Highrise energy storage core
Feasibility study for a hydro-electrical pumped energy storage system in a tall building

A.W.Oldenmenger
September 5, 2013
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MASTER OF SCIENCE THESIS

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Faculty of Civil Engineering and Geosciences (CE&G) · Delft University of Technology
Preface

Not quietly willingly, I was responsible for the climate system in the multidisciplinary Highrise project during my masters at the TU Delft. My task was to come up with a sustainable, innovative, and integrated climate concept for a tall building that matched the design of the project. Lacking the essential knowledge needed to design the climate system, and not having a basic idea of the concept design of the building in the first weeks of the project, despair was near. Nonetheless, I tried to fulfill my task in this group project and came up with a solution that has many similarities with what turned out to be the main concept of a “Smart Grid”.

The smart grid is a current topic in many research publications but it is not directly related to the knowledge attained at the faculty of Civil Engineering. Exactly at the point where uneasy tasks meet current research topics, there turns out to be an interesting, unexploited field of subjects that is worthy of investigation.

In retrospect, I cannot think of a course during my studies that does not, to a more or lesser extent, fit to the subject of the “Highrise energy storage core”. Unfortunately, not every course is treated in this document, but some subjects that have not been part of my studies are part of this thesis.

What seemed to be an unpleasant task in a group project a year and a half ago, turned out to be an interesting research topic that I enjoyed working on and that I would like to further develop.

I would like to thank my supervisors Prof.ir R.Nijssen, Ir. R. Schippers for their assistance during this period, and also Dr.ir. A. van den Dobbelsteen for his extensive and thoughtful feedback. Thank you to the people of Imtech, for providing the motivation at the start of this project. Mariana Orozco, thank you for being there and for checking my English. I would finally also like to thank my parents for their infinite patience.

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In the long term, fossil fuels like oil and natural gas become more expensive while the price of coal slowly drops\cite{72}. At the same time the demand is likely to grow\cite{46} and the evidence for the effects of emitting carbon dioxide into the atmosphere on the climate become more and more convincing\cite{74}. The energy claim from buildings is a substantial part of the total energy demand in the world\cite{45}. To counteract future energy shortages and rising costs, it is important to use energy more efficiently. Since the building industry has an important share in the total energy consumption, it should also play a major role in its decrease.

Reducing the energy claim and the dependence on fossil fuels starts with cutting back energy waste. Increasingly stringent building requirements, the awareness of the building industry, and the development of new products already helped to reduce the gas consumption of households in the Netherlands by almost 40\%\cite{13} with respect to 1980. Secondly, the footprint of the energy source should be as small as possible. Avoiding the need of fuels by heating up a building using the sun during the winter and keeping out the heat during the summer can be done with smartly placed windows in combination with sunshades. Also, making use of renewable energy sources or industry waste helps to reduce the energy footprint. Striving for a solution that does not involve any fossil or nuclear energy at all is a nice point in the horizon, but not yet realistic for the bulk of the building projects. Therefore, new methods to deploy fossil fuels more efficiently are being researched and implemented. Nowadays, generating heat and power simultaneously is a method to use fuel more efficiently that is already often applied. These Combined Heat and Power (CHP) systems need a larger initial investment compared to single purpose systems but the investment can be recovered with the lower operational costs. Rising energy costs and cheaper CHP solutions allow even small systems to become profitable.

Generating heat and electric power at the same time is only useful when the demand of both is almost equal. In most situations, the heat demand is not likely to match the electric energy demand. For example, just before employees arrive at their office on a winter day, the heat demand is expected to be relatively high and the electric energy demand is low. When the employees start to arrive, the electric energy demand will quickly exceed the heat demand. Smart grids help to overcome or reduce this problem. A smart grid is a coupled system of one or more energy producers and suppliers that actively communicate which each other with the aim to match demands and supplies.

In current smart grid networks, Supervisory Control And Data Acquisition (SCADA)
computers actively try to match the demand with the energy production for the best results. The computer system can be enabled to control many large energy consumers like washing machines, electric car chargers and industrial processes. When the CHP-unit of an office in the smart grid starts to produce heat to warm up the office in the morning and cannot use the produced electrical energy, the main computer turns on a washing machine somewhere else in the grid or it decides to charge an electrical car battery. Besides the more or less predictable overproduction of heat or electrical energy from CHP-units, the controller also needs to allocate energy from renewable energy sources like wind and sun. The computer system monitors all demand and energy supplies and uses that information to control the energy consuming devices in the (sub)-grid.

This requires a sophisticated information network. In the long term, this might lead to untenable complex systems and unfavorable consequences. The exchange of information has an impact on the privacy of its users (“Does the energy company need to know when I do my laundry?”). It also means that a lower service level is almost unavoidable. Letting a computer decide when to charge the battery of a car will always take more time than just start to charge it right away. If boundary conditions are implemented like ‘the car needs to be fully charged at 8 AM’ or ‘the washing machine should be finished at 7 AM’, then it is not likely that the smart grid can operate to its full potential. In case the smart grid gets bigger, more potential energy buyers or suppliers can be involved, but if all buyers are saturated or suppliers are depleted, the consequences are also bigger.

When the smart grid gets extended with a sufficiently large energy storage unit, the reliability of the smart grid can be assured. The storage unit can operate as a smart agent in the system. It can buy electricity when the price is low and make the energy available to the grid when the demand heaps up and the price is high. It makes the SCADA idea superfluous, and thus solves the privacy issue.

The value of a buffer system is clear, but the most optimal solution is still being looked for. Current solutions have their advantages and disadvantages. To level out small energy fluctuations, a flywheel is an effective and durable accumulator. Large electric accumulators can be used to flatten daily demand peaks that appear during the morning and in the evening. These batteries can be placed in a local grid or at the end-user. Batteries have a limited lifetime and the components of a chemical battery are not durable. Nonetheless, some chemical battery technologies attain a high charge-discharge cycle efficiency and have a high energy density such that the required space is limited.

Peak levels can also be flattened with large-scale energy storage systems in the main grid. The Pumped-Storage Hydroelectricity (PSH) technique takes the largest share in the total electric energy storage capacity throughout the world. Surplus electricity is stored by pumping water from a lower elevation level to a higher level and released when electricity is needed in the grid. These systems are usually located in mountain areas but there have been proposals to build a large scale PSH system in the Netherlands as well (e.g. Plan Lievense[84] and O-PAC Graethide[62]). The storage plants can have a gigantic capacity and are efficient, but require a robust and expensive energy transportation network and the transportation through the power lines comes with losses.

For end users in The Netherlands which also produce energy, it is expensive to ’store’ electricity in the main grid since the revenues of selling energy to the grid are lower than it costs to buy the same amount of energy from the grid. Unlike in Germany, there is not
only a technical reason to prefer local energy storage, but there is also a financial incentive to store energy locally.

The Highrise Energy Storage Core (HESC) as being researched in this thesis is a PSH that stores electrical- and thermal energy close to the end-users inside a tall building. The specific benefits and characteristics of this system will be discussed and are compared with currently available systems. The aim of this thesis is to investigate the technical- and economical feasibility of a Pumped-Storage Hydroelectricity (PSH) -system inside a highrise building.
Chapter 1

The transition to smart grids

1-1 A new 'technoeconomic' paradigm

Long-term economic growth follows a path with major discontinuities. In the 1920's, the Russian economist Nikolai Kondratieff tried to find the causes and the course of the interruptions in the growth of the capitalist economy. He came up with a theory which describes a sinusoidal pattern of fast and slow economic growth within a time frame of 40 to 60 years. The theory of a self-healing mechanism in the capitalist economy ran counter to the views of the Soviet regime, and as a result they punished Kondratieff by sending him to a Gulag. Nonetheless, his theory got the attention of the Austrian economist Joseph Schumpeter. Schumpeter suggested in his book *Business Cycles* to name the long cycles in honour of Kondratieff. The cycles are now known as “Kondratieff waves” or “K-waves”, and although the existence is still doubted by some economist[75], the long wave theory gained new interest in the 1980’s (e.g. [64, 50, 39]).

In Kondratieff’s book, *The Major Economic Cycles* [52], he proposes a relation between scientific or social development and economic growth in cycles which last approximately 40 to 60 years. He divides an economic cycle into three phases: expansion, stagnation, and recession. A shift in society characterises the start of the expansion phase. The cause of this shift lays in the evolution and adaptation of new technology or a changing mindset in the community.

We suggest that the upswing of a Kondratieff long wave begins when a harmonic complementarity has been achieved, through adequate social and institutional innovations, between the ‘technoeconomic paradigm’, which emerged and developed in the previous Kondratieff peak and downswing, and the socio-institutional climate. [64]

The ‘complementarity’ will be reached in the main mode of development but it will also greatly affect other markets in their development. It is likely that more than one development or shift can be identified within one cycle, but only one trend is dominating and the actual cause
of the wave. At the point of complementarity, which is also known as the 'Spring', major investments are attracted by the businesses which are active in the new 'technoeconomic paradigm'. The investments during the spring will accelerate the development of the new technology, which attracts even more investments. A precipitated growth marks the next phase of the cycle which is called the 'Summer'.

The branch that makes use of the key factor in which the main shift takes place is called the 'carrier branch'. The industries which provide the technology or products for this businesses are called the 'motive branches', and branches which grow indirectly due to the evolution of the carrier branch are called 'induced branches’. Induced branches are able to grow due to increased efficiency with the help of the products from the carrier branch or with new products which are somehow related to the carrier branch.

Saturation is marked by cheap products, many suppliers, decreasing investments, and a stagnating demand. For the demand side of the market this is the best part of the wave, but for the suppliers it becomes more difficult to make profit or to do new investments. Available resources are used to increase efficiency to stay competitive. A stagnating demand in combination with lower profits and increased productivity will lead to bankruptcy of suppliers and eventually to unemployment. When there is no place for the unemployed labour on the market, the economy will eventually get into the last phase of the wave, recession. The society needs to look for new opportunities which are outside the key branch. A next shift in society preludes the start of a new Kondratieff wave.

The first statistically identified wave (according to Kondratieff) came with the first industrial revolution which started in the United Kingdom. The development of cotton-based technology, machine tools, and the first steam engines initiated the expansion phase. Capital has been put into the first large scale factories and the required machinery. This led to upheavals in society and changed the daily life of people. Families moved to the city for a new life, started to work in factories, and had to change their diet, but also gained access to a new living standard. An economic stagnation was caused by the saturation of the textile market. The saturation of the market led to more competition, diminishing investments, increased output, and lower profits, but not to unemployment due to the forthcoming second industrial revolution.

The fifth, and current, Kondratieff wave was propelled by the emerging information technology in the 1980's. Companies like IBM, Microsoft, Apple, and later Google are part of the carrier branch. These companies provide products that are used in many places and changed the way people work, communicate, get access to information and spend their spare time. Intel and ASML are examples of companies which provide the technology and products which make it possible to implement the technology and are therefore part of motive branches. Almost all other branches are affected by the information technology, and are therefore part of the induced branches.

Economists like Perez[65] show that the fifth wave has many similarities with the previous waves. Perez compares the collapse of the dot-com bubble (which she calls a 'turning point') at the beginning of the 21st century with other economic crises in previous waves. The growth factors that piled during the spring burst with a bang or series of smaller crashes. After the first collapse, the (financial) market should find an equilibrium in which the access to capital is not based on the expectancy of exponential growth but on real wealth growth. When this equilibrium has been established, the link between financial capital and production will imply real growth and real profits. The graceful growth (or maturity) will last until
demand stagnates, technological development reached its limits and/or geographic migration of the production occurs. Perez’ characteristics of the maturity of the economy are similar to Kondratieff’s stagnation phase. In a stagnating market, capital will look for new opportunities according to Perez. If the displacement of capital are loans to distant countries it will lead to (public) debt. If the opportunities are found in the adaptation of new technology, this might lead to a new technoeconomic paradigm.

Dutch capital moved abroad during the past thirty years, especially in the period 1995-2000[14], a trend which can also be noted in other northern European countries. Almost ten years after the theory of Perez[65], the investments, particularly the southern European countries, indeed led to a debt crisis. The European economy, but also the economy in the Unites States, first entered the phase of stagnation and the debt crises turned the economy into a recession.

Assuming that the long waves in economic growth are really caused by the evolution and adaptation of new technology and given the fact that the state of the economy has many characteristics of the last phase of a Kondratieff wave, it is plausible that a new K-wave is forthcoming. The question comes up of what the key factor of this upcoming wave will be.

Economists (e.g. [65]) argue that nanotechnology will be the driving force for the new economic upswing. Perez[65] asserts that a new golden age will be a sustainable age. Since an important aspect of nanotechnology will be the development of new materials which have more sustainable properties, the age of nanotechnology and the age of sustainability might be the same cluster of progress and triggered by the same key factor.

The depletion of natural resources and the awareness of policy makers that the emissions of carbon dioxide should be reduced creates opportunities for further development of energy saving technologies and renewable energy sources. When the market succeeds to accommodate green technology, and is able to attract an increasing amount of investments, the shift in society will likely have the same social and economical impact as the first industrial revolution or the age of information technology. It will affect the way we transport ourselves, the utilities and appliances we have at home, what kind of jobs we have, what we eat, our landscape, our neighbourhood, how our energy is produced, how we construct and use our buildings.

### 1-2 Energy efficient buildings

Many policy makers try to encourage the adaptation of green technology. The arguments for changing legislations in a country or to come up with binding agreements between the legislators are numerous and diverse in nature. The conviction or fear that human activity has a damaging contribution on the climate has led to the Kyoto protocol in 1997[81]. The Kyoto protocol is generally seen as the first important step towards a global regime on the reduction of Green House Gas (GHG)[47, app. 3]. Reducing GHG emissions will also indirectly slow down the depletion of natural resources and the dependency of fossil fuel imports of several countries. The new search for efficiency might lead to a global upheaval of the economy as a positive side effect, while others also point out the extra costs and possible loss of prosperity due to GHG reduction[51, chap. 3]. On an interregional scale and local scale, green technology will have a positive effect on reducing environmental pollution. Clean and durable materials help to create a healthy and a pleasant environment at the individual scale. It also helps to
reduce rising energy costs, and it opens up a new area of job opportunities. At each level, the building sector will have a major role.

The building sector in 2004 was responsible for approximately 30% of global carbon dioxide emissions. The available information on the energy consumption is however insufficient and not proportional to its importance. Eurostat tracks the final energy consumption of the residential sector, the services sector, and four other sectors. The residential and services sector were accountable for almost 40% of the total energy consumption in Europe over 2010. In these figures from Eurostat, the building sector is not considered in isolation what makes it difficult to follow the course of the energy consumption in this sector. The 40% is mentioned in multiple other publications and also used by policy makers but the underlying understanding of this figure is difficult to track.

Although a precise measurement is not available and probably difficult to acquire, it is clear that the building sector takes a major share in the energy consumption and GHG emissions. This implies that in order to achieve the targets, the building sector needs to be part of a new energy strategy. The first step in such a strategy is to increase the efficiency by using less energy during construction and reduce the energy need during the lifetime of the building. This introduces some big challenges to the building sector.

Policy makers have to create the conditions in which every stakeholder has the incentive to build an energy efficient building. In a traditional building process, it is often not in the interest of the construction company nor the real estate developer, to maximize the efficiency of a new building. The end-user has an incentive since the operational costs of an efficient building are lower than the costs of an inefficient building. However, the end-user is often not in the position to do the necessary investment or does not have the required knowledge to control that part of the building process. The community benefits can be defended with legislation, compulsory building codes, and making the building industry and the end-user more aware of the topic of energy efficiency. In the building sector it is already demonstrated that mandatory codes can help to reduce the energy consumption significantly. The compulsory nature of these construction guidelines is important.

When it comes to the energy performance of a building, the end-user in the European Union has the right to know the performance of a building. Each building needs a performance certification that should give an indication of the gas and electricity consumption based on standard use characteristics. However, the certification methodologies are merely an estimation of the actual consumption, and it turns out that the expected energy savings based on the labelling system in the Netherlands are less than what could be expected following the underlying theory of these labels. An investment that leads to a better label results in a lower energy consumption, but the actual savings are less than the theoretical savings. Besides inaccuracy of the labels, the certification process currently does not take into account...
the embodied energy of the building[12]. Policy targets are set on the theoretical savings rather than the actual consumption, and thus there will be a gap between the predicted energy demand and the actual future energy demand. Also, the payback time for energy saving investments is in reality larger than calculated.

Currently, the indicator gives only insight in the expected $CO_2$ emissions during the use phase and even that is not very accurate. In the transition towards renewable energy sources and a more sophisticated use of energy, the building will be a cog in the wheel of a much larger and more complex system. The building will not only be a consumer of gas and electricity, it might also become a provider of electricity and heat. A building that is able to take up energy during a surplus of energy in the grid will eventually have a lower impact on the $CO_2$ emissions compared to a building that requires the same amount of energy from the grid when the demand peaks.

1-3 The electrical grid

The electrical grid can be divided into the electrical power transmission grid and the mains. The transmission grid is the bulk transfer between the utilities and the electrical substations. This is a high voltage network that mostly uses an Alternating Current (AC) or a DC to transport energy over long distances with lower losses. The mains provide the distribution between the substations and end-users. In many countries, the ownership of the grid is separated from the energy suppliers to avoid a monopoly. In the Netherlands, the state is the biggest shareholder of the grid.

1-3-1 Energy sources

The gross world energy consumption in 2008 was about 535 EJ$^{1}[82]$, equivalent to 148,000 TWh. The most important energy source in the world is oil (32%), followed by coal (28%), gas (21%), renewables (13%) and nuclear energy (6%). The energy demand is still growing with an average of 1.6 percent a year, but this figure is closely related to economic growth and therefore difficult to predict for the coming years. Nonetheless, a total growth of 50% is expected for the year 2035, though the increase will mainly be in the emerging economies of China and India. Europe’s share (EU-27) in the total energy consumption was 14% in 2010[28]. This figure will drop a little bit to about 11% in 2030.

Energy production in the EU drops slightly over the years. Since energy consumption still increases every year, the energy import has to rise even more. This causes European dependence on countries outside the EU, to increase as well. The dependence on imports harms energy security. Economic growth becomes vulnerable and less predictable when one of the main means of production becomes less reliable. The EU follows several strategies to maintain a solid energy supply. First is to spread the primary energy sources and suppliers. Diversification of fuels reduces the impact of a strong fluctuating price of a fuel like oil. Political instability also harms energy security. Therefore, it is important to have alternative suppliers which are able to increase their production and export in case a party fails. The recent gas disputes in Eastern Europe (2005 & 2007) showed the consequences of a

$^{1}EJ=10^{18}Joule$
predominant gas supplier which has the power to simply cut off supply in the middle of the winter. Russia seems to use natural gas as a political weapon and might be in search of a “gas containment policy”[8]. More recently, the EU and the energy supplying bonds seem to be successful in securing the oil supply during the Arabic revolt by the approach of multiple suppliers. The Arabic uprising has affected the oil price, but this did not lead to energy shortages and it did not have immediate consequences on the European economy.

The next strategy is to strengthen the bonds with key suppliers and transit countries. Free trading agreements and partnerships should avoid the risk of conspiring energy suppliers which raise the price whenever that is in their interest. The third strategy is to produce more energy locally. This can be done with an increase of the excavation of fossil fuels or an increase in the adaptation of renewables. Despite the economic crisis, the deployment of Renewable Energy Sources (RES) is increasing rapidly and a 40% growth is foreseen in the next five years. It is predicted that renewables will surpass gas in the global power mix by 2016[2].

The global penetration of RES has been estimated to 12.9%[22] of the gross energy supply. By far the most utilised RES is biomass, mainly for domestic use in developing countries. The share of renewables in EU energy production is 20%, but as the amount of imported renewables is close to zero, the share of renewables in the total consumed energy, is only 10%[28].

The EU-27 generated 3345.6TWh of electrical energy in 2010 (see table: 1-1). The electrical energy demand is expected to grow faster than the total energy consumption[46, chap. 2]. One of the reasons is that buildings have better insulation and therefore do not require the same amount of gas to heat the building as some years ago. This trend is likely to push through with the increase of electrical appliances and developments like the electrical car where burning gasoline is replaced with the consumption of electricity. A further shift to the use of electricity is important since the generation of electrical energy can be more easily replaced with RES than the use of petroleum products or gases.

1-3-2 Shifting towards renewable energy sources

In 2009, the European Commission adapted a directive that mandates the states to promote RES until a market share of 20% is reached by 2020, to promote energy efficient technologies and technological development[31]. States also have a binding individual target that should result in an averaged total of 20% renewables in the European energy consumption. The EU provided several new and enhanced policies like a mandatory minimum amount of biofuels in the transport sector and stricter rules to the origin of the biofuels. Member states also need to take steps to develop the transmission and distribution network in order to accommodate the further development of electricity production from renewables. This can lead to a more intelligent network, storage facilities in the grid, or a more robust network.

A second approach is the European Union Emissions Trading Scheme (ETS)[16, chap. 1]. The ETS creates a market for greenhouse gas emission allowances. An acquired allowance has a market value which companies can trade. The total allowance cap will be reduced by the EU yearly. If a company is able to cut greenhouse gases, it saves, in most situations, on the amount of energy expenditures and is able to sell the redundant greenhouse allowance to another company. Companies do now have an extra incentive to invest in energy efficiency or
The increased use of RES and the total energy reduction have a positive effect on the market share of renewables.

For the longer term the EU has a roadmap towards 2050[26]. The milestone in this roadmap is a domestic carbon reduction of 80% by 2050 with respect to the emissions in 1990. It is not considered possible to reduce the carbon emissions of the agriculture- and transport sector significantly. Since those sectors had an emission share of almost 24% in 1990[30], all other sectors have to reduce their emission with a lot more than 80%. Therefore, the use of fossil fuels to heat buildings should be reduced to almost zero, and the penetration of RES in the generation of electrical energy needs to be close to 100%. To increase the ‘natural’ rate of investments into low-carbon technologies, the ETS-cap will be lowered, or the price which companies have to pay for their allowance will be increased[23].

Studies[22, 42] show that the potential the resistance RES is big enough to cover the energy demand, even if the demand rises in the future. How the energy mix will look like in the future is hard to predict. The European Commission[27] makes a prediction for the coming 20 years based on demographic trends, the economic situation, and it includes the measures implemented by the EU member states (see table: 1-1). The Intergovernmental Panel on Climate Change[22] describes multiple scenarios based on a very large set of studies which predict the world future energy mix for the coming 40 years. Although these scenarios show a very large scatter, they also clearly show the renewables with the highest potential.

All scenarios show that the electricity generated with hydropower will not increase significantly, while electrical power generated with the combustion of biomass might double or triple the current production. The largest growth is, however, expected in the wind- and solar energy although here the scatter is also the biggest.
Assuming that indeed the biggest changes in the future energy mix are the rise of wind- and solar power, the reliability of the power supply is at stake. Biomass or potential hydropower can be converted to electrical power at anytime, but this is not the case for wind- and solar power. The availability of electricity from these sources is unpredictable and can therefore only be exploited on a large scale in combination with other sources like fossil fuels, biomass, or hydropower. Since the operational reliability of fossil fuels, biomass, and hydropower (Dispatchable Renewable Energies (DRE)) is higher than wind- and solar power (Variable Renewable Energies (VRE)), the economical value of these sources is also larger. Increasing the hydropower potential significantly is not realistic due to geographical limitations and the impact that hydropower plants have on the local environment. The increase of energy from biomass is already part of the future energy mix scenarios. The deployment of biomass is however closely related to the geographical location.

Europe’s dependence on energy import is not likely to decrease when biomass becomes the key primary energy source. The largest theoretical, geographical, and economic potentials for the production of biomass are outside Europe [42] (e.g. Russia and Africa).

### 1-3-3 Making the electrical grid smarter with NorNed

Several energy scenarios predict that 100% of the electrical energy will be generated from RES by 2050 (e.g. [67, 25]). In the meantime, fossil fuels are the dispatchable energy source since they can be used to generate energy at any time. With the increasing share of renewables, the generation of energy with fossil fuels becomes more expensive. Indeed, the payback time for utility plants becomes larger when the plants are only used as backup. Especially for nuclear power plants, and to a lesser extend for coal power plants, this is an issue since the investments in the power plant largely exceed the costs of the fuel.

NorNed, a High Voltage Direct Current (HVDC) cable between The Netherlands and Norway, helps to increase the occupancy rate of Dutch power plants and it helps increases the value of the available hydropower. The hydropower from Norway is used to level out the expensive peak load in Norway and The Netherlands. The fossil fuel power plants in Netherlands run the whole day to provide the energy for the grid base load in both countries. From the investor point of view, NorNed had a very successful start [77]. Production resources were more smartly deployed and the actual costs per kWh dropped a bit. From the GHG reduction point of view, NorNed does not contribute at this point. Even slightly more GHG will be exhausted since the distance between supplier and consumer is larger and thus the transportation losses will be bigger.

However, NorNed, and the proposed NorNed 2 cable, can also be used to store surplus energy generated by VRE in Pumped-Storage Hydroelectricity (PSH) systems in Norway. The coupling of grids with transmission cables that have a high capacity and are highly efficient, has a positive effect on the required storage and backup capacity (see section: 1-4-3). This cable enlarges the effective grid size and it gives access to relative cheap storage capacity. The super transmission grid is being extended in many locations in the world and thus the effective size of the electrical grids is growing. NorNed is now one the longest HVDC cables in the world.
1-4 Smart grids

1-4-1 The concept of smart grids

There is no agreement on a universal definition for the term “Smart Grid”, but according to Fox-Penner the meaning of the term is:

combining time-based prices with the technologies that can be set by users to automatically control their use and self-production, lowering their power costs and offering other benefits such as increased reliability to the system as a whole[34]

The term smart grid refers to a network of energy suppliers and consumers that actively communicate with each other in order to match the energy demand with the supply. The driving force behind the smart grid can be a simple price mechanism that has many similarities with a perfect market. In a perfect market it is assumed that all participants have all the required information, there is free formation of prices, there are no subsidies, there is an unlimited amount of consumers and suppliers, and each actor in the system acts rationally and tries to maximize its profits. The consumers will decide when to buy energy and at which price. The suppliers will decide to generate energy only if the price they get for their energy is large enough to make profit. When the demand rises, the consumers are willing to pay a higher price and more suppliers are willing to sell their energy. When the demand drops, the price will also drop and less suppliers will sell their energy.

The system only works when the actors know the current price and are able to do something with this information. Some consumers do not have a choice and will always buy energy at any price (e.g. an elevator, television screen, etc). Appliances like washing machines and, to a lesser extend, cooling systems are able to shift the point in time that they need the energy from the grid. For a washing machine the price of energy is usually much more important than the exact time is takes to clean the soiled clothes. These machines need to be smart enough to predict the energy prices for the coming hours such that they can decide to delay their energy request.

The smart grid needs to support two-way energy transmission and it has to support two-way communication between the consumer and the utility company. The utility company needs to know the energy consumption in detail for billing purposes and the consumer needs to know the exact actual price. Since a consumer of energy might also be supplier at another point of time, the grid also has to support two-way transmission.

In the transition towards a smart grid, not all actors in the grid are able to behave rationally as in a perfect market. The actors do not have the intelligence or enough knowledge to make the best decision. An intermediate solution is a grid with one control system that collects all information in the grid, place orders to the suppliers, and determines an actual price by itself. These Supervisory Control And Data Acquisition (SCADA) systems (also known as Single Agent Systems) replace the grid operator. A grid operator places orders to the energy suppliers to match the demand for the lowest price. The SCADA system does the same, but also tries to decide when certain appliances are turned on and off. The benefit is that more energy can be bought for the lowest price and less energy has to be bought when the price is high at peak load. Currently, the owner of the SCADA system and the smart meters which
are placed with customers, is often the same as the owner of the utility. Therefore, there is no direct incentive to reduce the price for the consumer.

A top-down architecture worked fairly well for a limited number of large industrial customers, but the required information flow from households, and any other actor in grid, comes with security, scalability and privacy problems\cite{63}. When all actors in a growing grid are managed by one single controller, the system becomes extremely complex. It should therefore be considered if an inherent complex system is a durable and safe solution for such an important infrastructure. Besides the complexity of the system, a single agent system also comes with privacy issues. The utility needs to have a lot of information from its customers to make the most efficient decisions. This information can be misused by the utility, by institutions, or by criminals that acquire access to that information.

The SCADA system is part of the vertical integration of the utility industry. A vertical integration of the power system has a positive effect on the costs\cite{34, chap. 11}, but it can also become a problem when there are not enough competitors on the market.

In a multi agent system, every actor has enough intelligence and knowledge to act on the market by itself. The energy suppliers have to come up with the lowest price, otherwise their place will be taken over by another supplier that has equal access to the grid. Privacy is assured since each consumer has his own sophisticated smart meter and there is no need to share that information with the supplier.

1.4.2 Matching energy demand and supply

The traditional task of the grid operator is to match the energy demand with the supply. The operator will have to choose the most efficient combination of utilities that generate the electrical power. Each utility has its own characteristics, like output, efficiency, location, and price per unit. One of the biggest challenges is to generate just enough energy to make sure that the supply always exceeds the demand without wasting energy. A small surplus in the grid is required to reduce the risk of blackouts.

Electrical energy generators produce an alternating stream of power with a frequency of 50-60 Hz. The frequency of the generator is proportional to the rotational speed of the generator times the amount of poles. A rising demand is initially absorbed by the inertia of the rotating generator. This implies that the frequency drops when the energy demand rises. The control system of the generator will quickly demand an extra force to compensate the loss of inertia. If the system cannot deliver that extra force, the loss of kinetic energy in the generator will continue\cite{35, chap. 3}. Since some of the components in the system (e.g. transformers) can only operate in a limited range of frequencies, they might fail when the frequency drops beneath a certain level. If one component fails in an already overloaded grid, the redistribution of the load will make that all components have to deal with an even higher load. The result can be a cascade of failing components and a major blackout in the whole grid. Nowadays, a modern well-maintained grid is equipped with many control systems to stop a starting blackout but still the occurrence of a major blackout cannot be ruled out.

A rolling blackout is the last resort for situations in which the operator cannot address enough backup capacity. This means that parts of the grid are cut off from supply. As a consequence, the total demand drops and a cascading failure can be averted. Rolling blackouts are rare.
in developed countries because they usually have enough power generators on stand-by to stabilize the grid in case of emergency. In countries with less capacity, a less robust grid, or regular failing components, rolling blackouts can be a daily phenomenon.

Matching the energy demand with the supply is getting more difficult when Variable Renewable Energies (VRE), like wind and sun, take a bigger share in the total energy supply mixture. The delivered energy from a wind farm depends on the amount of available wind power and energy from solar panels is related to the intensity of the solar rays. On a tranquil, cloudy day, the delivered energy from windmills and solar panels will be very limited; the supply will not be sufficient without the control of demand or additional backup supply. There are several ways to approach the issue of underproduction in a grid which has a relevant interest of VRE.

The first approach is to supplement the deficit with dispatchable energy sources like biomass or fossil fuels. Both have the major benefit that the potential energy can be released whenever required. This means however that the biomass power plant will not run constantly. In a simplified grid that only has windmills, solar panels, and a biomass power plant, the power plant will only operate during calm and cloudy weather at which the solar panels and windmills do not produce a lot of energy. This is not an appealing situation for potential investors. From the investor point of view, a biomass power plant should be as small as possible and constantly produce energy to maximize the profit. Contrary to the concern of the potential investor is the interest of the grid operator. The operator of a grid that has to deal with a significant share of VRE, would rather like to have a large power plant that only runs when other sources like wind energy do not supply sufficient energy. During peak hours, the operator is willing to pay more money. A higher price is a direct incentive for the investor of the power plant to build that extra capacity.

A second option is to get energy from a distant area. When the energy production area is bigger, the total average output will be less unpredictable and less fluctuating. In case of a local surplus, energy will be exported to an area with a deficit and imported in case of a local deficit. The transport of energy over large distances is complicated, inefficient and requires major investments into the grid. The advantages of Alternating Current (AC) make it predominant in the power grid [see 5, chap. 6]. Generators produce an AC which is being used by appliances which have a motor and it can also be used for lighting. Hence, these appliances do not require a rectifier or inverter anywhere in the system and will not have the loses which come with the change of movement. Rectification can be done relatively easy, but the other way around, from Direct Current (DC) to AC with an inverter, is more complicated. Devices like computers do require a single rectifier, which are usually placed between the power connector and the device. An important advantage of AC is however that the voltage can be stepped up and stepped down with relatively cheap and efficient transformers. Transporting electrical energy at a higher voltage reduces transport losses tremendously. The high voltage grid in The Netherlands operates at 50 kV or more and is decreased to 10 kV at electrical substations. Therefore the 25 kV output of a generator will first be transformed to 50 kV or more. Closer to client of the energy supplier, the voltage will be stepped down to 230 V for households and any other voltage for industrial or transportation purposes. The energy has to be transformed multiple times before it arrives at its destination, and therefore the transformation efficiency is an important aspect. One of the disadvantages of AC is the skin effect, which causes an extra resistance during transportation. This effect does not occur with DC and therefore it can be profitable to build an High Voltage Direct Current (HVDC) power...
line for long distance transportation. An HVDC power line needs an expensive rectifier and inverter, but these investments can be compensated with savings on the amount of conductors and the operational costs. The HVDC grid in Europe is being expanded (see section: 1-3-3) but is still marginal compared to the total amount of power distribution. A grid in which HVDC cables will be used to level out the energy underproduction of a tranquil and cloudy day at a specific location needs to be huge. Again, the investment will only yield money when, at one of two ends of the cable, the weather is calm.

Within a smart grid, it becomes possible and important to adapt the demand to the supply with the dynamic pricing of energy[see 34, chap. 4]. In case of an energy deficit, the price of energy will be higher than by an energy surplus. Smart appliances will decide if the energy will be bought for that price or at a later time when the price has dropped. A smart electricity consuming escalator can decide to interrupt operating when the price reaches an indicated threshold. Likewise the battery of an electrical car can be charged when the price of energy is low. This means that the total demand decreases when the price is high and the demand increases when the costs are low. A smart grid requires a two way information stream (see section: 1-4-1) and smart devices that decide automatically when to consume energy. This requires investments in the grid and in the appliances. Consumers become aware of the fact that choosing when to use energy comes with a price.

Peaks in demand or drops in supply can also be leveled out with Electrical Storage Systems (ESS). A storage system can be placed anywhere in the grid. For suppliers having an ESS it can be useful to optimize the deployment of capital, because than it becomes meaningful to produce energy even at moments that the total demand is low. For energy buyers, the storage system can be used to avoid high electricity prices during peaks and benefit from low energy prices when the demand is low or the production high. An ESS can even operate as an independent energy trader. It buys energy when it is cheap and sells the energy when it is expensive. Storage systems require an investment and they always have some energy loss.

Each solution has its drawbacks which are mostly related to the required investments, the potential availability of each resource (see section: 1-3-1), and the interaction of resources which do not always complement each other. The real answer lies in a sophisticated mixture of solutions which will gradually become part of the grid.

1-4-3 Modelling a 100% renewable Europe

Assuming that the implementation potential\(^2\) of RES for a certain grid matches the demand, there is a minimum amount of Dispatchable Renewable Energies (DRE) required to backup the Variable Renewable Energies (VRE) or the grid needs enough storage capacity to bridge the temporary supply deficits. The backup power capacity needs to cover almost 100% of the total demand at certain points in time\(^78\). The capacity credit\(^3\) of wind, for example, in a well connected Europe is about 14%\(^80\) (with a 12% wind energy penetration). For 100MW installed wind power, the grid needs 86MW backup power from DRE or from storage systems.

