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Jan Henning L'Abée-Lund & Jaime Otero Villar

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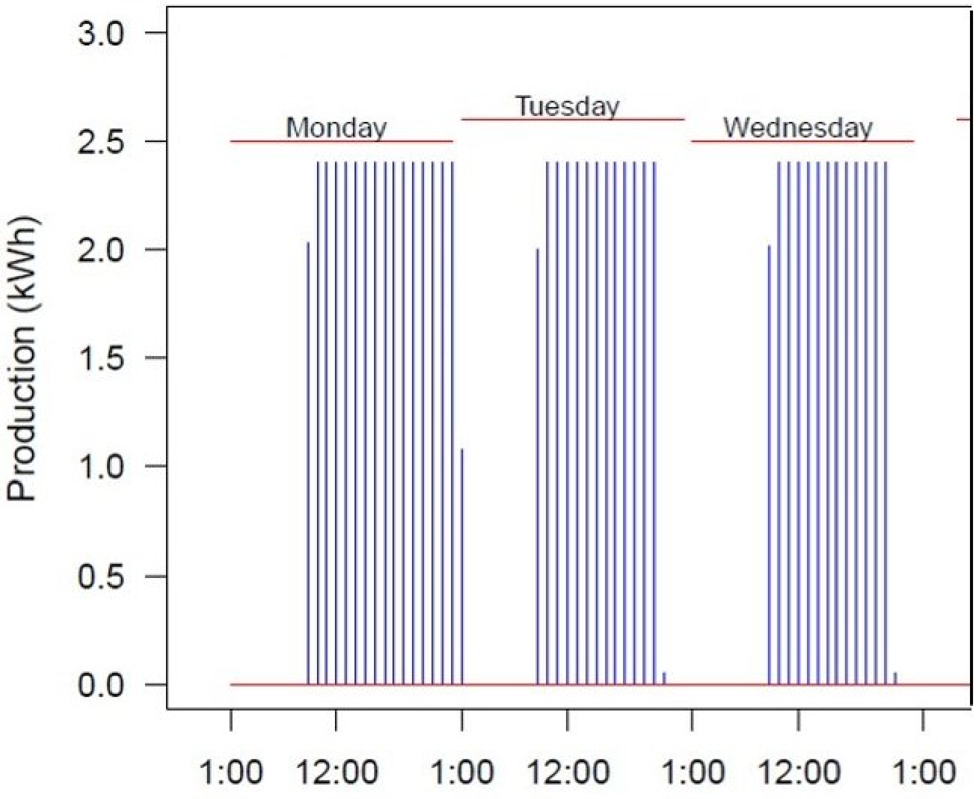

REPORT

Start-stop practice in small Norwegian hydropower plants

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Summary: Start-stop practice was analysed in 256 Norwegian hydropower plants in conjunction to a set of characteristics. The plants were on grid 2005-20014, and production data from 2015. Number of starts were counted for each plant finding a higher number in Kaplan turbines than in Francis and Pelton. Number of starts was not dependent on having a license to practice start-stop, and were related to the annual mean river discharge being negative for Francis, dome-shaped for Pelton, and no association for Kaplan.

Keywords: Start-stop practice, small hydropower, water discharge, precipitation, turbine type

Norwegian water resources
and energy directorate (NVE)

Middelthunsgate 29
Postboks 5091 Majorstua
0301 OSLO

Telephone: 22 95 95 95
Web: www.nve.no
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Preface

In the licensing procedure for hydropower development in Norway, costs and benefits connected to the project is evaluated. When a project gets a license this also contains a set of conditions. The conditions ensure specific environmental aspects that have been addressed in the licensing procedure. One such condition can be that the hydropower should be run smoothly and according to the discharge. Typical start-stop procedure to increase financial benefit is not allowed. Start-stop practice is negatively affecting the aquatic environment downstream the hydropower plant.

NVE is responsible to follow up the conditions set in the license for hydropower plants. Usually, supervision is targeting hydropower plants individually. With more than 1000 licenses, it is practically impossible to look after all this over a restricted time period. Thus, this project was initiated to get an overview of the production practice of small hydropower plants in Norway. The results can be used in targeting future supervision of small hydro power.

I konsesjonsbehandlingen av vannkraft blir fordeler og ulemper veid mot hverandre. Når fordelen er vurdert å overstige ulempene, blir det gitt tillatelse til tiltaket. Denne konsesjonen kan inneholde vilkår som gjenspeiler miljøforhold som ble belyst i konsesjonsprosessen. Et slikt vilkår kan være at kraftverket til enhver tid skal kjøres etter tilsiget, at alle endringer skal skje gradvis og at typisk start-stopp kjøring skal ikke forekomme. Typisk start-stopp kjøring vil kunne påvirke akvatiske organismer nedstrøms kraftverket negativt.

NVE følger opp at konsesjonsvilkår blir etterlevd. Vanligvis vil et slikt tilsyn være rettet mot konkrete anlegg. Med mer enn 1000 konsesjoner er det umulig å følge opp alle konsesjonsvilkår til alle anlegg innen en rimelig tidshorisont. Derfor ble dette prosjektet gjennomført for å få en oversikt over hvordan dette konkrete konsesjonsvilkåret blir etterlevd. Resultatene vil bli brukt i fremtidig tilsynsvirksomhet av små vannkraftverk.

Oslo, February 2017

Ingunn Åsgard Bendiksen

Ingunn Åsgard Bendiksen
Director
Supervision and Contingency
Department

Øyvind Leirset

Øyvind Leirset
Head of Section
Section for Environmental Supervision

Summary

Start-stop practice was analysed in a total of 256 Norwegian hydropower plants in conjunction to a set of characteristics that define each plant such as production, turbine type, river discharge, precipitation, and geographic location. We selected hydropower plants on grid in 2005 or later, and chose 2015 as a stochastic and representative year for hourly production pattern. Among the analysed plants, a vast majority, 75.8%, did not have a license to practice start-stop dynamics.

Most of the plants had Pelton turbines installed (70.3%), followed by Francis (27%) and Kaplan (2.7%), and production typically showed daily, weekly and annual cycles though shapes varied depending on turbine type and location. Further, daily production showed a positive relationship with precipitation regardless of the installed turbine type.

The number of starts were counted for each plant finding a larger number in Kaplan turbines as compared to Francis and Pelton. The number of starts was not dependent on having a license to practice start-stop. However, average duration and production of starts were higher for plants allowed to practice start-stop. In general, the number of starts varied widely among plants and were related to the annual mean river discharge. However, this relationship differed among turbine types, being negative for Francis and dome-shaped for Pelton, while in the case of Kaplan turbines the number of starts did not show any association with mean discharge. We know that 2015 hydrologically was special. The melting of snow during spring was extremely late, and high precipitation represented an increase in production of 31.5 TWh. This may indicate that number of starts would have been higher in a drier year. Financial proceeds is probably the most important factor explaining the start-stop practice.

Sammendrag

Start-stopp praktisering ble analysert for 256 norske konsederte kraftverk. Hvert enkelt kraftverk ble karakterisert ut fra produksjon, turbintype, vannføring i vassdraget, nedbør og geografisk plassering. Vi valgte ut kraftverk som var satt i drift i 2005 til 2014, og valgte 2015 som et stokastisk tilfeldig år til å dokumentere kraftproduksjon med timesverdier. Blant kraftverkene hadde de aller fleste (75,8 %) vilkår i konsesjonen om at start-stopp ikke var tillatt.

De fleste kraftverkene har installert Pelton turbin (70,3 %), deretter fulgte Francis med 27 % og Kaplan med 2,7 %. Forholdet mellom maksimal slukeevne til turbinen og årlig middelvannføring var i gjennomsnitt 1,9 for Pelton, 1,45 for Francis og 1,6 for Kaplan turbiner. Produksjonsmønstrene viste variasjon gjennom døgnet, uken og året selv om omfanget var avhengig av turbintype og geografisk plassering. Videre viste døgnproduksjonen en positiv sammenheng med nedbøren uavhengig av hvilken turbintype som var installert.

Antall starter gjennom året ble talt opp for hvert enkelt kraftverk og var ikke avhengig av konsesjonens ordlyd. Kraftverk som hadde forbud mot start-stopp hadde i gjennomsnitt flere starter enn kraftverk uten restriksjon. Forskjellen var ikke statistisk signifikant. Innen alle tre turbintypene ble det registrert kraftverk som hadde meget høye antall starter i 2015 – Pelton >250 starter, Francis >100, og for Kaplan >175. Av disse tre ekstremverdiene var det kun Francis turbinen som ikke hadde restriksjon i konsesjonen.

Den store forskjellen i antall starter blant kraftverkene var knyttet til middelvannføring ved inntaket. Sammenhengen var imidlertid forskjellig mellom turbintypene. Den var negativ for Francis, ikke-lineær for Pelton mens det for Kaplan ikke var noen sammenheng. For Pelton var det flest starter i elver med middelvannføring på 0,6 m^3/s. For Francis var det flest starter i elvene med den minste middelvannføringen (0,45m^3/s) der disse var installert. 2015 var et hydrologisk vått år. Dette kan indikere at antall starter ville ha vært høyere i et tørt år. Økonomisk fortjeneste er trolig den viktigste årsaken til start-stopp praktiseringen.

1 Introduction

Annual and weekly variation in water discharge in rivers is a normal phenomenon. This variation reflects climatic changes on a broad scale (e.g. Stahl et al. 2010). The shift occurs at a slow rate. Water discharge may also vary over short time periods such as several days. Heavy rainfall or torrential rain results in a significant increase in discharge, whereas the discharge is reduced much slower and over several days. The period of reduction reflects the characteristics of the watershed. Lakes and bog areas retain water making a long period of reduction. On the other hand, when the watershed has large areas of bare bedrock the discharge is reduced faster.

Development of hydropower has significantly changed the normal run off characteristics in rivers leading to multiple effects on the habitats and biota inhabiting the rivers (e.g. Pracheil et al. 2016; Nieminen et al. 2017). When a reservoir is included in the hydropower scheme, annual flows are lacking and the river discharge reflects the amount of flow released as compensation flow. Small hydropower schemes (<10 MW) build as run-of-the-river project affect the river differently. Their storage capacity of water is small or insignificant resulting in a "loss of water" when the discharge is higher than the turbine capacity. Downstream the intake, the dewatered reach will benefit from the "loss of water". Thus, some of the natural discharge variation, but at a lower scale, is maintained in the river. Most of the year, this river reach is characterised by the compensation flow.

In Norway, the distance from the intake to the small hydropower station is often 1000−1500 m. The watershed, directly connected to this dewatered river reach, is restricted in area implying that the contribution to the river discharge is small. Small hydropower schemes are typically situated in rivers with a distinct and high gradient. Before a hydropower scheme can be constructed an application should be evaluated by the authority. In the case when no public interests will be affected by the project, it may be classified as not subject to licensing and can be built without any conditions except release of compensation flow. However, when the project is judged by the authority to negatively affect public interests, a license is needed. This license also contains a set of conditions.

If the outlet from the plant is directly connected to a river reach that is assessable for anadromous fish species, the license includes a requirement prohibiting to practice start-stop production. This procedure is identical with the more common used term of hydropeaking. Hydropeaking can be characterised as a rapid and more frequent change in water discharge and water level than occurring in pristine rivers. The reason for this restriction is that a start-stop practice will automatically result in swift changes in discharge of which the reduction is much faster than under natural conditions. This reduction will affect aquatic organisms. Several studies have been conducted to show the consequences, and is best documented for salmonids (Bakken et al. 2016). Rapid reduction in water level may influence growth (Flodmark et al. 2004, Puffer et al. 2015) and survival of juvenile salmonids (Saltveit et al. 2001) as well as behaviour of river mussel (Bakken et al. 2016). Rapid increase in water discharge, on the other hand, severely affects the invertebrate fauna by a catastrophic drift shortly after the peak (Imbert & Perry 2000).

The aim of the present study was to elucidate how the start-stop restriction in the license was followed up by the owner. We hypothesised that number of starts during a specific year was lower for hydropower plants with restriction than those without such restriction.

2 Material and Methods

2.1 Data set

The study started selecting hydropower plants (HP) set in operation in the period 2005−2014. The reason for this selection was twofold. First, few licenses given before 2005 had any requirement regarding start-stop practice. Second, we used the 2015 as a random year to describe how the owner ran the HP. Then, we focused on small HP (installed effect <10 MW) with few exceptions. These criteria resulted in a data set of 256 HP distributed all along Norway (Fig. 1, Table S1).

