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Feasibility of Pumped Hydro Energy Storage in a River Cascade: Case Study of the Meuse

Jan Willem Lambach[1], Jeremy D. Bricker[2,3] and Miroslav Marence[4]

Abstract

The Meuse river in the Netherlands has been made navigable by the construction of a cascade of seven low head weirs. Because of environmental regulations, hydropower facilities exist at only two weirs. This implies the full hydropower potential of the Meuse cascade is not utilized. By using pump-turbines the river sections upstream of the weirs could be additionally usable as energy storage reservoirs and could improve and ensure river navigability under changed climate conditions.

The main goal of this study is to assess the possible utilization of the full energy storage- and hydropower potential of the Meuse cascade within Dutch environmental regulations. The novelty of this study is the evaluation of the concept of using canalized river sections for pumped-storage purposes within conditions of fluctuating discharge and -water levels throughout the year.

In order to meet the goal of the study the relatively fish-friendly Archimedean screw has been selected as pump-turbine. Next a conceptual design of a pumped-storage hydropower plant equipped with screws has been compiled. By using this design, the assessment of utilizing the hydropower- and energy storage potential of the cascade has been carried out by constructing and applying a numerical model.

The study shows it is possible to utilize the full hydropower- and the majority of the energy storage potential of the Meuse cascade. The cumulative installed turbine capacity for the cascade turns out to be 81 MW. The Annual Energy Yield (AEY) from regular hydropower alone is 225 GWh. In addition, the yearly surplus power that can be processed for energy storage purposes is 137.2 GWh, of which 77.2 GWh is returned to the grid by a round-trip efficiency of 56.25 %. In total 302.2 GWh can be delivered to the grid which can power up to 75.000 households. The specific cost is relatively high: roughly 15,000 euro/kW.

The method developed here can be applied to evaluate the storage- and hydropower potential of other canalized rivers as well, such as the upper Mississippi.

[1] jwlambach@hotmail.com; Faculty of Civil Engineering & Geosciences, Delft University of Technology, Delft, The Netherlands
[2] jeremydb@umich.edu; Dept. Of Civil & Environmental Engineering, University of Michigan, Ann Arbor, Michigan, USA
[3] Faculty of Civil Engineering & Geosciences, Delft University of Technology, Delft, The Netherlands
[4] m.marence@un-ihe.org; IHE Delft Institute for Water Education, Delft, The Netherlands

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Keywords

Hydropower, Pumped Storage Power, Archimedean Screw, Meuse, River Cascade, The Netherlands

1 Introduction

The Netherlands is a flat country with limited hydropower opportunities. Currently the installed capacity in the Dutch branches of the Rhine river is 10 MW, while it is 25 MW in the river Meuse (Chappin, 2019). The average discharge of the Meuse is 230 m^3/s. River flood wave peak discharges exceeding 3000 m^3/s have been recorded (Rijkswaterstaat Waterinfo, 2019). The Meuse river has been dammed into multiple sections along the trajectory Borgharen-Lith in order to make it suitable for shipping, as it is an important Dutch fairway. The cascade contains seven lock- and weir complexes (Figure 1).

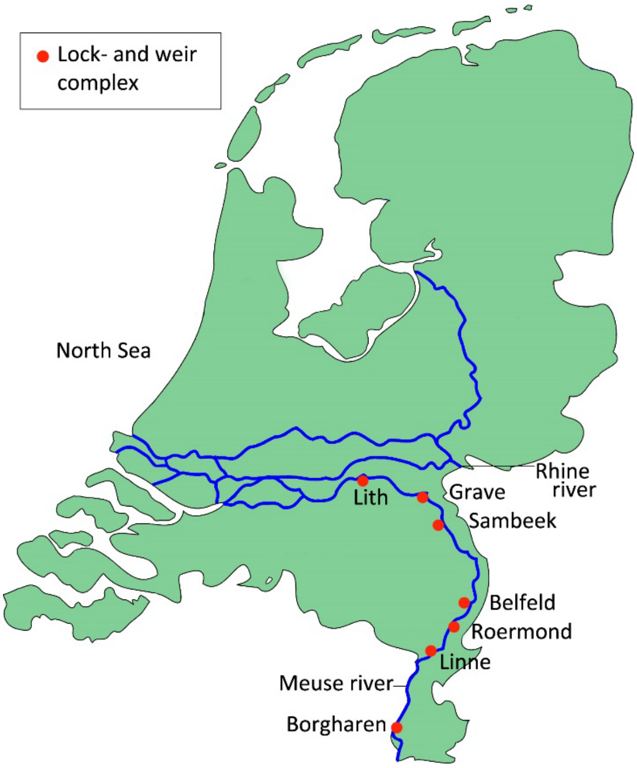
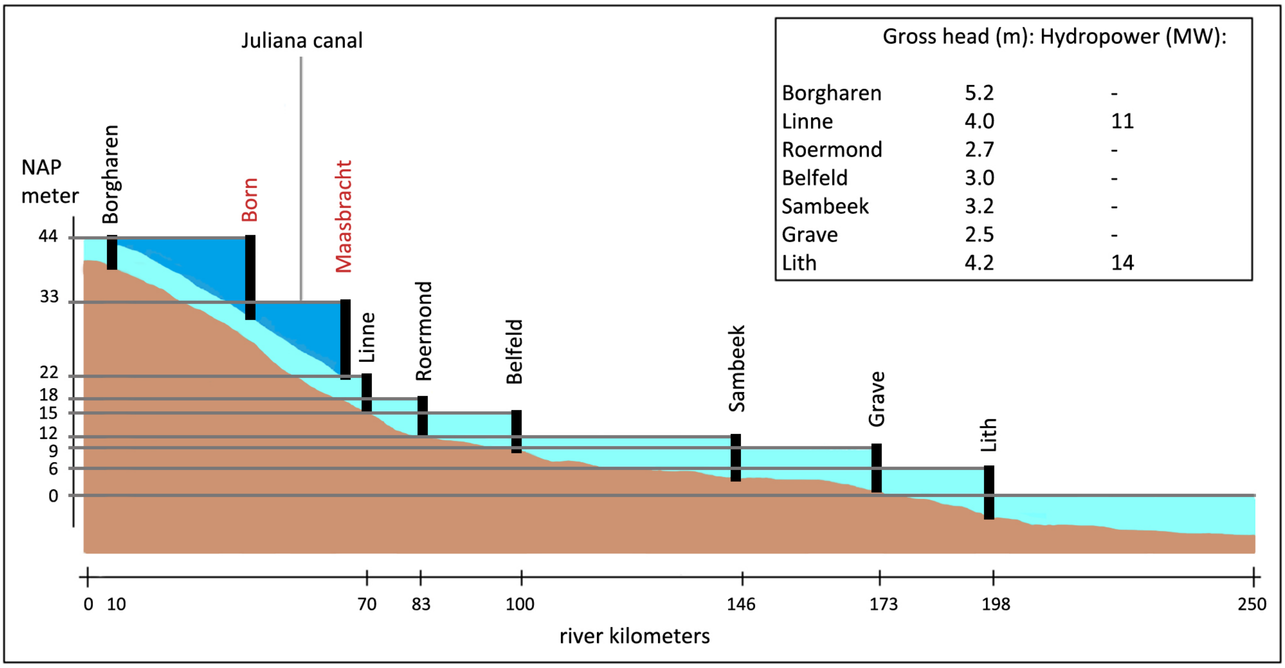


Figure 1: Meuse cascade and lock- and weir complexes (Lambach and van Mourik, 2022; Pixabay, 2022).

Between the Borgharen and Linne weirs the river bed is too steep for canalization, this trajectory is called *Grensmaas*. The head difference between these weirs is 23 meters. Ships are diverted into the Juliana canal, which hosts lock complexes at Born and Maasbracht. Five kilometers upstream from Linne the canal is connected to the river again. Using information from *Rijkswaterstaat* and Beurskens & van Dongen (2018) Figure 2 shows a longitudinal overview of the river cascade and the Juliana canal. NAP refers to *Normaal Amsterdams Peil*, the Dutch vertical datum that approximates mean sea level of the North Sea. At only two out of the seven weirs, hydropower is generated on the Meuse river. The weir at Linne is equipped with a 11 MW facility and the weir at Lith with a 14 MW facility. The weirs and their gross heads are presented in Figure 2 as well.

