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PUMPED HYDRO ENERGY STORAGE DEMO PLANNING

Energy Storage in our Future Low Carbon Society Project

School of Technology
2020

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TIIVISTELMÄ

Tekijä	Joonas Kaihovirta
Opinnäytetyön nimi	Pumped Hydro Energy Storage Demo Planning
Vuosi	2020
Kieli	Englanti
Sivumäärä	38 + 4 liitettä
Ohjaaja	Jukka Hautala

Tämä tutkimus toteutettiin osana Energy Storage in our Future Low Carbon Society -projektia, jonka tavoitteena on lisätä tietämystä liittyen energianvarastointimenetelmiin kehittämällä demoympäristöä Technobothnialla. Vaasan alueella tutkimustyönkehittämisen kysyntää on kasvattanut usea energia-alan toimija. Uusiutuvien energianlähteiden yleistyminen on kasvattanut tarvetta energianvarastointimenetelmien kehittämiselle. Tämä tutkimus keskittyy keräämään tietoa, ja luomaan suunnitelman pienen kokoluokan pumppuvoimalaitoksen toimivuudesta ja rakentamisesta.

Teoreettinen osuus tutkimuksesta käsittelee syitä energianvarastoinnin kasvaneeseen tarpeeseen, ja keskittyy erityisesti pumppuvoimalaitosten merkitykseen energianvarastoinnissa. Tutkimuksessa luodaan putki- ja instrumentaatio kaavio sekä simulaatio, pumppuvoimalaitosdemon toimivuuden arvioinnin ja suunnittelun helpottamiseksi.

Tutkimuksessa merkittäviä huomioita olivat pienen kokoluokan pumppuvoimalaitosdemon toteutettavuuden ja toimivuuden arviointi simulaatiota apuna käyttäen ja systeemin ylemmän ja alemman pinnan välisen korkeuden vaikutus tehokkuuteen.

Avainsanat pumppuvoimalaitos, energianvarastointi

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ABSTRACT

Author	Joonas Kaihovirta
Title	Pumped Hydro Energy Storage Demo Planning
Year	2020
Language	English
Pages	38 + 4 appendixes
Name of Supervisor	Jukka Hautala

The thesis is part of Energy Storage in our Future Low Carbon Society Project, whose objective is to extend knowledge and gain information regarding energy storage methods, by creating demo environment in Technobothnia. The Vaasa region possesses a huge variety of companies operating in energy sector creating significant demand for research regarding energy field. The growth of renewable energy sources produces increasing demand for energy storage research. This research will focus on documenting information, planning and creating layout of pumped hydro energy storage (PHES) located in Technobothnia area.

The theoretical part of research discusses the reasons of increased demand of energy storage systems generally and specifies the importance of pumped hydro energy storage systems among other available technologies. The thesis also includes the creation of simulation and piping and instrumentation diagram, to define the pumped hydro energy storage layout and functionality.

The research main conclusions were the evaluation of the small-scale PHES systems by utilizing simulation to assess feasibility and functionality of the system, and the signification of head height increase to the efficiency.

Keywords pumped hydro energy storage, energy storage systems

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1 INTRODUCTION

1.1 Background of the Thesis

The knowledge and awareness of consequences of fossil fuels has created massive shift from conventional electricity generating methods to utilization of renewable energy sources. The increasing energy generation of renewable energy sources has created a great demand for knowledge and research of possible energy storage methods because most of the renewable energy generating methods are highly volatile due to the weather and time the of day.

This research is part of Energy Storage in our Future Low Carbon Society Project and focuses mainly on pumped hydro energy storage (PHES) technology. The Vaasa region has the presence of several actors in energy field, increasing the demand for knowledge regarding future solutions to generate and store electricity.

Currently pumped hydro energy storage systems are dominant technology to store electricity generated from renewable energy sources, and PHES installations have significant occupation in maintaining the stability of the grid. PHES systems operation is highly corresponding to conventional hydropower plants, which has ensured extended development of the water generating technology.

1.2 Research Problem and Objective

As the hydropower and pumped hydro energy storage systems are quite thoroughly researched and developed, this thesis will focus more on small scale demo systems and their functionality to demonstrate PHES system operation. The anticipated efficiency of a small scale PHES system is low, and this research endeavors to create simulation to aid estimating the possibility and limitations to create functional PHES demo system in the available area.

2 UTILIZATION OF ENERGY STORAGE SYSTEMS

2.1 Emerging Demand for Electrical Energy Storage Systems

The conventional non-renewable electricity industry utilizing fossil fuels as coal, petroleum and natural gas has had traditionally no need to store electricity, as the fuels are quite easy to handle and functional energy storages as itself. It is easy to see the superiority of those conventional fuels as an electricity source when comparing to storage difficulties of electricity generated from renewable energy sources such as solar and wind power, and it has probably played a big part why renewable electricity generation has been taken to consideration just a few decades ago. To respond to the increased demand of electricity, even nuclear power has been a more comfortable way to proceed to generate more electricity. Regardless of all the side hustle, nuclear power plants are complicated to construct and maintain, the safety has been controversial, processing radioactive waste and mining and enriching uranium is laborious process. / 1 /

The amount of alternative renewable electricity generating methods has increased as the knowledge of environmental impact of fossil fuels has grown and the general electricity consumption has increased. This has led to high demand for energy storage systems to capture and store electricity generated from solar and wind farms during off-peak hours and maintain the system stability. / 3 /

2.2 Energy Storage Systems as Utility

Energy storage systems are also a crucial part of the power system to ensure continuous energy supply and maintaining desired voltage and frequency of the grid. As the solar and wind power are capturing larger share as a load power, the demand of load following power has increased due to fluctuating characteristics of solar and wind power. Load following power can be generated from energy storage systems, which creates double purpose to the energy storage systems and demand for them. Currently hydroelectric power is utilized widely as a load following power, and the pumped hydro energy storages are most commonly used load following power generation within the energy storage systems. / 3 /

3 ENERGY STORAGE METHODS

3.1 Classification of Storage Systems

There is some discrepancy regarding the classification of energy storage systems, but generally the storage systems are categorized in mechanical, electrochemical, and electrical together with subgroups. In this research the categorization created by Fraunhofer Institute for Solar Energy Systems is mainly followed.

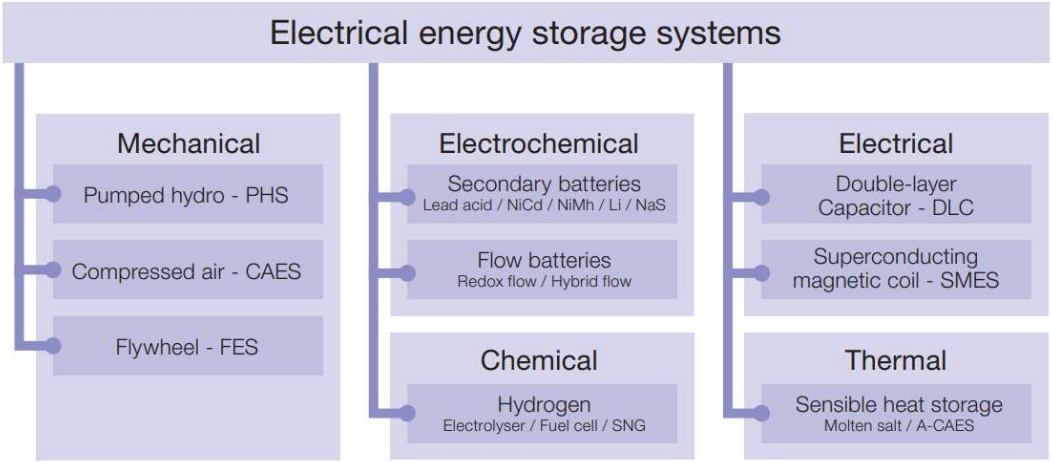

Figure 1. Electrical energy storage systems categories.

