Even Flow - Water coordination efficiency & Hydropower production under outflow regulation

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“If you could see all the roads I have travelled
towards some unusable last equilibrium”

- Tempus Fugit, Yes

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Abstract

This thesis sets out to investigate the impact of the European Union’s water framework directive on water coordination efficiency in the hydropower market, and whether water coordination inefficiency might offset the benefits of market competition. I implement a dynamic market model examining Stackelberg competition and a monopoly/collusion market type with regards to reservoir and production capacities and the impact of upstream production plans on downstream production possibilities. The main finding is that under limited storage possibilities, the lack of centralized coordination planning causes competition to be less desirable than a private monopoly from a consumer welfare maximizing perspective. However, granted that the reservoir and storage possibilities are big enough in relation to the outflow requirement – the benefits of competition outweigh this coordination cost and the need for collusive behavior.

Keywords: Stackelberg competition, collusion, water framework directive, water resource management, energy demand.
1. Introduction

The purpose of this thesis is to study the welfare outcomes, given potential market types, of introducing a regulation that forces hydropower-producers to release an adequate water outflow. This topic is motivated by the existence and implementation of the European Union’s water framework directive and the ongoing global tendency for marketization of the energy sector, including hydropower markets (Dorsman, et al., 2011; Yan, 2015).

Hydropower is the most utilized renewable source of energy production on a global level (IEA, 2016). In a time with huge global incentives to cut down on carbon emissions, hydropower is often considered a cornerstone to rely on in order to reach climate objectives\(^1\). However, hydropower is a source of several river-bound environmental issues regarding biological diversity and recreational values (Førsund, 2013; Edwards et al., 1999). This dilemma is one contributing aspect to the increasingly important topic of water resource management, striving towards healthy water bodies and water courses.

A typical hydropower plant is equipped with an upstream reservoir which allows for storage of water for later production. A hydropower producer therefore regulates the plant’s outflow as a function of the demand for energy, rather than in accordance to the historical fluctuations of the water level of the river. The cause for concern regarding the quality of river basins was an important reason for the European Union to introduce the so called Water Framework Directive (WFD) for its member states. The central aspect of the WFD with regards to hydropower production is that the water courses should support the criteria of “good ecological status”, which demands water level fluctuations in rivers to be similar to the historically unregulated fluctuations of the specific river basin (Directive 2000/60/EC, 2000). In order to implement the guidelines of the WFD with regards to outflow, water management and coordination becomes the strategic tools of importance among firms along the river.

While many hydropower markets have experienced restructuring from monopolization to competition during the last 20 years, earlier studies actually associate deregulation and decentralization of coordination decisions with water coordination inefficiency (Ambec & Sprumont (2000), Ambec & Doucet (2003), Lino, et al., (2003), Rangel (2004)). One might therefore assume that a competitive market might not be amenable to an efficient

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\(^1\) The existence of reservoirs can actually cause a significant alteration of carbon dioxide and methane emissions. This happens due to biomass decomposition when flooding causes trees and vegetation to rot and release carbon dioxide and methane into the atmosphere (Steinhurst et al., 2012).
implementation of the WFD. This thesis therefore sets out to answer the following questions in order to formulate valuable policy recommendations: How does the implementation of the water framework directive affect water coordination? And does the lack of coordination efficiency offset the benefits of competition?

To my knowledge, no earlier literature deals with how outflow regulations affect water coordination efficiency, and if decentralization of hydropower markets makes the implementation of such requirements less beneficial for consumers than a monopolized or collusive market.

1.1 Overview of hydropower operations & literature review

Hydropower is a unique source of energy production in the sense that a producer can respond swiftly and inexpensively to the dynamics of energy demand by regulating its output with the use of hydro-reservoir operations. The possibility to store water for energy production creates an intertemporal aspect of decision making and the producer has to compute the marginal cost of releasing water as a function of opportunity cost, since the input good of water is free (Philpott & Ziming, 2013). In order to achieve profit maximization, the producer therefore has to allocate its water resource in an efficient manner, representing an efficient allocation of a natural resource in a dynamic context. The main factors influencing the production plan decisions of a hydro producer that are of importance for this study can be summarized as:

- Correlation between inflow and energy demand
- Reservoir size compared to total energy demand
- Turbine capacity of the hydro plant
- Potential for overnight pumping

Source: (Van Ackere & Ochoa, 2010)

The inflow provides the producer with the input good of water which determines the production possibilities, and since water inflow often follows seasonal variations, a producer makes use of a reservoir in order to store water during off-peak demand for future use when inflow is low but demand is high. The reservoir size acts as a natural constraint on allocation possibilities,

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2 Hunt (2002) clarify that this is not equal to the possibility of storing energy, in the same manner that stacked coal isn’t stacked energy. However, I consider that the intertemporal trade off and possibility to regulate the output in response to demand dynamics through reservoir operations does the statement justice, at least for the analysis of this study.
and therefore also on future production possibilities. If a producer for example enjoys very plentiful inflow in an off-peak demand period and storage capacity is low, it might be forced to produce although it would be more profitable to store more water for future production. If a hydropower plant is equipped with a downstream reservoir, overnight pumping becomes a strategic tool for the producer. A hydropower producer might strategically pump water from the downstream reservoir during the night when electricity costs are low, and then use it for production during the daytime when electricity prices are high (Van Ackere & Ochoa, 2010).

The cost structure of production is a key factor affecting the optimal production behavior of the firm. Although hydropower plants are associated with high initial investment costs, these are present and fixed and shouldn’t be of concern when deriving the optimal production plan(s). The variable costs associated with hydropower production are at most very low (Eurelectric, 2015), and low enough to in most literature simply be normalized to zero. The employee wages associated with overseeing the production and maintaining the generator(s) can be viewed as a function of invested capital, rather than of output produced. The optimal production plan of a hydropower producer is instead determined by the opportunity cost of water, i.e. how much water that should be used for production today, and how much water that should be stored for later production (Førsund, 2013).

The consequence of hydropower production allocation not tallying with the adequate natural fluctuations of the river can be expressed as external environmental costs. These environmental costs involve the disturbing of fish spawning, the distortion of biological diversity and river-bound agricultural production possibilities, as well as damaging pristine landmarks resulting in diminishing recreational values of the river basin (Førsund, 2013; Edwards et al., 1999). In order to cope with these external costs, the WFD advocates for the outflow to be similar to the historically unregulated fluctuations of the specific river basin. The WFD also advocates for

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3 Reservoir sizes usually vary a lot amongst producers and therefore contributes to the coordination problem. Lake Vänern (The third biggest lake in Europe) is for example the biggest reservoir used for hydropower production in Sweden (Länsstyrelsen - Västra Götalands Län, 2014), while some smaller producers are limited to not having any storage capacity at all (“Run-of-river plants”).

4 In Norway and Sweden, the utilization of pumped-storage production is yet to become profitable. This could be due to the high investment costs associated with installing a sufficient pumping system in relation to the amount of conventional storage hydro plants in drift. On a closing note however, Norway actually utilize pumping at a few hydropower facilities during the wet season in order to increase the possibility of flexible power production. (RESAP, 2011).

5 Ambec & Doucet (2003) and Rangel (2004), both which serves as the main theoretical framework for this study choose to normalize the variable costs to zero.

6 Since the cost is not internalized by either energy prizes or any production costs, the cost will be dubbed as external as it is a third party (the ones utilizing the river for other purposes than energy production) that suffers the cost.
decentralized regulatory measures (Directive 2000/60/EC, 2000), which creates a scenario where outflow is regulated to preserve the environmental values of the river basins, an “adequate outflow requirement”.