Because of fish mortality the Dutch law has strict regulations considering hydropower plants. For the river Meuse, one can obtain a license only when the power plant meets requirements for downstream fish migration. An additional hydropower plant is therefore only permitted if the cumulative fish mortality in the Meuse is lower than 10 % (Dronkers, 2015). The hydropower plants at Lith and Linne are equipped with Kaplan bulb turbines. These are already responsible for around 10 % percent fish mortality in the Meuse river. For the remaining weirs new hydropower permits are provided only if they are equipped with fish friendly turbines (near-zero mortality), or when other experimental measures are applied aimed at preventing fish mortality (Uitspraken in vergunningszaken, 2019).

Currently no pumped-storage power facilities are present in the Netherlands. This is mainly due to the unsuitable geography as the country is flat (Gockel et al, 2017). However, it might be possible to use the sections of the Meuse cascade as energy storage reservoirs by pumping water upstream of each weir. Pumping would occur at hours of low electricity demand using surplus power from external sources, like wind farms. At times of high energy demand the stored water can be released downstream through the turbines, together with river discharge that had accumulated in the cascade section during the time of pumping. Additionally pumping back could be seen as an additional water storage possibility during extreme dry periods. Therefore, the main goal of this study is to assess the possible utilization of the full energy-storage and hydropower potential of the Meuse cascade using Pumped Storage Hydropower plants (PSH-plants) located at the weirs equipped with fish-friendly pump-turbines to meet Dutch regulations on fish-mortality.



	Gross head (m):	Hydropower (MW):
Borgharen	5.2	-
Linne	4.0	11
Roermond	2.7	-
Belfeld	3.0	-
Sambeek	3.2	-
Grave	2.5	-
Lith	4.2	14

Figure 2: Meuse cascade and Juliana canal (Lambach and van Mourik, 2022; based on information from Beurskens and van Dongen, 2018; Rijkswaterstaat Waterinfo, 2020).

As the discharge and corresponding water levels at the weirs fluctuate throughout the year the storage potential fluctuates as well. The higher the discharge, the less room for pumped-storage. The concept of utilizing the energy storage potential of a cascaded river under fluctuating discharge- and water level conditions forms the novelty of this study. During periods of drought the discharge in the Meuse can drop to 20 m^3/s (Rijkswaterstaat Waterinfo, 2019). During these periods locking processes at the weirs are put on hold until each lock chamber is filled to capacity with ships thereby reducing the loss of water downstream. The pump-turbines can additionally be used to pump back water thereby avoiding limited locking and serving navigability.

2 Assessment of pumped-storage and hydropower potential

2.1 Methodology

To achieve the main goal of this study - the assessment of utilizing the energy storage- and hydropower potential of the Meuse cascade within conditions of fluctuating discharge and -water levels throughout the year - the following methodological steps have been carried out:

1. The hydraulic boundary conditions of river discharge and corresponding water levels at the weirs, including the size of the storage volumes, have been determined. (section 2.2)
2. Multiple pump-turbines have been assessed for suitability within these hydraulic boundary conditions, and for usability with the combination of hydropower and pumped-storage, all of this within Dutch environmental regulations on fish mortality. (section 2.3)

3. Next a conceptual design of a PSH-plant using the selected pump-turbine has been compiled which can be used at the weirs in the cascade. The number of pump-turbines is determined using two methods: design discharge (method 1) and maximum volume to pump (method 2). (section 2.4)
4. Using this design an assessment of utilizing the full storage- and hydropower potential has been carried out. For this assessment a model is constructed which computes the Annual Energy Yield (AEY) of pumped-stored power and regular (river discharge) hydropower for each weir and for the whole cascade. (section 2.5)
5. Finally, in order to get an impression on the cost of hydropower- and pumped-storage in the Meuse cascade the concept of specific cost has been applied. (section 2.6)

2.2 Hydraulic boundary conditions

20 years of Meuse discharge data – provided by the webpage 'Rijkswaterstaat Waterinfo' from the Dutch agency *Rijkswaterstaat* (RWS) – were analyzed to construct a flow duration curve (FDC) in order to determine the design discharge for hydropower. In the FDC the average daily discharge is ranked from high to low. As RWS provides multiple measurement locations along the cascade four flow duration curves have been constructed to account for the bigger catchment area in the lower reach of the river cascade (for details see Lambach, 2021, p.106).

When the discharge increases the head difference across each weir decreases. Fluctuations in water levels up- and downstream of a weir will influence the gross head and thereby the energy yield from hydropower and pumped-stored power. Daily RWS data on water levels up- and downstream of each weir in the cascade have been analyzed as well.

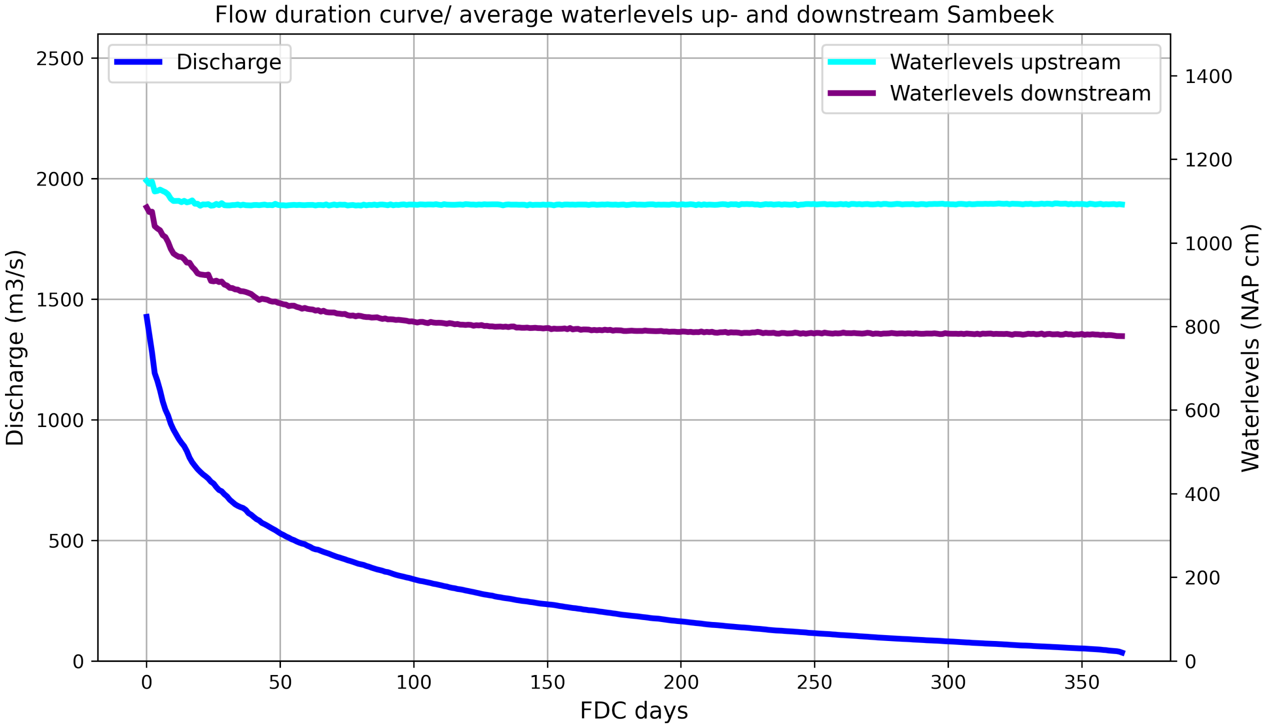


Figure 3: Sambeek flow duration curve and water levels at the weir (Lambach, 2022).

For the Sambeek weir the water levels as well as the flow duration curve (FDC) are shown in Figure 3. The water levels correspond to the discharge per FDC day. At for instance FDC day 252 the discharge is 66 m^3/s. One can observe mainly that the downstream water level fluctuates. However, during river flood waves the water levels up- and downstream of the weir become equal thereby reducing the gross head to zero (due to opening of each weir's sluice and navigation gates). This implies hydropower or pumped-storage is not possible under flood conditions.