3.2 Mechanical Storage Systems

Mechanical energy storage systems utilize kinetic and potential energy for storing energy. Generally mechanical energy storage systems are most commonly used due for their simplicity and quick response time for demand. / 2 /

3.2.1 Pumped Hydroelectric Energy Storage (PHES)

Pumped hydroelectric energy storage (PHES), also pumped-storage hydroelectricity is currently most universally method to store electricity. World-widely it covers almost 95 % of all installed electrical storage capacity. The base principle of PHES is the same as that of a regular hydropower plant, water is run through a turbine from an upper reservoir to a lower reservoir, but as an addition the waterflow can be directed from the lower reservoir to the upper reservoir by pumping to store electricity. PHES's can operate as devoted only for electricity storage or as a hybrid system with compilation of regular hydropower plant. The efficiency of PHES's fluctuates in the range of 70 % to 85 %. / 3 /

3.2.2 Compressed Air Energy Storage (CAES)

Compressed air energy storages are electrical energy storage systems where high pressure air is stored to a storage tank, common utility-scale applications are deserted underground mines. Utility-scale CAES plants generate energy of stored air generally by turbines, but small-scale or demo systems can utilize also air motors (pneumatic motor). The efficiency of air motors is considered very poor, but the efficiency is also weak point even for utility-scale CAES plants. CAES plants can be run also as a hybrid system with combustion gas turbines by using compressed air as an air mixture for gas engine. / 3 /

3.2.3 Flywheel Energy Storage (FES)

A flywheel energy storage system stores energy to a flywheel by using an electric motor. The flywheel motor is a reversible component that can be utilized during storing the energy, and when generating electricity from the flywheel. The strengths of FES are high storage density and good efficiency, even though the efficiency can decrease massively during long idle periods. / 2 /

3.3 Electrochemical Storage Systems

Electrochemical storage systems are battery systems, whose simplified principle is to store electricity in electrochemical energy and produce electricity from electrochemical reaction. Batteries are widely used in small-scale technology and devices, but they are getting prevailing technology due to electrification of vehicle market. Advanced development of batteries has increased the relevance of electrochemical storing systems also in large-scale operations. / 2 /

3.3.1 Secondary Battery

Secondary batteries are rechargeable batteries that store electricity in electrochemical cells. Secondary batteries are most conventional battery technology and generally used types are lead-acid, nickel cadmium, nickel hydride, sodium sulfur and lithium ion batteries. Secondary battery systems are capable to absorb and release energy rapidly and have great efficiency. But they can lose their effectivity during time and operation cycles, and long-term storing can cause loss of charge. / 4 /

3.3.2 Flow Battery

Flow battery systems use one positive and one negative tank of electrolyte liquid separated by a membrane to store energy. Liquid form of electrolyte enables potential to “refuel” the battery system by replacing the discharged electrolyte. The weakness of flow battery systems is low energy density, which has prevented the further utilization in the vehicles. Regardless of the low energy density of flow battery, there is prominent potential for utility-scale systems, as the scalability of flow battery systems can be achieved by simply increasing the size of electrolyte tanks, also the life cycle of flow battery systems is greater than conventional secondary battery systems. / 3 /

3.4 Electrical Storage Systems

Electrical storage systems are devices that utilizes electrical fields, magnetic fields and static charge to capture electricity. Currently these systems are considered as a short-term electricity storages and voltage compensation devices, but they are also researched and developed further to apply for energy storage systems. / 3 /

3.4.1 Superconducting Magnetic Energy Storage (SMES)

Superconducting magnetic energy storage systems utilize a superconducting coil to create a magnetic field and store energy in it. SMES systems have quick response time and great efficiency, but an issue in long-term energy storing is the dependence of superconducting coil on a refrigeration system to keep it in a superconducting temperature state. / 3 /

3.4.2 Supercapacitors

A supercapacitor, also known as a double-layer capacitor, has two electrolytes and two conductor electrodes between which the energy is stored as a static charge. Supercapacitors have improved capacitance over traditional capacitors, which enables increased energy storage potential. Despite the possibility to store more energy in supercapacitors, the energy density is still considered poor, and they are not suitable as long-term storages because of their high self-discharge rate. / 2 /

3.5 Thermochemical

Thermochemical energy storage (TCS) is approach to store thermal energy by reversible endothermic chemical reaction as chemical potential or adsorption in sorption systems. The main product of the thermochemical reaction is hydrogen fuel, that has a great potential in vehicle applications. / 2 /

3.5.1 Chemical Reactions

In the thermochemical storage process, the thermal energy is converted as chemical bonds by reaction, and later it can be released as an energy by reversed reaction, when the energy demand arises. Thermochemical energy storage systems offer a higher energy density compared to conventional latent- and sensible-heat storage methods, because the thermal energy is stored as chemical potential and heat. Chemical energy conversion is also generally a more efficient method compared to conventional heat storages. / 6 /

3.5.2 Sorption Systems

Sorption systems utilize adsorption or absorption depending of the used materials. The sorption method capitalizes adsorption to bind a gas or liquid on porous surfaces. Desorption is a process to store heat in the conservation material, and adsorption used to discharge the heat from the storage. / 7 /

3.6 Chemical

Primary methods of chemical energy storages are hydrogen and synthetic natural gas (SNG) as secondary energy carriers. Chemical energy storage has a huge potential as a scalable energy storage method for great amounts of energy. Hydrogen and SNG does not achieve the efficiency of Li-ion or PHES, but the option to store energy for long periods of time and usability in a wide variety of sectors does increase the interest in chemical energy storage methods. / 3 /

Hydrogen can be produced by water electrolysis by using electricity generated for example during off-peak hours to increase the efficiency of the system. The process to create hydrogen is to split water to hydrogen and oxygen by using an electrolyzer. Hydrogen is an attractive option due to its usability as an energy carrier because it can be utilized in transport, mobility, heating and chemical industry. / 3 /

3.7 Thermal

Thermal storages are applications to store usually waste heat for further use. The stored heat can be transferred in water or different fluids, concrete or in the ground. Thermal energy is most commonly utilized as in district heating to heat residences or in industrial applications, stored heat can be also used to generate electricity. Thermochemical storage systems discussed earlier can also be considered as a thermal energy storage system. Latent heat and sensible heat are considered as a more conventional thermal energy storage method. / 3 /

A sensible heat storage can be determined as a most pure and direct way to store energy, the heat is conducted into the heat storage material (liquid or solid). The sensible heat storage requires a large volume of stored energy to remain efficient. Latent heat uses phase change materials to store energy, the energy is stored in same temperature but in different phase. The lack or minimal temperature change is focal point of latent heat storage systems efficient heat transfer. / 3 /

4 PUMPED HYDRO ENERGY STORAGE (PHES)

4.1 Introduction and Theoretical Background of PHES

The pumped hydro energy storage system, also known as pumped-hydroelectric energy system, is one of the oldest and most capitalized methods to store energy and there is still potential sites available to the PHES systems. Australian National University has identified a great amount of feasible PHES sites, that could store approximately one hundred times more electricity what global completely renewable electricity system would require **(Figure 2).** PHES systems are based on the same operating principles as conventional hydropower plants; water is stored in an upper reservoir as a gravitational potential energy and transformed to electricity by running water downhill to a lower reservoir through a turbine. In the PHES system this same operation can be reversed to store energy, which is beneficial feature during low electricity demand periods. The usefulness of this process is to offer utility to gather energy otherwise wasted and store it as a potential energy. / 5 /

Figure 2. Potential available sites for PHES systems. / 17 /

The contribution of PHES as a utility for the electrical grids is crucial, because PHES systems are utilized to increase overall efficiency of the grid, work as a load-following power plant, adjust voltage and frequency to maintain power quality and function as a makeshift power plant in case of emergency or shortages. PHES systems are globally dominant utility in each field of grid utility functions. PHES plant scales range widely between 1 MW to over 3000 MW systems, while the round-trip efficiency remains in range of 70-85 %. The Francis turbine offering efficiency higher than 90 % has remained the most used turbine model in PHES systems due to its capability to operate as both pump and turbine. The capacity of energy storage is dependent on the volume of the upper reservoir and the altitude difference (head).

In theory, reservoirs can have distance between them but the longer pipe would decrease the efficiency of the system due to the friction losses of the pipe. Due to these friction losses in addition to the higher construction costs of building longer pipeline, the PHES systems are conventionally located in steep slopes to create only vertical distance between reservoirs. Most of the losses decreasing the efficiency of the system are from the turbine and the generator, and the friction losses of piping as cited earlier. The PHES systems round-trip efficiency is:

$\eta = \eta_c * \eta_d$, where (1)

η_c = Charging Efficiency
η_d = Discharging Efficiency

/ 5 /

4.2 PHES Technologies

Pumped hydro energy storage systems utilize all the same principles, two reservoirs located in different heights, a turbine to generate electricity from water flow and a pump to pump water back in upper reservoir, or a pump turbine to proceed with both operations. Regardless of the simplified operation of pumped hydro energy storage systems there are several variations to utilize this technology in variable conditions and geological locations. / 2 /

4.2.1 Hydroelectric Dams

Pumped hydroelectric dams are by far the most conventional technology in pumped hydro energy storage systems. The pumped hydroelectric dams resemble regular hydropower plants and they can originally be hydropower plants converted to the pumped hydro storage plants. Pumped hydro energy storages might operate as a hybrid system with regular hydropower plant. / 8 /

4.2.2 Seawater

Using sea as a lower reservoir is fairly unresearched option for PHES systems, but there have been some experiments in reasonable sized projects (30-300 MW). The pumped hydro energy storage system could utilize high and low tide to increase the efficiency of the system, but the issue of the application would be the lack of the suitable locations, and quite undetectable height differences in relation to the full head height. Concern would be also the salt concentration of sea water, that could be harmful for the components and decrease the maintenance intervals or the life cycle of the system. / 10 /

