteigert oder eine Pumpe installiert wird. Das Ziel ist es, herauszufinden, ob eine solche Änderung der Kraftwerksparameter wirtschaftlich ratsam ist und wie sie sich auf das Verhalten der Kraftwerke auswirkt. Es stellt sich heraus, dass, weil alle Ergebnisse in guter Übereinstimmung mit den Erwartungen und in sich konsistent sind, das Modell aus dem AutRES100 Projekt für die Region Venetien verwendet werden kann. Weiters kann geschlussfolgert werden, dass die Stromerzeugung durch Wasserkraft in Venetien das Potential hat wirtschaftlich verbessert zu werden, indem man Turbinen mit höherer Leistung oder Pumpen installiert.

Contents

1 Introduction and overview of the energy market

A lot of debates considering the change of energy production came up in the last few years. Nevertheless using renewable energies is not new at all. The contrary, they were the first possibilities of generating energy. However, things changed during the industrial revolution starting in the late 18^{th} century. In that period people began to use lignite, hard coal and crude oil as energy provider. Later on also natural gas was used. After some time it was noticed that the use of these fossil resources for energy generation had negative side effects on the environment and the climate. Hence rethinking started and ended in a trend towards renewable energy again. Thus these days environment- as well as climate-friendly ways to produce the needed energy are searched for. (Kaltschmitt et al., 2007)

Nowadays the access to energy, especially in first world countries, can be seen as a basic need. Above all we find a high need of energy in the economy. It is therefore not surprising that the energy consumption strongly depends on the economic growth. During the industrial revolution the economy started to boom and to grow rapidly which also caused a growth of the energy need. This economic growth slowed down in the last few years which had as a side effect the slow-down of the energy consumption growth. When talking about energy consumption there is a need of distinguishing between the OECD (Organisation for Economic Co-operation and Development) with its 34 members whose economies used to be strong on the one hand and the emerging countries with their emerging economies on the other hand. There is still a growth of energy consumption worldwide due to the emerging countries especially China and India whereas the energy consumption of the OECD members sank in four years in the period of 2007-2012. Summing up all the countries in the world a growth of energy consumption is noted but the growth rate is sinking e.g. in the year 2012 the world primary energy consumption rose by 1.8% and thus was lower than the ten-year average of 2.6%. (BP, 2013)

More details of the world's primary energy consumption can be found in table 1 where the energy consumptions of the world, the European Union and Italy are listed. Primary energy as defined by BP is 'commercially traded fuels, including modern renewables used to generate electricity' (BP, 2013) p.40. In the first years listed (2002-2005) the energy consumption rose all over the world as well as in the European Union and Italy. This trend stopped between 2005 and 2007. The consumption of primary energy sank in the European Union and Italy each about 1.5% from 2006 to 2007. This downwards trend held until 2009 with its maximum from 2008 to 2009. Due to the economic crisis the consumption of primary energy was reduced by 5.6% in the European Union and 6.6% in Italy from 2008 to 2009 (taking into account that 2008 was a leap year). Comparing these years to all the other years listed, one finds that the only time a decrease (of 0.8%) of the world's primary energy consumption is found from 2008 to 2009. This extreme value was followed by a rise of the consumption namely of 5.6% for the world, of 3.7% for the European Union and of 3.0% for Italy from 2009 to 2010 . Nevertheless this upwards trend could not be held for the next years in the European Union and Italy. Thus the little rise of energy consumption from 2009 to 2010 can just be seen as some kind of recompensation of the extreme decrease from 2008 to 2009 because comparing 2008 to

2010 a sinking consumption is found in the European Union and Italy. Moreover it is worth noting that there are quite different growth rates of 2011 to 2012 of the European Union and Italy which is due to the fact that the economy of Italy of the last years was weaker than the European average.

year	02	03	04	05	06	07
world	9597.8	9933.8	10409.9	10707.7	11005.6	11287.5
European Union	1743.1	1778.5	1807.5	1810.3	1818.2	1790.9
Italy	175.4	181.0	184.6	185.1	184.6	181.8
year	08	09	10	11	12	change 2012 over 2011
world	11438.7	11309.8	11943.4	12225.0	12476.6	1.8%
European Union	1788.0	1683.9	1745.6	1687.4	1673.4	-1.1%
Italy	180.4	168.1	173.2	169.6	162.5	-4.4%

Table 1: Consumption of primary energy (Million tonnes oil equivalent) (BP, 2013) p.40; growth rates are adjusted for leap year 2012

The sources for producing primary energy are manifold reaching from oil, coal, natural gases and nuclear energy to hydroelectricity and other renewable sources. As mentioned before during the industrial revolution coal and oil got the main sources for energy generation but have been being replaced ever since. Figure 1 shows the share of primary energy consumption of different sources of the last few years. First of all it can be seen that the world primary energy consumption is increasing every year minus the period from 2008 to 2009. Furthermore there is a clear slow-down starting at 2006 with its minimum at 2008 to 2009 when the world primary energy consumption rate sank for the first and only time due to the economic crisis in Europe. Moreover it is obvious that oil and coal still remain the main sources for primary energy consumption but until 2012 their shares have been decreasing to 33.1% and 29.9% respectively. On the other hand the consumption of energy of hydroelectricity and of other renewable sources have been increasing their shares having with a maximum value of 6.7% and 1.9% respectively in 2012. (BP, 2013)

Figure 1 gives a general overview of the world primary energy consumption. Nevertheless it is worth mentioning that the shares of primary energy consumption of different energy sources vary a lot in distinct countries or regions. A pattern of sources used to generate the needed primary energy of different regions of the world is shown in figure 2. The world is divided into six regions namely North America, Central and South America, Europe and Eurasia, Middle East, Africa and Asia Pacific (for detailed information on which country belongs to which region see (BP, 2013)). It can be seen that every listed region consumes primary energy produced from coal with Asia Pacific being the only region whose coal share is more than 50% and thus 69.9% of the global coal consumption is due to Asia Pacific. In contrast to this one finds the Middle East with a very little share of energy consumption generated from coal. The Middle East has two main sources namely oil and natural gas. These two sources (with almost equal percentage) provide nearly the whole primary energy consumed by this region. Hydroelectricity as the most important renewable source plays a role for every region minus the Middle East with very small

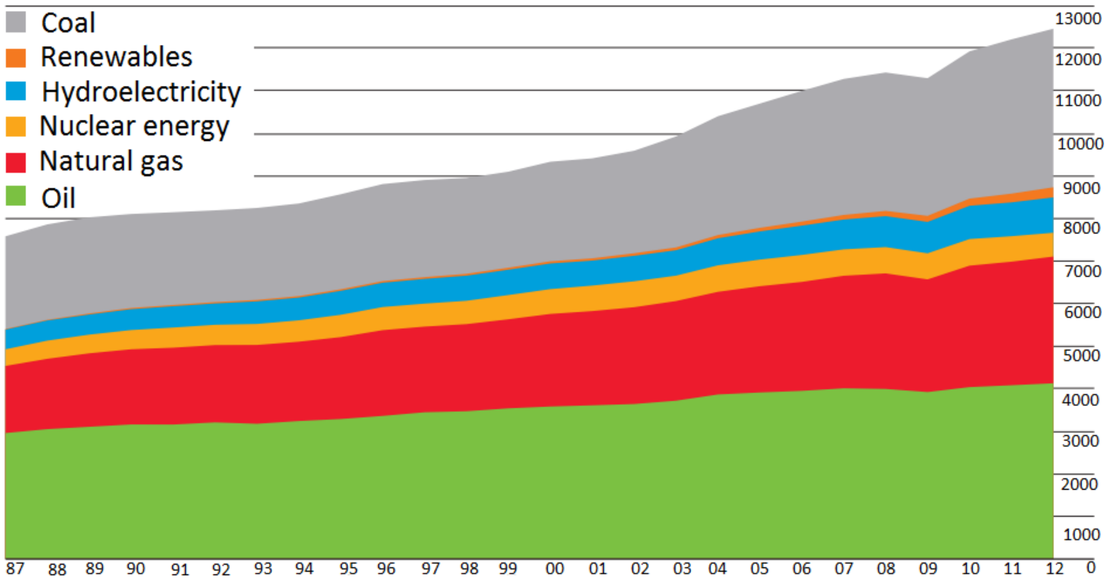


Figure 1: World primary energy consumption in Million tonnes equivalent for the years 1987 to 2012 (BP, 2013) p.42

percentage. The leading region when coming to hydroelectricity is South and Central America with about 25%. Other renewables do not play a leading role in any region but nevertheless there are regions where they give a certain contribution with Europe and Eurasia giving the leader with a share of 3.4% followed by South and Central America with 2.3% and North America with 2.1%.

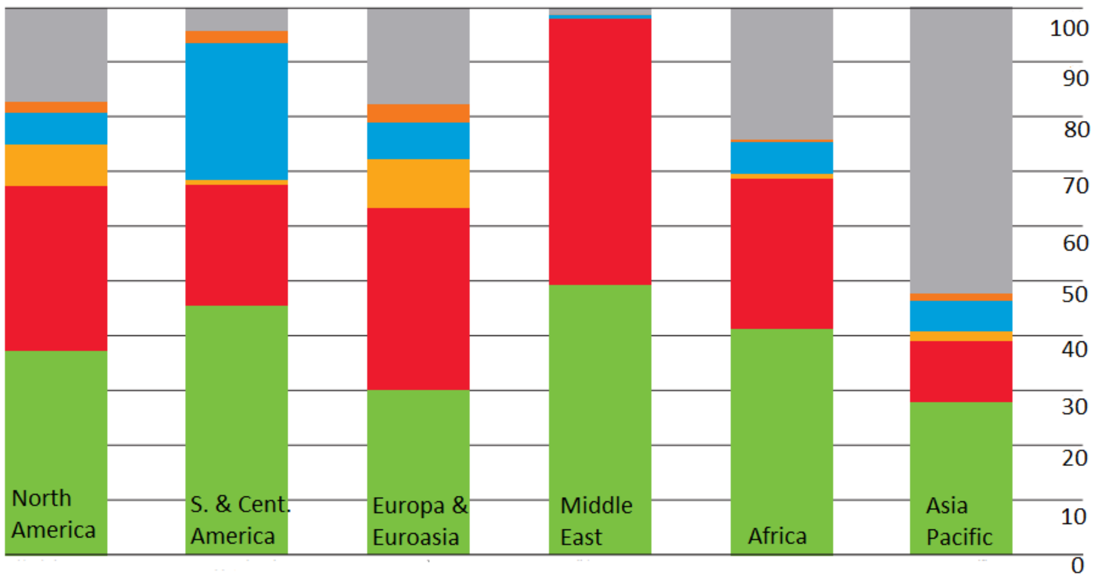


Figure 2: Regional consumption of primary energy in 2012 given in percent (BP, 2013) p.42 (the different colours represent the same as in figure 1)

The main focus of this thesis is on hydroelectricity thus the consumptions (based on gross primary generation) of hydroelectricity of the world, the European Union and Italy are listed separately in table 2. When having a look at statistical data of hydroelectricity one always has to keep in mind that hydroelectricity strongly depends on the environment and thus statistical data vary a lot due to the weather. Table 2 shows that in the period from 2002 to 2007 the European Union as well as Italy alone had their maximum values in the year 2004. This maximum is due to the fact that 2004 was a year with high precipitation. On the other hand in 2011 and 2012 there was less precipitation in Italy than in 2010 which gives a negative growth rate for 2012. These two outcomes show how high the dependence of hydroelectricity on the weather especially precipitation is. This connection will also play an important role later on in this thesis when we try to model the hydroelectricity output. However, it is not clear that the fact that the consumption of hydroelectricity in Italy sank from 2011 to 2012 is only due to the weather. Comparing Italy and the European Union one finds that the consumption of the European Union rose from 2011 to 2012 whereas in Italy it sank. Thus one may also conclude that the weak economy and thus the lesser need for energy in Italy also contributes to that minimum. Another fact which can be seen in this table is that the consumption of hydroelectricity of the world is increasing every year. This is due to two facts: First of all there is an increase of the share of hydroelectricity (see also figure 1). The second reason why a stable rise of consumption of hydroelectricity is found for the world but not for the European Union nor Italy is because the dependence of the weather is not so strong any more i.e. the effects of the weather fluctuations of the different regions balance each other.

year	02	03	04	05	06	07
world	598.5	697.1	635.2	662.2	688.1	700.7
European Union	72.4	69.7	73.3	69.6	70.3	70.6
Italy	8.9	8.3	9.6	8.2	8.4	7.4
year	08	09	10	11	12	change 2012 over 2011
world	727.6	737.7	782.1	794.7	831.1	4.3%
European Union	73.6	74.9	83.9	69.3	74.0	6.5%
Italy	9.4	11.1	11.6	10.4	9.4	-9.8%

Table 2: Consumption of hydroelectricity (Million tonnes oil equivalent) based on gross primary consumption (BP, 2013) p.36

Renewable energy has gained in importance especially in the last few years. The resource water persists the most important renewable energy source but nevertheless other sectors of renewable energy are growing. In table 3 the consumptions of renewable energy from other renewable sources such as wind, solar, geothermal, biomass and waste are listed for the world, the European Union and Italy. This table shows in more detail that there was a constant growth of the consumption of other renewable energy. The growth rate starting from 9.0% for the whole world, 17.3% for the European Union and 18.2% for Italy from 2002 to 2003, reached its maximum from 2010 to 2011 with 21.9%, 20.8% and 44.8% respectively. Comparing the growth values of this table 3 to table 2 showing the consumption of hydroelectricity and table 1 showing the consumption of primary energy the conclusion is that the other renewable energy sector is growing most. When considering renewables like wind or solar there is always a dependence on the weather whereas the production using geothermal, biomass or waste is not effected by a changing weather.

year	02	03	04	05	06	07
world	60.9	66.4	75.5	84.6	95.0	108.1
European Union	19.7	23.1	29.0	34.1	39.4	46.5
Italy	2.2	2.6	2.9	3.1	3.5	3.8
year	08	09	10	11	12	change 2012 over 2011
world	123.2	142.0	168.6	205.6	237.4	15.2%
European Union	52.7	59.1	68.3	82.5	95.0	14.9%
Italy	4.1	4.6	5.8	8.4	10.9	29.5%

Table 3: Consumption of other renewable energy such as wind, solar, geothermal, biomass and waste (Million tonnes oil equivalent) based on gross generation (BP, 2013) p.38

As shown in figure 2 the consumption of energy produced by using different sources vary a lot depending on the region. Hence Figure 3 gives a more detailed overview of the consumption of hydroelectricity and other renewables of different regions. As can be assumed from figure 2, Africa and the Middle East hardly consume energy generated from any renewable source and just Africa contributes a little to the hydroelectric consumption. The above-average of hydroelectric output growth rate is 4.3% with a high growth in Asia Pacific due to China. Having a look at renewables other than hydroelectricity an above-average of growth of 15.2% is found. At this growth the leading region is Europe and Eurasia which contributes 41.7% of the world market. Moreover a growth of both sections can be seen but it is very clear that the sector of other renewables grows a lot faster than the one of hydroelectricity. This is due to two facts. The first is that there are a lot of hydroelectric power plants so there is no big growing noticed if there are built a few new ones and the other is that there are regions especially along rivers where the possibility of building new hydroelectric power plants is exhausted whereas a lot of potential of building power plants for other renewable sources is found.

As mentioned before a trend towards renewable energy started. Even the European Union stated some goals to decrease greenhouse gas emission and to use more renewable energy sources for energy production. These goals were stated among others in the plan called *Europe 2020*.

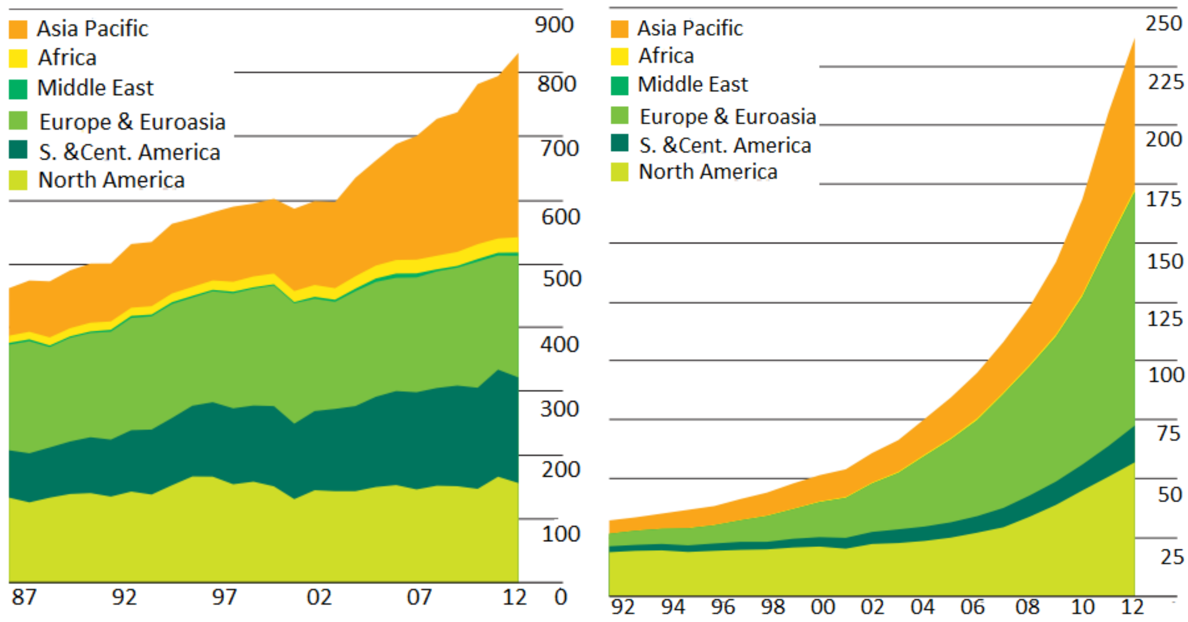
1.1 Europe 2020

Europe 2020 is the EU's growth strategy for the coming decade.

José Manuel Barroso

President of the European Commission (European Commission, 2010)

In March 2010 the European Commission set *a strategy for smart, sustainable and inclusive growth* (European Commission (a), 2010). Some targets for the year 2020 were stated with five main topics namely employment, innovation, climate change and energy,



(a) Hydroelectric consumption by region (b) Other renewables consumption by region

Figure 3: Consumption by region for either hydroelectricity or other renewable sources such as wind, solar, geothermal, biomass and waste (Million tonnes equivalent) (BP, 2013) p.37

education and poverty and social exclusion. The targets asserted for the climate change and energy sector are:

- The greenhouse gas emission should be at least 20% lower than that of the year 1990,
- the percentage of renewable energy produced should be at least 20% and
- the energy efficiency should be increased by 20%. (European Commission, 2010)

Beside these targets for the whole European Union there are special targets for every member state which were set by themselves in the National Reform Programmes in April 2011. The national targets for Italy for greenhouse gas emission and renewable energy are given as:

- The greenhouse gas emission should be 13% lower than that of the year 1990 and
- the percentage of renewable energy produced should be at least 17%. (European Commission, 2010)

In the following table 4 the percentage greenhouse gas emission for the European Union compared to 1990 as well as the share of renewable energy for the period of 2005 to 2011 are listed (for more details see (eurostat, 2013)). Comparing the percentage of greenhouse gas emission of 2005 to the emission of 2011 a reduction of 10.2% is found. Thus reaching the goal of having of 80% or less of the greenhouse gas emission of 1990 in 2020 (equates another reduction of 3% in nine years) seems very likely. On the other hand the target of a 20%-share of renewable energy produced seems harder to reach because its share was increased in six years by just 4.5% to 13% in 2011. Hence it has to be increased by 7% in nine years which means that the growth has to be accelerated a little.

year	05	06	07	08	09	10	11	target
greenhouse gas emissions to 1990	93.2	93.1	92.2	90.3	83.7	85.7	83.0	80
share of renewable energy produced	8.5	9.0	9.7	10.4	11.6	12.5	13.0	20

Table 4: Europe 2020 headline indicators in percent (eurostat, 2013)

Up to now a general introduction into the energy market and the European goal with little focus on Italy was given. Since this thesis is on hydroelectric power production in Italy the Italian power production is discussed in more detail in the following section.

1.2 Power production in Italy

In the early 1960s Italy started to produce nuclear power. After the Chernobyl disaster in 1986 a referendum forced the shut-down of all nuclear power reactors in whole Italy. In 2008 there was a big debate in Italy towards nuclear power again. The Minister of Economic Development Claudio Scajola wanted to build new reactors and to rise the share of nuclear power to 25% by 2030. The main argument of the minister was based on the high power price in Italy as well as the import dependence. (world nuclear news, 2008)

After the Japanese nuclear accident in 2011 the plans for building new nuclear power reactors were stopped and a referendum was held in June 2011 where 55.5% of the Italians voted with 94.28% against nuclear power in Italy. Thus the plans of Silvio Berlusconi's government to install nuclear power in Italy again failed. (Roe, 2011)

The number of renewable energy power plants is growing very fast in Italy. This growth is mainly caused by new photovoltaic (solar) plants as well as new bioenergy and wind farms. The following figure 4 gives an overview of the renewable energy power plants in Italy.