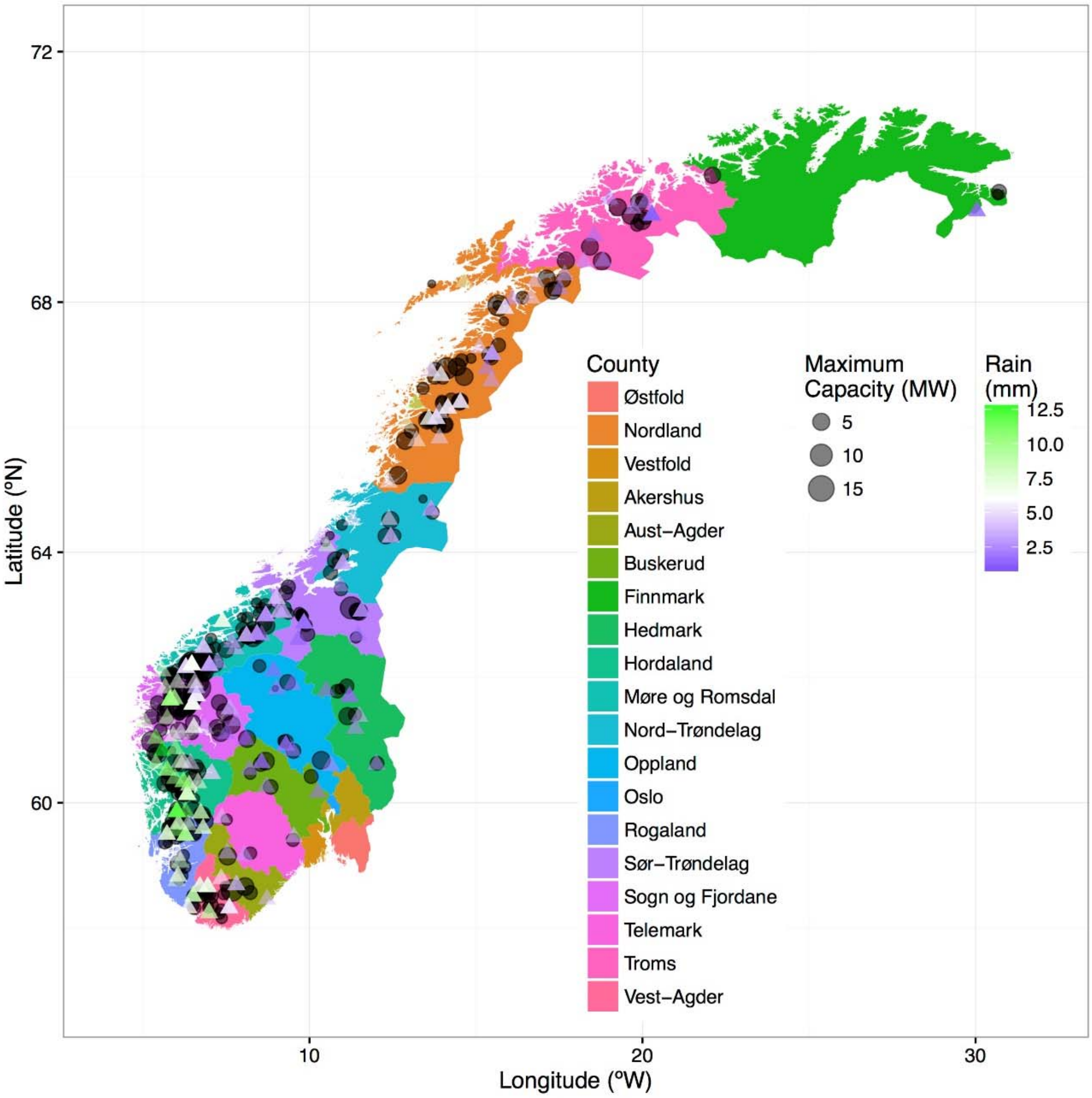

Fig. 1. Geographical distribution of 256 hydropower plants used in the study (the dot size varies according to the installed maximum capacity). Triangles indicate the position of meteorological stations recording daily precipitation.

For each HP there were collated basic characteristic information such as turbine type, annual average river discharge, maximum turbine capacity, volume of intake when this was a reservoir, and whether the HP was allowed to practice start-stop dynamics (http://nve.no). Statnett SF provided hourly production (in kWh) data in 2015 for every HP (http://Statnett.no).

Daily precipitation (in mm) data for 2015 were obtained for a total of 132 weather stations representative of rainfall conditions for all hydropower plants (Fig. 1, Table S1). Data were downloaded from the Norwegian Meteorological Institute (http://met.no).

2.2 Characteristics of hydropower plants

The data set consists of five different types of turbines: Pelton, Francis, Kaplan, Brekke and Turgo. The latter two were installed in only three HPs. Their characteristics resembles very much to a Pelton turbine and were treated as such in the analyses. Three HPs had two different turbine types installed, namely one Pelton and one Francis, but of different capacity. In the analyses, we classified the HP according to the turbine with the smallest capacity. This resulted in 180 HPs with a Pelton turbine, 69 HPs with a Francis turbine, and 7 HPs with a Kaplan turbine.

Due to climatic conditions, geomorphological characteristics of the watershed and characteristics of the turbine, the concise turbine type is selected for each hydropower plant. The Kaplan turbine are characterised by low head and large volume of water, and are therefore used in large rivers with low pressure usually <30 m head. The Pelton turbine are suitable for power extraction when the water energy is available at high head (often >500 m) and low flow rate. The Francis turbine operates in a water head from 40 to 600 m.

The seasonal run off varies considerably among Norwegian counties, as does the altitudinal conditions. High gradient watersheds and high annual precipitation are found on the west coast of Norway, namely the counties of Hordaland and Sogn og Fjordane. On the other hand, areas with low annual precipitation and low gradient watersheds are found in the eastern areas namely the counties of Finnmark and Hedmark (Fig. 1).

When a license for production of hydroelectric power includes start-stop restriction the license is not specific in how this should be expressed. However, the restriction is followed by an explanatory sentence saying that all changes in water discharge should occur at a slow rate. The intention is to secure a stable discharge in the river downstream the hydropower plant. In this study, we classified every hourly datum as start or stop if the HP was producing or not. Then, we counted the number of start and stop periods without taking into account any other rule, that is, the duration of the periods was not important for considering that a plant was on or off (Fig. 2A). In some cases, the periods with production and periods without production are very regular with production during daytime and stop during night (Fig. 2B). In addition, the time from zero to maximum production and from maximum to zero production is very short, apparently within few minutes. The finest time scale for available production data is on an hourly basis. Thus, there are no possibility to analyse the practice at a finer timescale.

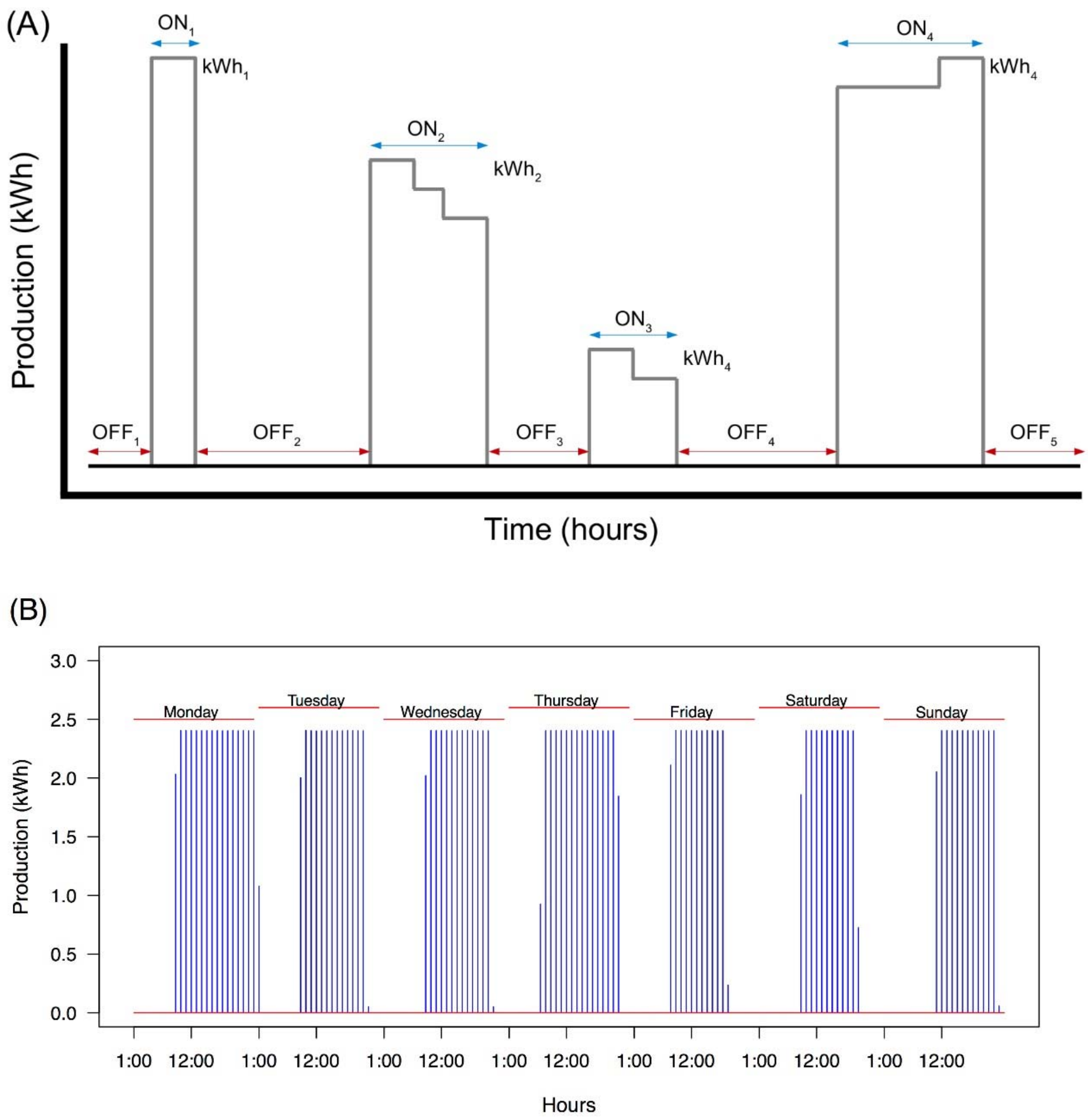

Fig. 2. (A) Schematic illustration of the start-stop procedure where five OFF and four ON events occurred with a given duration and average production for the ON events. (B) Example of hourly production during one week by a hydropower plant practicing start-stop procedure.

2.3 Data analyses

Daily precipitation dynamics for all stations were described using a generalized additive model (GAM, Wood 2006) according to the following general formulation:

$$P_{\mathrm{s,i}}=\alpha+\mathrm{g}(\mathrm{DoY}_{i},\mathrm{La}_{s})+\epsilon_{\mathrm{s,i}} \qquad [1]$$

where P denotes the precipitation recorded at a station s on a day i, α is an intercept, g is a two-dimensional non-parametric smoothing function describing the interactive effect of DoY (day of the year) and La (Latitude) that was fit by a thin plate regression spline using a maximum of 12 knots, and ϵ is the error term.

Hourly HP production dynamics were also described for each turbine type using a GAM as follows:

$$EP_{\mathrm{s,h,d,w}}=\alpha+\mathrm{g}_1(H_h,\mathrm{La}_s)+\mathrm{g}_2(\mathrm{DoY}_d,\mathrm{La}_s)+\mathrm{g}_3(W_w,\mathrm{La}_s)+\epsilon_{\mathrm{s,h,d,w}} \quad [2]$$

where EP denotes the energy production recorded for a hydropower plant s in an hour h, on a day d and in a week w. α is an intercept, g_{n} are two-dimensional non-parametric smoothing functions describing the interactive effects of H (hour of the day), DoY (day of the year) and W (week) with La (latitude) that were fit by thin plate regression splines using a maximum of 12 knots, and ϵ is the error term.

Daily energy production for each turbine type was further modelled as a function of precipitation and geographic location using also GAMs as follows:

$$EP_{\mathrm{s,d}}=\alpha+\mathrm{f}_1(\mathrm{DoY}_d)+\mathrm{f}_2(P_d)+\mathrm{g}(\mathrm{Lo}_s,\mathrm{La}_s)+\epsilon_{\mathrm{s,d}} \quad [3]$$

where EP denotes the summed energy production recorded for a hydropower plant s, in day d. α is an intercept, f_{n} and g are 1- and two-dimensional non-parametric smoothing functions describing the effects of DoY (day of the year), P (precipitation) and Lo (longitude) and La (latitude) that were fit by a cyclic cubic regression spline, a cubic regression spline and a thin plate regression spline using a maximum of 6, 3 and 12 knots, respectively. ϵ is the error term.

Differences in average values of any quantity characterizing the HPs between a given categorical factor (e.g. type of turbine, license) were evaluated using analysis of variance (ANOVA) and Tukey HSD post-hoc tests.

To study the among-HPs (i) variability in the start-stop procedure for each turbine type we modelled the number of starts using generalized linear models (GLMs, McCullagh & Nedler 1989) assuming a negative binomial (NB) distribution as follows:

$$\mathrm{NumStarts}_i \sim \mathrm{NB}(\mu_i,\mathrm{k}) \quad [4]$$

where the mean and variance are given by:

$$E(\mathrm{NumStarts}_i)=\mu_i \text{and } \mathrm{var}(\mathrm{NumStarts}_i)=\mu_i+\frac{\mu_i^2}{k} \quad [5]$$

$$\log(\mu_i)=\eta_i \quad [6]$$

$$\eta_i=\alpha+\beta_1\times L_i+\beta_2\times QR_i+\beta_3\times P_i \quad [7]$$

Covariates were used for the negative binomial models including license to practice start-stop (L), water discharge (QR) and precipitation (P). Two interactions were also explored, first, L by QR, and second, L by P. β_{s} are regression coefficients to be estimated.

All treatment of data and analyses were performed on R software (version 3.3.2, R Core Team 2016).

3 Results

3.1 Precipitation characteristics

Rainfall conditions showed wide daily variability (Fig. S1) in all stations, though a marked seasonal pattern emerged with highest precipitation values during winter and lower levels the rest of the year (Fig. 3). In addition, this cycle seems to be attenuated as you move northwards. Overall, precipitation was higher in Western Norway as compared to the rest of the country (Fig. 1).