To determine the storage volumes upstream of the weirs a literature study has been carried out. The Meuse river is primarily channelized by 'summer dikes'. During river flood waves floodplains are used to convey the increased discharge. In these circumstances the river is bounded by ‘winter dikes’, which form the last line of defense against high water levels (Bosman, 2020). Using information from Bosman (2020) a typical cross-section of the Meuse river is shown in Figure 4.

The storage volumes in the Meuse cascade are bounded by the summer dikes, as the floodplains serve agricultural purposes. For the canalized sections (see Figure 2) the width between summer dikes lies in the range 150 – 160 meters (Bodegraven, 2009). It is assumed the water level in a storage section can increase by roughly 1.5 meters before the lock complexes will overflow. This assumption has been verified in the field. Therefore, an allowable storage height 1 meter will be used. As a result, the storage volumes in the cascade vary between 1,950,000 m^3 and 7,360,000 m^3. In Figure 2 one can observe the storage section upstream of the Sambeek weir is the biggest in the cascade with its length of 46 river kilometers (Beurskens and van Dongen, 2018).

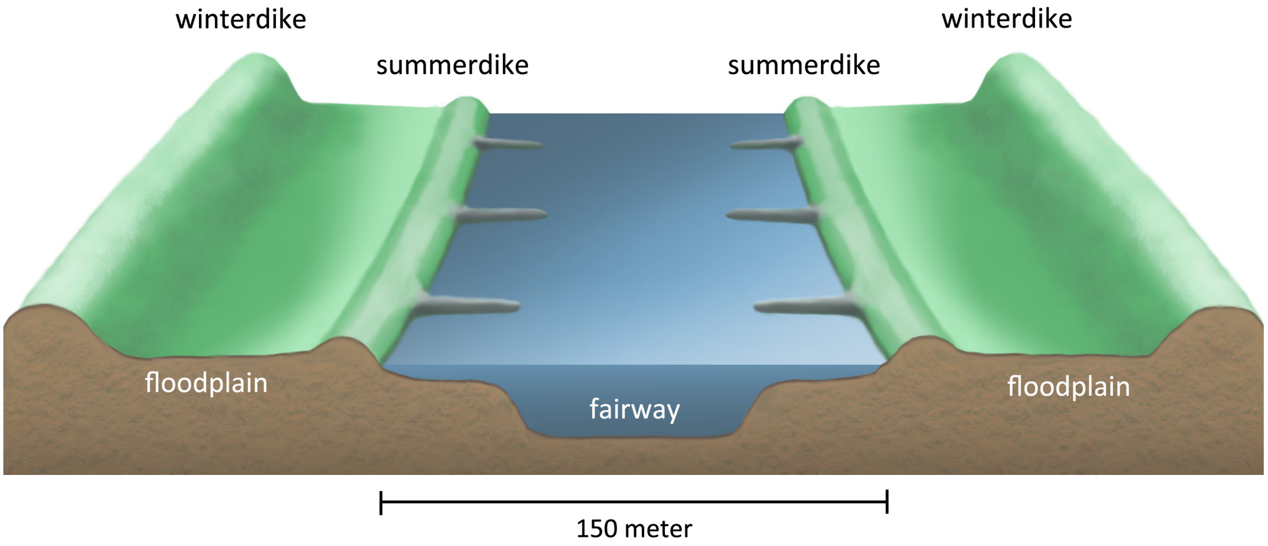


Figure 4: Typical cross-section of the Meuse river (Lambach and van Mourik, 2022; based on information from Bosman, 2020).

Between the Borgharen- and Linne weirs (see Figure 2) the river bed is too steep for canalization as the water elevation decreases from roughly NAP 44 meters at Borgharen to NAP 21 meters at Linne over a distance of 57 kilometers (Rijkswaterstaat Waterinfo, 2019). As a result, this steep bed slope causes limitations for energy storage. When the flow at the Borgharen weir is blocked and pumping starts the river is expected to fall dry within approximately four hours as the river water will flow downstream. For a detailed calculation see Lambach (2021, p. 112). Therefore, no storage occurs upstream of the Borgharen weir.

Upstream of the Linne weir a backwater curve profile is expected to develop when the discharge is blocked and pumping starts. This can result in overflowing of this weir. For this reason, no water is stored upstream of the Linne weir either. Therefore pumped-storage occurs at the weirs of Lith, Grave, Sambeek, Belfeld and Roermond, implying only the canalized sections of the cascade are used for storage. In this analysis, the Linne- and Borgharen weirs are used for hydropower production only.

2.3 Pump-turbine selection

Lambach (2021) presents an overview of available turbines for hydropower purposes. In this article only the turbines capable of pumping are discussed based on:

- Low head suitability
- Discharge capacity while turbining
- Pump capacity
- Fish friendliness

Furthermore, the selected pump-turbine has been analyzed based on pump- and turbine efficiency at fluctuating water levels, as well as the round-trip efficiency for the pumped-storage process.

Considering low head suitability, Francis turbines are typically used for high head conditions but become inefficient at low head, so was deemed not suitable. Kaplan bulb turbines, rotary lobe positive displacement devices, and Archimedean screws are applicable at low head conditions (Lambach, 2021, p. 44)

The fish friendliness of the selected pump-turbine has been assessed as the PSH-plants along the cascade have to meet Dutch environmental regulations. Fish mortality is usually measured on a turbine without racks or bypass systems or any other measure to prevent fish entrainment. By doing so one can compare the fish mortality rates of turbines. For instance, a Francis pump-turbine (30 % mortality rate) was ranked poorly on fish-friendliness, while Kaplan and bulb devices (10 % mortality rate) also did not result in sufficiently low fish mortality (Lambach, 2021). The rotational velocity of the rotary lobe positive displacement device is low, making the device fish friendly (Noortgaete et al, 2016). The Archimedes screw turbine has been tested in studies from Charisiadis (2015) and Vriese (2009). The test of Charisiadis shows zero fish mortality, although 4 % of the fish suffer scale loss and hematoma. The test of Vriese shows zero fish mortality and zero injuries. These tests show the screw turbine could fulfill the Dutch environmental regulations for the river Meuse.

Two pump-turbines remain potentially suitable: the rotary lobe positive displacement device and the Archimedean screw. The maximum discharge which can theoretically (as this device is in research phase) be processed by the rotary lobe positive displacement device is limited to 8 $\mathrm{m^3/s}$. According to manufacturer information (Lambach, 2021, p. 125) during turbining a screw can process a discharge up to 15 $\mathrm{m^3/s}$ when using a 5-meter diameter screw. The pump capacity for this diameter is roughly 11.6 $\mathrm{m^3/s}$, which is the average capacity provided by three manufacturers (Lambach, 2021, p. 125). After verification the Archimedean screw has been selected for equipping the conceptual design of the PSH-plant as it is suitable for low head conditions and fish-friendly. Furthermore, it has been used in practice already for decades, thereby providing background information.

When installed optimally with respect to the pump filling- and delivery point a screw pump shows an overall efficiency of 75 % (Spaans Babcock, 2020; Wijdieks and Bos, 1994). The rotational speed of a 5-meter diameter screw pump is fixed at 17.1 rpm (Lambach, 2021, p. 124). This rotational speed is based on Muysken (1932) and is relatively low, thereby minimizing fish mortality. As with pump operation, a screw turbine shows an optimal overall efficiency of 75 % (Spaans Babcock, 2019). The rotational speed of the screw turbine will be constant, as explained in the paragraph on the conceptual design (section 2.4, below) which will also discuss screw efficiency under fluctuating water levels. The theoretical round-trip efficiency of a PSH-plant in the Meuse river – equipped with Archimedean screws – is 56.25 %, obtained by multiplying the overall pump- and turbine efficiencies.