In this figure 4 the number and the capacity of power plants of different renewable sources for the years 2010 and 2011 as well as the percentage change are listed. It can be seen that in the years 2010 and 2011 most of the renewable energy of Italy was produced by hydroelectric power plants. Looking at the number of hydroelectric power plants it is interesting that in the year 2011 just about 10% of the power plants produced about 84% of the power. There are a lot of small hydroelectric power plants i.e. 64% of the power plants have a capacity less than 1MW. It is worth noting that from 2010 to 2011 one of the over 10MW power plants was closed down whereas over 100 of the less than 1MW power plants were taken into operation. The trend towards small and mini hydroelectric power plants could be observed over the last ten years. Thus the average size of a hydroelectric power plant in 2000 was 8.5MW whereas in 2011 it was just 6.2MW. This tendency is supposed to hold on in the next few years. Comparing the growth of the different sectors given in figure 4 we find no growth for geothermal power plants and hardly any growth (1.2% in capacity) for hydroelectric power plants whereas solar power plants list a huge

	2010		2011		2011 / 2010 % change	
	no.	MW	no.	MW	no.	MW
Hydro	**2,729**	**17,876**	**2,902**	**18,092**	**6.3**	**1.2**
0 _ 1 (MW)	1,727	523	1,858	568	7.6	8.5
1 _ 10 (MW)	700	2,210	743	2,328	6.1	5.3
> 10 (MW)	302	15,142	301	15,196	-0.3	0.4
Wind	**487**	**5,814**	**807**	**6,936**	**65.7**	**19.3**
Solar	**155,977**	**3,470**	**330,196**	**12,773**	**111.7**	**268.1**
Geothermal	**33**	**772**	**33**	**772**	**0.0**	**0.0**
Bioenergy	**669**	**2,352**	**1,213**	**2,825**	**81.3**	**20.1**
Biomass	142	1,243	170	1,289	19.7	3.7
- from municipal waste	*71*	*798*	*71*	*828*	*0.0*	*3.7*
- other biomass	*71*	*445*	*99*	*461*	*39.4*	*3.7*
Biogas	451	508	819	773	81.6	52.3
- from waste	*228*	*341*	*260*	*356*	*14.0*	*4.4*
- from slurries	*47*	*15*	*60*	*30*	*27.7*	*104.0*
- from animal dung	*95*	*41*	*165*	*89*	*73.7*	*116.3*
- from agriculture and forestry	*81*	*110*	*334*	*298*	*312.3*	*169.7*
Bioliquids	97	601	275	763	183.5	27.0
- vegetable oils	*86*	*510*	*234*	*654*	*172.1*	*28.2*
- other bioliquids	*11*	*91*	*41*	*110*	*272.7*	*20.1*
Total	**159,895**	**30,284**	**335,151**	**41,399**	**109.6**	**36.7**

Figure 4: Overview of all renewable energy power plants in Italy in the years 2010 and 2011 showing the number and capacity (GSE, 2012) p.7

growth of 268% in capacity. Even if hydroelectric power plants provided most of the energy capacity in 2011 it is not a growing sector at all. The growth rate as well as the capacity make it deem probable that in the following years solar power plants provided most of the energy of Italy.

As mentioned above Italy has to import a lot of energy. Figure 5 gives an overview of the national electricity balance of Italy of the year 2011. It can be seen that Italy had to import about 14% of its electricity which was 45.7 TWh in the year 2011 . Moreover the figure shows that the share of renewable electric energy was about a quarter whereas the share of conventional thermal energy meaning coal, natural gas and other fuels was more than 60%. Thus more than half of the electricity of Italy in the year 2011 was produced using non renewable sources of which natural gas takes the top position with a share of 42% of all electric energy production which was about 140 TWh. On the other hand hydroelectric energy production took the leading position in the renewable energy sector i.e. in the year 2011 13.5% of the electricity which was 45.3 TWh was produced by pure hydroelectric power plants not including pumped-storage which made up 0.6% or 1.9 TWh.

Having a look at the consumption side of figure 5 it is not a surprise to find industry as the main user of electricity. Thus in the year 2011 nearly half of all the electric energy (44.6%) was needed in the industry. On the other hand in the private sector i.e. households 22.4% of the energy was used. Last but not least it is worth mentioning that not all the energy produced can be used because losses occur. In the year 2011 the grid losses were 20.8 TWh which is more than 6% of the whole energy.

In section 1.1 the targets for Europe 2020 for the energy production and the greenhouse

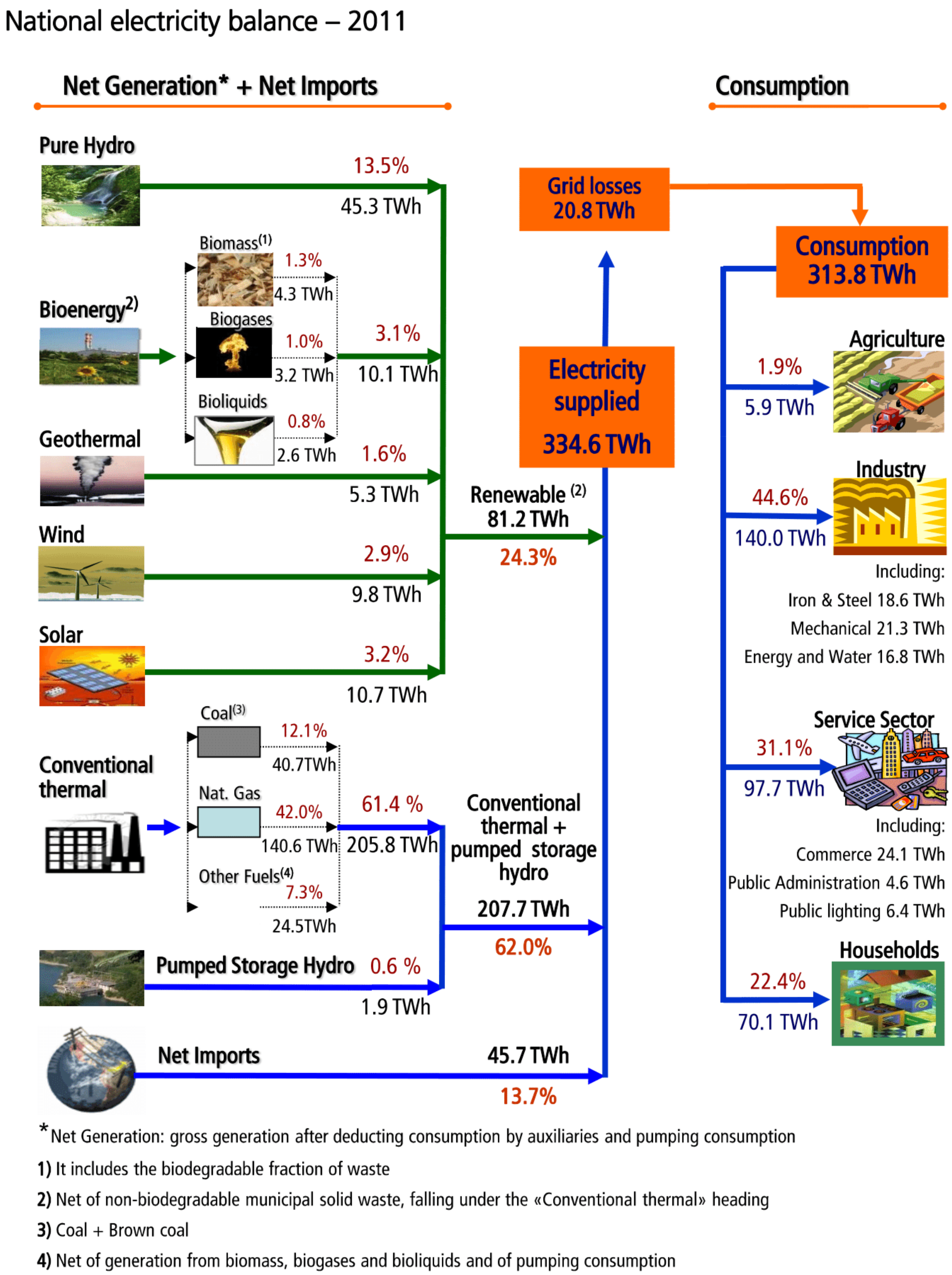


Figure 5: Electricity balance of Italy of the year 2011 (GSE, 2012) p.11

gas emission were discussed. In June 2010 Italy proclaimed a National Renewable Energy Action Plan which schedules a share for electricity consumption from renewables as at least 26.4% by 2020. The below figure 6 gives the progress towards this target. The trend visible in this figure makes it believable that the target of 26.4% of electricity consumption from renewables by 2020 will be achieved easily because in the year 2011 the share of renewable sources was 23.5% which was 3.9% higher than the target for 2011 of 19.6%. The quite high percentage is due to two effects. First of course the increase of renewable energy production and the second reason is the contraction of gross final energy consumption due to the economical situation of Italy. (GSE, 2012)

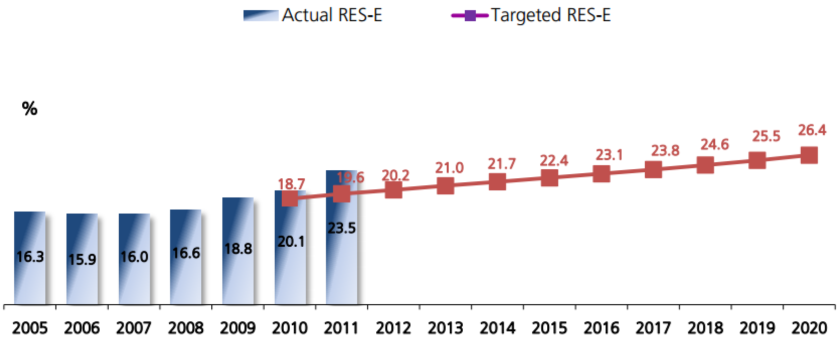


Figure 6: Progress towards the target in the renewable energy sector for electricity (RES-E)(GSE, 2012) p.14

In figure 7 details for the year 2011 are shown. The table lists values for normalised hydro and wind energy which means that these are not the actual values. Gestore dei Servizi Energetici (GSE) like other statistical institutes uses a normalisation formula to make it easier to compare the values. This normalisation formula which attenuates the effects of the changing weather in statistics can be found in (GSE, 2012) p.36. In the figure one finds that the value for normalised hydro energy outperformed the target value by 4.5% in 2011 and the values for normalised wind and bioenergy was surpassed by about 10%. The leading position takes energy from solar source because the target was exceeded by over 220% due to the fact that solar energy reached the target of 2020 in the year 2010. The only sector that does not fulfil the target is geothermal energy consumption.

Year 2011 GWh	GFEC RES		%
	Actual	Targeted	Actual / Targeted
Normalised Hydro	44,012	42,127	4.5
Normalised Wind	10,266	9,358	9.7
Solar	10,796	3,327	224.5
Geothermal	5,654	5,744	-1.6
Bioenergy	10,832	9,658	12.2
GFEC RES	**81,561**	**70,214**	**16.2**

Figure 7: Details of the gross final electricity consumption of renewable energy sources (GFEC RES) for the year 2011 (GSE, 2012) p.14

2 Hydroelectric Power

The last section provided an overview of the energy market with focus on hydroelectricity. Now a brief introduction to hydroelectric power plants and the occurring physical processes is given.

Nowadays one of the main foci when coming to power production is sustainability. Thus this section presents one of the main sectors of sustainable electric power production: hydroelectricity, which uses water as only resource. The usage of water for energy production dates back BC and the water wheel is considered to be the first invented machine to replace human muscle power.

Water can be found in three different states on the earth namely solid, liquid and gaseous. The following table 5 shows the distribution of water on our planet.

state	location	volume in ca. 10^3km^3	volume proportion in ca. %
gaseous	atmosphere	13	0.001
liquid	rivers and streams	1	0.00001
	fresh-water lakes	125	0.009
	groundwater	8 300	0.61
	oceans	1 322 000	97.2
solid	ice and glaciers	29 200	2.15
total		1 360 000	100.0

Table 5: Overview of water on earth (Kaltschmitt et al., 2007)

This table 5 illustrates that most, namely 97.2%, of the water on the earth is liquid and can be found in the oceans. All the water listed is under permanent change and undergoes a circle. Water, especially the one of the oceans, evaporates and later on precipitates amongst others as rain back to the earth. Figure 8 shows how much water evaporates from the sea and the soil during one year namely 425000km^3/a and 71000km^3/a respectively. The evaporated water condenses in the atmosphere and then precipitates back to the earth. About four fifth of the precipitation is over the seas and about one fifth is over the soil. The water in the soil splits into two parts of which the first part evaporates directly and the other seeps down to the ground water and thus to the seas where it is evaporated with the other water from the seas.

Moreover it is worth mentioning that beside this cycle water is also not homogeneous distributed on the earth. It hardly ever rains in some deserts whereas we have regular precipitation in Europe. Nevertheless the 'regular' precipitation in our regions is not very predictable. Some years have less precipitation whereas in other years big flooding is noted. The fact that the water undergoes such an unpredictable cycle makes it difficult to estimate the water amount provided for hydroelectric power use.

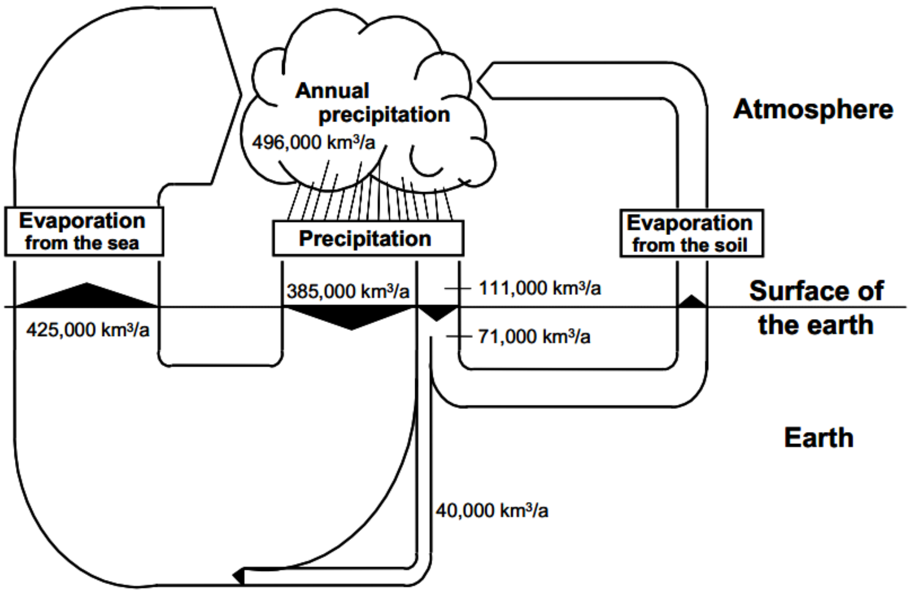


Figure 8: Overview of the water cycle on earth (Kaltschmitt et al., 2007) p.68

2.1 Principles of hydroelectric power

Hydroelectric power plants use potential energy of water to produce electric energy. Water flows from higher geodesic site to lower geodesic site due to gravitation. The flowing water has potential as well as kinetic energy. In order to describe those energies the flow is assumed to be stationary, friction-free and incompressible which allows the use of the *Bernoulli pressure equation* given by

$$p + \rho g z + \frac{1}{2}\rho v^2 = p_0 \tag{1}$$

with p the hydrostatic pressure, ρ the density of the fluid, $g = 9.81 m/s^2$ the acceleration of gravity, z the head, v the velocity of the fluid and $p_0 =$ const the total pressure. This equation (1) can be rewritten in the form of pressure level plus site level plus velocity level is constant.

$$\frac{p}{\rho g} + z + \frac{v^2}{2g} = \text{const} \tag{2}$$

This form of the Bernoulli equation and the differences of the pressure, geodesic height and flow velocity give an equation for the utilisable head z_{util} for the power production.

$$z_{util} = \frac{p_1 - p_2}{\rho g} + (z_1 - z_2) + \frac{v_1^2 - v_2^2}{2g} \tag{3}$$

This equation is idealised and does not contain any real losses like e.g. the losses caused by the friction of the water molecules. The differences of the pressure and the velocity in equation (3) are in general small in comparison to the geodesic height difference. Thus a first estimation is

$$z_{util} = z_1 - z_2. \tag{4}$$

Now as we have found the utilisable head we may focus on the potential energy stored in the head water. The potential energy E_{pot} is given by

$$E_{pot} = \rho g z_{util} V \tag{5}$$

with V the volume of the water. Thus the equation for the theoretical water power P in a hydroelectric power station is given by

$$P = \rho g \dot{u}(z_1 - z_2) \tag{6}$$

with $\dot{u}$ the volume-related flow rate.

Equation (6) is again a theoretical one which means just a part of this theoretical power can be used in real power stations. In order to get a more realistic form we take into account the part of the power that is lost for technical use for example because of energy transformation into heat due to friction. Thus a more realistic version of the Bernoulli equation (1) is given by

$$\frac{p_1}{\rho g} + z_1 + \frac{v_1^2}{2g} = \frac{p_2}{\rho g} + z_2 + \frac{v_2^2}{2g} + \eta \frac{v_2^2}{2g} = \text{const} \tag{7}$$

with a loss coefficient η. (Kaltschmitt et al., 2007)

2.2 Types of power plants

There are different types of power stations. Nevertheless there are no sharp classifications and a lot of combinations of the different types but there is a rough classification namely into low, medium and high head power stations which distinguishes the power stations according to the scale of their heads. Normally the classification says that low head power stations have a head up to 15 meters, medium head power stations refer to a head between 15 and 70 meters and the head of high head power stations is more than 70 meters. (Singh, 2008)

Moreover run-of-river power stations and storage power stations are distinguished. Run-of-river power stations do not have big storages but a weir to control the water of the river. Nonetheless some of these power plants also have pondages to store a little amount of water. This kind of power plants provide power continously with some small variation due to the seasonal dependence of the river flow. Hence run-of-river plants are good provider for base load. On the other hand there are storage power stations which in general have big reservoirs to store the water. Thus potential energy is stored in order to release it when needed. These power plants serve to overcome peaks in electricity demand. A special form of storage power plants are pumped-storage power plants of which an illustration is shown in figure 9. Such power plants pump water from geodetic lower reservoirs to higher ones during low cost peaks. Later on, during peak demands, the falling water is used to generate energy as in usual hydroelectric power plants. Thus pumped-storage power plants serve to optimise and stabilise existing power generation. It is worth mentioning that all kinds of energy storage always involve energy losses which means that more energy is needed to pump the water to the upper reservoir than is gained from the falling water. In European countries about 5% of the power generation comes from pumped-storage.

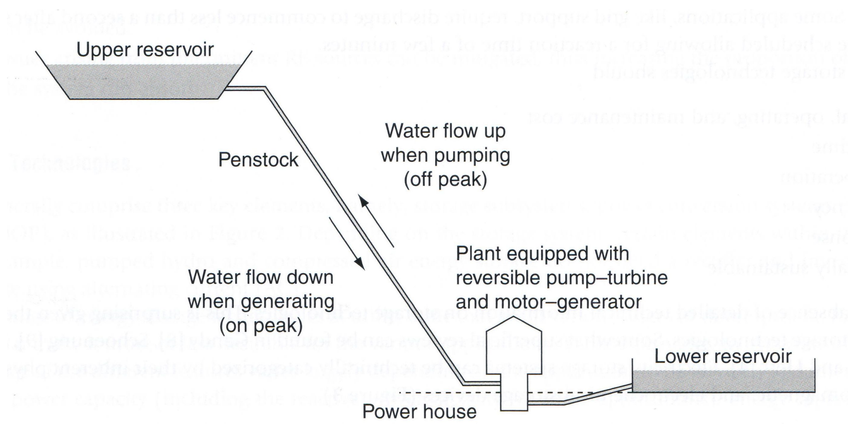


Figure 9: Schematic illustration of a storage hydroelectricity power plant (Sayigh, 2012) p.412

Further information on the different classification can be found in (Kaltschmitt et al., 2007) p.353 ff and (Singh, 2008) p.90 ff.

2.3 Set-up of a power plant

As mentioned in the previous section there are different types of power stations. Nevertheless there is a general set-up found in all of them. Figure 10 gives an insight into the set-up of a run-of-river power station which is with small modifications the same as in storage and pumped-storage power plants.

