MSc Program

Renewable Energy in Central and Eastern Europe

Optimization of Austrian Hydropower Plants in a Power Market with a High Share of Wind Energy

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by

Dr. Lukas Kranzl

Dr. Gerhard Totschnig

Diplom-Ingenieur

Kai Kemendy

e8425032

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Affidavit

I, **Dipl.Ing. Kai Kemendy**, hereby declare

1. that I am the sole author of the present Master Thesis, "*Optimization of Austrian Hydropower Plants in a Power Market with a High Share of Wind Energy*" , 76 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master Thesis as an examination paper in any form in Austria or abroad.

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Abstract

The supply of environmental friendly and affordable electricity is one of the most important tasks for the energy industry and science in the future. Therefore we need tools and methods to seek economical-technical-environmental optimized solutions. With this master thesis a unit commitment model of the hydro power plants in Styria, Upper Austria and Lower Austria with more than 5 MW is developed and then combined with the existing HiREPS model for Austria and Germany. This combined HiREPS model is then used to analyse two scenarios of the Austrian and German power system. One with a 7% wind generation and one with 45% wind generation in terms of electricity demand. The thesis analyses in detail the operation of pumped storage and run-off hydro power plants for both scenarios. The second scenario allowed 10% of annual wind energy to be curtailed if this is beneficial for the operation of the power system. By allowing this it is possible to increase the wind share from 7% up to 45%. In the high wind scenario an emission reduction of 155mio tonCO_2 per anno is achieved for Austria and Germany compared to the low wind scenario. This is a 60% reduction in CO_2 emissions. The fossil and nuclear energy share is decreased by 39 percentage points. The hope is that this model will make important contributions for planning the next generation power system in Austria and in European Union and helps to promote the development of renewable energy systems.

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Acronyms

AEA	Austrian Energy Agency
AG	Aktiengesellschaft
AHP	Austrian Hydro Power
AutRES100	Austrian Renewable Energies 100
AMPL	Advanced Mathematical Programming Language
BW	Back water: Area of reservoir between begin of water storage and weir or dam
EC	European Commission
EEX	European Energy Exchange
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
FBS	Fish bypass systems: Installations providing a route through the power plant for fishes and other biological species
GEN	Generator: a device to generate electricity
HHQ	Highest discharge ever
HPP	Hydro Power Plant

HRC	Headrace channel
HWL	Head water level: Water level in the backwater reservoir
KELAG	Kärntner Elektrizitäts AG
MHQ	Mean high discharge
(M)NQ	Mean low discharge
MQ	Long term mean runoff. Several types are existing for different investigation periods (MQ_{10}, MQ_{xx},..).
NGO	Non Governmental Organisation
NGP	Nationaler Gewässerbewirtschaftungsplan
NNQ	Lowest discharge ever
OF	Overflow: Water which flows over the dam/weir during floods, compensation water, flushing water). Could not be used to produce energy.
PHES	Pumped Hydro Energy Storage
PS	Power station: Building, where the power generating equipment is located
PSPP	Pumped Storage Power Plant
PV	Photovoltaic
RBMP	River Basin Management Plan
RES	Renewable Energy Sources
RPP	River Power Plant
SPP	Storage Power Plant
TIWAG	Tiroler Wasserkraft AG
TRAN	Transformer: a device to transform voltage levels (for delivery reasons)
TRC	Tailrace channel
TWL	Trail water level: Water level in the settling basin
UNFCC	United Nations Framework Convention on Climate Change
VEÖ	Vereinigte Elektrizitätswerke Österreich
WFD	Water Framework Directive
ZAMG	Zentralanstalt für Meterologie und Geodynamik

1 Introduction

1.1 Motivation

The progression of future greenhouse gas (GHG) emissions and the evolution of their drivers are highly uncertain. This is reflected in a large collection of GHG papers and models with emission scenarios. These scenarios are required for the assessment of anthropogenic climate change, caused by demographic, technological and economic developments. They should help us to predict future developments and to develop measures to influence GHG producers. That implies new and advanced alternative structures of energy producing systems and a sustainable management of natural resources.

Hydro power energy systems are one possible solution to produce electricity with less GHG emissions. The question is, how we can integrate and combine different systems into a modern (renewable and sustainable) energy production platform which is able to work cross border, guarantees good supply security, makes us independent from fossil fuels and saves GHG emissions[1]. Currently, Europe implements several ambitious programs to investigate ways to integrate renewable energy sources (RES) into the classic and traditional grown Austrian and European power plant platforms. What has to be done to achieve a 100% renewable power supply in Austria and Europe? How could energy technologies interact to increase efficiency?

These questions lead to a general problem of renewable sources: Energy – on a large scale – cannot easily be stored and the forecast planning for variable renewable energy sources is uncertain. Sometimes RES produce more energy than can currently be used[2]. In order to waste this energy surplus, the energy in excess should be stored, e.g. into pumped hydro power storages[3]. For the time being there is still a need to adapt the energy power plants and grids to pick up and release energy surpluses from intermittent renewable energy sources.

[1] That is really a challenge!
[2] Often Wind energy, sometimes PV.
[3] Additionally, in some other possible scenarios: hydrogen, latent heat storage, compressed air, superconductive magnetic energy storage, electrochemical double layer capacitor, Hydrogen2Methan

1.2 Core objectives

The EU supports the project AutRES100 to investigate general aspects of energy systems with high shares of renewable energy sources (target is a 100% RES share). The AutRES100 is a computer model and simulator with a high-resolution power system investment planning and supply security optimization model.

Following core objectives should be investigated:

- Determination of Austria's hydro power portfolio
- Inventory of existing hydro power plants in Austria bigger than 5 MW_{el} (dams, reservoirs and plants)
- Analyzing optimal operation of hydro power plants (reservoir management) regarding to a historical EEX price
- Analyzing the seasonal inflow patterns of different hydropower plants
- Assuming a high renewable energy surplus (Wind) in Austria, could it be stored in pumped hydro storages?
- Analyzing the possible maximum share of wind power in the Austrian power system

1.3 Structure of work

The goal of this master thesis is to improve and to develop the Austrian Hydro Power Model. All hydro power plants (run-off, diversion, storage and pumped storage plants) above $5MW_{el}$ are included. This model uses procedures of linear programming algorithms to calculate optimized solutions, regarding to economic viability, Austrian electricity demand and a certain share of renewable power sources.

Following structure of work was defined:

Introduction

- Motivation
- Core objectives
- Structure of work

Global Warming and Energy Strategies

- Common aspects of Global, European and Austrian energy strategies to guarantee electricity production and supply security in the future and what impact climate change might have on Austria's hydro power program

Austria's electricity supply and demand

- Overview of historic electricity production
- Current situation of Austria's electricity demand
- Current situation of Austria's wind energy

Technologies of Hydro Power Plant

- Summarization of basic classifications of hydro power plants
- Overview of actually used main hydro power plant technologies
- Description of basic hydro power plant design elements

Austrian Hydro Power Model

- Overview of linear and mathematical programming
- Concept of Austrian hydro power model
- AMPL program language
- Equations and framework conditions

Description of method of approach applied

- Methods of data research (technical and hydrologic data, sources, tools)
- Identification of hydro power plant (owner, name, technical data, location)
- Calculation of hydro power plant annual energy yield
- Assessment of hydro power plants (annual average discharge amount)
- Assessment of hydrologic data (discharge, inflows, side inflows)
- Research of historical wind data
- Research of historical electricity demand
- Research of historical energy prices

- Simulation and running model

Documentation of data and data collections

- Description of data explored during research

Description of results

- Analyzing and validating results
- Results aggregated from data

Conclusions

- Final statements and conclusions derived from research results and data collections

2 Global Warming in Context of Renewable Energy Sources

The greenhouse gases released by mankind since the mid 20th century are – with highest probability – the cause of the observed increase of the global average temperature. Politicians, Scientists and inhabitants of the European member states are aware that the global climate change has a serious impact on environment, society and economy. They are willing to take actions and to spend money to slow down the global warming impact or even to stop it - if possible.

2.1 Global and European Strategy

On December 11th, 1997 the Kyoto Protocol was initially adopted by the members of United Nations Framework Convention on Climate Change[4]. The goal of this protocol is to protect the environment and to reduce greenhouse gas concentrations in the atmosphere. After 55 members of UNFCC signed the protocol (in accordance with the Article §23), the protocol was entered into force on February 16th, 2005. Currently 193 states have ratified the protocol (2011).

Each Party, in achieving its quantified emission limitation and reduction commitments, shall [UNFCC, Kyoto Protocol: Article 2]:

- *"Implement and/or further elaborate policies and measures in accordance with its national circumstance"*
- *"Cooperate with other such Parties to enhance the individual and combined effectiveness of their policies and measures"*

The parties shall take measurements to reduce their anthropogenic carbon dioxide emissions of the GHG by 5,2 per cent[5] below 1990 levels in the commitment period of 2008-2012 [UNFCC, Kyoto Protocol: Article 3]. Until 2005, they should have "*demonstrable progress*" in achieving their commitments. Emerging and developing countries do not have restrictions to reduce their emissions because they have to build up their underdeveloped infrastructure and economy and they have already very low emission-per-capita rates. Additionally, one of the biggest difficulties is that the world's biggest economy and biggest GHG producer - the United States of

[4] Austria has signed it on April 29th, 1998 and ratified it on May 31st, 2002.
[5] EU: 8%, Austria: 13%

America - did not join the protocol. Main policy is to the trade with CO_2 certificates (emission trading).

For the first time, binding targets were set for GHG emissions in industrialized countries and GHG emissions are seen as the main cause of global warming. After Kyoto started well, currently the process is frozen, because the members could not find a solution to set further individual emission targets and time tables. Industrialized countries fear unfavorable conditions for their economies and high penalty payments. On the other hand, emerging and developing countries are not willing to be disproportionately affected by GHG restrictions.

In the light of the background of ongoing financial crisis, it is possible that important countries[6] will leave the protocol or measurements will be diluted, so it will be questionable if the protocol could be continued and if the ambitious GHG target can be met.

2.2 European and Austrian Strategy

European strategy is driven by establishing a framework for the use of energy from renewable sources to reduce greenhouse gas emissions, increasing energy efficiencies and promoting clean (green) transport systems. Therefore, directives and national action plans are defined to set individual measurements by each member of the European Union. Meanwhile, after the nuclear disaster in Fukushima (Japan), all parties are willing to increase their own share of renewable energy systems to be more independent from fossil fuels or to avoid GHG penalty payments. Although I do not consider nuclear power plants as renewable, sustainable and “good for next generations” energy systems, some countries still rely on this technology as major part of their electricity generation. This is based on the argument that nuclear power plants are CO_2 free and the fact that some countries have a big gap of natural energy sources like Wind, Solar, Hydro, Biomass and other sources. For example, Germany will reduce its nuclear power plants and increases the number of Windmill parks. France will still retain its nuclear energy system (because of lacking alternatives), also some other smaller countries in the

[6] November 2011: Canada left the protocol to avoid penalty payments

European Union. Currently, it is not foreseeable where we will lead go (more nuclear systems or more classic renewables).

Globally and in the European Union, the major issues of current energy production supply and climate change are:

- Getting independent from fossil fuel imports (oil, gas, coal, gas, uranium)
- Avoiding Greenhouse Gas Emissions during power generation and consumption
- Support of renewable energy systems
- Limited resources and reserves (Fossil, Renewable, Nuclear)
- Shortage of water and food
- Increasing energy and resource demands
- Supply Security
- Discrepancies between industrialized and emerging countries based on economic and environment issues

EU Directives and Potentials

European Union released some directives about the usage of water resources to protect human, animal and plant life and its impact on the natural climate cycle. The most important directive is "*Directive 2009/28/EC*"of the European Parliament and the Council of April 23th, 2009 *"on the promotion of the use of energy from renewable sources*" [EUR-Lex: Directive 2009/28/EC]. For each country a national target was calculated for the national Renewable Energy Systems (RES) share in gross final energy consumption [EUR-Lex: Directive 2009/28/EC, Annex 1].

The Directive's 2009/28/EC major targets for all member countries are (20/20/20) until 2020:

- Establish an overall share of 20% for energy from renewable sources
- Reduce Greenhouse Gas Emissions by 20% compared to the year 1990
- Establish an overall share of 10% for energy from renewable sources in transport

- Improve energy efficiency[7] by 20%

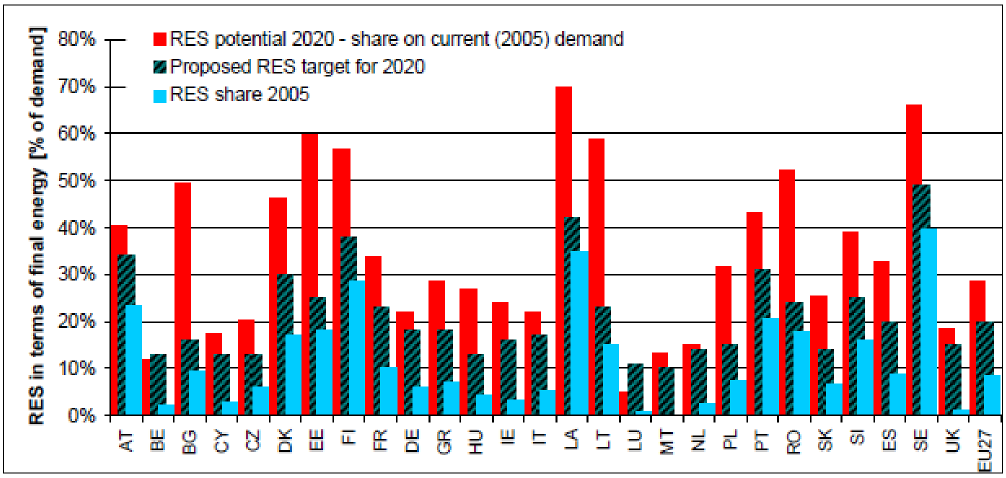


Figure 1: Mid-term potentials for RES in terms of final energy in the EU27[8]

Austria's national overall targets for the share of energy from renewable sources in gross consumption of energy in 2005 and should increase from 23,3% to 34% until 2020. Resch/Weissensteiner showed that nearly all member countries have potentials to achieve unique national targets [Resch G., Weissensteiner L. 2010, p.8/20]. Only Belgium and Luxemburg show some fundamental problems to meet the target, caused by missing potentials.

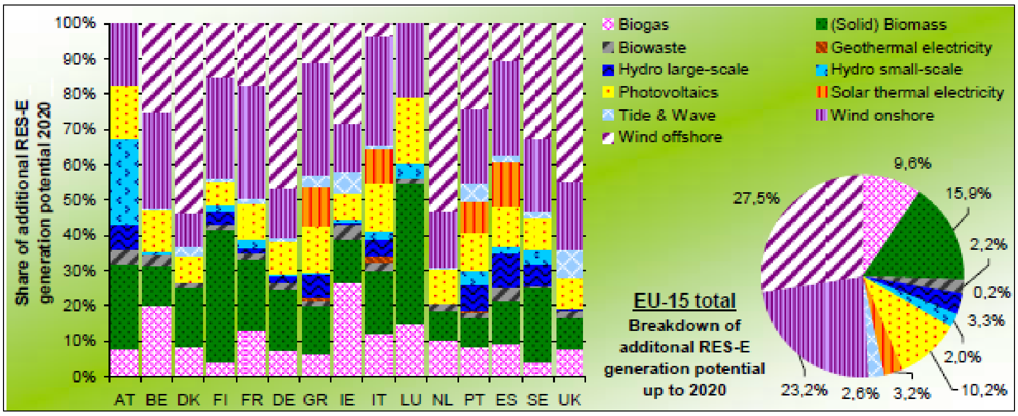


Figure 2: Technology specific breakdown of the additional realizable potential up to 2020 for electricity from EU15[9]

[7] Directive targets exist in the context of the of the 20% improvement in energy efficiency by 2020 set out in the Commission communication of 2006 "Action plan for energy efficiency"
[8] Figure: Resch G., Weissensteiner L. 2010, p.8/20
[9] Figure: Resch G., Weissensteiner L. 2010, p.10/20

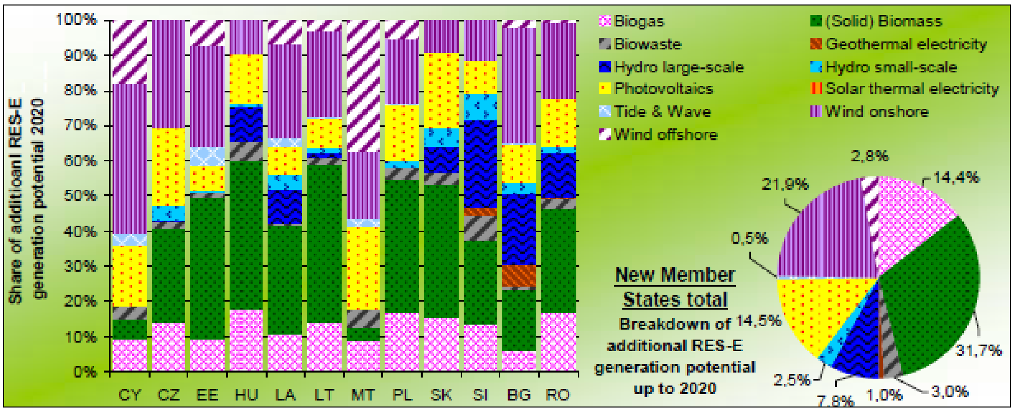


Figure 3: Technology specific breakdown of the additional realizable potential up to 2020 for electricity from new member states[10]

The technology breakdown shows a great potential for Wind, Biomass, Biogas and PV for old and new EU member states until 2020.

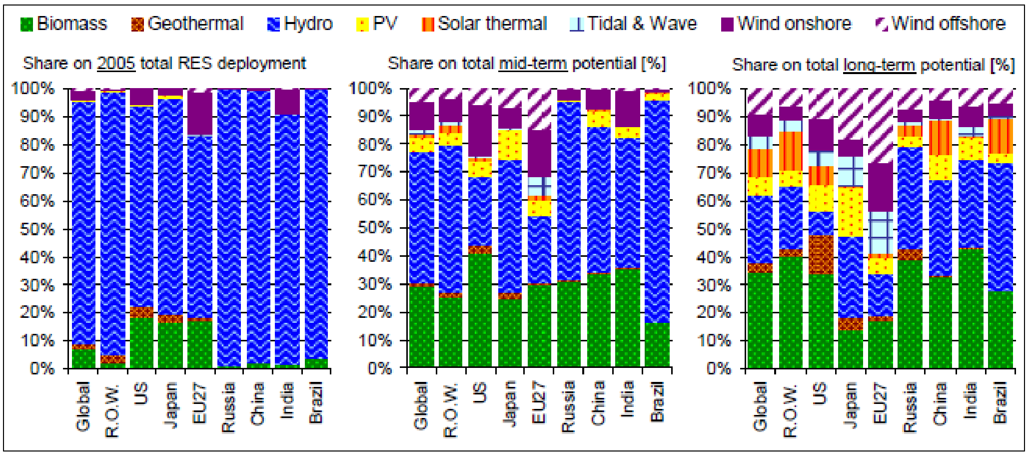


Figure 4: Technology specific breakdown of the current (2005) RES-E deployment, the mid-term (2020) and long-term (2030-2050) potential for RES-E[11]

In a global context and in the time frame of 2020-2050, the dominant share of hydro power will be reduced. This is compensated by growing share of wind and PV/Solar.

Water Framework Directive (WFD)

In 2000, the EU introduced a framework [Wasserrahmenrichtlinie] about the management and protection of water as natural resource [European Commission Environment: Water] based on hydrological and geographical issues over cross borders and is valid for rivers, coastal and transitional waters and lakes (surface and

[10] Figure: Resch G., Weissensteiner L. 2010, p.11/20
[11] Figure: Resch G., Weissensteiner L. 2010, p.19/20

groundwater). The goal is to ensure clean water for everyone to coordinate different EU policies and set a timetable for needed measurements until 2015 and is an umbrella for other frameworks (Groundwater Directive, Environmental Quality Standards Directive, Urban Wastewater Directive, Nitrates Directive, Bathing Water Directive, Drinking Water Directive, Floods Directive and Marine Strategy Framework Directive). The WFD should help to reduce pollution caused by households, industry and agriculture. Each river will be completely analyzed (from source to the mouth) to draw up a river basin management plan (RBMP, done by every EU member state for its rivers). The RBMP describes measurements to achieve a good chemical and ecological status based to protect human health, water supply and biodiversity. Detailed normative classifications of anthropogenic alterations of water bodies (defined as Water Status) could be found in the text of the directive [Water Framework Directive, p.45]. They are ranged from “High” over “Good” to “Moderate” and cover different key factors (physical-chemical-hydro morphological elements): Phytoplankton, Macrophytes and Phytobenthos, Fish fauna, Hydrological regime, River continuity, Morphological conditions, Pollutants.

The WFD has a serious impact on the construction and renovation of Hydro Power Plants: minimum flow regulations, smart transverse structures and restore of river continuity, fish bypassing, restore hydro-morphological and physicochemical conditions, trash rack material management, noise and vibrations, fish friendly turbines. It will be very difficult to maintain to continue promoting hydro power as green energy and to improve the ecological water condition at the same time with respect to the targets of RES-E. To find the right balance between the needs of hydro energy production and protection of environment will a challenging task for engineers and project managers in the next years.

2.2.1 Roadmaps

On December 15th, 2011 the European Commission adopted the “Energy Roadmap 2050” [EU Energy Roadmap 2050]. To achieve the target of reducing GHG emissions by more than 80% until 2050 compared to emissions in the year 1990, Europe’s energy production will have to be almost carbon-free. Based on analysis of energy scenarios and studies, the roadmap describes consequences of a renewable energy system and the needed policy framework.

The key outcome of this document is:

- Decarburization is technically and economically feasible
- Higher capital expenditure and lower fuel costs
- Electricity plays an increasing role
- Electricity prices rise until 2030 and then decline
- Household expenditure will increase
- Energy savings throughout the system are crucial
- Renewable sources rise substantially
- Carbon capture and storage has to play a pivotal role in system transformation
- Decentralization and centralized systems increasingly interact

The roadmap is supporting the 2050 objectives while improving Europe's competiveness and security of supply.

2.3 Climate Change and Water Management in Austria

Climate Change: The Austrian Ministry of Environment published a report [Reinhard Böhm, Reinhold Godina, Hans-Peter Nachtnebel and Otto Pirker, 2007] about the expected impact of climate change to the hydro energy production in Austria and to the environment. Summarized, they said that Austria's temperature will increase +2,5° until 2050 and +4,5° Celsius until 2100.

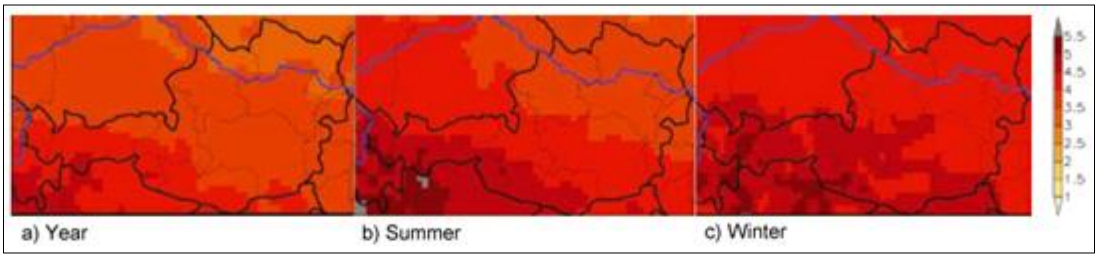


Figure 5: Change of temperature from 2071 until 2100[12]
(Reference to period 1961-1990)

[12] Figure: UBA 2008, p.111-115

As showed in figure 5, the change of precipitation will be very small during the year. In summer, precipitation will decrease a little bit, during winter there will be a little surplus. This has a direct impact on the water temperatures in water bodies. Measurements showed an increase of 1°-2° during the last 30 years [Reinhard Böhm, Reinhold Godina, Hans-Peter Nachtnebel and Otto Pirker, 2007: p.13]. This would lead into a change of the physical-chemical/hydro morphological quality of river and lakes.