Three conflicting objectives therefore arise: consumers on the energy market want the outflow of the generators to match their preferred consumption patterns, the producers want the outflow of the generators to match their profit maximizing allocation, while the goal of the WFD is for water outflow to match historical natural fluctuations. Water coordination efficiency becomes the key for these objectives to coexist on a functioning hydropower market.

Ambec & Doucet (2003) studies hydropower producers competing while operating on different rivers. They formulate two potential sources of welfare loss: Market power and coordination issues. While a monopoly acts with market power, it minimizes coordination issues due to being the single owner of all generators, thus regulating the outflow of individual generators based on an overall objective. Competing firms, while minimizing market power, however act independently. They might therefore face situations where production constraints allow certain producers to act as monopolies on residual demand, due to other firms not being able to store enough water for production in demand peak periods. Coordination issues therefore lead to a sort of market power on residual demand, as the opportunity cost is not naturally internalized when producers act competitively. As a monopoly regulates all the reservoir operations based on the same objective, it internalizes the lack of storage of one generator by storing more water in another reservoir with greater storage capacity. Coordination failure therefore seems to arise in the absence of a central coordinator, distorting the benefits of competition.

Rangel (2004) draws inspiration from Ambec & Doucet but instead choose to study cascading hydropower plants, when the production choice of the upstream producer influences the inflow to the downstream producer. In consonance with Ambec & Doucet, he underlines the welfare implications of market power and coordination issues, where competition minimizes the welfare loss associated with market power, and a monopoly minimizes the coordination issues. His model is based on a Stackelberg setup, where the upstream firm act as the quantitative leader, and the downstream producer act as the follower in a sequential game. The results show that the upstream producer might have incentives to manipulate their production plan based on the storage possibility of the downstream producer. However, his model lacks the dynamic

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7 Water coordination inefficiency is also discussed in the context of transboundary river systems where more than one country makes use of the river for economical purposes, thus creating the same possible coordination issue as with two competing firms. See Kouangpalath & Meijer, 2015.
aspect of demand and therefore fails to capture the intertemporal trade-off effect it creates. Rangel therefore choose to dub his model as a “false” dynamic model, and does conclude that the model is not appropriate when investigating off-peak and peak period behaviour. Therefore, this thesis will complement the findings of Rangel by trying to capture the effects of demand dynamics on the stratetic behaviour of competing cascade hydropower plants.

Arrellano (2004) studies the possibility of hydropower producers to exercise market power in two ways: regulating total production output, or allocating production intertemporally by over-producing in offpeak periods and then under-producing in peak periods, exploiting differences in the dynamics of demand. Ranking market types on the criteria of total output produced in relation to total output demanded would therefore miss the aspect of intertemporal allocation strategies. The potential market power of intertemporal allocation strategies is also underlined by the Swedish Competitive Authority (Konkurrensverket) and since it is not measurable in terms of total output, it will therefore be harder to detect. They do however stress that a hydroproducer with restricted storage possibilities should naturally overproduce today if expectations point towards high inflow tomorrow, since water overflooding the reservoir would yield zero marginal value for the producer. Ineffective allocation of water from a consumer perspective could therefore simply be an unfortunate consequence of weather and capacity restrictions, rather than market power (Konkurrensverket, 2005).

The conclusion of existing research that competition is associated with poor coordination efficiency goes in line with the collusion-esque behaviour of Swedish hydropower producers through so called water management companies. Although Swedish hydropower producers operate on the Nordpool-market, known for its transboundary competition (Hjalmarsson, 2000), each regulated river in Sweden has it’s own water management company that consists of the competing firms along that specific river (Vattenregleringsföretagen, 2016). According to earlier literature (Ambec & Doucet, 2003; Rangel 2004), this collusive behavior should yield less coordination issues through centralized management, but at the same time enable the producers to act with market power. In a report evaluating the competition on the energy market of Sweden, Konkurrensverket urges for the government to take action against the collusive behaviour of the water management companies. Their claim is that the existence of water management companies increases the possibility of exercising market power by sharing valuable information regarding production strategies and thereby allowing for anti-competitive behaviour (Konkurrensverket, 2009).
This thesis will pursue to complement existing literature by answering the question of whether the benefits of competition might be offset by an outflow regulation, and whether a monopolized or collusive market would be preferred and thus underline the potential importance of water management companies or other centralized coordination planners. This would be of great value for policy makers facing the question whether to allow collusive behavior when introducing or maintaining competition in a hydropower market, or as a benchmark on how the implementation of an outflow regulation might negate the perks of decreased market power. The policy implications should yield the most value in hydropower dense economies. In Norway for example, 98% of total energy is produced by hydropower generators (Gonzales, et al., 2011). The corresponding share of total production in Brazil is 75% (Luomi, 2014), and 45% in Sweden (Rudberg, 2013).

1.2 Disposition

The thesis is organized as follows. Section 2 introduces the theoretical model. I then derive the optimal unconstrained production plans with regards to consumer utility maximization, and firm profit maximization under monopoly and competition. These outcomes are compared in section 3 in order to rank which market type is more suitable under no capacity or storage restrictions. Next I model the effects of the WFD on water coordination through a quantitative outflow regulation, and once again compare the outcomes of different market types in order to rank them. Section 4 concludes, followed by a critical discussion and suggestions of future research questions on the subject. Some derivations and massaging of equations has been relegated to the appendix.
2. The model

The core of the model is the intertemporal aspect of allocation of a natural resource, more specifically water for energy production. Efficient allocation of water can be viewed from a market perspective (where firms and consumers in the energy market decide on the production levels through supply and demand), or an environmentally beneficial perspective (taking into account for the externalities of inadequate water level fluctuations). Following any textbook source (for example Perman et al. (2011)), this allocation problem makes for some general assumptions, including scarcity (at the end of the time horizon, the expected resource stock should be 0 following the last period). This translates to an assumption that water is scarce enough to assume that in the long run; a hydro producer cannot have a net storage of water deviating from zero. This assumption is probably more suitable on a global level where water is regarded as scarce while in the Nordic countries, water scarcity is not prominent (UN-Water, 2012). Ambec & Doucet (2003) motivates the assumption by stating that, since water is a free input good, it should be a sign of ineffectiveness to not make use of the whole production possibilities by the end of the time horizon (assuming no variable costs). The assumption of scarcity does allow for the simplification of expressing later period production as the residual of the production in the first period. The consequence of this assumption is, if following Arellano (2004), that it would limit market power to only be exercised through intertemporal allocation, not through decreased total production output. This can thereby be viewed as the major limitation of this model, along with the models presented by Ambec & Doucet (2003) and Rangel (2004) amongst others.

The profits from production of energy is defined for every period as $\pi_t, t = 0, ..., T$, but the interest of the firm differs somewhat when studying different market types. A monopoly firm, owning every generator along a river is only interested in total production, $\pi_t(Q_t)$, while a competing producer only owning one of the generators along the river is interested in generator specific production, $\pi_t(q_t)$. Since an upstream producer’s outflow will add to the inflow of the downstream producer, competition along one river would yield a Stackelberg market. I will limit my model to only containing cascading hydropower plants with an upstream reservoir (or no reservoir at all). This means that a producer cannot manipulate market supply by reusing

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8 Rangel (2004) also choose to describe the market of cascading hydropower plants as a Stackelberg competitive market. Ambec & Doucet (2003) briefly mentions the implications of a Stackelberg setup in an earlier version, but it was later left out of the published paper.
water for production by storing outflow in a downstream reservoir\(^9\) (pumping). Assuming a Stackelberg market limits my model to a duopoly competitive market. Expanding the number of producers along one river should homogenize the production conditions. Instead of having one producer acting as the leader, and one as the follower, every producer except the one furthest upstream and furthest downstream should all act as both leaders and followers when thinking in a Stackelberg framework. A Cournot analogy might therefore be more appropriate, a consideration made by Arellano (2004) for example. The importance of this study’s conclusions for a policy maker does not lie with the exact form of competition, but rather the understanding of why competition might be inappropriate when operating under an adequate residual outflow requirement, and how to fit policy measures thereafter in order to minimize overall welfare loss.