2.4 Conceptual design

Using the Archimedean screw a conceptual design of a PSH-plant at the Sambeek weir has been compiled (Lambach, 2021). The location of Sambeek has been chosen as this lock- and weir complex is currently not equipped with a hydropower facility. A profile view of the screw compartment is shown in Figure 5. A decisive consensus on the optimal screw turbine angle of inclination is missing in the literature. The range is 15 °–25 °. As the majority of the sources suggest to apply an angle of 22 ° for optimal turbine performance (Renewable First, 2019; Akbarzadeh et al., 2017; Amgain and Dhakal, 2018) this angle has been used for the conceptual design. When the lower end of the screw becomes submerged this efficiency is reduced by 20 % (Dellinger et al, 2016; Nuernbergk, 2012). This reduction in efficiency should be avoided in the design. In Figure 3 one can observe the downstream water level at Sambeek increases with increasing river discharge. As shown in Figure 5, the lower screw end can be adjusted to the downstream water level thereby eliminating the efficiency loss due to submergence. The jacking mechanism can also be used to optimize the pump filling point.

A screw pump is commonly installed under an optimal angle of inclination of 30 ° (Nagel, 1968). For every angle increase the discharge of pumped water decreases at least 3 % (Nagel, 1968, p. 36). The angle of inclination of the screw can be adjusted using the hydraulic pistons on its upstream side. By rotating the complete trough and screw on a hinge, the screw can switch from turbining to pumping mode and optimize the upper screw end with respect to the upstream water level and pump delivery point.

In case of breakdown, a compartment can be closed off by using a single leaf door, which can also close off the compartment for regular maintenance (Figure 5). On the downstream side a temporary door can be lifted in for maintenance purposes. By closing off a compartment – either by using the single leaf door or by lifting a screw out of position – the turbine capacity of the PSH-plant can be adjusted to the discharge conditions in the Meuse river. By doing so the discharge for the screws in operation is more or less ‘constant’ and so will be the rotational speed. All that changes is the number of screws in operation.

The PSH-plant can be constructed in a modular way by placing multiple screw compartments next to each other. For the thickness of walls and slabs, relevant rules of thumb with respect to caisson construction – for instance a wall thickness of 0.5 meter or a slab thickness of 1 meter – have been applied (Molenaar, Voorendt and Bezuyen, 2016). The PSH-plant has a concrete slab roof with a width of 18 meters. This slab can be used to host a mobile crane in order to replace components like generators. Furthermore, a crane vessel can be maneuvered into position at the up- and downstream sides of the plant, as shown in Figure 6.

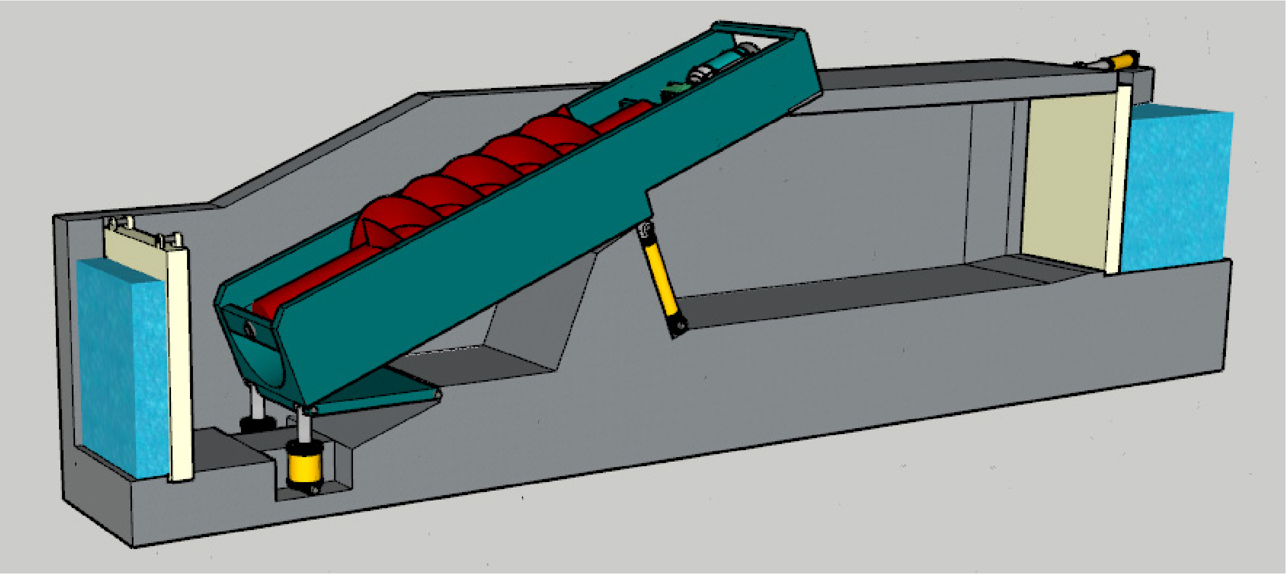


Figure 5: Screw compartment closed off from the water by gates at down- and upstream end (Lambach, 2021, p. 65).

Currently the Sambeek weir is equipped with Stoney- and Poiree weirs (Frijns, 2019, p. 12). These weirs will be replaced in the nearby future, possibly with radial gates as proposed by Frijns (2019) in his design of an adaptive weir. An overview of the PSH-plant at Sambeek hosting 20 screws is shown in Figure 6. Next to the PSH-plant future radial gates and locks are present.

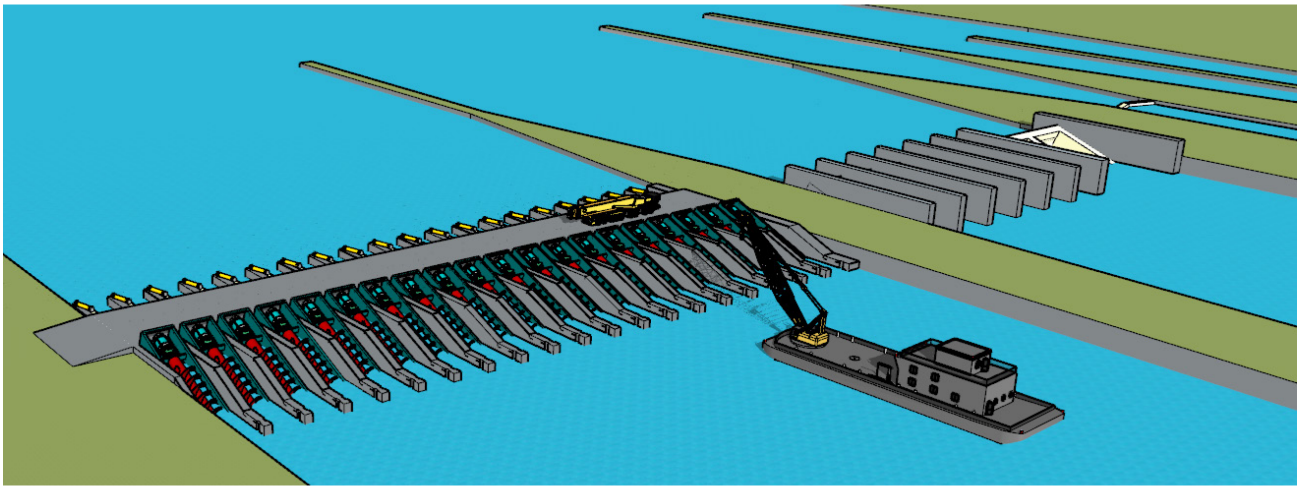


Figure 6: Sambeek PSH-plant equipped with 20 screws of 5 meter diameter each (Lambach, 2021).

The PSH-plant design has been scaled according to the head differences at the other weirs in the Meuse cascade by extending or shortening the main trough (Lambach, 2021, p. 134). Based on the studies performed by Charisiadis (2015) and Vriese (2009) the cumulative fish mortality in the Meuse cascade is expected to be lower than 10 % using PSH-plants equipped with screws. The hydropower- and energy storage potential of the Meuse cascade can be utilized within Dutch environmental regulations using this design.

2.5 Meuse model

As the conceptual design is scalable to the head differences at the other weirs, it is used for the assessment of the utilization of the full energy storage- and hydropower potential of the Meuse cascade. For this assessment a model has been constructed called the 'Meuse model' (Lambach, 2021, Ch. 11) which computes the AEY for hydropower and pumped-stored power for each weir and for the whole cascade. In the model it is assumed the same conceptual design is present at every weir, although the number of screws differs per weir depending on the design discharge or maximum volume to pump.