\(^2\)“The implementation potential is the maximum amount of economic potential that can be implemented within a certain time frame, taking constraints and incentives into account”\(^42\)

\(^3\)The capacity credit is defined as the amount of conventional generation capacity that can be replaced by VRE

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Steinke et al. [80] modelled a 100% renewable Europe to quantify the required storage capacity given that the maximum share of DRE is roughly limited to 10% of the total energy mix in 2050. The energy mix in this model (see scenario 'b' in table 1-1) is exactly equal to the total yearly consumption. To model the characteristics of the electrical grid, a 50km by 50km raster has been placed over Europe. Each cell in this raster has its own storage capacity, weather model, and ratio between the amount of energy generated with solar power and wind power. It is assumed that the energy transportation losses within one cell are zero. The cells can be connected with each other, but this requires a robust and expensive network. In an interconnected network, the probability that the Variable Renewable Energies (VRE) match the demand is larger than in a single cell. Consequently, the backup power in a small network needs to be larger than the backup power in a large network.

Assuming that there is no storage capacity in the grid and energy cannot be transported to other cells, the median of the model shows a required backup energy capacity that is 40% of the total energy consumption. This is significantly more than the potential 10% share of DRE. Running the same model with all cells connected, the need for DRE is only 19% (see figure: 1-1A). In the real electrical grid, all cells are connected, but energy cannot be transported without losses as in the model and the amount of transported energy is physically limited by the size of the transmission lines.

When the cells contain their own storage capacity, the simulation shows that a storage capacity equal to the total consumption of a single day, is enough to reduce the need for backup energy from 40% to 20% (see figure: 1-1B). When the storage capacity is large enough the store the energy consumption of 90 days, the need for backup energy is close to zero. With a 10% share of DRE, the total energy storage capacity in the grid needs to be between 7 and 30 days. For a realistic simulation of the current and future grid in Europe, a combination of storage systems and an interconnected grid needs to be considered.

If the expected increase in the electrical energy demand is neglected and the effective grid radius is assumed to be 500km, the required storage capacity is between 0.5% and 1.5% of the total yearly consumption. With a yearly energy consumption in The Netherlands of 118.68 TWh [14, StatLine], the storage capacity needs to be between 0.65 and 2.00 TWh. The real grid is more complex and other renewable sources like hydro power are only dispatchable to a certain degree, nonetheless, this study gives a rough idea of the required storage capacity in a 100% renewable Europe and the storage capacity needed in The Netherlands.

### 1-4-4 Local micro grids in developing countries

One of the preconditions for economic development is access to electricity. In developing countries, and especially in the rural areas, this is often a problem. The main problems are the transportation infrastructure for electricity, which does not exist or is far from robust, and the costs of the energy sources. Building and maintaining a dense energy grid like in the developed countries is very expensive and even more expensive in sparsely populated areas. Long distant transportation also means an increase of loses.

Therefore, basic electricity needs for lightning, health centers, and small workshops in remote districts are now usually met with diesel generators. The increasing costs of gas makes it more difficult to fulfill even the most elementary needs, a situation which is not likely to change. Often, the availability of RES in those distant places is not scarce at all. There
are many opportunities for generating energy with biomass, wind, sun, and hydropower since those sources are usually widely available. Small Distributed Generators (DG) are expensive but do not require the large investments in the transportation infrastructure and if RES are used, the fuel costs are zero.

The efficiency and reliability of DG can improve if different type of generators are connected with each other into a Local Micro Grid (LMG). Another benefit is that extra capacity only requires the investment of another DG which can be spread over the whole community. In this way, the size of the grid can increase gradually and only requires a relatively small initial investment. Initially, the LMG operates in island mode since the grids are not connected to the main electrical grid. Erbato et al. [24] describe how multiple LMG’s can gradually be connected and finally bond with the main electrical grid.

The essential difference to the implementation of smart grids in the developed countries is that it follows a bottom up approach. Users connect with each other in a LMG, in a second phase multiple LMGs connect into a larger grid, and in the last step the larger grids will be connected to the main power grid. At each level, it is possible to gradually extend the grid with relatively low investments and low risks. In the developed world, where everything is connected to the national grid, the transition process has to compete with the status quo. In well developed smart grids for example, the peak demand will be significantly lower than in the traditional grid. The smart grid requires less production buffer capacity, but in case that capacity is available in the national grid, the benefit will not result in lower overall costs. This will only happen when the electrical energy consumption grows, or the most inefficient generators are turned down.

A second threshold is that consumers from developed countries are used to use energy whenever they want. The buffer capacity is big enough to deal with peak demands and buffer capacity costs are covered in one price per kilowatt hour. In a smart grid, controlled by Supervisory Control And Data Acquisition (SCADA) systems or not, the consumer will have to use energy in such way that the electricity demand coincides with the supply to avoid black outs. In the end, the consumer has to accept that doing the laundry during the evening is more expensive than at night. For consumers in underdeveloped countries it works just the

(A) Grid size versus DRE, no storage capacity
(B) Storage capacity versus DRE, single cell

Figure 1-1: Required share of Dispatchable Renewable Energies (DRE) (source: Steinke et al. [78])
other way around. Electricity is available for only a limited amount of time per day but the implementation of smart grids will gradually extend the daily availability of electricity.
Chapter 2

Storing electrical energy

2-1 Energy storage systems

According to Zito[89, chap. 1] there are three main purposes to store energy. The first reason is to make energy portable from a non-portable energy source. For example, an electrochemical battery which holds energy generated in a coal power plant and will be used in a portable photo camera. The second purpose is the ability to change the Power-To-Energy (PTE) ratio of an energy generating source. The energy generator in combination with a storage system is able to increase or decrease its power capacity for a short time while the energy production of the generator remains constant. The third reason to store energy is to use it at a later time. When electrical energy storage is available, the production of the energy does not exactly have to match the demand. The second and third application mainly differ in the time scale.

Each of the three purposes requires a storage system with specific properties. The first property is the PTE-ratio of the system. This ratio defines how fast the energy storage system can be charged or discharged. The PTE value expresses the ratio between the power capacity and the energy capacity. A system with a high ratio can quickly respond to small supply interruptions or demand peaks. However, a large power capacity comes with high costs[79]. To level out small demand fluctuations in a small part of the grid, the controlling storage system needs to have a high PTE-ratio without losing its properties over a large amount of charge and discharge cycles. The energy will only have to be stored for a few seconds until a few minutes. Therefore, the losses in time and the energy storage price per kWh are not decisive. A flywheel or electrochemical capacitor has these characteristics and is therefore often used to level out small demand fluctuations.

When a system has the aim to provide energy during blackouts, it is required that the system has a low self-discharge, low energy storage costs, low maintenance costs, and it must be placeable near the location of the owner. For these situations, a technology with a low PTE-ratio is a suitable solution. The lifespan, when defined in the amount of charge and discharge cycles, will not be the crucial factor. Lead acid batteries have all these properties, but have the disadvantage that the energy carrier is highly toxic.
The lifespan of the system is a second important characteristic. An electrochemical battery system has in general a limited lifetime compared to a mechanical storage solution. For a battery setup with lead acid batteries, the lifetime is closely related to the amount of charge and discharge cycles. This means that the expected lifetime of an Electrical Storage Systems (ESS) with a high occupancy is not the same as a system that only runs on days with an abundant solar energy production. The lifetime of lead acid batteries can be increased with a partial discharging strategy. When the Depth of Discharge (DOD) is limited to 50%-60%, the capacity decay goes significantly slower. A storage system with lithium-ion batteries is less affected by the amount of charge and discharge cycles, but still has a limited lifetime compared to its mechanical alternatives.

The third and fourth aspects are the efficiency and the price of the technology. Cheap storage energy solutions like Compressed Air Energy Storage (CAES) might have a favorable present value, but if the efficiency is low, the net present value can still be very low. Systems with a low efficiency will have a limited field of application. These systems might be used to backup rare periods of low production from Variable Renewable Energies (VRE).

2-1-1 Energy and power storage capacity

In section 1-4-3 it has been worked out that the energy storage capacity in the grid needs to be large enough to cover between 2% and 8% of the total yearly energy consumption. The premise of this calculation is a fluctuating supply rather than a fluctuating demand. Some of the calculated capacity will hardly ever be addressed. That capacity is needed to bridge extreme periods in which the production of VRE is low. This capacity can be placed somewhere in the system in large Pumped-Storage Hydroelectricity (PSH) plants far away from the end user or the energy generator. It is not a problem when the PTE ratio of such a system is much lower than 1 and also the round-trip efficiency is less relevant. Another approach is to calculate the required storage capacity from the demand side. The timescale
for such a system is only limited to the duration of the peak demand. When the storage system is meant to level out peak demand, the power and energy capacity of the Electrical Storage Systems (ESS) determines the number of users that can make use of the storage system. Assuming that the energy capacity of the storage device is large enough to flatten the power demand curve to a straight line like drawn in figure 2-1, the power capacity of the ESS should be large enough to cover the difference between the peak demand and the average grid power supply (see: \( P_{\text{peak}} \) in figure 2-2A). When the power capacity is insufficient to cover the difference between the peak and average demand, it is still possible to reduce the power peak demand. This is called Peak Shaving.

Figure 2-1 shows an optimal constant energy supply and a typical residential demand curve. A constant power supply means that the utility can optimally deploy their capital and the grid investments can be minimized. This is the starting point for the power- and energy capacity requirements exploration, but the actual power supply will never be constant. With the increase of the Renewable Energy Sources (RES) share in the grid, the predictability of the energy supply is becoming less certain and one of the reasons that the actual energy supply fluctuates in time (see section: 1-4-2). This can be an argument to equip the storage system with a power capacity that is equal to the total power demand (\( = P_{\text{peak}} + P_{\text{grid}} \)).

The required energy capacity for a fixed amount of users can be defined as the average power surplus times the hours of the surplus, or the average demand surplus times the hours of the demand surplus. Just like the power capacity, the unpredictability of the energy surplus (or demand surplus) can be a reason for a bigger or smaller energy storage capacity. The area \( C_{\text{max}} \), in figure 2-2A, shows the required capacity with the default demand curve and a constant energy supply.

The explicit costs per kWh stored energy are in general smaller when the size of the storage system is bigger. It also applies that the revenues from a large storage system are smaller than the revenues from a small system. Scale benefits in large systems and the costs of storage capacity that is hardly used or does not gain enough revenue entails that there is an optimum size of the storage and power capacity for a certain number of users. Figure 2-2B shows the most valuable storage capacity for the default demand curve with a constant power supply. In this figure, the stored energy does not match the demand surplus area. The system needs to take up more power from the grid for a short period of time. It will be more useful to accept a higher energy price for a short period of time and only have the capacity to store.
energy when the demand peaks above a certain level. When the grid demand peaks, energy is scarce and thus the price that has to be paid for the energy peaks as well. In figure 2-2B, the most valuable storage capacity coincides with the typical residential demand curve, but the real grid demand curve does not have to be the same. A real world example is therefore likely to be more complex.

When constraining the purpose of the energy storage system to load shifting, the number of energy consumers per ESS can be related to the system scale. The technologies can then be classified into three groups: single households, local grid systems, and systems attached to the transmission grid.

2-1-2 Energy storage classification

Single household storage systems

Individual consumers in many countries are encouraged to invest in their own local generated RES. Local, sustainable energy generation has many benefits, but compared to large scale solutions, the absolute investments per kWh are not so beneficial. Another typical disadvantage is the probability of a match between demand and supply. In large systems, the change of a (partial) match between demand and supply, is much bigger than in a single household. The main electrical grid is often used to compensate these fluctuations but from a technical point of view, this is not the desirable solution. Interchanging energy with the main electrical grid or store it at a distant PSH, comes with distribution losses, grid power peaks, ESS losses, and extra investments into the power capacity of the main grid. To limit these implicit costs, it is preferred to consume the generated energy at the same place as where it is produced. This can be achieved with a combination of demand control, Distributed Generators (DG) and distributed energy storage systems. When the demand control cannot find a match, the implicit costs and losses are the least when the abundant energy is also stored at the same place as where it is generated. For single households, the most conventional small scale ESS is a system with batteries.

Unlike the production of electrical energy, storing energy with mature electrochemical battery technologies can be done relatively efficiently at a small scale. The synergy advantages of large battery systems are limited. Therefore, the unit price per kWh energy storage capacity of a small scale battery system can be of the same order as much larger systems. A developed but not mature technology like lithium-ion\[15\], still has a major scale advantage. The price that a single household has to pay for a lithium-ion battery per kWh, is approximately 70% higher than the market unit price (see table 2-2 and appendix A).

Batteries have the disadvantage that the expected lifetime is limited and related to the amount of charge and discharge cycles. In single households, the number of charge and discharge cycles per day is relatively small. This means that the expected lifetime is relatively high and the expected replacement costs are slightly lower in comparison with local grid or main grid battery systems.

The total round-trip efficiency of a battery system in combination with solar panels can be very efficient. Storing locally produced energy spares the implicit costs and losses that comes with storing energy in the grid. Solar panels produce a Direct Current (DC) that can be stored without the need of a rectifier. The DC from the batteries does not need to be converted...
to an Alternating Current (AC) for appliances that require a DC anyway. Under optimal conditions and with true deep cycle charging, the chemical storage process can approach an efficiency of almost 98%. This means that the efficiency of round-trip is hard to exceed.

In practice, the optimal conditions for a ‘perfect’ setup are difficult to attain. The efficiency of the battery system is negatively affected by the charging speed, the ambient temperature, and the age of the battery. Under normal conditions, the round-trip efficiency of nickel cadmium batteries is only 65%. The efficiency of lead-acid batteries is slightly higher. With a regular charging procedure, the efficiency is 75 to 85%. Batteries produce a DC that can theoretically be used by many appliances without the need of a converter. However, this requires a double power wiring network for AC & DC. This leads to extra initial expenses and extra implicit costs.

Although lithium-ion batteries are starting to become available for single household storage systems, the benefit right now is, from the economical point a view, not so relevant. The purchase price of these systems has to drop since the specific benefits of the lithium-ion battery are not really used.

**Local grid storage systems**

Storing energy in the local grid has the benefit that the occupancy rate is better than the storage in single households. The batteries in the grid are more often charged and discharged. Since lithium-ion batteries keep their capacity over a longer amount of charge and discharge cycles, the specific benefits of this technology are more relevant in a grid. A second advantage is that these batteries have a major synergy advantage in relation to micro setups. When the technology becomes more mature, the price for single households is likely to drop as well.

A grid storage solution is also suitable for sodium-sulphur batteries, but since these batteries are more expensive than the other battery technologies, the field of application seems to be limited. The efficiency is quite high, but it cannot compete with lithium-ion technology (see table: 2-1). This is also reflected in the amount NaS storage manufacturers. Right now, there is only one manufacturer that ships NaS storage solutions.

In table 2-2 flywheels are also considered, but they are not really meant to deal with load shifting. Losses in time are significant and the power capacity costs are large. The flywheel has a different field of application.

An energy storage system in a local grid helps to stabilize the grid. Peak demands are locally bridged by the storage system such that the components in the distribution network and the transmission grid are not overloaded.

**Main grid storage systems**

By far the most important storage technology in terms of storage capacity is Pumped-Storage Hydroelectricity (PSH). Currently, large PSH plants are mainly used to temporarily increase the grid energy production in order to absorb peak demand, store the overproduction of energy at night, and to increase the occupancy of utility plants. A high occupancy rate helps to maximize the profitability of the power plants. The production of energy in coal fired and nuclear power plants can be regulated, but it cannot be reduced below a given
When the minimum production of these type of power plants, minus the energy production from energy plants that can be turned off, exceeds the minimum demand, the energy production surplus has to be stored. In a grid with a significant share of nuclear power like the French power grid, the generation surplus at night is stored in PSH-systems. With a power capacity of 1800MW and a maximum energy storage capacity of 400GWh, barrage Grand’Maison is the largest pumped storage system in France. The major part of the electricity in The Netherlands is produced with gas-fired generators. Gas-fired power plants can be turned on and off much quicker than coal-fired or nuclear-powered generators and thus the need for storage capacity is not so big at this moment.

In a PSH-system, electrical energy is converted to potential energy by pumping water from a low-lying reservoir into a second high-lying lake or an artificial created reservoir. Logically, the vast majority of these systems are located in mountain areas by building a dam between two mountain slopes. Nonetheless, there have been plans to build such storage systems in The Netherlands as well (e.g. Plan Lievense and O-PAC Graetheide). The large initial costs, the required minimum size to be economically feasible, and the large storage capacity makes this technology particularly suited for the main grid. The geographical dependence usually also implies a large distance between the power generators, consumers and the storage system. The total distance comes with power losses and requires investments in the transportation capacity of the grid.

Large Gravitational Potential Energy Storage (GPES) systems attached to the transmission grid can store energy for a very low price per kWh (see section 2-1). The construction costs of the dam and the costs of the investment due to the long construction period of the dam need to be recovered by the low marginal storage capacity costs of the system. The marginal costs are low when the total storage capacity exceeds a certain lower bound.

An emerging technology with a similar field of application is Compressed Air Energy Storage (CAES). CAES-systems store energy by compressing and decompressing air in underground caverns. The requirement of a large underground cavern makes these systems geographically dependent as well. Multiple types of geologies are suitable for underground reservoirs, but the costs and environmental impact of the cavern excavation are different. The excavation costs of the volume required to store 1 kWh in a salt geology are only €2, while the costs to create the same amount of storage capacity in a rock layer are approximately €25. The average storage costs of these systems are low, but currently the efficiency is also low. Table 2-1 shows a round-trip efficiency of 0.70. This is a maximum value for an adiabatic CAES-system. A substantial amount of heat is needed to recover energy from the compressed air before it enters the turbine since air cools down while expanding. Only when the required heat is stored in an additional thermal energy storage system or waste heat is used from a gas plant, a round-trip efficiency of 0.70 can be attained.

The energy carrier of both technologies are environmental friendly and freely available. Nonetheless, a PSH has a significant impact on the environment since it requires a large amount of space in often vulnerable mountain ecosystems. The environmental disadvantages of the CAES-construction are very limited.

With these cheap energy carriers, it is possible to store large amounts of energy for a price that is significantly lower than the alternatives in the local grid. The price of the installed power systems per kW is of the same order as the technologies in the local grids. Since the energy storage price is very low and the self discharge is almost negligible, it is convenient to
use PSH- and CAES plants for long term energy storage purposes. When VRE take a bigger share of the total energy production, these technologies can primarily be used to bridge the gab of days with low energy production and the days with a production surplus. The timespan of these main grid storage solutions is several hours to multiple days or even weeks. When the PTE-ratio is in the order of 1:100, the system is able to fulfil multiple roles. It can help to balance the grid throughout a day, but it can also be used to store energy over longer periods of time.

Efficiency and the implicit expenses are the main disadvantages. The round-trip efficiency of PSH is 70-80% and CAES systems have a maximum storage efficiency of 70%. Since both technologies are geographically dependent, investments must be made to connect the storage plants with the grid.

Another disadvantage is that an Electrical Storage Systems (ESS) in the main grid does not solve the issue of power peaks in the grid. It is able to support the total power generation during demand peaks, but it cannot reduce those power peaks. The grid stability still depends on the power capacity of the weakest link. Every component in the grid needs to have a capacity that is big enough to withstand the utmost power peak. Local grids with a storage systems have the possibility to (partly) disconnect from the grid in case of extreme power peaks. These sub-grids will then operate in 'island mode'. This reduces the risk of blackouts in the distribution and transmission grid, and eventually it reduces the costs of the grid components. Table 2-2 shows which ESS are sensitive for these implicit disadvantages with rated values from -3 to +3.

Load shifting with ESS in the main grid is particularly useful when the storage system needs to have a minimum size to be feasible or when it is used to store energy for a longer period of time. When the synergy advantages are limited, it makes more sense to have ESS in the vicinity of the energy production or consumption.

2-1-3 Energy storage costs

Comparing the costs of the storage technologies can only be done when the storage preconditions are equal. For this reason, the technologies have been compared in a mid duration storage setup where the PTE-ratio for each technology is the same (see: 2-2 & appendix). The purpose of this storage setup is to shift the energy load over a longer period of time. This time interval is within the range of several hours to a few days. A PTE-ratio between 1:2 and 1:4 is then a plausible assumption. This value can roughly be derived from the graphs in figure 2-2.

The costs in table 2-2 are expressed as the present value of the storage system per kWh for systems with an economic lifetime of 30 years. This value includes the power costs, future maintenance costs, energy carrier costs and the costs to replace the energy carrier if necessary. To make a full comparison, the net present value needs to be calculated as well. The present value comparison excludes future revenue differences due to efficiency variances and it does not include the investment periods costs to build a system. A battery setup can be built within a few months or less, but it can take up to several years to build a large PSH-plant. During the construction time, there is no return on investment at all and that costs money. The construction time of a large PSH-system should be minimised in order to maximise the profitability.
<table>
<thead>
<tr>
<th>Storage system</th>
<th>Discharge time</th>
<th>Efficiency</th>
<th>Self discharge</th>
<th>Typical PTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-acid</td>
<td>Seconds-Hours</td>
<td>0.75</td>
<td>« 1%&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Lithium-ion</td>
<td>Minutes-Hours</td>
<td>0.93</td>
<td>« 1%&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Sodium-sulfur</td>
<td>Seconds-Hours</td>
<td>0.85</td>
<td>« 20%&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Conventional PSH</td>
<td>Hours-Months</td>
<td>0.80</td>
<td>« 1%&lt;sup&gt;b&lt;/sup&gt;</td>
<td>≈1:100</td>
</tr>
<tr>
<td>CAES</td>
<td>Hours-Months</td>
<td>≲ 0.70</td>
<td>« 1%&lt;sup&gt;b&lt;/sup&gt;</td>
<td>≈1:4</td>
</tr>
<tr>
<td>Flywheel</td>
<td>Milliseconds-Minutes</td>
<td>0.90</td>
<td>5-15%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>≈4:1</td>
</tr>
</tbody>
</table>

<sup>a</sup> Hourly self discharge  
<sup>b</sup> Daily self discharge

Table 2-1: Storage system properties

<table>
<thead>
<tr>
<th>Storage system</th>
<th>Explicit costs per kWh (€)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Implicit costs&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single households</td>
<td>Micro grids</td>
</tr>
<tr>
<td>Lead-acid</td>
<td>2600</td>
<td>2800</td>
</tr>
<tr>
<td>Lithium-ion</td>
<td>4300</td>
<td>2600</td>
</tr>
<tr>
<td>Sodium-sulfur</td>
<td>4000</td>
<td>4000</td>
</tr>
<tr>
<td>Conventional PSH</td>
<td>5000</td>
<td>1000</td>
</tr>
<tr>
<td>CAES</td>
<td>4300</td>
<td>500</td>
</tr>
<tr>
<td>Flywheel</td>
<td>4300</td>
<td>4300</td>
</tr>
</tbody>
</table>

<sup>a</sup> The explicit costs are defined as the present value of the initial and maintenance costs of the ESS per [kWh].  
<sup>b</sup> The implicit costs contain the costs of transport and costs of transport losses. The values are defined in a range from -3 (savings) to +3 (extra costs or investments).  
<sup>c</sup> Default PTE-ratio (1:2)  
<sup>d</sup> Typical PTE-ratio

Table 2-2: Present value costs of currently available storage technologies per kWh
According to table 2-2, the cheapest technology to store electrical energy in the transmission grid with a PTE-ratio of 1:2 is CAES. However, CAES systems have a low efficiency and the storage location needs to match the geological requirements. The cheapest solution in the local grid are lithium-ion batteries. They also have the highest round-trip efficiency, though the efficiency figures as in table 2-1 do not include the losses that come with the required conversion of AC to DC.

2-2 Storing electrical energy in a tall building

A PSH-system in the main grid is able to store energy for a low price with an acceptable round-trip efficiency. However, these systems also have some disadvantages as discussed in the previous sections. Having a PSH near the energy producer or consumer is, from the energy efficiency point of view, a better solution to the problem of storing electrical energy as long as the efficiency and costs of the storage system are of the same order. This would also have a positive effect on the stability of the grid and it does not need a mountainous landscape.

The downside is that a GPES system in the local grid can never attain a significant size, which makes it unlikely that the marginal energy storage costs get close to the storage price of large systems. Nonetheless, the fact that storing energy in the local grid has an additional value makes it interesting to investigate the feasibility of such a system. The required height difference in the local grid can be found in underground shafts or in tall buildings. As buildings are part of the local grid, it might be possible to adapt the construction of buildings in such a way that it becomes feasible to store electrical energy inside newly constructed buildings.

Figures 2-3 until 2-6 show eight alternatives to use the height or mass of a building for a Gravitational Potential Energy Storage (GPES). The concepts are compared on their impact on the building dimensions (see table: 2-3). Each storage concept is calculated for a building with a fixed height and a fixed storage capacity. The dimensions of the buildings used in the storage concepts overview are based on a square reference building. The height of this Reference Building Concept (RBC) is 80m (∼ 25 storeys) and the assumed desired storage capacity is 400kWh. The storage capacity is, roughly approximated, enough to level out the demand peaks throughout a day in the building itself and a second building with a similar size.

The concept systems in figure 2-3 are very similar to the storage systems in mountain areas where water is pumped from a lower lying reservoir into an elevated reservoir. During demand peaks, the water in the tube or the top reservoir of the building is released through the turbine and collected in the lower reservoir. When the demand is low or the energy production high, the water from the lower reservoir is pumped up into the tube or upper reservoir. Concept A makes use of the space inside the concrete core to store water. The inner part of an highrise building has the least value and can therefore be used as a storage volume for a low price (see section: 3-3-1).

Concept B has a bigger energy storage capacity per m$^3$ building volume, but it requires the total floor space of the top storey of the building. A structural advantage of the reservoir in this part of the building can be the additional force in the concrete core when the top reservoir is filled. The pressure of the water on the top floor will (partly) be carried by the
26 Storing electrical energy

Concrete-core Energy-tube Motor / generator

(A) Water column and reservoir

(B) Water column and two reservoirs

Figure 2-3: Tube storage system with a water column and water reservoirs

Piston Return pipe

(C) Water column with piston and reservoir

(D) Water column with a piston and a return pipe

Figure 2-4: Tube systems with a water column and a piston

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concrete core. This will induce an extra compression stress that will have a favourable effect on the stresses in the core when extreme lateral wind forces hit the facade. These lateral forces are causing tensile stresses that cannot be handled by the concrete if not compensated. Tensile stresses in the core and the foundation should always be avoided when possible to limit the building costs. Solutions which abduct tensile stresses require extra investments in tensioning steel, tensile foundation piles or extra mass. When extreme weather conditions are predicted, the upper reservoir needs to be filled. This temporarily cancels out the storage function in favour of the structural benefits.

Water accumulations in the top of the building will also affect the eigenfrequency and the damping of the building. This principle is used as a passive mass damper in seismic active areas. However, the fact that the reservoir is not always filled and earthquakes are unpredictable makes it too uncertain to combine the ESS with a system to reduce the impact of a potential earthquake.

In a building with a residential function or a commercial function like offices, the top is the most rentable and valuable part. To adapt the RBC in such way that it can store 400kWh, the substituted height in the building is almost 3m. This means that almost one floor needs to be dedicated to the energy storage system. It also implies a discontinuity in the floor stacking as the top floor needs to be built for a significantly larger floor loading compared to the other floors. The second concept has a storage capacity and stabilization advantage, but it also has serious implications for the construction of the building and the rentable floor space.

Table 2-3 shows the theoretical storage capacity and required building volume per concept leaving out the efficiency losses and extra structural spatial demands. Therefore, the values in the table are only meant to broadly give insight in the characteristics of the concepts. When the efficiency losses are left out of the comparison, the basic energy storage calculation and building volume formula of concept A are given by:

\[
C_A = \frac{1}{2} \cdot h^2 \cdot A \cdot g \cdot \rho_{water} \cdot \eta \quad [kWh] \\
V_A = h \cdot A \cdot 2 \quad [m^3]
\]

where \(C_A\) is the storage capacity, \(h\) is the building height, \(A\) is the section area of the tube, \(g\) is the gravitational acceleration, \(\rho_{water}\) is the density of water, \(\eta\) is the system efficiency, and \(V_A\) is total volume of the storage system.

The two concepts in figure 2-4 have a piston to increase the storage capacity. The weight of the piston presses down on the water, which increases the hydrostatic pressure under the piston. When the weight of the piston gets bigger, the total storage capacity increases as well. To calculate the capacity of the concepts with a piston, the specific weight of iron ore is used. Iron ore has a specific weight of about 5500 kg/m\(^3\), is a widely available commodity, and relatively cheap.

A watertight closure between the piston and the inner wall of the tube needs to ensure that the pressured water does not leak upwards. When the piston moves up- or downwards, the sliding seal along the wall comes with some friction. This friction is at the expense of the total efficiency of the ESS. Wear of the sealing makes it necessary to replace it regularly.

Concept D does not require reservoirs to store the water. When the piston moves downwards, and the system delivers energy, the water flows back through the return pipe towards the
Figure 2-5: Tube systems with a water column, and an air filled balloon

Figure 2-6: Waterless potential energy systems
top of the tube. This comes again with some efficiency losses because the stream of water through the pipe will have some friction with the sidewall of the return pipe. Since the bulk water stays inside the tube, it is difficult to carry out maintenance and to replace the sealing between the piston and the side wall. Unlike alternatives A until C, the static water pressure at the bottom of the pump is constant during operation. Only when the piston rests on the bottom will the pressure be lower. A constant pressure has major pump efficiency benefits since it is easier to match the demand or supply with the Best Efficiency Point (BEP) of the pump set (see section: 3-1-4).

The concept systems in figure 2-5 have an air filled balloon or caisson inside the tube. The balloon will move upwards to generate energy and downwards to store energy. When the balloon consists out of fabric, the inner air pressure should (in case of the adapted RBC) be 800kPa(8atm) to avoid large deformations of the balloon when it is near the bottom of the tube. The fabric should be strong enough to avert tearing when the balloon is near the top of the tube. Alternatively, the balloon can be replaced with an airtight caisson or blocks of lightweight expended polystyrene (EPS). The difference in weight between the water and pressured air (or EPS) is much lower than between water and the weight of a piston filled with iron ore like in concept D. The storage capacity is therefore much lower or the required space to get the desired storage capacity is much larger.

The balloon in E has to push the water through the return pipe. Again, the water will try to find the path of least resistance in between the balloon and the wall of the shaft. To prevent this leakage, the sliding connection between the balloon and the shaft needs to be watertight. This will cause friction that will reduce the efficiency of the system.

A solution with a pulley like in concept F will not need a watertight connection. Water can move along the balloon and through the return pipe when the balloon shifts up- or downwards. When the balloon is smaller than the shaft, the return pipe only functions as a bypass.

Concept G requires the least building volume to store the desired 400kWh. Although the required volume is an important parameter of the GPES, the structural implications of concept G are significant. The total weight of the piston is carried by a pulley with a strong steel cable and a reel in the top part of the tube. The weight of the piston is about $1/5^{th}$ of the total weight of the building. To lift this mass, a steel cable with an effective diameter of approximately 10cm is required. It is however more efficient and safer to divide the force over multiple smaller cables.

The concrete core needs to convey the weight of the building, the weight of the piston, and the lateral forces on the building. The weight of the piston acts on top of the core and will cause extra vertical stresses in the core. Vertical compressive stresses reduce the need of reinforcement which is needed to convey the lateral forces. An extra force on top of the building will increase the deflection caused by imperfections and the initial inclination. This increases the effective buckling length of the core as well, and the extra force also makes it necessary for the core to have a bigger resistance against buckling. When the piston is placed inside a tube with 30cm thick bearing walls and the tube is part of a bigger concrete core, calculations show that the construction is not sensitive to global buckling. Nonetheless, overdimensioned cables and a sufficient stiff bearing shaft does not make this concept inherently safe. Since the consequences of a failure would affect the whole building, additional constructional measurements to ensure the safety should be taken. Energy losses in this concept are caused by the friction in the pulleys and the efficiency of the winches.
## Storing electrical energy

<table>
<thead>
<tr>
<th>Concept</th>
<th>Surface(^a) ([m^2])</th>
<th>Volume ([m^3])</th>
<th>Capacity ([kWh])</th>
<th>Efficiency</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>45.9</td>
<td>7300</td>
<td>400</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>-</td>
<td>4500</td>
<td>400</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>C(^{c,d})</td>
<td>23.3</td>
<td>3700</td>
<td>400</td>
<td>±</td>
<td></td>
</tr>
<tr>
<td>D(^{c,d})</td>
<td>46.6</td>
<td>3700</td>
<td>400</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>E(^c)</td>
<td>211.6</td>
<td>16900</td>
<td>400</td>
<td>-</td>
<td>(\rho_{\text{air}} \approx 800\text{kPa})</td>
</tr>
<tr>
<td>F(^c)</td>
<td>211.6</td>
<td>16900</td>
<td>400</td>
<td>±</td>
<td>(\rho_{\text{air}} \approx 800\text{kPa})</td>
</tr>
<tr>
<td>G(^{c,d})</td>
<td>38.1</td>
<td>3000</td>
<td>400</td>
<td>±</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>-</td>
<td>-</td>
<td>400</td>
<td>±</td>
<td>Elevation (\approx 13.8\text{m})</td>
</tr>
</tbody>
</table>

\(^a\) Tube surface ground floor area, this does not include the surface area of the reservoirs or the return pipes.

\(^b\) This value does not take into account the efficiency losses.

\(^c\) Piston or balloon height: \(d_{\text{piston}} = \frac{1}{8} \cdot h\)

\(^d\) Piston material is iron ore.

### Table 2-3: The energy storage capacity and the required volume of the six alternatives given a 80m tall building and a demanded storage capacity of 400kWh

In concept H, the weight of the building is used to store energy. The building floors are lifted upwards during energy peaks and slide downwards during demand peaks. The elevation that is needed to store 400kWh within the RBC is almost 14m. This does however not include the weight of the bearing construction. Making the support structure part of the displaceable mass will decrease the necessary elevation but also increase the complexity of the whole system. Figure H shows a system in which the concrete core is elevated as well. The vertical cylinders which carry the core can however only convey forces along a single axis. Additional cylinders are required to convey the lateral forces. All this makes that the structural and practical complications become too complex to compete with the other concepts.

From table 2-3 it can be concluded that the most space efficient concepts are alternatives C and G. The required excavation in C for an underground reservoir is however costly and therefore not further investigated. Alternative G requires a system of pulleys to lift the piston. The pulleys in the top of the building reduce the effective height and reduce they cause some resistance. This concept might nonetheless be the most effective concept of the eight alternatives by meaning of the required volume and overall efficiency. One of the starting points of this research is however that the Highrise Energy Storage Core (HESC) incorporates multiple functions into one system. Concept D can provide additional functionality and is therefore subjected to a deeper investigation in chapter 3. This concept requires a slightly bigger building volume and the expected efficiency is less due to friction between the piston and the tube.