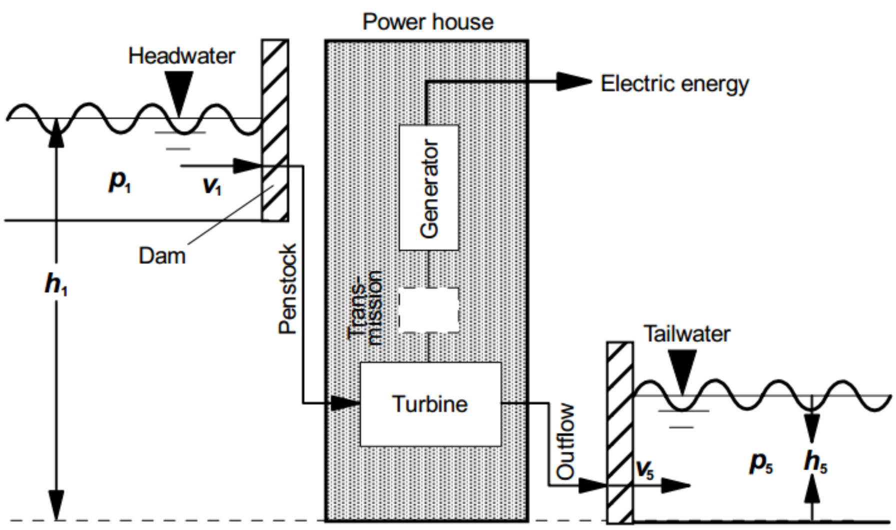


Figure 10: Schematic of a run-of-river power station (Kaltschmitt et al., 2007) p.353

In the upper left corner of figure 10 the headwater with pressure p_1, velocity v_1 at a geodesic height of h_1 is found. The headwater abuts on the dam from which the water is led via penstocks to the power house. The main components of the power house are the turbine and the generator. The turbine converts the energy of the water into mechanical energy and then the generator converts this mechanical energy into electric energy. Sometimes transformers can also be found in the power house. After the transformations in the power house the water is led to the tailwater at a geodesic height of h_5 with pressure p_5 and velocity v_5 via the outflow. The main parts of the power plant, namely the turbine and the generator, differ a lot depending on the plant configuration because there are several executions to gain the best efficiency of the power station.

2.3.1 Different components of a power plant

The first important part of a power station is the *dam* or also a weir or barrage. The job of the dam is to concentrate the natural head of the river or stream in one place and to control the water. The realisation of dams differ a lot i.e. every dam is a specific solution to its site circumstances and a balance between the technical and economic considerations. Once more there is no tough classification. However there are two generic groups according to the principal construction material namely embankment and concrete dams.

Embankment dams are more frequent because they are adaptable to a lot of site circumstances and thus provide less technical and economic effort. Such dams are built out of rockfill and/or earthfill. The face slops are similar for upstream and downstream and are of moderate angle. Moreover compared to the height they have wide sections as well as a high construction volume.

Concrete dams are built out of concrete or masonry. Another difference to embankment dams is that the face slopes are not similar. Thus the downstream face slope is generally steep whereas the upstream face slope is nearly vertical. Moreover depending on the type they have a narrow profile. To build such a dam advanced construction skills are need. Furthermore in general the construction of a concrete dam is more expensive than the one of embankment dams.

More details about the different dam types can be found e.g. in (Sayigh, 2012) p.28 ff.

A part of power stations just found in storage and pumped-storage ones is the *reservoir* where the water is stored. In some regions especially in mountainous regions there are natural lakes for water storage. If there is no natural reservoir it is built artificially. As mentioned above power stations with a storage are used to overcome peaks in electricity demand. Thus the reservoirs of these plants serve to control the water and to use it when needed.

The next part found in all power stations builds the *intake* which is the connection between the headwater and the power house with the turbine. The intake also includes trash racks and gates or stoplogs which help to let the power station run stable.

One of the two main components of power stations is the *turbine* which converts the energy of the water into rotation. In farmer times water wheels were used as turbines but they are hardly found nowadays. Since the amount and conditions of the water transformation differ a lot in different power stations the types of turbines vary a lot too. We distinguish between reaction and impulse turbines. The main difference is that reaction turbines transfer the pressure energy of the water into rotation whereas an impulse turbine converts the impulse of the water into velocity. The three most important types of reaction turbines are propeller, Kaplan and Francis with a maximum power of the Kaplan turbines of 500MW per unit and of the Francis turbines of 1000MW per unit. The most used impulse turbine is the Pelton turbine with a maximum power of 500MW per unit. Later on in the simulations Francis, Kaplan and Pelton turbines will be used. The different types of turbines serve for different head and flow rates. Figure 11 shows the range of application of the most common turbines. The Pelton turbine is used in power stations with high heads and low flow rates whereas the vertical Kaplan turbine is found for lower heads but bigger flow rates. The Francis turbine is the one with the biggest range of possible use.

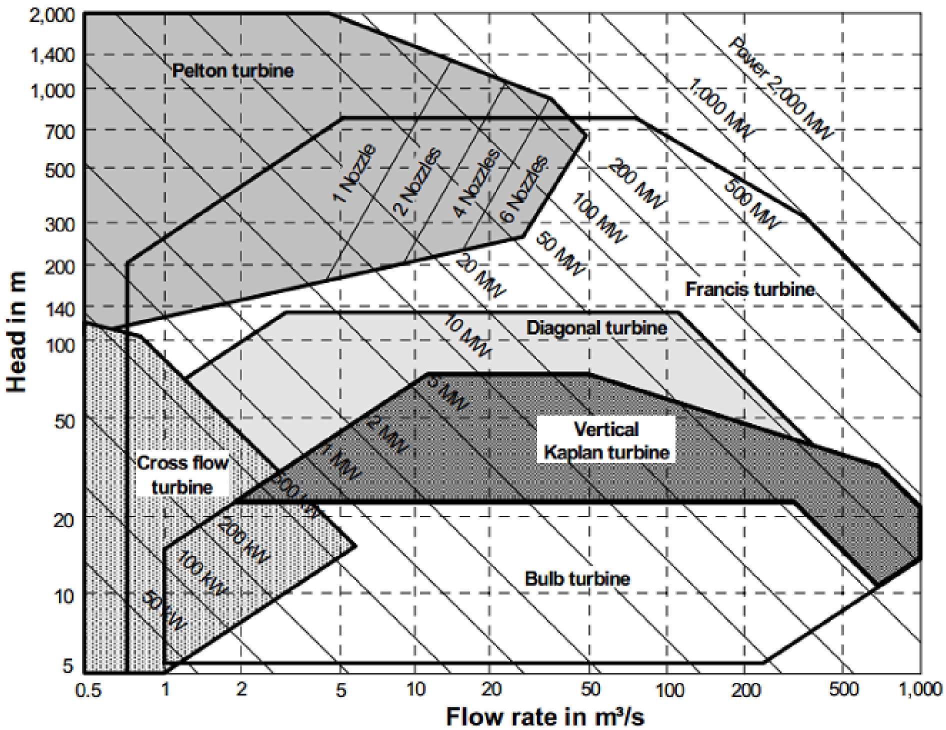


Figure 11: Overview of the range of use for the most common turbines (Kaltschmitt et al., 2007) p.362

Beside the different application ranges the various types of turbines have diverse efficiencies mostly between 85 − 93%. Since the turbines are designed for a certain flow the efficiency depends on it. This relation is shown in figure 12. It can be seen that the efficiency curves differ depending on the type of the turbine. On the one hand the Pelton turbine has a good efficiency even if the ratio of flow to design flow is about 0.2

whereas on the other hand the Francis turbine, especially the high speed one, has a good efficiency at ratios of 0.7. This means that Pelton turbines can be used in power stations with varying amount of water whereas Francis turbines require a constant inflow of water to work efficiently.

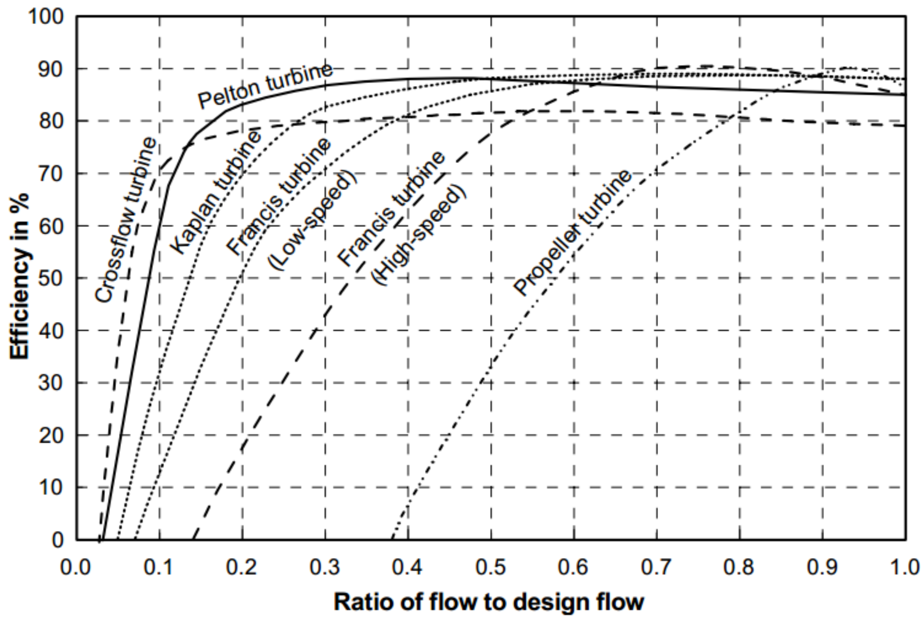


Figure 12: Dependence of the efficiency of a turbine on the ratio of flow to design flow for the most common turbines (Kaltschmitt et al., 2007) p.363

Since Kaplan, Francis and Pelton turbines will be used in the simulations later on the three types are explained in the following in more detail.

The *Kaplan turbine* which is a reaction turbine was invented by V. Kaplan in 1913. It is a reverse operating propeller with an axial flow through the turbine. The only exception is the vertical shaft Kaplan turbine whose flow goes radial. The runner blades of Kaplan turbines are adjustable which makes it usable for different flow rates and thus efficiency can be optimised. In comparison to that the efficiency of a propeller turbine with fixed runner blades is just high if the ratio of flow to design flow is high too (see figure 12). An illustration of a Kaplan turbine is shown in figure 13.

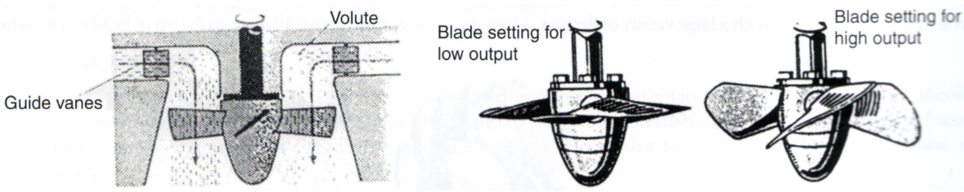


Figure 13: Kaplan turbine with its adjustable blades (Sayigh, 2012) p.26

Francis turbines (see figure 14) are also reaction turbines and have been developed from water turbines by J. B. Francis in 1849. The first big difference to Kaplan turbines is that the blades are fixed and cannot be adjusted. Thus the inflowing water has to be controlled which is done by guide vans most of the times. Another difference to Kaplan turbines is that Francis turbines cause a redirection of the flow. The water coming from the guide vans goes radially into the scroll case. After that it flows over the runner blades and goes out axially again. Two main types of Francis turbines are distinguished namely the so-called low-speed and high-speed runners which are divided depending on the speed of the rotating turbine wheels. In general the aim is to use a high-speed runner because the torques are lower at the turbine axis which allows a smaller machine dimension. On the other hand good efficiency is only reached if the ratio of flow to design flow is about 0.6 which rises the need for a nearly constant inflow rate. Such a constant inflow rate cannot be guaranteed easily. These two aspects have to be considered when deciding which turbine should be used.

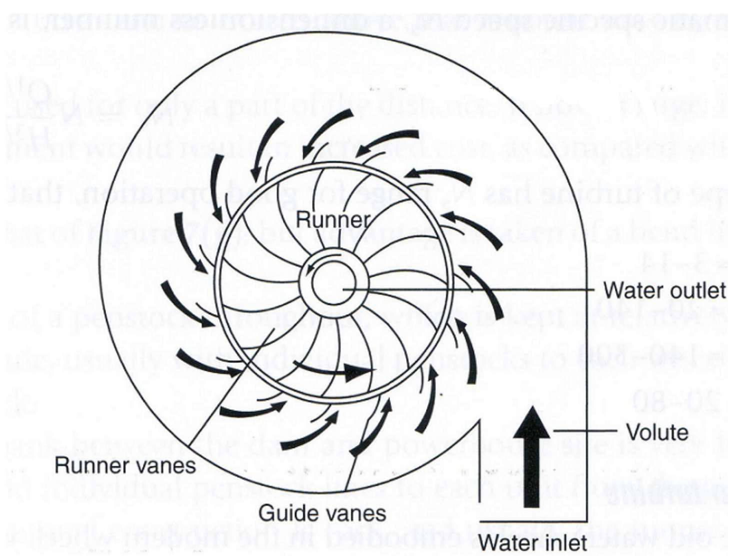
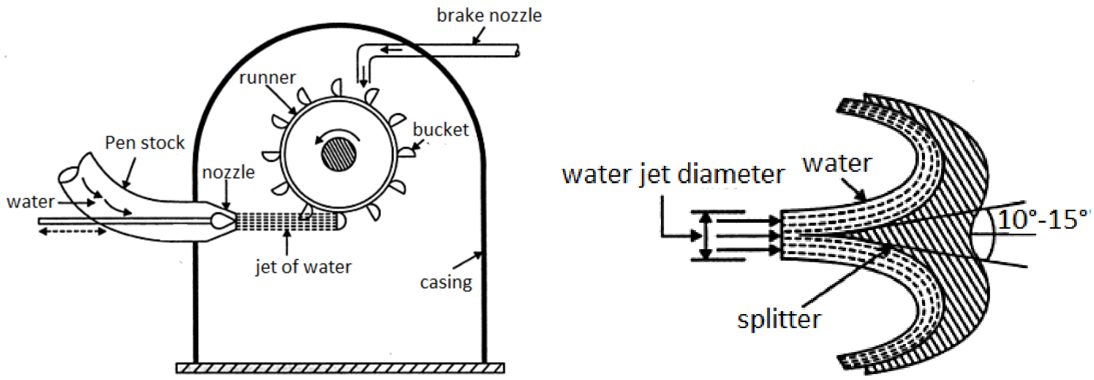


Figure 14: Illustrations of the Francis turbine (Sayigh, 2012) p.26

The *Pelton turbine* is the most used impulse turbine. It was invented by L. A. Pelton about 1880. A Pelton turbine consists of a runner called Pelton wheel with fixed buckets on it. Several nozzles produce a water jet which is led tangentially to the wheel into the spoon shaped buckets. The whole energy of the water is transferred to the Pelton wheel and thus converted into mechanical energy. Hence the water has nearly no energy when reaching the reservoir. High efficiency is reached in a wide range of ratio of flow to design flow. As can be seen in figure 12 the range goes from 0.2 to 1.0 which makes it a perfect turbine for power stations with highly variable flows. Figure 15 shows a Pelton wheel as well as a bucket.

The second indispensable part of a hydroelectric power station is the *generator*. This part is important because it converts the mechanical energy of the turbine into electric energy. There are several types of generators but the main principle is the use of Faraday's law of induction which describes how a magnetic field and an electric circuit interact to produce



(a) The wheel (b) The bucket

Figure 15: Illustrations of the Pelton turbine (Rajput, 2005) p.358

an electromotive force i.e. if an electrical conductor is moved in a magnetic field, voltage emerges along the conductor. Thus the mechanical energy of the turbine is used to move a conductor in a magnetic field in order to get voltage.

In some power stations there is also a *transformer* which raises or lowers the voltage. This is needed if the produced voltage does not correlate to the voltage of the fed grid. In general there are hardly any losses in such a transformation since efficiencies up to 99% are reached.

After the electric power has been produced the water flows through the *outflow* to the tailwater.

Furthermore there are a lot more components in a power station modified for the special needs of each constitutions. Nevertheless the main parts were focused on above.

(Kaltschmitt, 2007), (Sayigh, 2012)

2.4 Energy transformation

All the described components of a power plant interact and thus energy is transformed during the water makes its way through the power station. Figure 16 shows an overview of the energy transformation in a hydroelectric power station.

In the first step the potential energy of the water is transformed into kinetic and pressure energy which is led to the turbine where the energy is converted into mechanical energy. Depending on the design of the power station sometimes a transmission is necessary before the generator can convert the mechanical energy into electric energy. Such a transmission is just a transformation from mechanical energy into mechanical energy again. After the obligatory transformation into electric energy there are two options depending on the different constructions of power stations. If possible the electric energy is directly fed into the grid, if not a transformer is needed. Such a transformer transforms electric energy into electric energy again and thus converts the voltage to an appropriate

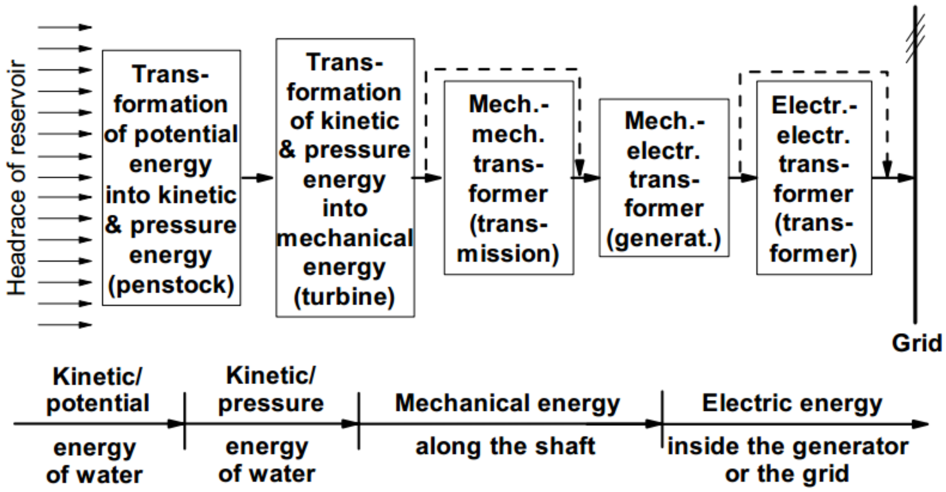


Figure 16: Overview of the energy transformations in a power station (Kaltschmitt et al., 2007) p.370

one which can be fed into the grid.

All these transformations come along with losses. Figure 17 gives an overview of these losses and shows that the biggest losses occur at the turbine. Moreover in general big losses are made at the intake as well as in the channels and the penstocks. All these losses cause that just a percentage of the theoretical available energy can be produced. In modern hydroelectric power stations this percentage is between 70 and 90% or even higher whereas for older ones the percentage is lower.

(Kaltschmitt et al., 2007)

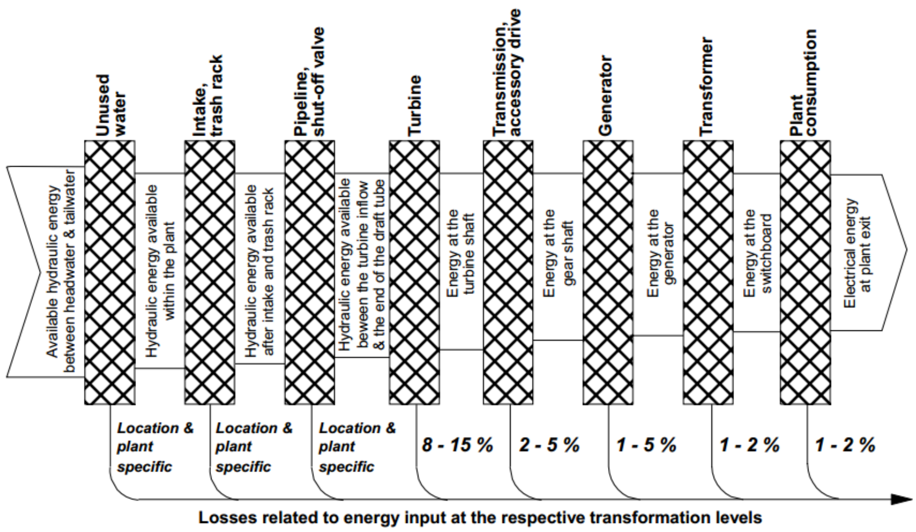


Figure 17: Overview of the energy losses in a hydroelectric power station (Kaltschmitt et al., 2007) p.371

2.5 Environmental effects of hydroelectric power plants

Since hydroelectric power stations are built into the nature and make use of a natural source they do have an effect on the environment. In the following a short overview of the effects is given.

First of all there are these environmental effects which occur during the fabrication of the components needed in the power station. These effects will not be discussed below since they are also found in any other power station and thus are not specific for hydroelectric power stations.

The main environmental pollution hydroelectric power stations cause is water pollution which starts when the power station is built. During the building process particles or soil may get into the stream by excavation or even more simple by inapt cleaned building machinery. When the power station is in use it sometimes occurs that oil pollutes the stream which in general is caused by improper handling of the hydraulic systems. These kinds of pollution are avoidable or at least can be kept to a minimum. The fact that there are no toxic substances used in hydroelectric power systems other than e.g. in nuclear power stations and the fact that environmental pollution can be minimised are great advantages of such power stations.

Beside this minimum of environmental pollution the construction of a hydroelectric power station effects the nature in other ways. First of all the needed impoundment has an impact on the ecological conditions of a stream. One main problem is that the flow velocity of the stream is reduced radically which has bad side effects. Firstly this causes an increase of sedimentation of small particles which then cover habitats of fish and other small biota which leads to the extinction of such animals in the stream. Moreover the reduction of flow velocity causes the increase of water temperature in the stream. This fact and the moving barrier due to the power station may change the composition of species in and around the stream dramatically. All these disadvantages are even increased if there are several power stations at one stream.