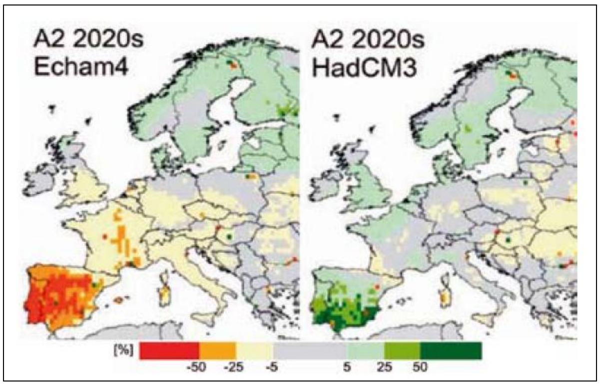


Figure 6: Change of mean annual run-off[13] for Europe until 2020

Evaporation will increase significantly during summer, annual run-off will decrease moderately and precipitation will be stable. Solid precipitation (snow) [Reinhard Böhm, Reinhold Godina, Hans-Peter Nachtnebel and Otto Pirker, 2007: p.16] will decrease -50% which will lead to reduced run-offs during spring and summer months and increased run-offs during winter months.

Glaciers: In 1998, the ice volume of Austrian glaciers was estimated [Lambrecht and Kuhn 2007] with 17km^3 (16% of Austria's precipitation). In the period of 1960 until 1990, glaciers area was shrunk from 567km^2 to 471km^2 and from 23km^3 to 17km^3 (-17%). Although the melting run-off from glaciers is only 1% of Austria's water balance during last 30 years (<2mm/year), the effect is significant in some Austrian high alpine valleys caused by short melting periods.

Hazards: A change of floods could not be predicted. But low water levels will be decreasing significantly.

Energy generation: Hydro power energy is a large and important component of renewable energy sources in Austria. This source is influenced by climate change. The trend of production will be shifted a little bit during summer and winter period (winter run-off increases). A study [Nachtnebel, H.P., K. Hebenstreit, W. Diernhofer und M. Fuchs 1999] showed a reduction of annual production of 3-8% (large uncertainty included). More realistic is a stable production. Caused by a reduction of

[13] Figure: IPCC 2007, WG-2 Report, fig. 12.1

snow and ice volumes at glaciers and mountains, power management of (pumped) storage power plants will be more challenging. Thawing of alpine permafrost will lead to instabilities in slopes and increased amounts of sediments in water bodies.

2.4 Austrian Mitigation Measures Interfering Hydro Power

Summary of Austria's Energy Action plan for 2010:

RES shares (targets[14]) until 2005 should be 23,3% and until 2020 34,0% based on two conditions. 13% reduction of final energy consumption (for efficiency target) and 18% increase (reference 2008) of renewable energy share until 2020.

The paper includes technical specifications and measures for buildings (better insulation), grid development (intelligent networks, IT tools, storage facilities), grid operations (smart grids, demand-side management, monitoring), biofuels (monitoring/verifying compliance with targets, management of agriculture materials).

Measures with focus to hydro power:

- Improved energy consumption monitoring
- Increase capacities for pumped storage plants
- Grid expansion
- Investment grants for Small Hydro Power Plants
- Additional 700MW hydro capacity until 2015 (+3,5TWh)
- Support only for hydro power plants <20MW

Table 1: Estimate of total contribution expected in Austria to meet the binding 2020 targets

Electricity (GWh)	2005	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Hydro (without pumping) (MW)	7 907	8 235	8 257	8 286	8 322	8 367	8 423	8 493	8 580	8 690	8 826	8 997
(GWh)	37 125	38 542	38 649	38 783	38 951	39 161	39 423	39 750	40 160	40 672	41 312	42 112
<1 (MW)	308	455	456	458	460	462	465	469	474	480	488	497
(GWh)	1 448	2 129	2 135	2 142	2 152	2 163	2 178	2 196	2 218	2 247	2 282	2 326
1 MW - 10 MW (MW)	692	726	728	731	734	738	743	749	757	767	779	794
(GWh)	3 247	3 400	3 409	3 421	3 436	3 454	3 477	3 506	3 543	3 588	3 644	3 715
> 10 MW (MW)	6 907	7 053	7 073	7 098	7 128	7 167	7 215	7 275	7 349	7 443	7 560	7 707
(GWh)	32 430	33 013	33 105	33 220	33 364	33 543	33 768	34 048	34 399	34 838	35 386	36 071
Plus pumping (MW)	3 929	4 285	4 285	4 285	4 285	4 285	4 285	4 285	4 285	4 285	4 285	4 285
(GWh)	2 738	2 732	2 732	2 732	2 732	2 732	2 732	2 732	2 732	2 732	2 732	2 732

Source: [National Renewable Energy Action Plan 2010 for Austria (NREEAP-AT), p.84]

[14] Action plan includes also annual targets for period 2010-2020.

As we can see in table 1, to achieve the targets, Austria's large hydro power portfolio should be increased from 7,0 GW (33 GWh) in 2010 to 7,7 GW (36 GWh) in 2020. This results in capacity increase of 700 MW in 10 years. Increase of capacity of pumped hydro power storage systems is not planned, even it is strongly advised to store energy surplus from fluctuating renewable energy sources.

River Basin Management Plan 2009

RBMP [River Basin Management Plan 2009] covers three periods until 2027. Main goal is to protect Austrian rivers and lakes and to set measures to improve the quality[15] of the water. The RBMP is very close connected to the WFD. Both have in common regulations to achieve good chemical and ecological water quality and "close to nature" water bodies.

The RBMP does not generally prevent commercial usage of water bodies, but will restrict the progress of hydro power development. This is based on the fact that in the future no deterioration of water bodies is allowed and the river continuity reestablishment is ensured. This will lead to reduced hydro power investments and higher costs for modernization activities.

[15] Physical-chemical-hydro morphological elements: Phytoplankton, Macrophytes and Phytobenthos, Fish fauna, Hydrological regime, River continuity, Morphological conditions, Pollutions

3 Electricity Generation in Austria

Electricity generation in Austria has started in 1873 with a direct current machine for Krupp Company. After two nationalizations (1946 & 1947), capacities was strongly increasing with the help of US-Marshall-Plan [Hans Auer 2011, p.5]. Nuclear power plant was shut down after a national referendum in 1978.

Currently, Austria has 130 local and national electricity companies [e-control 2012] and the main players are: KELAG, EVN, VKW, Energie AG, Salzburg AG, TIWAG, Wien Energie, WienStrom, Ennskraft, STEWAG, Oekostrom and Verbund-Austria Hydro Power (market leader).

The figure 7 shows Austria's power grid lines and major areas of large electricity production. Austria's most important 380kV ring is nearly completed. Main run-off power plants are located along major rivers (Danube, Enns, Inn, Mur, Drau and Salzach). Largest storage power plants are located in core alpine areas in Tyrol and Salzburg.

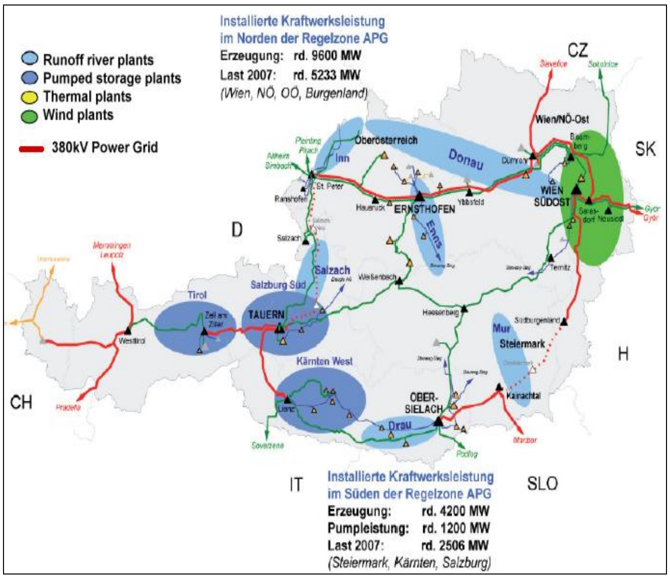


Figure 7: Power Grid and main electricity production areas in Austria[16]

Austria was divided into multiple control zones to ensure security of supply (management of energy transfer, control of power plants for energy balance[17]). Since 2012 all control zones are consolidated and replaced by only one main zone under the control of Austrian Power Grid AG [APG 2012].

[16] Figure: Hans Auer 2011, p.45
[17] To stabilize the power grid.

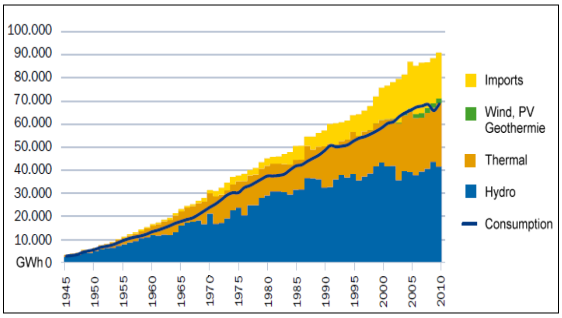


Figure 8: Electricity production[18] in Austria until 2010

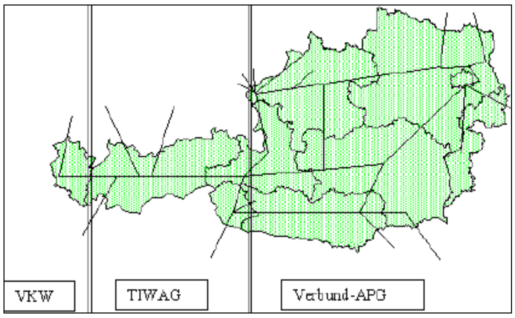


Figure 9: Old Austria's Control Areas (Regelzonen)[19]

Imports are necessary since 1970 with a fast growing trend until today. Renewable energy sources were starting in 2000 with growing shares[20]. **In 2010, Austria has generated electricity of about 71.075 GWh** [E-Control (2011), p.24].

Table 2: Electricity Production from Hydro[21]

Cross Electrricity Production 2010 in Austria			
Hydro	**Runoff**	>10MW	23.472 GWh
		<10MW	4.528 GWh
	Storage	>10MW	13.117 GWh
		<10MW	455 GWh
	Total Hydro		**41.572 GWh**

Main electricity generation in 2010 is done by Hydro (58,5%, 41.572GWh) and fossil Thermal power plants (31,3%, 22.278GWh) [E-Control 2011, p.25]. The total capacity of run-off hydro power plants is 5.395MW and of storage hydro power plants 7.524MW. The Austrian Hydro Power Potential Report from Pöyry/VEÖ shows a table about Austria's electricity production in 2007, categorized by rivers [Pöyry and VEÖ, p.21]. For electricity production by run-off plants, the most effective river is the Danube with 19,3TWh, followed by Drau, Inn, Enns, Mur and Salzach. On the other hand, the largest storage plants are located at Rhein (2,1 TWH), Drau (2TWh), Salzach (1,9TWh), Danube and Inn. The base load is supported by large run-off rivers and the peak load by storages at locations in alpine regions.

[18] Figure: Umweltbundesamt & e-Control
[19] Figure: Hans Auer 2011, p.26
[20] Imports & Exports since 2001
[21] Table: e-Control 2011, p.25

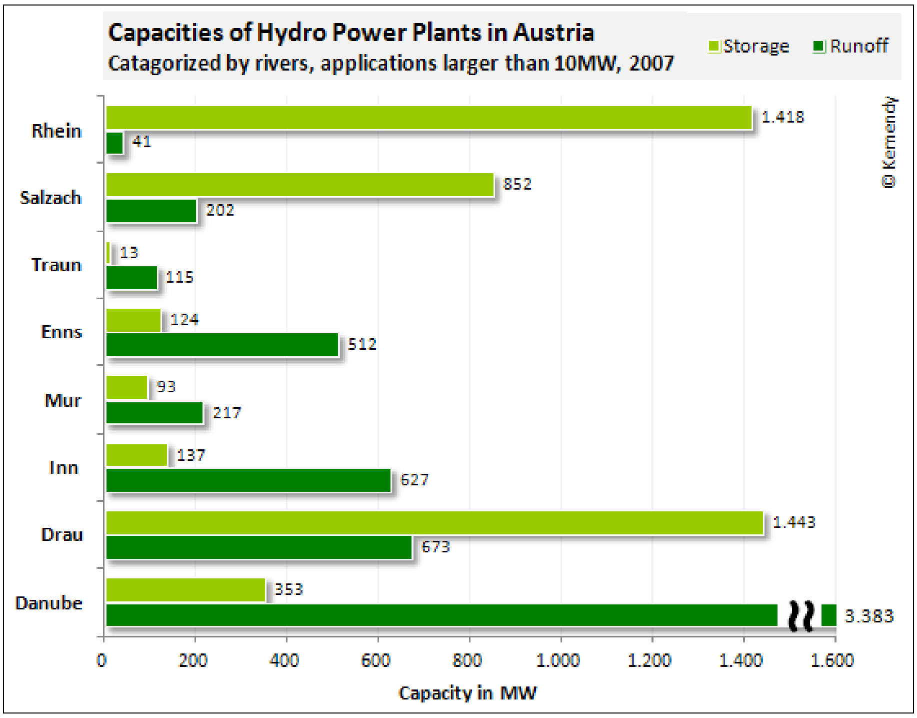


Figure 10: Austria's hydro power capacity categorized by rivers[22]

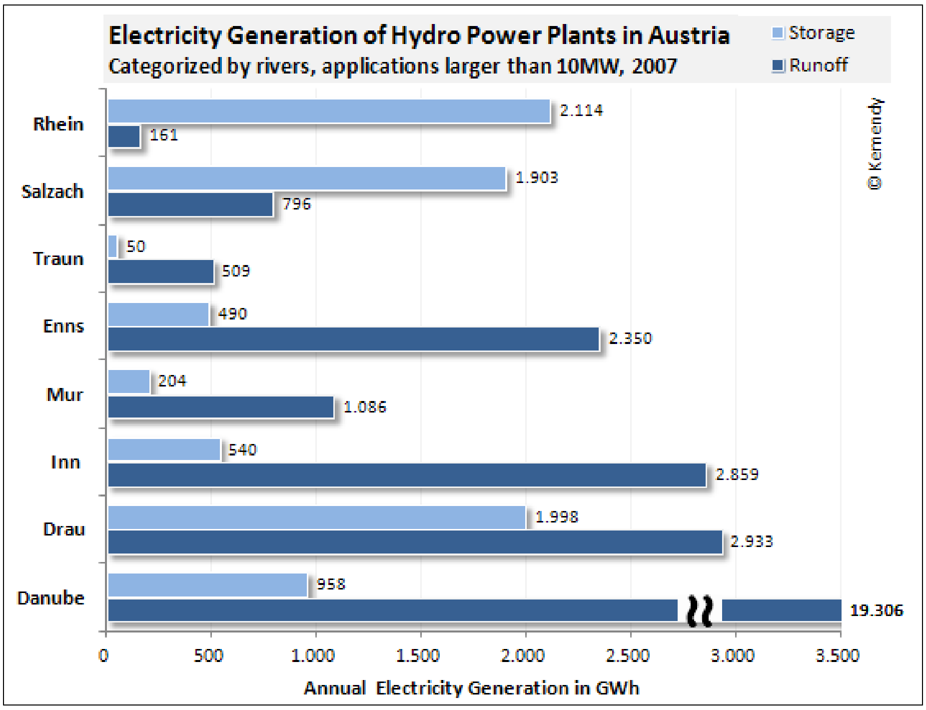


Figure 11: Austria's hydro electricity generation categorized by rivers[23]

[22] Figure: Kemendy 2011, data from Pöyry and VEÖ, p.21
[23] Figure: Kemendy 2011, data from Pöyry and VEÖ, p.21

Renewable energy sources are supported by Austrian's government with policies and Feed-In-Tariffs, specified in the Ökostromgesetz.

Austria Wind capacity was dramatically increasing since 2010 up to 1.850MW [e-Control (2011a), p.138].

Austria's electricity generation by **Wind in 2010 was 2,1TWh** [e-Control 2011, p.25]. That is 2,9% of overall electricity production. In relation, hydro power produced 41,572TWh (58,5%).

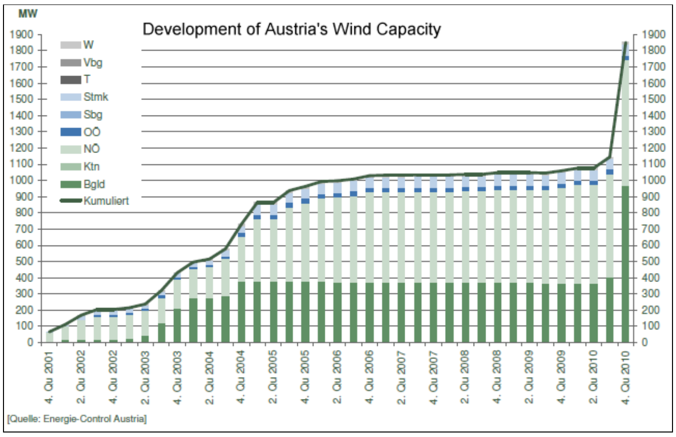


Figure 12: Development of Wind capacities in Austria[24]

[24] Figure: e-Control 2011a, p.138

4 Technologies of Hydro Power Plants

Hydro power plants use a mature and sophisticated technology. Additional advantages are good public acceptance, operational security, renewable energy sources, no pollution of soil, air and water, no GHG emissions. But it should also be considered that hydro power could have serious impacts to the environment (disadvantages): Consumption of land use, hydrologic impacts (surface, groundwater, water regime, river continuity, morphological conditions).

For electricity production, the major key elements of a Hydro Power Plant are

- available discharge
- head (difference of upstream and downstream level)

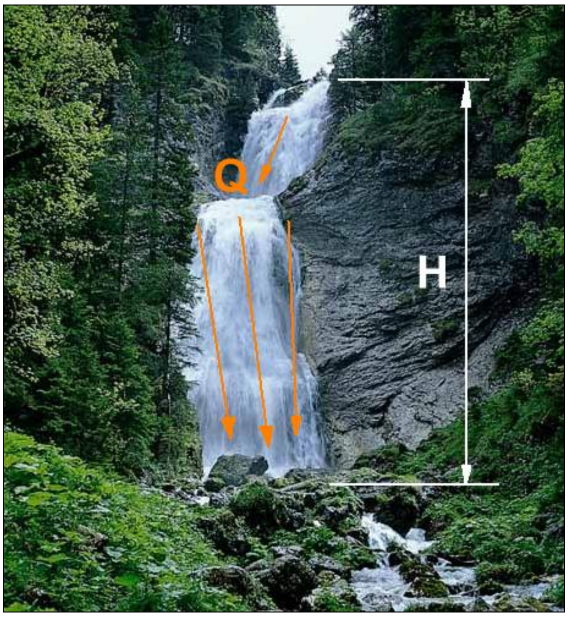


Figure 13: Major elements of a hydro power plant: Discharge and head[25]

4.1 Major classification of Hydro Power Plants

Technical	Run-off river plant, diversion plants, high head diversion plant, storage power plant, pumped storage power plant, wave plant, tidal plant [Giesecke, Mosonyi (2009), p.99]
Head	Low, medium and high pressure plants
Energy supply	Base, medium and peak load
Operation	Stand alone or connected to a power grid
Size	Small, medium, large capacity

[25] Image: Verkehrsamt Halblech 2011: Picture with own comments

Table 3: Classification of Hydro Power Plants[26] (simplified version)

Classification of Hydro Power Plants			
Design	**Low pressure**	**Middle pressure**	**High pressure**
Head	<15m	15-50m	>50m
Topografic	Low land	Low mountain regions	Low mountain regions, alpine regions
Back water system	Fixed weirs and movable weirs	Reservoirs, dams	Reservoirs, dams
Head race channel	Run of, diversion	Diversion	Diversion, penstocks
Installed power	<1MW	<100MW	>100MW
Turbine	Kaplan, Propeller, Francis	Kaplan, Propeller, Francis	Francis, Pelton
Storage size	Runoff, daily storage	Daily or weekly storage	Daily, weekly, yearly storage
Load managment	Base load	Base load	Base, medium, peak load

It should be considered that all elements of a hydro power plant must fulfill safety quality standards and should have a good cost-benefit ratio with a long lifetime. In this paper, I will focus on hydro power plants currently used in Austria and Europe (plants utilizing flowing water from rivers and lakes/storages). In addition, other types like tidal and wave energy at seaside are also used.

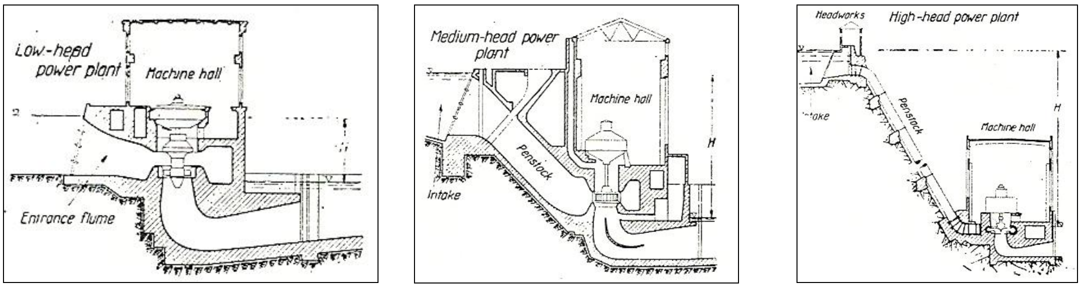


Figure 14: Major HPP types I: Low-/Medium-/High-head power plants[27]

Low and medium head types are used as run-off plants (inclusive diversion types), high head types as storage power plants (inclusive pumped storage).

[26] Table: Giesecke, Mosonyi 2009, p.100
[27] Figure: Emil Mossonyi 1987, p.135

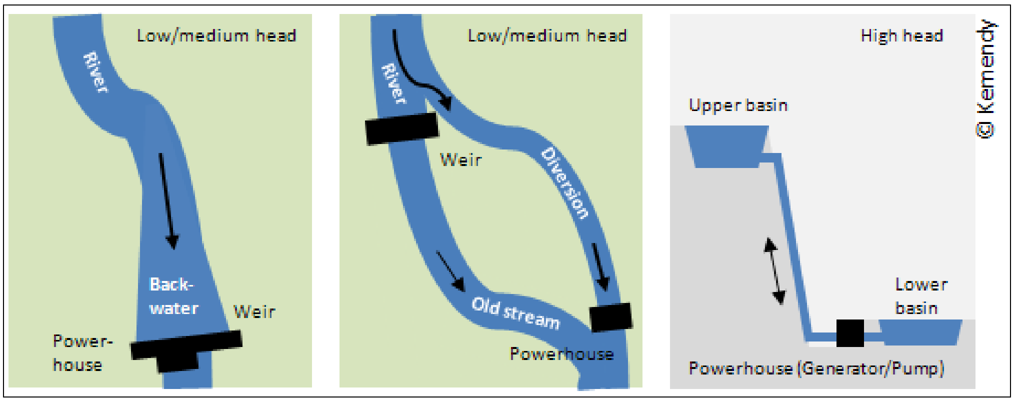


Figure 15: Major HPP types II: A) Run-off B) Diversion C) Storage[28]

Hydro power plants compared with other conventional fossil and renewable power plants, showed that hydro efficiencies with nearly 90% are much better than conventional systems (fossil) with 20-55%, wind and biomass with 40%.