The model is based on two operational modes, which are:

- Storage mode: when water is pumped-stored upstream of the weirs
- Energy mode: when river discharge and stored water are powering the turbines

Multiple boundary conditions are incorporated in the model, described in detail in Lambach (2021, p. 75):

- The pumped volume at each weir (with the exception of the most downstream PSH-plant at Lith) is bounded by the volume pumped up at the weir further downstream, in order to avoid a decrease in water level below that needed for navigation.
- The model is programmed such there will be no more pumping of water at storage mode than can be released by the turbines at energy mode, as the turbines are primarily needed to process the ever-occurring river discharge. It would be a waste of energy to pump up more water than can be processed at energy mode in combination with the river discharge.
- At river peak flood mode there will be no energy storage or hydropower production as up- and downstream weir water levels are equal, resulting in zero head difference.
- The volume of water pumped into the upstream section(s) of the Meuse cascade is bounded by the inflow of river water during storage mode, to prevent an unacceptably high water level upstream of each weir.

The model is constructed to compute the hydro- and pumped-stored power yield per FDC day per weir, taking into account the head at the weirs which correspond to each river discharge, as in Figure 3. By summing up the results the AEY for hydropower and pumped-storage power for the weirs and ultimately the cascade are obtained. The AEY for hydropower is solely related to river discharge passing through the turbines. The AEY for pumped-stored power is related to stored water released through the turbines, so pumped-storage is not producing, just releasing stored water. The model is described mathematically by a straightforward volume balance (Eq. 1):

$$\Delta V = V_{in} - V_{out} = 0 \tag{1}$$

Lambach (2021, p. 137, p. 141) presents details of the computations for the volume balances per weir and interrelationship of the weirs for two different days in the FDC, namely day 252 (average river discharge 66 m^3/s) and FDC day 315 (average river discharge 26 m^3/s). During one FDC-day cycle of 24 hours the change of water volume in a storage section as a result of energy storage will be zero. Using this principle results in the possibility of storing energy on a daily repetitive basis. For the computations of pumped-storage and hydropower the general hydropower formula (symbols: see Notation appendix) is applied (Eq. 2):

$$P = \rho * g * Q * H * \eta \tag{2}$$

Variables in the model are pump- and turbine efficiency, the duration of storage mode, the size of the storage volumes and the number of screws per PSH-plant (Lambach, 2021, p. 148). In the computations the model takes into account the change of head at the weirs due to the storage process.

Two methods to determine the number of screws per weir have been applied:

- Method 1: using the design discharge resulting from the FDC
- Method 2: using the maximum volume a PSH-plant must pump

2.5.1 Method 1: design discharge

For the design discharge a rule of thumb is that the 100-day exceedance discharge is used to determine the number of turbines in a hydropower facility (Bricker & Marence, 2018). Using the FDC's (and adjusted for losses due the presence of a fish passage, locking- and leakage losses) the design discharge for Borgharen and Linne is 265 $\mathrm{m^3/s}$. Roermond, Belfeld, Sambeek and Grave show a design discharge of 300 $\mathrm{m^3/s}$ while Lith processes a design discharge of 335 $\mathrm{m^3/s}$ (Lambach, 2021). Since a 5 meter diameter screw with a turbine capacity of 15 $\mathrm{m^3/s}$ is used in the design, the number of screws per facility is 18 for Borgharen and Linne, 20 for Roermond, Belfeld, Sambeek and Grave and 22 for Lith (Lambach, 2021, p. 74).

As mentioned in the hydraulic boundary conditions, the weirs at Borgharen and Linne are used for hydropower production only. As a result during storage mode river water is discharged downstream from the Linne weir in the storage section Roermond-Linne, which implies this section is partly filled with river discharge from the upstream end at Linne, and with pumped water from the downstream end at Roermond. When the river discharge increases the complete Roermond-Linne (see Figure 2) section is filled by the river and the discharge will partly fill the storage section Belfeld-Roermond and so on. The water pumped up at Grave is in turn pumped up at Sambeek, as each PSH-plant hosts 20 screws. Upstream of Lith some pumped volume will be stored as it contains 2 more screws than Grave.

The model results for the cascade for hydropower production, river storage, surplus power used and pumped-stored power are shown graphically in Figure 7 by the use of 'power graphs' (Lambach, 2021). In Figure 7 the average Meuse FDC is included. When the discharge increases the screws of the PSH-plants are solely used for hydropower purposes as there is no room for energy storage anymore.

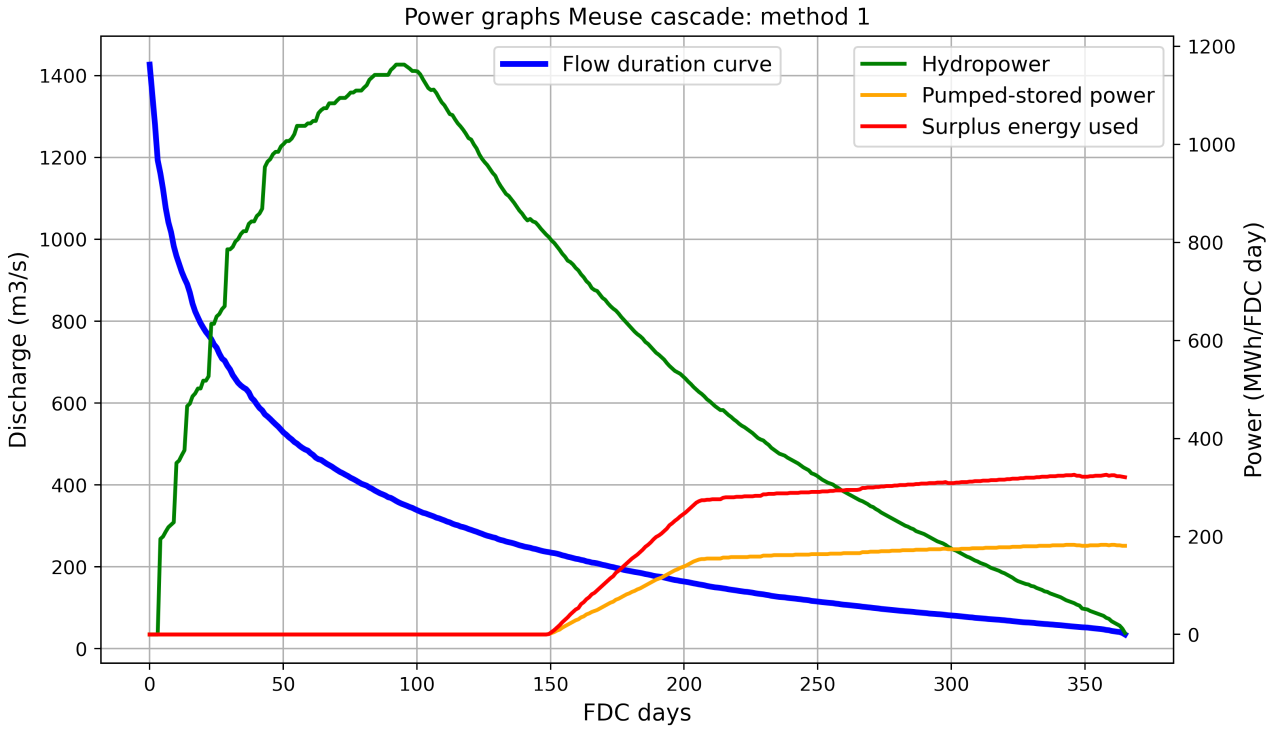


Figure 7: Power graphs for the full cascade using number of screws per plant based on method 1 (Lambach, 2022).

FDC day 1 is representative of river peak flood mode conditions. The river discharge is so high the corresponding head difference at the weirs is zero (see Figure 3 to observe fluctuating water levels corresponding to discharge conditions) and there is no hydropower production. About FDC day 90 the combination of maximum head and available discharge results in the maximum hydropower production. When the discharge is low there is maximum room for storage, as the screws are minimally needed to process river discharge and can be used solely for pumped-storage. The stepwise pattern of the power curves is elaborated on in the discussion section.