(Kaltschmitt et al., 2007)

2.6 Cost

Opponents of hydroelectric power often raise the argument that the construction of a hydroelectric plant is very expensive. Indeed there are high costs for the realisation of dams, reservoirs and power houses but the costs can be kept low by following some simple rules. First of all relative high head and small flow lead to low cost whereas low head and large flow give high cost. Moreover discharge assured by storage gives lower cost than variable flow with small minimum. The next condition is a good dam site meaning a narrow valley as well as a minimum of material in the dam versus bad dam site with a wide valley and a lot of material in the dam. Furthermore the number and size of turbines have to be considered. Thus a small number of large turbines favours low cost whereas a lot of small-capacity turbines favours high cost. One last requirement for low cost is keeping the transmission to market short.

Even if the building cost is high it has to be kept in mind that the energy gain of such power plants is very efficient. As mentioned above modern power plants may transform more than 90% (but at least more than 70%) of the energy of the moving water into electricity whereas the percentage for fossil fuel plants is about 60%. Moreover the energy payback ratio, which gives the ratio of the energy produced by a plant during its lifetime and the energy needed to build, keep up and run the generating equipment, has to be considered. Hydroelectric power plants have energy payback ratios of up to 200 whereas nuclear power plant have ratios about 16 and solar photovoltaic power plants about 9. Comparing these ratios hydroelectric power production is a cheap option.

The last point to be mentioned is that hydroelectric power is independent of the fuel price variation which means that it does not have any uncontrollable input price variation like sometimes found for power stations depending on fuel.

(Sayigh, 2012)

3 Veneto

Since a simulation of whole Italy would be very time-consuming this thesis focuses on Veneto which is the northernmost zone of Italy. A map of Veneto is shown in figure 18.

Figure 18: A map of the region Veneto from google maps

It is the eighth largest region of Italy with a surface area of 18364 km^2 and borders on Austria in the north, Trentino-Alto Adige in the northwest, Lombardy in the west, Emilia-Romagna in the south and Friuli-Venezia in the east. The topology of Veneto varies a lot i.e. there are Alpine zones, plains, lakes, lagoons and islands. In the very north the Dolomite Mountains are situated with the highest peak of Veneto named Marmolada. The Dolomites fade into the pre-Alpine and then into the sub-Alpine zone. After that one finds the vast plain making up more than 50% of Veneto's surface. The most important rivers crossing this region are Po, Adige, Brenta, Piave, Livenzaa and Tagliamento. Moreover the country's largest lake named Lake Garda is located in Veneto. The climate is overall sub-continental but varies a lot depending on the area. Thus it is milder near Lake Garda and along the Adriatic coast and colder in the mountainous areas. (Fabris, 2006)

The energy balance in Veneto is important for whole Italy since it has a border to Austria and thus energy exchange which is necessary for the energy balance in whole Italy takes place. Moreover due to the topology of Italy the distribution of power plant varies i.e. in the north hydroelectric power plants are favoured because of the mountainous topology whereas in the south less hydroelectric power plants are found.

4 Data research

In order to model the energy generation of hydroelectric power plants the first step is to find out details about the existing hydroelectric power plants. Moreover environmental effects have to be considered. Thus the next step will be to find out about precipitation and the consequential inflow to the systems.

4.1 Power plants

Italy does not have any data base with full information of all power plants. Thus the research for the existing power plants and their technical data was not an easy task. Hence a lot of time was spent on the collection of these data.

Power plants with a capacity higher than 10MW were considered. Searched-for items were above all location (coordinates), plant type (see section 2.2), turbine type (see section 2.3.1), turbine power, pump power, year of construction, dam, headwater and tailwater level and length of conduits. Some data like e.g. the year of construction were easily found whereas data like the headwater and tailwater level were hardly available. Furthermore the exact localisation of the power plants caused difficulties. The most reliable sources was Enel S.p.A. (Ente Nazionale per l'energia Elettrica) (Enel, 2014) which is the biggest Italian electric utility company.

In the following the focus will be on the river Piave because it is the most important river of the region Veneto. The following figure 19 illustrates all hydroelectric power plants along the river Piave and its affluents. Out of these 17 hydroelectric power plants fulfilling the criteria were found and included in the model. The exact location of these power plants is shown in figure 20.

4.2 Dams

The important properties of dams were the maximum and minimum water level, the volume, the surface, the location again as well as the inflow. This time the localisation was not as difficult as the localisation of the power plants because at least the bigger water surfaces could be seen with google earth. Moreover finding the data for the dams was a little easier because the book (Associazione Nazionale Imprese Produttrici e Distributrici di Energia Elettrica, 1961) gives an overview for at least the old dams (built before 1961).

There are 28 dams (including 13 run-of-river dams) which are relevant for our model. An overview of all dams and their geographical location can be found in the following figure 21.

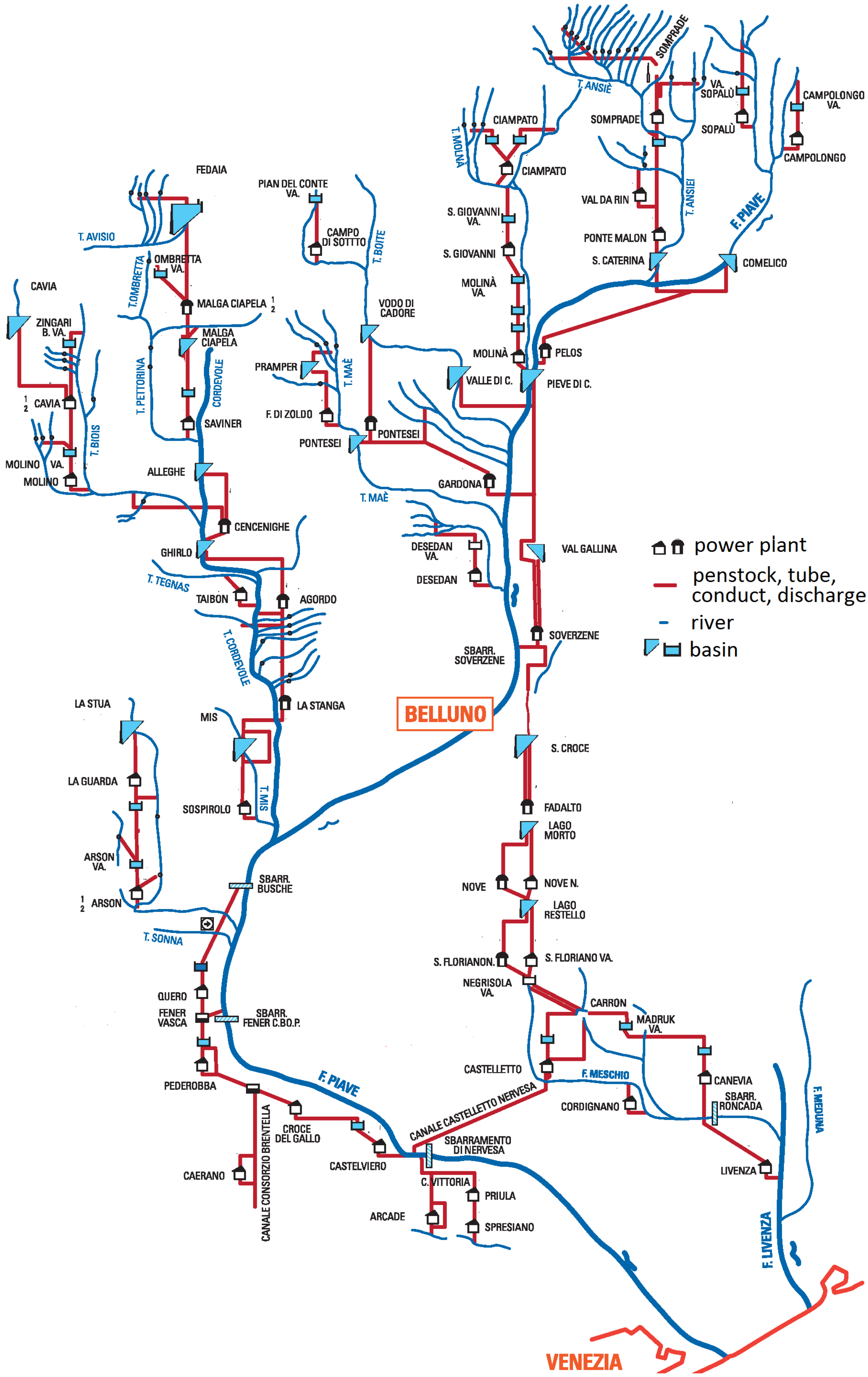


Figure 19: All hydroelectric power plants of the river Piave and its affluentes (Webdolomiti, 2014)

Figure 20: The exact location of the power plants which have been included into the model (produced by google earth)

4.3 Inflow Data

Finding the inflow data was the most difficult task. During this search it was necessary to contact several gauging stations in Italy to ask for data. Not even half of all contacted institutes responded. In the end the Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto (ARPAV) was found. This agency provides data for some gauging stations in the region Veneto and sent the data to us after an official request of the Vienna University of Technology. Regrettable the gauging stations run by ARPAV are not overarching all wished data but nevertheless we had at least some data. These gauging stations of ARPAV used for this thesis and the dams can be found in figure 22. As one can see there is a very little number of stations for all the dams needed namely just seven gauging stations for 28 dams. This is why many approximations and estimations are needed.

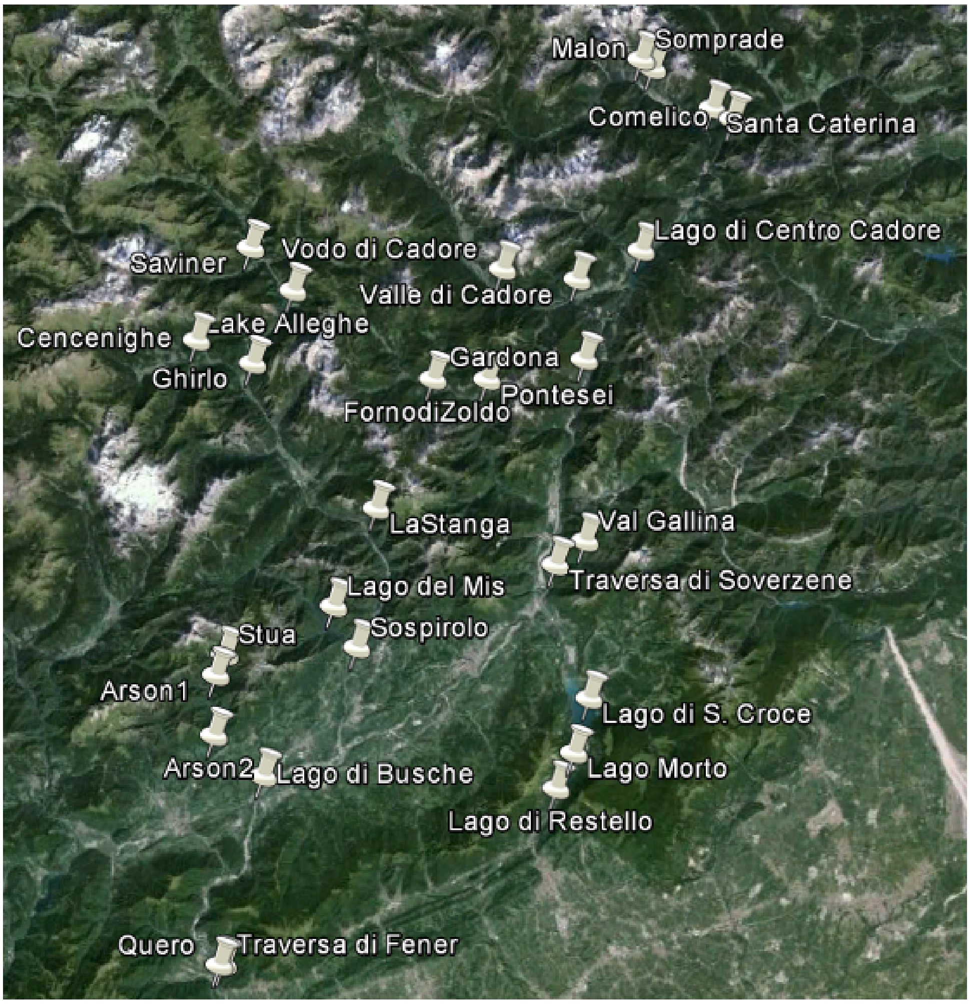


Figure 21: The exact location of the dams (including the virtual ones) which have been included into the model (produced by google earth)

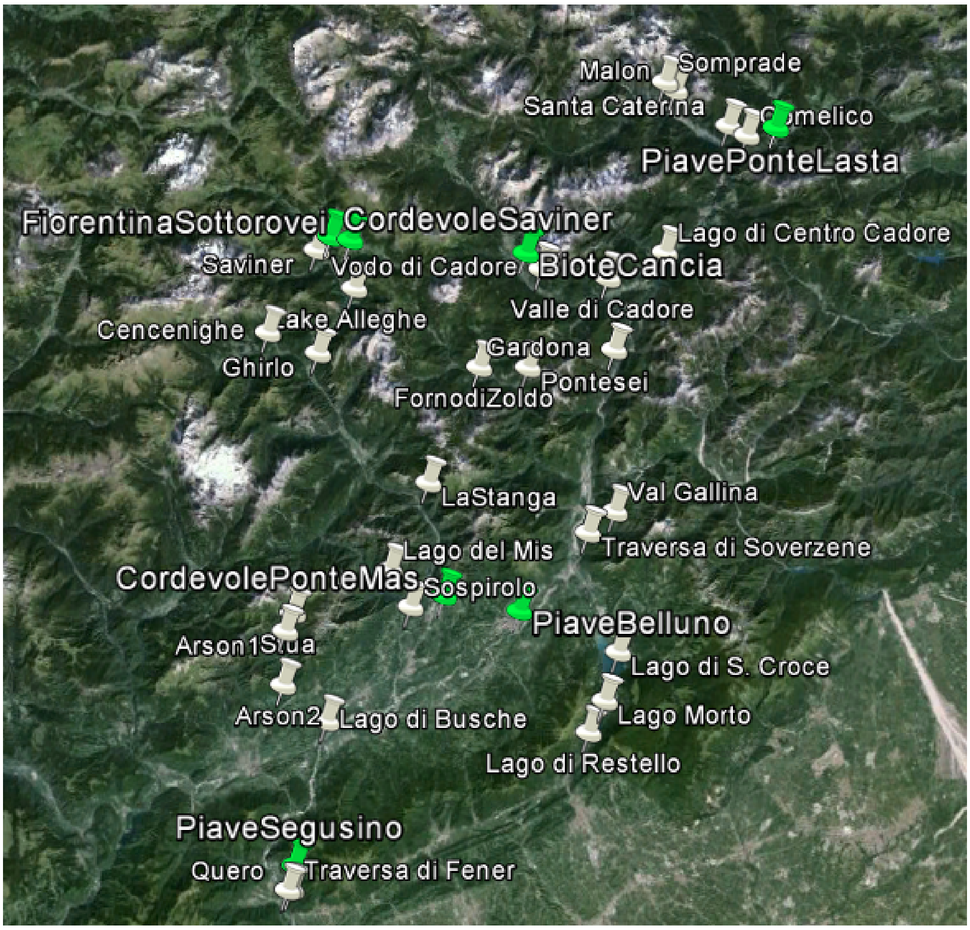


Figure 22: The exact location of the gauging stations and the dams included into the model (produced by google earth). The white smaller pins represent the dams and the bigger green ones the gauging stations.

5 Model

The model used in this thesis is the High Resolution Power System Model (HiREPS model) whose development started in 2009 and was organised by G. Totoschnig at the Vienna University of Technology.

The HiREPS model provides a dynamical system simulation and optimisation. All important constrains are included endogenously to integrate the fluctuations of the renewable electricity generation into the dynamical power system. Problems that have to be considered are first of all the variability of the electricity generated by renewable energy sources. Moreover there are some problematic limits such as the limits of the electricity grid, of the hydro storage capacity and last but not least of the flexibility of thermal power plants. The model tries to overcome these problems by first including inflow data which are spatially and temporally highly resolved for wind, solar as well as for hydroelectric power. Furthermore a lot of other details are involved in the model of which the most important one for this thesis is the detailed model of hydroelectric power and pumped-storage. This inclusion is so important because storage hydroelectric power turns out to be the best storage to balance the fluctuations of solar and wind energy.

This diploma thesis is related to the AutRES100 project (2010-2012 at the Vienna University of Technology) whose main aim was to find technically and economically viable ways to supply Austria with 100% renewable power. Moreover power systems for whole Europe were investigated always trying to include high shares of renewable power.

(Totschnig, 2012)

The model uses the programming language AMPL. Programming this model was not part of this diploma thesis. Thus the model from the AutRES100 project was taken which was primary designed for Austria. Nevertheless there was no falsification by using it for the region Veneto since the topology in northern Italy is similar to Austria.

5.1 AMPL

AMPL was designed around 1985 and was enhanced ever since. It is a programming language for linear and non-linear optimisation problems which is known for being similar to the algebraic expressions to customary algebraic notation as well as being able to handle large scale optimisation problems. Another advantage in the use of AMPL is that it provides a flexible interface so that several solvers are available at the same time. Moreover AMPL transforms the found optimal solution back to the modeller's form which makes it easier for the user to interpret the results. Furthermore there are many options for formatting the data. (Fourer et al., 2003)

A lot of different solvers are provided for AMPL users. The model simulated is best to solve with MOSEK which can solve linear, quadratic, conic and mixed integer problems by making use of the simplex or the interior point method. (mosek, 2014)

5.2 Linear optimisation and solving methods

The main idea of linear optimisation is to minimise or maximise a linear function whose variables fulfil equality or inequality constrains. The general *linear programming problem* is given by

$$\begin{aligned} \text{minimise} \quad & c'x \\ \text{subject to} \quad & Ax \geq b. \end{aligned} \tag{7}$$

In the above equations x is a column vector of dimension n containing the so-called *decision variables*. Every vector x which fulfils all constraints is called *feasible vector* or *feasible solution* and the set of feasible solutions is referred to as *feasible set*. The n-dimensional column vector c is named *cost vector* and the function $c'x$ is in general referred to as *cost function* or *objective function* and should be minimised. There is no need in studying linear programming maximisation problems separately because maximising $c'x$ is equal to minimising $-c'x$. A is a $m \times n$ matrix of scalars and b is a m-dimensional column vector of scalars. The columns of A are sometimes called *resource vectors* and the vector b *target vector*. Inequalities such as $Ax \geq b$ are interpreted componentwise which means every component fulfils $(Ax)_i \geq b_i$ for all $i = 1, \ldots, m$.

The *standard form problem* is given by

$$\begin{aligned} \text{minimise} \quad & c'x \\ \text{subject to} \quad & Ax = b \\ & x \geq 0. \end{aligned} \tag{6}$$

It can be shown that any general linear programming problem (7) can be transformed into an equivalent problem in standard form (6). A detailed description on how such transformations would look like can be found for example in (Bertsimas et al., 1997) p.5 ff.

There are a lot of methods for solving such linear programming problems. The first work dates back to Fourier who developed the first noted algorithm in 1824. However the first big progress came when Dantzig developed an algorithm called simplex method in 1947. Since then a lot of research has been done and a lot of progress has been made. In the following a little introduction to the solving algorithms used by the solvers CPLEX and MOSEK is given.

5.2.1 Simplex Method

Before getting started we have to define two new terms. The first term to define is *polyhedron* which is a set described by finitely many linear constraints (equalities and inequalities).

Definition 5.1 *Let A be a $m \times n$ matrix and $b \in \mathbb{R}^m$ then a* polyhedron *χ is defined as the set described by $\{x \in \mathbb{R}^n | Ax \geq b\}$.*

The feasible set of any linear programming problem is a polyhedron. The one of the general linear programming problem (7) is like the one given above and the one of the standard form problem (6) is $\{x \in \mathbb{R}^n | Ax = b, x \geq 0\}$. We need the term polyhedron to define *extreme points* in a general way.

Definition 5.2 *A vector x of a polyhedron χ is called an* extreme point *of χ if no vectors $y, z \in \chi$ unequal to x and no scalar $\mu \in [0, 1]$ exist so that $x = \mu y + (1 - \mu)z$.*

The main core of the simplex method is to make use of the fact that if a linear programming problem of the form (6) has an optimal solution then an extreme point, which is optimal, exits.

The idea of the simplex method is now to move from one extreme point to another in cost reducing direction until an optimal extreme point is found. If there is no cost reducing direction in which the procedure could go on the optimum is found. Such an optimum is a locally optimal solution. Since the function and the over-minimised set are convex a locally optimal solution is also a globally optimal solution.

In order to understand the full implementation some more definitions are needed. We just consider standard form problems (6) in this section. Nevertheless the next terms are also defined for the general linear programming problem (7). In the following $\overline{A}_i$ is the i-th row of the matrix A of either (7) or (6) and A_j is the j-th column.