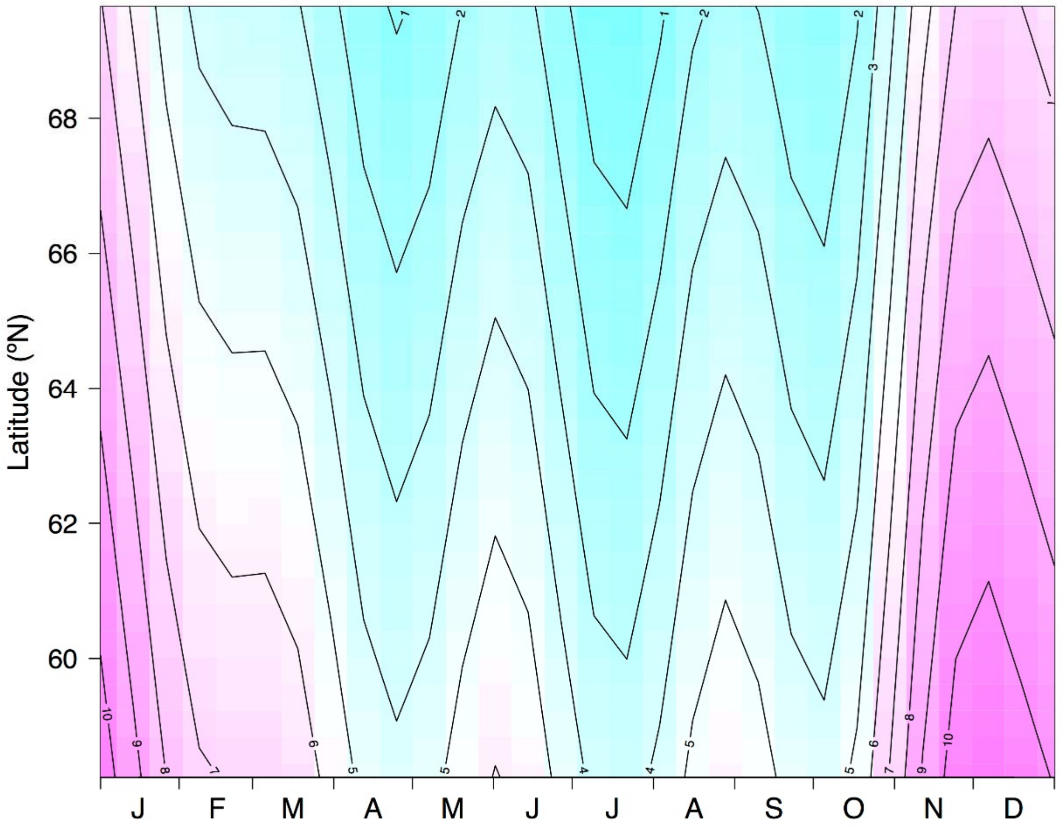

Fig. 3. Seasonal cycle of daily precipitation (in mm) along latitude resulted from fitting a GAM to all data. See numerical results in Table S2. Contours show the smooth function outlined in eq. 1 where colour gradient goes form high rain values (pink) to low values (blue).

The catchment area to the different HP is a continuous variable and, in combination with regional differences in annual precipitation, the mean annual discharge in the rivers where HPs were build showed large variation. Mean annual discharge (in m^{3}s^{-1}; mean ± sd) in rivers where Pelton turbines were installed was on average lowest 0.90 ± 0.66 (range 0.08−5.93), rivers with Francis somewhat larger 2.77 ± 2.88 (range 0.45−23.10), and highest in rivers with Kaplan turbines 10.37 ± 8.35 (range 1.01−22.00).

3.2 Turbine characteristics and production

Pelton turbine was the most common installed type (70.3%), followed by Francis (27%) and Kaplan (2.7%) ones. The variation in climatic and geomorphological conditions, in combination with turbine characteristics, result in an unevenly distribution of turbine types across Norwegian counties (Fig. 4). In general, Francis and Pelton turbines are installed in HPs in almost all counties.

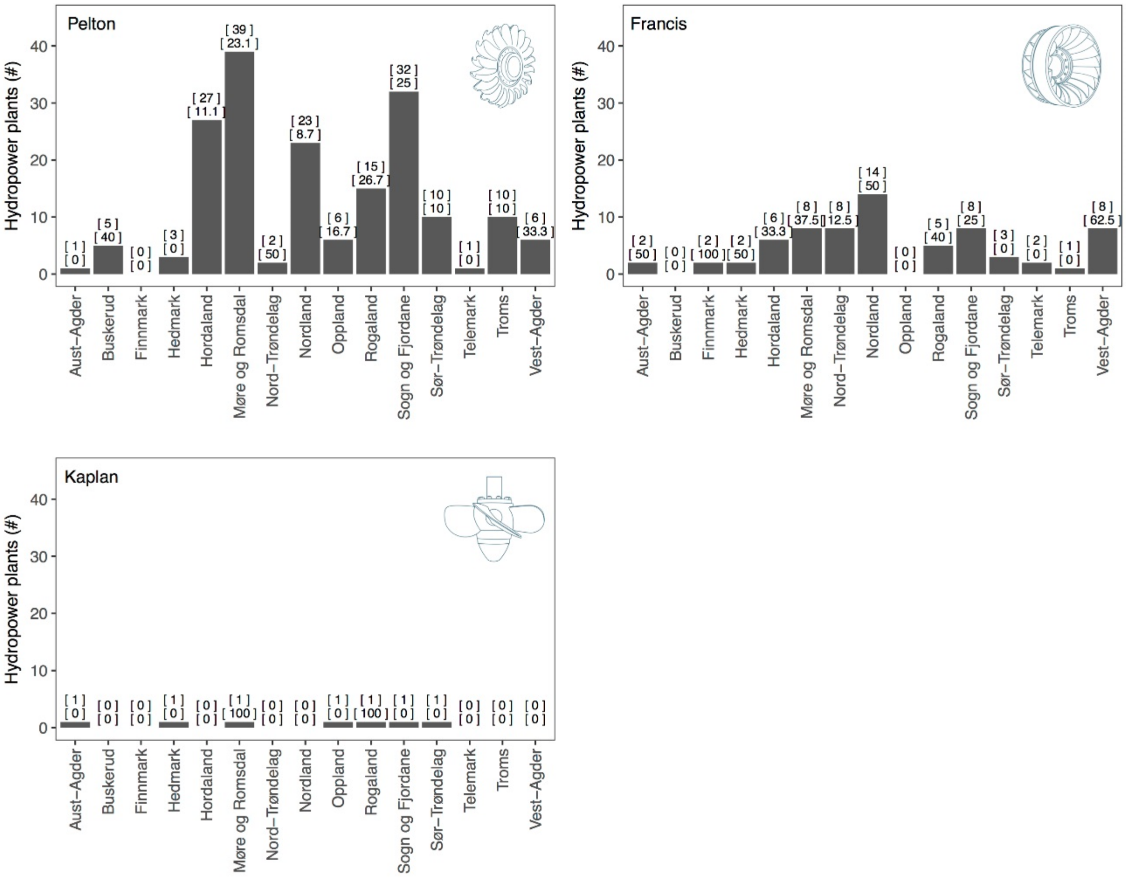

Fig. 4. Distribution of hydropower plants in Norwegian counties for each of the three turbines. For each column the number (upper value) of HPs and the proportion (lower value) of HPs with license to practice start-stop (i.e. no restrictions) are shown.

Maximum turbine capacity (in m^3s^{-1}; mean ± sd) varied considerable both among and within different turbine types. Pelton turbines were on average smallest 1.53 ± 0.93 (range 0.95−4.5), Francis somewhat larger 4.03 ± 2.65 (range 0.8−18.0), and Kaplan much larger 16.95 ± 15.22 (range 1.01−27.5). Maximum turbine capacity was related to the mean annual discharge in all turbine types (Fig. 5). The turbine capacity was chiefly higher than the mean annual discharge except for eight Pelton, six Francis, and one Kaplan turbine.

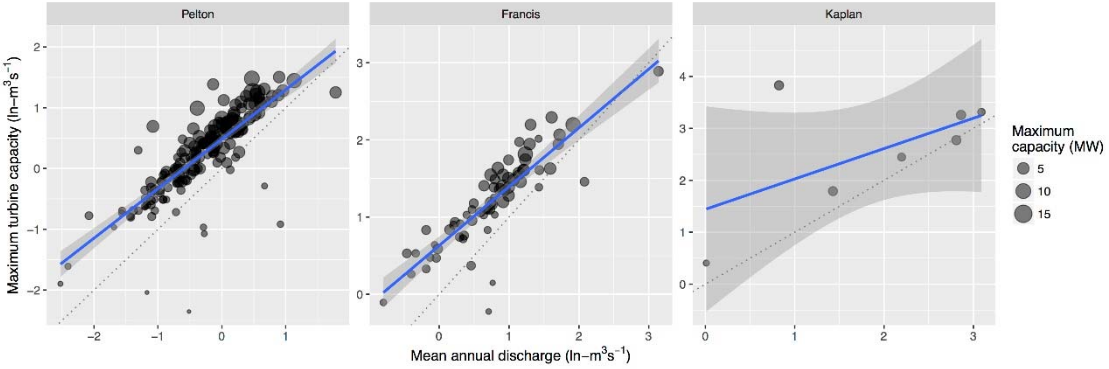

Fig. 5. Relationship between maximum turbine capacity and mean annual discharge per turbine type. The dotted line indicates the 0:1 relationship. Note that values were ln-transformed.

Overall, hydropower production showed clear daily, weekly and annual patterns though shapes varied depending on turbine type and the geographic location (Fig. 6). In general, the production showed great latitudinal variability for all turbine types. Highest values were recorded at 60−61 and 67−68°N. The production is mostly uniform throughout the day, although there are indications of highest production in the evening at least for Francis. On a weekly basis, higher production tended to occur from Wednesday until Saturday in both Pelton and Francis at lower and higher latitudes. In the case of Kaplan turbine, the larger production was during the weekend at 61ºN. The annual production by Francis and Pelton was similar with a higher production in summer months. Additionally, a secondary peak of production in December was mostly performed for Francis. The annual variation in production for Kaplan turbines was more heterogeneous showing high values in May, August/September and December. The maximum in May and December coincide with Francis and Pelton, whereas that in August/September could be an amplification of what it is seen in Francis and Pelton turbines.

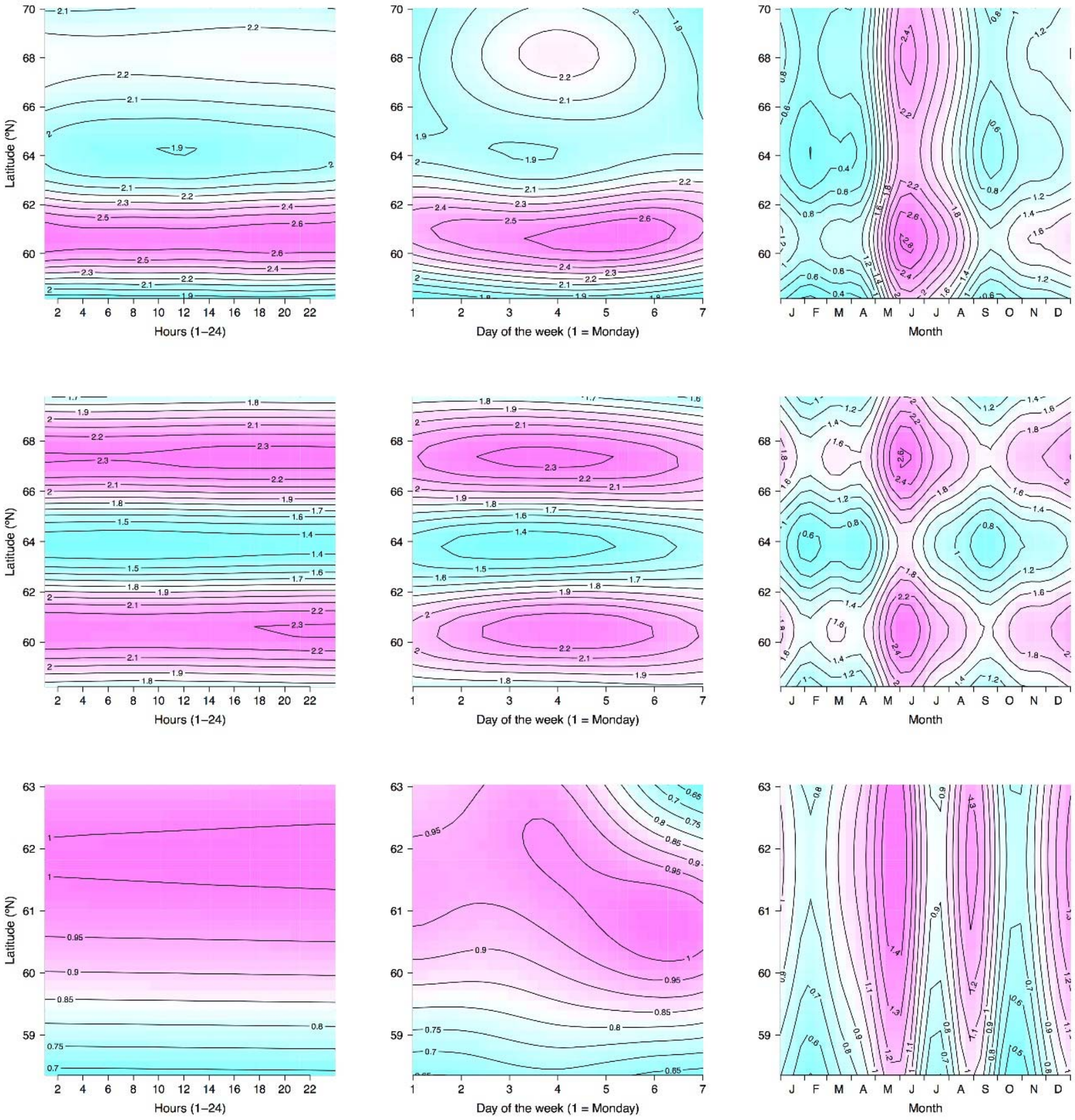

Fig. 6. Contour plots of daily (left panels), weekly (centre panels) and annual (right panels) production cycles along latitude for hydropower plants with Pelton (upper panels), Francis (middle panels) and Kaplan (lower panels) turbines installed. Each panel shows the three smooth functions outlined in eq. 2 where colour gradient goes from low production values in blue to high production values in pink. See numerical results in Table S3 (Pelton), S4 (Francis) and S5 (Kaplan).

Apart from the different temporal cycles, production on a daily basis was positively related to precipitation for all types of turbines, though the strength of the relationship was somewhat higher for Pelton (Fig. 7).