Table 4: Overview of different power plant types[29]

Overview of different power plant types (classic and renewable)		
	Full load hours	**Efficiency**
	Hours/Year	%
Small hydro	ca. 6000	65-88
Runoff hydro	ca. 8000	
Storage hydro	ca. 2500	
Photovoltaic	ca. 1500	5-15
Solarthermie (Heat)	ca. 1500	25
Wind	ca. 2000	32-40
Biomass (Heat)	ca. 8760	40
Coal	ca. 6500	25-42
Oil	ca. 6000	22-38
Natural gas	ca. 6000	25-55
Nuclear	ca. 7500	40

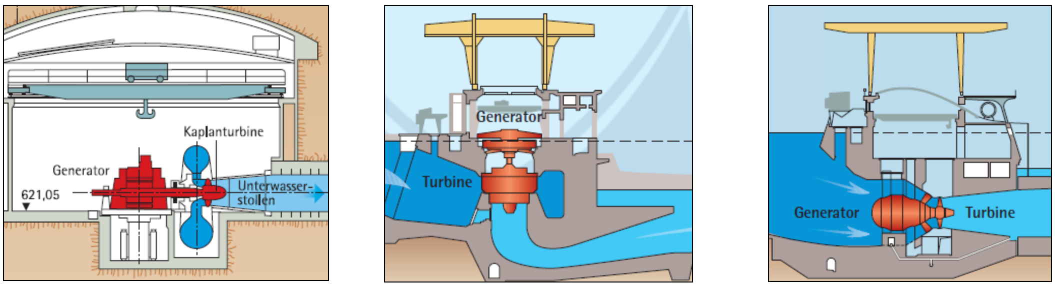
28 Figure: Kemendy 2012
29 Table: Giesecke, Mosonyi 2009, p.20

4.2 Major Design Elements of Hydro Power Plants

4.2.1 Shaft Settings

The design of bearings and turbine shaft are dependent on the configuration of turbine and generator and some restrictions should be considered if a specific type has to be selected (horizontal / vertical / bulb):

- Available space around turbine and generator
- Flow, amount of water discharge, velocity of injection and pressure
- Easy maintenance
- Rotation velocity (axial load, weight of rotating elements)
- Robustness against erosion (waste loaded water)
- Fluctuating efficiency in case of variable flow



A) Horizontal-shaft B) Vertical-shaft C) Bulb

Figure 16: HHP design elements: Main shaft settings[30]

[30] Figure: Verbund Austrian Hydro Power 2010, p.10

4.2.2 Major Turbine Types of Hydro Power Plants

Pelton turbines are characterized by less to medium discharge rates and very high heads. One or more water jets release water through nozzles with a needle valve which is a good method to control water flow and energy production. The heads are normally from 500m to 2000m and capacities could reach 400MW [Giesecke, Mosonyi 2009, p.592]. They are used to support peak load demands. These characteristics make the Pelton the best choice for storage power plants.

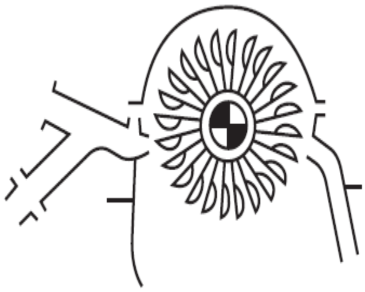


Figure 17: Pelton turbine[31]

Cross flow turbines have a simple construction with a wide range of discharge rates and heads (up to 200m). They are often used for small hydro power plants. The efficiency is lower (85%) compared to other turbine types, also capacities are lower (up to 1,5MW) [Giesecke, Mosonyi 2009, p.603]. The regulation of the flow is done by adjustable guide blades. The water enters the turbine and crosses it twice times before leaving again.

Figure 18: Cross flow turbine[32]

Francis turbines have water flows radial to the wheel and axial from it. For the highest efficiency of flow to and from the wheel a spiral casing is used [Giesecke, Mosonyi 2009, p.585]. The regulation is done by guide blades, the runner blades are fix mounted. A Francis turbine could be used for heads under 600m and capacities for up to 700MW. Francis is characterized by high revolutions with high discharges rates.

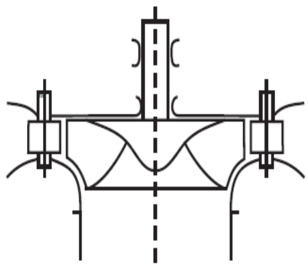


Figure 19: Francis turbine[33]

[31] Figure: Giesecke, Mosonyi 2009, p.510
[32] Figure: Giesecke, Mosonyi 2009, p.510
[33] Figure: Giesecke, Mosonyi 2009, p.510

Kaplan and propeller turbines are used for low heads until 80m. They have adjustable runner blades and guide blades. Double regulation obtains the best efficiency over a wide range of flows and heads during operation (Giesecke, Mosonyi, 2009, p.569). They can work between 20-100% of maximum design discharge. Kaplan is characterized by large discharge rates and low heads.

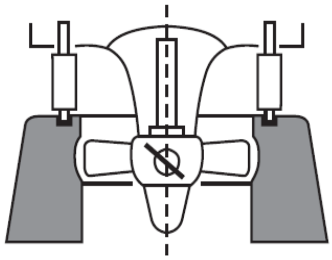


Figure 20: Kaplan turbine[34]

Most turbine type ranges are overlapping. An overview of operation ranges is showed in figure 21.

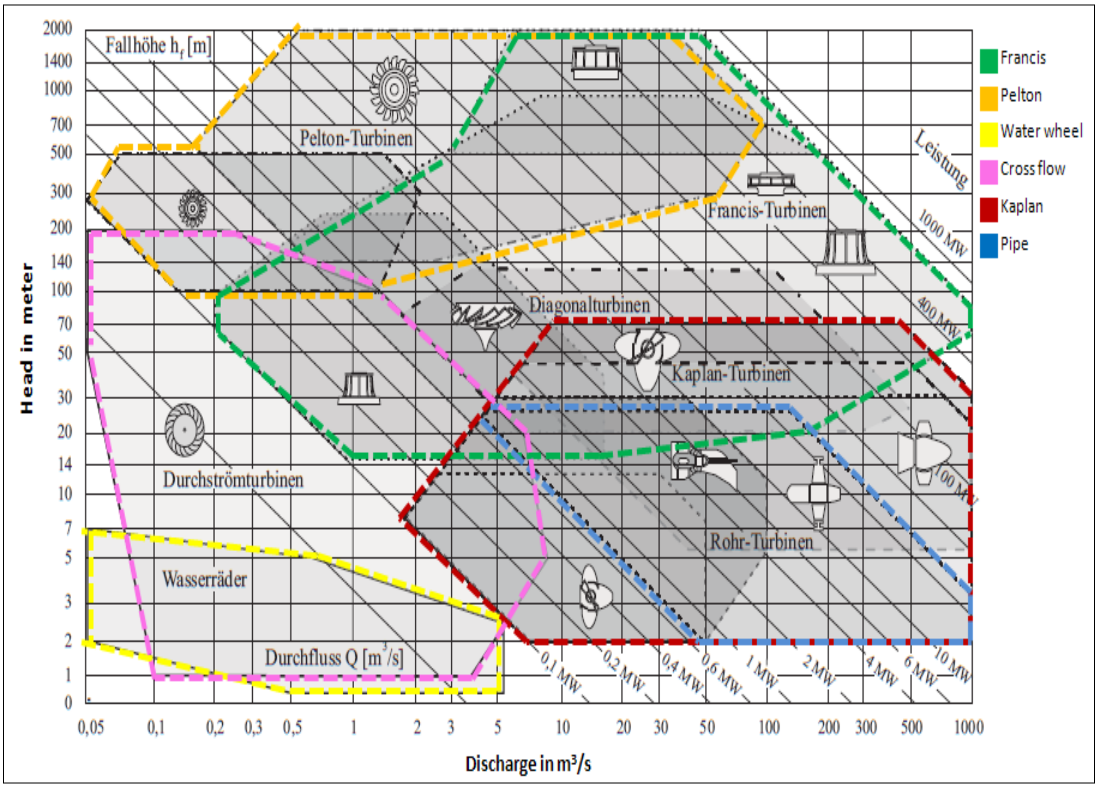


Figure 21: Operation ranges of turbines in dependence of discharge and head[35]

[34] Figure: Giesecke, Mosonyi 2009, p.510
[35] Figure: Giesecke, Mosonyi 2009, p.512

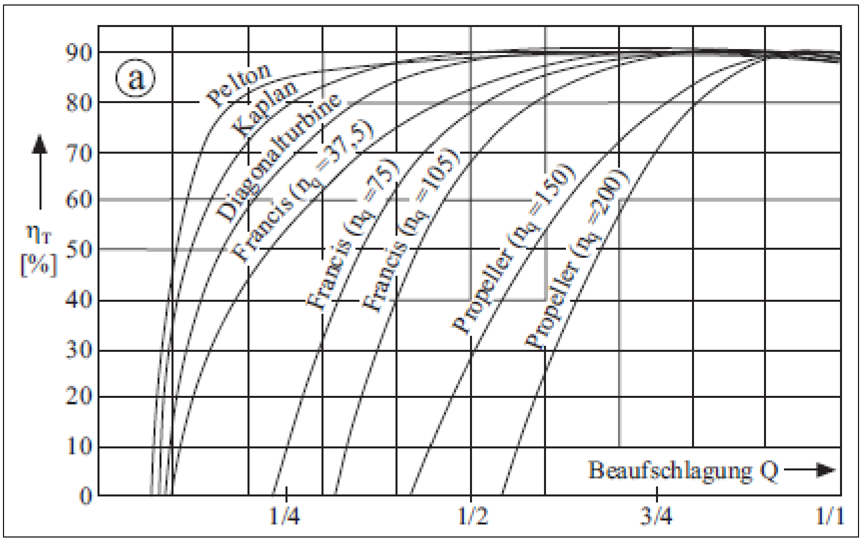


Figure 22: Operation ranges of turbines in dependence of discharge and efficiency[36]

4.2.3 Run-off Hydro Power Plant

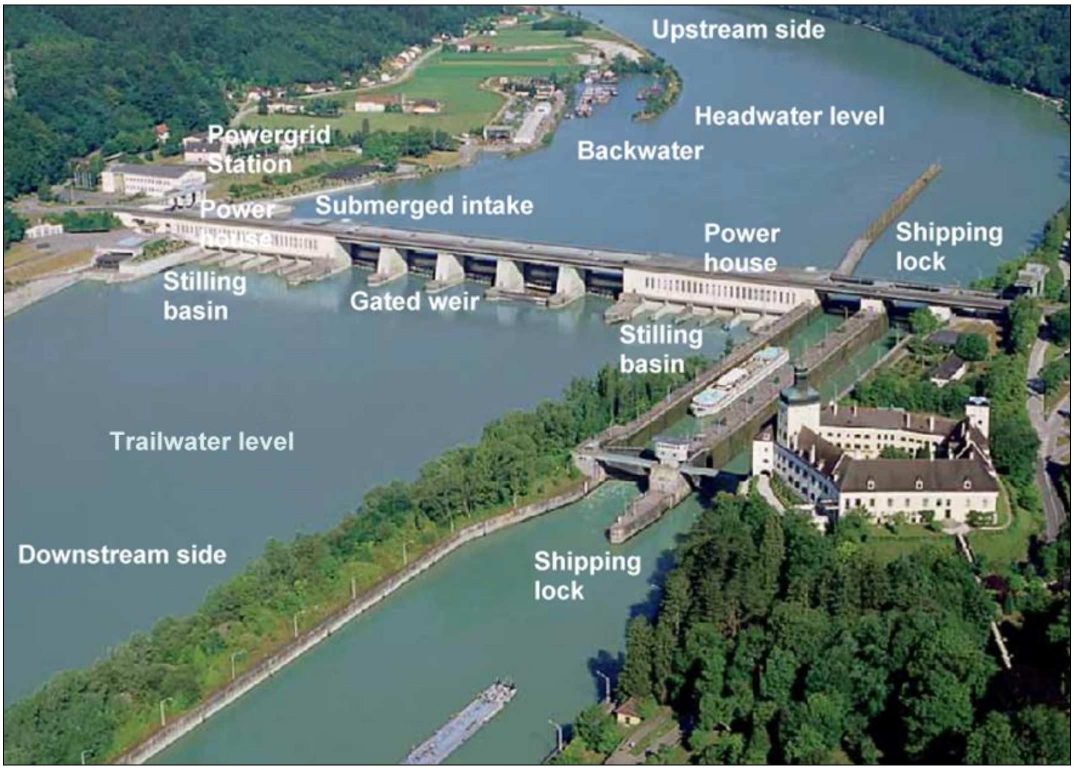


Figure 23: Major design elements of a run-off HPP[37]

[36] Figure: Giesecke, Mosonyi 2009, p. 524
[37] Image: Verbund Austrian Hydro Power 2010a, with own comments

The dominant element of a run-off hydro power plant is the discharge of water (volume per second). The water of the upstream side is directly taken from the backwater area to drive the turbines and generators in the powerhouse. The gated weir can control the height of the headwater level (important in periods with high water levels - floods). The power grid station is used to deliver the produced low voltage electricity to the high voltage power grid system. Shipping locks help to guide ships trough the hydro power plant. Additionally, fish ladders guarantee a save connection between both sides of a hydro power plant for fish and other morphological objects.

4.2.4 Storage (Pumped) Hydro Power Plant

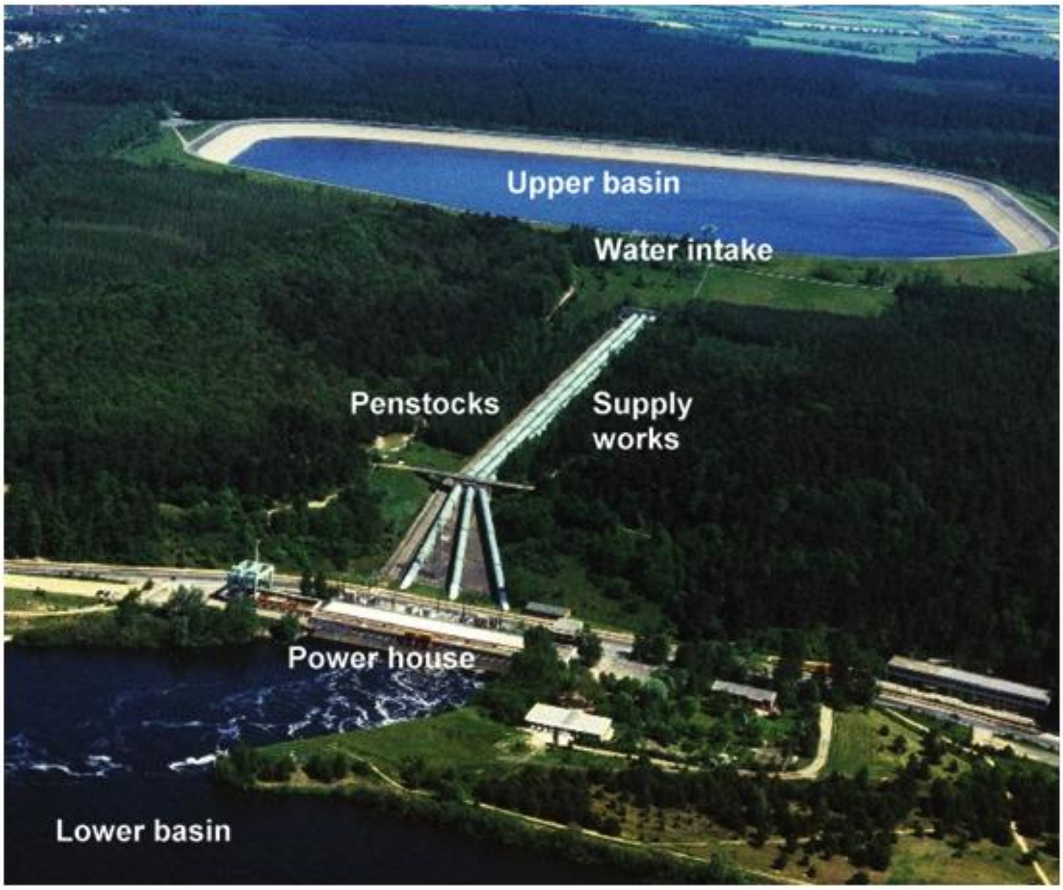


Figure 24: Major design elements of a pumped storage HPP[38]

[38] Image: Tage der Industriekultur, Pumped Storage PP Geesthacht with own comments

The dominant element of a (pumped) storage hydro power plant is the high difference of the upper and lower basin. The discharge is smaller than from a run-off hydro power plant. Water, from an upper reservoir can flow via penstocks – under high pressure – to the lower reservoir, driving turbines and generators in the power house. In some cases, water could be pumped up again to the upper reservoir (in times of energy surplus). In alpine areas, very large heights could be realized.

For an optimized energy management of storage power plants, the refill of upper reservoirs is recommended. To refill them, one or more pumps are integrated into the water flow system. During energy surplus periods, the generator is switched into motor mode to power the pump. Water can be pumped into upper reservoir and electricity can be generated again. This advantage has to be supported by higher costs for construction, machinery and water flow systems.

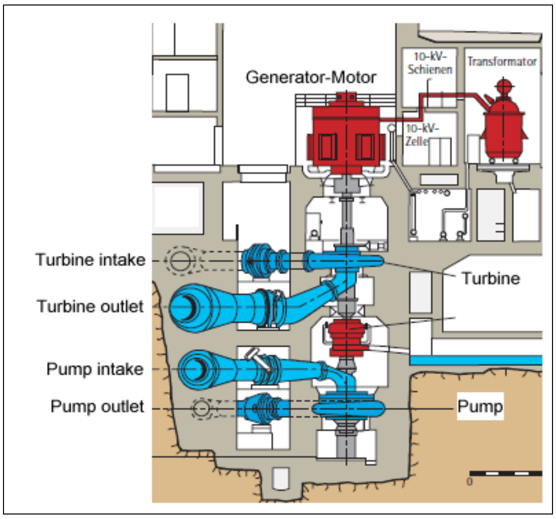


Figure 25: Generator/Motor-Pump System[39]

4.2.5 Water Catchment

A water catchment has a weir, trash rack and settling basin (sometimes necessary) and is used to control the floods and to sort out unwanted objects to protect the intake and turbines[40]. Unwanted objects are floating debris, sediments and ice flow.

4.2.6 Supply works

Water supply works are used to transport water from catchment into the power house to the turbines. This could be done by pipelines or penstocks (pressure pipelines) on ground or underground. It should be considered that the maximum discharge velocity should be about 4m/s to limit hydraulic and friction losses in the

[39] Figure: Verbund Austrian Hydro Power 2010b, p.7
[40] See Tyrolean weir or intake sills.

pipes and intake losses are on average 9%[41] [Drobir Helmut 2011]. Pressure tunnels a very expensive, but can handle higher pressures better than pipes. Surge tanks are needed to reduce the effect of acceleration or deceleration of water flow in the case of turn-on/turn-off turbines. A Power house contains machinery and additional applications for the production of electricity (turbines, gears, generators, transformers, control units and the connectors to the power grids).

4.2.7 Weirs

A weir is used to dam a water flow to form a small reservoir for the diversion of a definite quantity of water as input for a hydro power plant.

Fixed weirs: The headwater level is given by the discharge of the stream.

Gated weirs: The headwater level is controlled by a gate.

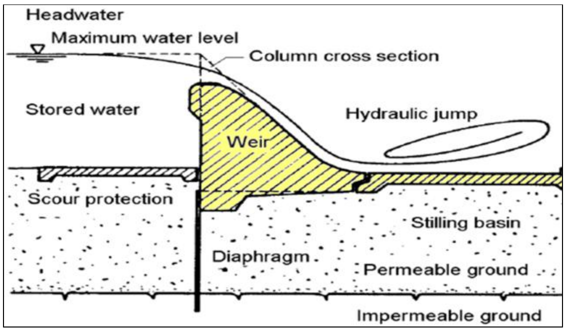


Figure 26: Fixed weir[42]

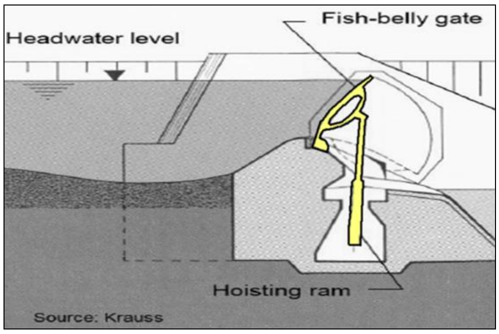


Figure 27: Gated weir[43]

[41] Experience from Mr.Drobir, given during his lecture for MSC Renewable Energy in CEE
[42] Figure: Drobir Helmut 2011, p.9/20
[43] Figure: Drobir Helmut 2011, p.9/20

5 Austrian Hydro Power Model

A computer based model is a well defined simulator to reproduce the current and future behavior of real physical, economic or biological systems. The behavior of a system will be transformed into mathematical formulas with equations, variables and boundary constraints. How well the model fits reality depends on the complexity of the real system, the numbers of required needed equations and variables and is restricted by efforts and budgets. Models or simulators are mostly approximations and could not replace the reality exactly. Models can be categorized into A) models for analysis (illustrate reality), B) Scenario models (forecast further development), C) Prediction models (forecasts) D) Optimization models (improve system) [N.Nakicenovic & R.Haas (2011), p.2-2]

Following major steps are necessary to set up a model:

- Analyzing system behavior (model)
- Analyzing of parameters (data, focus to relevant p.)
- Analyzing of mathematical model (equations, formulas)
- Defining system borders
- Defining input and output variables
- Defining a target function
- Defining boundary conditions
- Defining scenarios of forecasts
- Analyzing results and rerun model again is necessary

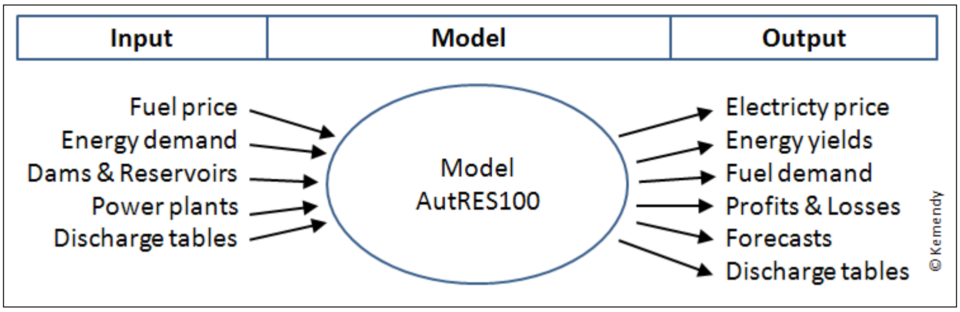


Figure 28: Example of an energy model with input and output variables

Linear Programming

"*The linear optimization or linear programming is one of the main methods of operation research and is used to optimize linear objective functions over a set which is restricted by linear equations and inequations."* [N.Nakicenovic & R.Haas (2011), p.7-1]

These methods could often be used to find solutions for complex problems which do not have unique designed solution methods. The result of this technique is an optimization to meet the targets of the objective function. A typical option of an objective function is minimizing costs and maximizing profits depending by resources, capacities and demands. Because of the size and the high complexity of many problems, nowadays computers are used to design the models and to calculate the target solutions.