Definition 5.3 *A constraint is called* active *at a vector y if $\overline{A}_i y = b_i$ for some $i = 1, \ldots, m$.*

Making use of this definition we can now introduce *basic solutions.*

Definition 5.4 *A vector $y \in \mathbb{R}^n$ is called a* basic solution *if*

- *all the equality constraints of the linear programming problem* (7) *are active at y and*
- *there are n linearly independent and active (at y) constraints.*

Definition 5.5 *A* basic feasible solution *is a basic solution which fulfils all the given constraints.*

It can be shown that the property of being an extreme point is equal to the property of being a basic feasible solution (see e.g. (Bertsimas et al., 1997) p.50 ff).

In the following we assume the rows $\overline{A}_i$ to be linearly independent which can be done without loss of generality because if $\chi \neq \emptyset$, linearly dependent rows $\overline{A}_i$ give redundant constraints. The linear independence of the rows $\overline{A}_i$ imply that $m \leq n$. Considering this linear independence the next theorem is found.

Theorem 5.6 *Assume that $Ax = b$ and $x \geq 0$ and consider the rows $\overline{A}_i$ to be linearly independent. A solution $y \in \mathbb{R}^n$ is basic if and only if $Ay = b$ and indices $B(1), \ldots, B(m)$ exist such that $A_{B(1)}, \ldots, A_{B(m)}$ are linearly independent and $y_j = 0$ if $j \neq B(1), \ldots B(m)$.*

A proof of this theorem can be found e.g. in (Bertsimas et al., 1997) p. 53 ff. Now the next is to focus on the basic concept.

Definition 5.7 *Let y be a basic solution and $B(1), \ldots, B(m)$ $(m > 0)$ the indices so that $y_i = 0$ if $i \neq B(1), \ldots, B(m)$. Then $y_{B(1)}, \ldots, y_{B(m)}$ are called* basic variables*,* $A_{B(1)}, \ldots, A_{B(m)}$ basic columns *and* $B(1), \ldots, B(m)$ basic indices*. Since $A_{B(1)}, \ldots, A_{B(m)}$ are linearly independent they form a basis of $\mathbb{R}^m$. Hence the* basis matrix *is the $m \times m$ matrix of the basic columns $B = (A_{B(1)} \ldots A_{B(m)})$.*

For the following iteration let c_B be the vector of costs of the basic variables.

Iteration of the simplex method

1. We start with a basic feasible solution y and a basis B of the belonging basic columns $A_{B(1)}, \ldots, A_{B(m)}$.

2. The next step is to determine the reduced costs $\bar{c}_j = c_j - c'_B B^{-1} A_j$ for all j that are not basic indices.
If all $\bar{c}_j$ are equal to or greater than zero the present basic feasible solution is already optimal and the algorithm stops;
else, chose j with $\bar{c}_j < 0$.

3. The next is to investigate $u = B^{-1} A_j$.
If all components of u are non-positive the optimal cost is $-\infty$ and the algorithm stops;
else, let k be such that $\frac{x_{B(k)}}{u_k} = \min_{\{i=1,\ldots,m|u_i>0\}} \frac{x_{B(i)}}{u_i}$.

4. Now $A_{B(k)}$ is replaced with A_j. The new basic variables are given by $y_j = \frac{x_{B(k)}}{u_k}$ and $y_{B(i)} = x_{B(i)} - \frac{x_{B(k)}}{u_k} u_i$ for $i \neq k$.

This algorithm has been effectively used to solve linear programming problems over a lot of years. Nevertheless there is a big disadvantage namely it is possible that the algorithm takes an exponential number of iterations to be successful.

(Bertsimas et al., 1997), (Padberg, 1995)

5.2.2 Ellipsoid Algorithm

The ellipsoid algorithm was developed in the Soviet literature. This algorithm has rare practical use but indeed shows that linear programming can be solved efficiently (but just seen from a theoretical point of view). One of the main advantages compared to the simplex method is that the ellipsoid algorithm is a polynomial time algorithm whereas using the simplex method sometimes means applying an exponential number of iterations until finding the optimal solution. The main idea of the ellipsoid method is to decide whether the polyhedron $\chi = \{x \in \mathbb{R}^n | Ax \geq b\}$ is empty or not.

In order to formulate this algorithm we first of all need to define the term ellipsoid.

Definition 5.8 *An ellipsoid E with centre $o \in \mathbb{R}^n$ is a set of vectors of $\mathbb{R}^n$ given by*

$$E = E(o, P) = \{x \in \mathbb{R}^n | (x - o)' P^{-1} (x - o) \leq 1\}$$

with a positive definite symmetric matrix P of size $n \times n$.

<u>Iteration of the ellipsoid algorithm</u>

1. The iteration starts with an ellipsoid E_t with centre x_t and $\chi \subset E_t$.
   If $x_t \in \chi$ then χ is not empty and the algorithm stops;
   else, there is an i so that $\overline{A}_i x_t < b_i$.

2. All $x \in \chi$ satisfy $\overline{A}_i x \geq b_i$ thus $\overline{A}_i x \geq \overline{A}_i x_t$. Hence $\chi \subset \{x \in \mathbb{R}^n | \overline{A}_i x \geq \overline{A}_i x_t\} \cap E_t$. The geometric properties of ellipsoids make it possible to find a new ellipsoid $E_{t+1} \supset \{x \in \mathbb{R}^n | \overline{A}_i x \geq \overline{A}_i x_t\} \cap E_t$ with $\text{Vol}(E_{t+1}) < \text{Vol}(E_t)$.

3. This is repeated until $x_t \in \chi$ is found or that $\text{Vol}(\chi)$ is very small which leads to $\chi = \emptyset$.

We take the conclusion that a small $\text{Vol}(\chi)$ leads to an empty χ as a fact. The mathematical correct argumentation for that can be found e.g. in (Bertsimas et al., 1997) chapter 8.

The following figure 23 shows an iteration of the above algorithm. In this step $x_t \notin \chi$ (χ is named P in the figure) but the next centre $x_{t+1} \in \chi$. E_t is the first ellipsoid and E_{t+1} is the next ellipsoid which covers the intersection of E_t and $\{x \in \mathbb{R}^n | \overline{A}_i x \geq \overline{A}_i x_t\}$ with $\overline{A}_i$ being named a' in the figure.

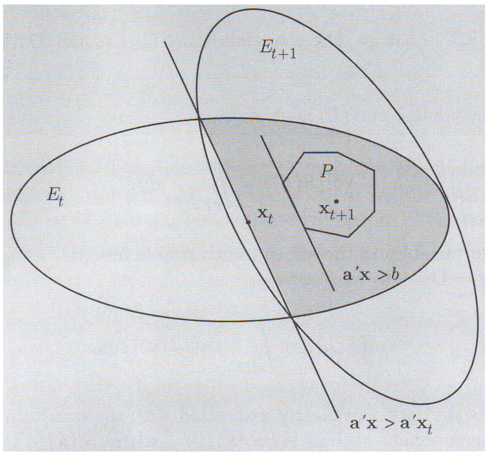


Figure 23: An iteration of the ellipsoid algorithm (Bertsimas et al., 1997) p.366

When using the ellipsoid algorithm for optimisation, a direct and often applied method is the so-called *sliding objective ellipsoid method.*

<u>Sliding objective ellipsoid method</u>

1. First the ellipsoid algorithm is used to find a $x_t \in \chi$ (or that $\chi = \emptyset$ which means no solution exits and the algorithm stops).

2. The next step is to run the ellipsoid algorithm to find out whether $\chi_t = \chi \cap \{x \in \mathbb{R}^n | c'x < c'x_t\}$ is empty or not.
   If $\chi_t = \emptyset$, x_t is optimal and the algorithm stops;
   else, a new solution $x_{t+1} \in \chi$ with $c'x_{t+1} < c'x_t$ is found.

3. The iteration is run until an optimal solution is found.

The name sliding objective ellipsoid method is motivated by the fact that each iteration gives a new constraint in the direction of c.

In figure 24 an iteration of the sliding objective ellipsoid method is shown (χ is named P again). A feasible solution x_t was found by the ellipsoid method. Now it is applied to the new polyhedron $\chi_t = \chi \cap \{x \in \mathbb{R}^n | c'x < c'x_t\}$. An ellipsoid with centre x_{t+1} is built. Next the method is applied to the polyhedron $\chi_{t+1} = \chi \cap \{x \in \mathbb{R}^n | c'x < c'x_{t+1}\}$.

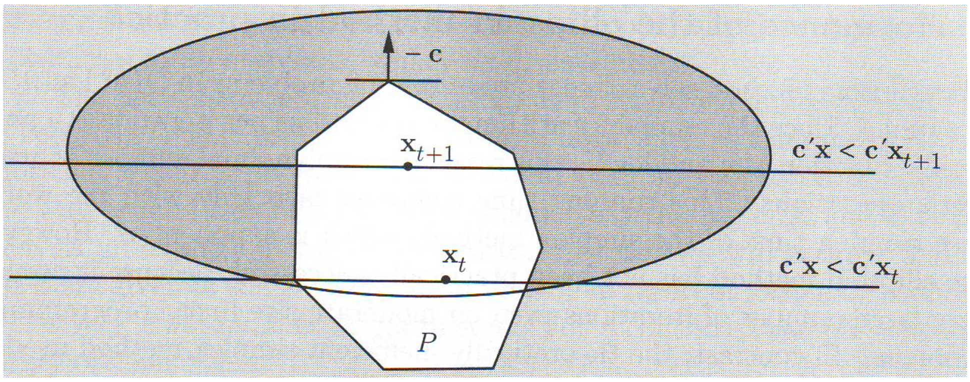


Figure 24: An iteration of the sliding objective ellipsoid method (Bertsimas et al., 1997) p.379

(Bertsimas et al., 1997), (Padberg, 1995)

5.2.3 Interior Point Method

In the 1980s new algorithms were developed. These new algorithms move in the interior of the given feasible set in order to find an optimal solution. That is why they are generally referred to as interior point methods. They combine the advantages of the simplex and the ellipsoid method. Three main types are distinguished.

1. Affine Scaling Algorithm

   The affine scaling algorithm is the one which is closest to the simplex method because it also uses the cost function as reference in its iterations. The algorithm is quite simple but even so has good practical performance. One of the main ideas of the interior point method is also used in this algorithm namely the idea to approximate the polyhedron by an ellipsoid. Other than in the ellipsoid algorithm where the ellipsoid contains the polyhedron here the ellipsoid is contained in the polyhedron. The underlying idea is that the minimisation of $c'x$ over χ often turns out to be very complicated whereas the minimisation of $c'x$ over an ellipsoid is a lot easier.

Since now the ellipsoid is contained in the polyhedron we need the new term *interior*.

Definition 5.9 *The* interior *of* χ *is given by* $I = \{x \in \chi | x > 0\}$. *The elements of* I *are called* interior points.

Iteration of the affine scaling algorithm

(a) The algorithm starts with a feasible solution $x_0 \in I$.

(b) An ellipsoid $E_0 \subset I$ centred at x_0 is created. The cost function $c'x$ is optimised over all $x \in E_0$. This results in a new interior point x_1.

(c) This is repeated until no new optimal solution is found.

An iteration of this algorithm is shown in the following figure 25. It starts at the feasible solution x_0 with the ellipsoid whose centre is x_0. The cost function $c'x$ is minimized over the ellipsoid centred at x_0 which gives x_1. The algorithm is repeated and a new vector x_2 which minimizes $c'x$ over the ellipsoid centred at x_1 is found.

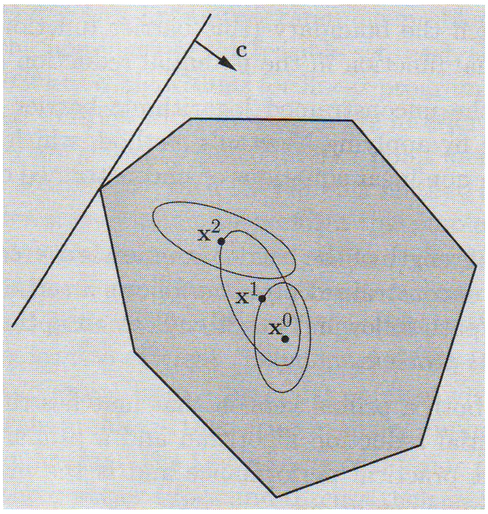


Figure 25: Illustration of the affine scaling algorithm (Bertsimas et al., 1997) p.396

Even though this algorithm is quite simple there has been a lot of research on its convergence.

2. Potential Reduction Algorithm

This algorithm uses the second idea of interior point methods: Other than the simplex method or the affine scaling algorithm progress is now not measured by reducing the objective function but by reducing a non-linear *potential function* which has to decrease the objective function as well as avoid the boundary of the feasible set. This is done because when using the affine scaling algorithm the boundary of the feasible set is reached very quickly and then the algorithm has to take very small steps because the ellipsoids get very small. If the current point is somehow kept away from the boundary the algorithm can make great progress in the next steps. The algorithm solves the primal problem (6) and its dual problem

$$\begin{array}{ll} \text{maximise} & p'b \\ \text{subject to} & p'A + s' = c' \\ & s \geq 0 \end{array} \qquad (5)$$

with p and s being vectors with the same dimension as b. (For further information on Duality theory see e.g. (Bertsimas et al., 1997) chapter 4.) Moreover we need the assumption that the rows $\overline{A}_i$ are linearly independent and that there is $x > 0$ which is feasible for the primal problem and a pair (p, s) with $s > 0$ which is feasible for the dual problem. This dual problem allows to define the *potential function* as

$$F(x, s) = k \log s'x - \sum_{i=1}^{n} \log x_i - \sum_{i=1}^{n} \log s_i. \qquad (6)$$

with a konstant $k > n$.

3. Path Following Algorithm

The path following algorithm is based on three main ideas.

(a) The first of these is the transformation of the constrained linear programming problem. One of the main problems in linear programming problems is the inequality $x \geq 0$. Thus the transformation persists in incorporating the constraints in a logarithmic *barrier function* which is similar to the potential function in the above algorithm. Thus the barrier function entails a growth when getting close to the boundary. The barrier function is given by (for $\nu > 0$)

$$B_\nu(x) = \begin{cases} \infty & \text{if } x_j \leq 0 \text{ for any } j \\ c'x - \nu \sum_{j=1}^{n} \log x_j & \text{else} \end{cases}. \qquad (7)$$

(b) The second idea is the application of the Newton's method which is in general used for solving non-linear equations or unconstrained optimisation problems (like in this algorithm). The so-called *barrier problems* which have to be solved by the Newton's method are given by ($\nu > 0$)

$$\begin{array}{ll} \text{minimise} & B_\nu(x) \\ \text{subject to} & Ax = b. \end{array} \qquad (7)$$

The minimiser to $\nu = \infty$ is referred to as *analytic centre* of the feasible set and is given by the solution of the problem

$$\begin{array}{ll} \text{minimise} & -\sum_{j=1}^{n} \log x_j \\ \text{subject to} & Ax = b. \end{array} \qquad (7)$$

(c) The unconstrained barrier problems have optimal solutions $x(\nu)$. These optima follow a *central path* which indicates the name *path following algorithm.* The limit of these optima $\lim_{\nu \to 0} x(\nu)$ exists and is an optimal solution of the original problem.

Such a central path with the analytic center can be seen in figure 26. The shown $x(\nu)$ are the optimal solutions of the barrier problems (7) and the analytical centre is the optimal solution of (7). At the end of this central path there is the optimal solution of the initial linear programming problem (in the figure denoted by x^*).

(Bertsimas et al., 1997)

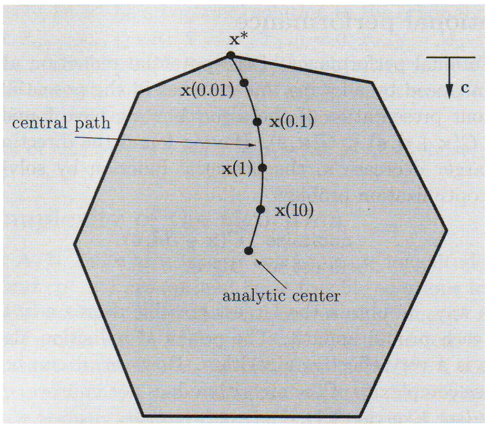


Figure 26: The central path with the analytical centre and the optimal solution x^* of the initial linear programming problem (Bertsimas et al., 1997) p.420

The decision which one of the mentioned algorithms works best depends heavily on the problem itself.

For further information on the given methods or on other or modified methods the reader is referred to special literature of linear optimisation such as (D. Bertsmias et al., 1997) or (Padberg, 1995).

6 Simulations of the existing power plants

In this and the following sections 7 and 8 some simulations are presented. The solver MOSEK and four iterations are used. Moreover the result of one iteration serves as the initial point for the following i.e. cyclic constraints are applied. The simulations focus on the years 2006, 2007 and 2008 because these are the years with the most reliable inflow data. Not only single years but also periods of more years are considered in order to compare the output and the dependence of the model on several parameters.

Now this section concentrates on the existing power plants of Veneto.

6.1 Turbine activity of storage power plants and price

First of all we start with a simulation of the turbine activity of storage power plants and later on we compare it to the electricity price. In order to discuss the behaviour of the simulated turbine activity we look at a special storage power plant named Soverzene. It is the biggest power plant included into the model and is located somewhere in the middle of the way along the river Piave. Moreover a plot of the whole period 2006 to 2008 or even of one year is to fuzzy to analyse it. That is why a eight days period is chosen.

In the below figure 27 a plot of the simulated turbine power of Soverzene of a eight days period of January 2006 is found. There are eight main peaks in this figure. Each of these peaks represents one day i.e. there is turbine activity during the day and no activity during the night. Furthermore the sixth and seventh peak are very narrow which indicates that on Saturday and Sunday there are just a few hours when the turbine is active.

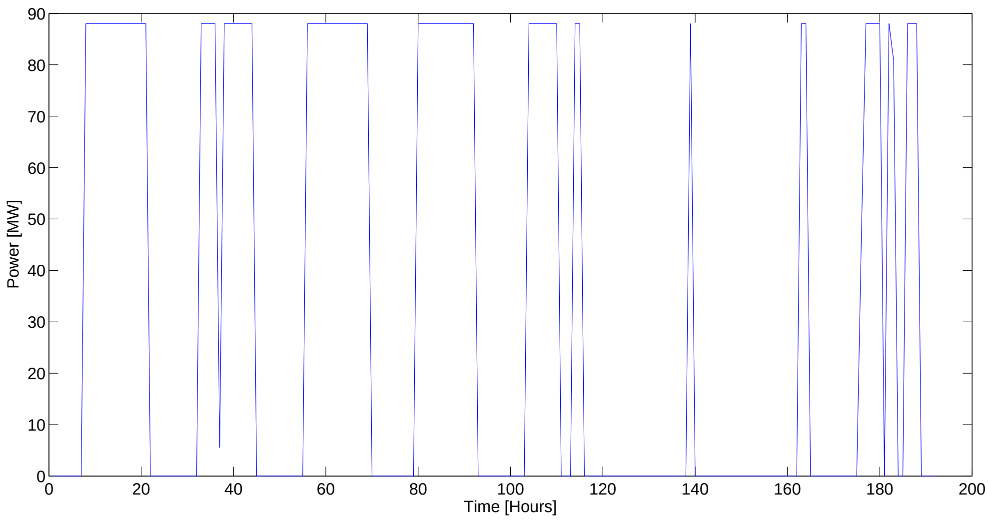


Figure 27: The turbine activity of the power plant Soverzene from 16.01.2006 00:00 until 23.01.2006 23:59

The next is to compare this activity to the electricity price. There are two available price data bases namely the one of the European Energy Exchange (EEX) (EEX, 2014) which is a leading platform for energy trading in Europe and the second one is the Prezzo Unico Nazionale- National Single Price (PUN) (GME,2014). The PUN is provided by the Gestore Mercati Energetici (GME) which organises and manages the Italian electricity market called Italian Power Exchange (IPEX).

First we try to find a relation between the EEX price and the turbine activity. Thus figure 28 shows the simulated turbine power of the power plant Soverzene and the EEX price for eight days of January 2006.