The advantages of G versus D are obtained by the application of water. Water under the piston makes it easier to ensure the safety of the system. In case of a leakage, the system is broken and the piston will move downwards, but the speed of descent is limited. The water can also be used for a sprinkler system in case of fire and to enlarge the thermal capacity of the core. Increasing the thermal capacity helps to flatten the temperature peaks during the
summer and the winter. In chapter 3 the advantages of each function will be quantified. By giving a value to each function, the governing functions can be identified. When the value of an additional functionality does not compensate the loss of efficiency, the most optimal concept does not have to be the concept with the biggest functionality.
The advantages of storing electrical energy in a local energy grid have been elaborated in chapter 1 and the options to this in a tall building have been discussed in chapter 2. In this chapter, the properties and the technical problems of a Gravitational Potential Energy Storage (GPES)-system in the construction core of a highrise building are investigated. Besides the storage of electrical energy, this Highrise Construction Tube (HCT) can fulfill a range of building functionalities that require a stand-alone system in most current building concepts. Replacing building systems with the HCT and extending the functionality with a GPES-system has an impact on the building plot, the construction, the building volume, and the building costs. The additional mass that is required in concepts A until G (see section: 2-2) also makes that the inner climate is affected and that foundation needs to support a bigger load.

To investigate the costs and benefits of the HCT, the building with the tube will be compared with a modern tubeless building. This Reference Building Concept (RBC) has the same dimensions, complies with current safety regulations, and already has several building systems that limit the energy consumption. A number of these systems are an activated concrete core, a Combined Heat and Power (CHP)-system, and a low temperature heating system. These systems are also applied in a second Adjusted Building Concept (ABC) that contains the HCT. To make a fair comparison between the two building concepts, the specific characteristics of both concepts are kept the same. The HCT should enhance the functionality of these systems or make it cheaper to implement them. The enhanced functionality or the costs that will be saved in comparison with the standard implementation, will be quantified and if possible expressed in an economic value.

This chapter will only investigate the value of concept A (see figure: 2-4D and 3-1). In this concept, energy is stored by lifting a piston inside the concrete core to the top of the building. When the piston moves downwards, energy is recovered with a hydro turbine. Concept D incorporates multiple building requirements with a limited impact on the building design. The outcome of the inquiry should also give insight in the applicability of the other alternatives.

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Figure 3-1: Highrise building with a Gravitational Potential Energy Storage (GPES)-system placed inside a local grid with solar- and wind energy attached to the grid (storage tube concept: D).
3-1 System characteristics

3-1-1 System size

The starting point of the energy storage capacity for the initial design is 400kWh. This is, roughly estimated, enough to level out the energy peak demand for about two large buildings or a small block of buildings as in figure 3-1. Shaping the tube such that it fits into the grid of the building as in figure 3-3, leads to a slightly larger capacity. The stored energy in the tube is then 432kWh, but the energy required to store this amount of energy is logically slightly bigger due to losses in the charging process. Similarly the effective energy output of the GPES is lower than the maximum stored energy in the tube.

The electrical energy needed to store the maximum energy capacity is:

\[ E_{\text{charge}} = \frac{E_{\text{GPES}}}{\eta_{\text{charge}}} \quad [J] \quad (3-1) \]

and the electrical energy that can be generated from the stored energy is:

\[ E_{\text{discharge}} = \eta_{\text{discharge}} \cdot E_{\text{GPES}} \quad [J] \quad (3-2) \]

where \( E_{\text{GPES}} \) is the potential energy storage capacity of the tube and \( \eta \) is summation of all efficiency losses.

Assuming that the length of the demand peak is 90 minutes and the efficiency is 100%, the average power capacity to charge the system needs to be \( \frac{432 \cdot 60}{90} = 288 \text{kW} \). Assuming that the absolute peak demand is twice the average peak demand, the power capacity needs to be 576kW. The ratio between the power capacity (576kW) and the energy capacity (432kWh) is expressed as the Power-To-Energy (PTE)-ratio. The maximum PTE-ratio is thus 3:2. However, to investigate the efficiency of the system at the average charging or discharging speed, the nominal rated power capacity of the system is only 400kW. The PTE-ratio of the system running at nominal speed is 1:1. This value neglects the extra energy required to compensate losses.

3-1-2 Piston

Piston mass

In the tube concepts with a piston, the mass of this piston has a significant impact on the energy storage capacity of the overall system. The capacity of the GPES is given by the parabolic equation 3-3. From this equation follows that the required building volume to get the desired storage capacity can be minimised by maximising the density of the piston filling and by approaching \( h_{\text{piston}} \) to \( \frac{1}{2} h_{\text{building}} \). In chapter 2, it is assumed that the optimal piston height is equal to \( \frac{1}{8} \) times the building height. This value is much lower than what follows from the equation in this section.

The costs of the piston mass increases proportionally with the height of the piston \( (h_{\text{piston}}) \). However, the storage capacity only grows by the descending differential of equation 3-3. This
means that there must be an optimal size of the piston. For the most optimal solution, the fixed costs and revenues should be known as well.

The equation to calculate the energy capacity is:

\[ E_{GPES} = A_{piston} \cdot g \cdot \frac{h_{piston} \cdot (\rho_{piston} - \rho_{water}) \cdot (h_{building} - h_{piston})}{3600} \cdot 10^{-3} \text{ [kWh]} \quad (3-3) \]

where \( A_{piston} \) is the horizontal cross section surface of the piston, \( g \) is the gravitational acceleration, and \( h \) is the height.

The piston costs comprise the costs of the casing, a watertight sliding connection between the casing and the tube inner wall, and the costs of the piston mass. Density is the most relevant parameter of the filling. Other relevant properties are the price per tonne, embodied energy, availability, and the safety of the material. A waste product will have the benefits of a low embodied energy value and the price per tonne is usually confined. Depleted uranium is probably the most dense waste material, but the considered safety issues make that the field of application is limited[10]. The main safety concerns relate to the emittance of alpha particles. These particles can easily be trapped with just a layer of clothing but when the uranium is damaged and small particles are exposed to people, the long term effects are unknown. When the field of application broadens, the price of depleted uranium is likely to approach the price of lead.

A waste product like a construction aggregate would score positively on all aspects except the density. The difference between the density of water and a construction aggregate is about 1000 kg/m\(^3\). The potential storage capacity will then be about the same as the storage capacity in concepts D and E. Concrete is only 25\% heavier than the aggregates but the storage capacity increases with 50\%.

Figure 3-2 shows the relation between the price and density of the piston filling, the height of the piston, the building height, and the costs per kWh. Three potential piston fillings (sand, iron ore and concrete) have been plotted against the storage costs of lead-acid electrochemical batteries. It also shows that the higher the building is, the more cost-effective the system will be. However, the figure does not include the fixed costs, costs of the casing, nor building volume costs and it does not take into the account the revenues of the HCT.

Sand is the cheapest filling of the three but it has a low density compared to the other materials, a GPES with a sand filled piston would require the largest building volume. The density of iron ore is much larger (5500 kg/m\(^3\)) and the costs are approximately 100€ per tonne\(^1\). The price of concrete is only slightly less compared to the price of iron ore but the density of iron ore is more than twice the density of concrete and, therefore preferred. Higher density materials like lead are not considered because of their high price per tonne (≈ 2000€/tonne). The gray line shows that the piston filling costs per kWh are doubled when the piston size gets to \( \frac{1}{2} h \). A piston height close to \( \frac{1}{2} h \) might be justified when the costs of the building volume are relatively high compared to the costs of the piston building volume, but this requires an optimisation evaluation including all other variables. To calculate the value of the initial design, a piston height of \( h_{piston} = \frac{1}{8} h_{building} \) will be used. The maximum

---

\(^1\)Source: Index Mundi (Nov 2012)
amount of energy stored in the tube, expressed in joule, is then given by:

\[
U_{\text{max}} = m_{\text{piston}} \cdot g \cdot (h_{\text{building}} - h_{\text{piston}}) \quad [J]
\]

\[
= 2.77 \cdot 10^6 \cdot 9.81 \cdot (80.0 - 10.0) = 1.90 \cdot 10^9
\]

The water pressure at the bottom of the tube is constant as long as the friction between the piston and tube is constant. When the friction is being neglected, the water pressure is 1150kPa (11.5bar).

\[\begin{align*}
\text{Concrete} & \quad 500 \quad 1000 \quad 1500 \quad 2000 \\
\text{Iron ore} & \quad 500 \quad 1000 \quad 1500 \quad 2000 \\
\text{Sand (wet)} & \quad 500 \quad 1000 \quad 1500 \quad 2000
\end{align*}\]

\[\text{Pb-acid} \quad \text{Concrete} \quad \text{Iron ore} \quad \text{Sand (wet)}\]

\[\begin{align*}
P_{\text{concrete}} = 90 \text{€/m}^3, \quad P_{\text{sand}} = 5 \text{€/m}^3, \quad P_{\text{ironore}} = 100 \text{€/m}^3
\end{align*}\]

\[h_{\text{piston}} = \frac{1}{2} h_{\text{building}}, \quad P_{\text{building}} = \frac{1}{2} P_{\text{building}}.\]

The price per tonne of iron ore as used in figure 3-2 is based on world commodity prices. However, this value does not take into account transportation costs and it does not include any costs for processing. Nor does it comprise the remaining value of the material after the economic lifetime of the system. This value might even be higher than the current costs of the raw material and it definitely surpasses the remaining value of concrete. To calculate the value of the Adjusted Building Concept (ABC), the processing costs are neglected and the transportation costs are assumed to be 10€/m$^3$. Since selling the ore after the 30 years will also come with some costs, the present value of the remainder worth will be reduced with 25%. The interest rate to calculate the present value is 4%, this can be seen as a conservative value considering the current market conditions. When the remainder value and transportation costs are taken into account, the price per tonne iron ore is 86€. The total costs of the piston mass is then approximately 240.000€.

\[\text{This value is based on the transportation costs of construction debris}[54].\]
Figure 3-3: Section of a highrise building with a Highrise Construction Tube (HCT) and a Gravitational Potential Energy Storage (GPES)-system. With: $h_{building} = 80\,\text{m}, h_{piston} = 10\,\text{m}, d_{piston} \approx 8.1\,\text{m}$. Note: it turns out that placing electrical equipment next to the tube is more convenient.
Piston design and failure modes

The piston slides along the inner wall of the tube. Three rubber tires at the top of the piston make a water tight connection between that inner wall and the piston. This connection (see A in figure: 3-4) will have some friction that directly affect the efficiency of the system. The level of watertightness is an optimization problem. Increasing the watertightness will also increase the friction and the efficiency. When the connection is less watertight, the friction will be less but then some of the efficiency is lost to the transport of water along the piston. By placement of three rings, the pressure gradient can be divided over the three rings. The rubber connection tires are placed at the top of the piston since these parts are subject to abrasion and therefore, must be maintained. The easiest way to replace the tires is by lifting the piston to the top of the building since the water pressure at the top of the building is zero.

When the piston is trapped due to irregularities in the tube wall or any other kind of failure, the piston can bury itself into the concrete wall. In case of failure, undesirable forces will be introduced into the main support structure. Measures should be taken to avoid the risk of forces on, or damage to, the main bearing structure. The wheels (B) at the bottom of the piston will keep the piston straight. This will however not completely take out the risk of a trapped piston.

It is relatively easy to identify irregularities in the lift or descent of the piston by measuring the water pressure at the bottom of the tube. Under normal conditions, the water pressure at that point will be constant. A pressure drop indicates that the weight of the piston and the water above the piston are no longer (or only partially) supported by the water column under the piston. The piston hangs in the tube as shown in figure 3-5A and figure 3-5B. The system should immediately respond to this new situation by pumping water into the bottom of the tube to ensure a counter force. If that fails as well due to a lack of power or a leakage in the return pipe, the bottom of the piston (C) will start to deform. Since the piston is

\[ \Delta p = \Delta p_{\text{water}} + \eta \cdot h_{\text{piston}} \cdot (\rho_{\text{piston}} - \rho_{\text{water}}) \cdot g \]
proportionally supported by the pressured water under normal conditions, the bottom of the piston casing does not need to convey moments as long as it stays supported by the water column under the piston. The bottom is closed but it should not be able to carry the weight of the filling when the force is reduced below the piston. If that is the case, the bottom starts to deform and the filling will move downwards. The deformation and rupture of the bottom plate makes that the piston empties gradually rather than as a sudden shock.

The wall of the piston should be designed to withstand the passive pressure of the iron ore and some of the hydrostatic water pressure. The cover at the top of the piston only keeps the filling on its place. It cannot convey moments and water will freely be able to enter the piston. The pressure inside the piston will then consists of the passive pressure of the piston filling and the hydrostatic water pressure. In the static state situation, the hydrostatic water pressure inside the piston is equal to the pressure in the tube. When the piston starts to move, the water pressure inside the tube proportionally increases or decreases if the piston is saturated. However, how the water pressure is distributed between the piston and the tube wall is not exactly known and depends on how fast the piston moves through the tube. A drag will cause some underpressure between the piston and the tube wall when the piston moves upwards. It is not likely that the pressure is much lower because an overpressure below the piston is the force that moves the piston upwards.

The minimum force on the lowest part of the piston in the static state situation is according to Rankine’s theory defined by equation 3-5. The maximum force is defined by equation 3-5 with \( \eta = 1.0 \). For the calculation of the ABC a value \( \eta = 0.2 \) will be used. The forces in the piston wall can be defined with the thin-walled hoop equation (3-7). From this equation it follows that the thickness of the piston wall in the ABC should be 4.3mm to resist \( P_{p,\text{min}} \) and 6.1mm to resist \( P_{p,\text{max}} \). The thickness in the building concept will be 8mm and the costs of...
the materials to build the piston casing are then approximately 22.500€ \[54\].

\[
P_{p,\text{min}} = K_p \cdot \rho_{\text{piston}} \cdot h_{\text{piston}} \quad [\text{kg/m}^3] \quad (3-5)
\]

\[
P_{p,\text{max}} = K_p \cdot \rho_{\text{piston}} \cdot h_{\text{piston}} + \eta \cdot h_{\text{building}} \cdot g \cdot \rho_{\text{water}} \quad [\text{kg/m}^3] \quad (3-6)
\]

\[
K_p = \frac{1 + \sin \phi}{1 - \sin \phi}
\]

\[
\phi = \text{Angle of internal friction iron ore} \quad (30^\circ - 48^\circ)
\]

\[
\sigma_\theta = \frac{P \cdot r}{t} \quad [N/mm^2] \quad (3-7)
\]

\[
\sigma_{\theta,\text{max}} = 355 \quad (S355)
\]

**Piston motion**

The velocity of the piston at maximum power capacity is 0.0259\(m/s\) and the average speed during peak hours is 0.0129\(m/s\). When the system needs to generate electricity, gravity will pull the piston downwards. For storing electricity, the piston has to be pushed upwards. The force to push the mass into an upward motion is larger than the water pressure in the equilibrium situation. The pumps have to deliver this extra force by means of an extra, temporary, head. A pump has a limited ability to increase the head of the discharge and during that period, the efficiency of the pump is lower than the efficiency during maximum capacity. From the efficiency point of view, the time to get to the maximum capacity should be as long as possible. However, this is only possible in combination with a pressure vessel system that has an unlimited capacity.

The total impulse required to get to the velocity of the maximum power capacity is given in equation 3-8. Startup time and required dimensions of the pressure vessel underneath the piston, are calculated in section 3-1-4. Friction that would slow down the piston, is settled into the required manometric discharge head that is used to calculate the maximum efficiency of the pump in the same section.

The maximum impulse of the piston moving piston is:

\[
E_k = \frac{1}{2} m \cdot U_{\text{max}}^2 \quad [J] \quad (3-8)
\]

\[
= \frac{1}{2} \cdot 2769.6 \cdot 10^3 \cdot 0.0259^2 = 930.7 \cdot 10^3
\]

where \(m\) is mass of the piston, and \(U_{\text{max}}\) is the velocity of the piston when the tube is charged or discharged in 45 minutes.

**Reciprocating sealing**

Water will always try to find the path of least resistance. The water in the tube underneath the piston is pressed by the mass of the piston. This water will flow along the piston towards the unpressed water above the piston mass. A sliding connection between the piston and the tube wall has to avoid the water from dodging the piston and has to guide the piston
movement. The pressure difference that needs to be sealed is equal to the increase of the water pressure caused by the weight of the piston plus a small raise caused by drag. In the Adjusted Building Concept (ABC), the pressure difference value is 0.45MPa plus an estimated pressure drop right underneath the seal caused by drag, of 0.15MPa. Dodge and leakage should be minimised, but minor losses are acceptable.

The reciprocating movement of the piston through the tube is analogous to a piston inside a hydraulic cylinder. In a hydraulic cylinder, a piston sealing ensures that the hydraulic overpressure in the pressure chamber is fully transferred to the piston rod. A rod seal keeps the piston in place and is also needed to avoid leakages from the cylinder and the penetration of dirt into the cylinder. With a properly installed seal, pressured liquid will not dodge the piston, dirt does not enter the cylinder, and the environment is protected from oil leakages or other pollution. The piston sealing undergoes a reciprocating movement and the rod sealing has to withstand a rotary motion. The different movements affect the required shape of both seals and the formation of wear. The HCT does not have a piston rod so only a reciprocating piston sealing is sufficient.

Common solutions to separate the pressure difference between the pressure chamber and the air pressure (or in this case, the water pressure without the weight of the piston) are rubber O-rings, plastic polymer seals in combination with a rubber O-ring(step seal), and composite seals that consists of a plastic polymer and a steel spring (for instance, U-seals and V-seals). O-rings and the composite seals are made of a “self-energizing” elastomer. The plastic seal needs to be energized with an additional O-ring. Energizing means that the seal is pressed against the cylinder inner wall by an initial deformation of the elastomer. The deformed, or squeezed, ring causes the seal to be pressed against the cylinder. The O-ring material under pressure acts like a liquid such that the system pressure difference is added to the initial squeeze pressure. It makes the sealing watertight, even under very high pressure. The O-ring has to be made from an elastomer that is incompressible but also has a high Poisson-ratio to accommodate the deformation.

Although the principle of the GPES piston is similar to the action of a hydraulic piston, the system dimensions are totally different. The operating pressure in hydraulic cylinders is usually much higher(≈ 30MPa) than the maximum pressure difference in the tube. The sliding connection between the piston and the tube only needs to separate a maximum pressure difference of approximately 0.60MPa. Also the speed of the piston is different. The GPES piston moves with a maximum velocity of 0.0259m/s, a piston inside an ordinary hydraulic cylinder moves with a velocity of about 0.2—0.5m/s. Especially for seals made of an elastomer, a low velocity holds or reduces the thickness of the film that is formed between the seal and the cylinder. The film has a positive effect on the friction forces since it acts like a lubricant that reduces the friction forces and the occurrence of wear. However, since the pressure difference in the ABC is relatively low, the friction force will be high[33]. The relation between the velocity and friction is the smallest when plastic polymers are used for the sealing. Plastic polymers (for instance, Polytetrafluoroethylene (PTFE)) also have a high wear resistance and are therefore a commonly applied sealing material. PTFE has a low elasticity which means that a seal requires an additional energizing O-ring or an integrated steel spring.

A PTFE seal can only operate properly when the surface roughness value (Ra) of the cylinder is below 0.25µm[33]. A lower roughness parameter should be strived for since that will reduce the system friction and seal wear. For the concrete core, this level of smoothness is hard to

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achieve. With abrasive smoothing methods like grinding or shotblasting, the roughness of generally applied concrete can only be reduced to $12.0 \mu m$ [36]. Although a roughness value of $\approx 5.0 \mu m$ can be reached by polishing the surface [11] and $\approx 0.5 \mu m$ with high-performance concrete cured in a vinyl mold [43], concrete cannot compete with steel. By polishing steel, a roughness value of $0.1 - 0.25 \mu m$ or lower is feasible. This makes concrete, according to current guidelines, unsuitable for a watertight sliding connection. However, the relative low pressure in combination with an accepted amount of leakage, high-performance concrete and easy replaceable seals might lead to an adequate solution. This requires specific research on the surface wear of concrete, wear of the PTFE seal and leakage due to surface irregularities.

In the design of the HCT, the concrete tube will be adapted such that all reinforcement of the concrete is placed on the inside of the tube (see figure: 3-6A). The steel now has the function of a smooth cylinder surface, it takes up the hoop forces, and it is able to convey tensional stress caused by lateral forces on the building. To bond the steel with the concrete, studs are attached to steel. Probably the biggest challenge during construction is to keep the tube deviations within the tolerances that are acceptable to the sealing system.

The friction force depends on the pressure difference, the velocity of the piston, the roughness of the cylinder, the shape of the seal, the size of the clearance, wear of the seal and the material where the seal is made of. The emergence and the thickness of the lubricating film is therefore hard to predict [33] and fluctuating due to unavoidable irregularities of the cylinder and changes in speed. A sealing system that comes close to the required properties is the single acting Trelleborg Turcon® Stepseal-system in combination with two Turcite Slydring® wear rings. Wear rings are meant to avoid metal to metal contact and to absorb transverse forces. These sealing systems are, up until now, not available in the dimensions required for the HCT ($\varnothing = 8100mm$). Trelleborg sells sealing systems with a maximum diameter of 2700mm.

To calculate the impact of the seal on the efficiency of the GPES, it is necessary to know the friction force. Therefore, it will be assumed that there are no technical limitations to increase the size of existing sealing systems. The friction force can be calculated by multiplying the total force of the seal against the cylinder wall, with a friction factor. As stated, the exact friction factor is not constant and difficult to determine without tests. An average friction factor of $0.1[69]^3$ will be assumed. This value is derived from tests of a reciprocating seal in a steel cylinder. The force that acts on the PTFE seal is conventionally derived with Lindley’s formula [49] (see equation: 3-10). It gives the force that acts on the seal by the initial deformation of the O-ring and it gives the surface of the ring that is connected to the seal.

---

3Samyn et al. measured a friction coefficient of 0.10 for a slowly moving piston under several high loads.
(A) Tube section (top view). Dowels connect the "cylinder" wall with the concrete tube.

(B) Tube section (front view). The water pressure $P$ in the clearance above the seal is equal to the water column pressure. The pressure beneath the seal is equal to the water column plus the pressure increase caused by the weight of the piston (0.6 MPa).

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Table 3-1: Force on cylinder ($F_N$) and friction force ($F_s$) between seal and cylinder wall.

<table>
<thead>
<tr>
<th>$C$</th>
<th>$\varnothing$ [mm]</th>
<th>$b$ [mm]</th>
<th>$P_i$ [MPa]</th>
<th>$\Delta P_f$ [MPa]</th>
<th>$F_N$ [kN]</th>
<th>$F_s$ [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>12%</td>
<td>12</td>
<td>3.76</td>
<td>3.45</td>
<td>0.19</td>
<td>350.7</td>
<td>35.1</td>
</tr>
<tr>
<td>18%</td>
<td>12</td>
<td>5.17</td>
<td>6.44</td>
<td>0.22</td>
<td>875.5</td>
<td>87.6</td>
</tr>
<tr>
<td>25%</td>
<td>12</td>
<td>6.81</td>
<td>11.16</td>
<td>0.26</td>
<td>1978.2</td>
<td>197.8</td>
</tr>
<tr>
<td>25%</td>
<td>8</td>
<td>4.54</td>
<td>7.44</td>
<td>0.26</td>
<td>889.3</td>
<td>88.9</td>
</tr>
</tbody>
</table>

The normal force acting on the cylinder is defined by:

$$F_N = b\pi D (P_i + \Delta P_f) \quad (3-9)$$

with:

$$P_i = dE(1.25 \cdot C^{1.5} + 50 \cdot C^6) \quad (3-10)$$

$$\Delta P_f = \alpha \cdot \frac{P_i (d\pi/2 - a)}{a} \quad (3-11)$$

$$b = \sqrt{\frac{6P_i d}{\pi E}}$$

$$C = \frac{a}{d}$$

where $P_i$ is the contact pressure due to the initial compression of the O-ring, $\Delta P_f$ is the contact pressure due to the system pressure difference, $D$ the tube inner diameter ($= 8100 mm$), $d$ the O-ring diameter ($12 mm$), $E$ elastic modulus of the O-ring material ($70$ shore $A = 5.52 MPa$) and $C$ is the fractional compression.

The pressed, flat section of the O-ring ($b$) due to the initial compression needs to be known to calculate the additional force caused by the system pressure difference ($\Delta P_f$). Yokoyama et al.[88] derived the empirical equation 3-11 to calculate the increase of the contact pressure due to the system pressure. In this equation, the unitless conversion coefficient $\alpha$ is assumed to be the same as derived by Yokoyama et al. (0.4).

The cross section of the O-ring is the largest available. Applying a smaller cross section will make the ring press with a lower force on the PTFE-seal causing less friction between the seal and the cylinder, but this also requires more stringent cylinder tolerances. The initial fractional compression ($C$) is given to be 25% as recommended in the literature. A lower fractional compression means, again, less friction and stricter tolerances. As a large O-ring cross section and a high initial compression might still not be enough to take up the deviations in the tube, minor leakage needs to be accepted.

Table 3-1 shows the initial forces at the cylinder and the resulting friction forces. Time factors like relaxation have been neglected in this calculation. O-rings will relax in time but also swell. These effects work against each other. Therefore, the expected effective contact stress is assumed to be constant over time. Temperature effects are also not considered since the O-ring does not dissipate the friction forces and the seal itself is less sensitive.

$$E_{th} = 2 \cdot \mu_k \int_{z_0}^{z_1} F_N dz \quad [J] \quad (3-12)$$

$$= 2 \cdot 0.1 \cdot 1978.2 \cdot 10^3 \cdot 70 = 2.77 \cdot 10^6$$
From the table it follows that the system pressure difference has a minor effect on the contact pressure. It is also clear that the size of the O-ring and the fractional compression have a major effect on the friction forces. As a conclusion, the mass of the piston does not have a significant impact on the friction forces rather than the cross section of the piston. Equation 3-12 gives the total friction losses for one storage cycle (charge and discharging the system). This is 1.5% of the storage capacity. The seal has a small but not negligible impact on the total round-trip efficiency of the storage system. The extra head delivered by the pumps needed to compensate the friction losses is given by equation 3-13. Seals as applied in this design are meant for pistons with a significant smaller diameter. The largest diameter currently shipped by Trelleborg is only 2700mm. Tolerances are a major issue for the construction of the tube to keep in line with the allowed tolerances for currently available systems. Whereas the tolerances are a bigger problem than some minor leakage, it should be considered to apply an O-ring with a much larger cross-section (>30mm) that is made of an elastomer with a lower Young’s modulus. This will increase the average contact surface with a lower contact stress. The contact normal force is then about the same. At the same time, the seal has more deformation space to adapt to irregularities in the tube wall.

$$h_{pfd} = \frac{F_s}{\rho_{\text{water}} \cdot A_{\text{tube}} \cdot g} \quad [m]$$

$$= \frac{197.8 \cdot 10^3}{1000 \cdot 51.5 \cdot 9.81} = 0.39$$

3-1-3 Water flow

Water transportation through pipes and valves comes along with losses caused by friction and turbulence. While charging the GPES, water is transported from the top of the tube through the return pipe towards the pump(s) and further pushed across an outlet pipe at
the bottom of the building into the tube again. During discharge, water flows in opposite
direction passing the turbine that extracts energy from the flow.
Pumps have to deliver extra power to overcome energy losses caused by friction in pipes, losses
at the water intake at the top of the pipe, and exit losses at the end of the outlet pipe. The
magnitude of these losses is related to the square of the flow velocity and can be minimised
by applying large pipes, by reducing the volume that is transported and, to a lesser extent,
by reducing the friction coefficient of the pipes and valves. The nominal velocity in the return
pipe is \(1.36m/s\) and the maximum flow speed is \(2.73m/s\). The flow of water in the pipes and
the tube is turbulent in all scenarios since the lowest Reynolds number is \(5.9 \times 10^5\) (Re\(=2300\)).

Although the flow in the tube is also turbulent, the losses caused there can be neglected.

Under the assumption of a uniform flow, the hydraulic head loss in the pipes due to friction is
given by equation 3-14. From this equation, it follows that the hydraulic head loss at nominal
charging speed is \(14.7cm\). In this equation, the roughness of the inner wall affects the friction
loss, but since the nominal thickness of the laminar sublayer is relatively small compared to
the diameter of the pipe, the final loss caused by the roughness of the wall is rather small.

A larger return pipe reduces the flow velocity and the corresponding friction- and exit losses,
but it also requires extra steel and building space. The maximum diameter of the return pipe
in the ABC follows more or less from the arrangement of the floor plan (see section: 3-3-1).
The empty corners in figure 3-16 are suited for a pipe, but the space is limited. Taking into
account a sufficient margin, the maximum outer cross-section is \(800mm\). When the diameter
is increased by \(10\%\), the hydraulic head loss is reduced to \(9.1cm\), and by reducing the diameter
with \(10\%\), the head loss becomes \(24.9cm\). It can be concluded that reducing the size of the
pipe rapidly increases the losses.

The resistance in the return pipe is given by:

\[
\Delta H_{v,\text{pipe}} = l_{s,\text{pipe}} \cdot i_w = 86 \cdot 1.7 \cdot 10^{-3} = 0.147 \quad [m]
\]

\[
i_w = f \cdot \frac{U_{\text{pipe}}^2}{2 \cdot D_{\text{pipe}}} = 0.0145 \cdot \frac{1.37^2}{2 \cdot 9.81 \cdot 0.78} = 1.7 \cdot 10^{-3}
\]

(Darcy-Weisbach)

\[
f = 0.0145
\]

(White-Colebrook)

where \(\Delta H_{v,\text{pipe}}\) is the head loss due to the friction in the return pipe, \(l_{s,\text{pipe}}\) is the length
of the return pipe, \(i_w\) is the slope of the pipe resistance and \(f\) is the friction coëfficient according
to White-Colebrook.

The hydraulic head losses caused by the shape of the pipe in longitudinal direction are
expressed by \(\xi\)-values. Multiplying the \(\xi\)-value with the square of the flow velocity results in
the corresponding energy drop. The bend at the bottom of the pipe in turbine mode causes
a \(\xi\)-coefficient of \(0.18\). This leads to a hydraulic head loss drop of \(\Delta H_w = 1.7cm\) at nominal
speed. Another relevant loss is the loss of impulse at the exit the pipe such that the water
level in the level equals the water level in the tube. These exit losses in the top of the return
pipe are approximated as if the pipe opens into a reservoir. The estimated head loss is then
\(16.5cm\) (see equation: 3-15).

\[
\Delta H_v = \frac{U_{\text{pipe}}^2}{2g} = \frac{1.37^2}{2 \cdot 9.81} = 0.165 \quad [m]
\]

(3-15)

Table 3-2 shows an overview of the losses flow losses in the GPES at three different charging
and discharging speeds. Running the GPES at maximum capacity causes significantly more

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Table 3-2: Water transportation losses during peak (t=45 min), average (t=90 min), and off-peak (t=180 min) charging and discharging.

<table>
<thead>
<tr>
<th>Route</th>
<th>$\varnothing$</th>
<th>$\Delta h (t=45)$</th>
<th>$\Delta h (t=90)$</th>
<th>$\Delta h (t=180)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return pipe charge-discharge</td>
<td>780</td>
<td>58.8</td>
<td>14.7</td>
<td>3.7</td>
</tr>
<tr>
<td>Tube charge-discharge</td>
<td>8100</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Entrance (top) charge</td>
<td>780</td>
<td>2.4</td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>Entrance (bottom) discharge</td>
<td>680</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Bends &amp; kinks charge</td>
<td>780</td>
<td>24.7</td>
<td>6.2</td>
<td>1.5</td>
</tr>
<tr>
<td>Bends &amp; kinks discharge</td>
<td>780</td>
<td>10.7</td>
<td>2.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Outlet pipe charge</td>
<td>680</td>
<td>8.1</td>
<td>2.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Inlet pipe discharge</td>
<td>680</td>
<td>12.2</td>
<td>3.1</td>
<td>0.8</td>
</tr>
<tr>
<td>Valves charge-discharge</td>
<td>31.2</td>
<td>7.8</td>
<td>4.1</td>
<td></td>
</tr>
<tr>
<td>Exit (bottom) charge</td>
<td>680</td>
<td>65.9</td>
<td>16.5</td>
<td>7.7</td>
</tr>
<tr>
<td>Exit (top) discharge</td>
<td>780</td>
<td>38.1</td>
<td>9.5</td>
<td>2.4</td>
</tr>
</tbody>
</table>

* Not specified

The main losses are caused by the size of the return pipe and the diameter of the outlet pipe behind the pump (see figure: 3-7).

3-1-4 Pump mode

Figure 3-7 shows the cropped floor section of the basement with the equipment required for the GPES. A single pump and a turbine are placed on the first storey beneath ground floor. To reduce the amount of curves, there is a separate water inlet and outlet. Demanding the GPES to be charged as quickly as being discharged during peak hours, a pump or a set of pumps should be powerful enough to convert an electric power surplus of at least 600kW into hydrodynamic energy. The pump or pumps need to be efficient, have a low maintenance level, and the investment should be low or in line with the other investments. It is preferred that the efficiency of the pump(s) is close to the optimal efficiency on any partial load between 0kW and 600kW.

Compact dimensions, a simple construction, and low maintenance costs make centrifugal pumps the most commonly applied type of pumps [58, Chap 1]. Water is sucked into an impeller that sweeps the water into a rotating motion towards the volute shaped casing around the impeller. The volute determines the direction of the output stream, it reduces mixing losses by forming a uniform flow, and it affects the ratio between the amount of kinetic energy and the velocity of the flow. The motion of the water leaves behind a drag or vacuum in the impeller; this vacuum is filled up again by new sucked water and results into a continuous flow. The efficiency of the pump and the Best Efficiency Point (BEP) is mostly determined by the size and shape of the blades in the impeller. The main disadvantage of centrifugal pumps for the application in the storage system is the relative small load range at which the pump operates close to its maximum efficiency. By making a setup with multiple
Figure 3-7: Pump and turbine top-view. Single pump solution. Pumps and turbine are placed on the ground floor next to the HCT.
pumps, an actuation system can decide how many pumps should be running to perform at maximum efficiency. However, small pumps have a lower BEP compared to pumps with a bigger capacity[17] and require a larger total investment.

An alternative to the centrifugal pump is the positive displacement pump. Positive displacement pumps like rotary pumps or reciprocating piston pumps, have a constant flow rate at fluctuating heads and the overall pump efficiency is slightly better compared to centrifugal pumps. However, the constant flow rate makes it difficult to control the acceleration of the tube piston during startup and during power input fluctuations while moving. A centrifugal pump will automatically generate a higher head at a low flow rate. This will give the tube piston an acceleration while the hydraulic power output and electric power input is almost constant. The power output of a positive displacement pump has to be controlled with a pump drive. The pump piston has to move slowly during startup and needs to accelerate evenly with the acceleration of the piston (see section: 3-1-4). It is not impossible to apply a positive displacement pump but it requires an extra actuator in this specific situation.