4.2.3 Underground Reservoirs

Underground reservoirs function as regular PHES systems, but the lower reservoir is located underground, potentially in abandoned mines. Underground reservoirs could offer PHES technology for otherwise unusable locations without required height difference. Underground pumped hydro storage systems could apply otherwise useless abandoned mines, but the construction of dedicated new underground pumped hydro storage system would be an expensive project. / 11 /

4.2.4 Stored Energy at Sea

The possibilities of offshore PHES systems are currently researched fractionally, but there would lie potential to use the depth of sea as a head of the system. The system would utilize a hollow sphere as a lower reservoir on the seabed, and during excessive electricity production, the pump turbine would work against water pressure of the sea to create cavity. When the electricity demand is increasing the empty sphere would be filled by seawater flowing through turbine. / 12 /

4.3 Main Components of PHES System

4.3.1 Reservoirs

The reservoirs represent the storage of the PHES system, a full upper reservoir would symbolize a fully charged battery as a potential energy. This potential energy could be converted to electricity by releasing the potential energy of upper reservoir through the turbine to the lower reservoir. The operation cycle of the PHES system is readily realized by the simplified picture of the PHES system. **(Figure 3)**

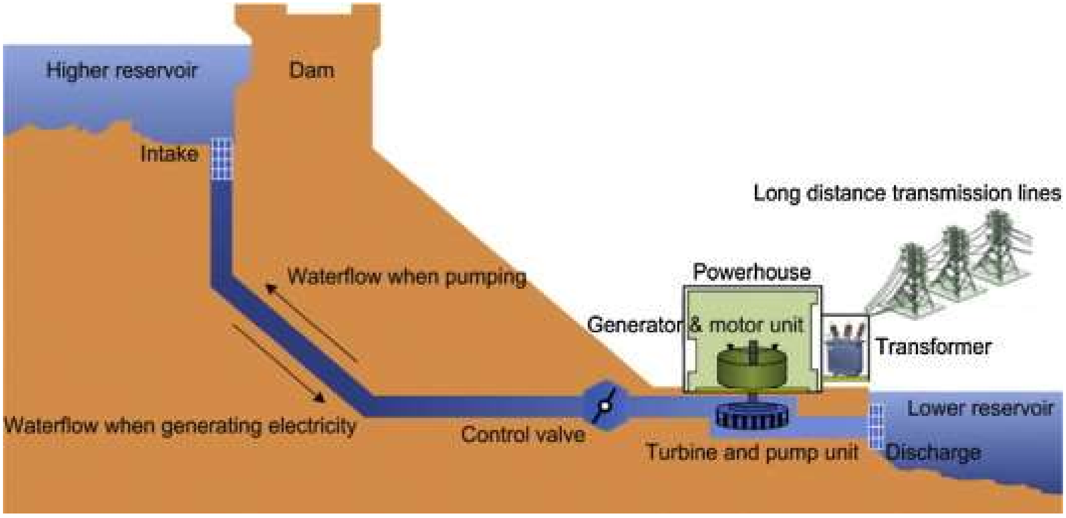

Figure 3. PHES system. / 2 /

The amount of energy a PHES system is capable to store is dependent on the height difference of the reservoirs, the term for this height difference is called “head”, and the volume of the upper reservoir. Naturally the lower reservoir must be at least as large as the upper reservoir to be able to capture the water mass. The stored energy or the capacity of reservoir can be calculated from the following formula:

$U = \rho V g H \eta$, where (2)

U = Potential Energy
ρ = Density of Water
V = Volume of The Water
g = Gravitation
H = Height Difference of Reservoirs (Head)
η = Efficiency of the system

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4.3.2 Turbines and Generating

Turbines, pumps, gearing and generator are generally the main source affecting the efficiency, and therefore the selection of these components is crucial in PHES systems. Theoretically, the higher the head the higher the power output but the capability of the turbine to generate electricity would decrease the benefit gained in massive height differences. The high head can also affect the usability of the turbine in the pumping process; this would create a requirement for separate turbines and pumps, which would increase the investment and maintenance cost. The efficiency of the turbine is also dependent of the rated power. Generally, the efficiency of the turbine is higher when the turbine is operating near its rated maximum power. **(Figure 4)**

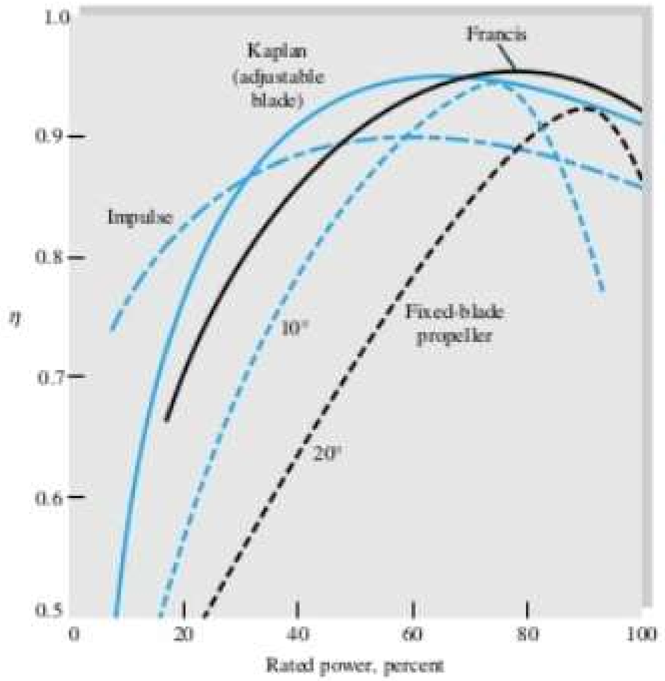

Figure 4. Efficiencies of turbine designs in proportion to rated power. / 14 /

The Francis and Deriaz turbines have been popular in PHES systems due to their ability to handle both processes in the system. These pump turbines might not achieve the efficiency of dedicated one-way turbines, but the efficiency of best pump turbines is over 90 %, which is usually good enough trade off to acquire only one pump turbine that can work on both ways. Visualized operating ranges of turbines demonstrates why the Francis turbine is appreciated in PHES systems. **(Figure 5)**

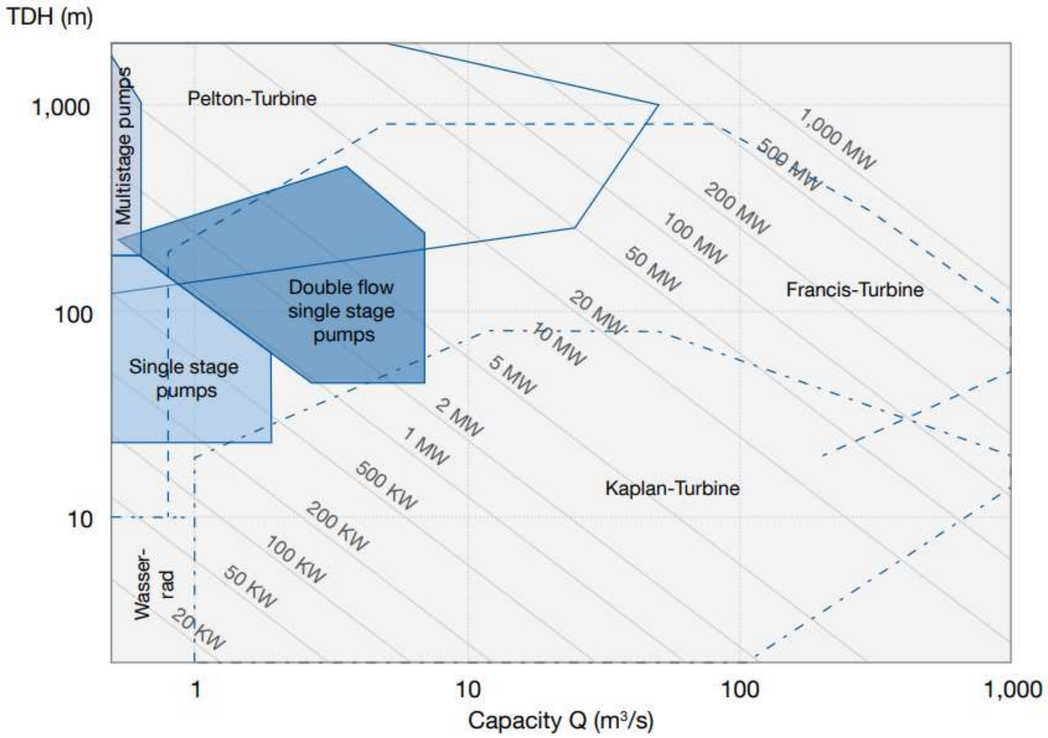

Figure 5. Operating ranges of turbines, pump turbines and pumps running in turbine mode. Total differential head (TDH), volumetric flow rate (Capacity Q). / 15 /