To specify the model: Consider an economy where all of the energy is supplied by two hydropower generators located along the same river \((i = 1,2)\), indexed from upstream to downstream. During a two period game\(^10\) the producer(s) maximize profits according to the general theory of the firm by choosing an optimal production plan, \(Q_t^M\) is the monopoly, \(Q_t^S\) is the Stackelberg production plan. The production possibility of the upstream producer is only affected by the exogenous water inflow, \(e_{it}\) (like rainfall and snowmelt), while the downstream producer enjoys both the exogenous inflow as well as the inflow resulting from upstream production, \(q_{it}\). In order to eliminate the element of stochasticity, the exogenous inflow is assumed to be perfectly forecasted\(^11\) by the producer(s). This allows for foresight of seasonal inflow variations, and thereby the natural fluctuations of production possibilities over a given time period. The intertemporal availability of water can now be described as a function of a

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\(^9\) In Norway and Sweden, the utilization of pumped-storage production is yet to become profitable. This could be due to the high investment costs associated with installing a sufficient pumping system in relation to the amount of conventional storage hydro plants in drift. On a closing note however, Norway actually utilize pumping at a few hydropower facilities during the wet season in order to increase the possibility of flexible power production. (RESAP, 2011).

\(^10\) Two periods are sufficient enough for analyzing demand dynamics and the trade-off it creates. This setup allows for studying off-peak and peak allocation of water supply for production to either satisfy the consumer preferences and/or the profit maximization of the firm.

\(^11\) Perfect foresight is of course highly unrealistic. However, if the game is designed to contain two periods defined in terms of seasons, the producer should be able to deduce which period will yield a higher inflow. For example, a producer in Scandinavia is surely aware that water inflow is high in late spring, compared to midwinter. This study will focus a lot on this typical setup with dynamics in both inflow and demand, therefore motivating the assumption.
fixed input stock and thereby simplify the analysis\textsuperscript{12}. This assumption is also made by Ambec \& Doucet (2003).

Since I assume water scarcity, all inflow of water has to be used for production over the two period game. The total production possibility of producer \(i\) will be denoted:

\[
\tilde{q}_i = q_{i1} + q_{i2}
\]  \hspace{1cm} (1.1)

and the total production in period \(t\) will become:

\[
Q_t = q_{1t} + q_{2t}
\]  \hspace{1cm} (1.1’)

The total production can then be expressed as:

\[
\tilde{Q} = Q_1 + Q_2
\]  \hspace{1cm} (1.1’’)

Each producer has the possibility to store water in a generator-specific reservoir. The storage capacity is denoted \(\bar{s}_i\). The indexation allows for heterogeneous storage possibilities, a concept that will be relevant for understanding the importance of storage for coordination efficiency. Both generators possess the same technology, and the productivity factor (how many units of water it takes to produce one unit of energy) is normalized to 1. Variable costs will in consonance with earlier literature be normalized to 0.

The consequence of this setup is two natural constraints: One capacity constraint (a producer cannot produce more energy than the inflow allows), and a storage constraint (a producer cannot store more water for future production than the reservoir capacity allows). Since we assume that all water is being used for production over the two periods, the production choice in period 1 will yield a remaining amount of stored water that represents the optimal production in period 2. Therefore, the constraints can be expressed in terms of first year production:

\[
q_{i1} \leq e_{i1} + q_{(i-1)1}
\]  \hspace{1cm} (1.2)

\[
q_{i1} \geq e_{i1} + q_{(i-1)1} - \bar{s}_i
\]  \hspace{1cm} (1.3)

Since the upstream producer is not affected by any inflow from upstream production, let \(q_{0t} = 0\). For any arbitrary production level, \(Q_t\), the producer’s face an inverse linear dynamic demand

\textsuperscript{12} Consider for example the Nordic market where the majority of water inflow happens in late spring. For a producer, the production possibilities in that year can then generally be expressed as a function of springtime-inflow (Olsson \& Pearson, 2005). If this concept where to be applied on a country with water scarcity, the availability of water can instead be expressed as a function of water inflow during a rainy season.
function, $P_t(Q_t) = a_t - b(Q_t)$, where $a_t$ captures the dynamics of demand. I also assume that $a_t > 0, b > 0$.

The consumption of energy yields utility for the consumer. In this case water is a source of utility through its use to produce the energy demanded on the market\textsuperscript{13}. In order to capture the welfare of all energy consuming individuals of the market, the utility is aggregated. Further I ignore the distribution of utility, which is a common assumption (Kincaid & Ross, 2009). The aggregated utility of energy consumption is defined for every time period as $u_t, t = 1,2$. Total aggregated utility of consuming $Q_t$ units of energy in period $t$ is denoted by $u_t(Q_t)$.

\[ U(Q) = u_1(Q_1) + u_2(Q_2) \]  

Utility is assumed to be increasing and strictly concave in quantity consumed. The model will be specified for studying the intertemporal tradeoff between seasons, for example summer and winter. Therefore, discounting should not have any significant impact on consumer behavior. As a result, I allow for a normalization of the discount factor to 1. To allow for preferences to vary over time\textsuperscript{14} let $u_1(Q_1) \neq u_2(Q_2)$ when $Q_1 = Q_2$. Consumers maximize their utility with respect to the budget constraint, yielding the indirect demand function of $P_t(Q_t) = u'(Q_t)$.

2.2.1 Utility maximizing allocation

The consumer preferred intertemporal production allocation will be derived through a maximization of the aggregated utility of consumption:

\[ \max_{q_{i_1}} u_1(\sum_{i \in N} q_{i_1}) + u_2(\bar{Q} - \sum_{i \in N} q_{i_1}) \]  

Subject to the production capacity constraint and the storage constraint:

\[ q_{i_1} \leq e_{i_1} + q_{(i-1)1} \]  

\[ q_{i_1} \geq e_{i_1} + q_{(i-1)1} - \bar{s}_i \]  

The corresponding Lagrange-function becomes

\[ L = u_1(\sum_{i \in N} q_{i_1}) + u_2(\bar{Q} - \sum_{i \in N} q_{i_1}) - \lambda_1(q_{i_1} - e_{i_1} - q_{(i-1)1}) - \lambda_2(e_{i_1} + q_{(i-1)1} - \bar{s}_i - q_{i_1}) \]  

\textsuperscript{13} Assuming that water is only used for energy production, otherwise it would generate zero utility for the consumer.