The main results of the model simulation for method 1 are (Lambach, 2021, p. 81):

- cumulative installed cascade capacity: 50.3 MW
- hydropower AEY: 205 GWh with a capacity factor of 0.47
- pumped-stored power AEY: 31.6 GWh processing a yearly surplus energy of 56.2 GWh
- round-trip efficiency PSH-process: 56.25 %
- combined capacity factor for hydropower and pumped-storage of 0.54

The round-trip efficiency of the pumped-storage process is obtained by multiplying the turbine- and pump overall efficiencies of 75 % each. The capacity factor is defined as the energy actually produced by the turbines divided by the energy that could be produced using the installed turbine capacity all the time. It is a measure of efficiency of the utilization of the installed turbine capacity. Using the screws for storage purposes increases the utilization of the installed capacity by 7 % as the capacity factor increases from 0.47 to 0.54. According to information provided by the government of the Netherlands at their webpage 'Nuclear Energy' (2020) an AEY of 4,000 GWh can power one million homes. Scaling this quantity to the AEY of hydropower and pumped-stored power it can be concluded up to 59,000 households can be powered by the Meuse cascade.

2.5.2 Method 2: maximum volume a PSH-plant must pump

However, when using the design discharge to choose the number of screws per facility in Method 1, the full storage potential of the Meuse cascade cannot be utilized, as the storage volumes in the downstream reach of the cascade are not completely filled. For instance, the water pumped up at Grave is in turn pumped up at Sambeek. Therefore, in method 2 the number of screws per PSH-plant has been calculated by dividing the maximum volume to pump by the duration of storage mode times the pump capacity of one screw.

By doing so the PSH-plant at Lith needs 59 screws as it has to pump up the volume of five storage sections (Lith, Grave, Sambeek, Belfeld and Roermond). The PSH-plant at Grave needs 48 screws as it has to fill four storage volumes. Sambeek needs 36 screws as it had to fill the storage volumes upstream of Sambeek, Belfeld and Roermond. The numbers of screws for Belfeld and Roermond do not change. This is explained by the fact Belfeld can pump up the volumes of the sections Belfeld-Roermond and Roermond-Linne already when using the number of screws determined by the design discharge. Furthermore, the PSH-plant at Roermond still only needs to store its own volume so its pump capacity is already sufficient.

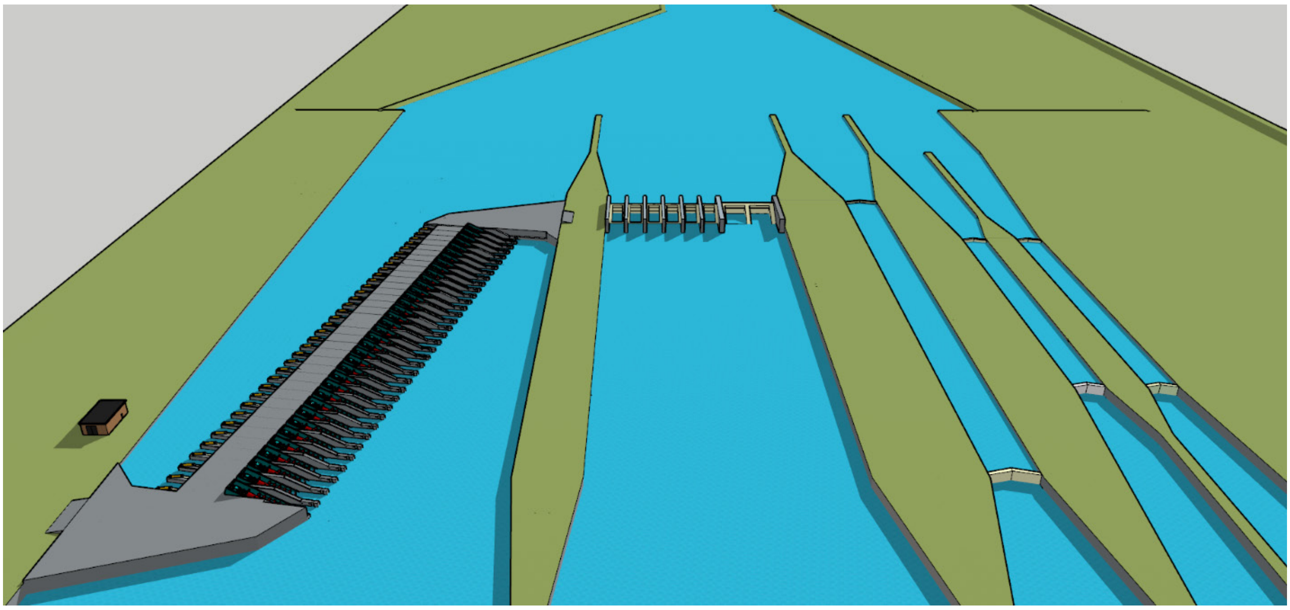


Figure 8: Sambeek PSH-plant (to the left) hosting 36 screws (Lambach, 2021, p. 85).

The updated number of screws per weir are (Lambach, 2021, p. 84):

- Sambeek: 20 → **36**
- Grave: 20 → **48**
- Lith 22 → **59**

In Figure 8 one can view an overview of the Sambeek lock- and weir complex (with future radial gates) hosting a PSH-plant equipped with 36 screws, which are placed oblique to the river bank because of space restrictions. As more screws are placed in parallel more turbulence and energy losses are expected. However, this is neglected in the model. The flow conditions accounted for in the model are fluctuations in water levels up- and downstream corresponding to the fluctuating discharge. For more detailed information see Meuse model in Lambach (2021).

Again a duration of storage mode of 8 hours was used. The main results for method 2 are (Lambach, 2021, p. 88):

- installed cascade capacity: increases from 50.3 to 81 MW
- hydropower AEY: increases from 205 to 225 GWh
- AEY pumped-stored power: increases from 31.6 GWh to 77.2 GWh
- yearly surplus energy used increases from 56.2 to 137.2 GWh
- the combined capacity factor decreases from 0.54 to 0.43
- the number of households which can be powered increases to 75,000 households

The power curves when utilizing the full storage potential of the cascade are shown in Figure 9.

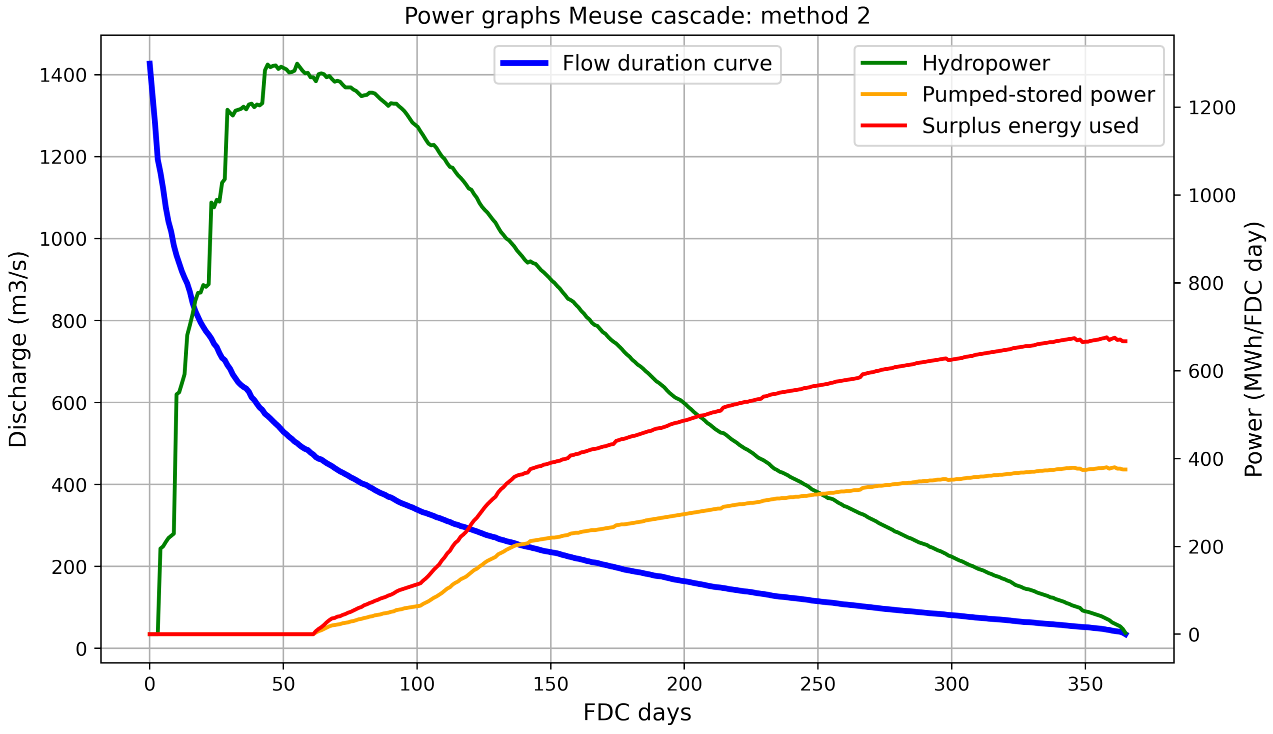


Figure 9: Power graphs for the full Meuse cascade with number of screws per plant based on Method 2 (Lambach, 2022).