Model Language

To run a model, a computer with linear programming software is needed. Depending on the available software, a unique high-level model language is used to define model, data and to prepare and run the program. Well known Software packages are AMPL (Algebraic Modeling Language for Mathematical Programming) and GAMS (General Algebraic Modeling System). In this model, AMPL is used. AMPL provides several solvers and a flexible development user interface to work with large and complex models. It is possible to set various options to optimize solver results and to format output and reports.

5.1 AutRES100, Energy Investigation Project

AutRES100 is an energy investigation project supported by the "Klima und Energiefonds" of the Austrian government and has the goal to look for technically and economically feasible ways to achieve a 100% renewable power supply in Austria.

Most important is the question, how Austria can integrate fluctuating renewable energy sources into an existing conventional power system without losing supply security and to be still economically successful. Which measures are necessary to guarantee advanced operational and economical power systems and what should be done to optimize balancing power provisions? The project also seeks for needed adjustments in Austria's historic power plant portfolio and for the future role of pumped hydro storage concepts. AutRES100 additionally deals with the importance of future electricity grid extensions and with flexible and intelligent demand side options (e-Mobility, Heating, Cooling, SmartGrids).

To find an answer to all this interrelated questions, the high-resolution European power system investment planning and supply security simulation and optimization model HiREPS was developed. It has an hourly resolution and includes several options for renewable sources (hydro, wind, solar), storages (hydro pumped and others), conventional power (oil, gas, coal, nuclear), transmission grid and future intelligent load responses (e-mobility, heating, cooling, smart grid). Investments and supply security are endogenously optimized within the model.

To run the model with a high share of intermittent renewable systems, high resolution weather data is needed (e.g. solar irradiance, wind speed and water discharges) which should cover the last 10 years.

5.2 AutRes100, Model Equations

The AutRES100 model is written in AMPL and optimizes the efficiency of power plant operation in case of available fuels, electricity generation and economic viability. The development of the model was not part of this master thesis and is kept confidential by AutRES100 project management. Only a general summarization can be given to show main and important equations to fulfill project achievements.

Equation electricity production:

The possible producible hydro energy potential is depending from the incoming and outgoing water discharge (volume).

$$\begin{aligned} V_{dam}(t+1) = {} & V_{dam}(t) + V_{natural\ inflow}(t) + V_{outflow\ of\ upper\ dam}(t) \\ & - V_{outflow\ into\ lower\ PP}(t) + V_{overflow\ of\ upper\ dams}(t) \\ & - V_{overflow\ into\ \ ower\ dams}(t) \end{aligned}$$

t is the time in hours, V is the volume in $1000m^3$. Inflow and outflow are the water streams through the turbines and overflow is the stream which flows over the weir without being used in the turbines[44].

Equation maximal hydro power capacity:

$$MW_{max} = V_{outflow\,into\,lower\,dams} \cdot g \cdot h \cdot \eta$$

MW_{max} is the maximal capacity in MW, g is the gravity acceleration in m/s^2, h is the head in m and η is the efficiency in %.

Equation energy output demand:

Thermal, hydro and wind power plants for each hour are included.

$$Demand - Power(Wind) = Power(GT) + Power(CCGT) + Power(Coal) + Power\,(Hydro) + Power(Nuclear)$$

Equation demand:

All power plants are subsumed as $PP = (GT, CCGT, Coal, Hydro, Nuclear)$ the cost function for each hour is:

$$Fuel\ cost(PP) = \frac{Power(PP)}{Efficiency(PP) \cdot Fuel\ price(PP)}$$

Equation capacity costs:

Costs for each hour:

$$Capacity\ cost(PP) = InstalledUnits(PP) \cdot CostPerUnit(PP)$$

Objective equation for power plant optimization:

System cost must be minimized:

$$Minimized\colon\ System\ cost = sum(PP) Fuel\ cost(PP) + Capacity\ cost(PP)$$

[44] Happens during high water levels (floods).

6 Description of Method of Approach Applied

To build the energy model, an inventory about location, machinery (turbines, pumps, capacity, energy production, heads, max. discharge rates,..), storages (water levels, volumes, discharge rates, surfaces,..) and water flows (inflows, side inflows, catchment area and precipitation) have to be compiled. Only run-off, storage and pumped storage hydro power plants with more than 5MW_{el} were included[45].

General steps of method of approach:

- Basic energy calculation for hydro power
- Identification and assessment of Austrian Electricity Provider
- Research of locations of hydro power plants and documentation of locations in GoogleEarth file (geographic register of Austrian Hydro Power Plants)
- Research and assessment of technical data of hydro power plants (capacity, heads, annual energy production, maximum discharge volume of turbines, designs,..)
- Research and assessment of hydrologic water regimes (from gauging stations, yearbooks, web sites)
- Analysis and preparation of hydrologic data (incl. calculation of side inflows)
- Research of historical wind data
- Research of historical electricity demand of Austria
- Preparation of model input files (DAT-Files)
- Model execution (simulator)
- Analysis of model output data and discussion about results and conclusions

6.1 Energy in Water Flows

Energy could be divided into two main types, kinetic and potential energy. Beside the main types, several forms of other energy types exist: thermal, chemical, electric, radiant, nuclear, magnetic, sound and mechanical energy. Energy could not be produced or destroyed, only converted from one form into another form (first law of thermodynamics).

[45] The model will be permanently improved. Next versions of this model will also include smaller power plants.

In a moving fluid, kinetic and potential energy is connected in each element of the fluid at the same time. The hydraulic energy in a pipe with different diameter is given by following formulas [Palffy Sandor (1998), p.2]:

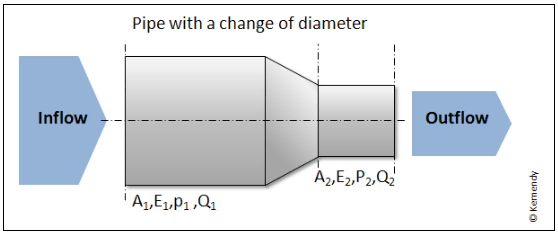


Figure 29: Principe of moving fluids

Assumptions: Density of fluid is const ($\rho_1 = \rho_2 = \rho$ in kg/m^3)

Friction in pipe is zero ($F_1 = 0$)

Energy is const (E_1=E_2)

$$E_{kin} + E_{pot} = \frac{v_1^2}{2g} + \frac{p_1}{\rho g} = \frac{v_2^2}{2g} + \frac{p_2}{\rho g} = const$$

$$Q_1 = Q_2 = Q = \int_A v \cdot dA$$ (Balance of mass)

$$Q = v_1 \cdot A_1 = v_2 \cdot A_2 \rightarrow v_1 = v_2 \cdot \frac{A_2}{A_1} \rightarrow$$

$$\frac{A_2}{A_1} < 1 \quad \rightarrow \quad v_1 < v_2$$

p Pressure in Pa
g Gravity acceleration in m/s^2
v Mean flow velocity in m/s
A Flow cross-section in m^2
Q Discharge in m^3/s
ρ Density of fluid in kg/m^3
H Difference of height in m

The result shows that the velocity after the pipe is higher than at the beginning. If the velocity is increasing, the internal pressure must be decreasing to keep the sum of both energy forms constant.

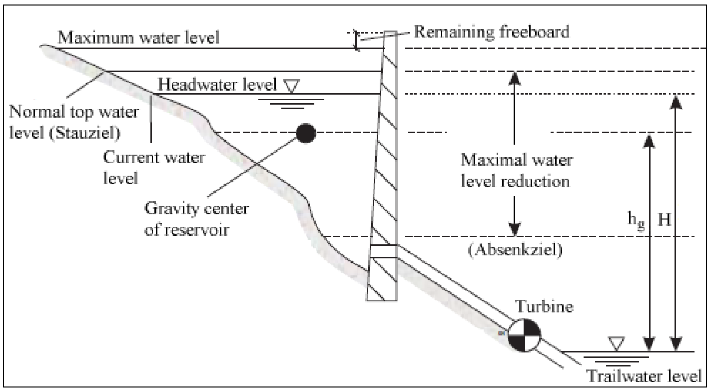


Figure 30: Principe of moving fluids[46]

[46] Figure: Giesecke, Mosonyi 2009, p.34 (translated and updated by author)

The hydraulic power [W] of a flowing fluid under constant conditions is given by

$$P_{hydo} = \rho \cdot g \cdot Q \cdot H = \Delta p \ \cdot Q = \dot{m} \cdot g \cdot H$$

whereby ρ is the fluid density kg/m^3, g (9,81) is the gravity acceleration m/s^2, Q is the discharge or volume flow m^3/s, H is the head in m, Δp is the change of pressure Pa and $\dot{m}$ is the mass flow per period kg/s.

For the sake of simplification and for a quick assessment of the electrical power of a hydro power plant in kW, the following formula can be used:

$\rho_{water} = 998{,}2 \ \frac{kg}{m^3} \ at \ 20°C$ Mean total efficiency of HPP is about 86%.

$$P_{ele} = \frac{\rho \cdot g \cdot Q \cdot H \cdot \eta}{1000} = \frac{1000 \cdot 9{,}81 \cdot Q \cdot H \cdot 0{,}86}{1000}$$

$$\approx 8{,}4 \cdot Q \cdot H$$

Where P_{ele} is the electrical capacity in kW, Q is the discharge in m^3/s, H is the head in m and η is the efficiency in %.

The energy of a potential stationary water reservoir [Giesecke, Mosonyi 2009, p.27] is given by

$$E_{pot} = \frac{1}{3{,}6 \cdot 10^6} \cdot g \cdot m \cdot H \qquad m = \rho \cdot V$$

whereby E_{pot} is the potential energy in kWh, m is mass in kg, V is Volume in m^3.

The theoretical maximal electricity generation per working period (anno) is [Giesecke, Mosonyi 2009, p. 33]

$$E_a[kWh] = \int_0^t P(t)dt = \frac{9{,}81}{3600} \cdot \eta_{tot} \cdot \int_0^t Q(t) \cdot h(t)dt$$

The total efficiency of a hydro power plant is built by the energy chain of separate electrical applications[47]: turbine, generator, gear and transformer.

$$\eta_{total} = \eta_{turbine} \cdot \eta_{gear} \cdot \eta_{generator} \cdot \eta_{transformer}$$

6.2 Annual Energy Yield of Hydro Power Plants

To estimate the annual energy production of a run-off hydro power plant, the hydrograph of the river’s discharge (water intake) must be available. This hydrograph should be measured by a (nearby) gauging station for a long period (>10 years) [Drobir Helmut 2011, p.11/20].

The cross head is given by the difference of headwater level and trailwater level.

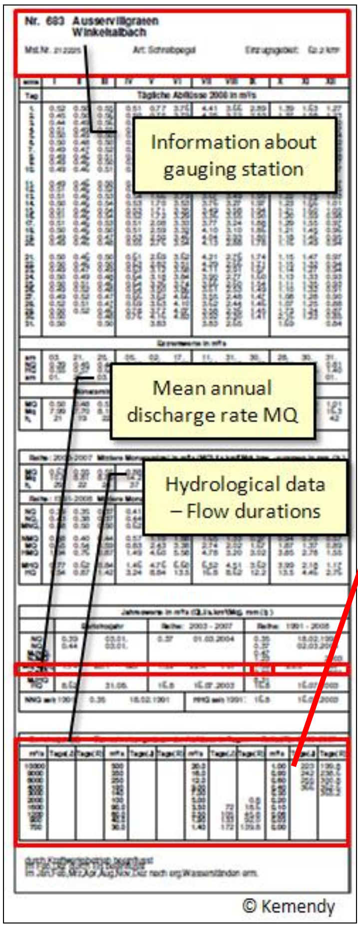


Figure 31: Data sheet of gauging station with hydrographic data[48]

Information about hydrologic data could be found in Austrian Hydrological Yearbooks.

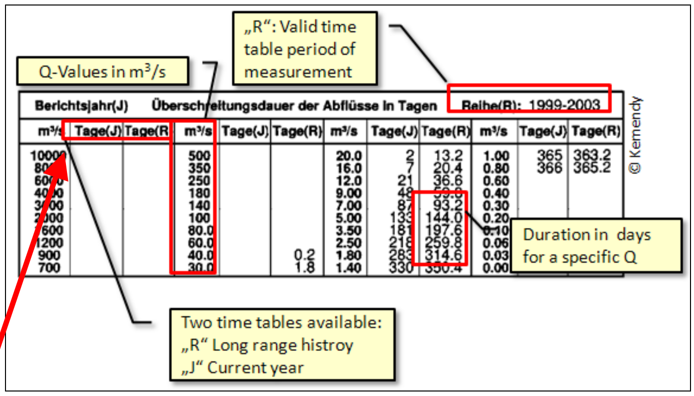


Figure 32: Detail data sheet for durations of specific discharge rates

Long range time tables should be according at least 10 years.

Discharge reduction for fish passes [Drobir Helmut (2011), p.12/20]:

≥3m³/s → minimum through fish pass = 1,0 m³/s

<3m³/s → minimum through fish pass = 0,5 m³/s

[47] Total efficiency of a HPP is about 86%.

Discharge rates can be sorted in order of their frequency (flows exceeded). High flows almost never exceed and low flows almost always exceed (in number of days per year). Duration curves show a summary of the run-off dynamics and water regime for a location.

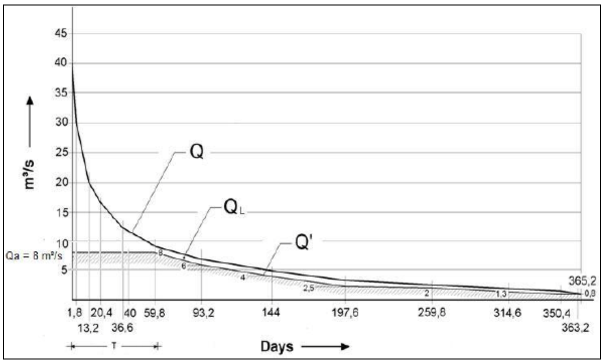


Figure 33: Rated annual discharge Q_a, duration curve[49]

Estimation of period for overflow at the weir/dam: T is between 40 and 100 days. With a given T it is possible to read the annual rated discharge from the duration curve: Q_a

Rated capacity P_a can be approximated:

$$P_a = \eta \cdot \rho_w \cdot g \cdot Q_a \cdot h_n$$

Where P_a is the rated capacity in kW, η the total efficiency in %, ρ_w the density of water in $1000 kg/m^3$, Q_a the rated discharge in m^3/s and h_n the net head in m.

Losses for pipeline and intake can be estimated [Drobir Helmut 2011, p.12/20][50]:

Losses 9% → $\sum h \approx 0{,}09 * Q^2$

$h_n = Gross\ head - head\ losses = H - \sum h$ → P_a

If possible, other losses should be also taken into account: Flow losses caused by technical issues (evaporation, seepage, hydraulic friction, machinery) and environmental issues (fish ladders, residual flows).

48 Figure: Lebensministerium Österreich 2012, Austrian Hydrologic Yearbook 2008, p.OG316

49 Figure: Drobir Helmut 2011, p.12/20

50 Drobir has estimated these losses with 9%

Q_i	$Q_i = \frac{Q_i + Q_{i+1}}{2}$	T_i	$T_{mi} = T_{i+1} - T_i$	T_{mi}	$H_n = 160 - 0,09 \cdot Q_m$	P_{ai}	$E_{ai} = P_{ai} \cdot T_{mi}$
m³/s	m³/s	days	days	hours	m	MW	GWh
8		0					
	8		59,8	1435,2	154,2	9,9	14,2
8		59,8					
	7		33,4	801,6	155,6	8,7	7,0
6		93,2					
	5		50,8	1219,2	157,8	6,3	7,7
4		144					
	3,25		53,6	1286,4	159,0	4,1	5,3
2,5		197,6					
	2,25		62,2	1492,8	159,5	2,9	4,3
2		250,8					
	1,65		54,8	1315,2	159,8	2,1	2,8
1,3		314,6					
	1,05		50,6	1214,4	159,9	1,3	1,6
0,8		365,2					

Annual energy output: $E_a = \sum E_{ai} = 42{,}9 \cdot 10^6$ kWh ≈ 43 GWh

Figure 34: Calculation table for annual energy production: Helmut Drobir[51]

For each discharge rate, days and head are calculated to get energy amounts per discharge. Summing up all will result in the annual energy yield of a hydro power plant.

6.3 Assessment of Hydro Power Plants

Average annual water discharge rate of hydro power plant can be estimated by the total annual energy production and the head. The discharge should be smaller than the current annual inflow (measured by gauging stations or calculated by precipitate and catchment area).

$$Q' = \frac{Annual\ Energy\ production}{365 \cdot H \cdot g \cdot \frac{1}{3600} \cdot \frac{1}{1000}} \cdot \frac{1}{\eta_{total}}$$

Q' is the average annual discharge in $1000 m^3/d$, H is the head in m, g (9,81) is the gravity acceleration in m/s^2, η_{total} is the efficiency in percentage.

To scale down the discharge into m^3/s:

$$Q = \frac{Q' \cdot 1000}{24 \cdot 3600}$$

The energy of a potential stationary water reservoir is given by the formula in 6.1.

[51] Figure: Drobir Helmut (2011), p.12/20 with own commends

6.4 Methods of data research techniques

6.4.1 Hydrologic Yearbook of Austria

Every year, Austria's ministry of Agriculture and Forestry, Environment and Water, publishes a hydrologic yearbook with statistic data and time tables about with regards to precipitations (rain and snow), surface water discharges, ground water discharges, long term average discharge rates, temperatures and evaporations. MQ and duration curve data can be used to calculate inflows and to estimate energy production of water flows.

Please notice additional information about anthropogenic impacts[52] at the bottom.

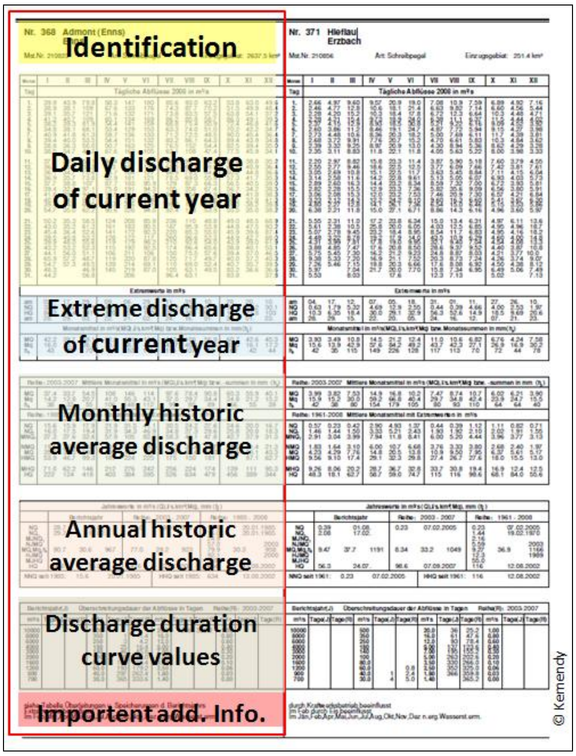


Figure 35: Hydrologic Yearbook[53] Austria 2008

52 Caused by power plant activities or other human and climate impacts

53 Figure: Lebensministerium Österreich (2012), Austrian Hydrologic Yearbook 2008, p. OG194, figure with own comments

Following historic time series and types can be downloaded as CSV file (raw data):

Time scale: annual, monthly, daily

Types:

- Surface water discharges
- Precipitation
- Ground water discharges
- Water springs
- Ground water areas
- Ground water bodies
- Alpine groups

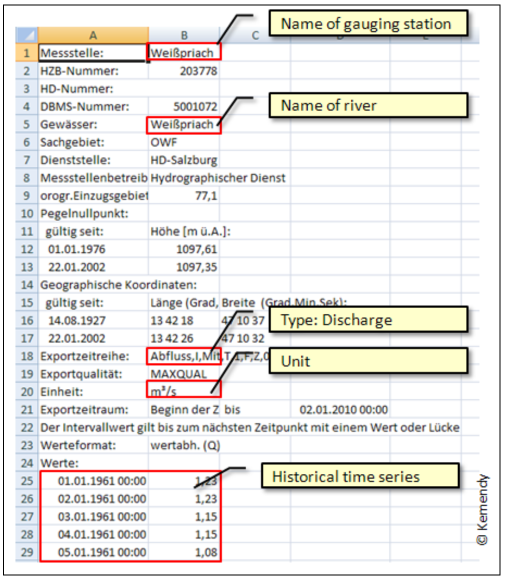


Figure 36: Details of downloaded historic discharge series[54]

6.5 Identification of Hydro Power Plants

Energy suppliers and producer publish promotional brochures, business reports and documents at their web sites. The content of those varies between basic data and detailed technical data with sketches of buildings, technical applications and dams. The most important data for our model are: capacity, annual energy production, heads, water levels, efficiency, topography of reservoirs and their connections (water cannels), inflows and side inflows and locations.

Identification by GoogleEarth:

Figure 37: HPP as satellite view at GoogleEarth[55]

To identify the location of a hydro power plant, follow river flows and locate reservoirs in satellite views supported by GoogleEarth.

[54] Figure: Kemendy 2012, Screenshot of downloaded CSV-File
[55] Figure: GoogleEarth Client 2012

To get “up-to-date” data from energy suppliers is a daunting task. Even if companies are publishing some basic data about their power plant portfolios (type, capacity, energy production), more detailed information is often classified. They are hiding their data caused by data protection policies or business reasons.

In addition, some pumped storage power plants can have complex reservoir, pump and pipe systems. In that case, detailed analysis for reservoirs, water flows, discharge volumes and pipe system must be taken into account.

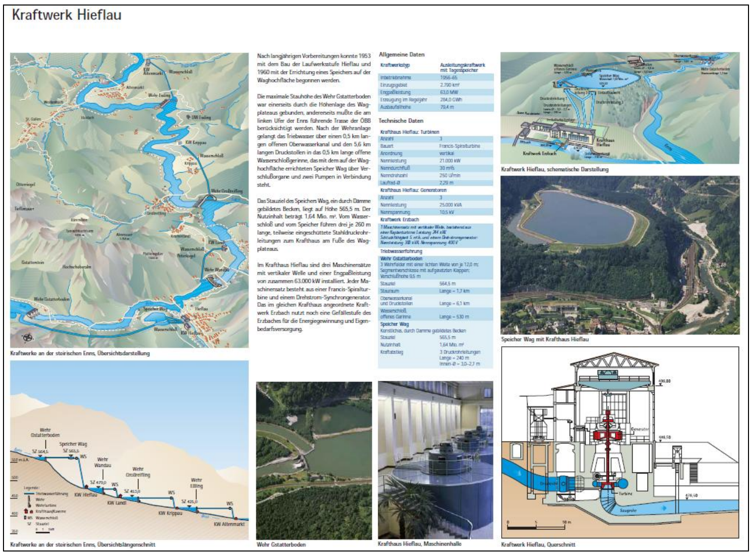


Figure 38: Example of the very well documented HPP Hieflaul. Handout by VERBUND AHP *“Die steirischen Wasserkraftwerke”*[56]

6.6 Assessment of Hydrologic Water Regimes

The energy model uses data concerning water side inflows in 1000m^3/day for each hydro power plant to optimize energy production in the long run. If specific hydrological data wasn’t provided by energy providers, they had to be taken from the hydrologic yearbook. Water inflows and regimes are the most dominant input for this energy model and they are responsible for the quality of output results.