\textsuperscript{14} For example: During a hot summer’s day, energy might be consumed for cooling purposes. On a cold and dark winter’s day however, it might be more preferably used for warming and illumination.
Maximizing equation 2.4 with respect to $q_{i1}$ yields the following first order conditions:

$$u'_1(Q_1^i) - u'_2(Q_2^i) - \lambda_i + \lambda_j = 0 \quad (2.5)$$

$$\lambda_i(q_{i1} - e_{i1} - q_{(i-1)1}) = 0 \quad (2.6)$$

$$\lambda_i(e_{i1} + q_{(i-1)1} - s_i - q_{i1}) = 0 \quad (2.7)$$

If the capacity constraint where to be binding, the following inequality would hold:

$$u'_1(Q_1^i) > u'_2(Q_2^i) \quad (2.8)$$

which means that all producers would produce up to their capacity in each period. As the production plan represents the preferences of the consumers in the optimal allocation, this translates to an inequality between marginal utilities. Considering the storage constraints to be binding, the inequality would instead read:

$$u'_1(Q_1^i) < u'_2(Q_2^i) \quad (2.9)$$

which would mean that all producers store water up to their reservoir capacity, thus representing a higher marginal utility of consumption in period 2 relative to period 1. If neither constraint where to be binding, the utility maximizing allocation would equalize marginal utilities, as follows:

$$u'_1(Q_1^i) = u'_2(Q_2^i) \quad (2.8)$$

Since $u'_i(Q_i^i) = P_i(Q_i)$, this allows me to express the efficiency condition for utility maximizing production allocation in terms of the linear demand function.

$$a_1 - b(Q_1) = a_2 - b(Q_2) \quad (2.9)$$

This is illustrated in Figure 1. The efficient production allocation is determined by the intersection of the demand functions. When the area under the demand functions is maximized, the production allocation will be welfare maximizing.
Figure 1: Utility maximizing production allocation. The horizontal axis represents the total production of the two periods. The right vertical axis represents the energy price in period 1, and the left represents the energy price in period 2. The intersection of the two demand functions represents equalized marginal utilities, yielding the optimal unconstrained production allocation from a consumer perspective. In the unconstrained optimum, prices are equalized.

Since the total production in period 2 is the residual of the total production period 1, equation 2.9 can be rewritten as:

\[ a_1 - b(Q_1) = a_2 - b(Q - Q_1) \]  
(2.10)

This expression allows me to solve for the optimal total quantity produced in the first period with regards to maximized aggregated consumer utility:

\[ Q_1^* = \frac{a_1 - a_2 + bQ}{2b} \]  
(2.11)

This allocation makes intuitive sense since if we assume that there are no dynamics of demand, \( a_1 = a_2 \), the optimal production plan in period 1 would simply be to produce half of the total quantity. Any deviations from this allocation would yield a welfare loss, which is illustrated in figure 2.
Figure 2: Welfare loss of a deviating arbitrary production plan. Any production allocation that deviates from the utility maximizing allocation will yield a welfare loss represented by the shaded area. In this figure, the over-production in period 1 will yield an under-production in period 2, not matching consumer preferred production. Marginal utilities and prices will not be equalized.

The arbitrary production plan of $Q_1$ represents an overproduction in period 1 in relation to the utility maximizing production plan of $Q_1^*$. By default, the overproduction in period 1 lead to an underproduction in period 2 and this allocation yields the welfare loss represented by the shaded area.

The measurement of welfare loss ($\emptyset$) of any production plan can be formulated as follows:

$$\emptyset = |Q_1 - Q_1^*| \times |P_1 - P_1^*|$$

Which in terms of the linear demand function yields:

$$\emptyset = |Q_1 - Q_1^*| \times |(a_1 - b(Q_1)) - (a_1 - b(Q_1^*))|$$

(2.12)
Which can be rewritten as:

$$\emptyset = |Q_1 - Q_1^*| \times |b(Q_1^* - Q_1)|$$  \hspace{1cm} (2.14)

The size of the welfare loss is therefore determined by the difference of an arbitrary production plan and the utility maximizing production plan. This allows me to rank different production plans with regard to their welfare loss by simply measuring the difference between a chosen production plan and the utility maximizing production plan. If $|Q_1^a - Q_1^*| > |Q_1^b - Q_1^*|$ then $\emptyset_a > \emptyset_b$. Given this, I can use $Q_1^*$ as a point of comparison in order to determine the effectiveness of any arbitrary production plan $Q_1$.

### 2.2.2 Monopoly Outcome

With the point of comparison derived in the previous section, I now go on to examine the production plan choice from a market perspective in order to determine the interaction between the power plants along the river and the resulting total output. I consider both generators along the river to be owned by a single private firm, thus the maximization problem is expressed in terms of total output, i.e. the sum of generator specific output levels:

$$\max \pi = \pi_1(\sum_{i \in N} q_{1i}) + \pi_2(Q - \sum_{i \in N} q_{1i})$$  \hspace{1cm} (3.1)

subject to the capacity constraint (equation 2.2) and the storage constraint (2.3) yields the corresponding Lagrange-function:

$$L = \pi_1(\sum_{i \in N} q_{1i}) + \pi_2(Q - \sum_{i \in N} q_{1i}) - \lambda_i(q_{1i} - e_{1i} - q_{(i-1)i}) - \beta_i(e_{1i} + q_{(i-1)i} - \bar{s}_i - q_{1i})$$  \hspace{1cm} (3.2)

In the case of no binding constraints, the monopoly will equalize marginal profits over the two period game:

$$\pi_1'(Q_1) = \pi_2'(Q_2)$$  \hspace{1cm} (3.3)

Using the linear demand function, the equalization of marginal revenues can be expressed as follows:

$$a_1 - 2bQ_1 = a_2 - 2bQ_2$$  \hspace{1cm} (3.4)

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15 The case of a public, welfare maximizing monopoly will be identical to the utility maximizing allocation on the count that the welfare function is derived from consumer preferences.
This condition is illustrated in figure 3. The unconstrained production allocation is determined by the intersection of the marginal revenue functions.

![Figure 3: Utility maximizing and monopoly production allocation. The optimal production plan of the monopoly firm is determined by an equalization of marginal revenues. In the case pictured above, the monopoly over-produces in the off-peak period and under-produces in the peak period, resulting in a welfare loss represented by the shaded area.](image)

Just like in the case of utility maximizing allocation, equation 3.4 can be rewritten in terms of first year production as:

\[ a_1 - 2bQ_1 = a_2 - 2b(\bar{Q} - Q_1) \]  

which allows me to solve for the optimal quantity produced by the monopoly owned generators in the first period:

\[ Q_1^M = \frac{a_1 - a_2 + 2b\bar{Q}}{4b} \]  

(3.6)
This shows that, just like with the utility maximizing production plan, the monopoly divides total production in half given that there are no dynamics in demand. The intuition lies with the fact that independent of market type, the net-storage after period 2 has to be 0. If the demand structure would be the same in the two periods, there would be no reason for the monopolist to produce less in one period and more in the second period, thus mirroring the utility maximizing allocation. The case with no dynamics of demand is illustrated in figure 4.

![Diagram](image)

**Figure 4:** With no dynamics of demand, the monopoly production allocation mimics the utility maximizing allocation. No incentives for any deviating production strategy exists, and prices are equalized over the two periods, yielding no welfare loss.

### 2.2.3 Stackelberg Outcome

So far I have examined the production plan derived from a utility maximizing perspective, and a monopoly profit maximizing perspective. Consider now that competition is introduced to the market, meaning that each of the two generators are owned by separate, independent firms that act competitively. In the case of collusive behavior on the competitive market, the outcome
should mirror the monopoly production outcome derived in section 2.2.2. The upstream producer \((i=1)\) will as earlier stated only be affected by the exogenous inflow \(e_{1t}\), while the downstream producer \((i=2)\) will also be affected by the outflow from the upstream producer. This creates the Stackelberg game framework.