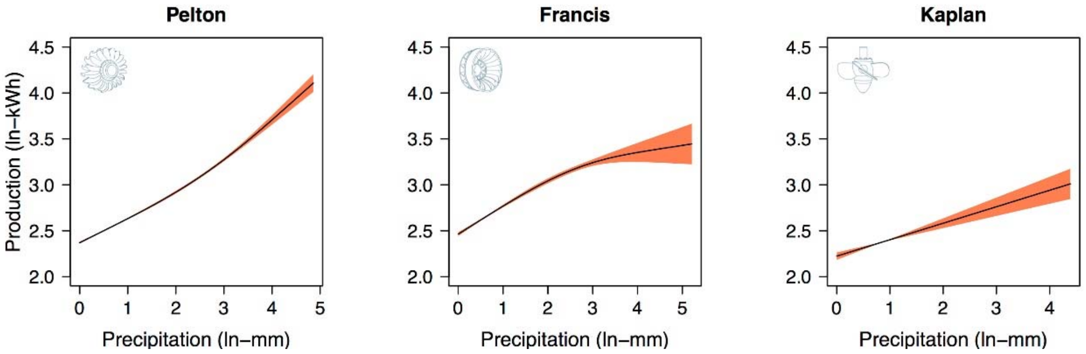

Fig. 7. Relationship between daily production and precipitation for each turbine type accounting for the seasonality in production and the geographic location of each HP (eq. 3). See numerical results in Table S6 and complementary plots in Fig. S2.

3.3 Start-stop procedure

A vast majority of HPs (75.8 %) had restrictions in the production and should secure a water discharge without swift changes. The rest (n = 62) could produce hydropower without having reflections to the aquatic environment (i.e. they were allowed to practice start-stop dynamics).

The number of starts ranged from 1 (two plants that never stopped during 2015) to 256, with a wide heterogeneous average duration of the starts (Fig. 8). For all three turbine types, one HP showed considerable higher number of starts than the rest. The highest number of starts was 256 for one Pelton, >100 for one Francis, and >175 for one Kaplan turbine. Of these three, the Pelton and the Kaplan had restriction in practising start-stop. For most Pelton (74.4%) and Francis (72.5%) turbines, the average duration of stops was less than 75 hours, and at the lower extreme of the distribution of the average duration of starts these were closely related to the duration of stops (Fig. 8).

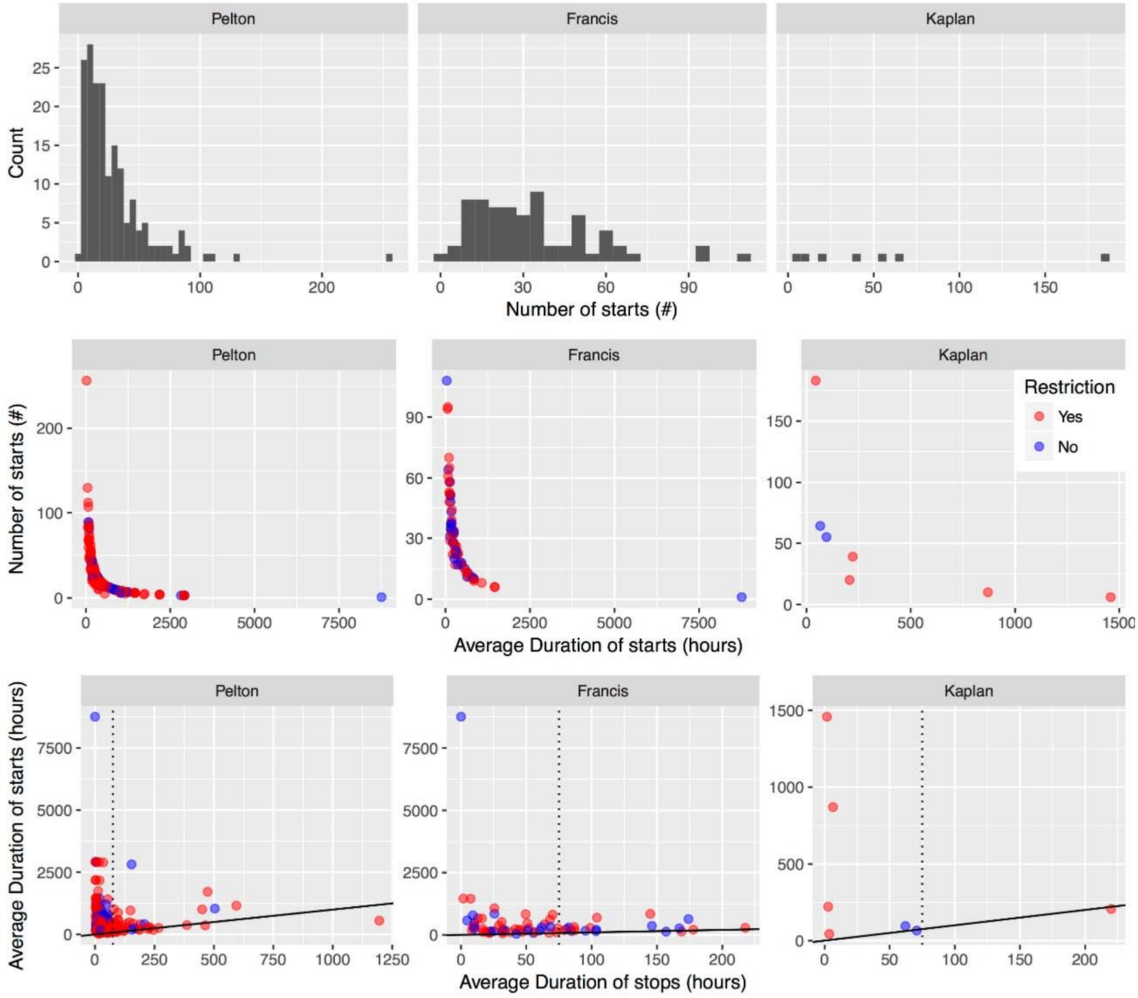

Fig. 8. Distribution of the number of starts for the three turbine types (upper panels). The middle panels show the association between the number of starts and their average duration. The lower panels show the relationships between the average duration of starts and average duration of stops. The vertical dotted lines indicate a threshold of 75 hours.

The number of starts was slightly higher (though not statistically significant) in Kaplan turbines as compared to Francis and Pelton ones (Fig. 9A). However, both duration and mean production of starts were lower in Kaplan though statistically homogeneous among turbines (Fig. 9B, C). Regarding the start-stop license, the results were unexpected. The number of starts was higher for HP with restrictions (i.e. no permit to practice start-stop), although not statistically significant (Fig. 9D). A consequence of this was significantly longer duration and higher production of starts for plants licensed for practising start-stop procedures (Fig. 9E, F).

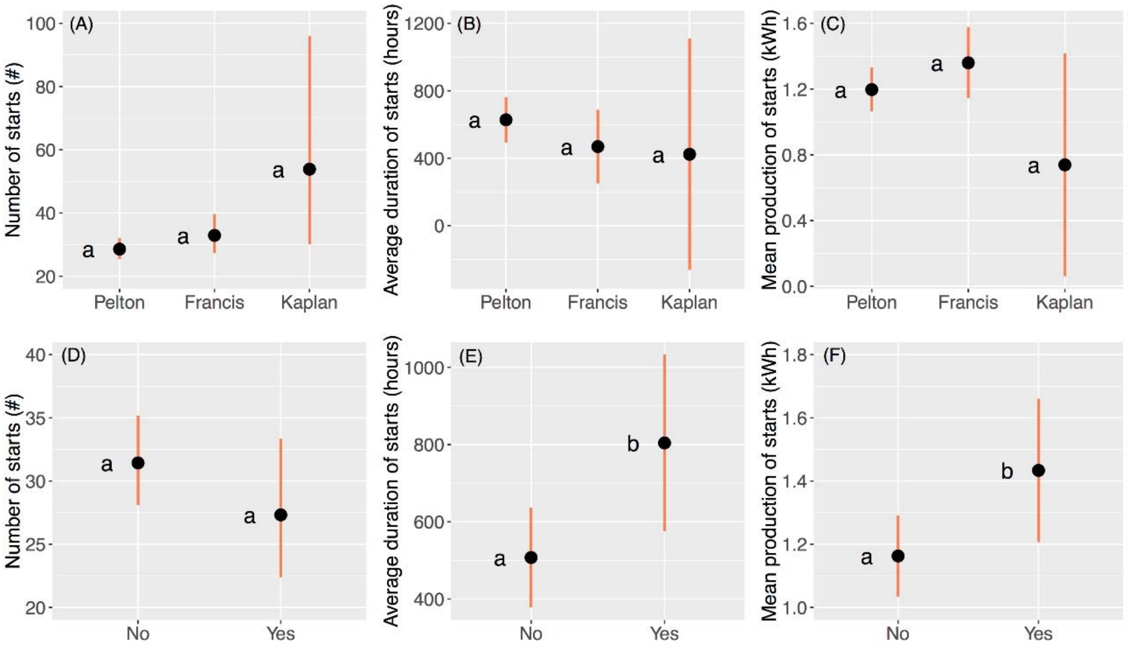

Fig. 9. Variation in the number of starts (A), their average duration (B) and production among turbines (C). The same characteristics were compared between plants authorised (Yes) or not-allowed (No) to practice start-stop schedules (D–F). In panels (A) and (D) comparisons were performed by means of fitting a generalized linear model assuming a negative binomial distribution. An analysis of variance were used otherwise. Error bars indicate 95% CI. Different letters show statistically significant differences according to Tukey's HSD test.

Simple models revealed that the number of starts for all hydropower plants was related to the mean annual river discharge, and that this variability differed among turbine types, being negative for Francis and nonlinear with a maximum around 0.6 m^3s^{-1} for Pelton. However, this relationship was not significant for Kaplan turbine (Fig. 10). The graph also shows that small Pelton turbines demonstrate low number of starts reflecting a more or less constant production. This is in contrast to the Francis turbines where the smallest demonstrate the highest incidence of starts.

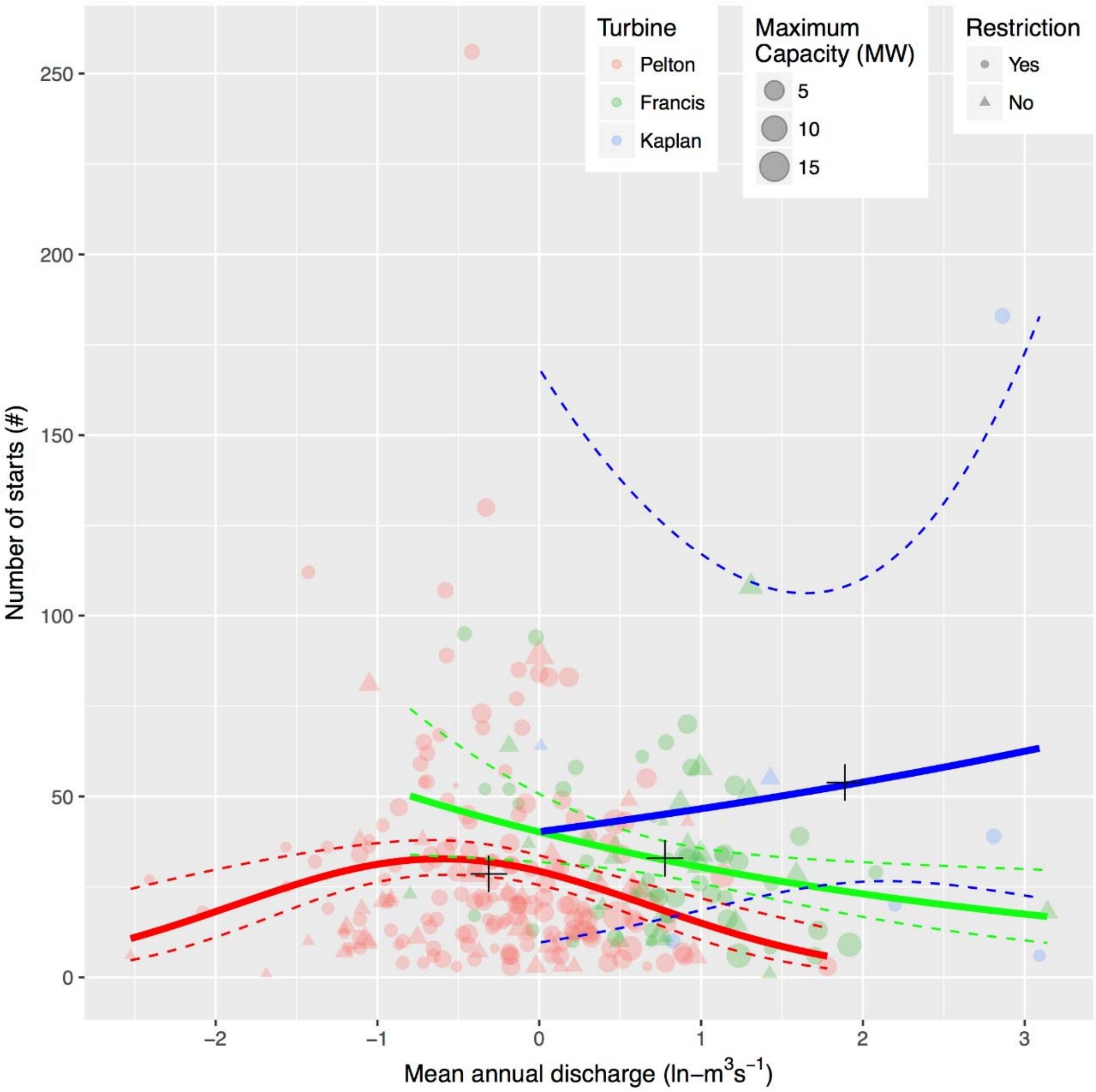

Fig. 10. Relationship between the number of starts and the mean annual river discharge (ln-transformed) for each turbine type. Lines are the result of fitting a negative binomial generalized linear model to the per turbine data. The crosses show the average number of starts for each turbine type.

When fitting the full model (eq. 7) including river discharge, rainfall and license as covariates (annual rainfall and river discharge were not correlated; slope = −0.03, p-value = 0.17) different patterns emerged depending on turbine type. First, the shape of the relationship with mean annual discharge varied within Pelton turbines if the hydropower plant had a license to practice start-stop procedures being roughly positive if the license was approved and dome-shaped if the plants did not have the permission (Fig. 11). Mean annual discharge was negatively associated to the number of starts in Francis turbines (Fig. 11), and did not have any influence in Kaplan ones (Fig. 11). Regarding annual precipitation, this factor had a positive effect on the number of starts for both Pelton (Fig. 11) and Kaplan (Fig. 11) turbines, and was non-significant for Francis turbines (Fig. 11). The interaction between precipitation and having a license to practice start-stop dynamics was not statistically significant in any case.