Most blades in the impeller of centrifugal pumps are optimized to pump water in a single direction. However, the GPES requires a bidirectional system that pumps water up during an excess of electricity and generates electricity during energy shortages. Although a centrifugal pump is able to operate in the opposite direction and act like a turbine (Pump As Turbine (PAT)), the efficiency is not as good as can be achieved with turbines. The shape of the blades in the impeller can be adjusted such that the efficiency of the pump acting as a turbine is better than with a standard pump, but it will not reach the efficiency of dedicated equipment [73, 87]. A dedicated system is logically more expensive than a solution with pumps only. Since in general, the power costs of GPES systems are high in relation to the energy storage costs (see appendix: A), it is attractive to consider a solution in which lower power costs may be exchanged for a little lower efficiency. This especially applies for small hydro power plants and certainly applies for small hydro power plants in developing countries where spare parts for a more efficient turbine solution are difficult to acquire[19]. Since a GPES in the HCT is not a solution that can be compared to other hydro storage solutions, a new assessment should be made. A solution in which a turbine acts like a pump will is not considered.

**Pump design**

The key parameters for the design of the pump setup are given in table 3-3. These parameters follow from the dimensions of the ABC, the transportation losses in pipes, and the friction losses of the seal. These design values are needed to select the most efficient pump. Since differences in the transported water volume through the pipe affect the friction losses, table 3-3 is only valid for a tube charging time of 90 minutes. Choosing a pump system based on the parameters derived for a 90 minute charging time, means that other pump configurations might perform better at lower or faster charging speeds. However, since the characteristic system curve between 0 and 6000m³/h is almost flat (see figure: 3-10), the required dynamic head delivered during a partial load does not differ significantly in relation to the full load. The starting point of the pump design (t = 90) is the average duration of the supply peak which is assumed to be of the same length as the demand peak.

Pumps suck water from the return pipe into the tube. The pressure at the bottom of the
### Table 3-3: ABC nominal pump design parameters based on a single pump setup (configuration: t=90, single pump).

<table>
<thead>
<tr>
<th>Type/series</th>
<th>N</th>
<th>Impeller [mm]</th>
<th>Flow [m³/h]</th>
<th>Efficiency [%]</th>
<th>Shutoff [m]</th>
<th>Price [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) KSB-RDLO 500-835 A</td>
<td>1 e 2</td>
<td>850.0</td>
<td>2351.8</td>
<td>87.5</td>
<td>55.6</td>
<td>25,000$^a$</td>
</tr>
<tr>
<td>(B) KSB-Omega 350-430 B</td>
<td>1 e 2</td>
<td>440.0</td>
<td>2279.2</td>
<td>86.8</td>
<td>64.8</td>
<td>25,000$^a$</td>
</tr>
<tr>
<td>(C) KSB-RDLO 350-575 B</td>
<td>2 e 4</td>
<td>575.0</td>
<td>1175.8</td>
<td>86.2</td>
<td>50.8</td>
<td>-</td>
</tr>
<tr>
<td>(D) KSB-RPH 300-630</td>
<td>2 e 4</td>
<td>618.0</td>
<td>1175.5</td>
<td>86.0</td>
<td>53.2</td>
<td>-</td>
</tr>
<tr>
<td>(E) KSB-RDLO 600-705 A</td>
<td>1 e 1</td>
<td>740.0</td>
<td>4702.2</td>
<td>88.3</td>
<td>65.63</td>
<td>40,000$^a$</td>
</tr>
</tbody>
</table>

$^a$ Estimated pump costs based on [85, pag. 349].

### Table 3-4: BEP characteristics of a single pump that serves the GPES at nominal system capacity ($H_t = 45.2$, $t = 90$) and maximum system capacity ($H_t = 47.2$, $t=45$). $N =$ simultaneous running pumps

pipe and the inlet of the pump is 7.8 bar. This high water pressure at the inlet of the pump has a positive effect on the efficiency and lifespan of the impeller since it counters the emergence of bubbles caused by cavitation. The bubbles will arise when the pressure drops beneath the Net Positive Suction Head Required (NPSHR)-threshold of the pump. This local pressure decrease is caused by an increase of the water velocity and by turbulence inside the impeller. When the water pressure drops beneath the point that water starts to boil, bubbles may be formed around the blades. The collapse of these bubbles cause small shock waves that eventually damage the blades of the impeller. By maximising the pressure at the intake, the occurrence of cavitation can be minimized. Although a high Net Positive Suction Head Available (NPSHA)-pressure at the inlet does not entirely take away the creation of cavitation bubbles, the consequences of the bubbles are acceptable when the pressure is above the NPSHR-value of the pump. This NPSHR-value can be approximated by calculations but is usually supplied by the manufacturer of the pump as well. Since the water column in the pipe and the atmospheric pressure presses on the inlet of the pump, the required pressure is being fulfilled for all configurations.

A KSB-RDLO-pump in a single pump setup with an impeller diameter of 850.0mm, has an efficiency of 87.6% at a discharge of 2404.7m³/h and a rotational speed of 744rpm (see pump (A) in table 3-4 & figure 3-8). When the total capacity is distributed over two smaller pumps, the efficiency drops to 86.4% even though the two pumps also perform at their BEP. Looking
Highrise construction tube

Figure 3-8: Pump curves for a RSB-RPH pump. Pump performance curve based on a four pump setup with a single pump running (source: http://www.ksb.com, accessed August-2013).

Figure 3-9: Pump curves for a RSB-Omega pump. Pump performance curve based on a two pump setup with a single pump running (source: http://www.ksb.com, accessed August-2013).
at the pump efficiency, the best choice is to place a single pump that operates with a constant discharge. The efficiency drop of the two pumps with a smaller discharge in this comparison is likely to be caused by the physical condition that large pumps have relatively less friction than small pumps, but it could also be caused by a suboptimal application of the pump types. The efficiency of the largest pump is even better, but this gain is nullified by the extra friction losses in the pipes caused by the larger flow.

The main advantage of a multiple pump setup is to charge the tube at various speeds without a significant drop in the efficiency. With more than one pump, it becomes easier to adjust the system to the power supply. Changing the performance of a single pump is also possible, but it comes with extra investments and, especially in this case, the adaptability of such a system is limited. Under standard conditions a pump will always run at full load and the power consumption is only related to the difference in head between the intake and the outlet. However, by throttling the discharge of the pump or by regulating the rotational speed of the impeller, the performance and the power absorption can be regulated. With both methods, efficiency is lost since the pumps will perform outside their BEP. In the first method, a controllable valve narrows the discharge pipe. To overcome the additional resistance, the pump has to deliver a larger head. Since the discharge and power absorption is lower when the required head is higher (see figure: 3-8 & 3-9), the pump power absorption can be regulated to a certain extend. The second methods requires a variable pump drive. The nominal performance curve of the pump can then be shifted by reducing or increasing the rotational speed of the impeller.

The applicability of both methods is limited, since the pumps already have to deliver a large head in the steady state situation, and the available head that can be used to shift the performance curve is rather small. The clearance space at low pump flows hardly gets bigger since the slope of the system characteristic curve is almost horizontal (see figure: 3-10).
investigate the configurability of a pump setup with a variable pump drive, the performance can be approximated by the affinity laws for a constant impeller diameter. The three laws are:

\[
\frac{Q_1}{Q_2} = \left(\frac{n_1}{n_2}\right), \quad \frac{H_1}{H_2} = \left(\frac{n_1}{n_2}\right)^2, \quad \frac{P_1}{P_2} = \left(\frac{n_1}{n_2}\right)^3 \quad (3-16)
\]

where \(n_1\) is the nominal rotational speed of the impeller, \(n_2\) is the adjusted speed of the impeller, \(H_{1,2}\) is the head delivered by the pump and \(P_{1,2}\) is the power input.

The pump power equation is given by:

\[
P = \frac{Q}{3600} \cdot \frac{(H \cdot \rho_{\text{water}} \cdot g)}{\eta} \quad [W] \quad (3-17)
\]

where \(P\) is the energy of the discharge flow, \(Q\) is the discharge flow given in \(m^3/h\) and \(\eta\) is the efficiency of the pump.

Equations 3-16 and 3-17 can be used to calculate the performance of the pump at a reduced or increased rotational speed. The shut-off head of pump (A) is 56.1m but the maximum head at the minimum discharge flow is only 55.2m. When the rotational speed is reduced from 744rpm to 678rpm by a variable drive, the pump discharge head can still be maintained at 45.2m and the minimum discharge flow prescription is still fulfilled. The discharge flow will drop from 2404.7 \(m^3/h\) to 979.8 \(m^3/h\). The efficiency of the pump with the reduced speed drops from 87.6% to 69.0%. To pump the same amount of water with a single smaller pump (C), the nominal rotational speed needs to be reduced from 939rpm to 921rpm. The efficiency of the smaller pump will only drop from 86.2% to 83.9%. This example shows that when the system is required to handle a range of power quantities, a variable pump drive in a single pump setup is insufficient since the energy losses become unnecessarily large.

Table 3-5 displays the calculated minimum values at which the pump setup operates, and it shows the power absorption by running the system with a minimum accepted mechanical pump efficiency of 82.5%. The 82.5% is an arbitrary chosen value that reflects an acceptable efficiency such that a realistic operation range can be defined. With this condition, and also allowing an increase of the rotational speed, the total operation range of a single pump (C) powered by a variable pump drive is 131.2kW until 236.8kW. The losses of a partial loaded pump in this system become significant when the rotational speed of the impeller is lowered such that the absorbed power is reduced by 20% or more. It can be concluded that a variable pump drive only moderately increases the operation range.

<table>
<thead>
<tr>
<th>Pump</th>
<th>N</th>
<th>Minimum power ([m^3/h])</th>
<th>Minimum efficiency ([%])</th>
<th>Efficiency threshold ([kW])</th>
<th>Nominal absorbed power ([kW])</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C) KSB-RDLO 350-575 B</td>
<td>1 e 4</td>
<td>105.2</td>
<td>69.2</td>
<td>131.2-236.6</td>
<td>165.8</td>
</tr>
<tr>
<td>(A) KSB-RDLO 500-835 A</td>
<td>1 e 2</td>
<td>172.2</td>
<td>69.0</td>
<td>227.9-556.9</td>
<td>329.7</td>
</tr>
<tr>
<td>(E) KSB-RDLO 600-705 A</td>
<td>1 e 1</td>
<td>368.0</td>
<td>61.2</td>
<td>485.7-1186.8</td>
<td>683.8</td>
</tr>
</tbody>
</table>

Table 3-5: The operation range of three pump setup configurations. The minimum power column represents the absorbed power of the pump at the minimum advised pump flow. The efficiency threshold is the absorbed power with a minimum accepted mechanical efficiency of 82.5%.
The minimum absorbed power of a single pump (E) exceeds the nominal absorbed power of pump (A). Pump (E) operates at a much lower efficiency such that one pump (E) running at part load still can be used to replace two smaller pumps (A) running at nominal speed. However, the maximum absorbed power of the single pump is larger than the multiple pump configurations but since the system resistance curve is quadratic (see figure: 3-10), friction losses become significant when the system is charged faster than the nominal speed of pump (E). From the values in the table it can also be concluded that the operational range is only moderately increased with a variable pump drive. When the pump system contains multiple pumps, only one pump has to be equipped with a variable pump drive since the pressure at the inlet of the pump is constant.

Motor/pump drive

The pump is driven by an electric motor which directly transmits the power from the motor to the shaft of the pump. Similar to the characteristic curve of the pump itself, the efficiency of the pump motor is defined by a curve that describes the relation between the load and the efficiency of the motor. The motor has one point where it operates at maximum efficiency and less at any partial load. However, the characteristic curve of the motor is less steep in the relation to the pump performance curve and is here simplified by the assumption of being constant. The partially loaded system employs multiple motors which all perform close to their maximum efficiency point. When a system is powered by a variable speed drive, the efficiency drop of the partially loaded motor should be taken into account.

Size effects also apply to the motors similar to the size effects of pumps. Again, large motors are more efficient [44] but this especially applies to motors with a rated capacity below 100kW. Table 3-6 shows the characteristics of the motors which are needed to drive the pumps.

Startup time

The piston at maximum capacity has an up- or downward velocity of 0.0259 m/s. The impulse of the piston at this speed is 9588.3 \times 10^3 \, J. When the piston is at rest in the top of the tube,
Highrise construction tube

gravity will be able to pull the piston into a downward motion and add impulse to the piston. For the piston in the bottom position, another force is required to accelerate it into the upward motion. This force can be delivered by a pump. The maximum force that can be generated by the pump to lift the piston is related to the difference between the minimum force required to start the acceleration and the maximum head of the pump.

The problem of a centrifugal pump is that it has to deliver the force together with a certain minimum discharge flow. At the start of the acceleration, there is no space for the discharge of the pump. When the pump runs at zero discharge or the discharge flow is only small, the same water keeps rotating in the impeller. This will be the cause of vibration and the temperature of the liquid in the impeller may rise such that it eventually vaporises. Vapor will lead to excessive wear of the blades in the impeller and it reduces the cooling capacity that is needed to cool the bearings. It should be avoided that a centrifugal pump has to run dead-headed (=zero discharge), or the time that it runs with a low discharge flow should be minimized. The pump manufacturer specifies a safe lower limit for the minimum discharge flow such that problems caused by a low flow are prevented. This lower limit is the $Q_{min}$ in figure 3-8 and 3-9.

Since water is incompressible and there is no other space for any discharge at $t = 0$ in the reservoir underneath the piston, the pump cannot start to push the piston upwards without solving the problem of a pump running dead-headed. Therefore, the startup process should be such that the pump can generate enough head to lift the piston while the pump discharge is accommodated.

There are several methods to accelerate the piston from standstill to the desired steady state velocity. The first and simplest method is to accept that the pump runs dead-headed at the initial point of the startup process. During pressure build up and in the initial point of the piston acceleration there is no discharge, so stuttering of the pump and an increase of the water temperature has to be accepted. This has a negative effect on the lifetime of the pump, it is inefficient, and can only last for a short period. Nonetheless, it is not impossible and it does not require any additional investment in controlled valves, pressure vessels, or spring systems. The pressure in the reservoir increases with the same speed as the pump is able to accelerate. When the piston is getting speed, the pump discharge can be accommodated in the freed space underneath the piston and the delivered head will drop. This method is analysed as a reference alternative in a numerical simulation since it is not a desired solution (see appendix: B).

A second solution is achieved by the addition of an air pressured vessel that acts like an expansion tank or a spring loaded accumulator. At $t = 0$, the piston rests at bulkheads in the bottom of the tube. The pressure between the bulkheads and in the vessel is then equal to the static water pressure in the return pipe (7.8 bar). Once the pump starts to run, the water pressure between the bulkheads and in the vessel will increase to 12.3 bar. As the pressure further increases towards the pump shut-off pressure (max 14.2 bar for an Omega 350-430B pump), the piston starts to accelerate. Once the piston moves, there is space for the discharge of the pump. The vessel capacity should be large enough to accommodate the pump’s discharge until the velocity of the piston times the tube section surface plus the discharge flow of the vessel, is larger than the discharge at the maximum head of the pump. This solution needs a relative large vessel capacity. The piston velocity and the pressure in the reservoir for this solution is also analysed in appendix B.
The third solution is a derivative of the second solution and contains an actively pressured vessel. Before the pumps are started, the vessel is pressured with an additional pump that is able to increase the pressure inside the vessel (> 12.3 bar). The GPES is started by opening the valve that closes the vessel. Since water is incompressible, and when losses are ignored, the pressure under the piston is then instantly increased to the vessel pressure. This overpressure will put a force on the piston that accelerates the piston until the pressure drops beneath 12.3 bar. As soon as the piston starts to move, the pressure drops together with the acceleration of the piston. At this point, the pump needs to take over the pressure delivered by the vessel. This solution requires a neat match between the opening of the valve and the acceleration of the pump itself. The size of the vessel and the pressure inside the vessel needs to be large enough to accelerate the piston until the velocity of the piston times the tube section surface plus the discharge capacity of the vessel, is larger than the discharge at the maximum head of the pump. Since the reservoir pressure does not drop beneath 12.3 bar, the pump does not have the time to build up pressure which makes it even more difficult to match the vessel size with the characteristics of the pump.

By placing springs on the bulkheads, the acceleration of the piston can be further increased and the pressure required to start the acceleration can be reduced. When the piston lands on the end of the GPES discharge path, the springs are charged. With the potential spring force, it is possible to accelerate the piston with a much larger force. The vessel is charged with a pressure equal to the water pressure plus the pressure resulting from the piston mass (> 12.3 bar). When the vessel is charged, a valve closes the interaction between the tube and the vessel. At t = 0, the piston mass leans on a plate with holes. This plate is carried by the pressed springs that are placed on the bulkheads. To get the piston into motion, the overpressure in the vessel is released into the reservoir underneath the piston. The overpressure in combination with the springs, will push the piston into an upward motion. Under the same conditions as in the second and third alternative, the pump has to take over the lifting force once the piston has a sufficient velocity.

With the numerical simulation model, the reference solution and the air pressured vessel alternative are verified. The model checks for a given configuration if the initiated motion is enough to accommodate the discharge of the pump and if the pressure in the reservoir during the startup process does not surpass the shutoff-head of the pump. It does not optimize the design values of the vessel but it gives insight in the timescale and the effect of the mass on the inertia of the whole system. With a similar model, it is analysed if the pump tolerances are large enough to accelerate the piston along the charge path in a multiple pump setup.

The first conclusion from the simulation is that the timescale of the piston acceleration itself is only 0.02 seconds. The overpressure that can be delivered by all investigated pumps is more than enough to accelerate the piston to the desired steady state velocity. Springs to increase the lifting force are not necessary. From the short acceleration time it could be concluded that just the reference solution might be sufficient as the pump runs outside its recommended operation range for only about 0.02 seconds. However, the simulation does not take into account the inertia of the pump itself. The pump will also run dead-headed during its own acceleration. This makes that the total time to accelerate the piston is larger than the calculated timescale.

The simulation of the solution with the air pressured vessel predicts that the piston will stutter during its acceleration. Before the maximum pressure is reached, the piston already
starts to accelerate. Once the vessel is charged by reaching the maximum reservoir pressure, the pump discharge drops. At this point, the vessel continues the acceleration of the piston while losing pressure. This goes on until the pump is able to catch up again. Although the simulation again does not take into account the inertia of the pump, it does show that the interaction between the pump and the air pressured vessel has negative side-effects. An undulating acceleration of the piston might even be more damaging to the whole system then the damage caused in the reference alternative. It can also be concluded that an expansion vessel that is often used in piping systems to limit the damage caused by a potential water hammer cannot be used in a GPES system, since it causes stuttering during acceleration. Overpressure in the system should be reduced with a relief valve or vessel that dissipates energy.

A dashpot that is able to dissipate the pump energy will solve or at least reduce the amplitude of the stuttering piston. The required size of the dashpot vessel is approximately $0.5m^3$ plus the volume needed to store the discharge during the acceleration of the pump. Another commonly applied solution to solve the problem of a pump running dead-headed is a recirculation line. When the pressure at the discharge side of the pump gets above a certain value, an automatic recirculation valve opens and recirculates water from the upstream to the pump’s inlet. This recirculation valve should also open when the pump itself starts to accelerate and the overpressure is still low. The recirculation valve requires an extra actuator such that it also has to open during the pressure build up of the pump. When the system contains at least one pump with a variable pump drive, a smart controlled system that slowly increases the rotational speed of the impeller, will also help to reduce the amplitude of the stuttering.

In all solutions, the time it takes to accelerate the piston is insignificant to the total operation time of the GPES. The pump does not operate at full efficiency during startup but the resulting losses can be neglected.

### 3-1-5 Turbine mode

As power is needed from the GPES to level out a demand peak, a generator driven by a turbine wheel (prime mover), converts the mechanical energy of the rotating turbine into electrical energy. The purpose of the turbine wheel or runner is to convert water pressure, the kinetic energy of the flow, or a combination of both into mechanical energy. A water turbine in a Pumped-Storage Hydroelectricity (PSH) system usually has a more or less constant supply, but the demand can differ especially when the turbine operates in island mode. This has many similarities with a generator attached to a wind turbine. Wind turbines are also connected to the grid but have to operate with a fluctuating mechanical power supply at a constant voltage and frequency. These similarities are used to identify the best generator type for the HCT.

The mechanical power delivered by the runner per rotation relates to the magnitude of the force and the size of the flow. The delivered power can be controlled to a certain extent by regulating the force acting on the blades or by throttling the flow passing the runner. However, the runner has only one point where the power conversion per rotational speed is optimal, so it is preferred to stick with the nominal speed.
The rated power capacity of the turbine should be approximately 400kW as stated in section 3-1-1. A turbine with this capacity is classified as a small hydro power installation. The capacity classification makes sense since it has a clear link with the size, rotation speed, and the efficiency of the different components.

**Generator selection**

All utility plants powered by fossil fuels or driven by hydropower have a Synchronous Generator (SG) that converts the mechanical energy of the prime mover into electrical energy[40]. The prime mover firstly converts the pressure and kinetic energy of the gas or water into mechanical energy by putting the turbine into a rotational motion. The rotor speed multiplied by the amount of pole pairs in the generator defines the frequency of the alternating current delivered by the generator. When generators are attached to a large grid, the generated frequency and voltage have to be equal to the frequency and voltage of that grid. Since the frequency of the mains is constant and cannot be influenced by a rather small generator, the rotational speed of the SG, and consequently the velocity of the prime mover, needs to be constant as well. When the prime mover speed is substantially smaller than the required rotor speed and the amount of pole pairs cannot be raised due to a limited amount of space, a gearbox has to be placed between the prime mover and the generator shaft. This is undesirable but usually only required for wind turbines. Hydro turbines have a much higher specific rotational speed and can usually be attached to the generator through a direct drive mechanism. The rotor of the generator has to have a fixed speed but the power output of the generator can still be adjusted by changing the amount of current delivered by the generator.
A turbine will be put out of service when the flow and force acting on the turbine is not large enough to keep up with the required and fixed rotational speed of the generator. To avoid extreme loads on the blades and in the generator, the turbine will also be turned off when the flow reaches its cut-off speed. This reduces the operational time which is especially an issue for wind turbines since the wind force constantly changes. Regulating the flow towards the turbine or controlling the energy extracted from the flow can cancel out, or at least reduce, the effects of fluctuations. The turbine will then not extract an optimal amount of energy from the flow at all times but the delivered power will be more constant and predictable. The driving force of a water turbine can be throttled by narrowing the wicket gates, narrowing the nozzle supply, or by rotating the blades of the runner. Modern wind turbines have a similar pitch control system that enables the blades to rotate around their own axis such that the force captured by the blades can be increased or decreased. The driving force in the selected GPES alternative is constant and stays constant over the whole discharge process.

An alternative approach to enhance the operation range of a turbine in combination with a Synchronous Generator (SG) is the generator running in a variable speed mode. The turbine and the generator will rotate with a fluctuating speed depending on the amount of available power at the runner. As a consequence, the generator running at a partial load will produce electricity with a lower frequency. In order to synchronize the electricity with the grid, a frequency converter is placed behind the generator. This converter contains a rectifier that transforms the Alternating Current (AC) from the generator to a Direct Current (DC). The DC is then inverted back to AC at the frequency of the grid.

When the prime mover delivers more power, the current in the stator increases. A higher current through the stator windings will also increase the magnetic stator field. This leads to a decrease of the rotor magnetic field strength and subsequently in a decrease of the output voltage. The voltage produced by the SG has to be equal to the voltage in the mains and because of the difference between the terminal voltage and the voltage in the grid, the generator will start to use reactive power from the grid. The generator is then said to be under-excited. When the grid cannot supply the required reactive power, the generator starts to operate as if it is an induction generator. To catch up with the grid voltage, the exciter has to increase the DC through the rotor. This exciter contains therefore an Automatic Voltage Regulation (AVR) system that supplies the voltage required in the excitation windings such that the terminal voltage increases together with the resulting output voltage[9].

A variable speed generator in combination with a system that controls the force on the turbine does not only extend the operation range but it also enables a shift of the optimal working point. The shape and size of the blades define the characteristic curve of the runner. By changing the shape of the blades or changing the angle between the flow vector and the plane of the blade (angle of attack) the characteristic curve of the turbine can be changed as well. Each curve has its specific maximum working point. The collection of optimal working points is also known as the turbine operating power curve. When the turbine operates at one of these maximum efficiency points, it will obviously generate more energy, it will cause less noise, and the arise of cavitation bubbles will be less problematic. The widened operation range and the enhanced overall efficiency have to outweigh the initial costs of the electronic devices and the loss in efficiency due to these controlling devices.

In contrast to the Asynchronous Generator (AG), a SG does not have to be attached to a larger grid. The SG is able to regulate its own frequency, voltage and the delivered current.
can be regulated between the efficiency boundaries of the runner and the generator. This enables the turbine to run in island mode [40].

An AG or induction generator works on quite a different principle and has to be attached to a grid. When there is no load on the generator, the rotor turns with almost the same frequency as the grid. A loaded generator makes the rotor turn slightly faster and thus at a little higher frequency. Higher loads make the rotor go faster with a larger torque and partial loads make that the rotor operates closer to the frequency of the grid with a lower torque. The force on the generator is limited between the highest and lowest point of the torque-speed characteristic curve of the generator. Although the rotor frequency of an AG differs from the grid frequency, the produced electric power alternates at the grid frequency.

Utilities do prefer SG’s since these generators are able to produce reactive power. Reactive power is needed to keep the voltage up during transportation and it is required in networks with inductors like motors and transformers. Large AG’s need reactive power where SG are able to absorb and supply reactive power. The reactive power to excite the magnetic field of the stator in the AG can be provided by the grid, a converter, or a capacitor. This implies that there is a dependency relationship between AG’s and SG’s in a grid and that there is also a maximum amount of AG’s in that grid. Therefore, as a rule of thumb, the origin of the electric power delivered in a grid by AG’s should not exceed 30%. During power shortages and high loads the demand of reactive power increases what cannot be delivered by AG’s.

Many older wind turbines and small hydroelectric power stations have an AG since the design is simple, the generator is rather cheap, and it does not require additional electric devices. The power range of the generator is relatively large but the rotational speed differences are rather small, which makes the total operation range also quite small compared to a synchronous variable speed generator. Most modern wind turbines employ a Doubly Fed Induction Generator (DFIG) which is able to cover even a larger speed range by shifting the torque-speed characteristic curve along the speed axis [40]. A low frequency AC current is injected into the rotor windings such that the equilibrium rotor speed of the generator is lowered or raised. DFIG generators are able to produce reactive power.

**Generator protection**

Generators should be protected against abnormal operating conditions caused by faults of a single component in the electric-, or mechanical system or by extreme fluctuations in the grid [86]. Besides the precautions that should be taken in any power generating system, the electric- and mechanical system of the HCT should be designed such that even in abnormal situations, the generator and turbine gradually slows down. Often caused by broken transmission lines in the mains, the electric system can be exposed to very high loads or zero load. In case of zero load or an open line, the generator might runaway since the counterforce to react with the mechanical driving force is gone. An increase of the rotational speed leads to extra heat caused by friction and extra centrifugal forces in the turbine and the runner. This should be stopped as quickly as possible by holding the mechanical energy delivered by the runner. A sudden shutdown of the runner will cause damage to the turbine and might excite a waterhammer in the pipes and the tube. Therefore, the speed-governing mechanism, a break, or a water bypass around turbine should take away the mechanical energy supply and gradually slow down the generator.
Another issue that could arise for SG’s attached to the grid is a voltage drop in the grid during a power overload. This overload can in example be caused by a drop-away of a single generator or by an unpredicted sudden increase in demand. The equations for complex impedance show that the voltage drop for heavy loaded transmission lines is larger than in average loaded lines\(^4\). To compensate the voltage drop, extra reactive power has to be injected into the grid but this reactive power will also put an extra load on the transmission lines and it reduces the power factor of generators. The exciter will try to increase the voltage output of the generator but since a single generator cannot increase the voltage of the whole grid, the generator will only start to produce reactive power. Extreme production of reactive power in an overloaded grid should be avoided. The generator needs therefore to be protected against over-production of reactive power.

**Table 3-7: General overview of generator type characteristics**

<table>
<thead>
<tr>
<th>Synchronous generator</th>
<th>Synchronous generator with an AVR</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Enables to run turbine in island mode</td>
<td>+ Wide range of operation speeds</td>
</tr>
<tr>
<td>+ Can produce or absorb reactive power</td>
<td>– Requires protection against over-excitation</td>
</tr>
<tr>
<td>– Single rotational speed</td>
<td>–– Expensive generator and electronic devices</td>
</tr>
<tr>
<td>– Expensive generator and electronic devices</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Asynchronous generator</th>
<th>Doubly Fed Induction Generator (DFIG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Low initial investment</td>
<td>+ Speed adjustments possible</td>
</tr>
<tr>
<td>+ Simple design, low maintenance costs</td>
<td>+ Can produce or absorb reactive power</td>
</tr>
<tr>
<td>± Minor speed adjustments possible</td>
<td>± Moderate initial investments</td>
</tr>
<tr>
<td>– Needs reactive power from the grid</td>
<td>± Limited amount of relative cheap electronic devices</td>
</tr>
<tr>
<td>– Depending upon the frequency of the grid</td>
<td></td>
</tr>
</tbody>
</table>

**Efficiency of generators**

The maximum efficiency of generators lays generally between 93% and 99% where the latter is merely attainable for very large generators running at a fixed speed. SGs are seemingly slightly more efficient than AGs\(^4\) but this cannot be stated from data provided by manufactures. The optimal working point of a SG is at approximately 75% of the rated capacity. The rated power of a SG should therefore be about 533kW and the maximum efficiency is then 96%\(^4\).

An overview of a few potential generators to be employed in the ABC are given in table 3-8. The characteristic curve of an SG is much flatter than the characteristic curve of a pump. When the minimum accepted efficiency of the generator is 94%, the operating range is between 240kW and 640kW. Partial loaded generators that operate outside this range run with a much lower efficiency. The AG efficiency curve has a similar shape\(^5\) but is not further defined.

\(^4\)See i.e. *Electrical Power System Essentials*[70]

A.W.Oldenmenger

Master of Science Thesis
### Table 3-8: Generator characteristics for a turbine setup with a rated capacity of 400kW.

<table>
<thead>
<tr>
<th>Label</th>
<th>Type</th>
<th>Rated capacity</th>
<th>Maximum efficiency</th>
<th>Price (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Literature</td>
<td>Syn-/Asynchronous</td>
<td>500kW</td>
<td>96.0%</td>
<td>-</td>
</tr>
<tr>
<td>GAK315 L4 (4-pole)</td>
<td>Asynchronous</td>
<td>400kW</td>
<td>95.6%</td>
<td>??</td>
</tr>
<tr>
<td>GSH400 L4 (4-pole)</td>
<td>Synchronous</td>
<td>640kW</td>
<td>95.4%</td>
<td>??</td>
</tr>
</tbody>
</table>

### Table 3-9: ABC nominal turbine or PAT design parameters (configuration: t=90).

<table>
<thead>
<tr>
<th>Param</th>
<th>Composition</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_s$</td>
<td>$\frac{P_{ns}+P_{ntb}}{\rho \cdot g}$</td>
<td>124.1m</td>
<td>supply head</td>
</tr>
<tr>
<td>$h_d$</td>
<td></td>
<td>80.0m</td>
<td>discharge head</td>
</tr>
<tr>
<td>$h_{gs}$</td>
<td>$h_s - h_{fs} - h_{pfs} - \Sigma h_{fvs}$</td>
<td>123.6m</td>
<td>manometric supply head</td>
</tr>
<tr>
<td>$h_{gd}$</td>
<td>$h_d + h_{fd} + \Sigma h_{fvd}$</td>
<td>80.3m</td>
<td>manometric discharge head</td>
</tr>
<tr>
<td>$H_g = H_t$</td>
<td>$h_{gs} - h_{gd} - \frac{v^2_{max}}{2g} + \frac{v^2_{inj}}{2g}$</td>
<td>43.1m</td>
<td>total dynamic head / turbine head</td>
</tr>
</tbody>
</table>

### Turbine selection options

There are four principal types of generally applied hydraulic turbines which have their own field of application. The Pelton turbine extracts energy from an incoming water flow by converting its impulse to a mechanical rotation of the turbine runner. Water is piped by a nozzle towards the buckets of the turbine wheel and leaves the turbine with a much lower velocity and thus with a lower impulse. The impact of the water hitting the buckets on the blades gives the torque that is needed to rotate the generator. The impulse principle makes the Pelton wheel most suitable as the head difference is large. This type of turbine is therefore usually employed when the head difference is between 100m and 1770m\[21\]. Besides the friction losses in the pipe system, energy is lost due to water turbulence near the nozzle, friction in the bearings and due to the remaining impulse of the water flow near to the exit nozzle. The rotational speed of the turbine is controlled by a needle valve that throttles the flow in nozzle. Since the remaining impulse loss is almost equal to the exit losses that are already defined in the transportation losses table 3-2, these can be subtracted from the wheel efficiency losses. The Pelton turbine has a maximum overall efficiency of approximately 90% but this does not take into account the pipe and tube friction losses. The total dynamic head in the HCT is only 43.3m (see table: 3-9) and the system requires that the exit nozzle head is 80.3m. An impulse flow hitting the buckets underwater would come with large losses. It is clear that the Pelton turbine is unsuitable for the HCT.

For large flows with a low head difference, the most commonly applied turbine type is the Kaplan turbine. The Kaplan is an axial reaction turbine that looks and acts like an inversed marine propeller with the difference that it has adjustable runner blades. The water pressure and the impulse of the flow pushes the blades into a rotational motion around the axis of the flow direction. Along the turbine blades the water pressure drops gradually. By rotating the runner blades around their own axis, the operation point can be changed and the efficiency enhanced at partial loads. With wicket gates at the water intake, the working range can be further increased but this imposes an extra need for space at the intake. A Kaplan turbine
running at a partial load hardly effects the efficiency of the turbine. Since the turbine has
to accommodate large flow rates to get sufficient energy from the low head difference and
also has a good performances when the flow is small, this turbine is pre-eminently suitable
to extract energy from a water flow in a river. A Kaplan turbine has a maximum efficiency
of 94% and is usually applied when the head is between 6m and 70m.

The Francis turbine proposes the highest potential efficiency and is widely used in the head
height range between 20m and 900m. Similar to the Kaplan turbine, energy is extracted from
the flow by converting the pressure and the impulse to a rotational movement of the runner
around its axis. The water flow enters the turbine through a tapered shaped volute that
surrounds the runner. Guide vanes around the runner direct the flow towards the runner.
Separate adjustable wicket gates enables a wider operation range by changing the flow rate.
Losses are mainly caused by friction in the volute and the runner, by the residual energy
in the exit flow and by friction in the bearings. The Francis turbine can reach a maximum
efficiency of 95 to 96%.

A cross-flow turbine, also known as the Ossberger or Banki-Michell turbine, is often used in
small hydropower stations with a capacity up to a few megawatts. It optimally operates with
a head between 2.5 meters and 200 meters. The simple and self cleaning design makes it
easy to maintain. Cross-flow turbines are impulse turbines, have a flat efficiency curve, and
are classified as a slow speed turbines. The main disadvantage is the relative low maximum
efficiency.

The Pelton turbine is not suitable due its operation range which is not efficient in relation
the characteristics of the HCT. The cross-flow turbine is relatively inefficient and the low
maintenance benefits are better reflected in a situation where the water flow contains pieces
of wood or grass. The Kaplan turbine is not as efficient as the Francis turbine but does have
a wider operation range.