The Stackelberg game is solved by using backward induction (following any textbook on microeconomics, such as Varian (1992)). First step will therefore be to derive the so called response function of the downstream firm. Since it is a sequential game, the downstream producer will act on the residual demand after the upstream producer has produced its optimal quantity. Therefore, the downstream plant basically operates as a monopoly on the residual demand and solves the following maximization problem:

\[
\max_{q_{2t}} \pi_2 = P_1(q_{11} + q_{21}) + P_2(q_{12} + q_{22})(q_{22})
\]  

(4.1)

Since all water is used in production in the two periods, I can rewrite the production choice of \(q_{22}\) as \((\hat{q}_2 - q_{21})\). This allows me to restate equation 4.1 in terms of the demand function:

\[
\max_{q_{2t}} \pi_2 = \left(a_1 - b(q_{11} + q_{21})\right)q_{21} + \left(a_2 - b(q_{12} + (\hat{q}_2 - q_{21}))\right)(\hat{q}_2 - q_{21})
\]  

(4.2)

The producers face the same storage constraint and capacity constraint as presented in equations 2.3 & 2.4. The corresponding Lagrange-function becomes:

\[
L = \left(a_1 - b(q_{11} + q_{21})\right)q_{21} + \left(a_2 - b(q_{12} + (\hat{q}_2 - q_{21}))\right)(\hat{q}_2 - q_{21}) - \lambda_2(q_{21} - e_{21} - q_{11}) - \hat{\lambda}_2(e_{21} + q_{11} - s_2 - q_{21})
\]  

(4.3)

Maximizing with respect to \(q_{21}\) yields the following first order conditions:

\[
a_1 - a_2 + b(q_{12} + 2\hat{q}_2 - 4q_{21} - q_{11}) - \lambda + \hat{\lambda} = 0
\]  

(4.4)

\[
\hat{\lambda}(q_{21} - e_{21} - q_{11}) = 0
\]  

(4.5)

\[
\lambda(e_{21} - s_2 + q_{11} - q_{21}) = 0
\]  

(4.6)

For the unconstrained response function, I assume that none of the constraints are binding \(\hat{\lambda} = \hat{\lambda} = 0\), then solve for \(q_{21}\):

\[
q_{21} = \frac{a_1 - a_2 + b(2\hat{q}_2 + q_{12} - q_{11})}{4b}
\]  

(4.7)

With the response function of the downstream producer derived, the next step is to solve the profit maximization of the upstream producer.
max \pi_1 = P_1(q_{11} + q_{21}(q_{11}))q_{11} + P_2((\hat{q}_1 - q_{11}) + (\hat{q}_2 - q_{21}(q_{11}))) (\hat{q}_1 - q_{11}) \hspace{1cm} (4.8)

The corresponding Lagrange-function becomes as follows:

\[ L = \left( a_1 - b\left(q_{11} + \frac{a_1 - a_2 + b((\hat{q}_1 - q_{11}) + 2\hat{q}_2 - q_{11})}{4b}\right)\right) q_{11} + \left( a_2 - b\left(\hat{q}_1 - q_{11}\right) + \left(\hat{q}_2 - \frac{a_1 - a_2 + b((\hat{q}_1 - q_{11}) + 2\hat{q}_2 - q_{11})}{4b}\right)\right) (\hat{q}_1 - q_{11}) \]

\[-\lambda_1(q_{11} - e_{11}) - \lambda_2(e_{11} - \hat{s}_1 - q_{11}) \hspace{1cm} (4.9)\]

See the appendix for how I arrived at equation 4.9. Given this maximization problem, the unconstrained optimal quantity produced by the upstream producer in the first period becomes:

\[ q_{11}^* = \frac{a_1 - a_2 + 2b\hat{q}_1}{4b} \hspace{1cm} (4.10)\]

With the upstream producer's production plan derived, the follower’s best response production plan will yield (the simplification steps can be found in the appendix):

\[ q_{21}^* = \frac{a_1 - a_2 + 4b\hat{q}_2}{8b} \hspace{1cm} (4.11)\]

The total produced quantity in the first period given the Stackelberg market setup will then become:

\[ Q_1^* = q_{11}^* + q_{21}^* = \frac{3(a_1 - a_2 + 4b(\hat{q}_1 + \hat{q}_2))}{8b} \hspace{1cm} (4.12)\]

Facing no dynamics of demand, the Stackelberg outcome will mirror the monopoly and the utility maximizing production allocation by simply producing half of the total production in period 1. The same intuition applies here: considering that the firms has to use all of the water inflow for production, there would be no benefits from over- or under-producing if demand wasn’t dynamic.
3. Comparison of Utility maximizing, Monopoly & Stackelberg outcomes

The optimal production plans derived in section 2 turned out as the following expressions:

\[ Q_1^* = \frac{a_1-a_2+b\bar{Q}}{2b} \]  
(Utility max.)  
(5.1)

\[ Q_1^M = \frac{a_1-a_2+2b\bar{Q}}{4b} \]  
(Monopoly)  
(5.2)

\[ Q_1^S = \frac{3(a_1-a_2)+4b\bar{Q}}{8b} \]  
(Stackelberg)  
(5.3)

As earlier stated, I can rank the outcomes with regards to welfare by measuring the distance of the market production plan with the utility maximizing production plan.

Monopoly:

\[ |Q_1^M - Q_1^*| = \left| \frac{a_1-a_2+2b\bar{Q}}{4b} - \frac{a_1-a_2+b\bar{Q}}{2b} \right| = \left| \frac{a_2-a_1}{4b} \right| \]  
(5.4)

Stackelberg:

\[ |Q_1^S - Q_1^*| = \left| \frac{3(a_1-a_2)+4b\bar{Q}}{8b} - \frac{a_1-a_2+b\bar{Q}}{2b} \right| = \left| \frac{a_2-a_1}{8b} \right| \]  
(5.5)

The result doesn’t yield any real surprise: If demand would be static, both market outcomes would simply mirror the utility maximizing outcome. In order to compare the outcomes when introducing dynamics, I allow for \( a_2 \) to increase.

**Proposition 1:** When increasing the dynamics of demand, the Stackelberg production allocation will yield less welfare losses than the monopoly production allocation, given no binding constraints.

\[ \frac{\partial |Q_1^M - Q_1^*|}{\partial a_2} = \frac{1}{4b} = \frac{2}{8b} \]  
(5.6)

\[ \frac{\partial |Q_1^S - Q_1^*|}{\partial a_2} = \frac{1}{8b} \]  
(5.7)

The greater the difference between any arbitrary unconstrained production plan and the utility maximized production plan, the greater will the welfare loss be. When increasing \( a_2 \) by one unit, the unconstrained production plan of a monopoly market will therefore be unambiguously worse than the Stackelberg production plan. When introducing dynamics of demand, the Stackelberg competitive market will be preferred to a monopoly market. Intuitively the result
shows that since all producers use all water for production, the market power lies with the possibility to under-produce during peak demand periods, and over-produce during off-peak demand periods. The strategic variable isn’t total quantity, but rather the allocation of production. Both the Stackelberg and the private monopoly market leads to welfare losses when introducing dynamics of demand, in line with Arellano (2004). The Stackelberg market will however yield a more preferable allocation than the private monopoly. This due to the fact that in an unconstrained Stackelberg market, the follower’s possibility to produce for the residual demand will decrease market power and welfare loss. The profit maximizing unconstrained production plans of a monopoly market and a Stackelberg market compared to the utility maximizing production allocation is illustrated in figure 5.