Francis turbines are the most common solution in PHES systems. Due to its quite simple fixed design and ability to operate in both directions it is considered as a high cost-effective compromise. Although the blades of the Francis turbine are fixed, the guide vanes are adjustable to meet the fluctuating demand of the grid. **(Figure 6)**

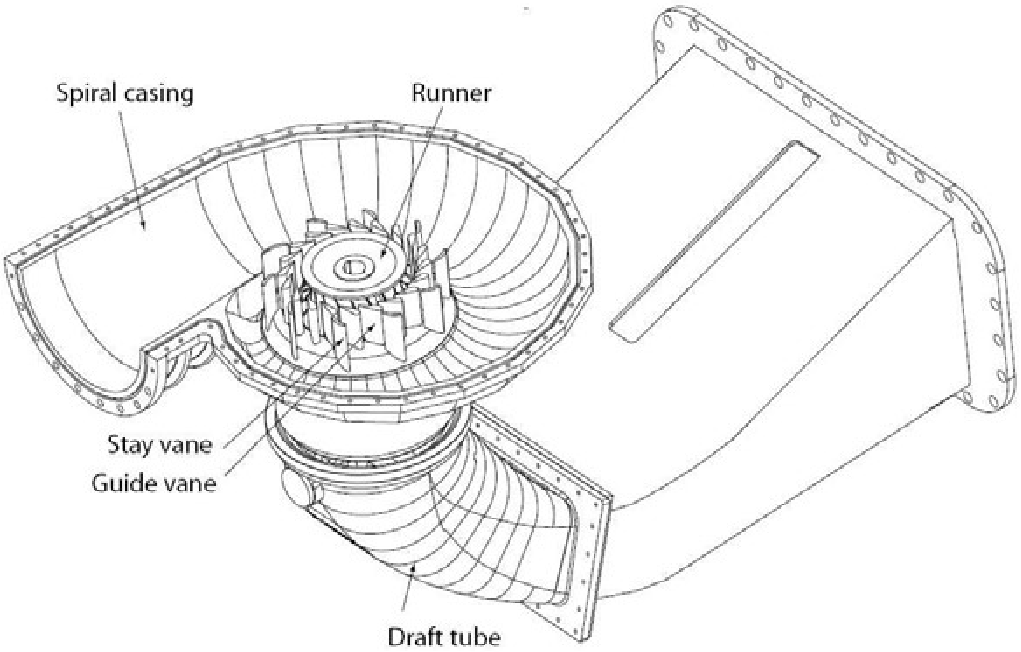

Figure 6. The layout of the Francis turbine. / 13 /

Deriaz is similar in design to the Francis turbine but its blades could be adjusted to optimize both generating and pumping. The adjustability of the blades increases the efficiency of the Deriaz turbine but with the complexity of design comes the higher cost. The Deriaz turbine is also widely utilized in PHES systems, but Francis has remained the most popular option due its cost effectivity.

The Kaplan turbine has adjustable blades similarly to Deriaz turbine, but Kaplan turbines blades are deigned to maintain high efficiency in low head heights. The design of the Kaplan turbine applies a large water entry area, which makes Kaplan turbines desirable in application where huge volumes of water flow through. Kaplan turbines are a general choice for low head systems.

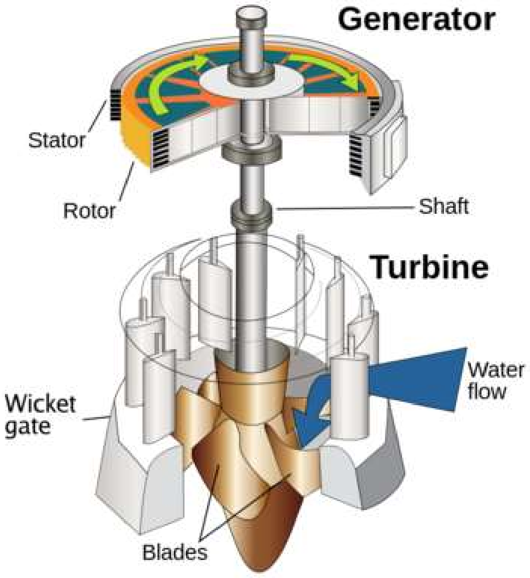

Figure 7. The design of the Kaplan turbine.

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5 SYSTEM LEVEL DESIGN

5.1 Location

The location planned for the PHES demo is in an energy laboratory or construction laboratory space in Technobothnia. The energy laboratory is the primary location for the demo, because it would simplify the education from the standpoint of laboratory assignment supervisor. The secondary option would be the construction laboratory space to offer higher head to the demo system if the height difference of the primary location was considered too shallow.

The energy laboratory room has a sloping roof, whose highest point is 7,1 m and lowest 4,3 m. The sloping roof disables the possibility to utilize the full height of the room, if the container is required to keep level for example to enable the ability to effortlessly measure the volume of the higher container. The smaller sized container would apply the possibility to better utilize the full height of the room. The utilization of stacker truck was considered, but lift height is not enough even in the energy laboratory area.

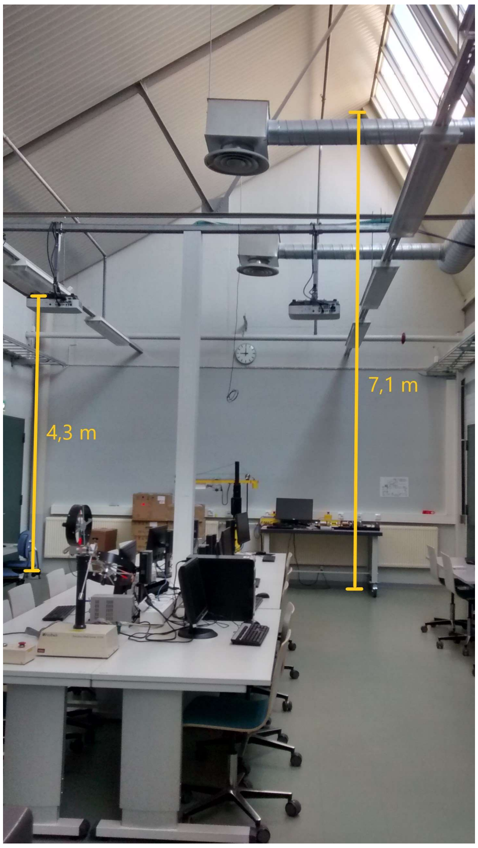

Figure 8. Energy laboratory area in the Technobothnia.

The construction laboratory offers much higher roof clearing, but it would be a more complicated location for the demo because it is separated from the energy laboratory area. The separated location would hamper the supervision of the laboratory assignments. The construction laboratory space has a similarly sloped roof as the energy laboratory room, the highest clearing being 11,8 m and lowest point of the roof being 8,18 m. The construction laboratory has also an overhead crane which might be problematic for piping of the demo system, which enables the maximum clearing from floor to beam below overhead crane of 7,15 m. The overhead crane could be still probably bypassed by the gap between the crane and laboratory wall.

5.2 Layout

The demo system would follow the design of a full sized functional pumped hydroelectric system, including upper reservoir, lower reservoir, pump turbine and measuring devices. The requirements of PHES demo is to offer a suitable time frame for operation to enable monitoring and measuring of the process. The acceptable time frame of system operation would be from approximately one minute to several minutes. The system operation time of one cycle should provide sufficient duration for monitoring of the process, consequently the duration of several seconds is not suitable for proper monitoring of the process flow. On the other hand, the duration of process could not be too extended, regarding the limited time available for the laboratory assignments. The operation cycle time could be adjusted by the volumetric flow rate of the turbine and pump, while taking the suitable container size to consideration.

Generally full sized functional PHES systems utilize a pump turbine to perform both the generation of electricity and loading the upper reservoir. The utilization of only single component to perform both actions offers significant savings in both investment and maintenance expenses, but suitable pump turbines are hard to come by for a small-scale laboratory scale demo system, which might inflict the requirement for two separate components as pump and turbine, because they are more likely available. In addition, the cost difference of separate components to both way operating pump turbine in a laboratory scale system is not as significant as it would be in an industrial scale system. This does not inhibit the base functionality of the PHES demo, since the separate pumps and turbines are also utilized in some functional utility scale PHES systems. The installation of pump and turbine would be executed in parallel.