**Turbine characteristics and operating efficiency**

Similar to the principles of pumps, the turbines can only reach their maximum efficiency
when they have a certain minimum size. In smaller turbines the friction surface between the
wall and the water is relative large. Since the required turbine is rather small, the maximum
efficiency of the turbine types will not be met. Assuming that the efficiency drop for both
turbine types is equal, the choice of the Kaplan is justified when the GPES system is mainly
used to match the fluctuating demand of a rather small grid. When the storage system is
used to support the mains, the optimal efficiency of the Francis turbine is a more crucial
characteristic.

Selecting the most suitable turbine type in a specific situation can be based on the head range
of a turbine type(as done in the previous section), the capacity, the operation range, and the
optimal specific speed. The specific speed is the scaled rotational velocity of a turbine type
and will always refer to the optimal efficiency point. A Kaplan turbine operates optimally
when the specific speed is between 1.8 and 5.0 radians per second and the specific speed of
a Francis turbine lies between 0.4 and 2.2[21]. The cross-flow and Pelton turbines have their
specific speed below the specific speed of a Francis turbine.
The specific speed is defined as:

\[ \Omega_{sp} = \frac{\Omega \sqrt{P/\rho}}{(g \cdot H_g)^{5/4}} \quad [Rad/s] \]  

(3-18)

where \( \Omega_{sp} \) is the power specific speed in radians per second, \( \Omega \) is the rotational speed of the generator divided by the amount of pole pairs, \( P \) is the rated power of the turbine and \( H_g \) is the dynamic head at the turbine inlet.

Solving equation 3-18 for a tube power input of 400kW and a four pole generator leads to a specific speed of 1.63rad/s. This is an appropriate value for a high speed Francis turbine with a maximum efficiency of 96%[53]. A cross-flow turbine would also suffice with an eight pole generator at a specific speed of 0.82rad/s but the operating principle comes with significant larger losses. The Kaplan turbine needs a 2-pole generator and the specific speed is then 3.26rad/s. When the turbine is partially loaded to exactly match the power demand in a small grid, the Kaplan turbine is the preferred turbine type. Francis turbines are however the most efficient turbines and are therefore the favored solution in the ABC. Unlike most slow rotating wind turbines, the water turbine in this situation does not require a gearbox to run at an optimal velocity. The use of a gearbox should be avoided when possible.

Equation 3-18 describes the power specific speed of a turbine. The method followed here to acquire the dimensions of the Francis turbine as described in table 3-10 is to calculate the shaft specific speed with the relation found by Lugaresi and Massa[53]. Subsequently, the shaft specific speed is used to derive the rotational speed of the turbine. The turbine speed derived with the shaft speed is then rounded to a speed that matches a viable frequency for the generator. A recalculated shaft specific speed is used to get the specific diameter of the turbine. Equation 3-19 can than be used to calculate the diameter of the turbine runner.

\[ D_2 = D_s \cdot \sqrt{Q} = \frac{1.41 \cdot \sqrt{1.037}}{(9.81 \cdot 42.2)^{5/4}} = 0.31 \quad [m] \]  

(3-19)
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotational speed</td>
<td>$\Omega = 1500\text{rpm}$</td>
<td>Derived from the shaft specific speed</td>
</tr>
<tr>
<td>Number of poles</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Mechanic power output</td>
<td>400kW</td>
<td>Shaft power</td>
</tr>
<tr>
<td>Rated output capacity</td>
<td>500kW</td>
<td>$\text{BEP} = 0.80 \approx 400\text{kW}$</td>
</tr>
<tr>
<td>Flow rate</td>
<td>$1.037\text{m}^3/\text{s}$</td>
<td>$Q = \frac{P_{\text{francis}}}{\eta H_{\text{g}}}$</td>
</tr>
<tr>
<td>Shaft specific speed</td>
<td>$\Omega_s = 1.70$</td>
<td></td>
</tr>
<tr>
<td>Power specific speed</td>
<td>$\Omega_{sp} = 1.63$</td>
<td>$\Omega_{sp} = \sqrt{\eta_{\text{francis}}} \cdot \Omega_s$ with $\eta = 0.916$</td>
</tr>
<tr>
<td>Blade speed</td>
<td>$U_2 = 24.3\text{rpm}$</td>
<td></td>
</tr>
<tr>
<td>Number of blades</td>
<td>$Z = 13$</td>
<td>$\frac{1}{U_2^2} \geq Z \leq \frac{13\Omega_s}{U_2^2}$. $Z$ should be a prime number</td>
</tr>
<tr>
<td>Hydraulic and mechanical efficiency</td>
<td>91.7%</td>
<td></td>
</tr>
<tr>
<td>Minimum efficiency range (90%)</td>
<td>$310\text{kW} - 472\text{kW}$</td>
<td>Operation range with a minimum</td>
</tr>
<tr>
<td>Minimum efficiency range (85%)</td>
<td>$219\text{kW} - 526\text{kW}$</td>
<td>accepted efficiency.</td>
</tr>
<tr>
<td>Inlet diameter</td>
<td>$D_1 = 0.27\text{m}$</td>
<td>Derived from source: [4]</td>
</tr>
<tr>
<td>Runner diameter</td>
<td>$D_2 = 0.31\text{m}$</td>
<td>See equation 3-19</td>
</tr>
<tr>
<td>Outlet diameter</td>
<td>$D_3 = 0.37\text{m}$</td>
<td>Derived from source: [4]</td>
</tr>
</tbody>
</table>

Table 3-10: Characteristics of the Francis turbine and generator in the ABC with a rotational turbine speed of 1500rpm.

The efficiency of the turbine is given by $\eta = \eta_m \eta_H$[21] where $\eta_m$ is the mechanical efficiency and $\eta_H$ is the hydraulic efficiency. Hydraulic efficiency losses include swirl losses, diffuser losses at the exit of the turbine, and losses caused by the residual impulse of the exit stream. The residual impulse loss is already defined in table 3-2. Since the turbine is relatively small, the mechanical efficiency coefficient $\eta_m$ will be quite low and this should be considered in the overall efficiency calculation.

The efficiency of the turbine is given by $\eta = \frac{\eta_m \eta_H}{\eta_{\text{francis}}}$[21] where $\eta_m$ is the mechanical efficiency and $\eta_H$ is the hydraulic efficiency. Hydraulic efficiency losses include swirl losses, diffuser losses at the exit of the turbine, and losses caused by the residual impulse of the exit stream. The residual impulse loss is already defined in table 3-2. Since the turbine is relatively small, the mechanical efficiency coefficient $\eta_m$ will be quite low and this should be considered in the overall efficiency calculation.

The runner diameter of a Kaplan turbine is given by[4]:

$$D_e = 84.5 \cdot (0.79 + 1.602 \cdot \eta_s) \cdot \frac{\sqrt{H_t}}{60 \cdot n}$$  \hspace{1cm} (3-20)

where $n$ is the rotational speed of the runner in rps and $\eta_s$ is the specific speed. The specific speed is defined by:

$$\eta_s = 2.76 \cdot \left( \frac{30}{H_t} \right)^{0.486} \cdot \frac{1}{2\pi} \text{ [rps]}$$  \hspace{1cm} (3-21)

The Kaplan hub diameter is given by:

$$D_i = \left( 0.25 + \frac{0.0951}{\eta_s} \right) \text{ [m]}$$  \hspace{1cm} (3-22)

The runner diameter($D_e$) of the Kaplan turbine in the ABC is then 0.450 meter and the hub diameter($D_i$) is 0.270 meter. Although the Kaplan runner cross section is larger than the cross section of the Francis turbine, the required service area for the Kaplan turbine is still less due to the favourable direction that the water has to enter the runner.

Predicting the efficiency of the turbines is difficult since manufacturers usually do not provide a characteristic curve or other information on the performance of their turbines. Nonetheless,
a prediction has to be made to investigate the overall efficiency of the storage system. Generically applicable information is therefore used to predict the performance of a fictitious turbine with the given workload at the requested capacity. Francis turbines can reach a maximum efficiency of 96% when the specific speed requirements are met and the turbine has a certain minimum size. The specific speed condition in the GPES design is met but the turbine is classified as a micro turbine due to its low capacity. The expected efficiency is therefore definitely lower than 96%. In order to make an estimation of the efficiency of the small hydro turbine, the method of Moody and Zowski for reaction turbines will be used. The efficiency of a medium sized turbine will be scaled by the runner diameter as stated in equation 3-23. The assumed efficiency of the large Francis reference turbine is 95.0% since the specific speed of the small turbine is not exactly equal to the optimal specific speed. A Kaplan turbine has a lower maximum efficiency. The efficiency of the reference Kaplan turbine is assumed to be 91%. By first scaling up the capacity to 25MW, the diameter of the reference turbine can be found. Subsequently the efficiency of the small turbine is calculated by means of the Moody and Zowski equation:

\[
\frac{1 - \eta_p}{1 - \eta_m} = \left( \frac{D_m}{D_p} \right)^n
\]

(3-23)

where \( \eta_p \) is the efficiency of the large reference turbine, \( \eta_m \) is the efficiency of the employed turbine, \( D \) is the diameter of the turbine and \( n \) is the power factor which is between 0.20 and 0.25.

The enlarged Francis turbine needs a generator with 30 poles, has a rotational speed of 200rpm, and the diameter of the runner is 2.30m. Applying equation 3-23 leads to an overall efficiency of 91.7% for the small turbine. An efficiency drop of 3.3% solely caused by the fact that the turbine is rather small. The electric power output operation range of this turbine with a minimum accepted efficiency of 90% lays between 310kW and 472kW. When a minimum efficiency of 85% is accepted, the output range increases from a minimum of 219kW to a maximum output of 526kW. The efficiency of the small Kaplan turbine is also 3.3% lower than the reference turbine. This leads to an overall efficiency of 87.7% and the operation range of the Kaplan turbine with a minimum accepted efficiency of 85% lays between 241kW and 603kW. The efficiency curve of the Kaplan turbine is less steep but this does not increase the operation range significantly in this situation. Only if an even lower operating efficiency is accepted and when it is likely that the turbine operates a lot far below its BEP, the advantage of the Kaplan turbine becomes clear. The turbine efficiency curves are read and interpreted from the characteristic curves of reference turbines (see: [55, p. 482]).

For a more detailed approach on the overall efficiency, losses in the draft tube and the tailrace should be taken into account. A draft tube or diffuser is needed to gradually slow down the velocity of the water that comes from the turbine exit and flows from there through a tailrace into the reservoir. The diffuser has to match the turbine exit diameter \( D_3 \) (see table: 3-10) with the return pipe diameter by an angle of 6° to 8° degrees. The length of the diffuser is then approximately 2.0 meters. This is more than the recommended length of the draft tube (\( \approx 2.5 \cdot D_3 \)) but here the exit diameter has to match the pipe diameter. Since the turbine exit passes into the return pipe, the turbine does not have a tailrace as in most hydropower stations but the shape of this transition section is similar to that of a diffuser. The hydraulic
losses occurring in this diffuser are defined by:

\[ H_d = K_d \cdot \frac{V_3^2}{2 \cdot g} = K_d \cdot \frac{\pi (\frac{2a_3}{2})^2}{2 \cdot g} \quad [m] \quad (3-24) \]

where \( V_3 \) is the turbine exit velocity. \( K_d \) is defined by:

\[ K_d = (1 - \eta_d) \left( 1 - \frac{A_3^2}{A_4^2} \right) \quad (3-25) \]

where \( \eta_d \) is the diffuser efficiency (= 0.9), \( A_3 \) is the turbine exit section and \( A_4 \) is the return pipe section.

The value of \( K_d \) turns out to be 0.08 and the head loss \( H_d \) is then 0.045 meter. It can be concluded that the diffuser head loss is insignificant and that the shape and length of this diffuser does not cause extra losses compared to regular draft tubes. The diffuser efficiency loss is therefore blended into the overall turbine efficiency.

**Turbine mode equipment costs**

Aggidis et al.\cite{3} did statistical research on the costs of small hydro plants by investigating the data obtained from multiple small hydro power plants in North-West England. One of the results of this research is that the average costs of the mechanical and electrical equipment is 34% of the total costs. The mechanical and electrical equipment of the HCT in discharge mode is comparable to the equipment of the investigated hydro plants. These costs are defined by:

\[ C_{EM} = 10.000 \cdot \left( \frac{P}{H_g^{0.2}} \right)^{0.56} \quad [\text{€}] \quad (3-26) \]

where \( C_{EM} \) are total costs of the turbine equipment in euro, \( H_g \) is the hydraulic head and \( P \) the rated power in kW. The accuracy of the approximation formula for the English hydro plants is ±25%.

Table 3-11 distinguishes the costs of the different turbine types and it shows the total costs of all the equipment. Although the choice for a Francis turbine in the previous section is not merely based on price, the costs of the alternative solutions are also given as a reference. The Pelton turns out to be the cheapest solution, but the relevance of this value is low since the specific speed and head range of these turbines is the furthest away from the calculated specific speed. From the price of the turbine and the approximated total equipment costs, it can be concluded that the price of the turbine is the most important part of the total equipment calculation. The total equipment costs calculation is an averaged value and it does not make a distinction between the selected turbine type nor does it separate the costs of the selected generator. Since the costs of the turbines are different from each other and the price of the Synchronous Generator (SG) differs from the less expensive Asynchronous Generator (AG), the total equipment approximation should be taken with care.
Table 3-11: Costs or turbine types and the total equipment costs of a small hydro power plant with a rated capacity of 400kW (price level 2008, source: [3]).

<table>
<thead>
<tr>
<th>Turbine Type</th>
<th>Costs (low, €)</th>
<th>Costs (high, €)</th>
<th>Costs (avg, €)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelton turbine</td>
<td>89,000</td>
<td>127,000</td>
<td>108,000</td>
</tr>
<tr>
<td>Kaplan turbine</td>
<td>161,000</td>
<td>172,000</td>
<td>166,000</td>
</tr>
<tr>
<td>Francis turbine</td>
<td>135,000</td>
<td>176,000</td>
<td>156,000</td>
</tr>
<tr>
<td>Total equipment</td>
<td></td>
<td>188,000</td>
<td></td>
</tr>
</tbody>
</table>

Pump As Turbine (PAT) design

An alternative to the relative expensive stand-alone turbine system, is the Pump As Turbine (PAT)-solution. In a bidirectional flow, the centrifugal pump adds energy to the flow by rotating with the stream in the principal direction and recovers energy by rotating in the opposite direction. By rotating with the flow in the discharge direction, the pump is capable to drive a generator and thus able to act as a turbine.

With respect to the PAT-solution, the turbine needs a separate branch in the piping network, takes up extra space in the installation room, requires an investment in turbine machinery and it requires a separate generator. By the application of the PAT-solution, the investment in a turbine can be omitted and service room space is saved. This solution only requires that the electric motor is also able to operate as a generator and the impeller (called runner in turbine mode) needs to be optimized such that the pump also performs well in turbine mode. However, the efficiency of the PAT remains low compared to a dedicated turbine solution.

Since pump manufacturers normally do not provide the characteristic curve of their pumps operating in turbine mode[19, 87], the actual behaviour and efficiency has to be predicted with relations found by experiments or by using a Computational Fluid Dynamics (CFD) model. However, modeling the pump in turbine mode with CFD technology turns out to be inaccurate at this point[19, 20, 87]. Derakhshan et al. did an experimental study to the characteristic curves of PATs in different specific speeds and derived a relation between the BEP of a pump and the BEP of the PAT[20] and compared their approach with the results found by other researchers. Although the experiments did not cover the size of the pump used in the HCT, the relations found in this study will be used to estimate the performance of the pumps in turbine mode.

The BEP of the turbine shifts to the right and upwards in relation to the BEP of the pump (see figure: 3-13). A PAT operates optimally with a higher discharge and a higher head. These relations are given by the dimensionless parameters:

\[
h = \frac{H_{tb}}{H_{pb}}, \quad q = \frac{Q_{tb}}{Q_{pb}}, \quad p = \frac{P_{tb}}{P_{pb}}, \quad \lambda = \frac{\eta_{tmax}}{\eta_{pmax}}
\]

(3-27)

where subscript \( t \) stands for turbine mode, \( p \) for pump mode and \( b \) for the best efficiency point.

The variables \( h \), \( q \) and \( p \) in equation 3-27 are larger than 1.0 but the exact values differ per study. The \( \lambda \) parameter lies between 0.8 and 1.0, which means that the mechanical efficiency of the PAT in turbine mode is in some cases almost equal to the efficiency in pump mode.
The PAT applied in small hydro power stations is often used as a cheap alternative to a solution with a turbine. In the specific situation of the PAT’s applied in the HCT, the pumps also have to act as a real pump during the charge phase. The design method presented by Derakhshan et al. assumes a situation in which the PAT only has to act as a turbine. This leads to a pump with a relative small capacity. Here the head delivered by the pump and the head available to the turbine are more or less the same and thus the dimensionless parameter $h$ has to be 1.0. The PAT has to run at part load and thus the rotational speed of the impeller is lower than the rotational speed at the BEP of the PAT. As stated in section 3-1-4, the efficiency of a pump running at part load is lower than a pump running at nominal speed and it can be assumed that this is also the case for a PAT running at part load. The selection of the pump should therefore be such that the pump runs slightly overloaded and the PAT runs a little bit below the BEP. This has to be done in the optimisation phase of the design and will here be neglected. The water flow and the power output of the PAT running at part load can be approximated by equations 3-28 and 3-29.

$$\frac{H_t}{H_{tb}} = 1.0283 \left(\frac{Q_t}{Q_{tb}}\right)^2 - 0.5468 \left(\frac{Q_t}{Q_{tb}}\right) + 0.5314 \quad (3-28)$$

$$\frac{P_t}{P_{tb}} = -0.3092 \left(\frac{Q_t}{Q_{tb}}\right)^3 + 2.1472 \left(\frac{Q_t}{Q_{tb}}\right)^2 - 0.8865 \left(\frac{Q_t}{Q_{tb}}\right) + 0.0452 \quad (3-29)$$

Figure 3-13 shows the estimated BEP’s for the RDLO 500-835 pump running as a turbine as derived by five different estimation methods. The differences between these methods turns out to be quiet large but the method derived by Derakhshan et al. is close to their own measurements and will therefore be used to estimate the performance of the pumps in the ABC (point D). Some of the differences can be explained by the fact that not all of these methods are accurate for the specific speed of the pump used in the HCT. The figure also shows the shift of the BEP to the operation point that matches the available head in the system. Contrary to figure 3-10, the system curve bows downwards. The system resistance at high flow increases, which shows that the head available to extract energy drops.

Table 3-12 gives an overview of the PAT’s as if they would operate under optimal conditions and it shows the characteristics of these pumps under the conditions in the HCT. When the pumps that charge the HCT are also used to generate electricity, the mechanical efficiency is less than 50%. The different calculation methods to determine the BEP show a scattered outcome and the error of the part load calculations is unknown. Therefore, it is difficult to assess the accuracy of the efficiency approximation and tests might show less unfavourable values. An optimization of the PAT inlet and a shift of the blade angles might also slightly increase the efficiency[87].

The PATs have to generate electricity far beneath their BEP. A smarter selection of the pump impeller diameter will lead to less inefficient running conditions but also to less optimal conditions for the PAT operating in pump mode. By using a separate set of smaller PATs that are only used in turbine mode, the PATs and pumps can operate at their BEP and than the efficiency can be raised to more than 70%. This is still far below the maximum efficiency of any of the in section 3-1-5 discussed turbine types. However, the space saving argument is invalidated and investment savings are less relevant since the these smaller pumps also require an extra investment.
The PAT solution cannot compete with a dedicated turbine solution. The efficiency is too low and the specific benefits do not apply in the HCT.

3-1-6 Overall round-trip efficiency

The efficiency of the GPES relates to the efficiency of the mechanical and hydraulic efficiency of the pumps and turbines, the hydraulic losses in pipes and through valves, friction losses at the seal between the piston, and the HCT inner wall and the efficiency of the electric components. Charging or discharging with high flows has an efficiency advantage in the mechanical components. Large pumps, generators, turbines, and motors are in general more efficient than types with a lower rated capacity. Meanwhile, hydraulic components like pipes and valves have a higher resistance at larger flows. In order to optimize the design, it is important to know which of the effects are governing at a certain flow through the system.

The efficiency in charge mode is defined as:

$$\frac{P_f}{P_0} = \frac{P_r}{P_t} \cdot \frac{P_o}{P_t} \cdot \frac{P_t}{P_t} = \eta_p$$

(3-30)
\[ P_f = \frac{H_0 - \sum_i^i \Delta H_i}{H_0} \eta_m \eta_e = \eta_p \] (3-31)

where \( H_0 \) is equal to the total dynamic head (see table 3-3), \( \sum_i^i \Delta H_i \) is the summation of the hydraulic- and friction losses in the charging direction of the HCT, \( \eta_m \) is the mechanical efficiency of the pump and \( \eta_e \) is the electric efficiency of the motor/pump drive.

At the nominal capacity (\( t \approx 90 \)) this leads to an efficiency of 82.2% in a two pump setup with one pump in service. The mechanical pump coefficient (\( \eta_m \)) has in this case a value of 0.8748 and is by far the most important value in the efficiency equation. At higher charging speeds, the system resistance becomes an important parameter as well. Table 3-13 gives the performance of the system in multiple pump setups and at three charging speeds. From this table it follows that charging the system at variable speeds in a multiple pump setup drops the efficiency but it also shows that these efficiency losses are within bounds. A single pump performs optimally by rotating at its nominal speed. A pump powered by a variable pump drive has the ability to run at lower speeds but this comes with larger losses. The efficiency drop of the pump in the single pump setup running at 50% of its rated capacity is 12.5%. Further lowering the pump speed is limited by the head delivered by the pump and the minimum flow discharge requirement. Lowering the discharge to one fourth of the rated capacity is not possible in this system. Small deviations from the nominal speed in combination with a variable pump drive comes with lower losses.

The overall efficiency in charge mode as given in table 3-13 is calculated with equation 3-31. The mechanical efficiency of the pumps is derived from the performance characteristic curves which are provided by the manufacturer. These curves are drawn up by interpolating a set of test results. Subsequently, points at this curve are read and used to describe these curves parametrically. The performance of the pumps running at part load is calculated accordingly to the affinity laws (see 3-16). Each of these steps has an interpretation or conversion error.
3-1 System characteristics

### Table 3-13: Efficiency comparison in charge mode for three pump setups at three different charging speeds.

<table>
<thead>
<tr>
<th>Setup</th>
<th>$t_{45}$</th>
<th>$t_{90}$</th>
<th>$t_{180}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$t / P_0 / \eta_p$</td>
<td>$t / P_0 / \eta_p$</td>
<td>$t / P_0 / \eta_p$</td>
</tr>
<tr>
<td>Single pump</td>
<td>45.0/705.6/0.802</td>
<td>90.0/420.4/0.670</td>
<td></td>
</tr>
<tr>
<td>Two pumps</td>
<td>48.6/658.5/0.796</td>
<td>90.0/342.7/0.822</td>
<td></td>
</tr>
<tr>
<td>Four pumps</td>
<td>49.4/660.2/0.767</td>
<td>89.1/350.1/0.809</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Nominal design.

$^b$ Requires one pump with a variable pump drive

$^c$ Pump(s) running below mechanical efficiency lower bound (set at 82.5%)

$^x$ Below minimum pump discharge.

The size of the error in each step is unknown but it is possible to define an upper limit for the mechanical efficiency error of the pumps.

The volumetric discharge ($Q$) of the pump directly influences the time it takes to charge the HCT. The total storage capacity of this tube is 432kWh. Dividing the flow by the total water volume and multiplying this value by the storage capacity results in the effective power on the piston.

$$P_f = \frac{V_{\text{water}}}{Q} \cdot E \quad [\text{kW}] \quad (3-32)$$

The division of the effective force ($P_f$) on the piston and the electric power input ($P_0$) should be equal to the results of equation 3-31. The difference between these two values is the absolute error of the calculated efficiency caused by the difference between the real and the interpreted characteristics of the pump. At nominal charging speed in a two pump setup, the absolute identified error is 1.9%. The real error for the calculated efficiency is most likely less since the system will find an equilibrium between the two calculations. The absolute error of the single pump setup is even a little bit larger and the error for the four pump setup is slightly smaller.

Corresponding equations can be used to define the efficiency in discharge mode:

$$\frac{P_e}{P_0} = \frac{P_t}{P_0} \cdot \frac{P_i}{P_t} \cdot \frac{P_o}{P_e} \cdot \frac{P_r}{P_o} = \eta_d \quad (3-33)$$

where $P_e$ is the electric generator output, $P_0$ is the power delivered by gravity acting on the piston, $P_t$ is the jet fluid power underneath the piston, $P_i$ is jet fluid power at the turbine inlet, $P_o$ is jet fluid power at the turbine output, $P_r$ is the jet fluid power at the top of the return pipe, and $\eta_d$ is the efficiency of the HCT in discharge mode.

Formula 3-33 can subsequently also be written as:

$$\frac{P_e}{P_0} = \frac{H_0}{H_0 - \sum_{i=0}^{i} \Delta H_i} \eta_m \eta_e = \eta_d \quad (3-34)$$

where $H_0$ is the total static head, $\sum_{i=0}^{i} \Delta H_i$ is the summation of the hydraulic- and friction losses in the discharge direction, $\eta_m$ is the mechanical efficiency of the turbine, and $\eta_e$ is the electric efficiency of the generator.
Table 3-14 shows the results of equation 3-34 for a Francis turbine setup, a Kaplan turbine setup and for the case that the pumps are also used as turbines. Again it is clear that PATs do not perform well. Since running the PATs at part load will require an extra system that controls the rotation speed and will also further decrease the performance, that situation has not been considered. The Francis turbine performs optimally at discharge speed $t = 60$. This discharge performance is slightly better than the performance at nominal speed. Apparently, the system resistance curve between the nominal speed and the discharging speed ($t = 60$) is more curved than the Francis efficiency curve at the same section. Selecting a smaller turbine might therefore lead to a slightly more efficient solution. This table also shows that discharging the HCT in more than 90 minutes is really at the expense of the efficiency.

By multiplying the efficiency values of table 3-13 with the values in table 3-14, the overall round-trip efficiencies as given in table 3-15 can be calculated. The table shows the efficiency of three loading and discharging speeds and gives the best combination of charging and discharging velocities. Charging the system in 90 minutes with one pump in a two pump setup and discharging it with a Francis turbine in 60 minutes proves to be the most efficient way of operating the HCT. This leads to a maximum round-trip efficiency of 69%.
Table 3-14: Efficiency comparison in discharge mode with two turbine types and three PAT setups.

<table>
<thead>
<tr>
<th>Setup</th>
<th>Nominal(^{a})</th>
<th>(t_{45})</th>
<th>(t_{60})</th>
<th>(t_{90})</th>
<th>(t_{135})</th>
<th>(t_{180})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\tau/P_c/\eta_p)</td>
<td>(\tau/P_c/\eta_p)</td>
<td>(\tau/P_c/\eta_p)</td>
<td>(\tau/P_c/\eta_p)</td>
<td>(\tau/P_c/\eta_p)</td>
<td>(\tau/P_c/\eta_p)</td>
</tr>
<tr>
<td>Francis turbine</td>
<td>55.5/381.0/0.833</td>
<td>45.0/453.0/0.800</td>
<td>60.0/353.1/0.835</td>
<td>90.0/223.6/0.793</td>
<td>135/131.2/0.698</td>
<td>180/86.5/0.614</td>
</tr>
<tr>
<td>Kaplan turbine</td>
<td>52.9/381.0/0.794</td>
<td>45.0/448.9/0.759</td>
<td>60.0/353.4/0.801</td>
<td>90.0/225.6/0.795</td>
<td>135/136.3/0.734</td>
<td>180/93.1/0.637</td>
</tr>
<tr>
<td>Single PAT(^{c})</td>
<td>-</td>
<td>45.9/245.9/0.444</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Two PATs(^{c})</td>
<td>-</td>
<td>54.2/170.9/0.383</td>
<td>-</td>
<td>60.5/98.1/0.401</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Four PATs(^{c})</td>
<td>-</td>
<td>54.1/159.2/0.339</td>
<td>70.2/133.4/0.369</td>
<td>103.3/96.2/0.392</td>
<td>-</td>
<td>206.5/50.4/0.406</td>
</tr>
</tbody>
</table>

\(^{a}\) Nominal design. Turbine shaft power output is 400 kW.
\(^{b}\) Turbine runs below mechanical efficiency lower bound (set at 90.0%)
\(^{c}\) The efficiency of the generator (\(\eta_c\)) is assumed to be the same as the efficiency of the motor.
\(^{c}\) PATs equipped with a speed control system have not been considered.

Table 3-15: Overall round-trip efficiency table at three charging- and discharging speeds and a combination of the optimal charge- and discharge speed (\(t \approx 45, t \approx 90, t \approx 180\) and \(t = \text{opt}\)).

<table>
<thead>
<tr>
<th>PAT</th>
<th>Kaplan turbine</th>
<th>Francis turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\eta_{45})</td>
<td>(\eta_{90})</td>
</tr>
<tr>
<td>Single pump</td>
<td>0.36</td>
<td>~</td>
</tr>
<tr>
<td>Two pumps</td>
<td>0.30</td>
<td>0.33</td>
</tr>
<tr>
<td>Four pumps</td>
<td>0.26</td>
<td>0.32</td>
</tr>
</tbody>
</table>
3-2 Systems integration

3-2-1 Sprinkler system

The legislation on fire safety of buildings aims to reduce the spread of fire and smoke, to reduce the propagation of fire, and to guarantee a safe escape route to the occupants of the building in case of emergency. All people in the building must be able to leave quietly and there should be enough time for rescue workers to search the building. The requirement for a safe escape route is in the Dutch building code[60] quantified as the time between ignition and failure of the construction in adjacent fire compartments. Smoke needs to be discharged and the entering of smoke into the escape route must be restricted. When a building has an accommodation area with a floor higher than 13m above the level of measurement, it must be proven that the escape route is safe for at least 120 minutes.

The methods to determine the fire resistance of building materials and the duration before failure of the support structure are defined in the Eurocodes[5] and the national supplements. There are several options to meet the minimum requirements. The first method is to limit the propagation of fire by applying poorly combustible materials or by limiting the amount of combustible materials per fire compartment. A second option is to oversize the supporting structure. Fire slowly degrades the load capacity of the structure. By oversizing the load capacity, it simply takes more time before the structure has been affected in such way that it fails. Another option is to pack the support structure with fire resisting materials like fire retardant paint or a cover of concrete. The last method is to fight the fire right after the start of the fire with an active sprinkler installation, though a single method like sprinklers is rather a complement to other methods than a replacement. Usually a combination of these methods is needed to meet the requirements for a tall building with a residential- or office function.

A sprinkler system does not only increase the safety for its occupants, it also decreases the damage caused by fire. Therefore, the insurance expenses can be reduced by installing a sprinkler system. The installation costs are eventually offset completely by insurance savings[11]. In large tall buildings, the consequences of a propagating fire are bigger than in small buildings because there is more to lose, while the risk of a starting fire somewhere in the building is bigger. Once a fire has started it is also more difficult to fight in a highrise building with other methods than sprinklers, and sprinklers make it easier for firemen to get to the source of fire. The last argument to implement a sprinkler system is that the marginal costs are reduced for buildings with a big floor surface. The costs per square meter are less for buildings with a large floor surface in comparison with the costs for a building with a small floor surface. Because of the effectiveness and the modest investment costs, practically all tall buildings have a sprinkler installation.

A sprinkler installation includes pipes, sprinkler-heads, alarm valves, shut-off valves, flow meters, test drains, and pumps when the water pressure is not enough to reach the remotest sprinkler heads. When the grid is used to extract water for the sprinkler system in a highrise building, booster pumps are always required since the water pressure in the grid is not enough to reach the top of the building. The costs of the total installation relate to the prescriptions in force at the location of the building, the availability of water, the pressure of the water from

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the grid, and its maximum flow rate. Since 2010, the Dutch instructions for extinguishing systems are defined in the NEN-standards\(^6\).

**Sprinkler system and the HCT**

Assuming that all modern highrise buildings have a sprinkler system and that the public water grid cannot provide enough pressure to reach the top of the building, some of the systems required for the GPES can also be used for the sprinkler system. By integrating the functionality of both systems, the total costs can be reduced. When the pumps to lift the piston can also be used to serve the sprinkler system, only one set of pumps is needed instead of two. The possible savings are related to the required pumps, access to water, and riser pipes. All these elements are part of the GPES and the sprinkler system. As requirements for fire fighting equipment are very strict, there is a difference in the technological possibility to integrate both systems and a level of integration that is restricted by building codes. The value of the potential savings and the limitations in this overview are based on Dutch legislation and Dutch buildings codes.

The characteristics of the sprinkler system have to be related to the level of safety for the building. The maximum risk of fire in multi-purpose highrise buildings should be classified as an “Ordinary Hazard” (OH3). If functions like a cinema are programmed into the building, a new hazard level should be assigned to that part of the building. Since the maximum height of a sprinkler section is 45 m, the sprinkler system should be divided into two sections and water supply should be conducted as “super feed”. This means that additional reliability to the water supply needs to be ensured.

Figures 3-14 & 3-15 show the layout of the sprinkler systems for the RBC and the ABC. The building is split into two sprinkler zones since the maximum height of one sprinkler zone is 45m. Each zone has its own risers but it shares the set of pumps and the water source. The pumps and the water extraction points are in both cases redundant.

**Availability NEN-EN 12845 §4**

Maintenance and predictable failures may not be the cause of prolonged unavailability of the entire sprinkler system. The yearly availability of the sprinkler system must, therefore, be demonstrated. The required availability is expressed as a minimum yearly percentage that the system is in operation and that downtime should be undone within 24 hours. All downtime due to maintenance and due to failure of components needs to be accumulated. The most important possible failures are a lack of water, a lack of pressure, leakages in manifold pipes and a blocked riser or supply pipe. Components like sprinklers or valves need to be proven as well and their downtime is proportionally part of the performance requirements of the system.

This sprinkler concept uses the water present in the tube. The supply of water is guaranteed except for the moments that the piston rings need to be replaced. During the replacement, all water in the tube must stay there to keep the piston in place. To limit the downtime, it is important that the rings have a long service life and can be replaced within a few hours.

\(^6\)See NEN-standard: NEN-EN 12845+A2; NEN 1073
Figure 3-14: Sprinkler layout of RBC. Super supply, two limited water tanks and two multistage pumps. Based on NEN-EN 12845 figure E.1

- Limited water source
- Alarm valves & jockey pumps
- Multi-stage pumps
- Flow meter
- Test drains
- Lower sprinkler zone
- Upper sprinkler zone
- Risers

Figure 3-15: Sprinkler layout of ABC. Super supply, 'inexhaustible' water reservoir and two booster pumps. Based on NEN-EN 12845 figure E.1

- Booster pumps
- Bottom extraction points
- Bypass extraction points
- Inexhaustible water source
Otherwise, a second source of water is required. Pistons in combustion engines are subjected to a similar kind of wear. Many kinds of coating have been developed to slow down wear.

Failure of the booster pump will only cause a partial system downtime in the most unfavorable situation. The water pressure at the bottom of the return pipe is not big enough to serve the top floors in case the piston is at the bottom position and the pump fails. Although the likelihood of this occurring is small, the possible consequences still have to be taken into account. The codes focus on the consequences of occurring rather than the likelihood of occurring. In contrast to failure, pump maintenance is something that can be foreseen. Placing the piston at the top of the tube before maintenance takes place, makes that the hydrostatic pressure is large enough to serve the sprinkler installations in the whole building without booster pumps. The GPES is then temporarily out of order but safety is ensured. Since for this hazard class a redundant pump set is prescribed, the risk of a failing pump does not have to be accounted for.