The results for pumped stored power and surplus power used change the most spectacularly, as both increase by 144 %. The combined capacity factor decreases from 0.54 to 0.43 indicating a less efficient use of installed screw capacity compared to method 1. However, as the PSH-plants process surplus energy which is wasted otherwise, it might still be economically interesting to increase the number of screws.

2.5.3 Sensitivity analysis to increased storage volumes

Based on method 2, two additional model simulations have been carried out, one with increased storage volumes and one including the Juliana canal. In Figure 4 one can observe a typical cross section of the Meuse river cascade. So far the width between the summer dikes (150 meters) was used to calculate the storage volumes. By tripling this width to 450 meters (an approximation of the width between the winter dikes) the installed capacity for the cascade becomes 193 MW. For instance, the PSH-plant at Lith needs 173 screws. The main results are (Lambach, 2021, p. 89):

- hydropower AEY: 228.9 GWh.
- surplus energy used: 559,9 GWh
- pumped-stored power AEY: 314.9 GWh
- combined capacity factor: 0.32
- up to 136,000 households can be powered

The surplus power used and the pump-stored power AEY increases when tripling the storage volumes. For comparison, the Dutch offshore windfarm Egmond aan Zee (OWEZ) has an installed capacity of 108 MW and a capacity factor of 0.41. The AEY of OWEZ is 393 GWh (Bedon et al, 2018). It can be assumed this AEY is partly produced at periods of low energy demand (nighttime) resulting in the production of surplus energy. For the duration of storage mode in the Meuse cascade a period of 8 hours is used. Therefore, it is assumed OWEZ produces 131 GWh of surplus power. (8/24 * 393 GWh.) A Meuse cascade redesigned for storage purposes could process the yearly surplus power of four times the OWEZ windfarm. However, it is questionable if a Meuse cascade with enlarged storage sections is feasible as it will probably require unrealistic investments, and will have a major impact on the environment. This question might serve an objective of further research.

2.5.4 Sensitivity analysis to including the Juliana canal

As explained in the hydraulic boundary conditions section, energy storage ends at the Linne weir, as the river bed between Linne and Borgharen is too steep for canalization. Downstream of the Borgharen weir ships are diverted from the Meuse river into the Juliana canal, as shown in Figure 2. A simulation has been carried out in which the model has been expanded with the Juliana canal, which has a total head difference of 23.2 meters. PSH-plants are present at Linne, Maasbracht and Born as well. (It is assumed no backwater curve develops upstream of Linne.) Furthermore, it is assumed the design discharge of Borgharen is bypassed via the Juliana canal, so there will be no power production at Borgharen itself. As the width of the Juliana canal is 60 meters – instead of 150 meters in the Meuse river – the capacity for energy storage is reduced. The main results of the simulation are (Lambach, 2021, p. 91):

- hydropower AEY: 393.1 GWh
- surplus energy used: 229.8 GWh
- AEY on pumped-stored power: 129.3 GWh
- up to 131,000 households can be powered by hydro- and pumped-stored power.

The surplus power used is on the order of almost two times the yearly surplus of the OWEZ-windfarm. Including the Juliana canal increases the AEY of hydro- and pumped-stored power. Up to 131,000 households could be powered by hydro- and pumped-stored power. However, a canal in general is not designed to process high discharges like those that occur in a river. The economic- and environmental feasibility of redesigning the canal for hydropower- and energy storage purposes is a recommendation for further research.

2.6 Cost

In order to get an impression of the costs of hydropower- and pumped-storage the concept of specific cost has been applied for the Sambeek PSH-plant. This plant is used as the main dimensions were determined for the conceptual design. Furthermore, with its average head compared to the other Meuse weirs (see Figure 2) it is considered to be representative. The specific cost comprises all construction costs divided by the installed capacity resulting in a unit of euro/kW. Construction costs are estimated as in Marence (2018):

- civil work: cost of all civil structures

- mechanical- and electrical work: cost of turbine, generator, hydraulic steel structures etc.
- preparation costs
- cost of design and control during construction
- contingencies

Observing Figure 3 one can notice the head at Sambeek is not constant. It decreases with an increasing river discharge. Therefore, in the Meuse model the installed capacity is determined per FDC day and its corresponding head. By summing up these results and dividing by 365 days the installed capacity of the Sambeek PSH-plant is set at 6.5 MW using 20 screws (method 1) with a flow capacity of 15 m^3/s each (so 300 m^3/s in total) and an overall efficiency of 75 % (Lambach, 2021, p. 79). For method 2 (36 screws) the installed capacity is 11 MW (Lambach, 2021, p. 86).

The cost analysis was performed based on the dimensions of one screw compartment, which is 7.5 m x 60 m x 15 m (Lambach, 2021, p. 127), The volume of concrete, the area of formwork as well as the tonnage of reinforcement steel have been estimated. Furthermore, the volume of soil which needs to be excavated and the volume of crushed stone needed as foundation layer is estimated. Ultimately, the cost of civil work has been determined using rules of thumbs provided by van der Horst (2018). These costs are shown in Table 1.

The dimensions of the single leaf door are 9 x 6 x 1 meter (Lambach, 2021, p. 131). According to Levinson (2018, p. 75) a total cost estimate – including mounting – for a mitre gate type of door is 6400 euro per ton. For the cost of the hydraulic cylinder manufacturer information from Changzhou (2021) has been used.

In 2021 the Dutch screw turbine manufacturer Landustrie is the only company which has thus far installed a 5 meter diameter 15 m^3/s screw. According to information provided by their webpage 'Linton Lock' (2021) this occurred in 2017 at a hydroelectric plant on the River Ouse in North Yorkshire, England. Landustrie offers a water level adjustable trough using hydraulic pistons (Landustrie. 2015, p. 7). Therefore, this company has been consulted (2021) for a rough price indication of one screw (including gearbox and generator) and adjustable trough which is assumed to be representative of the Sambeek PSH-plant. These mechanical and electrical costs are estimated to be 2 million euros.

According to Lipinski & Olkowski (2017) the cost estimate of electro-mechanical equipment for small hydropower plants (< 10 MW) often amounts to 30–40% of the total budget. However, the cost indication of Landustie comprises turbine and trough including generator and gearbox. Therefore, for the remaining cost for electrical work an estimate of 10 % of the construction cost so far has been applied.

Preparation and cost of design and control (running cost) have been estimated using Norwegian information for small hydropower plants. This is estimated at 20 % (Slapgard, 2012, p. 7) of the cost of civil- and electrical/mechanical work.

Type of cost	Specification	Cost estimate
1. Civil work including labour:		Euro:
• concrete	3400 m^3	430,000
• formwork	1900 m^2	170,000
• reinforcement steel	270 ton	375.000
• excavation	3000 m^3	12,000
• foundation	450 m^3	18,000
2. Mechanical and electrical work:		
• screw, trough, generator, gearbox		2.000.000
• single leaf door, cilinder	18 ton	135,000
• additional electrical work	10 % of (1) and part of (2)	315,000
3. Preparation and running cost	20 % of (1) and (2)	690,000
4. Contingencies:	15 % of (1), (2) and (3)	620,000
Construction cost one screw compartment:		**4,765,000**

Table 1: Construction cost for one screw compartment of the Sambeek PSH-plant.