5.3 Piping and Instrumentation Diagram

Piping and instrumentation diagram was created to delineate required instruments and the layout of the PHES demo. Two slightly different P&I diagrams were created to indicate both potential layouts of the PHES demo, parallel and multi proportional pump turbine setup. A3 templates of P&I diagrams are available as an appendixes. **(APPENDIX 1, APPENDIX 2)**

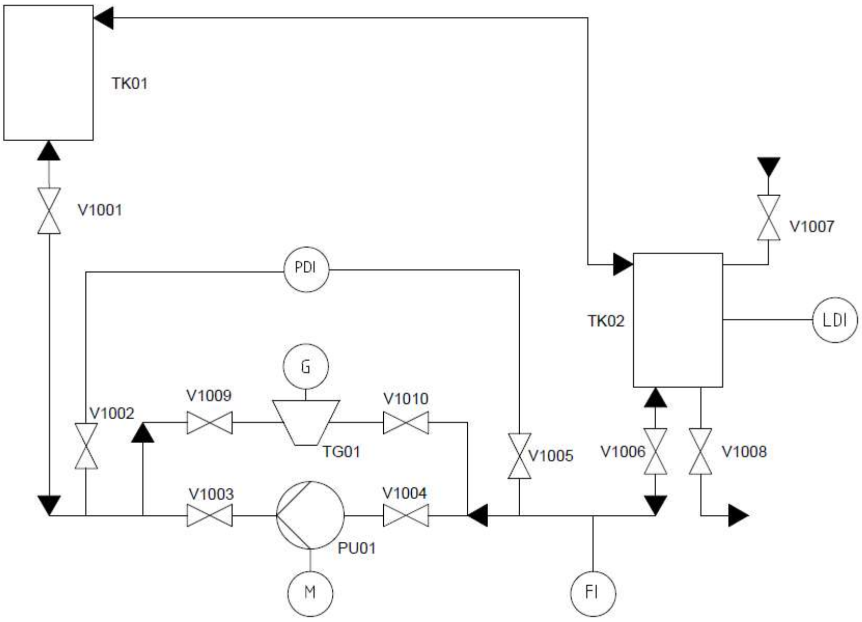

Figure 9. Piping and instrumentation diagram of parallel installation of PHES system.

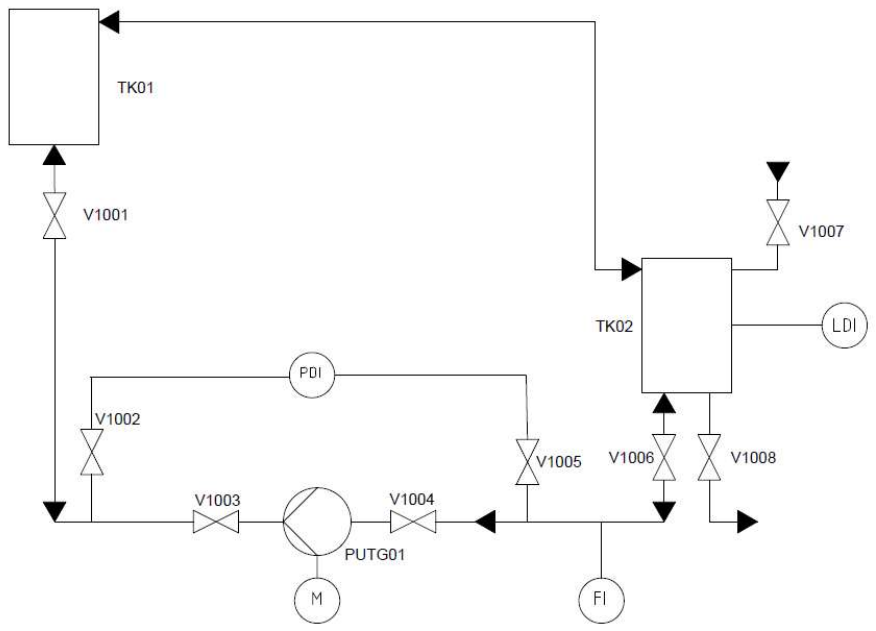

Figure 10. Piping and instrumentation diagram of multi proportional pump turbine PHES system.

The list of abbreviations in P&I diagram:

FI	Flow Indicator
G	Generator
LDI	Level Difference Indicator
M	Electric Motor
PDI	Pressure Difference Indicator
PU	Pump
PUTG	Pump Turbine
TG	Turbine
TK	Tank
V	Valve

The P&I diagram includes all the components of the PHES system mentioned earlier but has also more specified measurement instruments and more precise locations of the different components within the system. The system is basically point to point process between two tanks and in addition excess pressure pipe connected between the tanks. The measurement instruments include pressure difference indicator (PID) located on both sides of generating and pumping equipment, flow indicator (FI) after the turbine to indicate flow out, and level difference indicator (LDI) in lower tank to indicate the head. Only one LDI is required if both tanks are similar. The base operation process described in the P&I diagram remains unchanged, except the parallel system utilizes two separate components as a turbine and pump. Component list of P&I diagram is located in appendixes. **(APPENDIX 4)**

6 MODELLING AND SIMULATION

6.1 Simulink Simulation

A Matlab Simulink simulation was created to model the flow of the small-scale hydropower plant demo to assess the effect of several variables and to help to size the components suitable for the setup. This model does not include the pumping section of the PHES system. By this model the size of the components and piping could be assessed, and the length of full generating cycle process could be estimated with various setups. **(APPENDIX 3)**

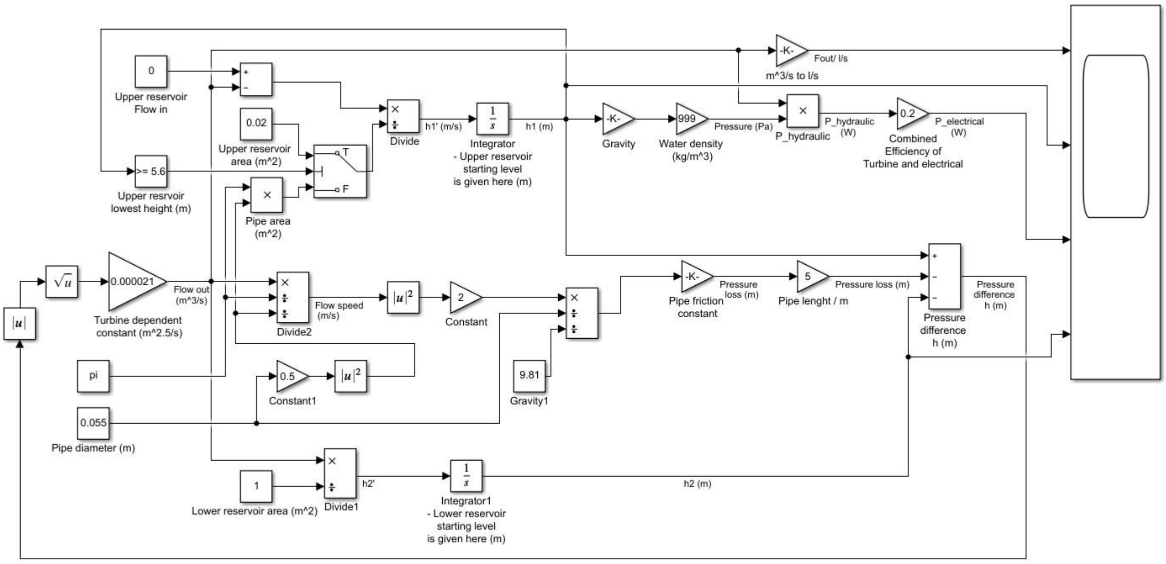

Figure 11. Simulink template breakdown.

6.2 The Head of Simulation and Variables

The most basic variable in the simulation is the starting height difference, which can be basically applied by indicating the water surface levels in both the lower and upper reservoir. Both heights can be modified individually, and the difference of selected heights would be the head of the system. The lowest height of the upper reservoir indicates the floor height of the container, the difference of the upper reservoir starting level and upper reservoir lowest height is the height of the container, if the container is considered being full at the selected starting level.

The surface area of both reservoirs could be modified, and it has also an effect on the head height of the demo system. The head could be increased by choosing as wide as possible a lower reservoir, and narrow bottom surface to the upper reservoir to raise the water surface level, but decreasing the bottom surface area of the upper reservoir would cause a rapid decrease of the surface level and the pressure level. In this PHES demo, the smaller size of upper reservoir would be beneficial to facilitate utilizing the full available height in the Technobothnia laboratory area.

6.3 Generation Efficiency and Turbine

Hydraulic power is the wattage of the system at the chosen time, and it is multiplied by the constant that indicates the combined efficiency of the turbine and electrical machine. This constant is adjustable to address assumed efficiency of the system.