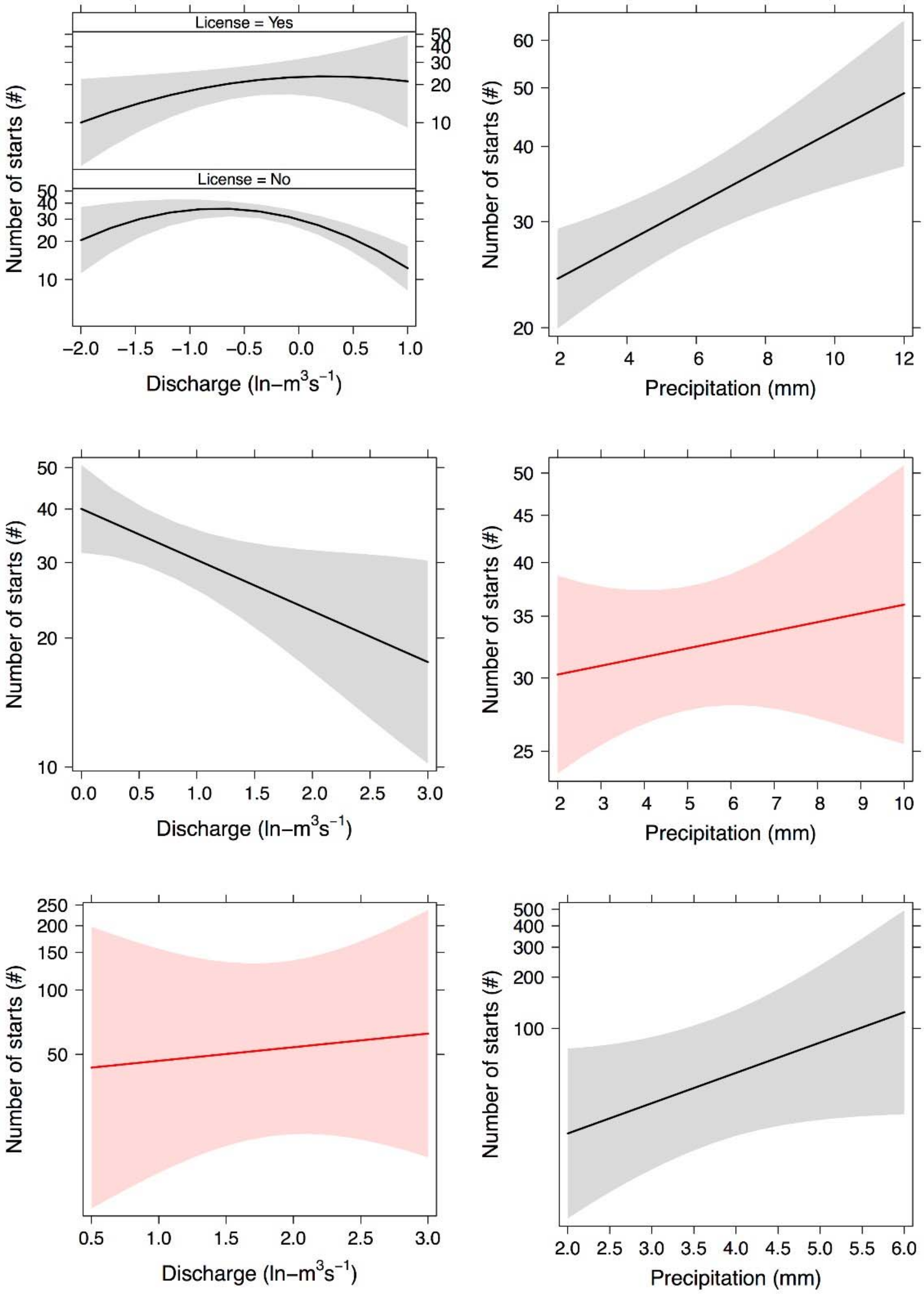

Fig. 11. Results from fitting a negative binomial GLM to the annual number of starts in Pelton (upper panels), Francis (middle panels) and Kaplan (lower panels) turbines including mean annual discharge, mean annual precipitation and license as covariates. Note that for Kaplan turbine two separate NB-GLM were fitted due to the low number of cases. Pink colour indicates statistically non-significant relationships. See numerical results in Table S7.

We also modelled other characteristics of the start-stop procedure. In particular, we evaluated the effects of the environmental variables and licensing on the average production of the starts. In doing so, we found a positive water discharge effect on production for both Pelton and Francis (Fig. 12). On the other hand, precipitation had a positive significant effect for Pelton turbine with a stronger effect in the case of having a license to practice start-stop procedure (Fig. 12). Regarding Francis turbine, the effect of precipitation was not significant (Fig. 12). Neither discharge nor precipitation had a significant effect on Kaplan average production of the starts (Fig. 12).

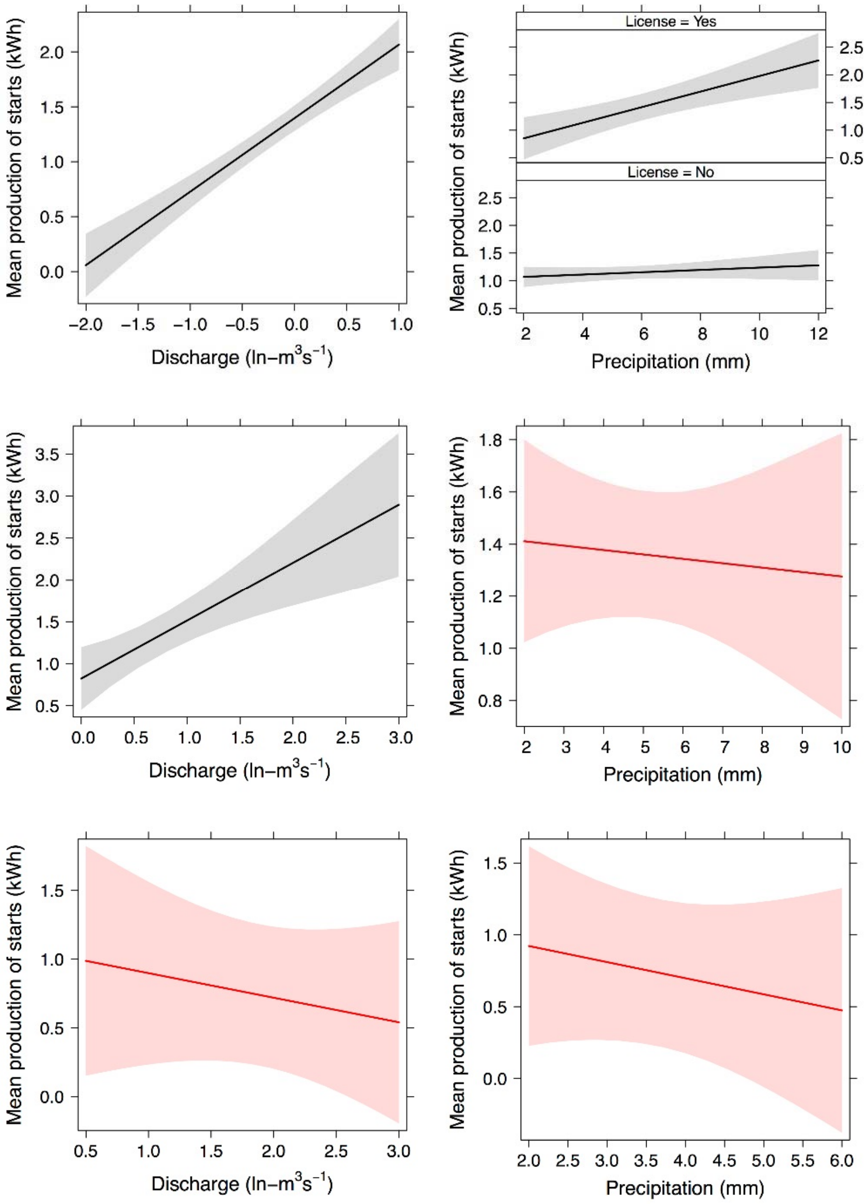

Fig. 12. Effects plots depicting the relationships of water discharge (left panels) and precipitation (right panels) with the average production of starts for Pelton (upper panels), Francis (middle panels), and Kaplan (lower panels) turbines. Pink colour indicates statistically non-significant relationships.

Finally, the average duration of starts was positively and negatively related with discharge and precipitation, respectively, in Pelton turbines (Fig. 13). Environmental parameters did not affect average duration of starts either for Francis or Kaplan turbines.

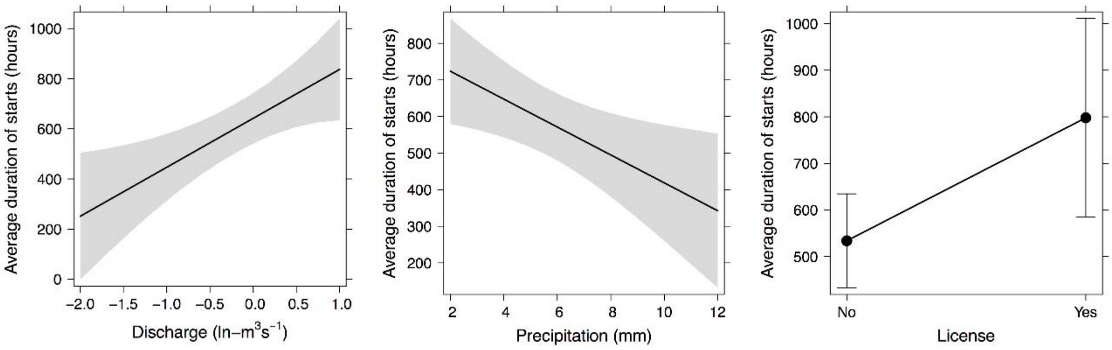

Fig. 13. Effects plots depicting the relationships of water discharge, precipitation and license to practice start-stop procedures with the average duration of starts for Pelton turbines. Note that one HP that never stoped was removed from the model because of the large influence of this observation.

4 Discussion

The detailed analysis of the production data from each hydropower plant revealed two major results:

- Hydropower plants with restriction to practice start-stop demonstrated higher number of starts than those without restrictions.
- Many turbines have an approved maximum capacity that is too high in relation to the mean annual river discharge to secure that the restriction in the license can be complied.

Our analyses are based on the unbiased observation of running practice. One should bear in mind that precipitation is not evenly distributed all year round. This means that the number of starts recorded is occurring during short time intervals. As our analysis only covered one specific year cycle, we are not able to consider the consequences of the hydrological regime of another year. In any case, 2015 was a special year in hydrological terms. The spring was cold and the melting of snow started later and continued therefore into a period of the year that usually is less humid. On an annual basis, 2015 received more precipitation than a “normal” year. Converted into HP production, the precipitation increase was equivalent to 31.5 TWh or 24% of a “normal” year. As 2015 was a wet year, there are reasons to believe that our results are conservative. In a dry year, the number of starts are expected to be higher as the discharge is reduced. How this will affect the difference between HP with restrictions and those without, can only be speculations. However, as HPs with and without restrictions experience the same hydrological regime, we should expect that any differences would be the result of running of the HP and not attributable to the water discharge.

Another important point is that mean annual discharge is the basis for several analysis. Specific seasonal run-off would have improved the modelling, but likely not the main conclusion. Thus, our results are a result of a whole-year analysis. In fact we know that a start-stop procedure when the discharge is higher than maximum turbine capacity would result in a reduction in financial profit. This means that number of starts are restricted to the periods when discharge is lower than the maximum turbine capacity.

We found that mean number of starts for hydropower plants with restrictions had a tendency to be higher than those without restrictions. In addition, the average duration of starts was significantly shorter for plants with restrictions compared to those without restrictions. The latter demonstrate that HPs with restrictions more frequently shift between production and no production than those without restrictions. This implies that HPs with restrictions make more variable and harsher aquatic environment than the other group. Thus, the environmental factors that the restriction was supposed to take care of (most often anadromous salmonids), are mostly affected. To quantify the effect is complicated, however, several studies show that variable water level/discharge affect aquatic environment negatively (review by Bakken et al. 2016). The main conclusions of this review are:

- Aquatic insects demonstrate reduced density and biodiversity when exposed to variable water level in rivers, and a catastrophic drift may occur during the first 15 minutes of peaking.
- Studies on river mussels are not conclusive. Norwegian studies of mussel behaviour showed increased movements of those exposed to changing water level, and no increased mortality during the experiment. International studies have shown increased mortality in populations exposed to fluctuating water level.
- Fluctuating water level affects salmonids in different ways. Stranding of juveniles is of most concern. The extent depends on the season of the year (summer is more critical than winter), time of day (day is more critical than night in winter), fish size (fry is most vulnerable), species (juvenile brown trout is more exposed than juvenile Atlantic salmon), and habitat characteristics (low transect gradient is more critical than steep).

In periods where the run off is larger than the maximum capacity of the HP, start-stop practice has now value. The HP is run constantly for a long period. Otherwise, the company will lose income. In periods where run off is lower than maximum capacity, the HP can be run in two different ways. Either reduce the production in accordance with the discharge, or keep production at maximum as long as possible and stop when appropriate. In the latter case, the intake will be drained in few hours and the HP must stop. After some hours, the intake is filled and the HP can start production again. In the present study there is one example demonstrating this very clear (Fig. 2B). The water level in the intake for this power plant may be regulated by 1 meter making a volume of water available for 14 hours maximum production without any addition of water. The mean duration of starts for this plant was 19.8 hours and mean duration of stops 14.4 hours. This HP has restriction in practicing start-stop schedules, and the application confirmed that the purpose of the intake was to secure a stable and smooth production. In another HP observed in 2008, the intake was much smaller and the production continued for 1 hour (observational data, not modelled) that was identical for emptying the intake. There are no restrictions for this HP.