The total estimated system availability is given by equation 3-35. In this equation, pump maintenance does not lead to downtime, yearly rubber bands maintenance takes four hours, and the estimated amount of leakages in distribution pipes is two. A pump failure is solved within 24 hours and affects 20% of the building. Since the system is redundant, the share on the expected system downtime equation is zero. This leads to a 99.94% system availability. The minimum required system availability for this hazard class (OH3) is 99.8%.

\[
\Xi = \frac{(8760 - (RT_{nb1} + RT_{nb2} + RT_{nb3} + RT_{nb4} + RT_{nb5}))}{87.6}
\]

\[
= \text{Yearly system availability} = 99.94\%
\]

\[
RT_{nb1} = \text{Pump failure} \Rightarrow 24 \times 0.2 \times 0 = 0.0
\]

\[
RT_{nb2} = \text{Pump maintenance} \Rightarrow 6 \times 1.0 \times 0 = 0.0
\]

\[
RT_{nb3} = \text{Rubber bands maintenance} \Rightarrow 4 \times 1.0 = 4.0
\]

\[
RT_{nb4} = \text{Leaks in distribution pipes} \Rightarrow 6 \times \frac{1}{26} \times 2 = 0.5
\]

**Minimum water pressure NEN-EN 12845 §7.3.1**

For a wet sprinkler system (OH3), the minimum required water pressure is 1.7 bar and the minimum flow rate is 1100 l/min. Since the average flow rate during power peaks is 0.67 m³/s, the minimum flow rate requirement is amply fulfilled by the booster pump of the GPES. For the minimum pressure requirement, the pressure at ground level needs to be at least 10.0 bar (see equation: 3-36). This is also fulfilled by the pump since it needs to boost the water pressure to at least 11.5 bar to lift the piston.

Until the 21st floor, the hydrostatic pressure in the tube due to the weight of the water alone is large enough to provide water for a period of at least 60 minutes. For the other three floors and the service room, the installed pump needs to provide extra pressure to serve all sprinkler installations. When the GPES booster pump is used to provide that extra water pressure, it has to meet the reliability requirements for sprinkler installations. If these cannot be met, a second separated pump needs to be installed. This is however only the case when the piston is resting at the bottom of the tube. During the greater part of the day, the weight of the
piston can be added to the hydrostatic pressure on the bottom of the tube. The pressure is then large enough for all floors.

\[
p_{\text{min,sprinkler}} = (h_{\text{building}} + h_{\text{service}} + \Delta H_v) \cdot 10 + 1.7 \text{bar} \\
= (80.0 + 3.4 + 0.1) \cdot 10 + 170 = 10005[\text{kPa}]
\]  

\((3-36)\)

**Water supply and maximum water pressure NEN-EN 12845 §8**

The water reservoir for risk level OH3 should be large enough to supply the sprinklers for at least 60 minutes. This reservoir is preferably under own management. If not, the supply of water must be guaranteed by a third party. In the ABC, the water supply is in own management and big enough to supply the sprinklers for more than 60 minutes.

As long as the piston does not rest on the floor of the tube, the water pressure at the bottom is 11.5 bar. The maximum hydraulic head in the return pipe is equal to the height of the pipe. This is less than 80 m and thus, the maximum water pressure in the return pipe is less than 8 bar. All extra pressure delivered by the pump or by the hydrostatic pressure in the tube is dissipated at the exit of the pipe. Since the sprinkler system needs at least 2.0 bar additional water pressure, a separated riser pipe to serve the upper sprinkler section is needed. This is also in line with §8.3 since that paragraph prescribes a closed sprinkler system. It is not allowed to use the sprinkler riser pipes for something else than sprinklers. The reason behind this prescription is that additional taps introduce a risk of pressure losses during emergencies. Taps do not have to meet the same reliability standards that come with sprinklers and they just might be in use during emergencies. The water availability and water pressure cannot be guaranteed in that case. This does not make sense to the GPES since that is a closed system and there is a large surplus of water and water flow. The lower sprinkler section can technically make use of the return pipe for its water supply, but that is not allowed by the building codes and the potential savings are small.

The codes demand that the maximum pressure in the fittings of the sprinkler system does not exceed 12 bar. There is no risk of overpressure but in case the piston height is more than 10 m or the building height is more than 80 m, valves are needed to reduce the pressure on the lowest floors. It is allowed to have a larger pressure in the riser pipe.

**Water supply types NEN-EN 12845 §9**

Water can be extracted from the public grid, an inexhaustible water source, or a limited water source. For hazard-class OH3, access to water should be conducted twice to increase the reliability of the total fire fighting system. When water is extracted from the grid, the building should be connected to two independent main water pipes. For a limited water source, water should be stored in two tanks with each having the capacity required for one firefighting section. Access to water should be redundant but it is not necessary to have a double capacity of the total storage volume. Higher hazard classes do require redundant access to water and a double storage volume. Inexhaustible water sources require multiple extraction points to ensure the access to water.

The minimum required effective water supply for a limited reservoir in the RBC is 185m³ per sprinkler section. These reservoirs can be placed at the bottom of the building in combination
with multi stage pumps or at the top of the building in combination with booster pumps. The HCT contains a water reservoir of approximately $4000 \text{m}^3$. When a reservoir contains more than $1500 \text{m}^3$, the reservoir can be designated as an inexhaustible water source. Unlimited water reservoirs can be used as a source for a double conducted water supply but it needs multiple extraction points to ensure the supply. Unlike the High Hazard-class, class OH3 does not need two fully independent water supplies, a single inexhaustible water supply is sufficient.

Water sources for sprinklers in highrise buildings have to be carried out as a “super supply”. A super supply has the aim to increase the reliability of the water supply by storing the water in multiple tanks or by increasing the amount of extraction points in an inexhaustible water reservoir. This means for the HCT setup, that four intake points are needed since the location of the piston might close off two extraction points (see figure: 3-15). To comply with the codes, two extraction points have to be placed at the bottom of the tube and two at the top of the bypass. The bypass intakes should be placed at least $h_{\text{piston}}$ above the intakes at the bottom of the tube. It also requires a redundant pump arrangement to increase the reliability of the pump. Therefore, the capacity of the pump that serves the GPES has to be distributed over two pumps. Nonetheless, following the capacity requirements of the GPES, the pump still has an overcapacity for operating the sprinklers. A single pump is powerful enough to serve the sprinklers, both pumps together deliver the maximum power capacity of the GPES. A valve should make sure that in case of emergency, the pressure at the discharge side of the pump is directed towards the sprinklers and not towards the tube. Unlike other water tank or reservoir solutions, there is no need to include additional provisions to avoid frost because the HCT is an element in the entire heating system of the building. Frost will not occur.

**Pumps NEN-EN 12845 §10**

A set of pumps is preferably placed in a separated or adjacent building that has a fire resistance of at least 60 minutes. If that is not possible, the area in the building itself should have direct access to an outdoor space. When the pumps are placed in a recessed place, the pumps have to be placed on a pedestal to avoid contact with water. The rooms with the pumps should not be used for something else than fire protection purposes.

Each sprinkler pump needs to have a minimum capacity of at least $3100 \text{ l/min}$ ($0.052 \text{ m}^3/\text{s}$) and needs to boost the pressure from approximately 8.0 bar to 10.0 bar. The minimum required capacity per pump to serve the maximum design load of the GPES is $20100 \text{ l/min}$ and it should boost the pressure from 8.0 bar to 11.5 bar. The pumps of the GPES have a significant overcapacity in relation to the pumps that need to serve the sprinkler system.

**Conclusion**

Ensuring the reliability of the sprinkler system requires a thought-out design of pipes, pumps, and water supplies. To limit the risk of failure, the building codes prescribe a dedicated system of risers, water tanks, taps, and compartments for pump sets. This limits the technical options to integrate the sprinkler system into the HCT, though the vast supply of water in the tube can be used as an inexhaustible source. Water can be extracted from the tube to serve
the sprinkler installation. This replaces the need of dedicated water tanks or alternative water supplies like extraction points in a lake or a double conducted connection to the public grid. Especially when external water supplies are difficult or expensive to implement, the inexhaustible water source in the tube is a major advantage. The hydraulic head of the water in the tube also enhances the reliability of the system. However, this advantage cannot really be expressed into a value since pumps are still needed to boost the pressure of the water to serve the top floors. These booster pumps have to be redundant to comply with the super supply prescriptions.

Using extraction points in a nearby lake or river requires multiple pipes and provisions to ensure operability during frost. Extracting water from the grid requires two connections to different main pipelines. This is not always possible and requires an extra investment into underground pipes and connections to the building. It turns out that there is no solution that fits all and that comparing the value of the integrated HCT solution with existing solutions can only be approximated.

The cheapest alternative of elements that are part of the HCT and the sprinkler system can be extracted from the total costs of the HCT. When comparing the HCT with a conventional highrise solution that has a double water reservoir and two pumps, the expenses of the water tanks and the pumps can be extracted from the total costs of the HCT. The costs of risers and all parts behind the zone valves stay the same. Extra costs to make the HCT sprinkler ready should also be taken into account. The sprinkler system needs two pumps with a modest amount of power compared to the GPES that does not have to meet the reliability requirements. The operational reliability of the GPES increases when the power capacity is divided over two pumps, but that is not crucial like it is for sprinkler installations. Additionally, a second or a third pump has a positive effect on the efficiency of the system. When multiple pumps are installed, it is easier to match the power demand or supply with the BEP of the pump. Pumps operating at low load or peak load conditions are less efficient than moderately loaded pumps [48]. This is, again, an optimisation problem. The total costs of the sprinkler pumps can be extracted from the total costs of the HCT, but the costs that solely have to made to improve the reliability should be added again.

Financial implications and impact on the demand for space

It is assumed that the most cost effective sprinkler solution in the RBC that complies with building codes has two water tanks and two pumps that provide just enough pressure to serve the whole building. The costs of these tanks and pumps can be extracted from the total costs of the building. The demand for space of the water tanks and the pumps can be extracted from space demand of the HCT.

The RBC needs to have two water tanks with an effective water capacity of at least 185m$^3$ each. The pumps need to have a capacity of at least 3100l/min with a pressure of at least 11.5 bar.

3-2-2 Thermal mass buffer

Mass has a positive effect on the indoor climate of a building. The heat capacity of the mass will naturally damp the thermal fluctuations. When the air temperature is above the
Heat capacity

<table>
<thead>
<tr>
<th>Heat capacity</th>
<th>Concrete floors</th>
<th>Concrete core</th>
<th>Water in tube</th>
<th>Iron ore in piston</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Building Concept (RBC)</td>
<td>0.52</td>
<td>0.22</td>
<td>0.00</td>
<td>0.00</td>
<td>0.73</td>
</tr>
<tr>
<td>Rectangular expansion</td>
<td>0.51</td>
<td>0.26</td>
<td>0.92</td>
<td>0.12</td>
<td>1.82</td>
</tr>
<tr>
<td>Bidirectional expansion</td>
<td>0.51</td>
<td>0.28</td>
<td>0.97</td>
<td>0.13</td>
<td>1.88</td>
</tr>
<tr>
<td>Double core</td>
<td>0.59</td>
<td>0.22</td>
<td>0.69</td>
<td>0.09</td>
<td>1.58</td>
</tr>
</tbody>
</table>

Table 3-16: Thermal mass buffer capacity per net square meter (in MJ/K). *(Thermal capacity: concrete = 840 J/(kg·K), iron ore = 692 J/(kg·K), water = 4186 J/(kg·K)).*

Temperature of the building mass, heat will be taken up by the mass. Heat is stored and further heating-up of the inner spaces is slowed down. During a cold day, the stored heat will be transferred back to the inner environment.

The concrete core will automatically function as a thermal buffer, but since the thermal dispense surface is small and the core is far away from the heat sources, the total effect is limited. A second obstacle is the large thermal inertia of the concrete. It takes time to transmit heat or cold to the concrete and the other way around. This seriously hampers the interaction between the heat and cold production that supplies the indoor spaces [76]. Activating the core and the floors will increase the dispense surface and it will reduce the time it takes to take up heat. Water is transported with a pump through pipes inside the floors and the concrete core. The dispense area then becomes much bigger since the upside and underside of the floor is much larger than just the envelope of the core. Also the area that interacts with the buffer increases due to the additional surface of the pipes. This makes that a larger part of the buffer can be addressed.

The energy tube extends the total mass of the building. This implies that the total thermal buffer capacity increases and that the effectiveness of the mass activation system enlarges as well. The Highrise Construction Tube (HCT) in combination with activated floors and an activated concrete core works as a heat pump with cold temperature heating and high temperature cooling. Heat pumps that store a surplus of heat during the summer and cold during the winter in underground aquifers are already a common solution to reduce the total energy consumption of a building but these systems still require a significant amount of energy since water has to be circulated through pipes in underground aquifers. The system of underground thermal storage requires an initial investment and it needs to be maintained. Once in a while the pipes in the heat pump has to be flushed with a lot of water. The HCT automatically distributes temperature differences and it does not require additional distribution pipes that need to be maintained. The heat pump is already an integrated part of the HCT.

The absolute thermal storage capacity per net square meter of a building with an HCT is approximately 150% larger than the storage capacity without this tube (see table: 3-16). The absolute storage capacity is derived by summing the amount of mass in the building and multiplying this value with the specific heat of the used materials. In a more advanced calculation, the thermal conductivity of the materials should be taken into account. Concrete for example has a low thermal conductivity compared to materials like steel and for this reason it is not possible to activate all the concrete. Water is even less conductive but due to transport while charging or discharging the energy tube, local thermal differences are mixed.
and distributed through the tube. Therefore all water inside the tube can be activated.

The water is in direct contact with the conductive steel inner wall of the tube. Dowels attached to the steel (see figure: 3-6A) will help to distribute the heat or cold into the concrete part of the tube. Pipes inside the concrete take up the heat or cold and distribute it further towards the floors. If the thermal flux from the water in the tube through the steel inner wall and the concrete towards the water pipes is large enough, it needs to be checked with a dynamic thermal model.

Unlike the underground aquifers storage systems, the HCT cannot be used to store thermal heat throughout the seasons. Surplus generated heat by a Combined Heat and Power (CHP) system in the summer cannot be stored in the HCT such that it could be used in the winter. The tube can only be used as day storage or to bridge a shorter period with extreme temperatures. A CHP can generate power whenever needed and can transmit the generated heat through a heat exchanger with the water in the tube. This heat can then be used whenever needed in the building. In the summer, an air-conditioner can cool down the tube water temperature at night by exchanging heat with the low air temperature. This cold can therefore be used to cool the inner spaces at the hottest time of the day with a minimum amount of energy.

3-3 Building implications

To investigate the implications of the energy tube system on a building concept, some principles and the system scope have to be defined. One of the basic principles is that the storage system is an additional function to a building rather than a storage system with an additional residential- or office function. The building height is more or less delimited by the principle that the tube is assumed to be an integrated part of the stabilizing structure. In super tall buildings (200 meters or more), it is more common to use an outrigger system. The outrigger will activate the facade to convey the lateral forces. The core is still used for vertical transportation and service space but it is not the main structure to convey the lateral forces anymore. Super tall buildings do have the potential of storing energy but that question is out of the scope of this research paper.

The energy storage capacity is already established in section 3-1-1. The dimensions of the storage tube are being deducted from the demanded storage capacity and the height of the building.

3-3-1 Floor plan

To store 400kWh electric energy in a 80 meters tall building with an iron ore piston and a return pipe, the inner size of the tube should be at least $46.6m^2$ (see table: 2-3). That space cannot be rented out or sold. Therefore, the tube is preferably placed into the building in such way that it will not, or only scarcely, have an effect on the Net Internal Area (NIA). The NIA is defined as the usable floor area or as the Gross Floor Area (GFA) excluding the space occupied by the construction, pipes, circulation area, elevators, mechanical area, escape routes and (escape) stairs. Combining some of the building systems that take up space increases the profitability of the building project and should therefore be something to pursue.
Enlarging the size of the core also makes it possible to increase the NIA. The building floor area is more or less limited by the prescription that each accommodation area has direct access to daylight. Although the legislation that prescribes this directives differs slightly per country, it always comes down to a restriction in the distance between the facade and the core of the building. When the perimeter of core increases, the perimeter of the building and the NIA increases as well. An increase of the core does however have a negative effect on the ratio between the NIA and GFA. This figure is often used to indicate the 'efficiency' of architectural design and the floor layout. An attractive design or additional building functionality, like an energy storage system, can be a reason to accept a lower ratio.

Making the tube system part of the concrete core also has a positive effect on the stability of building since the modulus and the moment of inertia have an exponential relation with the dimensions. The tube becomes an integrated part of the stabilising structure and the demanded space of the integrated system is less than the required space of the sum of the individual components. With the same amount of material, the stresses in the core and the bending of the building due to lateral forces will be less. It also holds that a lower amount of material is needed to get to the same stiffness when the dimensions increase. These statements are true until the elements of the core are so thin that there is a risk of local buckling or the resistance to torsion becomes insufficient. In the design process, the amount of material to build the core can be seen as a minimization problem.

The dimensions of the core are usually not optimized to the quantity of required material. It is more important that the available floor space is optimally used. Therefore, the dimensions of the core are normally based on the architectural building grid and the functions that can be placed into the building core. The bearing wall thickness, concrete quality and reinforcement follows from the required strength and stiffness. When additional functions are placed into the core, the size of the core increases and the required material slightly decreases. This means that the space that is taken up by additional functions is partly compensated by the fact that the core needs less material and space to provide the same amount of strength and stiffness.

Figure 3-16A shows a basic floor plan of a square building with an almost square concrete core. The core takes up the lateral forces in combination with a shear frame in the facade. Elevators, pipes, a service area, stairs and a lobby are all placed inside the core. The floor plans in figures 3-16B, 3-16C and 3-16D show three alternatives to extend the functionality of the core with an energy tube. The wall thickness, the thickness of the facade, and the distance between the core and the facade are the same in all four floor layouts, the size and shape of the floor plans have been adapted. The cross-hatched area shows the NIA plus the horizontal circulation surface. In the comparison of the alternatives, 15% of the cross-hatched area is assumed to be needed for the horizontal circulation. The darkened patches show the additional space to the floor plot in comparison with the basic floor plot. Alternative A has two separate cores to avoid torsion. The surface between the two cores cannot be used as an accommodation space since it does not have direct access to daylight. The value of that space is accordingly less although it still can be used for something like a conference room or a sanitary block as part of an office. In the comparison with the alternatives, the area will not be part of the NIA and it therefore has a negative effect on the Net-Gross Ratio (NGR).

In table 3-17 until 3-20, the four floor concepts are being compared on their dimensions, required material, resistance and stiffness. The three alternatives with a tube are set against
the basic floor plot. The wall thickness is for this case more or less arbitrarily chosen and only meant to compare the performance of the different layouts.

A wall requires less space and is still sufficient because the stabilizing element on the left only has to convey forces in one direction. When a function can be assigned to the space between the two cores, the NGR becomes less futile. If that is the case, the value of the extra space that is taken up by the core increases as well.

Between the alternatives with a tube, the rectangular expansion has the most efficient floor layout. The efficiency of the RBC expressed in the Net-Gross Ratio (NGR) is 3% behind the tubeless design. Three percent of the Gross Floor Area (GFA) that is used to store electrical energy at the expense of the Net Internal Area (NIA). Therefore, the section of the tube is equal to 7% of the GFA. By increasing the GFA, the impact of the energy tube on the NGR decreases under the condition that the distance between the core and the facade remains equal.

To calculate the costs of the effective floor loss, a price per $m^2$ has to be defined. The price to build one $m^2$ of office space is 1500€. This includes the costs of installations, elevator capacity etcetera. The assumed price of just the floorspace is 1000€.

The costs for the lost floor space per floor can than be calculated with:

$$C_{floor} = (NGR_{RBC} - NGR_{ABC}) \cdot GFA_{RBC} \cdot P_{floor} \quad [\text{€}]$$

$$= (0.673 - 0.644) \cdot 865.0 \cdot 1000$$

$$= 25,950$$

Figure 3-16: Building floor plans. The shaded cross-hatched area shows the net floor space, the darkened regions show the spatial implications of a storage tube on the floor plans.
where $NGR_{RBC}$ is the Net-Gross Ratio (NGR) of the Reference Building Concept (RBC), $NGR_{ABC}$ is the Net-Gross Ratio (NGR) of the Adjusted Building Concept (ABC), $GFA_{RBC}$ is Gross Floor Area (GFA) of the RBC, and $C_{floor}$ is the price of the effective floor space that cannot be used for office space.

Table 3-17 shows that the NGR of all three alternatives is less than the basic floor concept. The alternative with the least efficient NGR is concept D. It should though be noted that a rectangular building with a floor plan like in concept D requires at least two stabilizing elements. The energy tube is the second stabilizing element and takes up the space that has the least value in the concept. Another option to ensure the stability would be to replace the tube by a single thick wall.
### Table 3-17: Indexed floor dimensions of the comparative building concepts. Index tube-less floor plan = 100

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Without tube</td>
<td>100.0</td>
<td>100.0</td>
<td>0.673</td>
<td>100.0</td>
</tr>
<tr>
<td>Rectangular expansion</td>
<td>132.1</td>
<td>126.3</td>
<td>0.644</td>
<td>92.1</td>
</tr>
<tr>
<td>Bi-directional expansion</td>
<td>127.4</td>
<td>120.3</td>
<td>0.635</td>
<td>93.9</td>
</tr>
<tr>
<td>Double core</td>
<td>187.0</td>
<td>168.8</td>
<td>0.608</td>
<td>85.6</td>
</tr>
</tbody>
</table>

*Net-Gross floor space ratio.*

*Meters envelope per net square meter floor space (m/m²).*

### Table 3-18: Indexed floor space dimensions of the comparative building concepts. Index tube-less floor plan = 100

<table>
<thead>
<tr>
<th>Floor plan</th>
<th>Gross area [m²]</th>
<th>Net area [m²]</th>
<th>Envelope/Net [m²/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without tube</td>
<td>655.0</td>
<td>518.7</td>
<td>0.197</td>
</tr>
<tr>
<td>Rectangular expansion</td>
<td>865.0</td>
<td>655.3</td>
<td>0.182</td>
</tr>
<tr>
<td>Bidirectional expansion</td>
<td>834.4</td>
<td>623.7</td>
<td>0.185</td>
</tr>
<tr>
<td>Double core</td>
<td>1225.0</td>
<td>875.6</td>
<td>0.169</td>
</tr>
</tbody>
</table>

*Net/gross floor space ratio.*

*Meters envelope per net square meter floor space (m²/m²).*

### Table 3-19: Core stiffness

<table>
<thead>
<tr>
<th>Floor plan</th>
<th>$A_{core}$ [m²]</th>
<th>$A_{section}$ [m²]</th>
<th>$I_{xx}$ [m⁴]</th>
<th>$I_{yy}$ [m⁴]</th>
<th>$W_{xx}$ [m³]</th>
<th>$W_{yy}$ [m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without tube</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Rectangular expansion</td>
<td>175.4</td>
<td>152.7</td>
<td>398.2</td>
<td>159.4</td>
<td>193.0</td>
<td>159.4</td>
</tr>
<tr>
<td>Bidirectional expansion</td>
<td>178.7</td>
<td>156.3</td>
<td>299.1</td>
<td>230.1</td>
<td>189.3</td>
<td>164.4</td>
</tr>
<tr>
<td>Double core</td>
<td>178.4</td>
<td>167.9</td>
<td>298.3</td>
<td>274.3</td>
<td>160.2</td>
<td>160.8</td>
</tr>
</tbody>
</table>

*The size of the (concrete) section of the core.*

### Table 3-20: Section dimensions and core stiffness in the comparative building concept.

<table>
<thead>
<tr>
<th>Floor plan</th>
<th>$A_{core}$ [m²]</th>
<th>$A_{section}$ [m²]</th>
<th>$I_{xx}$ [m⁴]</th>
<th>$I_{yy}$ [m⁴]</th>
<th>$W_{xx}$ [m³]</th>
<th>$W_{yy}$ [m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without tube</td>
<td>86.1</td>
<td>17.20</td>
<td>180.5</td>
<td>170.6</td>
<td>35.9</td>
<td>39.2</td>
</tr>
<tr>
<td>Rectangular expansion</td>
<td>151.1</td>
<td>26.27</td>
<td>718.6</td>
<td>272.0</td>
<td>69.3</td>
<td>62.5</td>
</tr>
<tr>
<td>Bidirectional expansion</td>
<td>153.9</td>
<td>26.89</td>
<td>539.9</td>
<td>392.6</td>
<td>68.0</td>
<td>64.5</td>
</tr>
<tr>
<td>Double core</td>
<td>153.7</td>
<td>28.78</td>
<td>298.3</td>
<td>274.3</td>
<td>57.6</td>
<td>63.0</td>
</tr>
</tbody>
</table>

*The size of the (concrete) section of the core.*
Chapter 4

Feasibility

4-1 Technical feasibility

In this document, some of the key aspects of the Highrise Energy Storage Core (HESC) have been investigated together with the consequences of the design choices. One of the answered questions is the effect of the selected equipment, pipe diameters, and charge and discharge speed on the efficiency of the system.

In section 2-2 it is examined how electrical energy can be stored inside a tall building. Concept D consists of a water filled tube, a piston, and a return pipe. The pressure at the outlet of the pumps and the inlet of the turbine is constant. In section 3-1-4 and 3-1-5 it is elaborated that the pumps and the turbine perform optimally at a single specific speed. When the pressure changes, the specific speed changes as well and thus there will be only one point where the pump and turbine operate optimally. Since the efficiency is closely related to the specific speed, a lot of energy is lost in the concepts that have a varying pressure at the bottom of the tube during the charge and discharge process. The only alternative to concept D with a similar potential and requires less building space is concept G. The specific problems for this concept have not been investigated, but it is clear that concept G requires less building space and does not require such a smooth surface of tube inner wall. On the other hand, it introduces a very large force on the top of the tube and it does not increase the thermal capacity of the building (see section: 3-2-2).

By investigating the properties of the equipment, it becomes clear that size is an important factor. The pump, pump drive, turbine, and generator all perform better when they have a bigger size. The same is true for the height of the building. Less piston material is needed, or the storage capacity is larger, when the height difference is bigger. The height of the investigated building (the Reference Building Concept (RBC)) is 80 meters and thus all properties of the HESC will turn out better for a taller building.

The sealing between the piston and the tube inner wall seems to be quiet unique. There is no similar application for these kind of seals with this size. However, there are many smaller applications where seals are even more heavily loaded. For an optimized solution that meets
the requirements, tests have to be done to investigate the minimum required pressure in the O-ring and the actual wear of the seal. In section 3-1-2 the friction force between the piston and the tube inner wall is calculated with a conservative assumption of the force that has to act on the O-rings to get a sufficient watertight connection. According to this calculation, approximately 1% of the total round-trip efficiency is lost.

The required smoothness of the inner wall to limit the wear of the seal, can only be attained with steel. The reinforcement of the tube can be placed on the outside of the concrete rather than on inside of the concrete. This has a positive effect on the thermal conduction, but it might also be the most expensive part of the whole system. A composite construction element needs many studs to transfer the shear forces and the limited tolerances of the tube might lead to a complex construction and assembly process. The extra costs of the selected solution have not been investigated. A core wall finish in which the seal is more subject to wear might still be a favourable solution in terms of money.

Several pump setup (1, 2 and 4 pumps) have been investigated in order to find the most efficient solution to charge the HESC. The aim was to find a system that is able to store energy at any given amount of surplus power. When the building or the smart-grid produces more energy than it consumes, that power should be stored. This requires a flexible pump setup since it is unknown what the surplus will be. From section 3-1-4 it can be concluded that this flexibility comes at a cost. A flexible pump setup is a bit less efficient and requires a variable pump drive. When the overproduction of the building (or smart grid) is not likely to exceed 131.2kW (see table: 3-5), there is no reason to install a variable pump drive and the choice should be made to install 1 or 2 pumps.

In section 3-1-5 the turbine selection is elaborated upon. Again, an important factor is the size of the turbine. Just as the aim to use the pumps as flexibly as possible, the operation range of the different turbine types have been discussed. Although the Kaplan turbine promises a wide operation range, this benefit is at the expense of the maximum efficiency. There is indeed some benefit at low discharge speeds but this is outweighed by the nominal efficiency benefit of the Francis turbine. Operating the smart grid with this storage solution in island mode is possible, but the efficiency drops significantly when the demand fluctuates. It is more efficient to use the storage system as a distribution backup that supports the power produced by the utilities. As a grid backup unit, the turbine can run at nominal speed and thus at the highest possible efficiency.

A cheap alternative solution to a dedicated turbine is the Pump As Turbine (PAT). The properties of these PAT-systems in the HESC have been evaluated and the conclusion is that a PAT is unsuitable. Although the pump can be optimized, losses in this specific situation are simply too big.

### 4-2 Economical feasibility

The maximum round-trip efficiency of the system operating at nominal speed turns out to be 69%. This is slightly more efficient than currently installed Compressed Air Energy Storage (CAES) systems, but below the efficiency of modern Pumped-Storage Hydroelectricity (PSH)-systems. However, the figures for existing PSH-plants do not include the losses that occur in the grid transportation network.
4-2 Economical feasibility

When comparing the HESC with electrochemical storage solutions, the latter turns out to be more efficient. Lead acid battery solutions have an efficiency of 75% and lithium-ion batteries have a round-trip efficiency of 93%. The round-trip efficiency as given in table 2-1 does not include the losses that are involved in rectifying the Alternating Current (AC) and inverting the Direct Current (DC) to AC. The generator produces an alternating current so the actual difference between the HESC and the electrochemical batteries is less.

The power and energy costs of the PSH-system are given in table 4-2. The table is not intended to give a comprehensive overview of all costs, but it can very well be used to get insight in the key factors of the total costs. This information can than be used to optimise the design of the HESC. The cost estimation only includes the direct costs of the discussed components and the price of the piston raw materials. It lacks the engineering costs, construction costs, extra costs to build the tube, the costs of pipes and valves, and a system to replace the seal. Although there is some information on the price of equipment, the accuracy of these values is difficult to establish. Some manufacturers provide the technical details of their equipment, but the prices are usually not available for research purposes.

To compare the different storage methods on their net present value, the Power-To-Energy (PTE) of all storage systems have to be the same. In this comparative calculation the initial investment costs, the efficiency of the system and future maintenance costs are expressed into one value. The net present value of the HESC is 5870.00€ per kWh\(^1\). The storage and power costs are more than twice the price of a lithium-ion battery setup and, as mentioned before, this calculation does not include all costs.

By examining the factors that determine the costs of the HESC, further insights in the optimization of the system can be developed. Since the floor price takes a large share in the total storage costs, it is beneficial to increase the size and weight of the piston. By increasing the mass of the piston, the floor costs per kWh will drop and this will also decrease the total storage costs per kWh. The height of the building does have a positive effect on the properties of the system but the effect is limited since the most important factor evenly grows with the height.

Although the benefits of using an integrated system in which the water can be used as a reliable source to extinguish a starting fire and the thermal capacity of water than can be used to cool

\(^1\)See table 2-2 for the net present value of other Electrical Storage Systems (ESS) and appendix A for the calculation method

---

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
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<td>Height of the building</td>
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</tr>
<tr>
<td>Tube inner cross section diameter</td>
<td>8100mm</td>
</tr>
<tr>
<td>Piston mass</td>
<td>2.769.000kg</td>
</tr>
<tr>
<td>Energy capacity</td>
<td>432.4 kWh</td>
</tr>
<tr>
<td>Nominal power capacity (charge)</td>
<td>342.7 kW</td>
</tr>
<tr>
<td>Nominal power capacity (discharge)</td>
<td>381.0 kW</td>
</tr>
<tr>
<td>Nominal charge time</td>
<td>90.0 min</td>
</tr>
<tr>
<td>Nominal discharge time</td>
<td>55.5 min</td>
</tr>
<tr>
<td>Round-trip efficiency at nominal speed</td>
<td>69%</td>
</tr>
</tbody>
</table>

**Table 4-1: Specifications of the GPES in the Adjusted Building Concept (ABC)**
<table>
<thead>
<tr>
<th>Component</th>
<th>$W^a$</th>
<th>$E^b$</th>
<th>Costs [€]</th>
<th>Unit costs [€/kW] or [€/kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piston filling</td>
<td>x</td>
<td>240.000</td>
<td>555.00</td>
<td></td>
</tr>
<tr>
<td>Piston casing material</td>
<td>x</td>
<td>22.500</td>
<td>52.00</td>
<td></td>
</tr>
<tr>
<td>Turbine &amp; generator equipment</td>
<td>x</td>
<td>188.000</td>
<td>493.40</td>
<td></td>
</tr>
<tr>
<td>Two pumps setup</td>
<td>x</td>
<td>50.000</td>
<td>145.90</td>
<td></td>
</tr>
<tr>
<td>Floor space</td>
<td>x</td>
<td>648.750</td>
<td>1500.30</td>
<td></td>
</tr>
<tr>
<td>Total power costs per kW</td>
<td></td>
<td></td>
<td>639.30</td>
<td></td>
</tr>
<tr>
<td>Total energy costs per kWh</td>
<td></td>
<td></td>
<td>2107.30</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Power capacity costs
$^b$ Energy capacity costs

Table 4-2: Highrise Energy Storage Core (HESC) power and energy costs

or heat the building have not been quantified, it is clear that the costs of storing electrical energy in the Highrise Energy Storage Core (HESC) is rather expensive with the specifications as established for the Adjusted Building Concept (ABC). By optimizing the properties of this storage system and by evaluating the price benefits of the additional functionality, the HESC might be able to compete with current storage solutions.
In chapter 3, several aspects of the Highrise Energy Storage Core (HESC) have been worked out on the basis of a fictitious 80 meters tall Reference Building Concept (RBC). This building is located in an arbitrary place without any location specific aspects. In this chapter, the application of an HESC is elaborated for a project in a real context which includes more specific conditions, such as high temperatures and of lack of access to surface water.

Torre Sofia is a residential and office building project in the city-municipality of San Pedro Garza Garcia in the north of Mexico. The 160 meter tall building was designed by Pelli Clarke Pelli Architects and is being built adjacent to the larger Arboleda Master Plan[38]. In this planned urban area, commercial properties with retail stores and offices are combined with private residential areas. The 11 hectares project consists of three high-rise residential towers, two smaller office towers, and a number of smaller low and mid-rise buildings (see figure: 5-1). The different zones are posted around an elliptical park in the center of the development. Buildings around the park have multilayer outdoor spaces with terraces, flower beds, and walkways. This should create an integrated and lively environment with all facilities for daily activities within easy reach.

The building projects that are a part of the master plan are aimed for the upper segment of the market. Therefore, the level of comfort, safety, architectural design, and the amount of facilities needs to be high. In order to comply with modern building methods, the urban master plan will be compliant with LEED\(^1\) for Neighborhood Development and all buildings will be LEED certified. The LEED-ND certification rates the development of a neighbourhood on the principles of Smart Growth, New Urbanism, and green buildings. By Smart Growth is meant a method to grow cities within the context of long-term regional planning to produce a sustainable future[37]. It also aims to mitigate the sprawl on the outskirts of expanding cities. This applies to the Arboleda project site since it is located in a rather small town in the outskirts of the quickly growing metropolitan area of Monterrey.