Turbine dependent constant is variable dependent on the attributes of the turbine. The turbine dependent constant form is presented as $m^{2,5}/s$, and it can be determined by volumetric flow rate and water pressure indicated as height. The crude characteristic of model does apply the possibility to use simplified formula to determine the turbine dependent constant when the blades of the turbine is assumed to be fixed:

$$C = \frac{q_V}{\sqrt{H}}, \text{ where} \qquad (3)$$

C = Turbine dependent constant
q_V = Volumetric Flow Rate
H = Water Pressure as Height

6.4 Pipes and Pressure-losses

Pipes can be determined by applying pipe diameter, length, area and friction constant. These values affect the behavior of the simulation after the upper reservoir is empty and the pressure-losses within the pipeline. In this Simulink simulation the pressure-losses is calculated by the Darcy-Weisbach equation in terms of head loss.

$$S = \lambda l \frac{2v^2}{Dg}, \text{ where} \qquad (4)$$

S = Pressure Loss
λ = Pipe Friction Constant
l = Pipe Length
v = Flow Velocity
D = Pipe Diameter
g = Gravity

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6.5 Condition of the Upper Reservoir

A switch is used to determine when the upper reservoir is empty and there is water left only in the pipelines of the system. When the switch indicates that the upper reservoir empty condition has been reached, the simulation begins to use values of the pipes to calculate the water surface level. Basically, the switch changes the upper reservoir floor area used to calculate the upper reservoir surface level to cross-sectional area of given pipe.

6.6 Measurement Instruments of the Simulation

Monitored values in this simulation are flow out (l/s), electrical power (W) and surface level heights of both reservoirs (m). The current head can be determined by the difference of the surface levels in the reservoir.

6.7 Simulation Results and Analyzing

In this simulation selected conditions were as follows, the upper reservoir starting surface level was set to 6,6 m to cover the height of the energy laboratory room. The lowest height of the upper reservoir was set to 5,6 m, which indicates that the container height is 1 m and after that the pipe values are used in the simulation calculations. The lower reservoir starting surface level was set to 0,3 m. The upper reservoir area was 0,02 m^2, which makes 20 l to potential volume of the system in this simulation scenario. The combined assumed efficiency of turbine and electrical machinery was set 0,2 (20 %). The used pipe diameter was 0,055 m and the used turbine values of the simulation were values of the small scale 12 V DC water turbine. The turbine dependent constant was calculated from the turbines operating range graph:

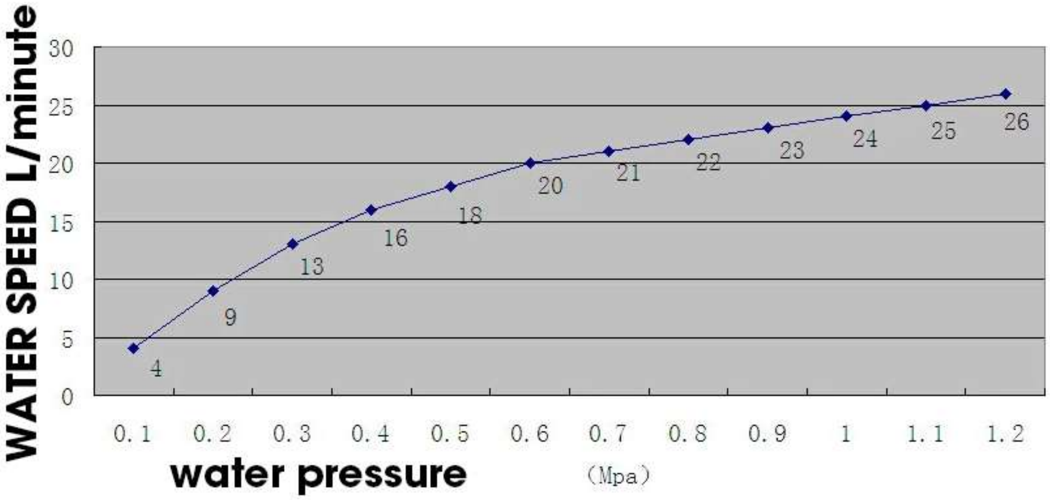

Figure 12. DC 12 V water turbine operating graph.

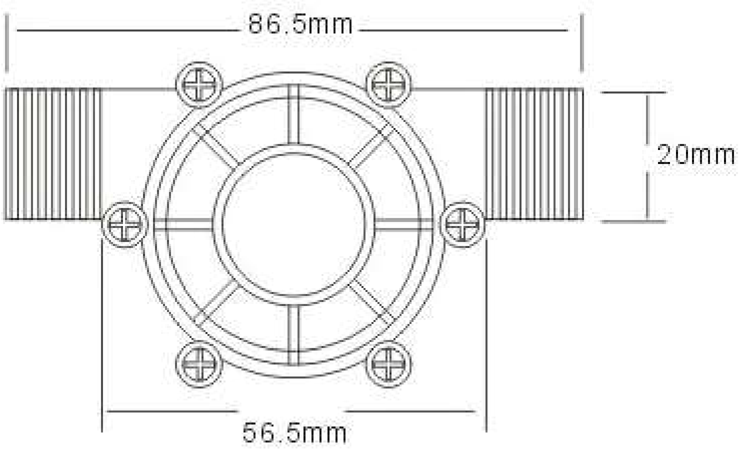

Figure 13. DC 12 V water turbine.

The turbine dependent constant was defined by selecting the nearest point from the turbine graph to the available height of the laboratory area, in this case the point 4 l/minute was chosen with water pressure of 0,1 Mpa. The water flow speed was converted to m^3/s, and the water pressure was converted to pressure lift height. With these values the turbine dependent constant 0,000021 was calculated using the earlier given formula (3).

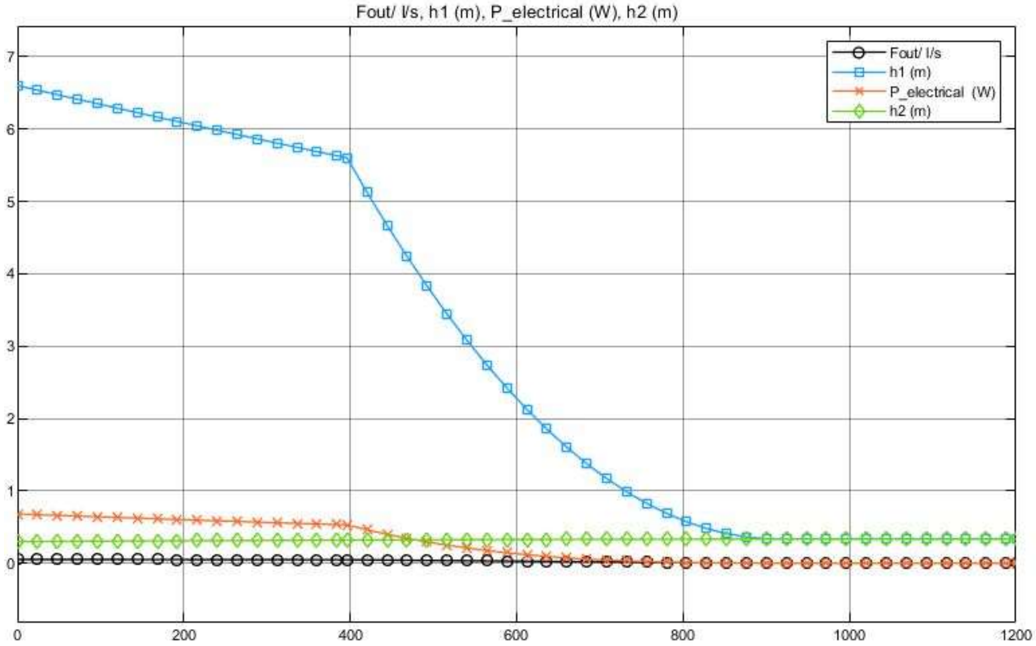

Figure 14. Simulation with 6,6 m head, duration 20 minutes.

The graph **(Figure 14)** shows the decrease of the upper surface level, and the upper reservoir empty condition reached in 400 second, the rapid decrease of the head simulates the dropping surface level in the pipeline. The lower reservoir base area was chosen to 1 m^2 in this simulation, which causes the slow climb of the lower reservoir surface level. The simulation is over when the blue and green lines meet, meaning the surface levels are even and the head is 0 m. If the base areas of both reservoirs were coherent, the change speed of the surface levels would have been identical until the upper reservoir is empty. Wattage is well below 1 even in the starting condition, the generated electricity would be enough to light a small LED pulp to visualize the electricity generation. This simulation demonstrates the importance of high head to create enough pressure to generate electricity and the volume of the reservoirs to maintain high head. In real world applications the upper reservoirs are probably never fully emptied, because the rapid decrease of the head minimizes the electricity from generating.

The second graph **(Figure 15)** is simulation with the same values as the previous, except the head height was changed to 11,4 m, to demonstrate the available maximum head of the construction laboratory. The results are quite similar as in the first graph, but the generated electricity is higher in relation to the head increase. This underlines that the efficiency is more appealing in higher pressure levels.