Please notice following important basic methods to access hydrologic data.

[56] Figure: Verbund Austrian Hydro Power 2010c

6.6.1 Hydrological Equation and Stream Gauging

Water balance and stream flow regime is driven by the sun. Higher temperatures cause water to evaporate into the air (vapor). Areas with lower temperature causes vapor to condense into clouds. These clouds are moved by global winds into other zones, where they are condensing and comingling down again as precipitation. The precipitation flows over the ground as surface run-off or as groundwater discharge, back into the ocean again. Run-off mechanisms and global water cycle could be seen in figure 39.

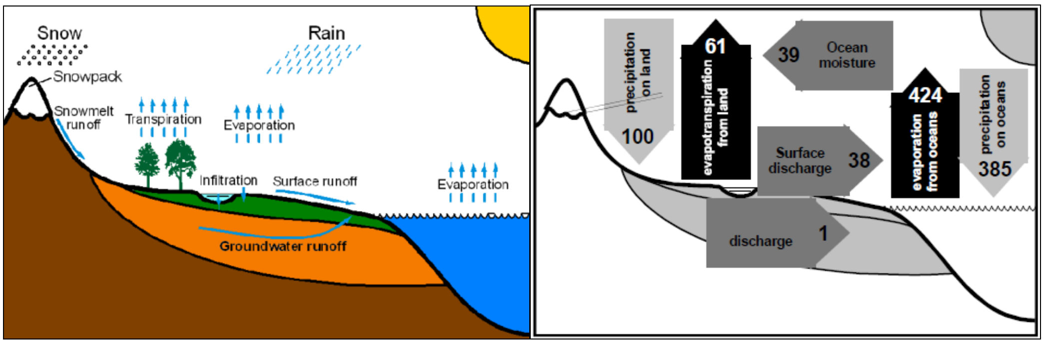


Figure 39: Run-off mechanisms and global water cycle[57] (values in %)

Basic hydrological equation (general budget equation): Contains the essential components of water balance. The water mass balance per period must be fulfilled: Incoming = Outgoing

(conservation of mass)

$$Pr = Q + Q_{GW} + ET \pm \Delta S \pm W$$

Pr	Precipitation	Q	Run-off
Q_{GW}	Groundwater flow	ET	Evaporation
ΔS	Change of storage	W	Water usage

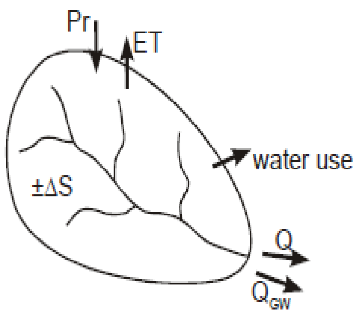


Figure 40: Catchment water balance[58]

[57] Figure: Günter Blöschl 2010, p.3/17
[58] Figure: Günter Blöschl 2010, p.4/17

Stream gauging

The velocity of the water and the discharge in the stream is difficult to estimate / measure.

$$Q = \int_A v \cdot dA = \bar{v} \cdot A$$

v Flow velocity $\bar{v}$ Mean velocity A Sectoral area

Measuring of stage h is possible by stream gauges: *f=h(t)*

Velocity could be measured by a flow meter (propeller) to get single data points over a cross section.

Getting a rating curve by calculating the stage-discharge relationship: *Q=f(h)*

Estimating hydrograph *Q(t)* from rating curve.

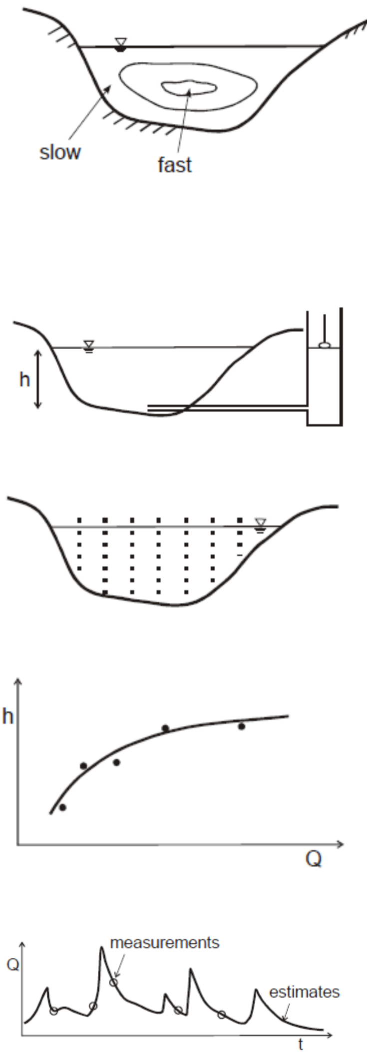


Figure 41: Catchment water balance and stream gauging[59]

6.6.2 Estimation of water flow data

Sometimes, no stream flow data at site location is available caused by not existing gauge stations or negative influenced stream data by anthropogenic activities (water use, power plant operations). Four alternative methods could be used to estimate stream flows[60]:

[59] Figures: Günter Blöschl 2010, p.5/17
[60] Figure: Günter Blöschl 2010, p.15/17

(a) Usable stream flow data close to location

Assumption: Specific discharge is spatially uniform.

$Q_i = \alpha \cdot Q_j$ with $\alpha = A_i / A_j$

A Catchment areas α depends from side inflows.

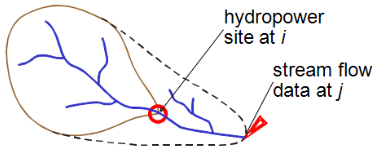


Figure 42: Stream close to each other[61]

(b) Similar catchment

Two catchments are hydrological similar, if catchment area, soils, topography, rainfall and geology are similar. Then transfer of stream flow to alternative location could be done.

(c) Dedicated stream gauging

Relate short records (only few records are available) to longer stream flow records by regression.

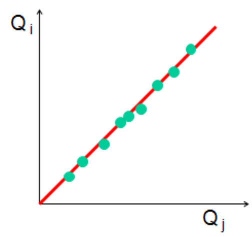


Figure 43: Dedicated stream gauging[62]

(d) Infer stream flow

(i) Estimate mean annual run-off MQ for the hydro power plant site(i)

(ii) Estimate scaled flow duration curve from catchments (j, regional) in the region and estimate stream flow at hydro power plant site (i, local) from scaled flow duration curve

and MQ: $Q_i = Q_j \cdot MQ_i$

(e) Usage of run-off computer models

Commercial computer programs can simulate run-off stream flows (input is rainfall, temperature, catchment area, soil conditions,....).

61 Figure: Günter Blöschl 2010, p.15/17
62 Figure: Günter Blöschl 2010, p.15/17

Measurement errors and data gaps:

It should be taken into account that a data analysis is subject to many error sources, which are not always calculation errors or misinterpretations of data. Sometimes the data themselves are incorrect, caused by measurements with large uncertainties. This can happened by climate issues (floods, snow melting, wind) or technical issues (changing the measuring instruments, shut downs).

Data gaps are not errors in the strict sense, because they are often caused by transmission, instrument problems or storage problems. Missing data in a table can be ignored or must be compensated by replacement[63] values.

6.6.3 Example 1: Side inflows of Hydro Power Plant Braunau-Simbach

The Hydro Power Model uses side inflows[64] to calculate the energy production of a hydro power plant. A side inflow is an additional stream flow from lateral branches between two points of a river section (or two power plants). Gauging stations could be located in the main river or in branches. If a (needed) gauging station is not available (no data, not existing), the new section is checked if the area is similar to the nearby reference section with a valid gauging station. In that case, stream flows could be estimated by methods described in chapter 6.7.2.

River Inn: Section Schärding-Braunau-Kirchbichl/Salzburg

The river Inn is coming from Tyrol, flows through Germany back to Austria again and is finally running into the river Danube. From Salzburg, the river Salzach is coming and is running into Inn just before the hydro power plant Braunau-Simbach. The question is now, what is the amount of the side inflows for the hydro power plant Braunau-Simbach?

[63] Temporal interpolation or spatial interpolation (reference stations)
[64] The model input DAT file needs discharge values in $1000m^3/s$.

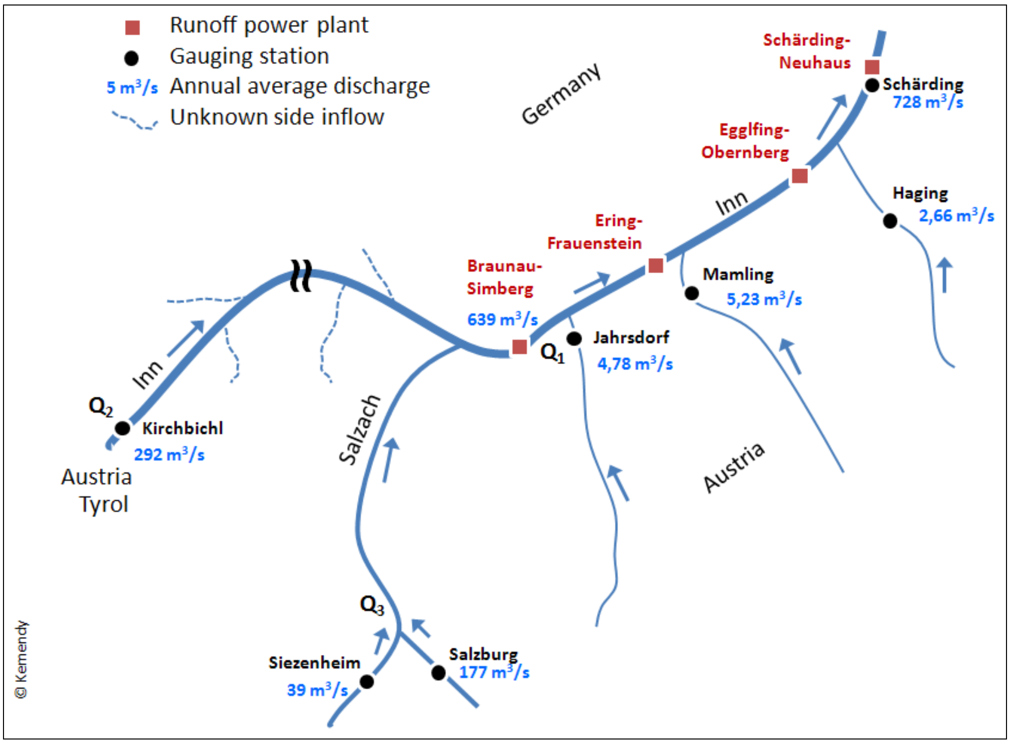


Figure 44: Example 1, estimate discharge rates at river Inn

As it can be seen in the figure above, main river Inn has one big branch (Salzach) and several small branches. All of them have useful gauging stations with valid historical discharge tables. Relevant side inflows are only in the section Kirchbichl-Braunau. Precondition: very small branches and its discharges are neglected[65].

On basis of annual average discharges, the total amount of side inflows in section Kirchbichl-Braunau is estimated:

$$\sum\bar{Q}_{SI} = \bar{Q}_{BS} - \bar{Q}_{SZ} - \bar{Q}_{SH} - \bar{Q}_{KB} = 639 - 177 - 39 - 292 = 131\ \frac{m^3}{s}$$

That is a relatively high value which should be neglected.

Calculation on basis of daily discharge rates: There are only two gauging stations located at the Inn, Schärding and Kirchbichl. At river Salzach, Siezenheim and Salzburg are useful stations.

65 Small streams have often discharges smaller than 1m³/s. Small streams could be neglected in relation to discharge of a large stream (>>1m³/s). Main stream Inn: >600m³/s.

The total water discharge after hydro power plant Braunau-Simbach is:

$$Q_1(t) = Mainflow(t) - \sum Sideinflow(t)$$
$$= Q_{Schärding}(t) - Q_{Haging}(t) - Q_{Mamling}(t) - Q_{Jahrsdorf}(t)$$

Where Q is the discharge in $1000m^3/d$.

The discharge at Tyrol Kirchbichl is:

$$Q_2(t) = Q_{Kirchbichl}(t)$$

The discharge at Salzburg/Siezenheim is:

$$Q_3(t) = Q_{Salzburg}(t) + Q_{Siezenheim}(t)$$

The “unknown” side inflow amount between Kirchbichl-Braunau is:

$$Sideinflow_{HPP}(t) = \sum Q_{SI,i}(t) = [Q_1(t) - Q_3(t)] - Q_2(t)$$

6.6.4 Example 2: Side Inflows of Hydro Power Plant Großreifling

Hydro power plant Großreifling is located at river Enns in Styria. Only one relevant side branch is important for side inflow estimation (river Salza). Two gauging stations are located nearby, Großreifling and Wildalpen. Station Großreifling fits perfectly, but no daily discharge tables are available. Only an annual discharge value of 25,3 m^3/s is known, supported by Styrian GIS. Station Wildalpen is not too far away and supports daily discharge tables by e-HYD. The annual discharge value[66] of Wildalpen is 20,5m^3/s. Issue: How can the discharge Q(t) for Großreifling are calculated to get the side inflow of hydro power plant Großreifling?

[66] MQ=20,5m^3/s: Value taken from Hydrologic Yearbook Austria 2008, p.OG196

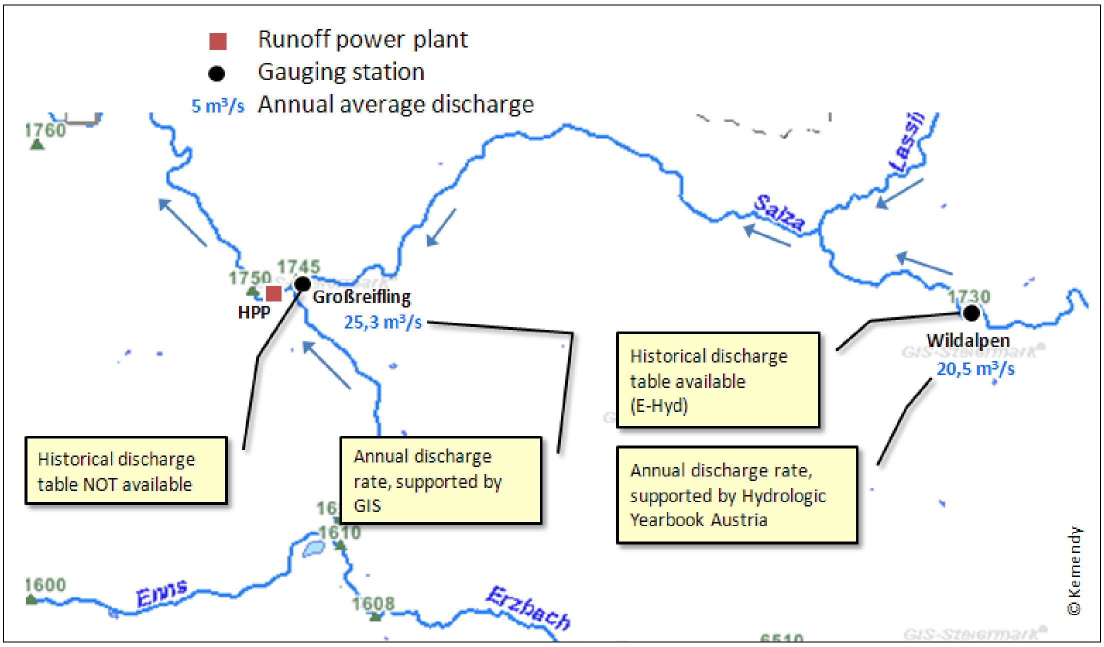


Figure 45: Example 2, estimate discharge rates at river Enns

Because of similar areas (catchments, topography) and little distance to reference location, it is possible to scale gauging station Großreifling with station Wildalpen:

$$Sideinflow_{HPP}(t) = Q_{Großreifling}(t) = \frac{25{,}3}{20{,}5} \cdot Q_{Wildalpen}(t)$$

6.7 Research of Historical Electricity Demand

The goal[67] of this energy model is to optimize the operation of hydro power plants, regarding to Austria's energy demand and the use of a certain share of renewable Wind power. As hydro and wind power capacities do not cover the gross energy demand, the model compensates the demand shortage with conventional thermal power plants.

The Austrian energy demand is supported by European Network of Transmission System Operators for Electricity (ENTSO-E).

[67] Minimize costs or maximize profits.

6.8 Research of Historical Wind Data

The ZAMG is an Austrian national meteorological and geophysical service provider. The range of information covers classic weather forecasts on studies of climate variability, model development, agricultural and environmental issues, pollutant dispersion, seismology and many more.

The data of the historical wind in Austria was provided by the Zentralanstalt für Meterologie und Geodynamik (ZAMG).

6.9 Research of Historical Electricity Prices

The historical electricity price data is supported by European Energy Exchange [European Energy Exchange AG 2012] and could be downloaded from their web site and is based on hourly values in Euro/MWh.

6.10 AutRES100: Simulation and Running the Model

All collected relevant data was converted into a defined format for input DAT[68] files.

Aggregation of demand statistics are used in an hour division for the years 2000-2009. The input data and the model were tested in several executions.

Reports are provided as normal text files, containing tables for energy content (potential energy related to sea height in MWh), hydro net power (turbine power minus pump power in MW), overflow amounts (for checks in m^3/s), pump power (in MW), turbine power (in MW), discharge turbine (water flow through turbine in m^3/s), discharge pump (water flow through pump in m^3/s) and water level (water level related to sea height in m).

[68] A normal text file. Organized in dams, plants and discharge tables.

7 Documentation of data and data collections

All collected data (technical and hydrological) is stored in Excel, Access, OnNote or normal text[69] files. Locations of power plants, dams and reservoirs are stored in a GoogleEarth file. All these files are part of the AutRES100 project, stored at a project server at TU as publicly available classified information[70].

7.1 Austrian hydro power plants

An overview of all collected hydro power plants greater than 5 MW can be seen in figure 46. Main run-off power plants are located along the large rivers like Danube, Inn, Enns, Mur, Drau and Traun. Storage plants are located in higher areas of alpine regions like Gerlos, Malta and Kaprun.

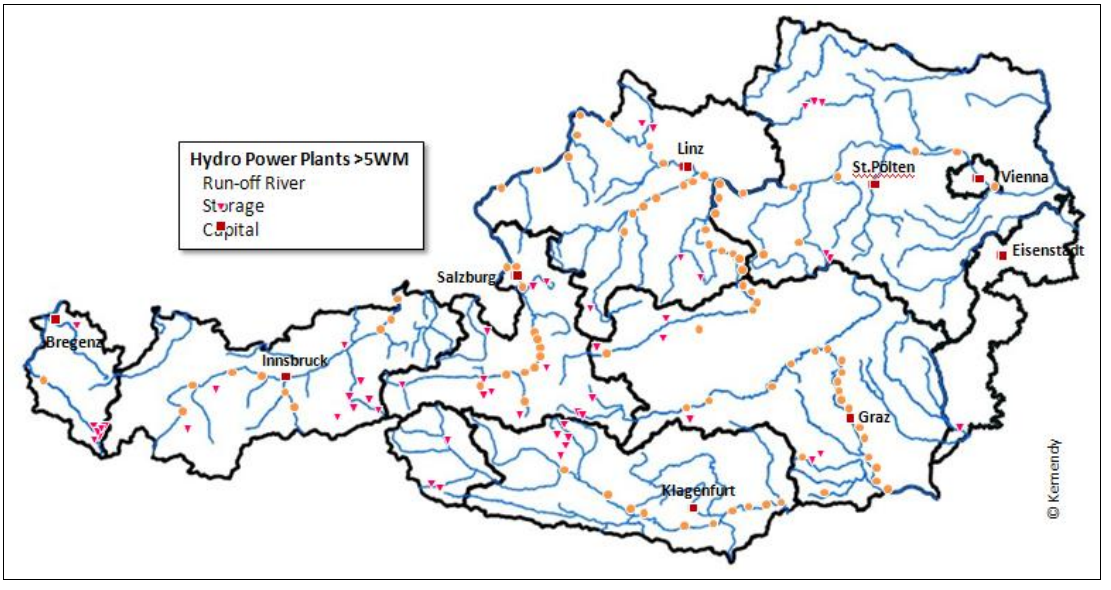


Figure 46: Austrian hydro power plants in Austria, larger than 5MW

Exemplary, figure 47 shows the power plants along the river Mur. The system is mostly characterized by run-off power plants (with some diversion power plants) and seven storage power plants.

[69] DAT files
[70] For further information, please contact Dr.Totschnig, Vienna University of Technology.

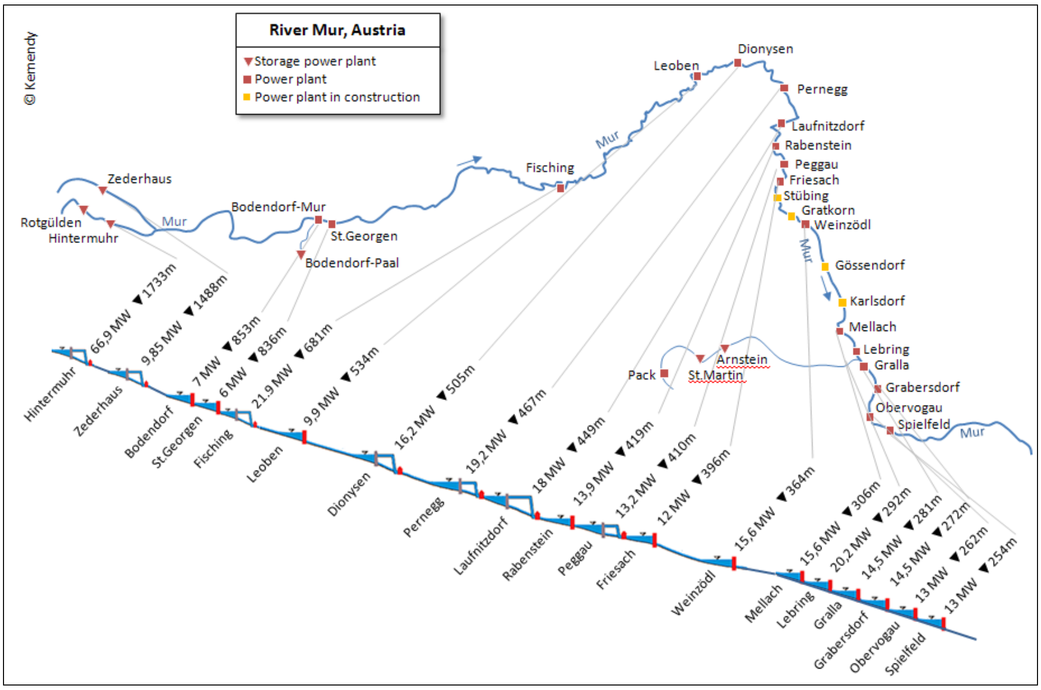


Figure 47: Hydro power plants along the river Mur

7.2 Historical Wind Data

Historic wind data is supported by Austrian Wind Atlas [ZAMG]. Figure 48 shows the annual wind production in Austria in 2006. There are lower capacities during summer ≈1,5GW, but in late autumn, winter and spring they are increasing up to ≈4-8GW (average values).