\(^1\)Leadership in Energy and Environmental Design (LEED) is developed by the U.S. Green Building Council and compromises a set of rating systems for the design, construction and operation of high performance green buildings, homes and neighborhoods.
Figure 5-1: The Arboleda Master Plan with in the top of the picture the Torre Sofia building project (source: Pelli Clarke Pelli Architects).

(A) Multilayer private and public outdoor spaces.  (B) Elliptical park in the center of the development.

Figure 5-2: Views on the Arboleda project (source: Pelli Clarke Pelli Architects).
New Urbanism comprises the principles of Smart Growth, but also puts a focus on the physical form of buildings, the environment, and on the use of universally accessible public spaces. In the public realm, spaces should be created in such way that they foster face-to-face social interaction. Similar to the structure of a traditional town, the New Urbanism neighbourhood has narrow streets and a public space in its center in order to create a pleasant environment at a human scale.

5-1 New Urbanism & technical integration

The shared principles of New Urbanism and Smart Growth include compact and attractive neighbourhoods that have a strong sense of place, a variety of uses concentrated within a walkable distance, and a wide range of housing opportunities and choices within the same area. These guidelines also encourage the use of less environmentally harmful means of transportation by prescribing easy access to different types of public transport and bicycle-friendly streets.

The term New Urbanism arose in the eighties but many of the principles behind this movement are much older. Ludwig Hilberseimer (1885-1967), the architect and urban planner, wrote his well known book "Großstadt Architektur" in 1924. In this book he exposed his ideas on solving the problems of rapidly growing cities in the first half of the twentieth century. According to Hilberseimer, traffic, the human-scale, and a lack of space were important problems that needed to be solved. In his proposal to solve these problems, the city consists solely of highrise buildings that are divided into a bottom section and a satellite or top part. Commercial and industrial uses are placed in the first few storeys of the highrise building along with infrastructure on ground level. Residential uses are strictly parted from the other functions and are located in the upper storeys. Most of the daily activities are vertically organized within the same building[83]. The transportation demand is therefore limited and the remaining part is handled by an external infrastructure. According to Velazquez et al.[83], Hilberseimer’s highrise city mainly solves the traffic problems and the physical limitations of future growth.

When Hilberseimer migrated to Chicago, he worked on a project known as “The New City” or “Decentralized City”. In this work, he described the transition of people moving to the city in the industrial age (centralisation) and moving towards suburbia in the post-industrial age (decentralisation). It will tend to be decentralized and it can thus combine the advantages of the small town with those of the large city[41, p. 149]. His second major project is a reaction to the increasing dispersion of Americans into the suburbs. The mono-functional suburbia caused major traffic problems in the city center and the lack of planning resulted in wrongly located industrial areas[6, 41]. His idea of dividing the city into smaller multifunctional towns clearly has many similarities to the New Urbanism movement. Whereas the High Rise City is a vertical solution that mainly solves the traffic problems, the Decentralised City is a horizontal approach that tries to tackle a much broader number of aspects such as sociological, ecological, economical, and defense. New Urbanism tries to solve many of the same problems but adds the aspect of sustainability.

Although the expressed purpose of the Arboleda development team is to be compliant with the principles of New Urbanism and Smart Growth, some of these starting points stand at
odds with the local level of public transportation and the customer needs of closed private
neighborhoods. Instead of a lively area in a larger agglomeration, this community might get
isolated from other communities.

**Technical integration**

Torre Sofia (see figure: 5-3) is currently being built conforming to modern building guidelines
and will be certified according to the LEED rating system. The building might well integrate
into the Arboleda neighbourhood in the sense of the principles of New Urbanism, but not
on a technical level. If the tower was equipped with an HESC, Torre Sofia could also get a
technical function in the neighbourhood. The urban planning methods like New Urbanism
focus on the social field and the ecology of the different uses in a neighbourhood, and the
HESC is able to do something similar on a technical level.

The principal use of the HESC is to store a surplus of energy in the grid and release that
energy during peak demand (see section: 2-1). Power demand peaks are flattened such that
the maximum demand from the grid will be lower than for neighborhoods without an electrical
storage system. The capacity of the Adjusted Building Concept (ABC)\(^2\) is, roughly estimated,
enough to flatten the energy demand curve of two buildings (see section: 3-1-1). Since Torre
Sofia is twice the height of the ABC, the storage capacity is almost four times the storage
capacity of the ABC with the same relative piston height (\(\frac{1}{t}\cdot h\)). Since Torre Sofia is the
tallest building in the neighbourhood, the capacity is likely to be large enough to level out
the peak demand of the whole Arboleda area. The capacity and properties of the HESC in
Torre Sofia are elaborated more in detail in section 5-2.

A second application is using the water in the tube as a source to extinguish a fire. Since
surface water is scarce and unreliable in Monterrey due to infrequent rainfall, it cannot be
used as a reliable source of water. As elaborated in section 3-2-1, the water in the tube
can be used to extinguish a fire. This eliminates the need for a redundant connection to two
independent water mains or a solution that provides an equivalent reliable supply of water like
a set of water tanks. The water reservoir in the tube can be designated as an inexhaustible
source. The capacity of the reservoir greatly exceeds the minimum size for 'inexhaustible
reservoirs' and thus the reservoir can also be used to serve the whole neighbourhood. Torre
Sofia will be the tallest building and therefore the pressure at the bottom of the tube is likely
to be large enough to supply the other buildings without the need of intermediate booster pumps.
This application requires an infrastructure of pipes that connect to the other buildings, but
that is likely to outweigh the costs of the other reliable alternatives.

The third application that has been elaborated upon in section 3-2-2 is the use of a thermal
buffer. The mass of the water and the piston can be deployed in such way that the indoor
temperature fluctuations are leveled out. With an annual average high temperature of 27.5\(^3\)
in Monterrey\(^61\), there is a demand for cooling throughout almost the whole year. The daily
mean temperature in January is 14.4\(^2\). With a well insulated facade and only short periods
of time with lower temperatures, there is no need to store heat in a thermal buffer. When
the thermal buffer is only used to store cold, a chiller can cool the water in the buffer during
the coldest days of the year and thus use the lowest amount of energy to cool the building.

---
\(^2\)This is a fictitious 80 meter tall building equipped with an Highrise Energy Storage Core (HESC)
\(^3\)The average of the daily highest temperatures over a whole year
Figure 5-3: Torre Sofia (source: Pelli Clarke Pelli Architects).
The buffer capacity of the ABC has been quantified but further calculations should clarify if that buffer is big enough to level out the cold demand for the whole summer and if the buffer could also be used to cool other parts of the neighbourhood.

5-2 Building properties

Capacity

The height in combination with the piston mass determines the capacity of the storage system. When the building is higher than the RBC, the capacity increases linearly with the height of the building. If the piston mass also increases, than the capacity exceeds the linear relation.

The optimal piston height in the Adjusted Building Concept (ABC) was assumed to be \( \frac{1}{8} \) times the building height. This value has not been justified with calculations. Since the power and energy costs are calculated in section 4-2, the information needed to define a minimization problem is known. Although not all costs are defined in the overview (e.g. engineering costs and building costs), the known costs can give insight on the optimal height of the piston by solving the optimization equations.

Since the size of the power demand peaks in the mixed uses Arboleda project are unknown, the best Power-To-Energy (PTE)-ratio for the storage system is also unknown and will therefore be left out of the optimisation equation. The remaining equations define the costs of the piston filling material, the piston casing material, and the floor space costs. In this simplification only the storage costs need to be minimized.

The minimisation problem for the energy storage costs in Torre Sofia is then defined by\(^4\):

\[
\begin{align*}
C_{\text{filling}} &= p_p \cdot \rho_p \cdot (\pi \cdot r_i^2 \cdot h_{pi}) \cdot 10^{-3} & \text{(piston filling price)} \\
C_{\text{casing}} &= p_{pc} \cdot \rho_s \cdot (2 \cdot \pi \cdot r_i \cdot h_{pi} \cdot t_{pc} + \pi \cdot r_i^2 \cdot d_{pc}) \cdot 10^{-3} & \text{(piston casing price)} \\
C_{\text{floor}} &= n_f \cdot C_{\text{floor}} & \text{(floor space price)} \\
E_{\text{GPES}} &= A_p \cdot g \cdot \frac{h_{pi} \cdot (\rho_{pi} - \rho_w) \cdot (h_b - h_{pi})}{3600} \cdot 10^{-3} & \text{(energy storage capacity in kWh)} \\
C_{\text{kWh}} &= \frac{C_{\text{filling}} + C_{\text{casing}} + C_{\text{floor}}}{E_{\text{GPES}}} & \text{(price of storage capacity per kWh)} \\
\end{align*}
\]

where

\[
\begin{align*}
p_p & \text{ is the price per tonne piston filling (iron ore)} \\
p_{pc} & \text{ is the price per tonne piston casing material (steel)} \\
\rho_p & \text{ is the density of iron ore} \\
\rho_{pi} & \text{ is the average density of the piston} \\
\rho_w & \text{ is the density of water} \\
\rho_s & \text{ is the density of steel}
\end{align*}
\]

\(^4\)The equations to calculate the capacity of the Adjusted Building Concept (ABC) in chapter 3 are more detailed. The aim of this optimisation problem is to get an idea of the optimal size of the piston rather than to get the exact optimal size.

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r_t is the radius of the piston (equal to the radius of the piston in the ABC)
l_p is the piston casing wall thickness
d_{pc} is the thickness of the piston floor plate
n_f is the number of floors
g is the gravitational acceleration
A_p is the piston cross sectional area
h_p is the height of the piston (the parameter that is being looked for)
C_{floor} is the price of the floor space that cannot be used per floor
C_{kWh} is the value that needs to be minimised

Solving the optimisation equation leads to an optimal piston height of 50.1 meter which is 31.3\% of the building height. This is much more than what has been assumed in chapter 3 ($\frac{1}{8}$ times the building height would lead to a 20 meter tall piston for Torre Sofia). Since the floor space costs turned out to be an important factor in the total storage costs, the influence of this assumed value also has a major effect on the optimal height of the piston. When the assumed value of the lost square meters is only 500€ per m$^2$ instead of 1000€, the optimal height of the piston is only 40.2 meters. A larger piston does not significantly change the amount of thermal storage capacity, but it takes more time to address all that storage capacity.

The electrical storage capacity of the Torre Sofia HESC storage system with the enhanced piston size are shown in table 5-1. The amount of energy that can be stored in Torre Sofia is almost eight times larger than the amount of energy stored in the ABC. The amount of water in the tube, and thus the amount of water that has to be transported, exceeds the amount of in water in the ABC. Since the system resistance is closely related to flow rate in the pipes, the pipes in Torre Sofia have to be slightly bigger.

<table>
<thead>
<tr>
<th></th>
<th>ABC</th>
<th>Torre Sofia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of the building</td>
<td>80m</td>
<td>160m</td>
</tr>
<tr>
<td>Piston height</td>
<td>10m</td>
<td>48m</td>
</tr>
<tr>
<td>Piston mass</td>
<td>2.769.000kg</td>
<td>13.339.000kg</td>
</tr>
<tr>
<td>Energy capacity</td>
<td>432,4 kWh</td>
<td>3331,4 kWh</td>
</tr>
<tr>
<td>Water volume</td>
<td>3525.6 m$^3$</td>
<td>5666.2 m$^3$</td>
</tr>
</tbody>
</table>

Table 5-1: Capacity properties of the GPES in the Adjusted Building Concept (ABC) and Torre Sofia with the optimised piston size

Pumps

Since the capacity of the system is significantly larger than in the ABC, other types of pumps have to be installed. The flow is only slightly larger but the difference between the inlet pressure and the outlet pressure is much larger.

In section 3-1, a situation is taken into account in which the building or the neighbourhood produces its own electricity. The energy production fluctuates and therefore at least one pump needed to have a variable pump drive to get a match between the energy taken up by
Table 5-2: ABC and Torre Sofia nominal pump design parameters based on a single pump setup (configuration: t=90, single pump).

<table>
<thead>
<tr>
<th>Param</th>
<th>Composition</th>
<th>ABC</th>
<th>Torre Sofia</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_s$</td>
<td>$P_{piston} + P_{tube}$</td>
<td>80.0m</td>
<td>160.0m</td>
</tr>
<tr>
<td>$h_d$</td>
<td>$h_s - h_f \Delta s - \sum h_{f,\Delta s} - \frac{v_{piston}^2}{2g}$</td>
<td>124.1m</td>
<td>372.2m</td>
</tr>
<tr>
<td>$h_{gs}$</td>
<td>$h_d + h_{fd} + h_{pf} + \sum h_{f,\Delta s}$</td>
<td>79.7m</td>
<td>159.3m</td>
</tr>
<tr>
<td>$h_{gd}$</td>
<td>$h_{stat} - h_s$</td>
<td>124.7m</td>
<td>372.9m</td>
</tr>
<tr>
<td>$H_{stat}$</td>
<td>$h_d - d_s$</td>
<td>44.1m</td>
<td>212.2m</td>
</tr>
<tr>
<td>$H_g$</td>
<td>$H_{stat} - h_{gs} + \frac{v_{piston}^2}{2g} - \frac{v_{water}^2}{2g}$</td>
<td>45.1m</td>
<td>213.7m</td>
</tr>
<tr>
<td>$Q$</td>
<td></td>
<td>2404.7m$^3$/h</td>
<td>3777.4m$^3$/h</td>
</tr>
</tbody>
</table>

The power taken up by the pumps cannot be retrieved since the pump manufacturer does not provide the performance curves for this size of pumps. In section 3-1 it is noted that all turbomachinery performs more efficiently when the capacity is larger. The pumps have to take up a lot more power to charge the GPES compared to the pumps of the ABC, but the flow rate through the pumps is only slightly bigger. The head at the pump exit is a lot larger. Compared to the ABC the specific speed of the pump is much lower and that has a negative effect on the efficiency. In table 5-3 it is assumed that the efficiency of the pump running at nominal speed will be equal to the performance of the largest pump in the ABC. For a more precise approach the test power curves need to be known.

The electrical power input of a single pump in a two pump setup running at nominal speed is 2631.4kW. The efficiency of this setup in charge mode is 84.4%. The performance gain in relation to the ABC running at nominal speed is more than 2%. Hydraulic system losses in the Torre Sofia building can be divided over a larger amount of energy and thus the losses per kWh are less.

**Turbine**

The method of Moody and Zowski has been used to estimate the efficiency of the rather small turbine in the Adjusted Building Concept (ABC) (see section: 3-1-5). The maximum mechanical efficiency of the Francis turbine is approximately 95% for large turbines. A smaller turbine has more losses and thus the efficiency is lower. Consequently, the turbine in Torre Sofia is likely to be more efficient than the turbine placed in the ABC.
In table 5-4 the specifications of the ABC turbine are compared with the turbine required in Torre Sofia. The specific speed is closer to the optimal specific speed for a Francis turbine [55, p. 455] and the bigger size leads to an efficiency of 92.8%. The overall discharge efficiency turns out to be 4.4% more favourable in relation to the efficiency of the turbine in ABC. The turbine is more efficient, the generator is slightly more efficient, and hydraulic and piston friction losses can be spread over a larger amount of energy.

### Overall efficiency and costs

Multiplying the nominal efficiency in charge mode with the efficiency in discharge mode results in a round-trip efficiency of 0.74. By optimising the size of the piston and doubling the building height, the system efficiency is increased by 5%. With the increased system efficiency in relation to the ABC, the total costs per effectively stored kWh are reduced.

A second important value is the increase of the energy density. The energy capacity per square meter building space is almost five times higher than in the ABC. The determining factor of the storage cost in the ABC turned out to be the floor space costs per square meter. In Torre Sofia, with the optimised piston height, the floor space costs per kWh are significantly lower.

With the calculated power and energy costs (see table: 5-5) the net present value of the storage system with a PTE-ratio of 1:2 is 2.160€ per kWh. This is less than the net present value of electrochemical lithium-ion (see table: 2-2). Although not all costs are included in this calculation, it can be concluded that the height of the building and the size of the piston play a very important role in the efficiency and present value of a Highrise Energy Storage Core (HESC).
<table>
<thead>
<tr>
<th>Parameter</th>
<th>ABC</th>
<th>Torre Sofia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotational speed</td>
<td>Ω</td>
<td>1500 rpm</td>
</tr>
<tr>
<td>Number of poles</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Mechanic power output</td>
<td>400 kW</td>
<td>3200 kW</td>
</tr>
<tr>
<td>Rated output capacity</td>
<td>500 kW</td>
<td>4000 kW</td>
</tr>
<tr>
<td>Flow rate</td>
<td>1.037 m³/s</td>
<td>1.693 m³/s</td>
</tr>
<tr>
<td>Shaft specific speed</td>
<td>Ωₛ</td>
<td>1.70</td>
</tr>
<tr>
<td>Power specific speed</td>
<td>Ωₛₚ</td>
<td>1.63</td>
</tr>
<tr>
<td>Blade speed</td>
<td>U₂</td>
<td>24.3 rpm</td>
</tr>
<tr>
<td>Number of blades</td>
<td>Z</td>
<td>13</td>
</tr>
<tr>
<td>Hydraulic and mechanical efficiency</td>
<td>91.7%</td>
<td>92.8%</td>
</tr>
<tr>
<td>Overall discharge efficiency</td>
<td>0.833</td>
<td>0.877</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Costs [€]</th>
<th>Unit costs [€/kW] or [€/kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piston filling</td>
<td>1.147,000</td>
<td>344,00 or 555,00</td>
</tr>
<tr>
<td>Piston casing material</td>
<td>315,00</td>
<td>95,00 or 52,00</td>
</tr>
<tr>
<td>Turbine &amp; generator equipment</td>
<td>601,00</td>
<td>194,00 or 493,40</td>
</tr>
<tr>
<td>Two pumps setup</td>
<td>160,00</td>
<td>48,00 or 145,90</td>
</tr>
<tr>
<td>Floor space</td>
<td>1,038,00</td>
<td>311,60 or 1500,30</td>
</tr>
</tbody>
</table>

Table 5-4: Characteristics of the GPES in discharge mode.

<table>
<thead>
<tr>
<th>Component</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total power costs per kW</td>
<td>242,00</td>
</tr>
<tr>
<td>Total energy costs per kWh</td>
<td>750,60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total power costs per kW</td>
<td>639,30</td>
</tr>
<tr>
<td>Total energy costs per kWh</td>
<td>2107,30</td>
</tr>
</tbody>
</table>

a Power capacity costs
b Energy capacity costs

Table 5-5: The power and energy costs for a HESC implemented into the Torre Sofia project
Chapter 6

Conclusion

6-1 The move towards renewable energy sources

The production of electrical energy in Europe will change drastically in the coming decades. The main driving forces behind this transition are the increasing scarcity of currently used energy sources, a growing awareness among the population of Europe, and energy policies initiated by the European Commission and other legislators. The three most important reasons for energy policies in consumer countries are: (a) ensure low supply costs, (b) ensure the security of supply, (c) environmental considerations[18].

The scarcity of fossil fuel resources and the increase of consumption in Europe is the cause of a growing dependency on energy imports (see section: 1-3-1). This trend is likely to continue if there is not a major shift towards other energy sources. In a world with rivalling economic blocks, import dependency is considered a major risk to security of supply. Geopolitical events already affected the energy security and were the cause of major fluctuations in the price of energy. At the same time the evidence for the effects of emitting carbon dioxide into the atmosphere on the climate become more convincing.

Domestic production of affordable non-fossil alternatives is seen as a solution to these problems. The long-term objective of the European Commission is that all electrical energy is obtained by Renewable Energy Sources (RES). Therefore, the European Commission adopted a set of directives which mandates the European states to promote energy efficient technologies and a binding target on the amount of RES in their total energy mix (see section: 1-3-2). Countries like the Netherlands are behind the goals that have been agreed on, but many other countries are well on schedule and already have a large share of renewables in their energy mix[29]. A second approach is the European Union Emissions Trading Scheme (ETS) which creates a market for greenhouse gas emission allowances. The allowances are meant to create an extra incentive to invest in energy saving technology and in RES. Since the start of the economic crisis, the value of the emission allowances dropped significantly. The incentive to invest in energy efficient technology diminished. Nonetheless, the share of renewables in the energy supply of Europe is growing[28].

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Predicting the exact energy mix of the future and the path towards a mix that solely consists of Renewable Energy Sources (RES) is difficult. The real success of legislation on the long term is not clear and the role of newly developed fuels like shale gas is unknown, but it is evident that fossil fuels are finite and thus have to be replaced at a certain point. The share of RES is increasing and that process is likely to continue. After the transition to a significant share of RES in the generation of electrical energy, storage is needed to absorb the fluctuations of the Variable Renewable Energies (VRE) (see section: 1-4-3).

Storage systems can be classified according to their absolute size (see section: 2-1-2) and according to their most suitable Power-To-Energy (PTE)-ratio. An Electrical Storage Systems (ESS) with a small energy capacity and a high PTE-ratio (≫ 1) is usually placed near to the consumers to level out small demand fluctuations or near to production facilities to temporarily increase or decrease the power output. Storage systems with a high energy capacity and a low PTE-ratio (≪ 1) can be used to bridge larger periods of energy generation deficits. To level out daily demand fluctuations, energy storage systems with a PTE-ratio of about 1:1 can be used.

6-2 Storing electrical energy in a tall building

Storing electrical energy near to consumers has a positive effect on the stability of the grid. It enables to supply the grid and the consumers with an almost constant amount of power. A flywheel or an electrochemical capacitor is able to flatten small disruptions and medium sized systems like electrochemical batteries can be used to flatten the daily demand and supply fluctuations.

The Highrise Energy Storage Core (HESC) as discussed in this thesis is particularly suitable for leveling out the daily demand and supply fluctuations. The approximated length of these fluctuations is about one hour and can take up to a few hours. Higher charge- and discharge speeds would lead to significantly higher losses due to friction in the pipes. On the opposite side, much lower charge- and discharge speeds require small and inefficient components (see section: 3-1-3, 3-1-4, and 3-1-5). Calculations show that charging the storage system with a single pump running in a multiple pump setup is not as efficient as single pump running in a two pumps setup (see table: 3-13), but the performance is still good. Much lower charging speeds with even smaller pumps are likely to be significantly less efficient but this has not been investigated. Also running a single pump at part load in combination with a variable pump drive shows significant performance degradation, but when there is a surplus in the local energy production (e.g. solar panels or a Combined Heat and Power (CHP)), efficiency is not always the most important argument.

The discharge speed is less flexible (see table: 3-14). It is practically and financially not a good idea to install multiple turbines. Therefore, the only option to change the electrical output of the system is by reducing the rotational speed of the turbine. The performance curve of a Francis turbine shows a major efficiency degradation for turbines running at part load and thus running the turbine outside its Best Efficiency Point (BEP) should be avoided. As mentioned in section 4-1, from a technical point of view it is better to use the turbine as a grid backup that supports the utility plants near the end-users, rather than a system which exactly matches the local power demand. It can be concluded that when there is no
specific reason to run the system in charge- or discharge mode at part-load, it should not run at part-load at all.

6-3 Field of application

The system size and the building height are important factors in the overall efficiency and economical feasibility of the storage system. Calculations in section 3-1-6 showed a maximum round-trip efficiency of 60% and section 4-1 showed that the costs of the electrical storage system per kWh in an 80 meter tall building were rather high. The same calculations with an optimized piston height in a taller building showed that the net present value of the HESC outperformed the costs of lithium-ion batteries and that the round-trip efficiency increased to 74% (see section: 5-2). As mentioned before, the cost calculations are incomplete, but it does give insight into the importance of the height of the building and the optimisation of the piston height. The HESC is mainly suitable for tall and very tall buildings.

The energy storage costs in the HESC are relatively high compared to other Pumped-Storage Hydroelectricity (PSH) plants and thus this system is not the best solution to solve the problem of storing large amounts of energy over a longer period of time. In a 100% renewable Europe, the total storage capacity needs to be the equivalent of the total energy consumed in 2 to 6 days (see section: 1-4-3). Leveling out the daily fluctuations only requires a storage capacity equal to the energy consumed in a few hours. Even when many buildings are equipped with a HESC, there is still a need to store large amounts of energy for a low price somewhere else in the grid. The storage tube is also not able replace the function of flywheels or electrochemical capacitors since it cannot respond to extremely unpredictable and varying loads.

The storage tube performs optimally when it is able support the distribution grid or when it is used in smaller grids in combination with other electrical storage systems with a high Power-To-Energy (PTE)-ratio and a small energy capacity. Besides the application of an electrical storage system, the water in the tube can also be used to extinguish a fire and as a thermal buffer. The electrical storage application and the water reservoir can be seen in a context that is larger than the building itself. The electrical storage system does not only serve the users of the building equipped with a storage system, it also serves other users connected to the same electrical grid. The “inexhaustible” water reservoir can be used to distinguish a fire locally or in near lying buildings.

The Highrise Energy Storage Core (HESC) is a multifunctional storage system that perfectly fits into the principles of Smart Grids. Matching electrical energy demand with the supply is a complicated process that gets even more complicated when Renewable Energy Sources (RES) take a larger share in the total energy mix. Storage is an important solution for situations in which the energy supply does not match the demand. The HESC provides a clean way of storing electrical energy near to end-users and at the same time it is an efficient thermal storage buffer.
6-4 Further research

In this thesis the arguments for storing electrical energy have been discussed and the benefits of a decentralised energy storage systems as part of a smart grid have been elaborated upon. The proposed solution of storing energy inside a building has been argued and some of the main technical problems have been identified and solutions for these problems have been developed. Nonetheless, the set of solutions is not complete and for some of the problems a better solution might have to be developed.

The determination of the costs of the storage system in this document is not complete and should also include the engineering costs, buildings costs, and a more detailed estimation of the components of the system. In a broader view on the costs, also the benefits should be taken into account by looking at the variable prices of energy or by looking at current research projects which involve other types of storage systems. By looking at other storage systems, the round-trip efficiency should also be part of the present value calculation\(^1\).

Another subject that should be researched is the practical implementation of the system. Who should be the owner of the system and if the system functions as a backup source (see section: 6-2), how should that be taxed?

List of some prominent technical research subjects:

- A better solution for the seal between the piston and the inner wall (see section: 3-1-2).
  
  The current solution is watertight and it is possible to make. However, the tolerances are tight, the steel inner wall is most likely an expensive component, it requires a lot of steel, and it complicates the building process. In the tube the pressure differences are relatively low and some leakage is acceptable. A lower pressure on the seal and an extremely smooth concrete surface might result in a much cheaper, but also satisfactory, solution.

- How to use the thermal storage buffer (see section: 3-2-2)

  The extra storage capacity of the Adjusted Building Concept (ABC) has been calculated. The water and piston mass can be used to store thermal heat or cold for high temperature cooling or low temperature heating but the timescale of this buffer is unknown. In Torre Sofia, the most optimal solution would be to store cold in the winter and use that cold in the summer. Is the buffer large enough or is the only benefit to cool the water at night and use that cold during the day? How can the buffer be used in a more moderate climate like in the Netherlands?

- What is the performance of the thermal buffer?

  Unlike thermal storage systems in underground aquifers, this thermal buffer does not require wells, underground pipes, and pumps to circulate the water from the building into the aquifer and the other way around. The performance of this thermal buffer depends on leakage at the top of the tube or through the tube wall when heat or cold is not required in the open building spaces. How does the heat transfer through the tube wall and is the heat flux large enough to cover the demand in the building?

\(^1\)The round-trip efficiency is incorporated in the net present value of the system components but not for future purchased electrical energy.
What happens when the building is subjected to a lateral force?

The building and the storage core will bend slightly when a lateral wind force hits the facade. The gravitational force on the piston keeps the piston straight, but due to the curvature of the tube there will be a force on the axes of the bottom guiding wheels (see B in figure: 3-4). The curvature is only very small but the mass of the piston is very large. What is the resulting force on the guiding wheels?

What happens when the piston gets stuck? (see figure: 3-5)

A situation in which the piston gets stuck in the tube should always be avoided, but the consequences of such a situation should still be known. When the piston is not stuck, the water column carries the piston and the tube only has to convey hoop forces. When the piston gets stuck in the tube, the hoop forces will be less and vertical compressive forces in the tube will be bigger. This increases the risk of buckling and it puts a bending moment on the concrete core. Since the normal centre of the core does not coincide with the centroid of the tube, the hanging piston will be the cause of an additional moment in the core. How big is this moment and is it smarter to separate the tube from the rest of the core to avoid this situation?
Calculating the present value of storage systems

The various storage technologies for a certain application can be compared on their initial costs, maintenance costs, specifications and environmental impact. In this section, the present value per kWh will be calculated for the most proven and promising chemical- en mechanical storage technologies. The base of the comparison will be a long term storage application in the micro grid, which provides the ability to store electrical energy from several hours to a few days. The economic lifetime which will be used to compare the different technologies is 30 years. This is the investment period for properties.

The starting point implies that the ratio between the power capacity and the storage capacity is more or less a fixed value. A simulation of the power network grid can later justify a bigger power capacity or a larger storage capacity. To compare the different technologies, a power-to-energy ratio of 1:2 will be assumed for chemical storage systems and flywheels. For every installed kW, the energy storage capacity is 2kWh.

For long term investments, the lifetime of the technology is an important variable. A battery solution has a limited lifetime, so future replacements of batteries need to be part of the present value calculation. The interest rate should therefore be taken into account as well. The present value will be calculated with three interest scenario’s (0%, 2% & 4%).

Besides comparing the technologies, the scale of the storage systems will be compared as well. It can be assumed that large scale applications are cheaper than smaller systems but the realisation of small systems is easier and the implicit costs are less. A single household often does not have access to (local) grid storage solutions and always need to implement its own system. To get insight into this disadvantage, the costs of single household storage systems will be calculated as well.

It should be noted that the accuracy of the present value calculations depends on many environmental factors which cannot be caught into a single value. The location of the system, the size, the market conditions, the ambient temperature, and technological progress will
affect the present value calculations. The aim of these calculations is to compare the available Electrical Storage Systems (ESS) targeted on load shifting.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Abbreviations</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>Energy storage capacity</td>
<td>kWh</td>
</tr>
<tr>
<td>P</td>
<td>Power Capacity</td>
<td>kW</td>
</tr>
<tr>
<td>i</td>
<td>Interest rate</td>
<td>%</td>
</tr>
<tr>
<td>n</td>
<td>Economical lifetime</td>
<td>y</td>
</tr>
<tr>
<td>CRF</td>
<td>Capital Recovery Factor</td>
<td></td>
</tr>
<tr>
<td>PC</td>
<td>Periodic Costs</td>
<td>€/y</td>
</tr>
<tr>
<td>PV</td>
<td>Present Value</td>
<td>€</td>
</tr>
<tr>
<td>SC&lt;sub&gt;storage&lt;/sub&gt;</td>
<td>System costs storage</td>
<td>€</td>
</tr>
<tr>
<td>SC&lt;sub&gt;power&lt;/sub&gt;</td>
<td>System costs power</td>
<td>€</td>
</tr>
</tbody>
</table>

Table A-1: Symbols and abbreviations

Chemical energy storage

A storage system with batteries requires a Battery Management System (BMS) and a power inverter. The BMS handles the charging process, discharging process and the State of Charge (SOC). The various chemical processes demand a tuned charging procedure. Managing the battery cell load is important for systems which suffer a ‘memory’ effect. To limit the negative consequences of the memory effect, the SOC of Pb-Acid batteries should not drop below 50% of the total storage capacity. When a Pb-acid battery gets discharged to a level beneath 50% of its total capacity, the lifetime of the battery drops significantly. A battery lifetime is assumed to be expired when the actual absolute capacity drops below 50% of its initial nominal capacity.

A power inverter transforms the output of the batteries into an alternating current. The lifetime of an inverter is usually less than the economical lifetime of the system. This means that the replacement of the inverter needs to be part of a present value calculation. It will be assumed that the replacement costs of the power inverter are 2/3 of the initial power costs per kW. A second assumption will be that the power costs (including the costs of the inverter) in the local grid and the main grid, are proportional to the capacity. The costs of single household systems are higher.

An example of such a system is the PowerRouter. The PowerRouter is an integrated system which is able to manage the battery charging process, to keep track of the power usage and power generation, to invert the direct current and to inject power into the main grid. The costs of single household PowerRouter are about 3500€ and combined with a Pb-Acid battery pack, about 5400€. The effective storage capacity of the system is 4.5kWh.
Lead acid batteries

Pb-acid batteries are the oldest type of rechargeable batteries. Despite the objectionable environmental impact of the use of lead, the low price and the ability to deliver a high current means that this technology still has a broad field of applications. It is a proven and mature technology. Therefore, it is not expected that developments in this technology will significantly change its current characteristics.

The lifetime of Pb-acid batteries is closely related to the amount of charge and discharge cycles, the power capacity, and the Depth of Discharge (DOD). The power capacity is not the key factor for a system which is used for load shifting. A system which charges and discharges with low currents, a method which is called “Deep Cycling”, can comply with the needs. When the typical DOD of a deep cycle battery is about 50%-60%, the lifetime is expired after approximately 1500 cycles. This property means that the effective storage capacity of a Pb-acid battery is about half the nominal capacity. Assuming a little less than one cycle a day, the estimated lifetime is about 6 years. Given the economical lifespan of 30 years, the amount of battery replacements will be 5. The Capacity Retention Ratio (CRR) drop throughout the years will not be accounted in the present value calculation.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Literaturea</th>
<th>Single householdsb</th>
<th>Local grida</th>
<th>Main grida</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balance of plant costs</td>
<td>$C_{bop}$</td>
<td>€/kW</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Unit costs energy capacity</td>
<td>$C_E$</td>
<td>€/kWh</td>
<td>175</td>
<td>200</td>
</tr>
<tr>
<td>Unit costs power</td>
<td>$C_P$</td>
<td>€/kW</td>
<td>325</td>
<td>800</td>
</tr>
<tr>
<td>Lifetime</td>
<td>$L$</td>
<td>years</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Operation &amp; maintenance</td>
<td>$C_{O&amp;M}$</td>
<td>€/kW</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Storage system efficiency</td>
<td>$\eta$</td>
<td></td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Implicit efficiency</td>
<td>$\eta_{\text{CO}_2}$</td>
<td></td>
<td>0.75</td>
<td>$\approx$</td>
</tr>
</tbody>
</table>

$^a$ See: [79, 15]
$^b$ Based on the NEDAP PowerRouter system and an Enersys EON Accupack
$^c$ Assumption based the fact that the storage system requires that the electricity gets transported to the storage system

Table A-2: Explicit costs and efficiency of Pb-acid systems. DOD=0.55, PTE=1:2, CRR=1.0

Calculations of the costs per kWh for a load shifting system (calculated for a single household system):

$$SC_{\text{storage}}(€) = C_E/(\eta \cdot DOD) = \frac{200}{0.75 \cdot 0.55} = 484.85$$ (A-1)

$$SC_{\text{power}}(€) = C_P \cdot P = 800 \cdot 0.5 = 400.00$$ (A-2)

$$SC_{\text{bop}}(€) = C_{bop}(€/kW) \cdot 0.5 = 80 \cdot 0.5 = 40.00$$ (A-3)

Averaged yearly costs of the storage capacity and the power the maintenance costs after 15
Calculating the present value of storage systems

year (calculated for a single household system):

\[ PC(€/y/kW) = \frac{C_P}{\eta \cdot DOD \cdot L} + C_{OKM} = \frac{200}{0.75 \cdot 0.66 \cdot 8} + 4 = 64.61 \] (A-4)

\[ PC(€/15y/kWh) = \frac{2}{3} \cdot SC_{power} = 266.67 \] (A-5)

where the power maintenance costs are estimated to be 2/3 of the initial power costs.