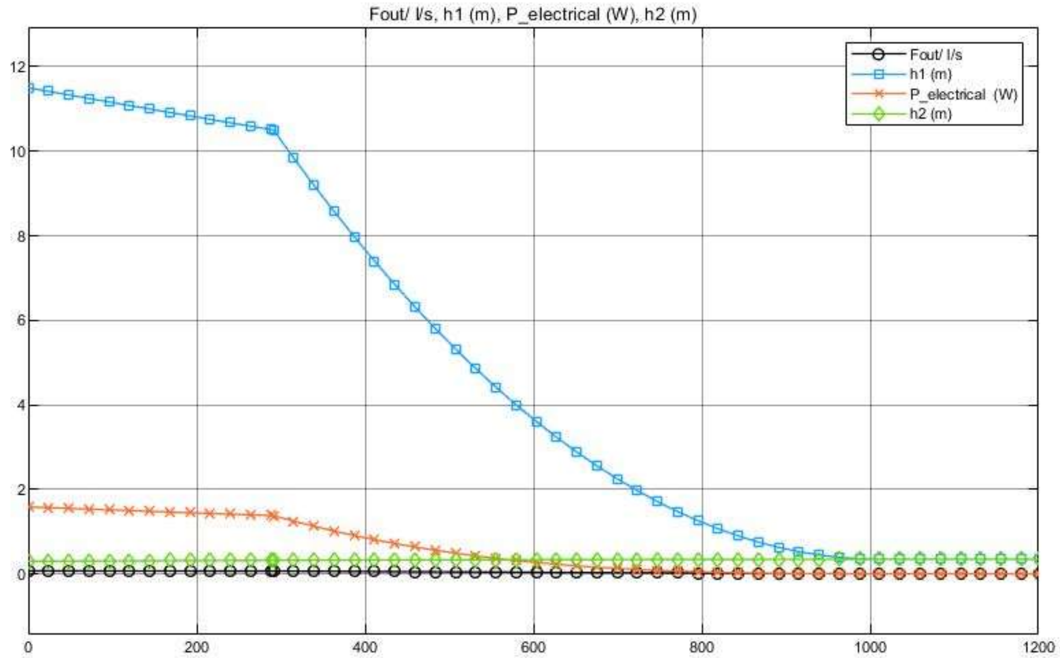

Figure 15. Simulation with 11,4 m head, duration 20 minutes.

7 CONCLUSIONS

The objective of the research was to gain information regarding pumped hydro energy storage systems and create a plan and schematics for a demo scale pumped hydro energy storage system. The aim was also to evaluate the functionality and feasibility of the implementation possibilities of the PHES demo.

The theoretical section of the thesis creates a compilation of available energy storage methods and presents different PHES technologies, after main characteristics and features of all methods were assessed. Towards the end of the theoretical part, the focus is paid on conventional PHES systems and in the most generally used turbines in PHES applications. The comparison of different turbine designs is not valid regarding the PHES demo planning because the characteristics of different turbine types are irrelevant or does not apply in a small-scale system. However, the review of the turbines is valuable regarding the creation of the theoretical section of PHES systems.

The system level design covers the creation of the piping and instrumentation diagram and the assessment of PHES demo implementation in the Technobothnia area. In quite early stage of the system level design it unraveled, that the multi proportional pump turbine might not be available for such a small-scale application. This presumption taken into consideration two P&I diagrams were created, one for multi proportional pump turbine, and another for parallel installation of a separate pump and turbine. The created P&I diagrams served as a system level design schematics but the creation of P&I diagrams was also advisable method to design the system layout.

The creation of Simulink simulation revealed the functions and proportion within the components of the PHES system and it helped to perceive the main variables and their consequences. The Simulink simulation exposed the importance of head height in PHES systems and the difficulties to create a functional small scale PHES demo due to lack of the available components. The required components under such a low pressure are so small, that they are extremely hard to find. This does not exclude the creation of the PHES demo, but the wattage levels and the efficiency would be small. The simulation duration with single small turbine used in the simulation was approximately 15 minutes with 20 liter tank. The length of the duration does apply possibility to utilize several similar turbines connected in parallel to decrease the operation cycle time and increase the flow rate and generated wattage. An interesting application in future researches would be the utilization of pump to simulate the pressure in low head areas. This would apply the adjustability of the "surface" level in the simulation but this would require the creation of a control model to simulate the pressure height reliably.

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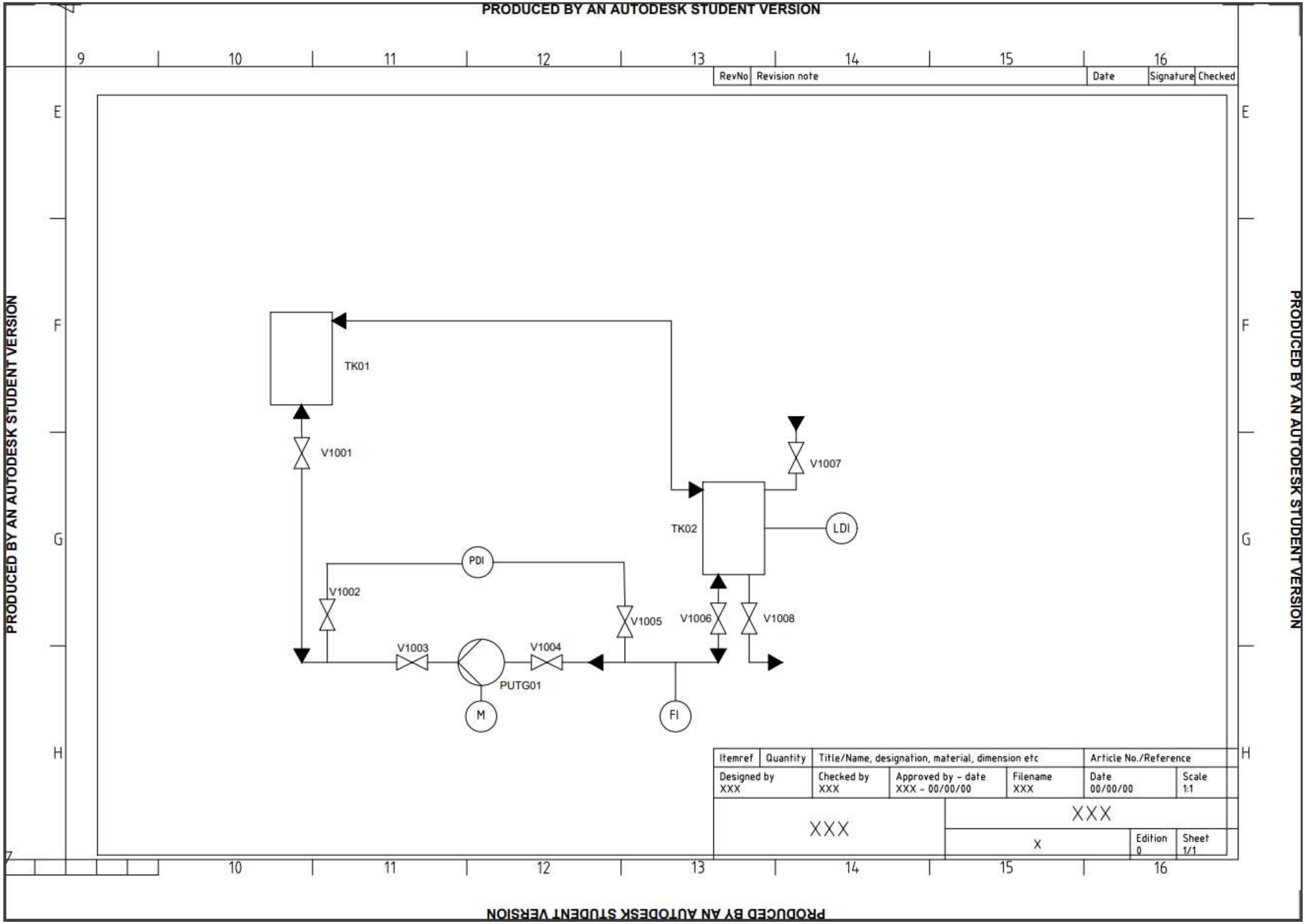
APPENDIX 1