In addition to these general conditions, efficiency of turbines to produce electricity depends on type and the discharge led through the turbine in relation to the maximum capacity. Pelton turbine is less sensitive to the amount of water for production than Francis and Kaplan.

That implies that Pelton turbines are run over a wider interval of water discharges (especially at low values) than Francis and Kaplan. Our results lend support to this. Given these conditions, we argue for two reasons to explain the comprehensive start-stop practice in small Norwegian hydropower plants.

First, large economic interests are connected to hydropower production. The economic value of the produced electricity varies between months, between days of the week, and between daily hours. High prices are achieved in cold periods with low run off, in the week when the demand is high (Monday through Friday), and during the day when consumption is high (daytime). For small HPs especially, daily aspects are mostly important when determining how the plant should be run if there are not sufficient water for continuous high production. Thus, in periods with restricted discharge in the river, there are economic incentives to maximize economic income. The consequence will be daily periods with maximum production and periods with zero production. The production will be coincident with high demand at daytime. Our results demonstrate large variation in daily production with reduced production during night. Maximum may vary among counties, but maximum is chiefly recorded at daytime and early evening.

Liberalization of the energy market has created incentives for hydropower suppliers to behave competitively (Cherry et al. 2005). The market prices affect the companies and the higher the price, the more firms are able to produce (Yucekaya & Metin 2013). In our context, this implies an active handling of the start-stop procedure when deficit in water supply occurs which are in summer and winter. During winter, changes in water flow in the tailrace can be difficult to observe due to snow cover, whereas in summer changing water flow is visible. However, the consequences for aquatic organisms may vary according to time of year. Juvenile salmonids are most sensible to seasonal changes. For instance, due to nocturnal behaviour at low temperature, juvenile brown trout (*Salmo trutta*) are more susceptible for stranding due to reduction in water flow at day time than at night during winter (Heggenes et al. 1993).

Second, the run of small HP is often outsourced. The owner is usually the landowner who through contracts have made agreements with larger companies to run the power plant. These companies may run many HPs, and there are no mechanisms to secure that they are aware of the details in each specific license. They are not responsible for an accordance between run of the HP and conditions in the license. This responsibility belongs to the owner. Thus, this separation between responsibility and daily running may lead to unintended results.

We found differences between Pelton and Francis turbines in number of starts related to river discharge. Being negative for the Francis turbine and nonlinear with a maximum around 0.6 m^3s^{-1} for the Pelton turbine. The results of nonlinear for Pelton is probably that very small turbines have been installed and that their maximum capacity is considerably lower than the mean annual discharge. The negative relationship between number of starts in Francis and mean annual discharge is probably a result of the function of this turbine. When the discharge decreases to low values, there are two options either increasing the frequency of start-stop or turn it off. The increasing number of start-stop at lower discharge indicates that turn it off is not the first option. This suggests that there seems to be a mismatch between the approved installed capacity and restrictions given in the license. A similar consequence appears for Francis turbines, but contrary to Pelton turbines, the mismatch occurs for the turbines with the smallest capacity. Thus, the approved maximum capacity installed is in many cases in contradiction to the restriction in the license to practice start-stop. This difference between Francis and Pelton is probably a result of their efficiency in power production over a variety of water discharges.

Norway is rich in water, and more than 99% of the Norwegian electricity production comes from hydropower. Thus, precipitation is a crucial factor. Considerable annual variation in precipitation exist, and the North Atlantic oscillation (NAO) is the most important factor explaining 55% of this variation (Cherry et al. 2005). Almost 30% of the variance of Norway's hydropower output has been explained by variation in the NAO index (Cherry et al. 2005). This shows that changes in climate will affect hydropower production and, consequently, the owners' management of the hydropower plants. Hamududu & Killingtveit (2012) estimated approximately a 1.5% increase until 2050 in hydropower production in Northern Scandinavia because climate change and increased precipitation. Although the change is small, it may lead to a reduction in number of starts during a year cycle.

5 Conclusions

The results of analysing hourly production data in 2015 from 256 small hydropower plants in Norway revealed two major results:

- Restriction in the license to practice start-stop did not affect the number of starts.
- There is a mismatch between this restriction, approved maximum installed capacity and turbine type.

6 Acknowledgements

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8 Appendix

Table S1. Characteristics of the hydropower plants (P-code) used in the analysis. Precipitation station ID as coded by the Norwegian Meteorological Institute (http://met.no).

P-code	River-ID	County	Latitude (UTM33 grid system)	License to practice start/stop	Turbine	Max turbine capacity (m3/s)	Mean annual disch. (m3/s)	Precipitation station ID
P1583	020.Z	Aust-Agder	6523245,440	Yes	Francis	4,500	2,700	39750
P2334	020.Z	Aust-Agder	6511557,770	No	Kaplan	26,000	17,500	36110
P2141	021.Z	Aust-Agder	6580277,640	No	Pelton	1,700	0,700	40250
P1325	021.Z	Aust-Agder	6518777,920	No	Francis	6,150	3,430	39750
P1584	012.Z	Buskerud	6742073,130	Yes	Pelton	3,600	2,600	25320
P2326	012.Z	Buskerud	6737437,500	No	Pelton	1,450	0,644	25320
P2338	012.Z	Buskerud	6708314,660	No	Pelton	1,000	0,564	20301
P1300	015.Z	Buskerud	6722708,030	Yes	Pelton	1,200	1,240	25630
P2113	015.Z	Buskerud	6695411,640	No	Pelton	0,800	0,500	29350
P2075	247.71	Finnmark	7817210,130	Yes	Francis	3,200	2,140	99460
P2073	247.71	Finnmark	7812031,410	Yes	Francis	2,800	1,480	99460
P2000	002.Z	Hedmark	6860396,670	No	Pelton	0,600	0,420	7660
P1695	002.Z	Hedmark	6813587,900	No	Pelton	1,200	0,670	7420
P2032	002.Z	Hedmark	6811554,340	No	Francis	4,400	2,900	7950
P2196	002.Z	Hedmark	6725271,776	No	Kaplan	46,000	2,280	6020
P2240	002.Z	Hedmark	6856827,668	Yes	Francis	3,250	1,640	8450
P2290	002.Z	Hedmark	6864926,360	No	Pelton	1,100	0,520	7660
P1696	036.Z	Hordaland	6656908,230	No	Pelton	0,980	0,650	46430
P2317	036.Z	Hordaland	6658518,870	No	Pelton	2,900	1,671	46430
P1753	041.4	Hordaland	6647712,250	No	Pelton	0,200	0,090	47600
P2267	042.11Z	Hordaland	6654545,080	No	Pelton	0,670	0,380	47600
P1982	042.3Z	Hordaland	6671490,160	No	Pelton	1,330	0,880	47820
P2061	042.61Z	Hordaland	6662036,920	No	Pelton	1,000	0,710	47890
P2263	042.61Z	Hordaland	6662065,740	No	Pelton	2,170	1,100	47890
P2264	042.711Z	Hordaland	6664363,990	No	Pelton	0,500	0,250	47890
P2067	042.712Z	Hordaland	6666108,605	Yes	Pelton	1,500	0,820	47890
P2056	045.31Z	Hordaland	6675944,190	No	Pelton	1,380	0,880	47890
P2126	045.4Z	Hordaland	6701715,530	No	Pelton	1,760	0,950	48780

Table S1. Cont.

P1593	046.32Z	Hordaland	6697502,230	No	Pelton	0,450	0,240	48780
P1862	046.42.Z	Hordaland	6699168,060	No	Pelton	1,100	0,930	48780
P2059	046.422	Hordaland	6698040,700	No	Francis	2,600	1,600	48780
P1594	046.51	Hordaland	6698324,370	No	Pelton	0,820	0,580	48780
P1679	046.5Z	Hordaland	6703764,570	No	Pelton	2,900	1,540	48780
P1949	047.2Z	Hordaland	6714456,520	No	Francis	3,310	2,500	49080
P1649	047.4Z	Hordaland	6724548,140	No	Pelton	2,990	1,820	49490
P2261	048.Z	Hordaland	6689331,890	No	Pelton	0,380	0,750	48780
P1863	052.1Z	Hordaland	6745848,890	No	Francis	2,140	1,428	49631
P0978	052.21Z	Hordaland	6736726,630	No	Pelton	1,750	1,040	49631
P1954	053.Z	Hordaland	6718720,750	No	Pelton	1,550	0,720	50110
P2268	053.Z	Hordaland	6718716,110	No	Pelton	0,950	0,420	50110
P2045	055.3Z	Hordaland	6722685,180	No	Pelton	3,300	2,200	50310
P1782	055.4	Hordaland	6728922,920	Yes	Francis	18,000	23,100	51010
P2288	057.1Z	Hordaland	6710564,460	No	Pelton	3,700	1,940	49080
P1521	061.41	Hordaland	6738659,570	Yes	Pelton	0,600	0,398	51010
P2322	062.Z	Hordaland	6754720,730	No	Pelton	2,400	1,200	51470
P1986	062.Z	Hordaland	6756267,250	No	Pelton	2,200	1,250	51440
P2023	062.Z	Hordaland	6754240,870	No	Francis	3,000	2,070	51530
P2042	064.7Z	Hordaland	6774961,890	No	Pelton	1,300	0,650	52400
P1870	064.Z	Hordaland	6779225,145	Yes	Francis	1,160	2,150	52310
P1321	067.1XZ	Hordaland	6777564,740	Yes	Pelton	2,300	1,000	52601
P2340	093.3Z	Møre og Romsdal	6915800,000	No	Pelton	0,500	0,210	59610
P2137	094.212	Møre og Romsdal	6911660,330	No	Pelton	0,550	0,330	59900
P1320	094.3Z	Møre og Romsdal	6919738,230	Yes	Pelton	1,000	0,690	59900
P1651	094.44	Møre og Romsdal	6911771,240	No	Pelton	1,200	0,600	59695
P1375	094.4Z	Møre og Romsdal	6909910,760	No	Pelton	1,880	0,830	59695
P1290	094.4Z	Møre og Romsdal	6908403,450	Yes	Pelton	0,900	0,486	59695
P1622	095.Z	Møre og Romsdal	6930151,320	Yes	Pelton	0,590	0,330	59695
P1727	095.Z	Møre og Romsdal	6927516,790	No	Pelton	0,900	0,520	59695
P2175	097.11Z	Møre og Romsdal	6932356,634	No	Pelton	1,300	0,530	59900
P1523	097.23Z	Møre og Romsdal	6915747,390	No	Pelton	2,260	1,530	59900
P2173	097.322Z	Møre og Romsdal	6917893,660	No	Pelton	2,500	1,210	59900
P2174	097.332Z	Møre og Romsdal	6917545,450	No	Pelton	1,500	0,750	59900
P1575	097.42Z	Møre og Romsdal	6926390,140	No	Pelton	3,500	1,750	59900

Table S1. Cont.

P1299	097.51Z	Møre og Romsdal	6932417,600	Yes	Pelton	2,000	0,900	59900
P2026	097.7Z	Møre og Romsdal	6933654,990	No	Pelton	1,800	1,238	59900
P2176	098.11Z	Møre og Romsdal	6932882,614	No	Pelton	3,000	1,350	59900
P1389	098.3Z	Møre og Romsdal	6930331,500	Yes	Francis	3,600	2,700	60240
P1477	098.3Z	Møre og Romsdal	6932105,690	No	Pelton	2,000	1,330	60240
P2207	098.3Z	Møre og Romsdal	6924660,150	No	Pelton	1,500	0,833	60240
P2102	098.5Z	Møre og Romsdal	6910859,390	No	Pelton	4,500	2,450	60240
P2101	098.5Z	Møre og Romsdal	6909403,110	No	Francis	7,900	5,600	60240
P2158	098.5Z	Møre og Romsdal	6909409,190	No	Francis	3,000	1,960	60240
P1362	099.1Z	Møre og Romsdal	6924129,570	Yes	Francis	4,700	2,090	60400
P2122	100.310	Møre og Romsdal	6946972,760	No	Pelton	1,500	0,740	60800
P2233	102.6Z	Møre og Romsdal	6952417,360	No	Pelton	0,500	0,271	60800
P2071	103.2Z	Møre og Romsdal	6946527,980	No	Pelton	1,700	0,840	61410
P2150	103.3Z	Møre og Romsdal	6968604,080	No	Francis	4,800	3,130	61820
P1951	103.4Z	Møre og Romsdal	6955421,730	No	Francis	2,800	2,216	61340
P1614	104.32	Møre og Romsdal	6979524,760	No	Pelton	1,130	0,624	61820
P2151	104.3Z	Møre og Romsdal	6968073,869	No	Pelton	2,850	1,850	61820
P1867	109.1Z	Møre og Romsdal	7000890,010	Yes	Pelton	0,450	0,240	64760
P1311	109.3Z	Møre og Romsdal	6975989,380	Yes	Pelton	3,200	1,780	63100
P1237	109.4Z	Møre og Romsdal	6967812,630	Yes	Pelton	1,800	1,250	63100
P2009	109.4Z	Møre og Romsdal	6962639,170	No	Francis	5,000	3,350	63100
P1641	109.4Z	Møre og Romsdal	6966243,800	No	Pelton	0,810	0,390	63100
P2313	109.4Z	Møre og Romsdal	6966513,560	No	Pelton	2,200	1,150	63420
P1513	109.7Z	Møre og Romsdal	6999065,480	No	Pelton	0,550	0,310	64760
P2029	111.70	Møre og Romsdal	6982021,060	No	Pelton	1,310	1,310	64760
P1329	111.712	Møre og Romsdal	6987174,820	No	Pelton	1,600	0,840	64760
P1487	112.3Z	Møre og Romsdal	7004155,340	Yes	Kaplan	6,000	4,170	64870
P2245	112.4Z	Møre og Romsdal	7004040,990	Yes	Pelton	0,940	0,470	64760
P2006	112.Z	Møre og Romsdal	7008988,290	No	Pelton	1,300	0,880	64900
P1861	112.Z	Møre og Romsdal	7005059,800	No	Pelton	0,800	0,385	64870
P2028	112.Z	Møre og Romsdal	7000156,290	No	Pelton	1,500	0,730	64900
P2187	113.41Z	Møre og Romsdal	7014020,440	Yes	Francis	2,500	1,350	62900
P2092	113.51Z	Møre og Romsdal	7019278,650	No	Pelton	1,450	0,810	62900
P1377	114.12	Møre og Romsdal	7023940,700	Yes	Pelton	0,540	0,300	62900
P2237	1202.51	Møre og Romsdal	6967849,602	No	Pelton	0,670	0,331	60800

Table S1. Cont.