Figure 5: Comparison of unconstrained production plans under dynamic demand. Since the Stackelberg market allows for the downstream firm to produce on residual demand, the benefits of competition will yield less welfare loss compared to the monopoly outcome. Both market types do however over-produce during the off-peak period, and under-produce during the peak period.
3.1 Introducing an adequate residual outflow requirement

In this section I will introduce a water outflow requirement designed to proxy the effect of the water management directive on water coordination. For the producer, an outflow requirement can either be an upper bound restriction (the producer wants to produce more in a period than the regulation allows), or a lower bound restriction (the producer wants to produce less in a period than the regulation allows). Given the assumption that all inflow has to be used for production over the course of the game, only one of the restrictions has to be examined, and in this study I’ve chosen a minimum outflow requirement, individually assigned each plant (an upper bound restriction in the first period would basically yield a lower bound restriction in the second period and vice versa). This allows for an adequate outflow criteria based on the river section downstream the producers and therefore the water flow can be fitted the biological conditions more efficiently.

Proposition 2: Depending on the relationship between reservoir size and the size of the outflow requirement, a monopoly market might actually be preferred to a competitive market because of coordination efficiency.

A producer faced by a minimum outflow requirement will have its storage capacity restricted by the size of the regulation. The minimum outflow requirement will be denoted $s_j$, and the result of its implementation will be a configuration on the reservoir capacity. For the upstream producer, the new storage constraint yields:

$$q_{11} = e_{11} - s_1 - s_1$$

(6.1)

And for the downstream producer the storage constraint now yields:

$$q_{21} = e_{21} + q_{11} - s_2 - s_2$$

(6.2)

Provided this alteration of the storage constraints, I will explore a theoretical illustration in order to examine the welfare effects of an outflow requirement. The theoretical illustration will center around the following parameter configurations: $a_2 > a_1$ & $e_{12} = e_{22} = 0$. This setup would for example be applicable on, but not limited to, the Nordic hydropower market where most of the inflow happens in late spring, during off-peak demand, while inflow is low during the winter months when energy demand instead is peaking. Implementing a minimum release requirement for the first period\(^{16}\), the producer will only be bound by the storage constraint it

---

\(^{16}\) Since the second period is peak demand, one might consider the producer’s unwillingness to release the water required for biological purposes without any outflow requirement.
creates if it can’t save as much water as it would like to for future production during the peak demand period. I will explore two scenarios:

1) When the upstream producer is bound by the minimum release requirement, but the downstream producer is not.

2) When the downstream producer is bound by the minimum release requirement, but the upstream producer is not.

If both producers were faced with a homogeneous outflow regulation, it would basically translate to a deterministic central planner outcome, independent of energy dynamics of demand. The yielding welfare effects would directly depend on which quantity the central planner forces the generators to produce during the two respective periods.

3.1.1 Upstream outflow regulation

The storage constraint will be binding given that \( q_{11} > e_{11} - \bar{s}_1 \), which in terms of the optimal production choice of the upstream producer in a Stackelberg market will yield:

\[
\frac{a_1 - a_2 + 2b\bar{q}_1}{4b} > e_{11} - \bar{s}_1 - \bar{s}_1 \quad (6.3)
\]

\[
e_{11} - \frac{e_{11}}{2} + \frac{(a_1 - a_2)}{4b} > \bar{s}_1 - \bar{s}_1 \quad (6.4)
\]

\[
\frac{e_{11}}{2} + \frac{a_1 - a_2}{4b} > \bar{s}_1 - \bar{s}_1 \quad (6.5)
\]

meaning that the larger the quantity of water outflow forced by the regulation, the larger are the chances that the producer will be bound by the storage constraint as it is more probable that the producer has to produce more in the first period than it would prefer.

As a reference, consider the most extreme case when the regulation forces the upstream producer to use all of the water inflow in period 1 for immediate production. As illustrated in figure 6, this will yield a production allocation that decrease welfare compared to the coordination of the private monopoly owned generators. The intuition lies with the fact that a monopoly is not interested in which generator that produces what quantity; it simply maximizes total output independent of the distribution of production over the generators. If the upstream producer is constrained, the monopoly will shift the water supply to the downstream producer and store it there instead. Under competition, that incentive to adjust production by the downstream generator does not exist due to conflicting objectives. The downstream producer
instead sees the opportunity to act as a monopoly firm on the residual demand in period 1, and then all of the demand in period 2. This can be regarded as the coordination cost of competition.

![Diagram showing competitive ineffectiveness due to coordination issues.]

Figure 6: Competitive ineffectiveness due to coordination issues. In the case pictured above, \( \bar{s}_1 = s_1 \), meaning that the upstream producer can’t store any water for production in the second period. The downstream firm acts as a monopoly on the residual demand in the first period and on all production in the second period, equalizing its marginal revenues. A monopoly firm instead stores more water in the downstream reservoir and internalizes the coordination, yielding less welfare loss than the Stackelberg market.

As long as \( \bar{s}_1 - \frac{s_{11}}{2} < s_1 \), holds, a private monopoly market will be preferred to a competitive market. This means that a market situation where the upstream producer has no storage capacity, mimicking a run-of-river plant, and the downstream producer is not constrained by storage, a monopolized market yields less welfare loss compared to the competitive market.
If instead \( \bar{s}_1 - \frac{\bar{e}_{11}}{2} > s_{31} \), the benefits of competition outweighs the lack of coordination efficiency, and will result in less of a welfare loss than the monopoly outcome. If equality would hold, the Stackelberg outcome would simply mirror the monopoly outcome. The example when equality holds is illustrated in figure 7.

Figure 7: Upstream producer’s internalization of coordination cost. If the upstream producer is able to store half of the inflow for production in period 2, the equalization of marginal revenues of the downstream firm on residual demand will emulate the monopoly outcome.

The size of the reservoirs and the size of the outflow requirement therefore directly determines whether it would be preferable with a private monopolized market or a competing Stackelberg market. The conflict here becomes between the welfare loss of monopoly market power and the welfare loss of coordination issues, and as proven above the size of the reservoir and the
adequate outflow regulation determines the more preferable market type from a welfare maximizing perspective.

### 3.1.2 Downstream outflow regulation

Now consider a river system where the downstream producer is located upstream an area of the river that demands a high outflow during the summer months in order to uphold the biological diversity, in consonance with the WFD. In order to illustrate the limit case, let’s assume that the minimum outflow requirement, $s_2$, is equal to the reservoir capacity of the downstream producer, $\bar{s}_2$. The consequence becomes that only the upstream determines how output should be allocated over the two periods, as it is able to fully manipulate the production possibility of the downstream producer. Given the assumption that there are no differences in productivity between the generators, every unit of energy produced by the upstream producer will increase production of the downstream producer by one unit. The downstream producer also has to produce all of its natural inflow, $e_{21}$, in period 1 as the result of no storage possibility. I can therefore formulate the production possibilities of the downstream producer as follows:

\[
q_{21} = q_{11} + e_{21} \quad (6.6)
\]
\[
q_{22} = (\hat{q}_1 - q_{11}) \quad (6.7)
\]

The upstream producer will take these production levels into account when choosing its optimal production plan (assuming the upstream producer is unconstrained and facing linear demand).

\[
\max \pi_1 = \left( a_1 - b(q_{11} + (q_{11} + e_{21})) \right) q_{11} + \left( a_2 - b((\hat{q}_1 - q_{11}) + (\hat{q}_1 - q_{11})) \right) (\hat{q}_1 - q_{11}) \quad (6.8)
\]

yielding the following first order condition:

\[
a_1 - a_2 + b(4\hat{q}_1 - 8q_{11} - e_{21}) = 0 \quad (6.9)
\]

which translates to the following production plan:

\[
q_{11} = \frac{a_1 - a_2 + b(4\hat{q}_1 - e_{21})}{8b} \quad (6.10)
\]