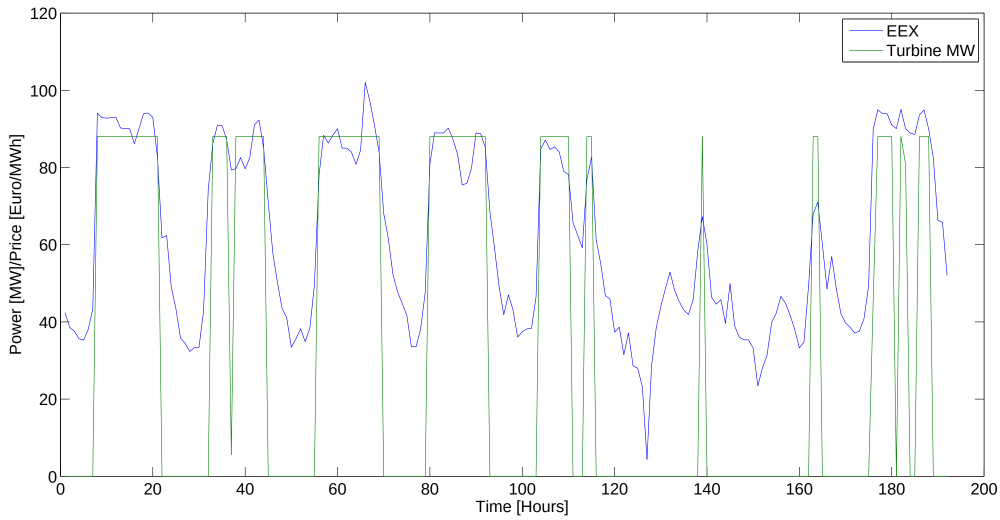


Figure 28: The turbine activity of the power plant Soverzene and the EEX price from 16.01.2006 00:00 until 23.01.2006 23:59

This figure 28 indeed illustrates a correlation between the two variables. If the price is low water is stored and less turbine activity is noted. Thus during the nights when less electricity is needed and the EEX price is lowest hardly any turbine activity occurs. On the other hand the high EEX price during the day is directly compared to high turbine activity because the aim is to sell the electricity to a high price and thus the power plants have to produce during these high price periods. If there was a pump in the power plant it would work contrarily to the turbine i.e. the pump activity would be high at low price and vice versa. It is interesting to note that the peaks of the price are higher during the week (the first five peaks and the last one) whereas on the weekend lower peaks are found. Moreover little daily fluctuations of the price can be seen - in the morning and evening the price is higher due to more electricity consumption. In contrast to this there is no variation in the height of the graph of the turbine activity i.e. if the turbine is active it runs with full power.

In the following we oppose the turbine activity of Soverzene to the electricity price for Italy, to the PUN, in order to see whether a similar relation can be found. The results for the same period of January 2006 are shown in figure 29. It is not a surprise that the correlation is the same as in figure 28 that is high turbine activity at high price and low activity at low price.

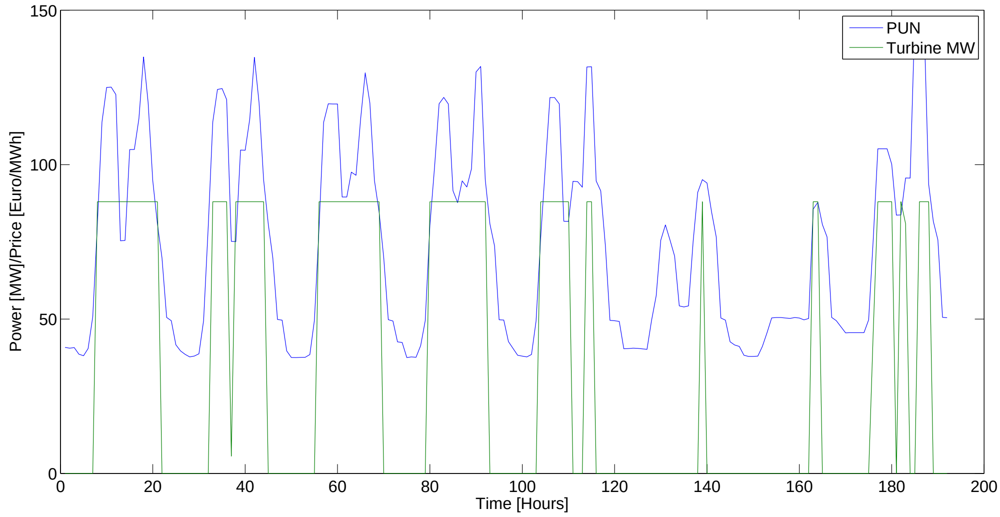


Figure 29: The turbine activity of the power plant Soverzene and the PUN from 16.01.2006 00:00 until 23.01.2006 23:59

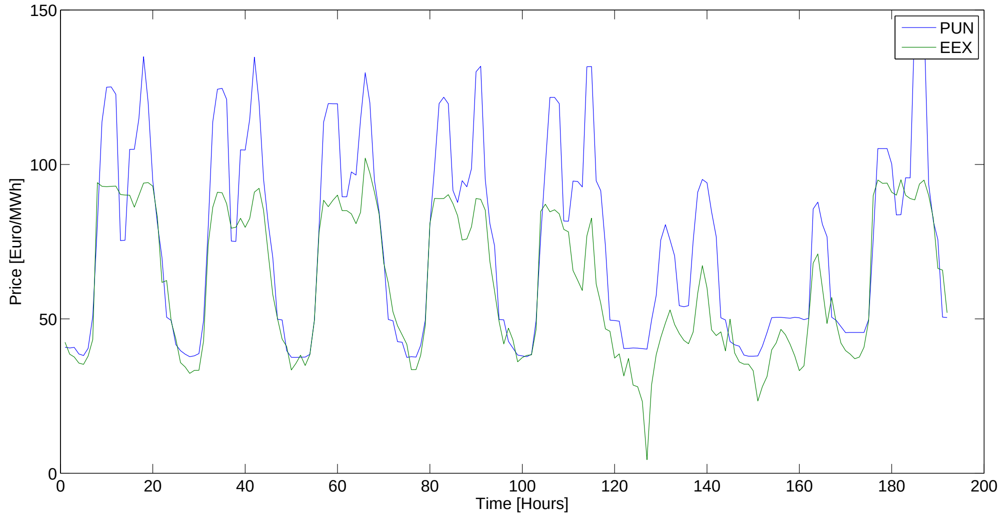


Figure 30: The EEX price and the PUN from 16.01.2006 00:00 until 23.01.2006 23:59

The prices of the two figures 28 and 29 resemble each other but nevertheless there are some differences. Figure 30 presents the two graphs of the prices. First of all it can be seen that the graph of the PUN is smoother than the one of the EEX. Moreover the values of the PUN are in general higher than the ones of the EEX. That is due to the fact that the electricity price in Italy is higher than the average price of the rest of Europe.
In order to see that the results found in figure 28 and 29 are representative for all power plants and all times figure 31 shows the PUN and the turbine power of two other power plants namely of Cenceinghe which is located at the river Cordevole and of Sospirolo of the river Mis for eight days in July 2007. Once more the graphs of the simulated turbine powers are high at high price and low at low price. Furthermore the peaks representing the weekend (sixth and seventh peak) are lower for the price and narrower for the turbine power than those during the week. Thus we can conclude that such accordances are found for every power plant and every period.

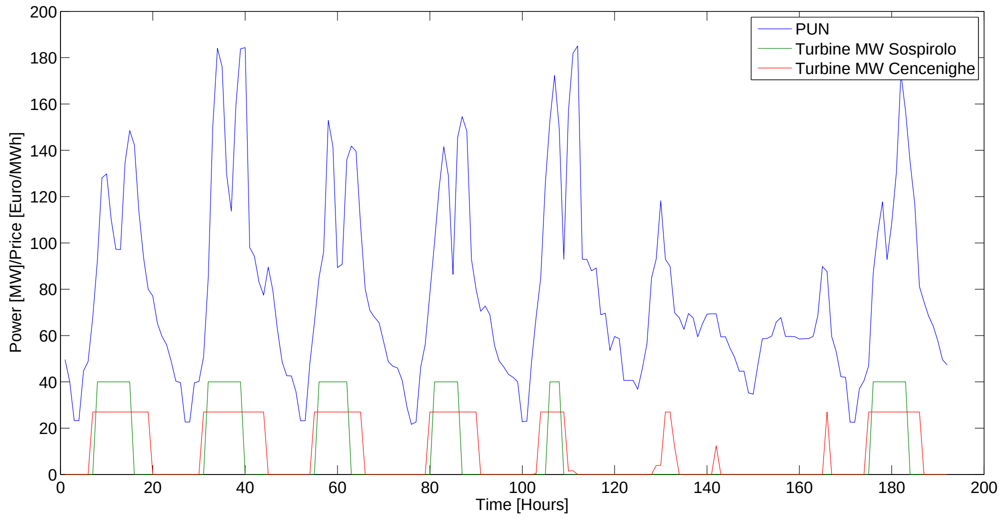


Figure 31: The turbine activity of the power plants Cencenighe and Sospirolo and the PUN from 02.07.2007 00:00 until 09.07.2007 23:59

6.2 Water level

Since the storage power plants are not working continuously we cannot expect a continuous water flow. Thus a variation of the water level is to be awaited as well. As to liken the results of the simulated water level to the simulated turbine activity of the last section we choose again the power plant Soverzene whose reservoir is Val Gallina. Figure 32 below illustrates the fluctuations of the water level of Val Gallina for the same eight days period of January 2006. The water level starts high on Monday morning, sinks during the day and and then rises a little again during the night to Tuesday. On the weekend the water level increases and builds up some reserve for the week.

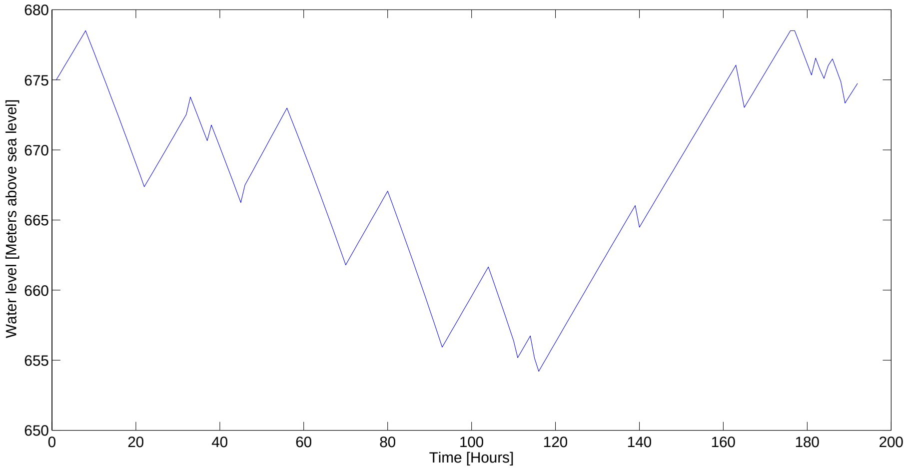


Figure 32: The simulated water level of Val Gallina (reservoir of the power plant Soverzene) from 16.01.2006 00:00 until 23.01.2006 23:59

The next figure 33 shows the relation between the turbine activity and the water level. Whenever the turbine works water is taken from the reservoir and thus the water level sinks. Later on when the turbine stops no water is taken from the reservoir and hence the water level rises again due to the inflow of the reservoir. Since less turbine activity is noted on the weekend just a little amount of water is taken and thus the reservoir can be filled for the upcoming week.

The found correlation of the turbine activity and the water level is reasonable and fulfils the assumed outcome.

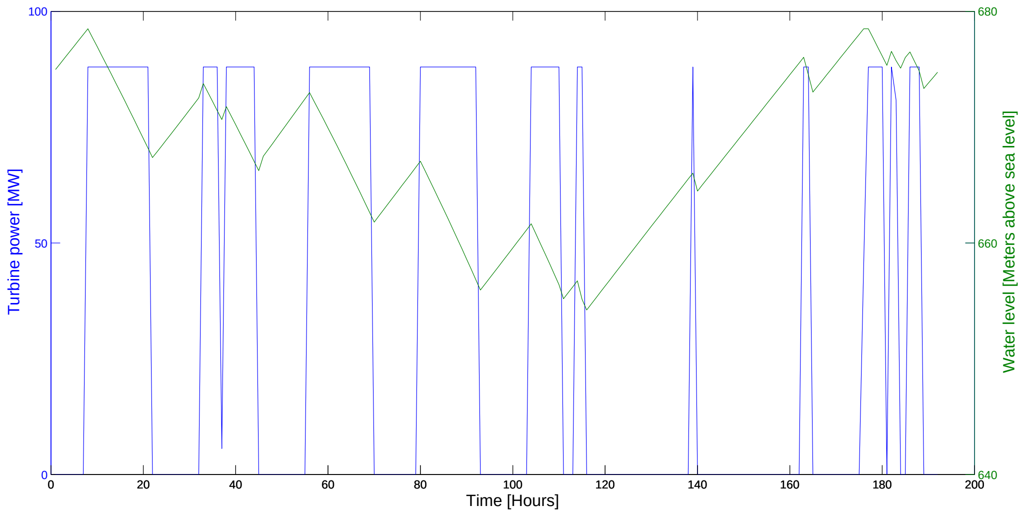


Figure 33: The simulated water level of Val Gallina (reservoir of the power plant Soverzene) and the turbine activity of the power plant Soverzene from 16.01.2006 00:00 until 23.01.2006 23:59

6.3 Run-of-river power plants and their inflows

The next is to turn to run-of-river power plants. Now we cannot expect a correlation like the one found in 6.1 because run-of-river power plants can hardly store any water i.e. their production depends totally on the inflows of the river. Thus a relation of the inflows and the turbine activity of such power plants is to be assumed. Once again specific power plants are chosen and the results are represented.

The first to be chosen is the run-of-river power plant Somprade. It is the first power plant in the model and is located at the river Ansiei. The following figure 34 shows the inflows and the simulated turbine activity of Somprade for the year 2006.

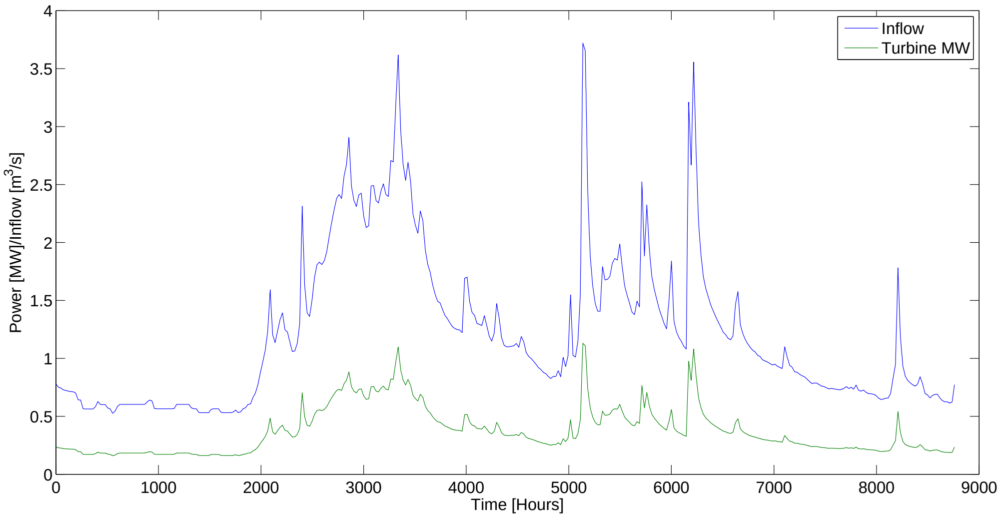


Figure 34: The inflows and the turbine activity of the run-of-river power plant Somprade for the year 2006

Moreover the results of a second run-of-river power plant are given in order to see that the data found for Somprade are representative for all run-of-river plants and all times. The second power plant is Saviner which is located at the river delta of Pettorina and Cordevole. The comparison of the inflows and the simulated turbine activity of Saviner for 2007 is found in figure 35.

Both figures 34 and 35 lead to the same result: a perfect correlation of the inflow and the turbine activity i.e. at high inflow rates the turbine activity is high and it is low for low inflows. This is the expected outcome since run-of-river power plants have to work when the water is available and cannot wait for an economically better moment. Another difference to the results found in section 6.1 is that now the values of the turbine power vary. In the above section the turbine was working on maximum power or not now there are all kinds of different values for the power which is of course due to the varying inflow.

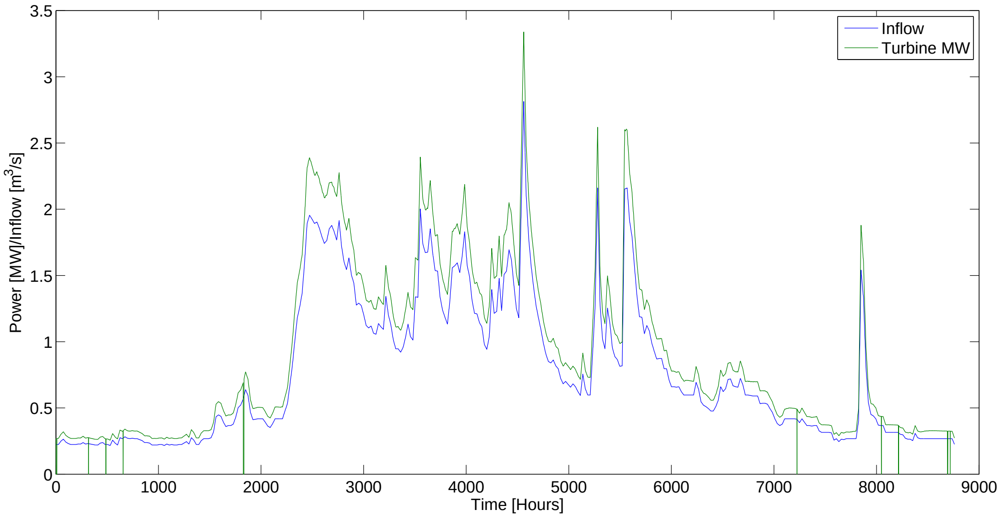


Figure 35: The inflows and the turbine activity of the run-of-river power plant Saviner for the year 2007

6.4 Total energy content

Now we focus on the simulated total energy content which gives the stored energy of all reservoirs of Veneto. The model assumes that the reservoirs have the same initial and end data for the amount of water which also causes same energy contents. In order to decide whether this assumption leads to a reliable outcome or not different simulation intervals namely the single years 2006 and 2007 as well as the period 2006-2007 are considered. The results of these simulations are plotted in figure 36 and 37.

In figure 36 one finds a gap between the two single years 2006 and 2007. This gap is due to the fact that the two years have been treated separately and thus the model does not have any input data from the last or next year. Furthermore what was to be expected can be observed namely that due to the cyclic constraint the energy content is the same in the beginning and in the end of each year. Moreover a summer peak can be found in the graphs for both years. There is always a summer peak but nevertheless due to the varying weather it is not always of the same intensity nor at the exact same time.

Turning now to figure 37 a plot of the single years as well as a plot for the whole period is found. The first to notice is that there is no gap between the two years in the graph for the period 2006-2007 because now the model knows the last value of the last day of 2006 and goes on for 2007. The cyclic constraint now applies to the whole period. Thus the first value of 2006 is equal to the last value of 2007. Moreover it is worth noting that during the years (not at the end or beginning) the values of the graphs are identical. This outcome indicates that the model does rarely depend on the initial and end data and thus gives good simulations for each period.

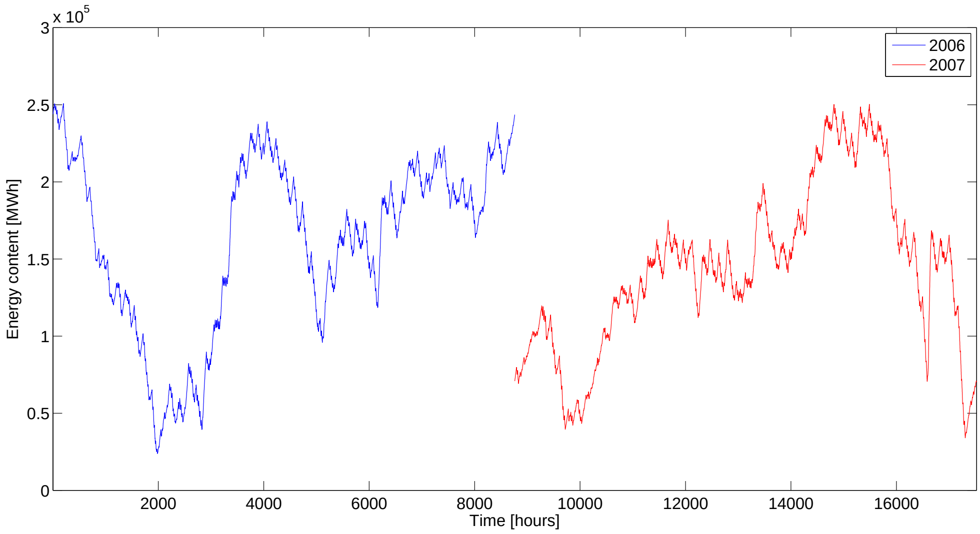


Figure 36: The simulated total energy content of all power plants for the single years 2006 and 2007

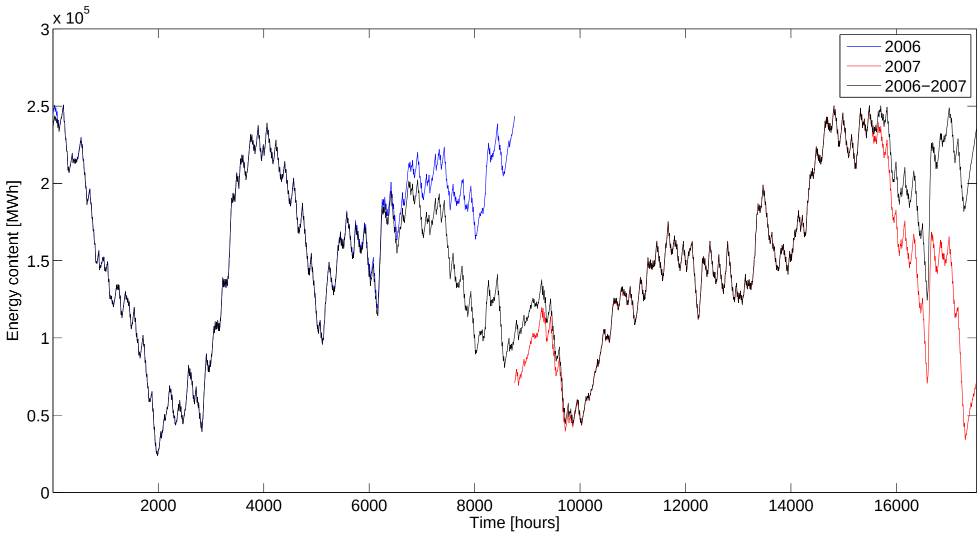


Figure 37: The simulated total energy content of all power plants for the years 2006 and 2007 and the period 2006-2007

6.5 Revenue

When talking about hydroelectric power plants one always has to keep in mind the revenue. There is no use in running a power plant without earning money with it. In the following table 6 the simulated revenue, the simulated produced MWh and the calculated revenue per MWh of four power plants of different simulation intervals are listed. Two of those namely Soverzene and Quero are storage power plants whereas the other two Somprade and Saviner are run-of-river power plants. The first thing to be noted is that in all years the revenue per MWh gained by the storage power plants is higher than the one gained by the run-of-river power plants. This outcome was to be assumed and is due to the fact that a storage power plant other than a run-of-river one can optimise its revenue by storing the water during low price periods and releasing it during high price periods. A different situation occurs for run-of-river power plants. These plants do not have the possibility to store water and thus have to produce energy when water is available even if the electricity price is low.