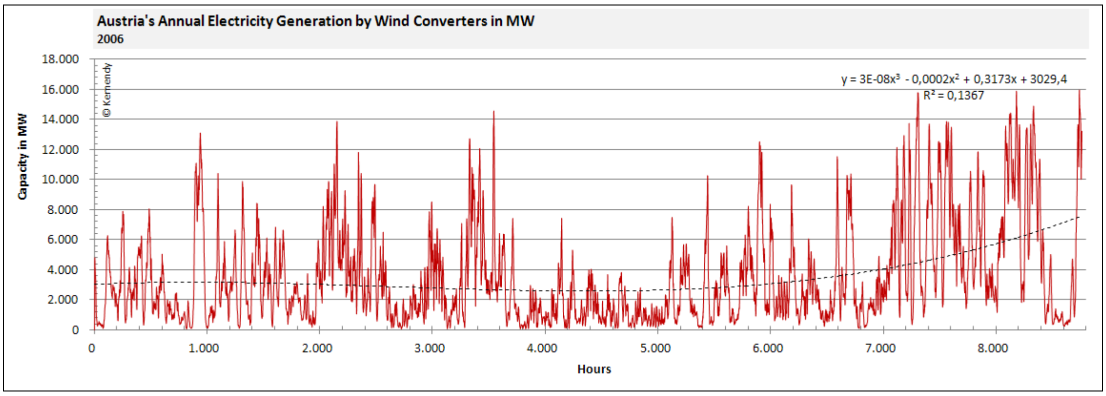


Figure 48: Historic Wind Production in Austria in 2006

7.3 Historical Electricity Demand

In figure 49 the annual electricity demand of Austria and Germany is shown in 2006. The demand is variable during days and weekends and has a range between 40 and 80MW. The demand is lower during summer, caused by lesser heating demands and longer days with lesser illumination demands.

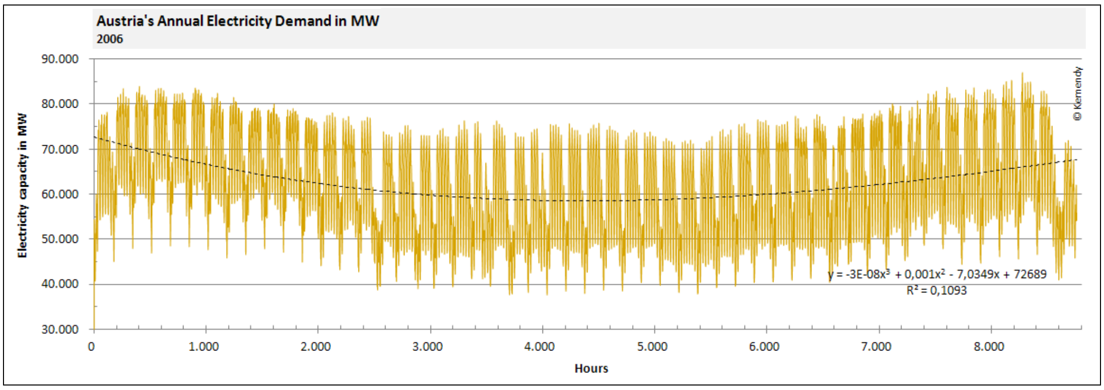


Figure 49: Historic Electricity Demand in Austria and Germany in 2006

7.4 Historical Electricity Price

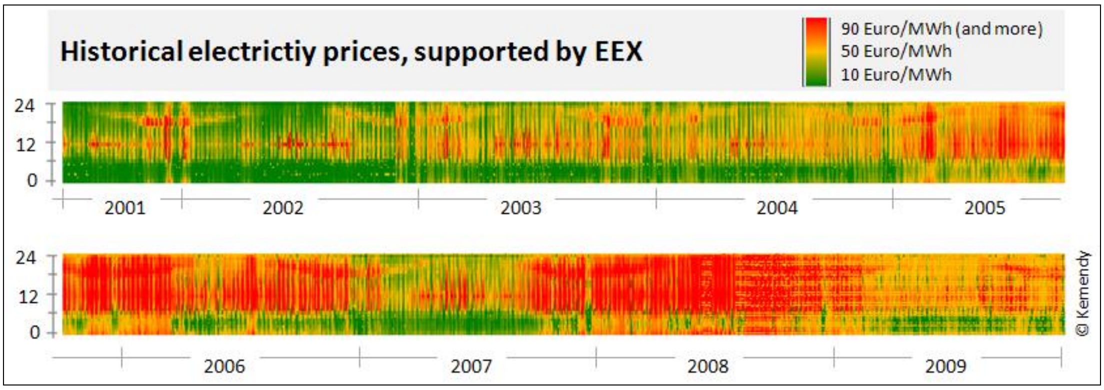


Figure 50: Historical electricity prices[71] by EEX

At the beginning of the Kyoto Protocol in 2005 and the starting discussion about the impacts of global warming, the picture shows an increase of electricity prices until end of 2006. Additionally, the war in Iraq (since 2003) and its destabilization effects to the whole region had strong negative impacts on the world's oil supply security.

[71] Figure: Kemendy 2012, with data from EEX

The financial crisis since 2007 and higher prices for fossil fuels led again to higher electricity price levels.

7.5 Water Inflow Data

Water flows into power plants are important model input parameters because the simulation depends on water quantities and their change over the time. Main methods to calculate and collect hydrological data (inflows, side inflows) are explained in chapter 6.7 of this master thesis.

In this chapter, for instance, the inflows and correlations of a run-off Inn group and a storage group are analyzed.

7.5.1 Inflow of Inn Group: Section Egglfing-Schärding-Passau

AHP, in cooperation with a Bavarian energy provider[72], has five run-off power plants at Inn section in Upper Austria. The plants have together a capacity of $438MW_{ele}$ and can generate annually 2500 GWh. The production supports 230.000 households in the region[73].

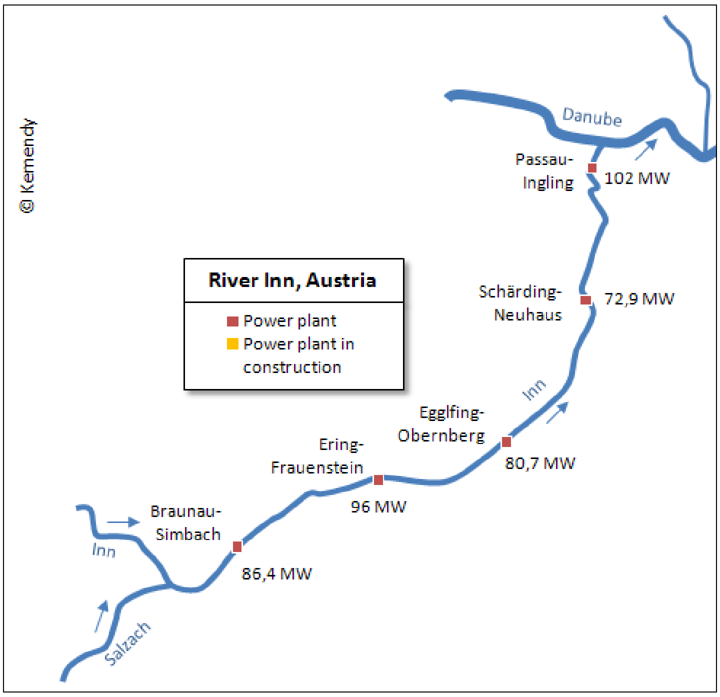


Figure 51: Inn Group – Run-off plants

The figure 52 compares additional inflows of Egglfing-Obernberg, Schärding-Neuhaus and Passau-Ingling in $1000m^3$/day. Additional inflow (side inflow) is not the total water inflow, they

[72] Österreichisch-Bayerischen Kraftwerke AG
[73] Production is shared 50:50 with Germany.

are discharges flowing from branches into the main river bed. The branches of hydro power plant Eggelfing and Schärding are not as big as the braches of hydro power plant Passau. The additional discharges of creek Rott, Doblbach and Pram gives hydro power plant Passau an extra inflow of about 500.000 m^3/d during the begin of 2008, caused by more rainfall and melting water. Egglfing and Schärding are very similar but Passau shows a significant higher and more fluctuant water regime. The average side inflows into Egglfing are about 346.000 m^3/d and into Schärding about 155.000 m^3/d while those into Passau are higher of about 816.000 m^3/d. The figure shows also high level inflows and heavy fluctuations during the first half of 2008 with powerful peaks over 500.000m^3/d. During summer and autumn, all graphs show lower inflows with only small fluctuations. Inflows are increasing again with December with begin of the winter period. I think this is caused by warmer Austrian winters which causes that rain could not easily be stored as snow.

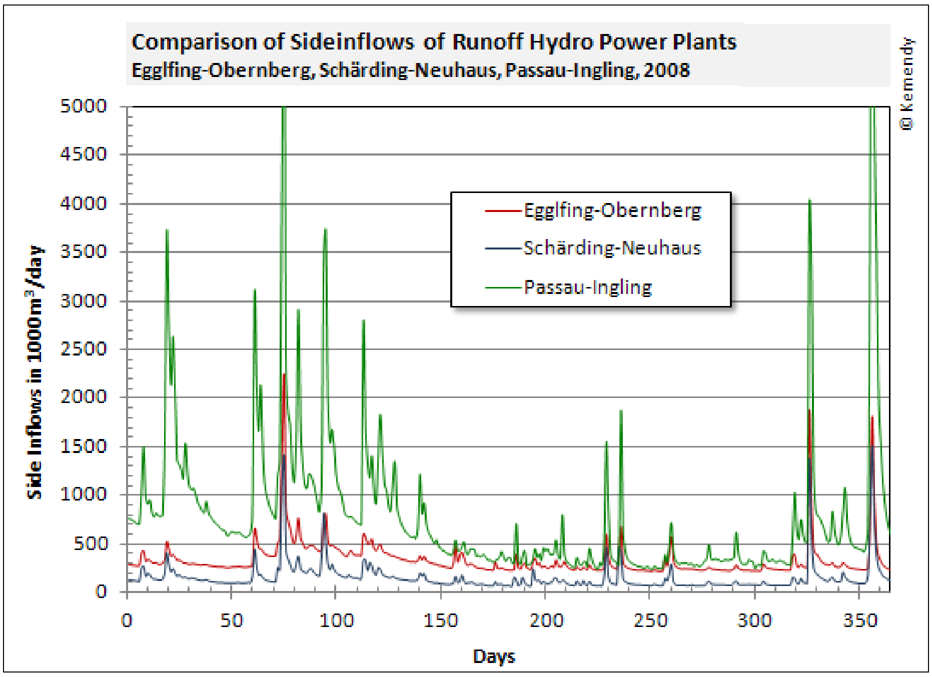


Figure 52: Comparison of Side Inflows, Run-off at river Inn

The next graphs show the side inflow change as histograms. The discharge alteration is the discharge difference during two consecutive days in 1000 m^3/d and how often it occurred. Histograms are used to make a discharge duration curve of a specific location and to predict the annual electricity production.

Egglfing-Obernberg:

The figure shows a relatively sharp peak around ±50.000m³ during 4/5 of the year 2008. Higher changes, greater than 300.000m³, are very rare.

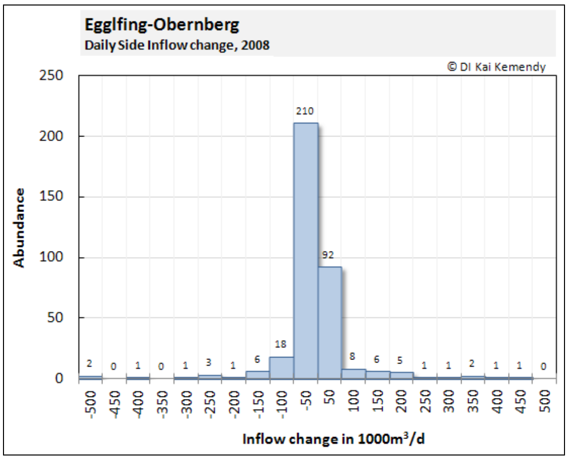


Figure 53: Discharge Histogram Egglfing

Schärding-Neuhaus:

As we already saw in daily water regimes, the histograms of Egglfing and Schärding are also very similar. Changes within ±50.000m³ are small during 4/5 of year 2008.

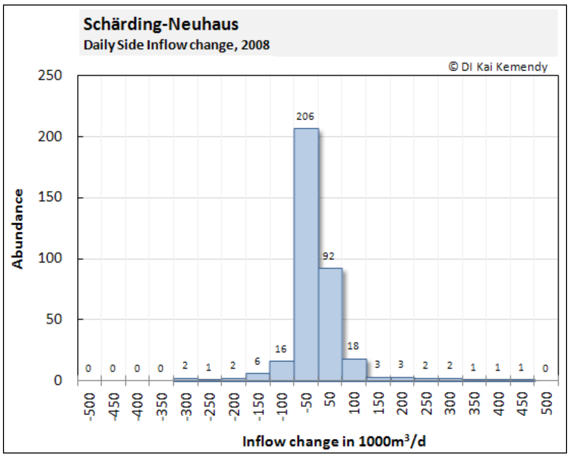


Figure 54: Discharge Histogram Schärding

Passau-Ingling:

The histogram shows a much wider range of discharge changes. Small ±50.000m³ changes are occurring only 1/2 of year 2008. Larger changes greater than 200.000m³ are occurring during 1/5 of year 2008.

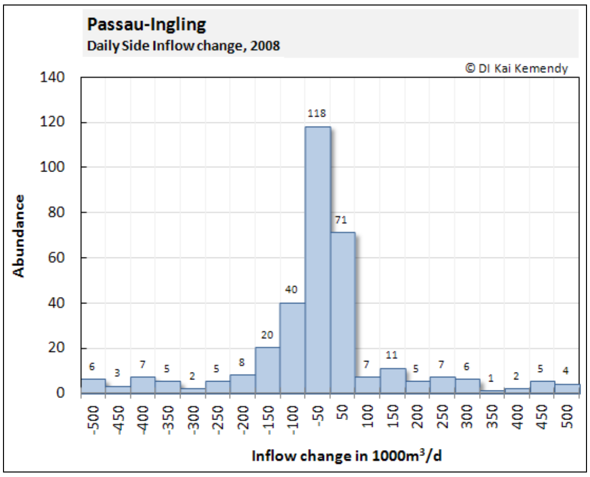


Figure 55: Discharge Histogram Passau

7.5.2 Inflow of Storage Group: Ottenstein

Ottenstein was built in 1954 as a three part hydro power storage system (Ottenstein, Dobras and Thurnberg) and is located near Zwettl in Lower Austria.

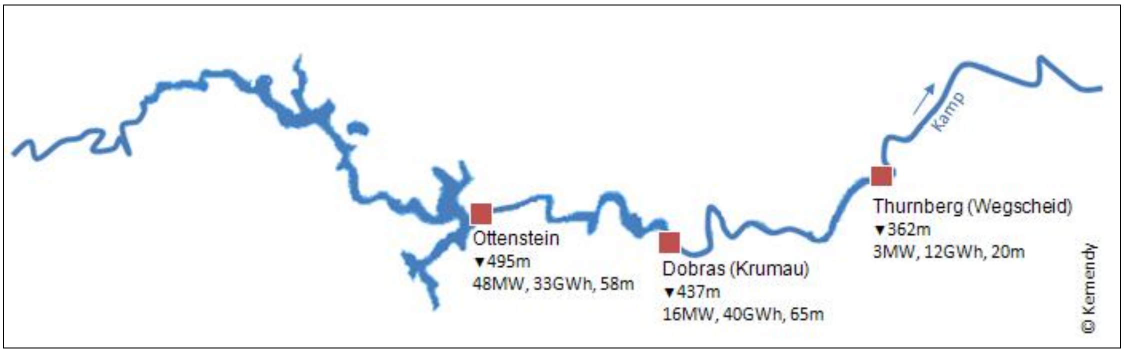


Figure 56: Hydro Storage Pump Power Plant: Ottenstein-Dobras-Thurnberg

Ottenstein has two pumps ($20MW_{el}$, $34m^3/s$) to utilize additional water from downstream Dobras dam and a capacity of $48MW_{el}$ (33GWh, $100m^3/s$).

Dobra (Krumau) as middle dam has a capacity of $16,2MW_{el}$ and the last dam Thurnberg (Wegscheid) has $3MW_{el}$. Ottenstein is designed as annual pumped storage plant and uses the river Kamp. There is only one pump at Ottenstein. It is not possible to pump water from Thurnberg to Dobras. The reservoirs are fed with water from the Weinsburger Wood in the west of Ottenstein with high discharges in spring and less discharges in autumn (annual average discharge rate is $7,9m^3/s$ in Rosenburg).

The following figure shows the inflows into Ottenstein for the year 2008 in $1000m^3/day$.

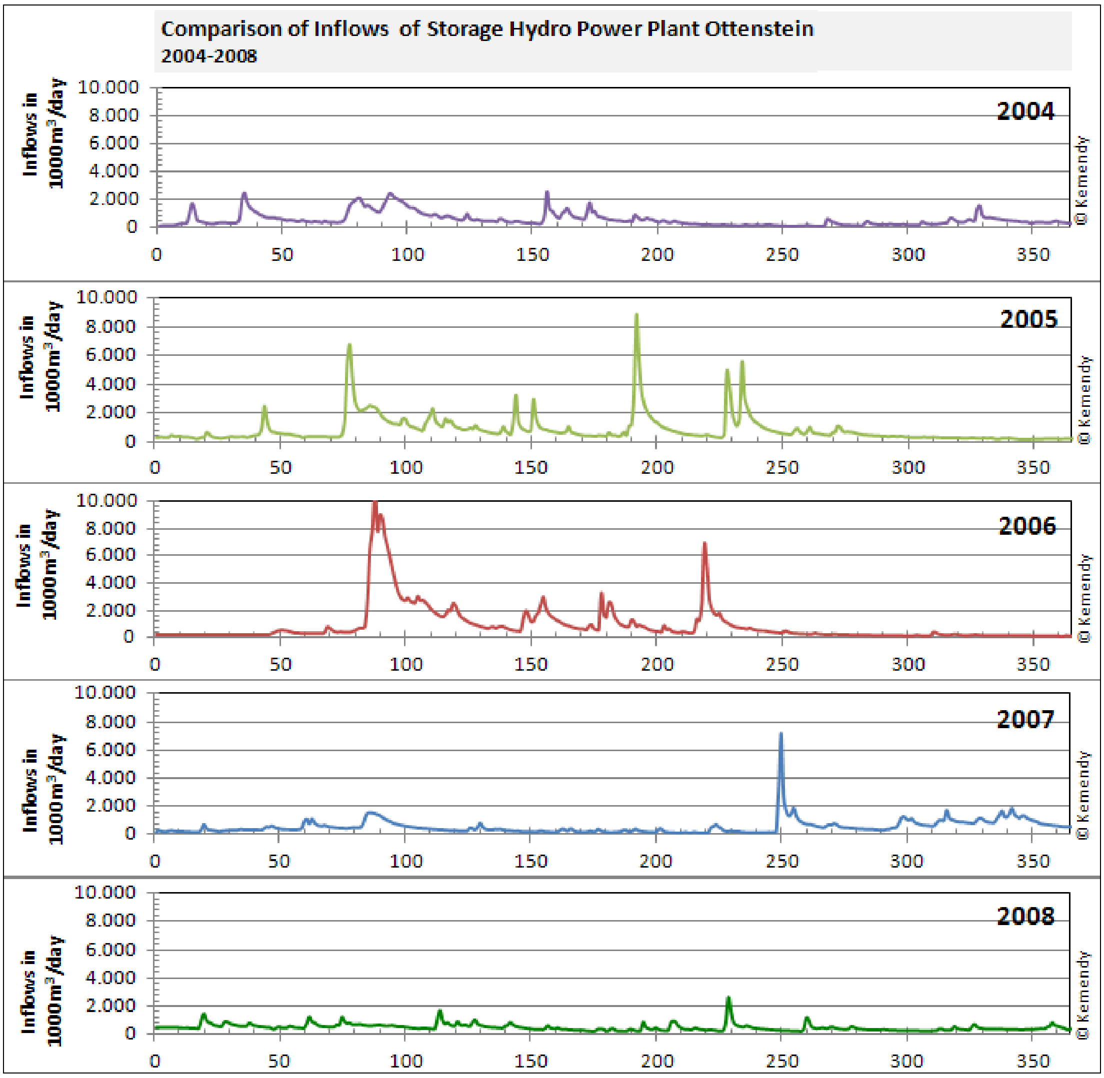


Figure 57: Inflows of Ottenstein from 2004 until 2008

The inflows of Ottenstein show not the typical snow melting characteristic of high alpine areas in spring. They have only stable discharges of about 1,5 mio.m^3/day with moderate peaks. Higher water levels, with intense peaks above 5 mio.m^3/day in 2005 and 2006, are not recurred and assumed as a historic exception.

8 Description of results

The high resolution power system model makes it possible to predict the behavior of complex energy systems in an hourly resolution. The simulation helps to analyze the behavior of single or multiple power plants or even on large national power production systems. The model calculates an optimized solution, which helps to increase the energy production efficiency and to analyze operation tasks of involved power plants.

In the current simulation, hydro and thermal power plants were used to cover the electricity demand with minimum costs. This could not be done only by hydro power. Additional thermal and renewable power plants must be included. The target is to minimize costs of required power plants and to reduce GHG as much as possible.

The simulation used a perfect foresight procedure, which means that the model knows exactly the timing of demand and inflows for its optimization.

In this chapter, two parts of simulations were executed. First, a simulation *"Austrian Power plants*" with an Austrian context was done to look into operation details of main hydro power plant types (storage and run-off). The second simulation *"Technologies"* had a larger context, including Austria's and Germany's power plants to analyze the behavior of technology trends (fossil, nuclear, renewable) and to look at produced GHG emissions. Austria's and Germany's power systems are very well connected and strongly dependent on each other. That was the reason why both countries were used in the second run. The simulation was compared with two scenarios, low and large renewable shares (wind).

8.1 Simulation 1 - Austrian Power plants

8.1.1 Model Output: Electricity Price

The figure 58 shows the annual time line of the electricity price in 2006, predicted by the model. It has a strong fluctuating behavior, depending to currently involved power plants and demands. The price varies between 25 and 65Euro/MWh.

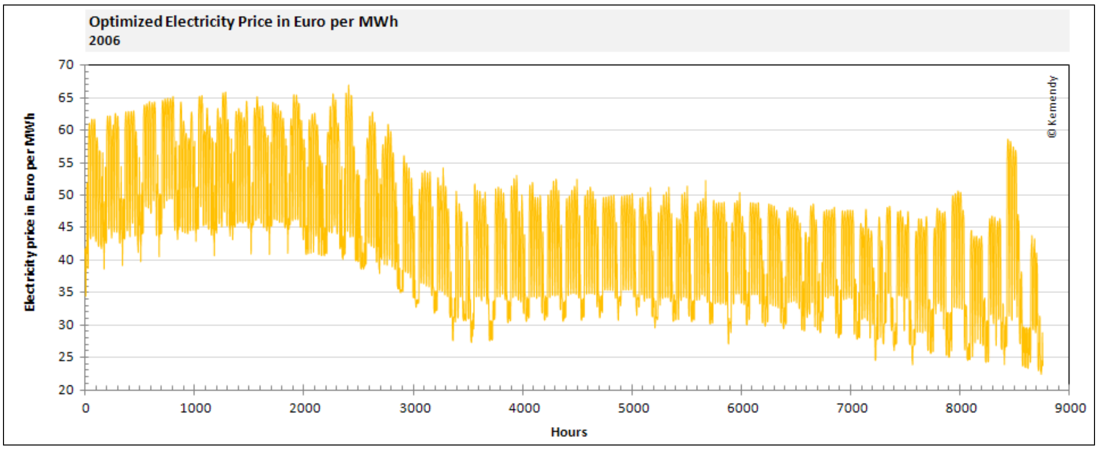


Figure 58: Model Output: electricity price in 2006

The next figure 59 shows the detailed electricity price during a week. During working days (from Monday to Friday), the price is low in the morning and is increasing until midday to his maximum when electricity is needed in offices, industry and households. At afternoon, the price is decreasing and reaching his minimum during the night. At the weekend, the price is low, caused by lower demand of offices and industries, with additional peaks for activities at evening.