P2121	145.2Z	Nordland	7236759,060	No	Pelton	3,400	1,700	76100
P2180	151.1Z	Nordland	7297799,700	Yes	Francis	7,000	3,650	77230
P2132	152.3	Nordland	7314784,314	No	Pelton	1,900	0,880	78250
P2336	155.21Z	Nordland	7333162,630	No	Pelton	2,400	1,670	78360
P2131	155.31	Nordland	7334899,140	No	Francis	3,280	2,090	79700
P2337	155.3Z	Nordland	7335019,880	No	Francis	2,310	1,160	78360
P2003	155.4Z	Nordland	7336884,742	No	Pelton	1,530	0,830	78370
P2307	155.Z	Nordland	7325175,940	No	Pelton	2,100	1,000	78610
P2328	155.Z	Nordland	7325175,940	No	Pelton	0,800	0,540	78370
P2343	155.Z	Nordland	7324482,640	No	Pelton	0,800	0,330	78370
P2118	156.22	Nordland	7345748,320	No	Pelton	1,350	0,705	79220
P1635	156.Z	Nordland	7366555,909	No	Pelton	1,500	1,137	79700
P1946	156.Z	Nordland	7369335,050	No	Pelton	1,300	0,870	79480
P2203	156.Z	Nordland	7365333,604	Yes	Francis	9,000	3,700	79700
P2331	156.Z	Nordland	7363150,560	No	Pelton	1,500	0,750	79480
P1652	156.Z	Nordland	7367704,810	No	Francis	4,000	4,170	79480
P1597	159.52Z	Nordland	7390428,110	No	Francis	2,800	1,890	80200
P2046	160.20	Nordland	7410020,640	No	Pelton	1,340	0,670	80705
P1585	160.51Z	Nordland	7424607,210	No	Pelton	1,000	0,510	80740
P2282	160.Z	Nordland	7409082,690	No	Francis	3,000	2,000	80740
P1650	161.1Z	Nordland	7425393,830	No	Francis	9,000	6,800	80705
P1326	161.4Z	Nordland	7439682,760	Yes	Francis	1,450	1,580	82110
P2298	161.Z	Nordland	7427974,360	No	Pelton	1,400	1,030	81650
P2285	161.Z	Nordland	7410407,124	No	Pelton	1,500	0,920	81775
P1571	162.6Z	Nordland	7442902,830	Yes	Francis	1,900	0,937	82000
P2110	163.2Z	Nordland	7449395,800	Yes	Francis	4,080	1,900	82000
P2184	163.5Z	Nordland	7443781,810	No	Francis	7,200	3,150	82000
P0768	166.4Z	Nordland	7466518,500	Yes	Francis	2,900	1,800	82000
P2183	168.4Z	Nordland	7509055,230	No	Pelton	0,750	1,950	83520
P2266	170.2Z	Nordland	7537508,880	Yes	Pelton	0,400	2,500	83520
P2265	170.2Z	Nordland	7536992,420	Yes	Francis	4,000	2,500	83520
P2148	171.Z	Nordland	7551845,070	No	Pelton	1,620	0,540	83710
P1713	173.4	Nordland	7586405,440	No	Pelton	1,930	0,640	84070
P2224	173.6Z	Nordland	7565155,682	No	Pelton	1,350	0,560	83880
P2044	173.71Z	Nordland	7567908,760	No	Pelton	1,000	0,480	84190

Table S1. Cont.

P2344	174.2Z	Nordland	7584598,980	No	Pelton	1,600	0,900	84500
P1987	180.5	Nordland	7576001,800	Yes	Pelton	0,150	0,080	85440
P2001	124.Z	Nord-Trøndelag	7037999,340	No	Francis	4,700	3,100	69100
P1815	128.Z	Nord-Trøndelag	7129765,250	No	Francis	4,300	8,000	70930
P2037	128.Z	Nord-Trøndelag	7129474,850	No	Francis	3,850	2,560	70930
P2015	129.5Z	Nord-Trøndelag	7097477,910	No	Pelton	1,550	0,750	71200
P2275	130.1Z	Nord-Trøndelag	7089539,350	No	Francis	4,700	2,500	71200
P2063	131.4Z	Nord-Trøndelag	7068005,690	No	Francis	4,000	2,190	71200
P1020	137.7Z	Nord-Trøndelag	7152588,330	Yes	Francis	7,500	4,150	75020
P1978	139.Z	Nord-Trøndelag	7157772,630	No	Francis	9,900	5,000	73550
P1999	307.3Z	Nord-Trøndelag	7169200,950	No	Francis	5,000	4,200	73800
P2226	307.3Z	Nord-Trøndelag	7193634,930	Yes	Turgo	0,380	0,185	73800
P1808	002.Z	Oppland	6869327,800	No	Pelton	0,130	0,310	14711
P2302	002.Z	Oppland	6878669,440	No	Pelton	1,660	0,830	16271
P2327	002.Z	Oppland	6911702,690	No	Pelton	0,850	0,430	16790
P1570	012.Z	Oppland	6756023,710	Yes	Pelton	1,200	0,980	22840
P1710	012.Z	Oppland	6735959,460	No	Pelton	2,350	1,560	11710
P2315	012.Z	Oppland	6775092,900	No	Kaplan	11,550	9,000	23160
P2332	012.Z	Oppland	6773641,100	No	Pelton	1,500	0,760	23160
P1524	026.Z	Rogaland	6498520,380	Yes	Kaplan	1,500	1,010	43090
P1582	026.Z	Rogaland	6495765,180	Yes	Francis	2,300	0,830	43090
P2139	026.Z	Rogaland	6516968,957	No	Francis	2,550	1,253	43010
P2341	026.Z	Rogaland	6517188,520	No	Pelton	1,200	0,500	43010
P2342	026.Z	Rogaland	6517187,020	No	Pelton	0,900	0,400	43010
P1505	030.2Z	Rogaland	6555518,010	Yes	Pelton	0,454	0,334	44900
P1900	030.2Z	Rogaland	6550153,500	Yes	Pelton	2,500	1,740	44520
P1514	031.12Z	Rogaland	6570488,440	Yes	Pelton	1,650	0,927	44900
P2030	032.Z	Rogaland	6576885,660	No	Pelton/Francis	3,500	5,930	45530
P1317	033.2Z	Rogaland	6590785,760	No	Francis/Pelton	2,450	1,230	45870
P1269	036.Z	Rogaland	6626940,460	No	Pelton	0,460	0,125	46150
P2202	036.Z	Rogaland	6647028,970	Yes	Francis	4,000	2,710	46300
P1685	036.Z	Rogaland	6626661,820	Yes	Pelton	0,700	0,350	46300
P2038	037.3Z	Rogaland	6643425,590	No	Pelton	1,200	0,700	46610
P2346	037.5Z	Rogaland	6630810,000	No	Pelton	1,190	0,560	46150
P2239	038.21Z	Rogaland	6628537,070	No	Pelton	0,980	0,490	46150

Table S1. Cont.

P2004	038.2Z	Rogaland	6627912,210	No	Francis	5,730	3,430	46150
P0512	038.3Z	Rogaland	6638216,620	No	Pelton	4,250	3,100	46850
P2152	039.12	Rogaland	6616582,770	No	Pelton	0,530	0,300	46930
P2221	039.2	Rogaland	6617865,034	No	Pelton	1,040	0,500	46930
P2324	041.320	Rogaland	6646809,410	No	Pelton	0,488	0,488	46930
P1322	068.61	Sogn og Fjordane	6799195,190	Yes	Pelton	2,700	0,680	52860
P1298	073.11	Sogn og Fjordane	6800495,070	Yes	Pelton	2,000	0,340	54110
P2297	073.Z	Sogn og Fjordane	6784508,626	Yes	Francis	3,900	2,390	54420
P2107	074.4Z	Sogn og Fjordane	6812148,850	No	Pelton	2,100	1,380	54780
P1714	075.5Z	Sogn og Fjordane	6835827,390	Yes	Francis	5,000	3,360	55300
P1627	076.Z	Sogn og Fjordane	6853824,410	No	Pelton	0,930	0,550	55300
P2036	077.1Z	Sogn og Fjordane	6809734,880	No	Pelton	1,530	0,602	55770
P2025	078.6Z	Sogn og Fjordane	6823862,540	No	Brekke	1,500	0,840	55928
P2143	079.310	Sogn og Fjordane	6805652,600	Yes	Pelton	0,610	0,304	55928
P2022	079.54	Sogn og Fjordane	6812239,840	No	Pelton	2,500	1,790	52990
P2191	080.4Z	Sogn og Fjordane	6818001,520	No	Francis	2,100	1,340	52970
P2031	083.12Z	Sogn og Fjordane	6838548,610	No	Pelton	1,600	0,840	56780
P1206	083.4Z	Sogn og Fjordane	6843355,420	Yes	Pelton	1,900	1,080	56420
P1511	084.612	Sogn og Fjordane	6852547,230	No	Pelton	0,830	0,567	57660
P1638	084.72	Sogn og Fjordane	6852551,900	No	Pelton	0,900	0,618	57660
P1240	084.Z	Sogn og Fjordane	6841990,030	Yes	Pelton	0,980	1,140	57660
P1330	084.Z	Sogn og Fjordane	6850598,040	Yes	Pelton	1,920	1,070	57660
P1469	084.Z	Sogn og Fjordane	6840985,070	No	Francis	1,390	0,830	57660
P1534	084.Z	Sogn og Fjordane	6850910,250	No	Pelton	1,800	1,310	58320
P2088	084.Z	Sogn og Fjordane	6851086,720	No	Pelton	0,700	0,527	57660
P2105	084.Z	Sogn og Fjordane	6849280,060	No	Pelton	3,000	2,000	57660
P2153	084.Z	Sogn og Fjordane	6851729,020	No	Pelton	0,850	0,500	57660
P2124	084.Z	Sogn og Fjordane	6851382,430	No	Pelton	1,300	0,670	57660
P2164	085.3Z	Sogn og Fjordane	6866130,581	No	Pelton	0,800	0,513	57660
P1592	085.Z	Sogn og Fjordane	6873273,670	No	Francis	2,300	2,000	58320
P1611	086.81Z	Sogn og Fjordane	6888715,090	No	Francis	4,300	3,200	58320
P1256	086.8Z	Sogn og Fjordane	6877661,170	No	Francis	7,000	5,500	57990
P2093	086.920	Sogn og Fjordane	6879780,000	Yes	Pelton	0,700	0,380	57940
P1334	086.Z	Sogn og Fjordane	6870376,090	No	Pelton	1,900	1,370	57990
P1328	087.40	Sogn og Fjordane	6881345,250	Yes	Pelton	0,500	0,350	58390

Table S1. Cont.

P1476	087.5Z	Sogn og Fjordane	6884774,320	No	Pelton	3,500	1,620	58390
P1648	087.Z	Sogn og Fjordane	6877995,460	No	Pelton	1,900	1,370	58320
P1667	087.Z	Sogn og Fjordane	6867505,660	No	Pelton	1,100	1,080	57390
P1468	087.Z	Sogn og Fjordane	6868207,280	No	Pelton	1,800	1,150	58320
P1580	087.Z	Sogn og Fjordane	6869595,760	No	Kaplan	16,000	16,600	57390
P1777	087.Z	Sogn og Fjordane	6867833,020	No	Pelton	3,000	2,180	57390
P2104	087.Z	Sogn og Fjordane	6861789,040	No	Pelton	0,970	0,644	57390
P2309	087.Z	Sogn og Fjordane	6857174,580	No	Turgo	0,095	0,598	57660
P1868	087.Z	Sogn og Fjordane	6868103,990	No	Pelton	1,900	1,080	57390
P2286	088.31Z	Sogn og Fjordane	6892077,470	No	Pelton	1,920	1,240	58900
P2142	089.412Z	Sogn og Fjordane	6899608,891	No	Francis	1,610	0,880	58780
P1637	002.Z	Sør-Trøndelag	6950517,950	No	Kaplan	27,500	22,000	10600
P2299	119.411Z	Sør-Trøndelag	7037151,040	No	Francis	1,800	0,980	65230
P1656	119.60	Sør-Trøndelag	7047633,090	Yes	Pelton	1,150	0,660	65230
P1896	121.Z	Sør-Trøndelag	6991928,898	No	Pelton	1,350	0,270	66620
P1944	121.Z	Sør-Trøndelag	7000131,510	No	Pelton	0,780	0,490	66620
P1895	121.Z	Sør-Trøndelag	6977200,490	No	Pelton	0,730	0,430	66620
P1671	121.Z	Sør-Trøndelag	6998082,940	No	Pelton	0,600	0,350	66620
P1898	121.Z	Sør-Trøndelag	6961740,150	No	Francis	4,440	2,220	63705
P2089	121.Z	Sør-Trøndelag	6994690,810	Yes	Pelton	0,700	0,300	66620
P2259	123.Z	Sør-Trøndelag	6997037,631	No	Pelton/Francis	4,000	0,872	68420
P2283	123.Z	Sør-Trøndelag	7003570,194	No	Pelton	4,400	1,600	68420
P2333	123.Z	Sør-Trøndelag	6995975,162	No	Pelton	2,120	1,060	68420
P2129	136.Z	Sør-Trøndelag	7123914,255	No	Pelton	0,342	0,760	71900
P2114	137.2Z	Sør-Trøndelag	7134774,917	No	Francis	0,800	2,030	71810
P2234	016.Z	Telemark	6645119,774	No	Pelton	0,700	0,350	33890
P2252	016.Z	Telemark	6598297,332	No	Francis	1,700	0,630	30380
P2270	019.Z	Telemark	6581314,100	No	Francis	1,600	0,960	37740
P2260	190.3Z	Troms	7619170,337	No	Pelton	3,350	2,420	88100
P2246	196.Z	Troms	7620773,145	No	Pelton	2,120	0,960	89650
P2235	196.Z	Troms	7645308,720	No	Pelton	3,080	1,030	89350
P2236	198.72	Troms	7717598,260	No	Pelton	2,850	1,240	90510
P2314	203.73	Troms	7729009,960	No	Pelton	1,640	0,820	91150
P2330	203.7Z	Troms	7728593,340	No	Francis	5,130	2,318	91380
P2231	203.Z	Troms	7703736,380	Yes	Pelton	3,300	1,460	91080

Table S1. Cont.