Total production in period 1 then becomes:

\[
Q_1 = q_{11} + q_{21} = \frac{a_1 - a_2 + b(4\hat{q}_1 - e_{21})}{8b} + \frac{a_1 - a_2 + b(4\hat{q}_1 - e_{21})}{8b} + e_{21} \quad (6.11)
\]
\[
Q_1 = \frac{a_1 - a_2 + b(4\hat{q}_1 + 3e_{21})}{4b} \quad (6.12)
\]
Finally, I compare the total production in period 1 under this market configuration with the utility maximizing production plan. See the appendix for details.

\[
\frac{a_1-a_2+b(4\tilde{q}_1+3e_{21})}{4b} - a_1-a_2+b(2\tilde{q}_1-e_{21}) = \frac{a_2-a_1+b\tilde{e}_{21}}{4b} - \frac{a_2-a_1+e_{21}}{4b} = \frac{a_2-a_1+\frac{e_{21}}{4}}{4b} \tag{6.13}
\]

In order to rank this outcome relative to the monopoly outcome in equation 5.4, which yields a difference of \(\frac{a_2-a_1}{4b}\), and therefore would result in a smaller welfare loss than the Stackelberg allocation. The intuition follows the same reasoning as with an upstream outflow regulation: Since the monopoly gains profit from both generators and therefore only cares about total production, it can internalize the forced production of the downstream generator by simply storing more water in the upstream reservoir (given that the storage capacity is not restricted). The upstream producer only enjoys the profit of the upstream generator production and therefore lacks the incentive to store more water to compensate for the forced production of the downstream producer. A monopoly would therefore be preferred as long as the reservoir capacity can’t store \(\frac{e_{21}}{4}\) or more of the inflow. The condition for competition to yield a smaller welfare loss than a monopoly allocation in terms of reservoir size and minimum outflow requirement therefore becomes:

\[
\bar{s}_2 - \frac{e_{21}}{4} > s_2 \tag{6.14}
\]

If the opposite inequality holds, the coordination efficiency of a monopoly will outweigh the welfare loss of market power when compared to the competitive outcome. If equality where to hold, both market types would yield the same allocation and therefore the same welfare outcome. One should of course take caution when interpreting the seemingly stringent efficiency conditions presented, as they do rely on the assumption of scarcity. The conditions for competitive ineffectiveness are in a way the conditions under which the monopolization on residual demand yields less beneficial outcomes when compared to monopolization on overall demand. One should expect them to be less stringent if slackening the condition of scarcity depending on which specific hydropower market one is examining. The results do provide us with the valuable insight that what really determines which market type is preferred under outflow regulation, is the storage ability of the producers in relation to the size of the outflow regulation.
4. Conclusions & Discussion

4.1 Summary of Results

This study was set out to investigate how quantitative outflow regulations in the essence of the European Union’s water framework directive could affect water coordination, production allocation and consumer welfare depending on market type. The main conclusive results are summarized in table 1. Unconstrained, and without dynamics of demand, the allocation of production would be the same independent of market types. This conclusion holds as long as we assume that all water inflow must be used for production, which might be considered a brave assumption when studying the Nordic market for example, but generally holds for most hydropower markets due to water scarcity.

Introducing dynamics of demand however, the monopoly will under-produce during the peak period, yielding a welfare decreasing outcome. The Stackelberg market also under-produces during the peak period but its competitive nature decreases the possibility for market power and thereby yields a smaller welfare loss. Without binding production constraints, competition will therefore be superior to the monopoly alternative from utility maximizing perspective.

Due to the lacking coordination efficiency amongst independent competitive producers, an outflow regulation might offset the benefits of competition. Even though a monopoly firm’s production objective differs from the utility maximization objective, the coordination efficiency can under certain conditions on reservoir size in relation to the outflow regulation yield smaller welfare losses than the competitive outcome. The intuition, as earlier stated, lies with the fact that the monopoly enjoys the profit of both generators and therefore has the incentive to coordinate water flow and fit reservoir storage of one generator when the other generator’s reservoir is regulated, while two competing firms sees the opportunity to act as monopoly producers on the residual demand rather than to internalize the storage limitations of the competitor.
Table 1: Summary of results derived in section 2 & 3.

<table>
<thead>
<tr>
<th></th>
<th>Utility max.</th>
<th>Monopoly</th>
<th>Stackelberg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconstrained optimal production plan</td>
<td>$Q_i^* = \frac{a_1 - a_2 + b\bar{Q}}{2b}$</td>
<td>$Q_i^M = \frac{a_1 - a_2 + 2b\bar{Q}}{4b}$</td>
<td>$Q_i^S = \frac{3(a_1 - a_2) + 4b\bar{Q}}{8b}$</td>
</tr>
<tr>
<td>Optimal production increase in period $i$ when increasing the dynamics of demand.</td>
<td>$\frac{\partial Q_i^*}{\partial a_1} = \frac{1}{2b}$</td>
<td>$\frac{\partial Q_i^M}{\partial a_1} = \frac{1}{4b}$</td>
<td>$\frac{\partial Q_i^S}{\partial a_1} = \frac{3}{8b}$</td>
</tr>
<tr>
<td>Condition for relative efficiency under upstream minimum outflow regulation</td>
<td>$\bar{s}<em>1 - \frac{e</em>{11}}{{2}} &lt; \bar{s}_1$</td>
<td>$\bar{s}<em>1 - \frac{e</em>{11}}{{2}} &gt; \bar{s}_1$</td>
<td></td>
</tr>
<tr>
<td>Condition for relative efficiency under downstream minimum outflow regulation</td>
<td>$\bar{s}<em>2 - \frac{e</em>{22}}{{4}} &lt; \bar{s}_2$</td>
<td>$\bar{s}<em>2 - \frac{e</em>{22}}{{4}} &gt; \bar{s}_2$</td>
<td></td>
</tr>
</tbody>
</table>

Introducing an adequate residual outflow requirement might therefore result in coordination costs high enough to make competition more ineffective with regards to utility maximizing allocation than a private monopoly. With the two potential sources of welfare loss, market power and coordination issues, outlined in earlier literature, this result shows that the same reasoning applies for producers along one river, and also determines whether it would be more preferable with a monopoly or competitive market.

4.2 Policy Implications

As previously stated, the results derived in this thesis should be of primary interest to policymakers in hydropower dense economies. If hydropower does make up for a considerable amount of the total energy produced in the economy, the possibility to exercise market power as a hydropower producer of course increases.

A policy maker has to take into account the public good-esque feature of water as an input good for hydropower production. No price mechanism determines how much of the water used for production by the upstream firm that becomes available for downstream production. Efficient water coordination amongst cascade hydropower producers is therefore hard to accomplish through marketization and decentralization of outflow decision making. The results of this thesis goes well in consonance with earlier research in this aspect. Allowing for collusive behavior or constituting some sort of centralized water management plan should be encouraged.
if the negative welfare effect of lacking coordination is greater than the benefits of decreased market power. A policy maker should study the conditions that determines which market type should yield a more desired outcome. Do all producers along the river have the ability to store water or are some of them run-of-river plants? What are the chances that a producer has enough storage to monopolize on the residual demand in such a way that the production allocation performs worse than a monopoly production plan? The focus should in other words not be on scouting for anti-competitive behavior as long as the improvement of coordination outweighs the potential welfare loss of market power.