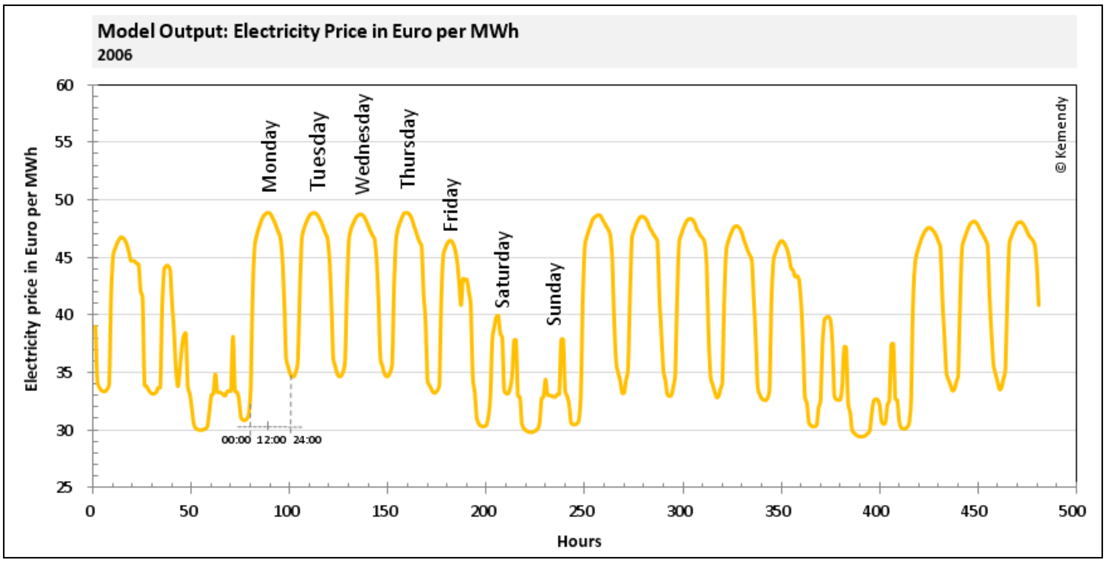


Figure 59: Electricity price during a week

8.1.2 Annual Pumped Storage Power Plant: Ottenstein

Figure 60 shows the model result for Ottenstein and Dobras. The hourly optimized water levels show in which periods of the year high discharges exist and at which time electricity is generated or water is pumped. Heavy water discharges are used to refill both reservoirs immediately ("perfect foresight" is included into model logic).

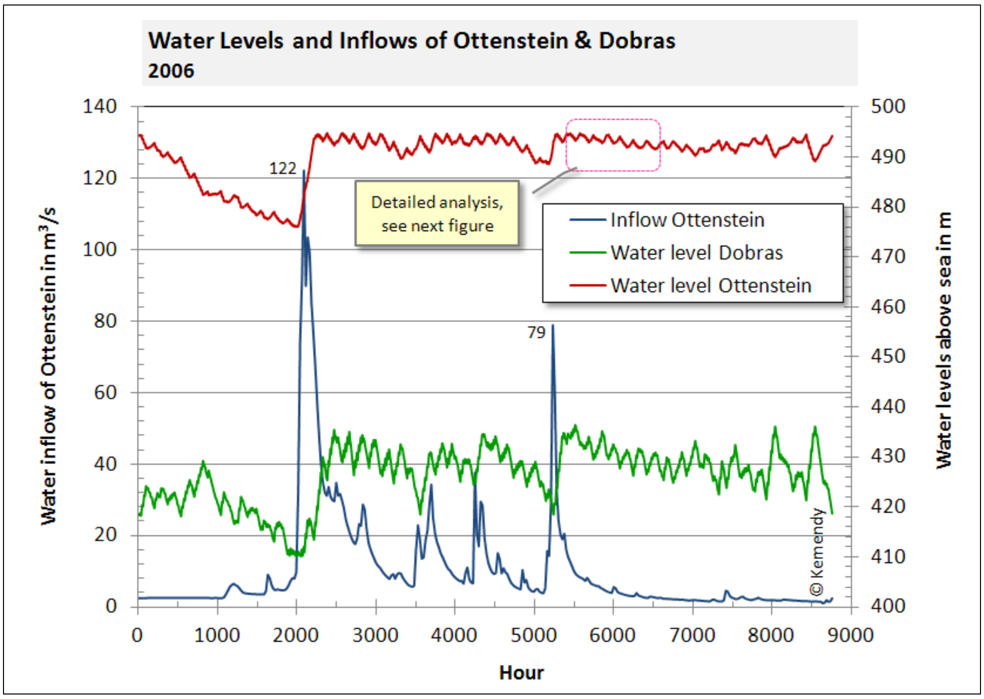


Figure 60: Levels and inflows of Ottenstein and Dobras in 2006

The water level of Ottenstein varies from 476 to 495 meters and Dobras water level from 410 to 436meters. The average water inflow is about 15m^3/s, with peaks of 79 and 122m^3/s.[74] The water level fluctuations in Dobras are larger than those in Ottenstein. This is caused by the fact that water amounts are delivered immediately from Ottenstein to Dobras and that the volume in Dobras is much smaller than Ottenstein.

Periods of lower electricity prices[75] are used to pump water from Dobras to Ottenstein (water level of Ottenstein is increasing, from Dobras decreasing). If the price is nearby 45Euro/MWh, electricity generation is started. Cheap electricity prices under 37Euro/MWh are used to pump water into upper reservoir.

[74] Power plant Thurnberg is not taken into account because it is smaller than 5MW.
[75] During nights and weekends.

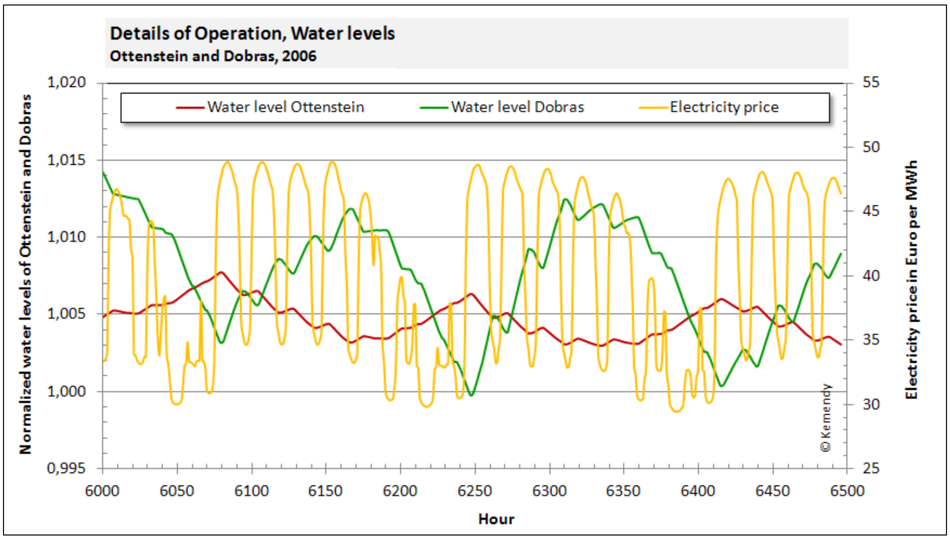


Figure 61: Ottenstein and Dobras, details of operation – water levels

Figure 62 shows the annual behavior of operation of Ottenstein and Dobras. It is obvious that water is pumped weekends and during every night. The generation in Ottenstein varies during the year and is depending by actual discharges. In periods of longer high water amounts (>60m^3/s), pumping is stopped (hour 2100-2500). The main electricity generation is done during spring and summer.

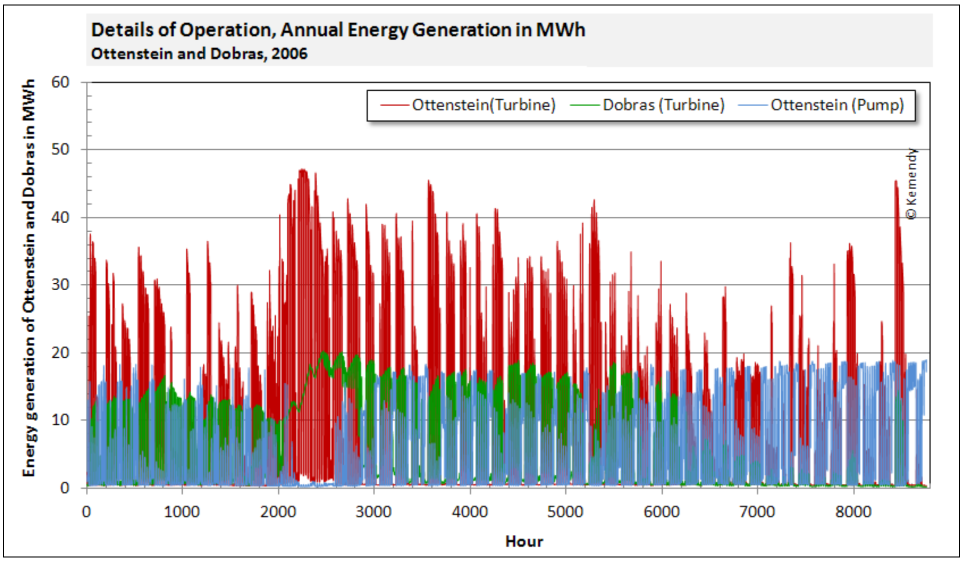


Figure 62: Ottenstein and Dobras, details of operation, annual behavior

The following figure 63 shows a specific view from the annual time line of the generating and pumping capacity during hour 350-600. The alteration of generation and pump periods is very well documented (Ottenstein red line, Dobras green line). Pump phases (blue line) are started after generation phases are completed (depending to current inflow and electricity price situation). Work days are used to generate electricity and profit and weekends and nights are used to pump water from Dobras to Ottenstein.

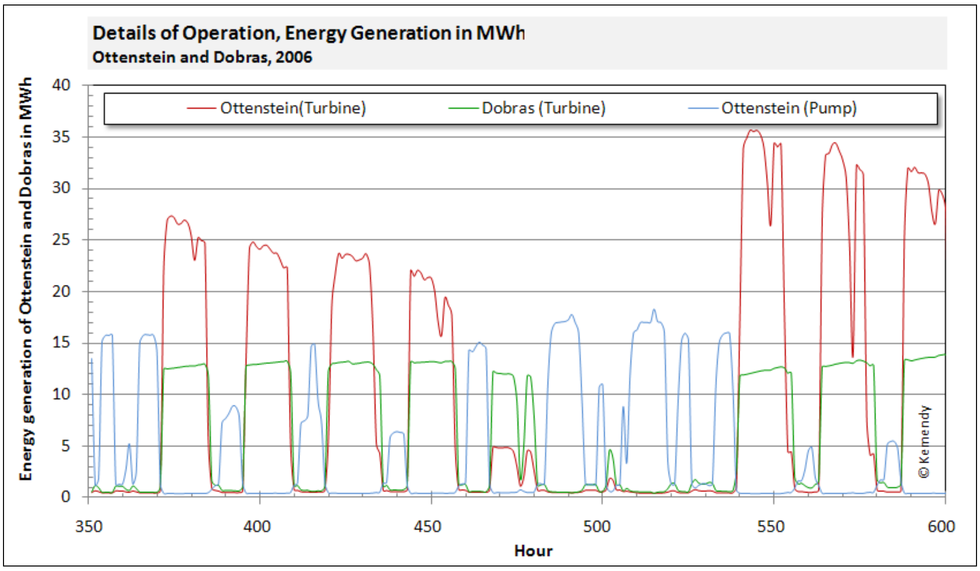


Figure 63: Ottenstein and Dobras, details of operation (1)

Figure 63 represents the normal behavior of operation. The next figure 64 shows the behavior from hour 2000 to 3000. This period is characterized by a strong water income with peaks more than 100m^3/s. The large incoming water amounts are quickly filling the reservoirs of Ottenstein and Dobras (please notice figure 60 – water levels) and reaching after 200 hours the maximal water level in Ottenstein. After some larger pump phases at the beginning (hour 2100), pumping is nearly absolutely stopped and water is used for generating energy (hour 2100-2550) in both power plants. Although Ottenstein has reached his maximum water level, alternation operation is still continued. Meanwhile Dobras smaller reservoir volume tries to dissipate Ottenstein's inflow, indicated by a constant increase of Dobras capacity. After hour 2600, the additional heavy water income is over. Normal operation behavior - with big pump phases during the weekends - is reestablished again. In this specific period, Ottenstein has generated 15,7GWh and Dobras 14,8GWh. The total 2006 electricity generation in this simulation is for Ottenstein 49GWh and for Dobras 57GWh.

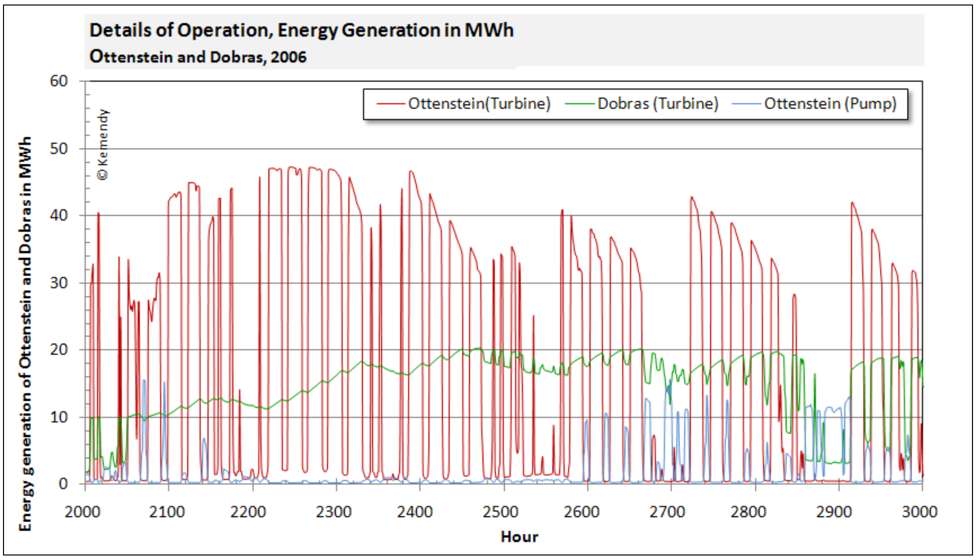


Figure 64: Ottenstein and Dobras, details of operation (4)

8.1.3 Weekly Pumped Storage Power Plant: Ranna

Hydro power plant Ranna is Austria's oldest pumped storage power plant and is located in Upper Austria near the German border. It is used as weekly pumped storage plant with a generation capacity of 19MW and 48GWh per anno. The 13MW pump could get water from river Danube up into Ranna with max. 6m^3/s. The lower water level is assumed as const, because Danube is seen as "inexhaustible" lower reservoir.

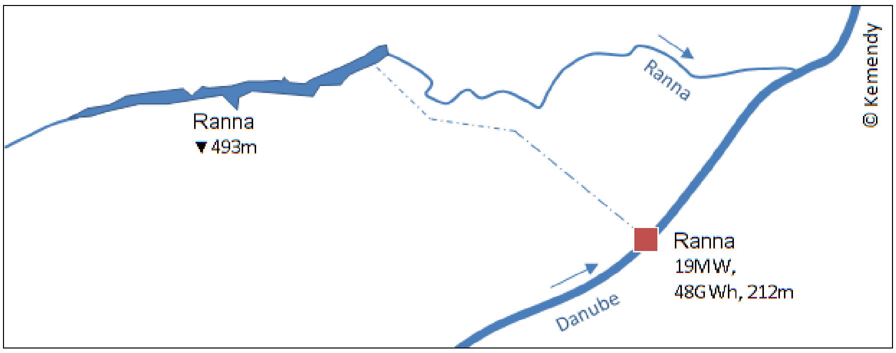


Figure 65: Weekly Pumped Storage Power Plant: Ranna

Figure 66 shows the water levels and the discharge of Ranna. The situation in Ranna is similar to Ottenstein, with similarly strong additional discharges at hour 2000 (with a maximum of 30m^3/s). Ranna's water level varies between 475 and 493m.

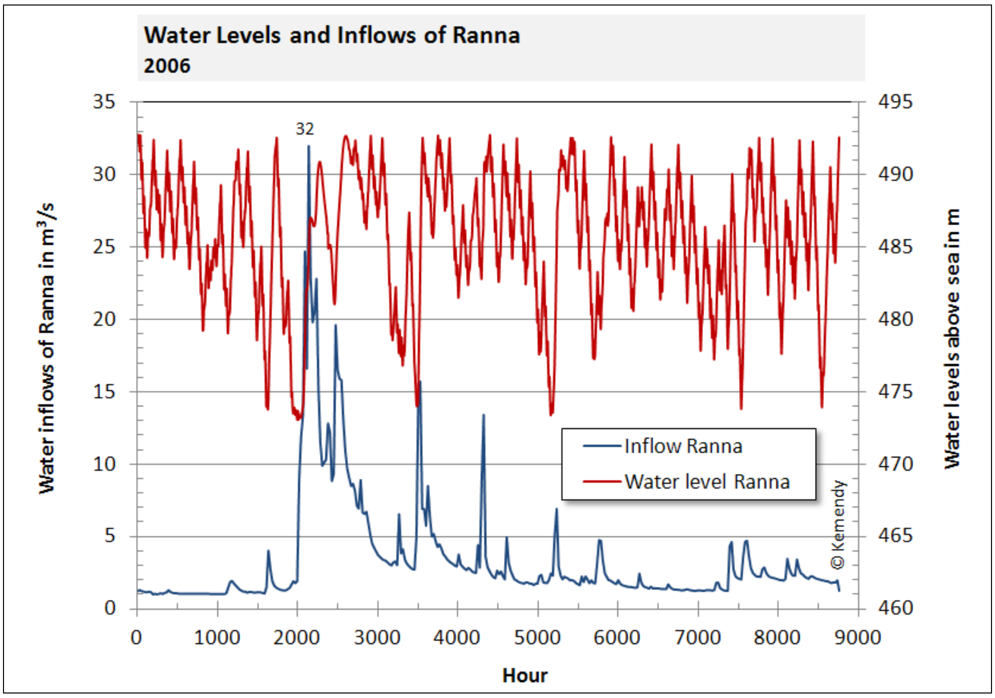


Figure 66: Water levels and inflows of Ranna in 2006

Again, during periods of lower electricity prices (weekends and nights), water is pumped into the upper reservoir.

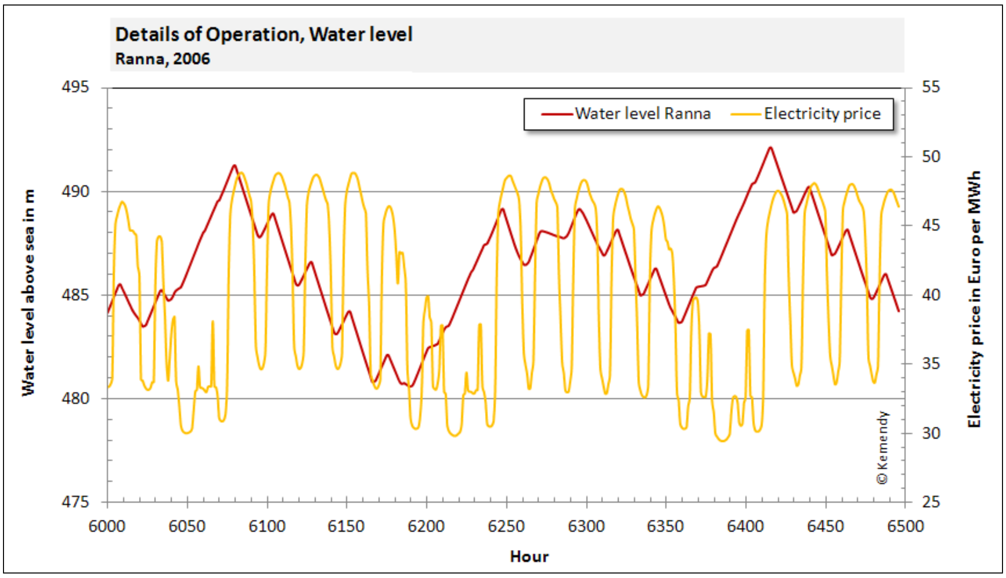


Figure 67: Ranna, details of operation – water levels

Prices over 45Euro/MWh starts generation and prices under 37Euro/MWh will stop it (pumping begins). Compared with annual storage Ottenstein, weekly storage Ranna shows main differences (see figure 62). Ranna has a very dominate generation phase during late spring and summer with high generation and low pump capacities caused by strong water income during hour 2000-6000.

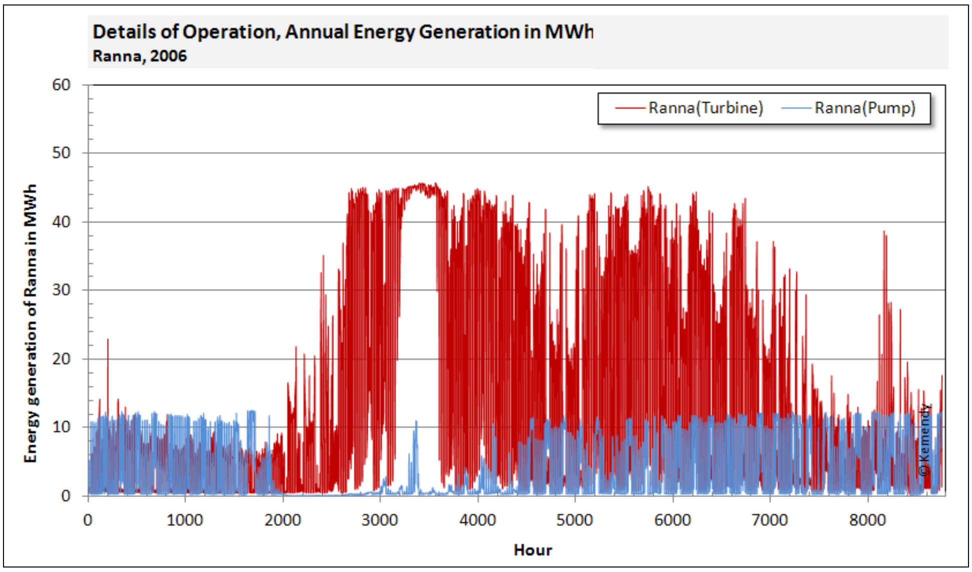


Figure 68: Ranna, details of operation – annual behavior

Figure 69 shows details during normal working phases of Ranna at the beginning of the year during hour 350-600. The alteration of generating and pump phases is obviously. Only the generation capacity is lower than possible (compared to summer), caused by too small discharges. The generation peaks in evening are much more developed than in Ottenstein because weekly storages are more used for balancing activities as annual storages.