Comparing the revenue per MWh of the different years it is found that the values of all power plants of 2007 are less than the values of 2006 although the value of the total production is higher e.g. the value for the calculated revenue per MWh of Soverzene of 2007 is 25.12% less than the value of 2006. Moreover it can be seen that the calculated revenue per MWh of the period 2006-2007 is the exact average of the values of 2006 and 2007 (despite some cent deviation) which is in consistence with our expectations because the revenue per MWh is a value averaged over the considered period. Thus this fact is another indication that the model is reliable.

	Soverzene	Quero	Somprade	Saviner
revenue 06 [€]	30652043.3	11254164.6	150829.9	324833.6
production 06 [MWh]	542616.2	195863.8	3250.3	7256.6
revenue/MWh in 06 [€]	56.49	57.46	46.40	44.76
revenue 07 [€]	25394790.4	8730766.8	138799.7	281242.5
production 07 [MWh]	600454.1	205593.6	3751.7	7977.9
revenue/MWh in 07 [€]	42.29	42.67	37.00	35.25
revenue 06-07 [€]	56046583.0	19876940.5	289636.1	606311.2
production 06-07 [MWh]	1142979.0	399455.3	7002.0	15240.6
revenue/MWh in 06-07 [€]	49.04	49.76	41.36	39.78
decrease revenue/MWh 06 to 07 [%]	25.14	25.74	20.26	21.25

Table 6: Overview of the simulated revenue, the production and the revenue per MWh of the storage power plants Soverzene and Quero and the run-of-river power plants Somprade and Saviner for the single years 2006 and 2007 and the period 2006 to 2007 as well as the decrease of the revenue per MWh from 2006 to 2007

7 Simulations with optimised investments in generation capacity

In this section the existing power plants are modified i.e. during the simulation the turbine power of storage power plants can be upgraded by the model. The model will do so if it is economical considering a price of 900€ per added kW. The assumption is that the capital including a weighted average cost of capital interest rate of 7% can be written of profitably over 35 years. Moreover additional fixed costs of 0.38% of the capital investment per year are presumed. The 7% are the yield expectations of the capital.

Simulations for the single years 2006, 2007 and 2008 as well as for the period 2006 to 2008 are presented. First of all we consider the added MW of two power plants on which we will focus in the following namely Soverzene with an initial turbine power of 88MW and Quero with an initial turbine power of 30MW. The values for the added MW for the simulation periods are listed in table 7. The first to find is that the values for Quero which has a smaller initial value of the turbine power are higher than those for Soverzene with a higher initial turbine power. Moreover the value for the period 2006 to 2008 is - as to be assumed - nearly the same as the average value of the other three years. Furthermore we find that the values for the different years vary. Thus we find relative high values for the year 2008 for both power plants.

	06	07	08	06-08
Soverzene	65.5	59.0	94.2	76.9
Quero	118.4	122.2	190.3	141.7

Table 7: Added MW for the power plants Soverzene and Quero for the single years 2006, 2007 and 2008 and the period 2006-2008

7.1 Turbine activity of storage power plants and price

Like in the previous section 6 we start with an investigation of the relation between the simulated turbine activity and the electricity price. The following figure 38 shows the simulated turbine activity of Soverzene considering optimised investments in generation capacity as well as the PUN for the same eight days period used in section 6. Comparing this figure to figure 29 we first of all find higher values for the turbine power which indicates an increase of the power by the model (see table 7). Moreover now the turbine activity follows the price fluctuation closer meaning that even small peaks are reflected. Furthermore we observe that the turbine is just working on peak values of the price and does not work on mean values as in section 6.1.

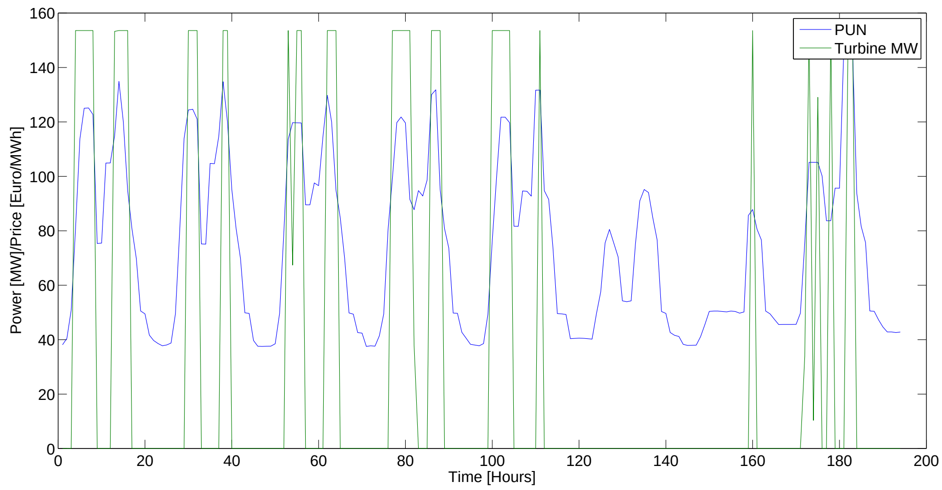


Figure 38: The simulated turbine activity of the power plant Soverzene considering optimal investments and the PUN from 16.01.2006 00:00 until 23.01.2006 23:59

7.2 Water level

Since we found some differences between the behaviour of the simulated turbine activity of section 6.1 and 7.1 we also expect some other outcomes for the simulated water level. We stick to the power plant Soverzene and present the simulation results for the water level of its reservoir Val Gallina and the turbine activity of Soverzene in figure 39. The same correlation of the turbine activity and the water level as in figure 33 is found i.e. whenever the turbine is active the water level sinks due to the removal of water form the reservoir whereas the water level rises during turbine inactive periods. Comparing the figures 32 and 39 more fluctuations are found in figure 39. These fluctuations are a direct consequence of the varying turbine activity.

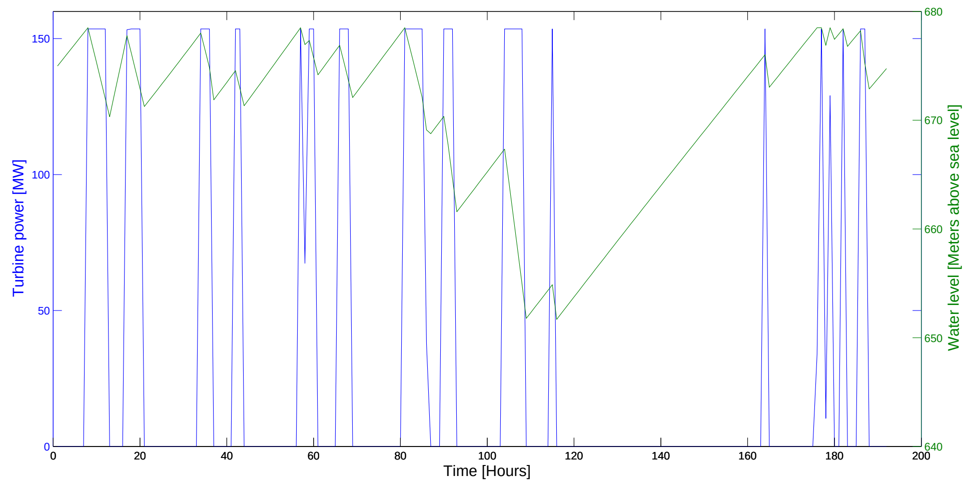


Figure 39: The simulated water level of Val Gallina (reservoir of the power plant Soverzene) and the simulated turbine activity of the power plant Soverzene considering optimal investments from 16.01.2006 00:00 until 23.01.2006 23:59

7.3 Total energy content

The next to discuss is the simulated total energy content considering optimised investments in generation capacity. Simulations of the single years 2006, 2007 and 2008 and the period 2006-2008 are presented. We choose a longer period than before to observe whether we find any differences in the behaviour of the simulations.

In figure 40 the energy contents of all power plants for the single years 2006, 2007 and 2008 considering optimised investments in generation capacity are plotted. Comparing this plot to figure 36 we notice again that the values in the beginning and in the end of each year are the same. Moreover we observe a lot more fluctuations and more pronounced peaks than in section 6.4. These fluctuations arise from the varying turbine power observed in the previous section 7.1.

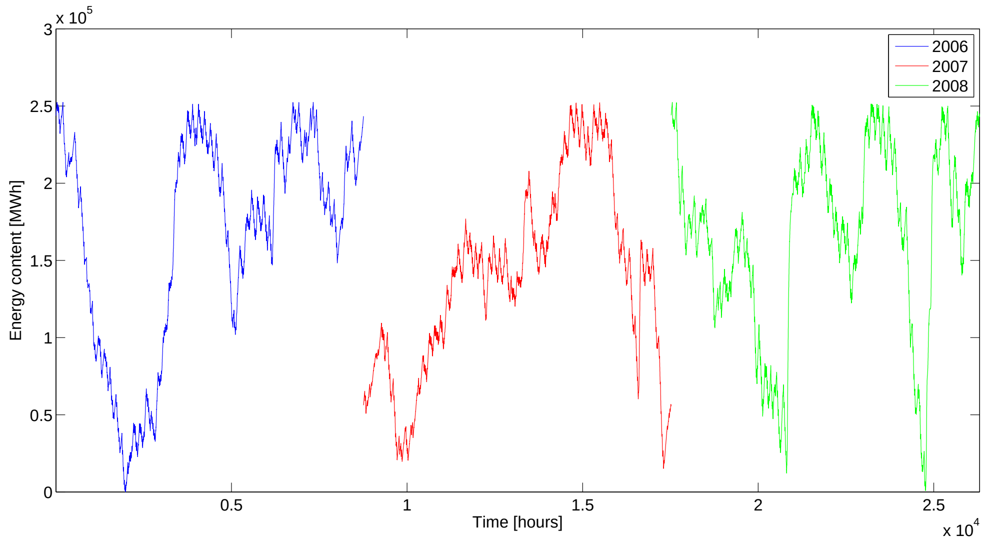


Figure 40: The simulated total energy content of all power plants considering optimal investments for the single years 2006, 2007 and 2008

The next figure 41 illustrates the total energy content for the single years 2006, 2007, 2008 as well as for the period 2006-2008. The comparison of the simulated total energy content of two single years to the two year interval (see figure 37) and the comparison of the simulated total energy content of three single years to the three year interval give the same result namely the graphs are nearly the same except in periods when the cyclic constraint of equal initial and end data comes into effect. Thus once again the model seems to be a reliable one since we find same outcomes for same years independent of the simulated interval.

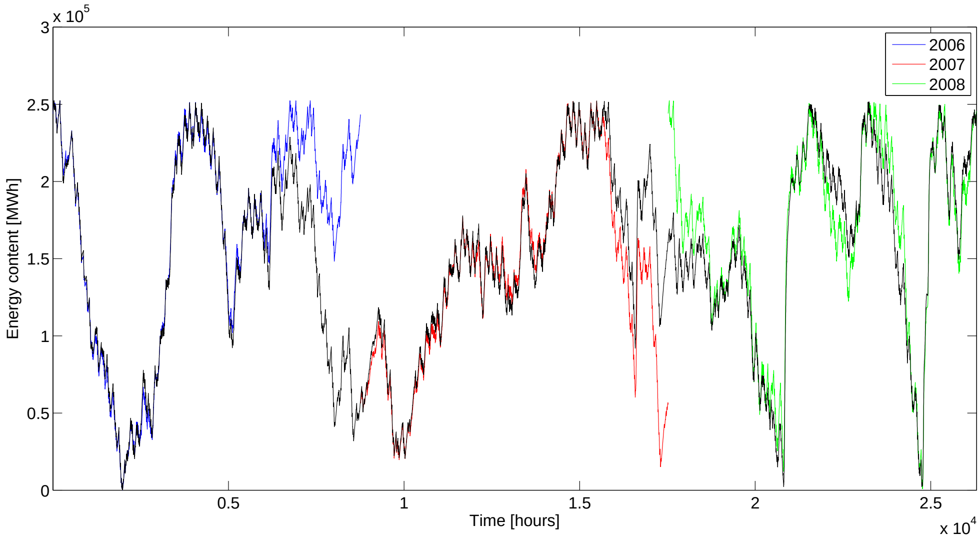


Figure 41: The simulated total energy content of all power plants considering optimal investments for the single years 2006, 2007 and 2008 and the period 2006-2008

7.4 Revenue

The last part of this section is to look at the revenue. Table 8 lists the simulated revenue, the produced MWh and the calculated revenue per MWh for the same four power plants we considered in section 6.5. More years and a longer period namely 2006, 2007, 2008 and the period 2006-2008 are simulated. In order to compare the revenues per MWh the increases are given in table 9. The first to find in table 8 is that - like we expect from section 6.5 - the revenues per MWh for storage power plants Soverzene and Quero are higher than those for the run-of-river power plants Somprade and Saviner. Moreover the average of the revenue per MWh of the three years is - even if not as exact as in section 6.5 - nearly the same as the one of the period 2006-2008.

The year 2007 is again the one with the least revenues per MWh but even higher productions as in 2006. Thus the calculated revenue per MWh of Soverzene of 2007 is just 76.54% of the one of 2006 which is a decrease of 23.46%. However, opposing the revenues per MWh of Soverzene of 2007 and 2008 we find an increase of 62.65% and for the power plant Saviner a rise of even 88.68% is noted. Comparing table 9 and 6 shows that even if the values of the revenues per MWh differ the percentage of the decrease for the year 2007 is nearly the same for all power plants.

Now it is interesting to check whether optimising investments in generation capacity can increase the revenue per MWh. First of all we compare the values of the run-of-river power plants Somprade and Saviner of table 9 to the values of table 6. What we find is that the values of Somprade do not differ at all and the ones of Saviner have a difference smaller than 0.05%. This outcome is little surprising because no parameters of these power plants were changed. A different situation occurs for the modified storage power plants. Thus the revenue per MWh of Soverzene was risen by 12.07% for 2006 and by 14.59% for 2007. Moreover the revenue per MWh increase of Quero was even higher namely 22.54% and 27.91% respectively. These results show clearly that the revenue of the considered power plants could be improved by upgrading the turbine power by the values given in table 7.

	Soverzene	Quero	Somprade	Saviner
revenue 06 [€]	38738533.0	35977392.5	150829.9	325345.6
production 06 [MWh]	611861.5	511005.3	3250.3	7266.3
revenue/MWh in 06 [€]	63.31	70.41	46.40	44.77
revenue 07 [€]	32775123.9	30441314.9	138799.7	281519.1
production 07 [MWh]	676301.6	557746.2	3751.7	7985.2
revenue/MWh in 07 [€]	48.46	54.58	37.00	35.26
revenue 08 [€]	65803928.1	67653663.9	306912.6	665598.3
production 08 [MWh]	834819.5	794721.0	4641.5	10004.3
revenue/MWh in 08 [€]	78.82	85.13	66.12	66.53
revenue 06-08 [€]	137447294.5	131803959.6	596551.4	1272921.5
production 06-08 [MWh]	2111955.9	1849431.0	11643.5	25272.1
revenue/MWh in 06-08 [€]	65.08	71.27	51.23	50.36

Table 8: Overview of the simulated revenue, the production and the revenue per MWh of the storage power plants Soverzene and Quero and the run-of-river power plants Somprade and Saviner considering optimal investments for the single years 2006, 2007 and 2008 and the period 2006 to 2008

	Soverzene	Quero	Somprade	Saviner
06 to 07 [%]	-23.46	-22.48	-20.26	-21.25
07 to 08 [%]	62.65	55.97	78.70	88.68
06_e to 06 [%]	12.07	22.54	0.00	0.02
07_e to 07 [%]	14.59	27.91	0.00	0.03

Table 9: The increases of the different revenues/MWh of the storage power plants Soverzene and Quero and the run-of-river power plants Somprade and Saviner - the values without index stand for the ones found in this section and the index e represents the values of section 6.5

8 Simulations with optimised investments in generation capacity including pumps

In the region Veneto no pumped-storage power plants are run. Nevertheless these kinds of power plants are very important to store energy (see section 2.2). Thus some simulations including hypothetical pumped-storage power plants are performed. Hence four storage power plants namely Soverzene, Sospirolo, Pontesei and Agordo are assumed to be pumped-storage power plants with a pump power of 0.1 MW. The model is allowed to increase the turbine power (like in section 7) and now also an upgrade of the pump power is permitted fulfilling the same conditions as before. Thus a value of 0.1 MW of the pump power enables the model to use any pump power.

Like in the previous section we have a closer look at the power plants Soverzene now having a pump and Quero which remains a simple storage power plant. In the following table 10 the values of the added MW for the different simulation intervals are given. Once more we see that the value for the period 06 to 08 is nearly equal to the average of the other three values. Comparing this table to table 7 we find of course higher values for Soverzene whereas the values for Quero are nearly the same.

	06	07	08	06-08
Soverzene	74.4	71.6	107.6	79.7
Quero	121.3	124.6	197.2	146.4

Table 10: Added MW for the power plants Soverzene and Quero for the single years 2006, 2007 and 2008 as well as for the period 2006-2008

8.1 Turbine and pump activity of pumped-storage power plants and price

Since now the power plant Soverzene is not only a storage power plant but a pumped-storage power plant the first is to have a look at the pump activity. Therefore we oppose the turbine activity and the pump activity. Thus figure 42 shows graphs of the two simulated activities for the same eight days period of January 2006 which was also used in the previous sections 6 and 7. What we see in this figure is that pumping and turbine activity do not occur at the same time i.e. during the day the turbine is working and the pump is inactive whereas during the night the pump is active and the turbine is standing. Thus during the day water is taken from the reservoir and energy is produced (indicated by an active turbine) whereas the exact opposite happens during the night when the pump is run and water is pumped back up to the reservoir in order to be provided for the next day.

Now as we found a relation between the pump and turbine activity we also expect some relation between the activities and the price. A comparison of the two activities and the price is shown in figure 43. Like in the other sections 6 and 7 the turbine is working when

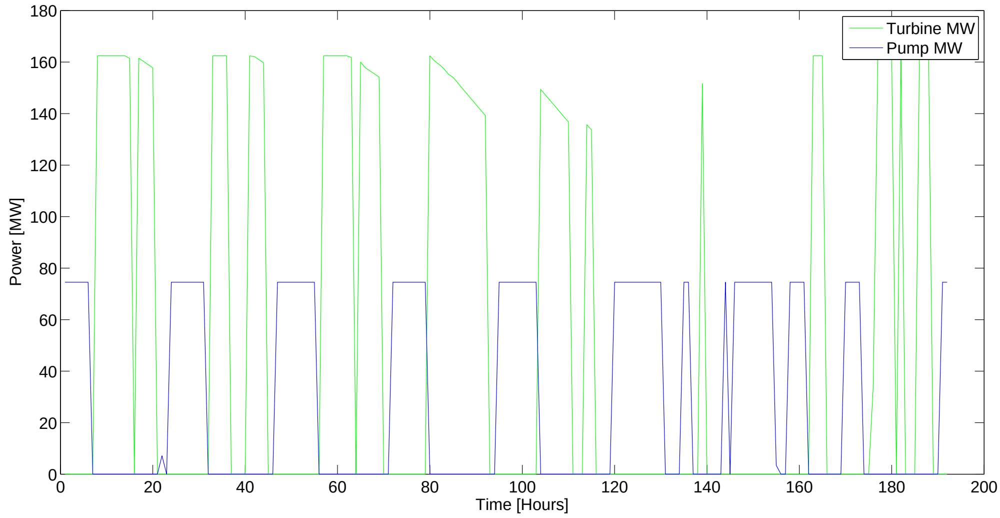


Figure 42: The turbine activity and the pump activity of the extended pumped-storage power plant Soverzene from 16.01.2006 00:00 until 23.01.2006 23:59

the price is high in order to produce electricity and to sell it at that high price. On the other hand pumping occurs when the price is low. Hence during these low price periods water is pumped to the reservoir where it is stored until the price is high.