As with the case of the Swedish competition authority and its concern regarding the collusive behavior of cascading hydropower plants through water management companies, it might therefore be unjustified. The cause for concern regarding the possibility of hydropower producers to exchange valuable information regarding their production volumes is only a guaranteed negative aspect when all producers has unconstrained storage.

For a policy maker facing the opportunity to introduce competition to a hydropower market, caution is needed. One could increase the chances of the market working effectively by subsidizing reservoir construction in order to guarantee that coordination ineffectiveness does not arise. On the other hand, an economy focusing on keeping the historically adequate water level fluctuations of the rivers, should instead consider run-of-river hydropower plants which eliminates the aspect of intertemporal allocation as the inflow directly determines the amount of energy produced during the same period. For a competing hydropower market where coordination failure arises due to the lack of storage possibilities of some producers, market reforms might be need. Allowing for collusive behavior or alternatively implementing some sort of centralized, deterministic outflow plan could be worth considering.

4.3 Further Research

The theoretical model used in this study paves the way for several alterations and modifications. A natural extension of the model would for example be to not limit market power to intertemporal allocation strategies, but also allow for limiting total production. This would however make the model more complicated as the assumption of scarcity allows for production in the second period to be expressed as the residual of the production in the first period. One should expect that the situations when a monopoly market would be preferred to a competing market would be fewer when slacking this assumption, and the conditions for efficiency less
stringent. A study focusing on the differences in the incentives to exercise market power during wet years and dry years would be a way to examine the possibility of limiting overall production. As a drought should act as a production capacity constraint, and a wet year should act as a storage constraint, it fits the analogy in relation to the model presented in this thesis.

Further research of interest would also be to empirically examine how water management companies manage the intertemporal production allocation from a market power perspective. Its purpose on the market is to centralize water management in order to coordinate water flows, but does this also allow for distortion of the price taking conditions of competing firms?

Expanding the number of producers in the model would be an alteration of interest, as is presumably should decrease market power, but also decentralize coordination decisions even further when allowing for competition. Policy makers should also be interested regarding if and how an adequate outflow regulation could affect incentives to entry the market. Large reservoirs are associated with very high investment costs, and their value as a strategic asset becomes prominent when producers face outflow requirements. A producer under regulation should therefore possibly be able to use storage possibility as a tool to maneuver out smaller producers from the market and inhibit incentives for entering the market as a small producer.

It would be interesting to see the outcomes and conclusions regarding efficiency when allowing for different assumptions regarding cost. In this study I define wage costs rather as a function of invested capital than as a function of output. Introducing variable costs should, as briefly mentioned earlier, force some model assumptions to change. For example, expanding the model to allow for pumping would translate to a variable cost related to the energy that it takes to transport water from a downstream reservoir to be used again for production. Another example would be the case with differences in generator depreciation. Maintenance costs should vary amongst hydropower generators with different technology. An older generator should depreciate at a faster pace in relation to output than a newer one, thus resulting in higher wage costs. One might expect it to be unrealistic that a firm would produce with all of its water inflow if the marginal cost were to be positive. Future research might want to explore the consequences of accounting for the existing, albeit very low, variable costs associated with hydropower production. There are seemingly many aspects that needs to be investigated before drawing extensive conclusions on how outflow regulations will affect market efficiency, not limited to production interactions of existing firms, but also how it affects market structure in the longer run.
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Appendix

A: Expressing the Lagrange function in equation 4.9

The following maximization problem is to be solved (subject to the storage constraint and the capacity constraint):

(A1) \[ \max \pi_1 = P_1(q_{11} + q_{21}(q_{11}))q_{11} + P_2 \left( \hat{q}_1 - q_{11} \right) \left( \hat{q}_2 - q_{21}(q_{11}) \right) (\hat{q}_1 - q_{11}) \]

I substitute the response function of the downstream producer:

(A2) \[ q_{21} = \frac{a_1-a_2+b(q_{12}+2\hat{q}_2-q_{11})}{4b} \]

Into the profit maximization problem formulated in equation 1. This yields:

(A3) \[ \max \pi_1 = \left( a_1 - b \left( q_{11} + \frac{a_1-a_2+b(q_{12}+2\hat{q}_2-q_{11})}{4b} \right) \right) q_{11} + \left( a_2 - b \left( \hat{q}_1 - q_{11} \right) + \left( \hat{q}_2 - \frac{a_1-a_2+b(q_{12}+2\hat{q}_2-q_{11})}{4b} \right) \right) (\hat{q}_1 - q_{11}) \]

Before deriving I make use of the identity that \( q_{12} = \hat{q}_1 - q_{11} \) and substitute it into the above maximization problem.

(A4) \[ \max \pi_1 = \left( a_1 - b \left( q_{11} + \frac{a_1-a_2+b(q_{11}-q_{11})+2\hat{q}_2-q_{11})}{4b} \right) \right) q_{11} + \left( a_2 - b \left( \hat{q}_1 - q_{11} \right) + \left( \hat{q}_2 - \frac{a_1-a_2+b((q_{11}-q_{11})+2\hat{q}_2-q_{11})}{4b} \right) \right) (\hat{q}_1 - q_{11}) \]

Subject to the upstream capacity and storage constraints:

(A5) \[ q_{11} \leq e_{11} \]

(A6) \[ q_{11} \geq e_{11} - \hat{s}_1 \]

This maximization problem will then respond to the Lagrange-function expressed in equation 4.9.
B: The downstream producer’s optimal response production plan in equation 4.10

The upstream producer’s optimal unconstrained production plan:

(B1) \[ q_{11}^s = \frac{a_1-a_2+2b\hat{q}_1}{4b} \]

Substituting this into the optimal response function of the follower yields:

(B2) \[ q_{21}^s = \frac{a_1-a_2+b(\hat{q}_{12}+2\hat{q}_2-a_1-a_2+2b\hat{q}_1)}{4b} \]

Once again using the identity that \( q_{12} = \hat{q}_1 - q_{11} \), the equation can be rewritten as:

(B3) \[ q_{21}^s = \frac{a_1-a_2+b\left((\hat{q}_1-a_1-a_2+2b\hat{q}_1)+2\hat{q}_2-a_1-a_2+2b\hat{q}_1\right)}{4b} \]

This expression simplifies nicely to:

(B4) \[ q_{21}^s = \frac{a_1-a_2+4b\hat{q}_2}{8b} \]

C: Measuring the distance between the production plan in equation 6.12 and the utility maximizing production plan

The optimal production plan in 6.12:

(C1) \[ Q_1 = \frac{a_1-a_2+b(4\hat{q}_1+3e_{21})}{4b} \]

I measure the distance between this production plan and the utility maximizing production plan.

(C2) \[ \left| \frac{a_1-a_2+b(4\hat{q}_1+3e_{21})}{4b} - \frac{a_1-a_2+b\bar{Q}}{2b} \right| \]

I can rewrite this given that the maximum production, \( \bar{Q} \), is identified as:

(C3) \[ \bar{Q} = q_{11} + q_{12} + q_{21} + q_{22} = q_{11} + (\hat{q}_1 - q_{11}) + (q_{11} + e_{21}) + (\hat{q}_1 - q_{11}) = 2\hat{q}_1 + e_{21} \]

And substituting this into C2 yields:

(C4) \[ \left| \frac{a_1-a_2+b(4\hat{q}_1+3e_{21})}{4b} - \frac{a_1-a_2+b(2\hat{q}_1+e_{21})}{2b} \right| = \left| \frac{a_2-a_1+be_{21}}{4b} \right| = \left| \frac{a_2-a_1}{4b} + \frac{e_{21}}{4} \right| \]