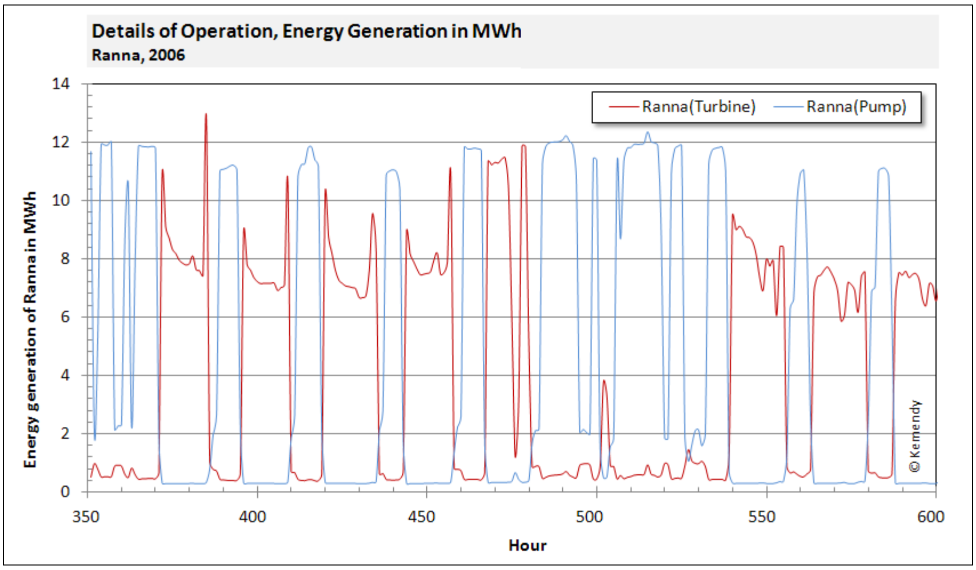


Figure 69: Ranna, details of operation (1)

The next figure shows the behavior during hour 3000-4000 with strong water incomes. The water has filled the reservoir during hour 2000-3000. After hour 3000, pumping activities are nearly stopped. From hour 3200 to 3600, the generation is constant on a high level of about 45MWh until fluctuation starts again after hour 3600. This is an energy surplus +460% in relation to spring period (8MWh).

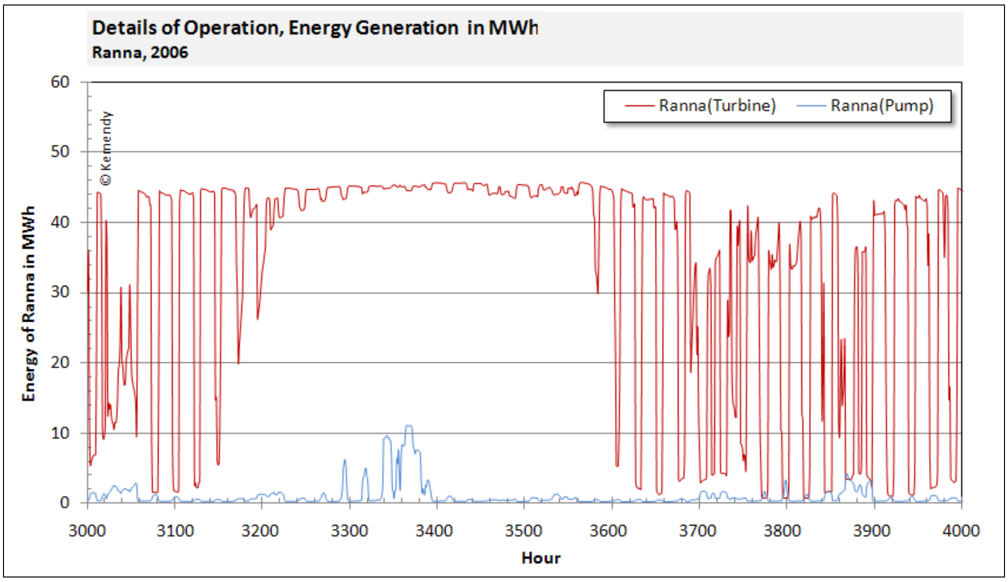


Figure 70: Ranna, details of operation (2)

In this simulation, the annual electricity yield of Ranna is 46,7GWh.

8.1.4 Run-off Power Plant: Passau-Ingling

To compare pumped storage power plant optimization results with run-off plants, run-off Passau-Ingling was exemplary selected. This plant has a capacity of 86,4MW, an electricity yield of 504,6GWh and an intake of 1140m^3/s. Next figure 71 shows the water level and side inflow stream of Passau.-Ingling. Remarkable is that although the side inflow very often fluctuates, the water level is kept constant by the simulation. This is because the water volumes of run-off and threshold[76] hydro power plants have normally less options for modifying water levels, caused by flood protection and the needs for waterway management.

[76] Schwellenkraftwerke

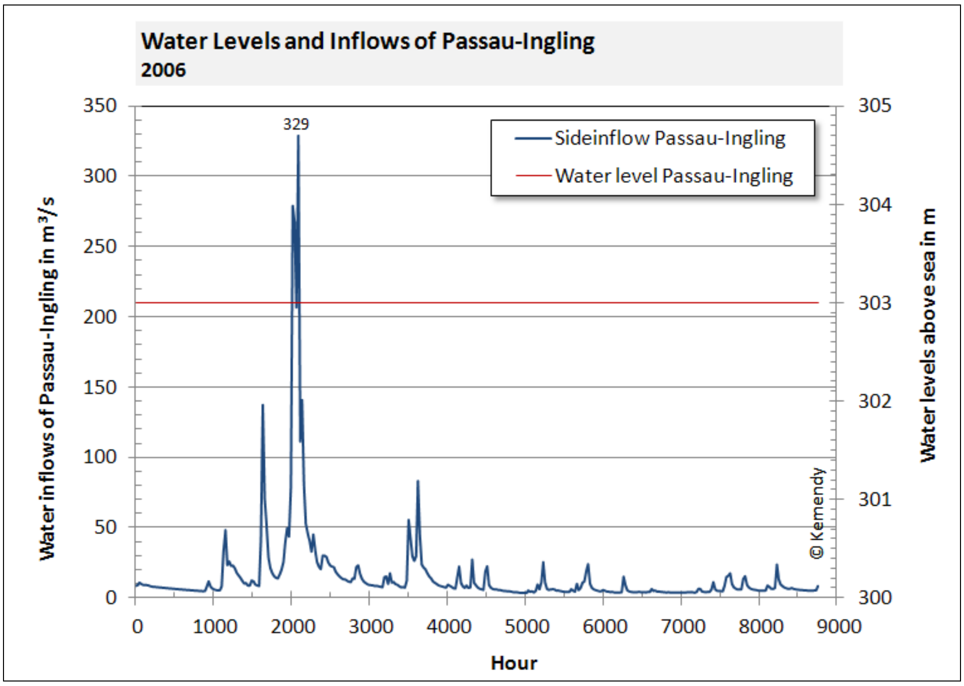


Figure 71: Passau-Ingling, water levels

Figure 72 shows the annual behavior of Passau-Ingling. The generation during the winter is on a low level of 40MWh (hour 7500-1000) and is than increasing during spring when the snow in the mountains is melting. During summer it is on its highest level of 85MWh.

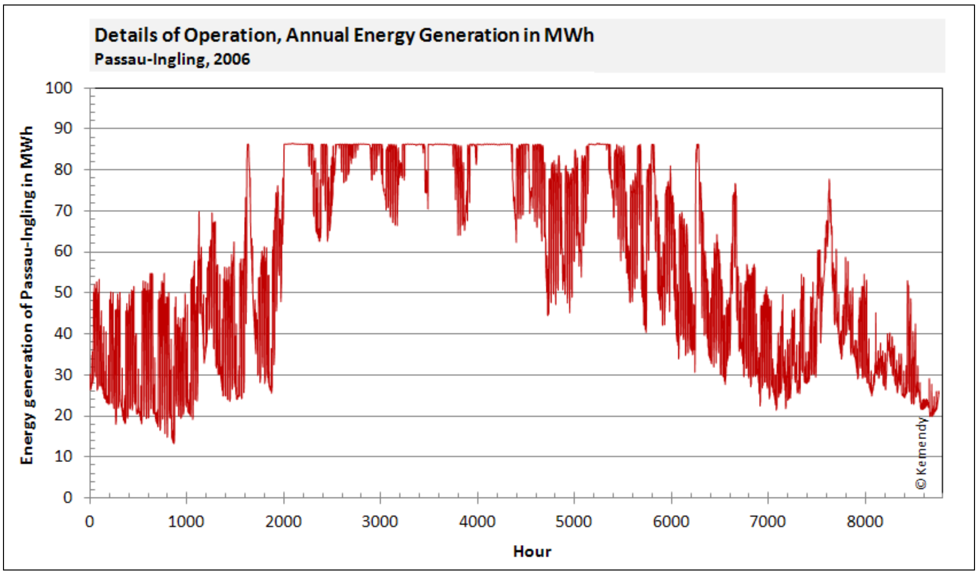


Figure 72: Passau-Ingling, details of operation, annual behavior

Next figure 73 shows the section hour 3000-4000. The overall generation level is constant about 80MWh with fluctuations of ±8MWh synchronized to discharges from previous hydro storage power plants.

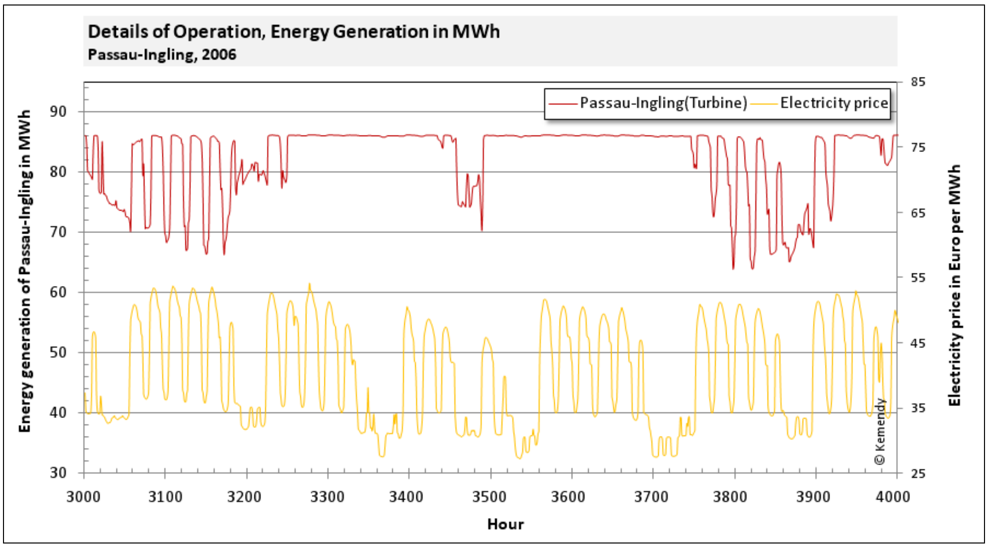


Figure 73: Passau-Ingling, details of operation (1)

The annual electricity yield of this simulation of Passau-Ingling is 505,3GWh.

8.2 Simulation 2 – Technologies

To check the impact of wind energy generation on Austria's and Germany's power plant management, a low and high wind share simulation was executed. Hydro, thermal and wind power plants were optimized to fulfill the electricity demand for 2006. The model installs the optimal number of thermal plants at lowest costs (fuel, investment) to compensate energy shortages.

Next figures give only a summary of the main findings out of 300MB packages of result data.

8.2.1 Renewable Energy Source – Low Wind Share

Boundary conditions: Because the total energy demand could not be covered by hydro power plants alone, the model compensates missing energy amounts by building conventional thermal power plants. Available wind is only used as necessary, additional wind energy could be wasted.

The behavior of different energy production technologies for the first 450 hours in the year 2006 with a low wind share shows figure 74. Additional, the electricity price was included into the figure to recognize the relationship between price and power plant management.

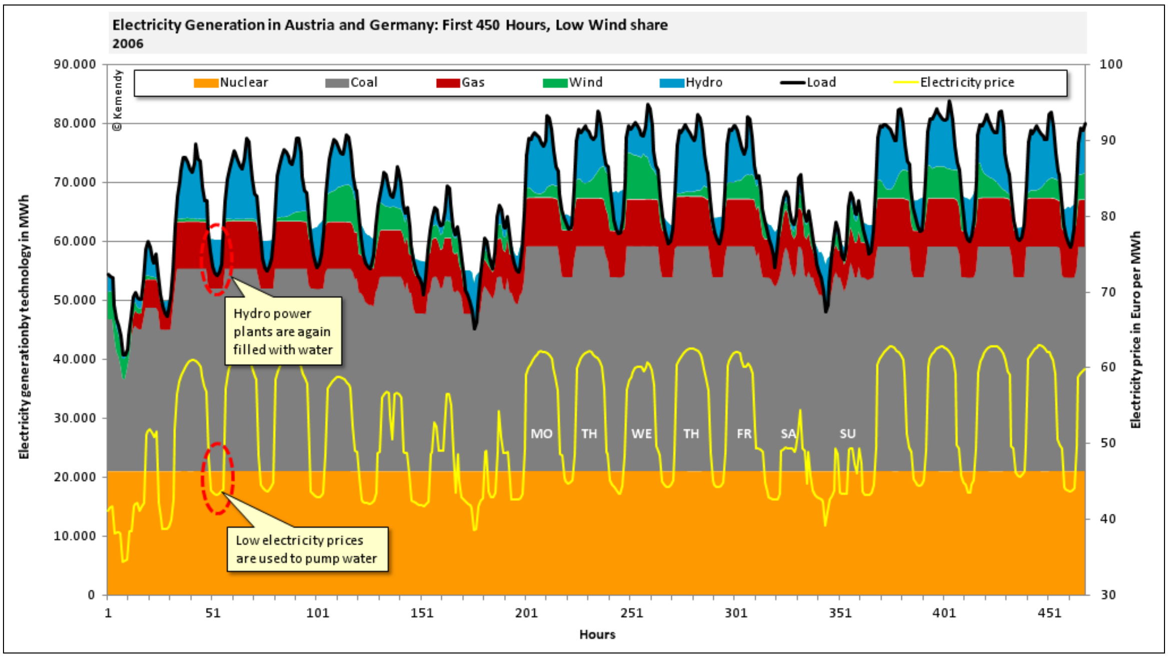


Figure 74: Generation (AT&GER) – Low Wind Share (first 450 hours)

The model result shows the typical progress, with high prices during the day and low prices in nights and weekends (this could be very well seen in the figure). Low price periods are used to refill hydro power storages. It is obvious that nuclear power plants are used to cover a large part (184TWh) of the base load. Coal (268TWh) is used to complete the rest of the base and to fill the middle load. Smaller shares of gas (32TWh), hydro (37TWh) and wind (31TWh) power[77] are used to complete the total demand balance. Hydro power shows a constant behavior with periods of pumping activities.

The final wind share in this solution was 7% and the average electricity price was 51,90Euro/MWh.

[77] For peak loads

8.2.2 Renewable Energy Source – High Wind Share

Boundary conditions: Renewable energy source wind is maximized. Only maximal 10% of available wind potential may be wasted.

As seen in figure 75, the new solution has changed the energy generation behavior completely. The electricity price has nearly lost his typical day-night-weekend progress. This is caused by the availability of the volatile wind energy. Additionally, the solution also generates negative prices, which are immediately used to refill hydro storages. Finally, the boundary condition forces the model to increase the wind share up to 45%. This is done by reducing nuclear and fossil shares dramatically, which can be seen in the figure as deep wind impacts into nuclear and fossil energy areas. Nuclear (150TWh) and coal (111TWh) energy is still covering the base load, with gas (16TWh) as middle load and for peak demands wind (246TWh) and hydro (32TWh). The final average electricity price is now only 40,11Euro/MWh.

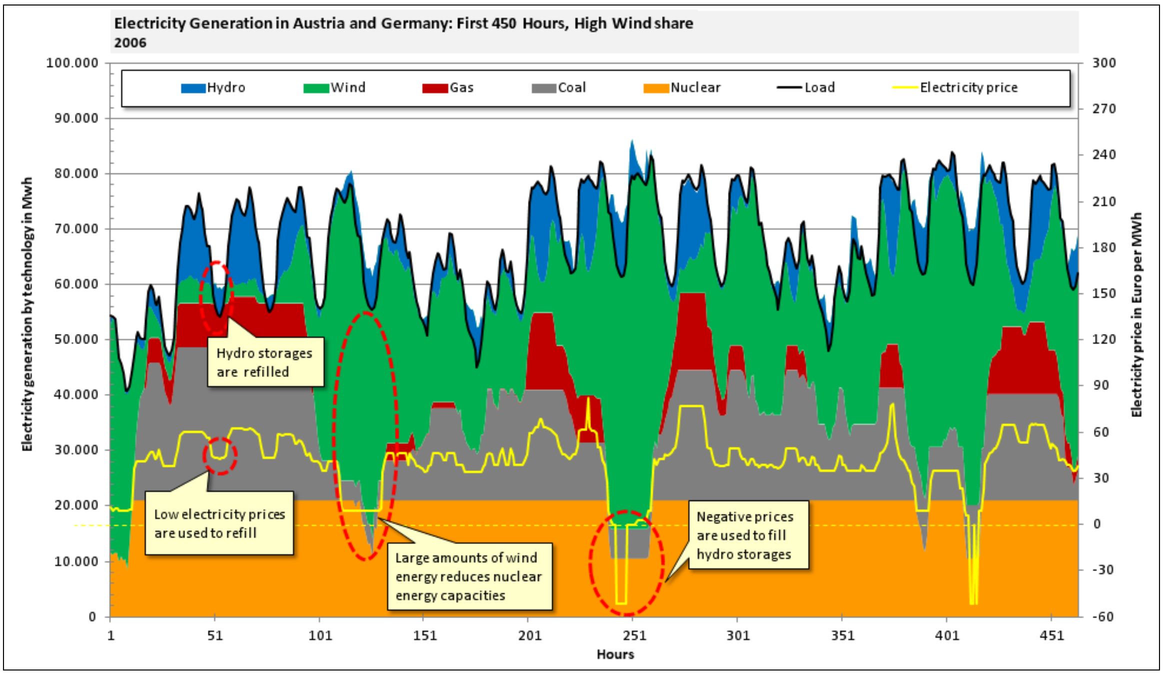


Figure 75: Electricity Generation (AUT&GER) – High Wind Share (first 450 hours)

8.2.3 Renewable Energy Source – Results

The compare of the two wind scenarios showed that – if wind is not wasted – the wind share could be increased from 7% to 45%! This could be only realized if the shares of nuclear(-7%), gas(-3%) and coal(-29%) are reduced. The dominate technology coal is significantly reduced by renewable wind source, caused by the model's target to minimize costs for fuels. The total pump energy to refill hydro power reservoirs is 4,1TWh (low wind share) and 7TWh (high wind share) that is 0,7% and 1,3% of total electricity demand.

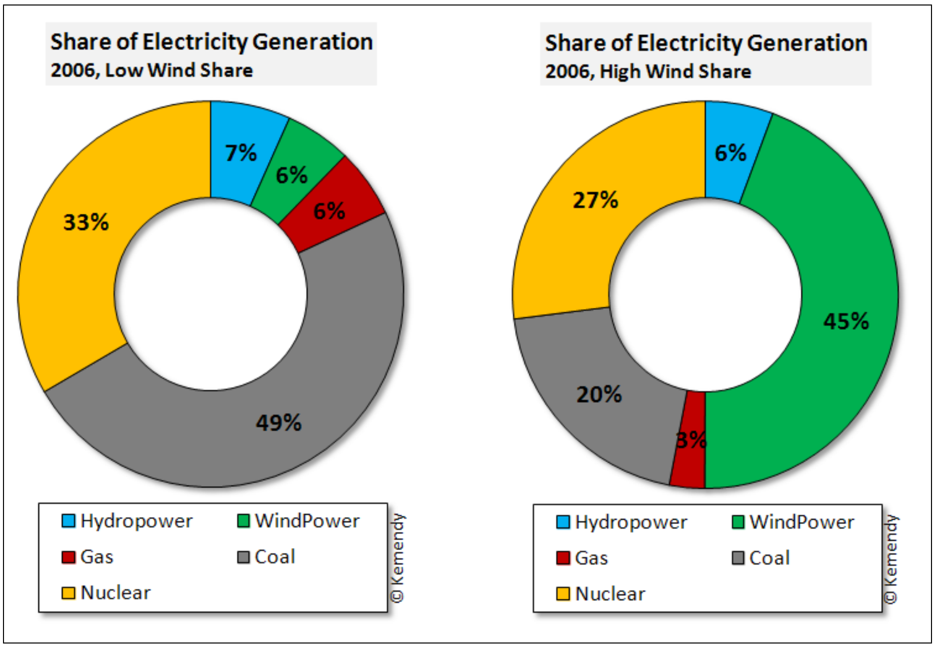


Figure 76: Electricity Generation (AUT&GER) – Results

Additionally, other very positive effects occurred in the second solution. The CO_2-emission factor was successfully reduced from 0,861 to 0,809 tonCO_2/MWh_{ele}. The reason is that old less efficient power plants generates lesser energy. Expressed in absolute terms, 155 mio. tons GHG emissions[78] (-60%) could be saved if wind energy is optimal used. The electricity price is reduced from 51,90 to 40,11Euro/MWh (-22,7%).

[78] CO_2-Emissions: Low wind share = 258 mio ton CO_2, high wind share = 102,8 mio ton CO_2

9 Conclusions

In order to improve our power generation and distribution systems to become more efficient and more environment friendly, we need tools and models to simulate the behavior of the complex power system with a high share of renewable energies. The models will not replace reality exactly, but they are very important to illustrate, to analyses and to improve the future power system. A unit commitment model of hydro power plants in Styria, Upper and Lower Austria with more than 5MW is developed in this master thesis and integrated into the HiREPS model for Austria and Germany. As an application, two scenarios – one with a 7% and one with a 45% wind generation in terms of total electricity demand – are defined to analyze the operation of run-off and pumped hydro power plants. The historical Inflows of the year 2006 are used in the simulations of the scenarios. The thermal power plants in this two scenarios are assumed to be the same that exists in the year 2006 in Austria and Germany. In the second scenario, 10% of annual wind energy is allowed to be curtailed if this is beneficial for the operation of the power system. The result of this scenario showed that it is possible to increase the wind energy share from 7 percent to 45 percent and to achieve a CO2 emission reduction of 155mio tonCO2 per anno in Germany and Austria (compared to the low wind scenario). Solar PV was not included in the scenarios since no solar photovoltaic generation data was available at the time of this master thesis. This is a very successful 60 percent reduction of CO2 emissions and a 39 percent reduction of the fossil and nuclear energy share in 2006. The conclusion of this result is that if we use more of our renewable energy potential (in this scenarios wind energy), we could reduce CO2 emissions and costs for fossil fuels significantly.

Outlook: A reliable electricity system is crucially important to our present economic and social system. The supply of environmental friendly and economical electricity is one of the most important tasks for the energy industry and science in the future. Decisions made today have long-term capital- and resource-intensive effects. Therefore, we need tools and methods to seek for economical-technical-environmental optimized solutions. The hope is that this model will make important contributions for planning the next generation power system in Austria and in European Union and helps to promote the development of renewable energy systems and finds ways to reduce the dependence of fossil fuels.

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Annexes