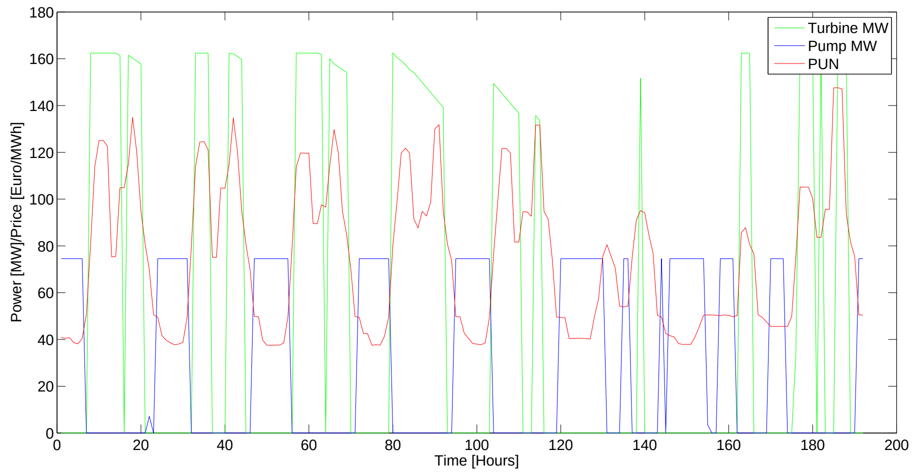


Figure 43: The turbine activity and the pump activity of the extended pumped-storage power plant Soverzene and the PUN from 16.01.2006 00:00 until 23.01.2006 23:59

Figure 44 shows the pump and the turbine activity of the extended pumped-storage power plant Pontesei for eight days in July 2007. The same behaviour as in figure 43 applies and thus we conclude that the found relation of the pump and turbine activity and the price is not specific for the power plant Soverzene nor the time period but representative for all pumped-storage power plants and all times.

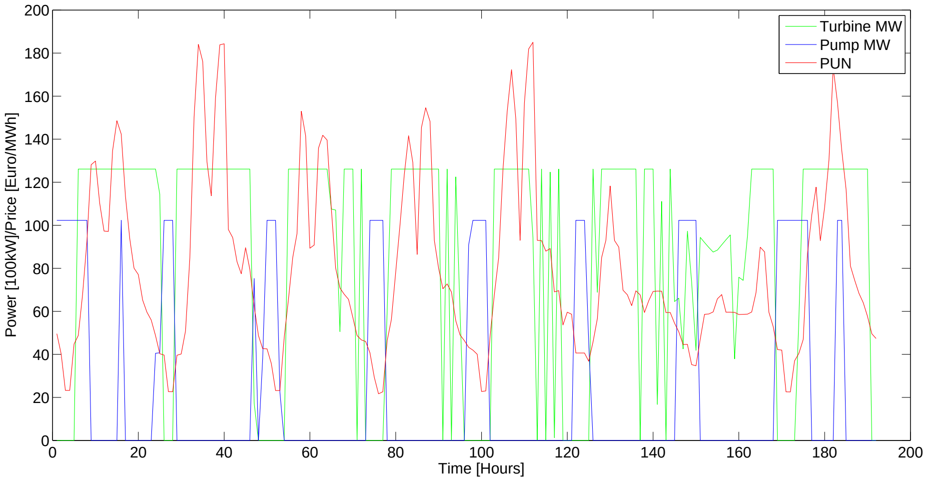


Figure 44: The turbine activity and the pump activity of the extended pumped-storage power plant Pontesei and the PUN from 02.07.2007 00:00 until 09.07.2007 23:59

8.2 Water level

Since in these simulations pump activity is imbedded it is probably that this inclusion also has an effect on the water level of the reservoir. In the simulations of the last sections the reservoir was not filled actively but rather depended totally on natural inflows. Once more we focus on the power plant Soverzene - figure 45 presents the simulated water level of its reservoir Val Gallina. Comparing this figure to the water level figures 32 and 39 of the last two sections the first to be observed is that after a lowering period the water level rises to higher values than in the simulations without a pump. This is not a surprise at all because a pump serves for increasing the water level. Beside this we find a similar behaviour as in the figure 32 and 39 i.e. a decreasing level during the day and an increasing one during the night.

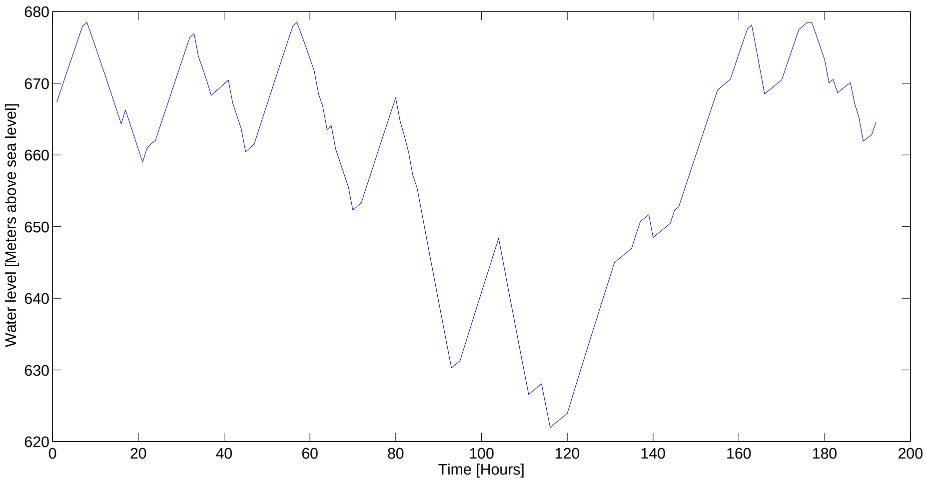


Figure 45: The simulated water level of Val Gallina (reservoir of the power plant Soverzene) considering optimal investments including pumps from 16.01.2006 00:00 until 23.01.2006 23:59

In order to check the consistency of the results the next two figures show the relation between the water level and the turbine activity (figure 46) and the connection of the water level and the pump activity (figure 47). The outcome is not astonishing: When the turbine activity is high the water level decreases whereas low or no turbine activity occurs during increasing water level. Having a look at figure 46 what can be concluded is that pumping occurs when the water level is rising. However, there are also periods when an increase of the water level is noted without pump activity. This is due to the natural inflow. These two figures confirm the correctness of our model since they represent exactly the theoretical outcome.

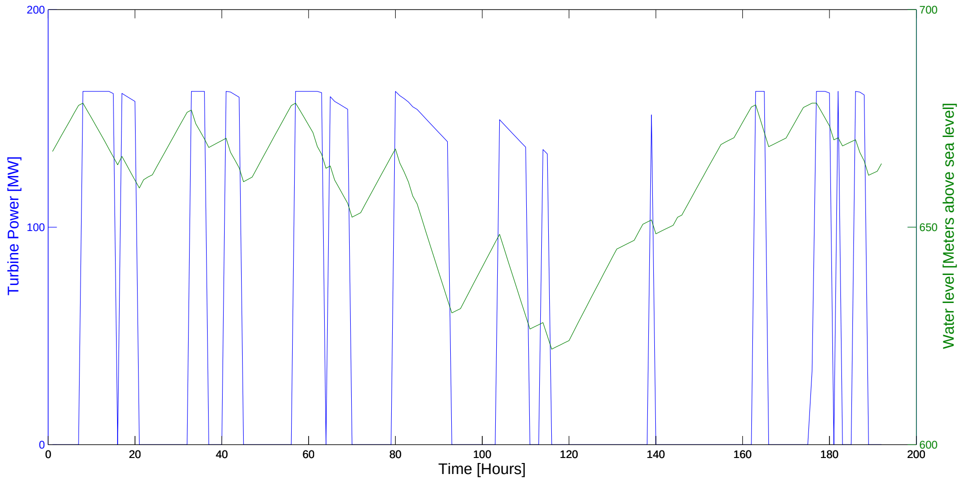


Figure 46: The simulated water level of Val Gallina (reservoir of the power plant Soverzene) and the turbine activity of the extended pumped-storage power plant Soverzene from 16.01.2006 00:00 until 23.01.2006 23:59

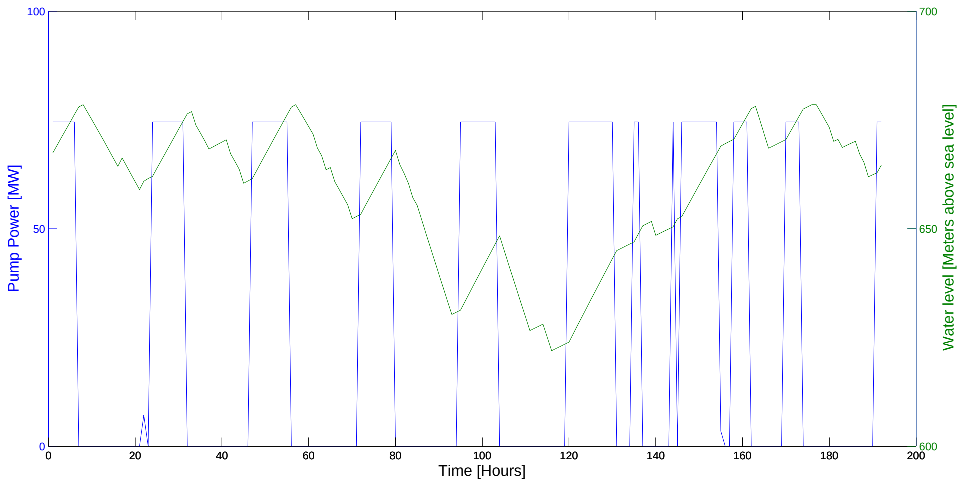


Figure 47: The simulated water level of Val Gallina (reservoir of the power plant Soverzene) and the pump activity of the extended pumped-storage power plant Soverzene from 16.01.2006 00:00 until 23.01.2006 23:59

8.3 Total energy content

Now we also discuss the total energy content considering optimised investments in generation capacity with pumps. Like in the section 7.3 we present the results of simulations for different intervals: the single years 2006, 2007 and 2008 and the period 2006 to 2008. The results of the single year simulations of the total energy content of all power plants are found in figure 48.

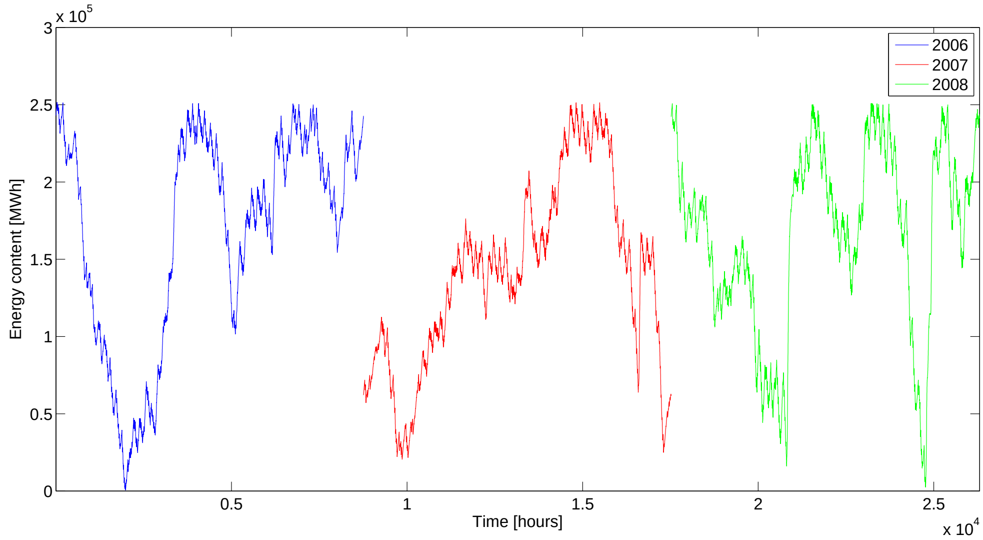


Figure 48: The simulated total energy content of all power plants considering optimal investments including pumps for the single years 2006, 2007 and 2008

There are hardly any differences between the two figures 40 and 48. Having a very close look one observes that in general the simulated energy content of figure 48 is a little higher than the one of figure 40. This little difference is caused by the pump since it brings water to the reservoir and more water in the reservoir implies more available energy. Nevertheless this effect is not as big as one may assume.

Figure 49 shows the graphs of all simulated intervals including the period of 2006 to 2008 and similar observations as in 7.3 can be made i.e. there are no differences between the values of the distinct graphs despite for the beginning and the end of each year when the cyclic constraint comes into effect.

8.4 Revenue

Last but not least we look at the revenue of the power plants simulated by considering optimised investments in generation capacity including pumps. In table 11 the simulated revenue, the produced MWh as well as the revenue per MWh of the pumped-storage power plant Soverzene, the storage power plant Quero and the two run-of-river power plants Somprade and Saviner are listed. Moreover a comparison of the different revenues

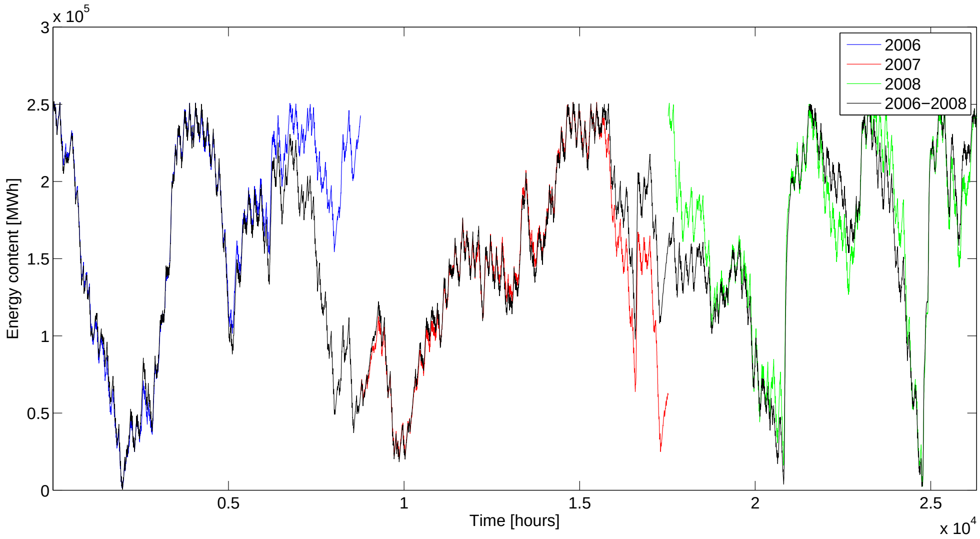


Figure 49: The simulated total energy content of all power plants considering optimal investments including pumps for the single years 2006, 2007 and 2008 and the period 2006-2008

per MWh are found in table 12. The first to see is again that in 2007 all power plants denote the smallest revenue per MWh even though more MWh than in 2006 are produced. Once again the percentage for the increase and decrease of the revenue per MWh of the different years are similar. Moreover the average of the revenue per MWh of the three single years is again close to the one of the period of all three years.

The calculated revenues per MWh of the untouched run-of-river power plants are the same as in section 6.5 and 7.4. Considering the pumped-storage and the storage power plant a big growth of the revenue per MWh is noted. Thus the calculated revenue per MWh of 2006 of Soverzene is now 19.44% higher than the one of section 6. The year 2007 denotes even a growth of 22.01%. Furthermore there is also a rise of the revenue per MWh compared to section 7 where pumps were not included i.e. 6.57% for 2006, 6.49% for 2007 and 3.69% for 2008. Turning to the storage power plant Quero we find - as to be expected - nearly no increase compared to section 8.4. The noted increases are around 1% and thus can be neglected.

These results let us conclude that installing a pump and upgrading the turbine capacity can rise the revenue per MWh significantly.

	Soverzene	Quero	Somprade	Saviner
revenue 06 [€]	41240623.8	36269608.9	150829.9	325341.4
production 06 [MWh]	611225.5	510848.9	3250.3	7266.2
revenue/MWh in 06 [€]	67.47	70.99	46.40	44.77
revenue 07 [€]	34883587.3	30675119.5	138799.7	281521.2
production 07 [MWh]	676064.1	557628.6	3751.7	7985.6
revenue/MWh in 07 [€]	51.60	55.01	37.00	35.25
revenue 08 [€]	68685251.9	68519818.6	306912.6	665561.8
production 08 [MWh]	840409.8	796142.9	4641.5	10003.9
revenue/MWh in 08 [€]	81.73	86.06	66.12	66.53
revenue 06-08 [€]	142957609.2	133429749.6	596551.5	1272982.8
production 06-08 [MWh]	2108718.5	1850711.9	11643.5	25273.2
revenue/MWh in 06-08 [€]	67.79	72.10	51.23	50.37

Table 11: Overview of the simulated revenue, the production and the revenue per MWh of the pumped-storage power plants Soverzene, the storage power plant Sospirolo and the run-of-river power plants Somprade and Saviner for the single years 2006, 2007 and 2008 and the period 2006 to 2008

	Soverzene	Quero	Somprade	Saviner
06 to 07 [%]	-23.52	-22.51	-20.25	-21.26
07 to 08 [%]	58.39	56.44	78.70	88.74
06_e to 06 [%]	19.43	23.55	0.00	0.02
07_e to 07 [%]	22.01	28.92	0.00	0.00
06_o to 06 [%]	6.57	0.82	0.00	0.00
07_o to 07 [%]	6.48	0.79	0.00	-0.03
08_o to 08 [%]	3.69	1.09	0.00	0.00
06-08_o to 06-08 [%]	4.16	1.16	0.00	0.02

Table 12: The increases of the different revenues/MWh of the pumped-storage power plants Soverzene, the storage power plant Quero and the run-of-river power plants Somprade and Saviner - the values without index stand for the ones found in this section, the index e represents the values of section 6.5 and the index o is for the values of section 7.4

9 Discussion and outlook

In the last three sections 6-8 results of some simulations were presented starting with analysing the model considering the existing power plant data of Veneto. All the found results were in agreement with the expectations and existing data. Thus we can conclude that the model is reliable.

After that some modifications were performed to get information on feasible economical advancement. The simulations with optimised investments in generation capacity and the simulations with optimised investments in generation capacity including pumps gave an insight into the possibilities of improving the revenue of the region Veneto by using turbines with higher powers or by installing a pump. Both modifications denoted big increases of the revenue per MWh (see sections 7.4 and 8.4). Hence the hydroelectric power grid of Veneto has the potential to be optimised economically.

On the first sight better results could be gained with more input stations but on the other hand more input data would cause an extended data base which would make it difficult for the programme to find a reliable solution. That is the reason why just the most important power plants were included.

As mentioned before the major weakness of these simulations is without doubt the incomplete inflow data. The model depends on the inflow data and thus estimations and approximations in these data bring imprecise output data. Nevertheless there was no way to overcome this problem because no better inflow data are available.

Moreover there are some more weak points of this model which could be enhanced:

- Veneto is simulated as an isolated region with no electricity exchange.
- Just hydroelectric power plants were considered and no interaction with other power plants are simulated.
- Power grid capacities are not included.
- A rise of capacities of the run-of-river turbines cannot be simulated.

Considering the aim to achieve a data base including all regions of Europe a lot of work has to be done. This thesis focuses on the region Veneto. Another diploma thesis covers the region Bolzano of Italy. Moreover France and Norway have been analysed. The models for France and Norway are finished but Italy has to be completed. The two regions Veneto and Bolzano are both in the north of Italy with high shares of hydroelectric power plants. Hence when modelling other parts the first problem to be dealt with is that the topological structure of Italy differs a lot from the north to the south from mountainous to plane and thus the south is not a preferable region for hydroelectric power plants i.e big shares of other power plant types occur. Above all photovoltaic power plants are favoured in the south because of the sunny weather. That is why just modelling hydroelectric power plants in the south is not very meaningful.

Beside the work on an European data base some research is done on creating models including all types of power plants considering different shares of renewables - first and foremost high shares of wind as well as solar power plants are regarded. The fact that different regions have varying shares of power plant types cause problems when trying to extend such models. Hence problems occur especially when trying to fit a model to distinct countries in Europe (or even to the world).

Last but not least the Vienna University of Technology works on simplifying the HiREPS model (see section 5) and extending it to whole Europe. This project is supposed to be finish in March 2015.

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Abbreviations

ARPAV Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto

EEX European Energy Exchange

Enel Ente Nazionale per l'energia Elettrica

GME Gestore Mercati Energetici

GSE Gestore dei Servizi Energetici

HiREPS High Resolution Power System

ICOLD International Commission on large dams

IPEX Italian Power Exchange

OECD Organisation for Economic Co-operation and Development; members: Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israël, Italy, Japan, Korea, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States

PUN Prezzo Unico Nazionale-National Single Price