Marence (2018) advises to use 5–25 % of the construction cost for contingencies. An estimate of 15 % of all the costs mentioned above has been applied for contingencies considering the relatively early project stage but also relatively accurate estimated electro-mechanical equipment costs. The estimated construction costs are summarized in Table 1.

For method 1 the installed capacity for one screw at Sambeek is 325 kW (6.5 MW divided by 20 turbines). By dividing the construction cost of 4,765,000 euro by 325 kW the specific cost for hydropower turns out to be about 15,000 euro/kW. The specific cost is of the same order for method 2. In reality there will be economies of scale when constructing multiple compartments next to each other. However, this is neglected in the cost assessment.

The specific cost for the Sambeek PSH-plant is relatively large. According to the International Renewable Energy Agency (2012, p. 20) in the United Kingdom (with a similar price level as the Netherlands) small hydropower plants have specific cost between 3000 and 3500 euro/kW. For micro-hydropower plants this can increase to 8500 euro/kW or even higher. The high specific cost at Sambeek is partly explained by the dimensions of a screw compartment resulting in the need of 3400 m^3 of concrete and 270 tons of reinforcement steel.

Furthermore, the cost of the screw and its mechanical/electrical components are considerable. When consulting Landustrie (2021, August 23) it became clear the interest in screw turbines is high. However, commercial projects are still only viable when subsidized. As only one 5 meter diameter screw has been installed worldwide it can be considered to be in the early stages of development. With maturity, the cost of the screws can be expected to decrease. However, when for instance assuming 1 million euros for the cost of screw and components, the specific cost for hydropower is still about 10,000 euro/kW.

Section 2.3 elaborates on fish-mortality rates of screw (near-zero fish mortality) and bulb turbines (about 10 % mortality). The discharge capacity of a 5 meter diameter screw is 15 m^3/s. This is relatively small compared to the capacity of a bulb turbine installed at the Linne weir, which is 102.5 m^3/s (Lambach, 2021, p. 10), due to the Archimedes screw's specific speed being much lower than that of a bulb device (Hoffstaedt et al., 2022). As a result, many screws are needed at the PSH-plants resulting in relatively high mechanical- and electrical cost. Therefore, we see that the benefit of a large number of fish-friendly screws comes at a very high economic cost compared to the higher fish mortality but significantly lower cost of a much smaller number of bulb turbines that can process the same discharge.

3 Discussion

The Meuse model computes the hydropower and pumped-stored power production per FDC day per weir, and sums these results up to obtain the AEY's for the weirs and cascade. During one cycle of 24 hours the change of water volume in a storage section as a result of pumped-storage will be zero, and therefore the change in water levels will be zero. For the next FDC day the model selects the corresponding data on discharge and water levels. Therefore, it makes 'jumps' in discharge and water levels, which explains the stepwise pattern in the power graphs (Figures 7 and 8). In reality the change in discharge and water level is a gradual process throughout the day. However, in order to get an idea of AEY, the construction of the model is discretized with a daily time step.

In the model overall efficiencies of 75 % have been applied for pumping and turbining, based on manufacturer information. However, these are variables in the model so higher or lower efficiencies can be assessed as well.

Model simulations have been carried out in two ways: by determining the number of screws per PSH-plant based on the 100-day design discharge, and by determining this number based on the maximum volume to pump. The economic optimal number of screws will lay somewhere in between.

In the model it is assumed a PSH-plant can switch instantly from turbining to pumping with constant water levels up- and downstream at that moment in time. In reality, a wave will develop when storage mode starts as river discharge – which is blocked – will accumulate at the upstream side of the PSH-plant and in turn will roll back upstream. This accumulation of water will increase the upstream water level. However, the inertia of the water – which is an open channel flow phenomenon – is neglected in the model.

Synergy effects of modular repetitive civil structures and electrical/mechanical equipment are not included in the cost estimation. This consideration will reduce the specific cost but could not be specified. In addition, the specific cost has been assessed using the only major cost items. No attention has been paid to the levelized cost of electricity (LCOE) or levelized cost of storage (LCOS).

The model provides reasonable outcomes on the AEY of hydropower and pumped-stored power. Although it will need some time to adjust, the model is generally applicable to assess the storage- and hydropower potential of any generalized river cascade. In order to do so the FDC's as well as the corresponding data on water levels per weir have to be implemented.

4 Conclusions

The Meuse river – showing an average discharge of 230 m^3/s – consists of seven weirs with head differences in the range 2.5 m–5.2 m in the trajectory Borgharen-Lith. Due to regulations on fish mortality, currently hydropower facilities exist at only two weirs in the Meuse river. The goal of this study was to assess the possible utilization of the full energy-storage and hydropower potential of the Meuse cascade within Dutch environment regulations. In order to do so the concept of pump-storing energy in the canalized sections of the Meuse under fluctuating discharge and -water levels has been evaluated, which forms the novelty of this study.

A conceptual design of a PSH-plant equipped with Archimedean screws has been compiled. This pump-turbine is expected to meet Dutch environmental regulations for the Meuse (near-zero fish mortality), and is suitable within the head differences at the weirs in the cascade. Screws can additionally be used to pump back locking water avoiding limited locking capacity during drought conditions and ensuring river navigability under changed climate conditions.

In order to compute the cascade AEY for pumped-stored power and river discharge hydropower, a model has been constructed. This 'Meuse model' computes power production- and storage per FDC-day per weir. By summing up the results the AEY's for the cascade are obtained. In the model it is assumed the conceptual design is present at the weirs, although the number of screws differs per weir. This study shows pump-storage is possible at the five downstream canalized Meuse sections.

Two methods have been applied for the number of screws per PSH-plant. Method 1 uses the 100-day design discharge related to the flow duration curve. In this way, the cumulative installed capacity of the Meuse cascade is 50.3 MW resulting in a hydropower AEY of 205 GWh with a capacity factor of 0.47. The AEY of pumped-stored power is 31.6 GWh processing a yearly surplus power of 56.2 GWh. The combined capacity factor for hydro- and pumped-stored power is 0.54. Up to 59,000 households can be powered by this hydro- and pumped-stored energy. The round-trip efficiency of the pumped-storage process is 56.25 % by multiplying the turbine- and pump overall efficiencies of 75 % each.

However, in order to utilize the full storage potential of the cascade more pump capacity is needed at the downstream weirs of Lith, Grave and Sambeek. Therefore, method 2 determines the number of screws per plant using the maximum volume to pump. This results in an increase of cumulative installed cascade capacity to 81 MW. The pumped-stored AEY increases to 77.2 GWh. Up to 75,000 households can be powered with this hydro- and pumped-stored energy. The combined capacity factor decreases to 0.43. Despite this decrease it might still be economically interesting as surplus power is used which is wasted otherwise when not stored.

Discharge and corresponding water levels fluctuate throughout the year. It can be concluded the lower the river discharge, the higher the capacity for pumped-storage. When the river discharge becomes large the turbines are solely used for hydropower purposes, as there is no volume left in the river section for pumped-storage anymore. Furthermore, hydropower production stops at peak flood discharge, as the necessary head difference across each weir disappears with up- and downstream water levels become equal due to opening of navigation and sluice gates.

The specific cost of hydropower in the conceptual design is relatively high: 15,000 euro per kW. This is partly explained by the high cost of electrical- and mechanical equipment – as a large number of screws are needed in a PSH-plant – and the huge volume of concrete needed for the screw compartments. This cost is due to the relatively low flowrate that each screw can discharge, but necessary when near-zero fish mortality is required, as no other established technology for reversible pump-turbines shows equivalent fish friendliness.

The results from this study show it is possible to utilize hydropower- and energy storage potential of the Meuse cascade within Dutch environmental regulations, thereby increasing the Meuse contribution to the production of renewable energy in the Netherlands.

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Author contributions (CRediT)

JWL: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. JDB: Resources, Supervision, Writing – review & editing. MM: Resources, Supervision, Writing – review & editing.

Notation

Name	Symbol	Unit
Gravitational acceleration	g	m/s^2
Discharge	Q	m^3/s
Head	H	m
Efficiency	η	-
Density	ρ	kg/m^3
Volume.	V	m^3

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