Present value of the averaged yearly power capacity costs and the present value of the power maintenance costs after 15 years (single household system, interest rate 2%):

\[ PV(€/y) = PC(€/y) \cdot \left( \frac{1 - (1 - i)^n}{1 - (1 - i)} \right) \] (A-6)

\[ = 61.61 \cdot \left( 0.98 \cdot \frac{1 - 0.98^{30}}{1 - 0.98} \right) = 1438.86 \]

\[ PV(€/15y) = PC(€/15y) \cdot \frac{1}{(1 + i)^n} \] (A-7)

\[ = 266.67 \cdot \frac{1}{(1 + 0.02)^{15}} = 198.14 \]

The present value per kWh storage capacity with a Power-To-Energy (PTE)-ratio of 1:2.

\[ PV(€) = 484.85 + 400.00 + 40.00 + 1438.76 + 198.14 = 2561.84 \] (A-8)

<table>
<thead>
<tr>
<th></th>
<th>0.00%</th>
<th>2.00%</th>
<th>4.00%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single households</td>
<td>3129.69</td>
<td>2561.84</td>
<td>2167.82</td>
</tr>
<tr>
<td>Local grid</td>
<td>3520.53</td>
<td>2775.09</td>
<td>2260.44</td>
</tr>
<tr>
<td>Main grid</td>
<td>3520.53</td>
<td>2775.09</td>
<td>2260.44</td>
</tr>
</tbody>
</table>

Table A-3: Overview of present value costs of lead acid battery systems per kWh in €

Lithium-ion batteries

Compared to Pb-acid batteries and many other chemical energy storage systems, Li-ion batteries have a very high energy density. A second major benefit is that Li-ion batteries are not affected by a memory effect. This means that the effective energy capacity is equal to the nominal capacity.

The lifetime of Li-ion batteries is only slightly affected by the amount of charge and discharge cycles[1]. For this type of batteries, the ambient temperature and the operating time are much more important to the decay of capacity. In this comparison, it is assumed that the lifetime of the Li-ion batteries is 15 years. Within this 15 years, the CRR drops to approximately 60%. To account this capacity drop in the present value calculation, an average CRR of 80% will be assumed. Therefore, the initial capacity needs to be 125% of the required storage capacity.
In the near future, the price of Li-ion batteries is expected to fall significantly. Because of this expectation, a price drop of 33% will be assumed when the batteries need to be replaced.

Table A-4 shows a significant difference between the unit power costs based on the PowerRouter system and the costs mentioned in [79]. One of the reasons is that large Li-ion battery setups have a cooling system. Cooling the Li-ion batteries has a positive effect on the lifetime and the CRR drop. The cooling system requires the extra initial investment.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Literature(^a)</th>
<th>Single households(^b)</th>
<th>Local grid(^a)</th>
<th>Main grid(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balance of plant costs</td>
<td>( C_{\text{bop}} )</td>
<td>€/kW 80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Unit costs energy capacity (^d)</td>
<td>( C_{E} )</td>
<td>€/kWh 1200</td>
<td>2250</td>
<td>1050</td>
</tr>
<tr>
<td>Unit costs power</td>
<td>( C_{P} )</td>
<td>€/kW 1200</td>
<td>800</td>
<td>950</td>
</tr>
<tr>
<td>Lifetime</td>
<td>( L )</td>
<td>years 15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Operation &amp; maintenance</td>
<td>( C_{O&amp;M} )</td>
<td>€/kW 8</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Storage system efficiency</td>
<td>( \eta )</td>
<td>0.93</td>
<td>0.93</td>
<td>0.93</td>
</tr>
<tr>
<td>Implicit efficiency</td>
<td>( \eta_{\text{CO}_2} )</td>
<td>0.93</td>
<td>≈</td>
<td>0.92(^d)</td>
</tr>
</tbody>
</table>

\(^a\) Reference literature (see: [79])
\(^b\) Based on the NEDAP PowerRouter system and a Akasol neeoQube Li-ion battery
\(^c\) Based on the current price levels & [15]
\(^d\) Assumption based the fact that the storage system requires that the electricity gets transported to the storage system

Table A-4: Explicit costs and efficiency of Lithium-ion systems. \( PTE=0.5, DOD=1, CRR=0.8 \)

<table>
<thead>
<tr>
<th></th>
<th>0.00%</th>
<th>2.00%</th>
<th>4.00%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single households</td>
<td>4858.92</td>
<td>4344.99</td>
<td>3970.80</td>
</tr>
<tr>
<td>Local grid</td>
<td>2953.39</td>
<td>2616.75</td>
<td>2373.39</td>
</tr>
<tr>
<td>Main grid</td>
<td>2953.39</td>
<td>2616.75</td>
<td>2373.39</td>
</tr>
</tbody>
</table>

Table A-5: Overview of present value costs of Li-ion battery systems per kWh in €

**Sodium–sulfur**

NaS batteries operate at high temperatures. It requires a sophisticated plant which can keep the battery at a high temperature during its lifetime. This makes that NaS batteries are not suitable for small scale storage solutions.

The biggest advantages are the lifetime and the price of the raw materials. The application of this technology is however limited.

In the present value calculation, a lifetime of 10 years is assumed with a DOD of 90%. A lower DOD can increase the lifetime to 15 years.
Calculating the present value of storage systems

<table>
<thead>
<tr>
<th>Unit</th>
<th>Literature&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Local grid&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Main grid&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balance of plant costs</td>
<td>$C_{bop}$ €/kW</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Unit costs energy capacity&lt;sup&gt;d&lt;/sup&gt;</td>
<td>$C_E$ €/kWh</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>Unit costs power</td>
<td>$C_P$ €/kWh</td>
<td>2400</td>
<td>2400</td>
</tr>
<tr>
<td>Lifetime</td>
<td>$L$ years</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>Operation &amp; maintenance</td>
<td>$C_{O&amp;M}$ €/kW</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Storage system efficiency</td>
<td>$\eta$</td>
<td>0.93</td>
<td>0.93</td>
</tr>
<tr>
<td>Implicit efficiency</td>
<td>$\eta_{CO_2}$</td>
<td>$\approx 0.84^d$</td>
<td>$\approx 0.83^d$</td>
</tr>
</tbody>
</table>

<sup>a</sup> Reference literature (see: [79])

<sup>b</sup> Based on the current price levels & [15]

<sup>c</sup> Assumption based the fact that the storage system requires that the electricity gets transported to the storage system

Table A-6: Explicit costs and efficiency of Sodium-sulfur systems. $PTE=0.5$, $DOD=0.9$

<table>
<thead>
<tr>
<th></th>
<th>0.00%</th>
<th>2.00%</th>
<th>4.00%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local grid</td>
<td>4812.94</td>
<td>4044.52</td>
<td>3506.62</td>
</tr>
<tr>
<td>Main grid</td>
<td>4812.94</td>
<td>4044.52</td>
<td>3506.62</td>
</tr>
</tbody>
</table>

Table A-7: Present value for Sodium-sulfur battery systems per kWh in €

Mechanical energy storage

Mechanical storage systems can be divided into kinetic- and potential energy systems. A kinetic flywheel system does not have a function in a single household and the potential energy systems are mostly applied in the main grid. Therefore, the present value of mechanical storage systems will be calculated for a high and low PTE ratio.

Conventional Pumped-storage hydroelectricity

The conventional Pumped-Storage Hydroelectricity (PSH) systems are currently the most widely used storage technology. The low costs per kWh and the low self discharge makes it possible to store large amounts of energy over a longer period of time.

In the present value calculations a high power-to-energy ratio will be used to compare the PSH technology with the other load shifting solutions. However, the low storage costs makes it convenient to store the power over a longer period of time. This makes that in many large sized PSH systems, a much lower PTE ratio is installed.

It is assumed that each 15 years, a maintenance has to be done which costs are equal to $1/4$ of the initial power costs. It is also assumed that the storage costs of a small system with a high PTE-ratio are significantly larger than a large system with a small PTE-ratio.
<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
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<th>Typical&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
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<tbody>
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<td>1:2</td>
<td>1:100</td>
</tr>
<tr>
<td>Balance of plant costs</td>
<td>(C_{bop}) (\text{€/kWh})</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Unit costs energy capacity</td>
<td>(C_E) (\text{€/kWh})</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>Unit costs power</td>
<td>(C_P) (\text{€/kW})</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>Lifetime</td>
<td>(L) (\text{years})</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Operation &amp; maintenance</td>
<td>(C_{Ok&amp;M}) (\text{€/kW})</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Storage system efficiency</td>
<td>(\eta)</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Implicit efficiency</td>
<td>(\eta_{\text{CO}_2})</td>
<td>(\approx 0.75^b)</td>
<td>(\approx 0.75^b)</td>
</tr>
</tbody>
</table>

<sup>a</sup> Based on: [79] & [15]

<sup>b</sup> Assumption based on the fact that the storage system requires that the electricity gets transported to the storage system

Table A-8: Explicit costs and efficiency of Pumped Hydro Systems

<table>
<thead>
<tr>
<th>PTE-ratio</th>
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<th>2.00%</th>
<th>4.00%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:2</td>
<td>1092.00</td>
<td>1020.63</td>
<td>969.45</td>
</tr>
<tr>
<td>1:100</td>
<td>117.00</td>
<td>92.85</td>
<td>76.17</td>
</tr>
</tbody>
</table>

Table A-9: Overview of the present value costs of Li-ion battery systems per kWh in €

Flywheels

Flywheels usually have a high PTE-ratio since the power costs are low compared to the storage costs. The self-discharge due to friction makes that flywheels are not suited to store energy over a longer period of time.

In the present value calculations, a PTE-ratio of 1:2 is used to compare the kWh price with other technologies. A 4:1 ratio is used to calculate the price of a typical ratio for this technology. The major service and/or replacements costs are assumed to be equal to the power costs.

Compressed Air Energy Storage

The energy carrier of a CAES system is air. Low carrier costs combined with relative low power costs make that the initial costs of CAES-systems are among the cheapest of the available storage technologies.

The major disadvantage is that the round-trip efficiency is less than 70%. A typical PTE-ratio is 1:4. Low energy storage costs and very limited self discharge make it possible to use this technology to store energy over a longer period of time. PTE-ratios lower than 1:4 are feasible.
Calculating the present value of storage systems

<table>
<thead>
<tr>
<th>Unit</th>
<th>Default$^a$</th>
<th>Typical$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power to energy ratio</td>
<td>1:2</td>
<td>4:1</td>
</tr>
<tr>
<td>Balance of plant costs $C_{bop}$</td>
<td>€/kWh 80</td>
<td>80</td>
</tr>
<tr>
<td>Unit costs energy capacity $C_E$</td>
<td>€/kWh 1000</td>
<td>1000</td>
</tr>
<tr>
<td>Unit costs power $C_P$</td>
<td>€/kW 350</td>
<td>350</td>
</tr>
<tr>
<td>Lifetime $L$ years</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Operation &amp; maintenance $C_{O&amp;M}$</td>
<td>€/kW 18</td>
<td>18</td>
</tr>
<tr>
<td>Storage system efficiency $\eta$</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>Implicit efficiency $\eta_{CO_2}$</td>
<td>≈ 0.88$^b$</td>
<td>≈ 0.88$^b$</td>
</tr>
</tbody>
</table>

$^a$ Based on: [79] & [15]

$^b$ Assumption based on the fact that the storage system requires that the electricity gets transported to the storage system

**Table A-10:** Explicit costs and efficiency of Flywheel Systems

<table>
<thead>
<tr>
<th></th>
<th>0.00%</th>
<th>2.00%</th>
<th>4.00%</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTE-ratio 1:2</td>
<td>3192.22</td>
<td>2722.59</td>
<td>2385.30</td>
</tr>
<tr>
<td>PTE-ratio 1:100</td>
<td>5642.22</td>
<td>4857.79</td>
<td>4290.50</td>
</tr>
</tbody>
</table>

**Table A-11:** Overview of the present value costs for per kWh in €

<table>
<thead>
<tr>
<th>Unit</th>
<th>Typical$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power to energy ratio</td>
<td>1:4</td>
</tr>
<tr>
<td>Balance of plant costs $C_{bop}$</td>
<td>€/kWh 80</td>
</tr>
<tr>
<td>Unit costs energy capacity $C_E$</td>
<td>€/kWh 8</td>
</tr>
<tr>
<td>Unit costs power $C_P$</td>
<td>€/kW 360</td>
</tr>
<tr>
<td>Lifetime $L$ years</td>
<td>40</td>
</tr>
<tr>
<td>Operation &amp; maintenance $C_{O&amp;M}$</td>
<td>€/kW 6</td>
</tr>
<tr>
<td>Storage system efficiency $\eta$</td>
<td>0.70</td>
</tr>
<tr>
<td>Implicit efficiency $\eta_{CO_2}$</td>
<td>≈ 0.68$^b$</td>
</tr>
</tbody>
</table>

$^a$ Based on: [79] & [15]

$^b$ Assumption based on the fact that the storage system requires that the electricity gets transported to the storage system

**Table A-12:** Explicit costs and efficiency of CAES-systems

<table>
<thead>
<tr>
<th></th>
<th>0.00%</th>
<th>2.00%</th>
<th>4.00%</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTE-ratio 1:2</td>
<td>602.86</td>
<td>530.42</td>
<td>479.43</td>
</tr>
<tr>
<td>PTE-ratio 1:4</td>
<td>467.86</td>
<td>406.98</td>
<td>364.45</td>
</tr>
</tbody>
</table>

**Table A-13:** Overview of the present value costs for CAES-systems per kWh in €
Appendix B

Modeling startup configuration with MATLAB

In this numerical model the startup motion of the piston is simulated. The purpose of this simulation is to determine the consequences of the inertia of the piston to the functioning of the Gravitational Potential Energy Storage (GPES). Several starting points will be used to appoint the difficulties in the acceleration of the large piston mass. In the steady-state situation, the piston moves with the speed that relates to the discharge of the pump operating at its Best Efficiency Point (BEP). As long as the piston does not reach the optimal velocity, it will gradually accelerate until it has the optimal velocity. During the acceleration period, energy is lost due to an inefficiently operating pump. As long as the time it takes to accelerate the piston is limited, these loses can be neglected.

The simulation is simplified by assuming that the torque of the pump driver is large enough to accommodate a power increase within the timescale of the piston acceleration. At first it will also be assumed that springs, vessels, and additional valves operate without friction loses and velocity dependent losses are being counted as if the system runs at working speed. The last important simplification is that valves open instantly and that pressure differentials are immediately spread in the reservoir underneath the piston.

The acceleration and the velocity of the piston in the numerical model are initially defined as:

\[ a_{\text{piston}} = \frac{F}{m} = \frac{P_{\text{gauge}} \cdot C \cdot A_{\text{piston}}}{m_{\text{piston}}} \quad [m/s^2] \quad \text{(B-1)} \]

\[ U_{\text{piston},h+1} = U_{\text{piston},h} + h \cdot \frac{a_{\text{piston}}}{2} \quad [m/s] \quad \text{(B-2)} \]

where \( P_{\text{gauge}} \) at \( t = 0 \) is the difference between the maximum delivered pump pressure and the minimum pressure that is needed to accelerate the piston, \( A_{\text{piston}} \) is the bottom surface of the piston, and \( C = \frac{2}{3} \) is a factor that accounts the effective surface that will be pushed by the gauge pressure.
Table B-1: Simulation parameters at \( t = t_0 \). Pressure is expressed in kPa. \( P_{pu} \) is the pump pressure, \( \Delta P \) is the gauge pressure, and \( a_{pi} \) is the acceleration of the piston in \( \text{m/s}^2 \).

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Pump</th>
<th>( P_{start} )</th>
<th>( P_{pu} )</th>
<th>( \Delta P )</th>
<th>( Q_{pu} )</th>
<th>( a_{pi} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>With vessel</td>
<td>RDLO 500-835A 1 e 1</td>
<td>1219.0</td>
<td>1143.9</td>
<td>0.0</td>
<td>0.86</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>RDLO 350-575B 1 e 4</td>
<td>1219.0</td>
<td>1095.0</td>
<td>0.0</td>
<td>0.51</td>
<td>0.0</td>
</tr>
<tr>
<td>Reference</td>
<td>RDLO 500-835A 1 e 1</td>
<td>1219.0</td>
<td>1326.6</td>
<td>107.6</td>
<td>0.0</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Omega 350-430B 1 e 1</td>
<td>1219.0</td>
<td>1281.7</td>
<td>62.8</td>
<td>0.0</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>RDLO 350-575B 1 e 4</td>
<td>1219.0</td>
<td>1281.7</td>
<td>62.8</td>
<td>0.0</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>RPH 300-630 2 e 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiple pumps</td>
<td>RDLO 350-575B 1 e 4</td>
<td>1219.0</td>
<td>1219.0</td>
<td>0.0</td>
<td>0.33</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Since the piston rests on bulkheads, the whole bottom surface will not be pushed at \( t=0 \). Once the piston moves, the reduction value quickly decreases to 0, though the simulation model does not take this reduction into account. Table B-1 shows the water pressure at the discharge side of the pump and in the reservoir underneath the piston at \( t = 0 \). The difference between the pressure that is needed to start the acceleration and the actual pressure in the reservoir is the force per unit area that is available to accelerate the piston. Since the acceleration at the maximum pump head (RDLO 500-835A, alternative 5) is \( 1.3\text{m/s}^2 \) and the steady state velocity is \( 0.013\text{m/s} \), the timescale of the acceleration is only 0.02 seconds. This maximum head is however only available at zero discharge.

**GPES in combination with a pressure vessel (1)**

The initial simulation setup contains an air pressured vessel that accommodates the pump discharge when the piston is at rest and the pump builds up the pressure in the reservoir (at \( t = 0 \) until the piston starts to move). The simulation starts when the valve behind the pump opens (instantly). At this point, the pump is at maximum discharge with a corresponding head that follows from the pump characteristic curve. When water enters the pressure vessel, the air pressure rises together with the pressure in the reservoir. This will continue until the piston has a enough velocity such that the freed space underneath the piston per second is large enough to accommodate the discharge of the pump per second. Before the pump starts to operate, the pressure in the reservoir and the vessel is equal to the static water pressure on the bottom of the return pipe. Since the initial pump head is larger than the pressure in the reservoir and the vessel, the actual pump performance during the startup process might slightly differ from the expected performance. This might also lead to a little overdimensioned pressure vessel. The initial values in the reservoir are shown in table B-1. The simulation is executed for three tank volumes (\( 0.5\text{m}^3 \), \( 1\text{m}^3 \) and \( 1.5\text{m}^3 \)). These tanks are initially filled with air by 75%.

The pressure in the vessel is defined by the ideal gas law (assuming the temperature remains constant).

\[
p \cdot V_{v,\text{air}} = C \quad \text{(constant)} \\
776.7 \cdot 0.75 \cdot 1.0 = 582.5
\]
where \( p \) is the static water pressure at \( t \leq 0 \) and \( V_{v,air} \) is the initial air volume in the vessel.

The formulas that describe the water volumes and pressures in the reservoir and vessel during acceleration are given by:

\[
\Delta P = P_{h-1} - P_h
\]

\[
Q_{ve} = Q_{pu} - \frac{C}{P - \frac{P \Delta P}{2h}}
\]

\[
\Delta V_r = h \cdot (Q_{pu} + Q_{ve}) = h \cdot (U_{pi} \cdot A_{tu} + Q_{ve}) \tag{B-4}
\]

\[
\Delta V_w = h \cdot (Q_{ve} - U_{pi} \cdot A_{tu})
\]

\[
V_{w,h+1} = V_{w,h} + \Delta V_w \tag{B-5}
\]

\[
P_{h+1} = \frac{C}{V_e - V_{w,h+1}} \tag{B-6}
\]

where \( \Delta \) is the step difference, \( h \) is the step size, \( V_r \) the volume in the reservoir, \( V_w \) is the water volume in the vessel, \( Q_{pu} \) is the pump discharge, \( Q_{ve} \) is the vessel (dis)charge, \( U_{pi} \) is the piston velocity, \( A_{tu} \) is the tube section surface, and \( P \) is the system pressure. The pump is at maximum discharge when the effective system head \( P \) is equal or lower than the corresponding pump head at maximum discharge.

The left graphs in figure B-1 show the results of the simulations. The pump discharge and head is constant until the pressure in the reservoir and vessel is increased such that pump head needs to be larger and the discharge drops. When the pressure gets above the piston acceleration threshold, the piston starts to move and space is freed underneath the piston. Since the piston has a low discharge at a high head, there is a tipping point where the vessel changes from taking up water to supplying water. Once the vessel starts to supply water, the system pressure drops and the pump discharge increases. This is the cause of the undulating behaviour of the piston discharge head, the piston discharge, and the piston velocity around the working point of the pump. In the graphs it can be seen that a small vessel size causes relative large fluctuations in the pump discharge head but it is also clear that a 0.5\( m^3 \) vessel volume is large enough to drop the maximum head beneath the shut-off head. A larger vessel drops the maximum pressure even further. The downside of a larger vessel is the increased amplitude of the stammering piston velocity and the time it takes to get the system to the constant working point of the pump. The duration of the first acceleration is approximately 0.05 seconds. This is of the same order as the calculated timescale.

**Zero discharge simulation**

The zero discharge or dead-headed variant is used as a reference simulation. In this variant the pump instantly operates with a maximum discharge pressure at \( t = 0 \). When the pump runs at its theoretical maximum head, the piston acceleration peaks and the pump water discharge is zero. It is a theoretical maximum since the pump cannot operate properly under these conditions. A zero discharge solution cannot be implemented in practice since it causes vibrations and it damages the pump. Therefore, this simulation is only used as a reference to...
Figure B-1: Startup performance curves for simulation 1 (left) and the reference simulation (right) in a single pump setup (RDLO 500-835A). Alternative 1 is simulated with three vessel capacities.

A solution that accommodates the water discharge in the initial phase of the startup mode.

This solution cannot be implemented in practice since it causes vibrations and it damages the pump.

The simulation starts when the check valve behind the pump opens and the pressure in the reservoir is equal to the maximum head of the pump at zero discharge. The energy and time that is needed to start the pump and to build up the pressure from 7.8 bar to the shut-off head of the pump at zero discharge is neglected. The pressure at \( t = 0 \) in the reservoir running a single RDLO-pump is then 1338kPa. This makes that the initial pressure pushing the piston into an upwards motion is equal to 107.3kPa.

The simulation results in figure B-1 show that the duration of the startup time is 0.02 seconds and thus as expected.
Multiple pumps

Having the possibility to change the velocity of the piston in a multiple pump setup enhances the functionality of the storage system. The GPES is then able to charge at a low speed when the energy supply is low or with extra speed when the supply peaks. Figure B-2 shows the results of a simulation in which a second pump with the same characteristics as the first pump is started while a single pump runs at a steady state velocity.

\[ Q_{ve} = 2 \cdot Q_{pse} - \frac{C}{r - \Delta P} - \frac{C}{2h} \]  \hspace{1cm} (B-7)

In the simulation, it is assumed that the second pump at \( t = 0 \) instantly has the same discharge as the first pump in the steady state. This will increase the pressure in the vessel and the reservoir. The increased pressure accelerates the piston and decreases the discharge of the pump until the vessel intake overturns to discharge. Since the pressure at \( t = 0 \) in the reservoir is exactly the same as the minimum pressure required to start the acceleration, the second pump will immediately start to accelerate the piston.

The piston velocity powered with a single RDLO 350-575B pump at \( t = 0 \) is 0.006m/s. When both pumps are operating in a steady state, the piston velocity has been increased to 0.013m/s. The graphs in figure B-2 show that the acceleration comes with a similar stuttering as has been seen in the startup simulation. However, the maximum pump pressure stays well below the pump shut-off head.

Conclusion

Since the acceleration timescale is in the order of magnitude of 0.02 seconds, the inertia of the piston mass is not likely to be the governing factor in the startup process. Therefore, the simplifications of instantly opening valves and pumps that run immediately at their maximum head are likely to be insufficient for a more final design. It is not plausible that the mass of the piston is the decisive factor in how the piston accelerates towards the velocity in the steady state situation. A more accurate simulation that takes into account the torque of the driver is required.

Since it takes time to get to the maximum head of the pump, it is clear that the capacity of the vessel needs to be larger than can be concluded from a simulation that leaves out the
inertia of the pump and the pump driver. What does follow from the simulation is that the piston in combination with an air pressured vessel will stammer during startup for a few seconds. A large vessel will increase stammering and the time it takes to get the piston at a steady velocity. The pump will stutter and get damaged when the vessel capacity is too small but when the vessel size is too large, the piston will stutter.

Although the consequences of the stuttering have not been elaborated, the dynamic forces that are induced by the mass of the shaking piston should be avoided. To reduce the stuttering of the GPES piston, the vessel should be equipped with a piston or other mechanism that is able to dissipate energy while being pressed. When this dashpot is pressed, it will store water without further accelerating the piston in the tube once the vessel intake overturns to discharge.
Matlab startup code (reference simulation)

1 clear all; clc; tic;
2 format long;
3
4 % Initiate model
5 r = runner(0.0005, 0.1, 'rdlo_500_835');
6
7 % Display result diagrams
8 r.display();
9 toc;

1 classdef runner
2 %RUNNER Primary runner class
3 % The runner calls relevant classes and tracks the results from
4 % methods in called classes.
5
6 properties
7 steps; % Amount of integration steps
8 h; % Step size
9 Q = 0; % 0 = Discharge starting condition
10
11 PISTON_A; % Acceleration of piston
12 PISTON_U; % System curve velocity (piston)
13
14 RESERVOIR_Q; % Reservoir discharge curve
15 RESERVOIR_P; % Reservoir pressure
16 RESERVOIR_G; % System gauge pressure (reservoir)
17
18 PUMP_QH; % Pump curve: Discharge Q – to head H
19 PUMP_QN; % Pump curve: Discharge Q – to efficiency N
20 PUMP_QP; % Pump curve: Discharge Q – to power P
21 PUMP_HQ; % Pump curve: Head to discharge
22
23 PUMP_H; PUMP_N; PUMP_P; PUMP_Q;
24
25 end
26
27 methods
28 function this = runner(h,t,pump_type) % h = timestep, t = running time (s)
29    this.h = h;
30    this.steps = t * 1 / h;
31
32    try
33        Pump = pump(pump_type); % Load pump characteristic curves
34        catch ME
35            disp(ME.message)
36            return;
37        end;
38
39        % Assign pump characteristic curves
40        this.PUMP_QH = Pump.QH;
41        this.PUMP_QN = Pump.QN;
42        this.PUMP_QP = Pump.QP;
43        this.PUMP_HQ = Pump.HQ;

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% Assign system curve array's
this.PISTON_A = zeros(this.steps,1);
this.PISTON_U = zeros(this.steps,1);
this.RESERVOIR_Q = zeros(this.steps,1);
this.RESERVOIR_P = zeros(this.steps,1);
this.RESERVOIR_G = zeros(this.steps,1);
this.TIME = 0:h:(t-h);

% Initialize classes
r = reservoir;
p = piston(h);
s = 0;
while s < this.steps
   s = s+1;
   % Reservoir step
   r_out = r.dPt(this.PUMP_QH(this.Q));
   % Piston step
   p = p.At(r_out.p_gauge);
   p = p.Ut();
   p = p.Qt();
   % Assign step values
   this.PUMP_H(s,1) = this.PUMP_QH(p.q);
   this.PUMP_Q(s,1) = p.q*1000;
   this.PISTON_A(s,1) = p.a;
   this.RESERVOIR_Q(s,1) = p.q*1000;
   this.PISTON_U(s,1) = p.u;
   this.RESERVOIR_G(s,1) = r_out.p_gauge;
   this.Q = p.q;
end
end

% Create figure
function display(this)
% Create figure
figure1 = figure(1);

% Create axes
axes1 = axes('Parent', figure1);
set(axes1, 'FontSize', 12, 'LineWidth', 1.3)
set(gca, ylim, [0, 0.025]);
box(axes1, 'on');
grid('on');
hold(axes1, 'all');

% Create xlabel
xlabel('Seconds');

% Create ylabel

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ylabel('Meters/second');
set(gca, 'GridLineStyle', '-', 'LineWidth', 1.0);

% Create title
set(gcf, 'FontSize', 15);
set(figure1, 'Position', [0 0 800 350])

% Create plot
plot(this.TIME, this.PISTON_U, 'LineWidth', 1.5);
set(gcf, 'color', 'white')
myaa('publish')
end
end
end

classdef pump < handle
  %PUMP Pump definitions
  % This class defines the available pump characteristics

  properties
    % Pump characteristic curves
    QH; QN; QP; HQ;
    H; N; P; Q;
  end

  methods
    function pump = pump(type)
      
      if(strcmp(type, 'rdlo_500_835'))
        H = [56.15 55.3 54.75 52.75 48.9 45.2 44.5 38.6];
        N = [-2 44.6 66.5 80.5 86.5 87.6 87.5 83.4];
        P = [150 191 224 270 308 337.6 347 376];
        Q = [0 500 1000 1500 2000 2404.7 2500 3000]*(1/3600); % /s
        % Fit data into a 3rd or 4th degree polynomial
        pump.QH = createFit4(Q, H);
        % Fourth order polynomial
        pump.QN = createFit4(Q, N);
        pump.QP = createFit3(Q, P);
        pump.HQ = createFitL(H, Q); % Linear polynomial

      elseif(strcmp(type, 'rdlo_350_575'))
        H = [51.6 51.4 50.8 49.75 48.0 45.2 44.7 40.3 35.0];
        N = [-2.0 32.0 59.0 74.3 82.4 86.4 86.5 85.2 83.0];
        P = [92.0 102.0 118.0 136.5 156.0 171.1 173.0 185.0 194.0];
        Q = [0 250 500 750 1000 1204.1 1250 1500 1750]*(1/3600); % /s
        % Fit data into a 3rd or 4th degree polynomial
        pump.QH = createFit4(Q, H);

      end

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pump.QN = createFit4(Q, N);
pump.QP = createFit4(Q, P);

else
    error('Pump characteristic curves are not defined for current type');
end;
end;
end;

1. classdef reservoir
2.  \% RESERVOIR reservoir underneath piston
3.  \% This class contains methods and properties of the reservoir underneath
4.  \% the piston. The reservoir is filled with liquid. The pressure inside
5.  \% the reservoir is instantly changed. Damping and loses inside the
6.  \% reservoir are ignored.
7.  
8.  \% Initial volume of the reservoir (\text{m}^3)
9.  V = (\cos(pi/180*45)\times1.05*2)^2;
10. p_init = 776.7304451; \% Pressure without the pump pressure but including the loses at BEP (\text{kPa})
11. p_start = 1218.965399; \% Pressure needed to start the acceleration of the piston (\text{kPa})
12. g = 9.81;
13. rho_water = 998.2071;
end

14. \% Calculate current pressure in reservoir (related to the discharge of the pump)
15. function out = dPt(obj, h_pump)
16.  \% Pump pressure
17.  p_pump = h_pump \times obj.g \times obj.rho_water;
18.  \% Current reservoir pressure
19.  out.p_reservoir = p_pump + obj.p_init \times 10^-3;
20.  \% Gauge pressure that accelerates the piston
21.  out.p_gauge = p_pump + obj.p_init \times 10^-3 - obj.p_start \times 10^-3;
end

1. classdef piston
2.  \% PISTON Piston properties and methods
3.  \% This class contains the properties of the piston motion and it
4.  \% contains the methods to calculate the changes in time.
5.  
6.  \% Initial volume of the reservoir (\text{m}^3)
7.  m = 2266708.518; \% kg
8.  A = 50.36586263; \% \text{m}^2
9.  g = 9.81; \% \text{m/s}^2
end

10. \% Properties
11.  u = 0; \% \text{m/s}
12.  a = 0; \% \text{m/s}^2

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q = 0; \% m^3/s

init = 0;

h = 1;

dend

definition piston = piston(h)

\text{piston.h = h; } \% \text{Set h}

dend;

function out = At(obj, p_gauge)

\% Calculate the acceleration of the piston
\% Force on piston (F(N))

\text{f = (2/3)\*obj.A*p_gauge;}

\% Set acceleration

\text{obj.a = f/obj.m; } \% m/s^2

\text{out = obj;}

dend

function out = Ut(obj)

\% Calculate the velocity of the piston

\text{if isequal(obj.init, 0)}

\text{obj.u = false;}

\text{obj.init = 1;}

\text{out = obj;}

\text{else}

\text{obj.a = obj.u + obj.h*(obj.a)/2;}

\text{out = obj;}

\text{end}

\% Calculate volume change at the current velocity of the piston
\% (m^3/s)

function out = Qt(obj)

\text{obj.q = obj.u * obj.A;}

\text{out = obj;}

end
Bibliography

[1] M. Abe et al. “Lifetime prediction for heavy-duty industrial lithium-ion batteries that enables highly reliable system design”. In: Hitachi Review 61.6 (2012–10), pp. 259–263.


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[78] Florian Steinke et al. “Grid vs. storage in a 100% renewable Europe”. In: *Renewable Energy* 50.0 (July 31, 2012), pp. 826 –832.


**Glossary**

**List of Acronyms**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HESC</td>
<td>Highrise Energy Storage Core</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
</tr>
<tr>
<td>DG</td>
<td>Distributed Generators</td>
</tr>
<tr>
<td>RES</td>
<td>Renewable Energy Sources</td>
</tr>
<tr>
<td>VRE</td>
<td>Variable Renewable Energies</td>
</tr>
<tr>
<td>DRE</td>
<td>Dispatchable Renewable Energies</td>
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<tr>
<td>LMG</td>
<td>Local Micro Grid</td>
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<tr>
<td>SCADA</td>
<td>Supervisory Control And Data Acquisition</td>
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<tr>
<td>PSH</td>
<td>Pumped-Storage Hydroelectricity</td>
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<tr>
<td>CAES</td>
<td>Compressed Air Energy Storage</td>
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<tr>
<td>ESS</td>
<td>Electrical Storage Systems</td>
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<td>HVDC</td>
<td>High Voltage Direct Current</td>
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<td>Power-To-Energy-ratio</td>
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<td>Best Efficiency Point</td>
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<td>PAT</td>
<td>Pump As Turbine</td>
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<td>NPSHA</td>
<td>Net Positive Suction Head Available</td>
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<td>Net Positive Suction Head Required</td>
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<td>PTFE</td>
<td>Polytetrafluoroethylene</td>
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<td>Computational Fluid Dynamics</td>
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<td>Synchronous Generator</td>
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<tr>
<td>AG</td>
<td>Asynchronous Generator</td>
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<td>AVR</td>
<td>Automatic Voltage Regulation</td>
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<td>Doubly Fed Induction Generator</td>
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<td>Gross Floor Area</td>
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<td>Net-Gross Ratio</td>
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<td>State of Charge</td>
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<td>Depth of Discharge</td>
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<td>Capacity Retention Ratio</td>
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<td>Leadership in Energy and Environmental Design</td>
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