P2293	204.82	Troms	7695744,760	No	Pelton	1,600	0,870	91380
P2200	204.92	Troms	7702327,097	No	Pelton	0,727	0,330	91380
P2210	204.Z	Troms	7688221,450	No	Pelton	0,920	0,410	91380
P2262	210.3Z	Troms	7784568,850	No	Pelton	2,300	1,180	91380
P1919	022.Z	Vest-Agder	6527500,492	No	Pelton	0,480	0,209	41550
P2053	022.Z	Vest-Agder	6513934,770	No	Francis	1,700	0,715	41200
P2140	023.Z	Vest-Agder	6487185,240	No	Francis	1,300	0,670	41200
P1660	023.Z	Vest-Agder	6471945,390	No	Pelton	1,250	0,800	41200
P1700	023.Z	Vest-Agder	6480717,000	Yes	Francis	3,000	1,600	41200
P1904	025.Z	Vest-Agder	6516252,500	Yes	Francis	3,500	2,190	42520
P1419	025.Z	Vest-Agder	6524783,970	No	Pelton	1,800	1,140	42520
P1439	025.Z	Vest-Agder	6493610,260	Yes	Pelton	0,600	0,400	41860
P1917	025.Z	Vest-Agder	6518149,570	Yes	Francis	0,900	0,450	42520
P2035	025.Z	Vest-Agder	6496312,890	No	Pelton	2,700	1,360	41860
P2251	025.Z	Vest-Agder	6512604,090	No	Francis	5,700	2,700	42520
P1926	026.Z	Vest-Agder	6523342,370	Yes	Francis	2,050	1,410	42810
P2281	026.Z	Vest-Agder	6518987,530	Yes	Francis	5,100	4,900	42810
P1473	026.Z	Vest-Agder	6518699,910	Yes	Pelton	1,400	0,900	42810

Table S2. Numerical results for the generalized additive model (equation 1 in the main text) fitted to the daily precipitation data (P). SE = Standard Error, EDF = estimated degrees of freedom, DE = deviance explained.

Parameter	Estimate (SE)	t-value	EDF	F-value	P-value
Intercept	5.12 (0.04)	121.7			<0.0001
DoY, La			10.95	285.2	<0.0001
N = 48068	DE = 6.1%				

Table S3. Numerical results for the generalized additive model fitted to the hourly production data for Pelton plants (equation 2 in the main text). SE = Standard Error, EDF = estimated degrees of freedom, DE = deviance explained.

Parameter	Estimate (SE)	t-value	EDF	F-value	P-value
Intercept	1.33 (0.001)	1131			<0.0001
H, La			10.99	335.7	<0.0001
W, La			9.99	2815.6	<0.0001
DoY, La			10	24453.6	<0.0001
N = 1576620	DE = 15.3%				

Table S4. Numerical results for the generalized additive model fitted to the hourly production data for Francis plants (equation 2 in the main text). SE = Standard Error, EDF = estimated degrees of freedom, DE = deviance explained.

Parameter	Estimate (SE)	t-value	EDF	F-value	P-value
Intercept	1.49 (0.002)	674			<0.0001
H, La			6.62	14.01	<0.0001
W, La			10	1357.18	<0.0001
DoY, La			10	2000.09	<0.0001
N = 604371	DE = 5.4%				

Table S5. Numerical results for the generalized additive model fitted to the hourly production data for Kaplan plants (equation 2 in the main text). SE = Standard Error, EDF = estimated degrees of freedom, DE = deviance explained.

Parameter	Estimate (SE)	t-value	EDF	F-value	P-value
Intercept	0.93 (0.003)	287.7			<0.0001
H, La			2	20.27	<0.0001
W, La			9.85	130.87	<0.0001
DoY, La			9.97	436.42	<0.0001
N = 61313	DE = 9.4%				

Table S6. Numerical results for the generalized model (equation 3 in the main text) fitted to the daily production data as a function of precipitation, day of the year and geographic location for each turbine type (A−C). Note that production and precipitation were natural log transformed. Note also that due to the low number of Kaplan plants the two-dimensional smoother was replaced by a HP factor. SE = Standard Error, EDF = estimated degrees of freedom, DE = deviance explained.

(A) Pelton

Parameter	Estimate (SE)	t-value	EDF	F-value	P-value
Intercept	2.69 (0.005)	532.1			<0.0001
P			1.98	2208	<0.0001
DoY			4	3048	<0.0001
Lo, La			10.83	277	<0.0001
N = 65604	DE = 23.2%				

(B) Francis

Parameter	Estimate (SE)	t-value	EDF	F-value	P-value
Intercept	2.76 (0.009)	294.7			<0.0001
P			1.93	462.6	<0.0001
DoY			3.99	205.8	<0.0001
Lo, La			10.88	67.1	<0.0001
N = 25146	DE = 9%				

(C) Kaplan

Parameter	Estimate (SE)	t-value	EDF	F-value	P-value
Intercept	2.38 (0.061)	38.95			<0.0001
P1524	−1.14 (0.086)	−13.22			<0.0001
P1580	0.87 (0.087)	10.09			<0.0001
P1637	0.48 (0.087)	5.48			<0.0001
P2196	0.93 (0.087)	10.73			<0.0001
P2315	−0.82 (0.087)	−9.45			<0.0001
P2334	0.57 (0.086)	6.65			<0.0001
P			1	58.87	<0.0001
DoY			3.60	19.73	<0.0001
N = 2555	DE = 32.4%				

Table S7. Numerical results for the generalized linear model (equation 7 in the main text) fitted to the data on number of starts as a function of annual discharge, precipitation and license for each turbine type (A−C). Note that in the case of Pelton a quadratic term was included in the model. Note also that for Kaplan turbine two separate NB-GLM were fitted due to the low number of cases that prevented fitting the full model (eq. 7 in the main text). Interactive effects are shown only if they were statistically significant.

(A) Pelton

Parameter	Estimate (SE)	z-value	P-value
Intercept	2.97 (0.13)	23.48	<0.0001
QR	−2.17 (0.92)	−2.36	0.01818
QR^2	−3.39 (0.96)	−3.53	0.0004
P	0.07 (0.02)	3.68	0.0002
L*	−0.35 (0.15)	−2.30	0.0214
QR:L	4.09 (1.86)	2.20	0.0282
QR^2:L	1.84 (1.92)	0.95	0.3403

*Note that the reference level for License (L) is yes (Y).

(B) Francis

Parameter	Estimate (SE)	z-value	P-value
Intercept	3.58 (0.20)	17.98	<0.0001
QR	−0.27 (0.12)	−2.33	0.0196
P	0.02 (0.03)	0.69	0.493

(C) Kaplan

Parameter	Estimate (SE)	z-value	P-value
Intercept	3.70 (0.73)	5.06	<0.0001
QR	0.15 (0.34)	0.44	0.661
Intercept	2.37 (0.75)	3.17	<0.0015
P	0.41 (0.18)	2.24	0.0252

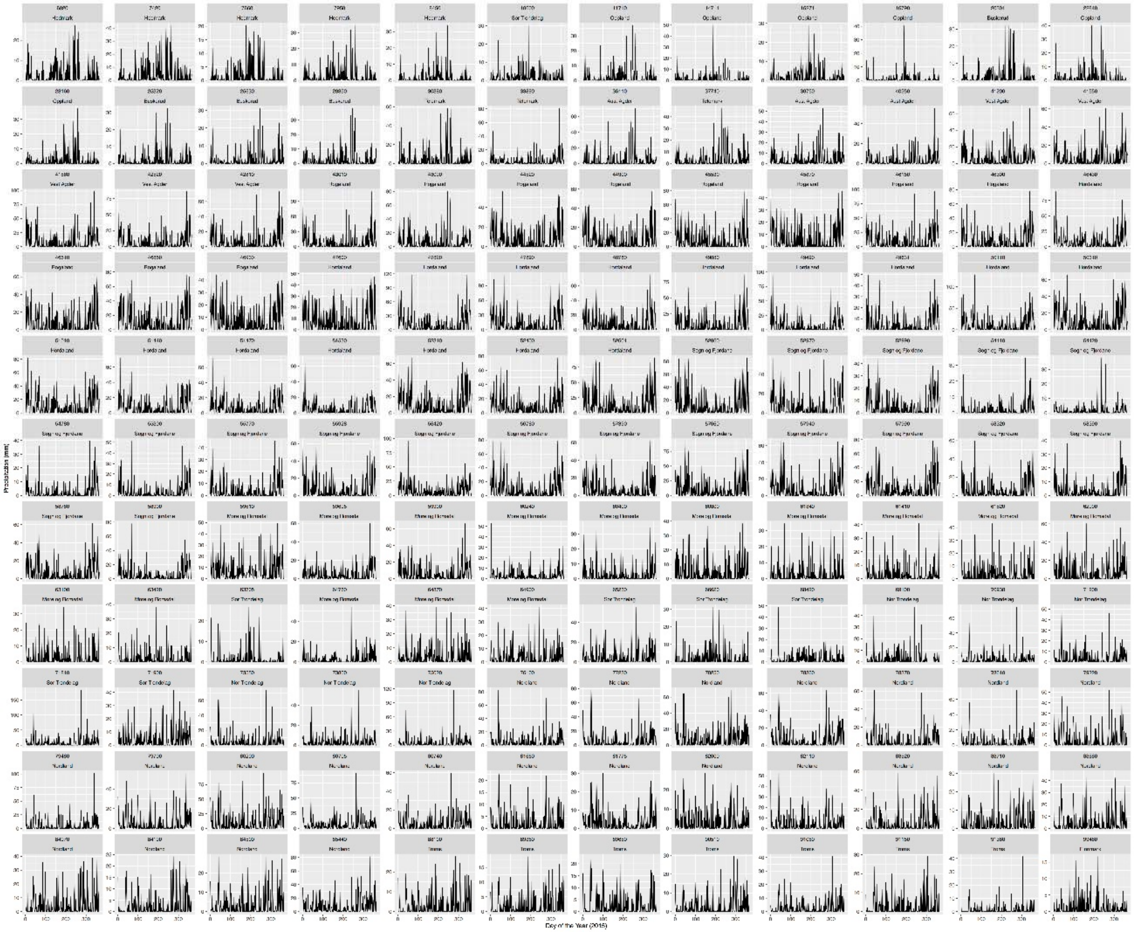

Fig. S1. Daily precipitation recorded in each weather station as downloaded from http://met.no. Numbers on top correspond to each station's code as classified on the web page (see Table S1 to match with the corresponding river).

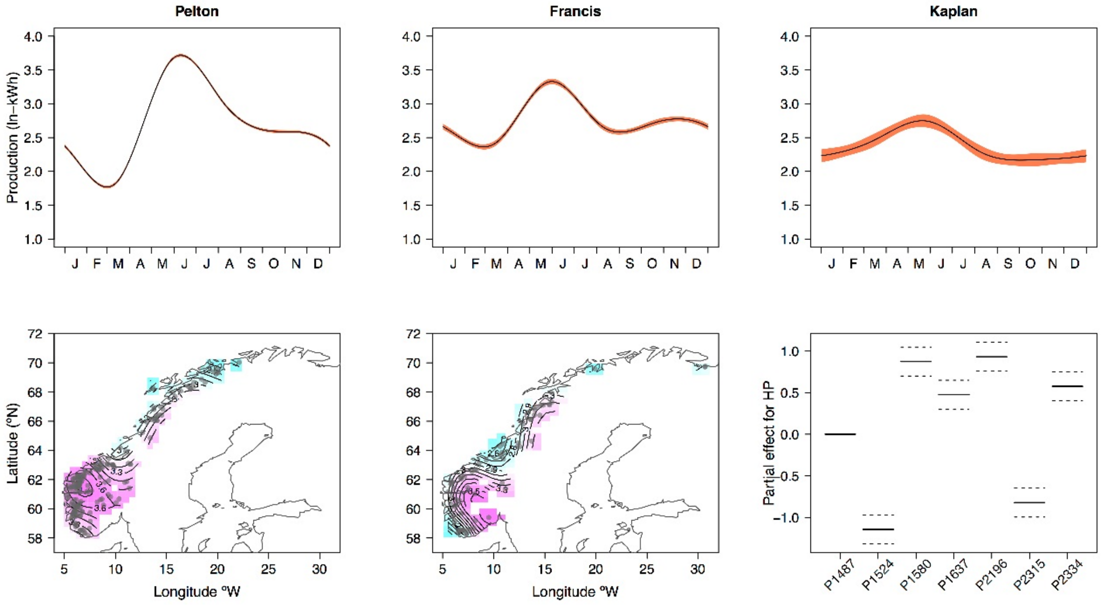

Fig. S2. Illustration of model depicted in Table S6 complementary to plots shown in Fig. 7 in the main text. Note that for Kaplan turbine the low number of observations prevented the fit of a geographic smoother thus HP wast treated as a factor (P-codes can be identified in Table S1).

NVE

Norwegian
Water Resources and
Energy Directorate

Norwegian Water Resources
and Energy Directorate

Middelthunsgate 29
Postboks 5091 Majorstuen
0301 Oslo

Telephone: 09575
Internet: www.nve.no