TK01
V1001
V1002
PDI
V1003
V1004
PUTG01
M
V1005
FI
TK02
V1006
V1008
V1007
LDI
RevNo
Revision note
Date
Signature
Checked
Itemref
Quantity
Title/Name, designation, material, dimension etc
Article No./Reference
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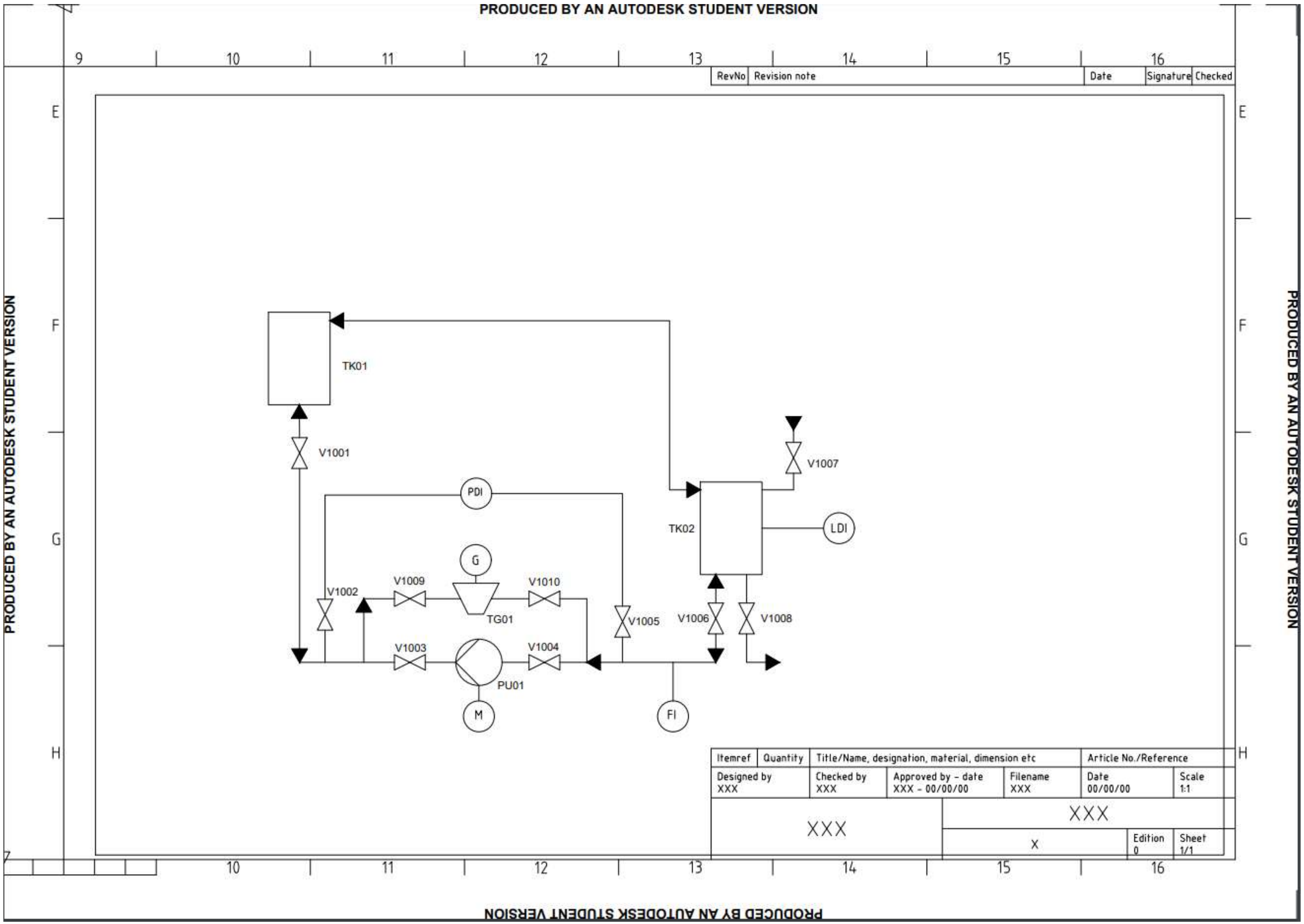
TK01
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PDI
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V1005
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PU01
V1004
M
FI
TK02
V1007
LDI
V1006
V1008
RevNo
Revision note
Date
Signature
Checked
Itemref
Quantity
Title/Name, designation, material, dimension etc
Article No./Reference
Designed by
XXX
Checked by
XXX
Approved by - date
XXX - 00/00/00
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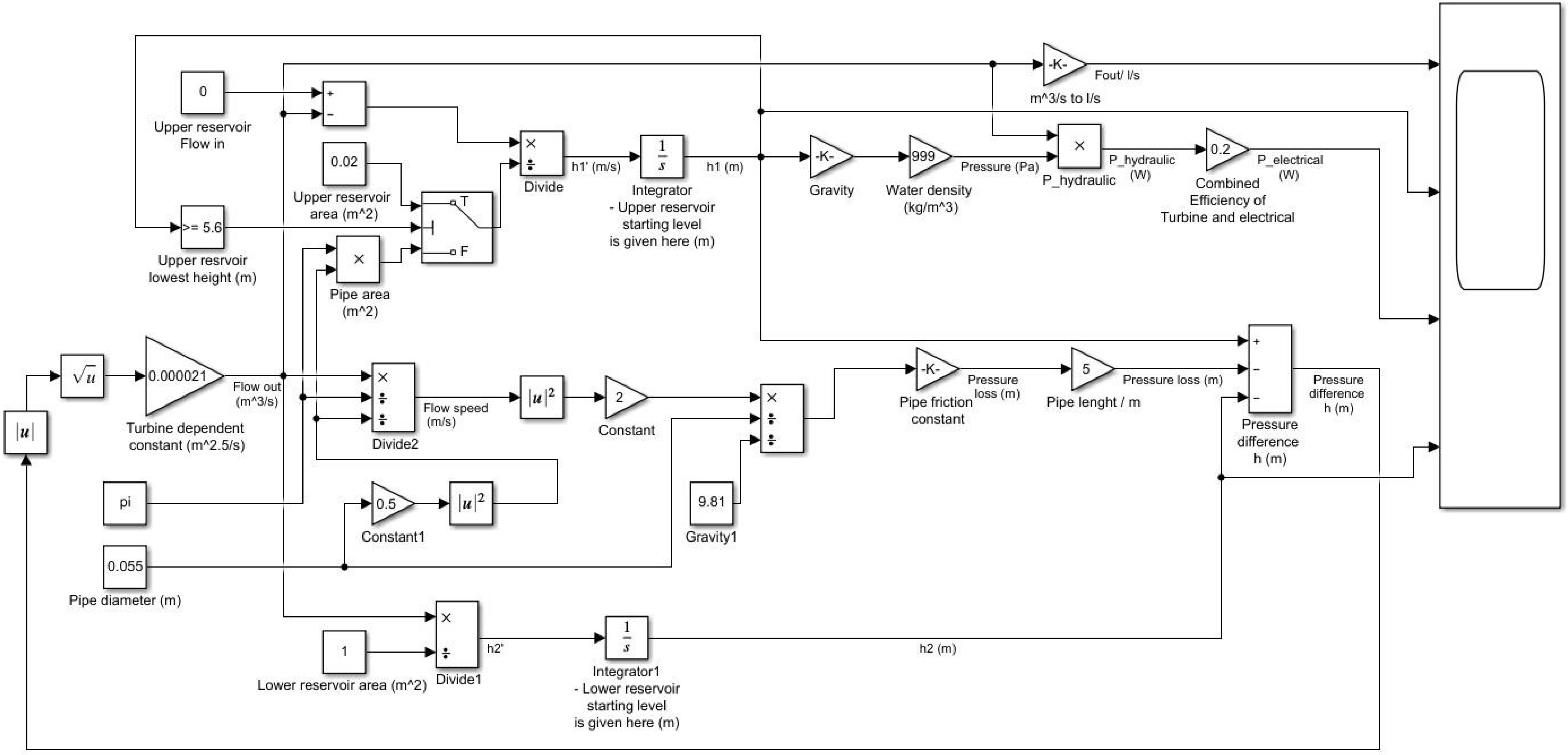
0
Upper reservoir Flow in
+
-
-K-
Fout/ l/s
m^3/s to l/s
0.02
Upper reservoir area (m^2)
×
÷
Divide
h1' (m/s)
1/s
Integrator - Upper reservoir starting level is given here (m)
h1 (m)
-K-
Gravity
999
Water density (kg/m^3)
Pressure (Pa)
×
P_hydraulic
P_hydraulic (W)
0.2
Combined Efficiency of Turbine and electrical
P_electrical (W)
T
F
>= 5.6
Upper resrvoir lowest height (m)
×
Pipe area (m^2)
|u|
√u
0.000021
Turbine dependent constant (m^2.5/s)
Flow out (m^3/s)
×
÷
÷
Divide2
Flow speed (m/s)
|u|^2
2
Constant
×
÷
÷
-K-
Pipe friction constant
Pressure loss (m)
5
Pipe lenght / m
Pressure loss (m)
+
-
-
Pressure difference h (m)
Pressure difference h (m)
pi
0.5
Constant1
|u|^2
9.81
Gravity1
0.055
Pipe diameter (m)
×
÷
1
Lower reservoir area (m^2)
Divide1
h2'
1/s
Integrator1 - Lower reservoir starting level is given here (m)
h2 (m)

APPENDIX 4

Abbreviation	**Component**
FI	Flow Indicator
LDI	Level Difference Indicator
PDI	Pressure Difference Indicator
PU01	Pump
PUTG01	Pump Turbine
TG01	Turbine
TK01	Tank
TK02	Tank
V1001	Valve
V1002	Valve
V1003	Valve
V1004	Valve
V1005	Valve
V1006	Valve
V1007	Valve
V1008	Valve
V1009	Valve
V1010	Valve