HydroCen
NORWEGIAN RESEARCH CENTRE
FOR HYDROPOWER TECHNOLOGY

CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

HydroCen Report nr. 21

ValueFlex – the value of flexibility

Pre-project under Open Calls in FME HydroCen

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NTNU SINTEF NINA

HydroCen

The main objective of HydroCen (Norwegian Research Centre for Hydropower Technology) is to enable the Norwegian hydropower sector to meet complex challenges and exploit new opportunities through innovative technological solutions.

The research areas include:

- Hydropower structures
- Turbine and generators
- Market and services
- Environmental design

The Norwegian University of Science and Technology (NTNU) is the host institution and is the main research partner together with SINTEF Energy Research and the Norwegian Institute for Nature Research (NINA).

HydroCen has about 50 national and international partners from industry, R&D institutes and universities.

HydroCen is a Centre for Environment-friendly Energy Research (FME). The FME scheme is established by the Norwegian Research Council.

The objective of the Research Council of Norway FME-scheme is to establish time-limited research centres, which conduct concentrated, focused and long-term research of high international calibre in order to solve specific challenges in the field.

The FME-centres can be established for a maximum period of eight years HydroCen was established in 2016.

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Abstract

The ValueFlex pre-project has collected and summarized current research provided by the HydroCen research partners on the topic of valuation of flexibility from hydropower. We found that existing knowledge from the technology (turbine, generator and structures) and environmental perspective were fragmented and did not address the value of flexibility directly. More insight on the topic of valuation of flexibility was found in the field of optimal production scheduling and energy system modelling. This was expected since this angle typically constitute the use of modelling and optimization to analyse trends and development of the energy and power system, price formation and optimal operations. In total, we found no holistic approach that covered the value of flexibility from an integrated perspective including the value of components, construction, market and services and environmental and social concerns. We did find, however, that there is a lot of work in HydroCen that gives individual pieces of knowledge that together will advance the understanding of the value of flexible hydropower. The pre-project has thus proposed an Open Calls proposal that will give the first steps in putting these pieces into a common framework. In addition, HydroCen has established an interdisciplinary group that will focus on the value of flexible hydropower, that will serve as a discussion group to generate new activities on the topic.

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Content

Foreword

This work has been funded by HydroCen and with broad participation from the disciplines in HydroCen. A special thanks to the WP-leaders in HydroCen for gathering information that is used as foundation of this work and for their comments and participation in the project workshops. Thanks also to my co-authors that have contributed significantly to this report.

2021-12-15 Michael Belsnes

1 Introduction

In 2019, users in FME HydroCen proposed that the centre should start research activities that focused on assessing the value of hydropower flexibility.

To initiate this work, it was proposed and approved by the board, to start a small pre-project and challenge a group of experts within FME HydroCen to gather existing information and knowledge on the topic of 'flexibility' within their respective competence areas. In parallel, the management group wanted to use a cross-disciplinarity approach where all the WP-leaders were involved and contributed to gathering the existing knowledge and providing their findings to inform the joint impact on further work. As such this project followed in the footsteps of the AlternaFuture project.

The aim of the ValueFlex pre-project was therefore defined as the task of collecting and synthesising existing knowledge in HydroCen and identifying any missing pieces for assessing the value of hydropower flexibility, as well as to suggest further steps needed for connecting the pieces in a holistic approach to value estimation.

It should be noted that both in this memo and in the work that has been discussed, the value of hydropower flexibility is understood as economic value of hydropower flexibility. The reason is to make it possible to compare different metrics such as revenues contra environmental impact, increased lifetime contra maintenance cost etc. An economic value can be negative and represent a cost rather than a revenue.

2 Work description

The approach to the work was to involve selected HydroCen experts representing all the work packages in HydroCen. They were given the challenge to find existing research within their field that was relevant for assessing the value of hydropower flexibility, with particular emphasis on the work from HydroCen partners, and with a focus on resent research from within the last 5 years.

Participants in the survey phase was:

- From WP1, Hydropower constructions, Prof. Leif Lia (NTNU)
- From WP2, Hydropower machinery, turbines and generators, Prof. Arne Nysveen (NTNU)
- From WP3, Market and services, Chief Scientist, Birger Mo (SINTEF)
- From WP4, Environmental design: Senior Researchers Torbjørn Forseth (NINA) and Atle Harby (SINTEF)

The information was collected in the project folder for ValueFlex on the HydroCen SharePoint. A small workgroup consisting of Ellen Krohn Aasgård and Michael Belsnes went through the collected information and identified four topics relevant for hydropower flexibility: 1) electric machinery, 2) machinery, 3) improvements in scheduling and 4) ecosystem and environmental impacts. A short memo with a summary of the findings for each topic was compiled by the working group and shared with the experts for adjustments and additional inputs. These memos can be found in App. 1-4.

To capture the complete research frontier within these four thematic areas, full-scale literature search could have been performed, but this was never the mandate or aim of the ValueFlex pre-project. Rather, the approach that was chosen (i.e., making use of the combined knowledge of the HydroCen experts) was a trade-off between workload and efficiency, and gave valuable information for outlining a way to assess the value of flexibility based on the existing knowledge base in HydroCen. The collection of materials also gave insights into knowledge gaps and thereby input for how to define new research activities to fill these gaps when taking on an integrated approach to the value assessment.

From the material that was collected, it became clear that there exist a lot of relevant research on technical aspects of hydropower constructions and machinery, as well as relevant methods for calculation of revenues, including socioeconomic models for the power system, and not least the legacy from CEDREN and HydroCen on environmental design. But we found very little on an integrated methodology for calculation of the actual value of flexibility.

The work group also assessed other types of documents. For instance, Statnett has published a report highlighting the value (the term "value" could have been replaced with the term "importance" here) flexible hydropower has for balancing the power grid [1]. Other documents also stress the importance of hydropower flexibility, for instance the policy document [2], where it is stated: "Flexible hydropower gives good resource use by itself, but also helps providing better market conditions for wind and solar power". Even so, the actual *value* of flexible hydropower is not quantified in these documents, and there is also a question of what types of value should be included in such calculations. It could be value (revenues) for individual power companies, or it could be the societal value of secure and stable power supply, which has a much wider scope.

The next step in the project work was therefore to figure out how to define a quantifiable method to value the importance of hydropower flexibility. How would the competence in HydroCen, represented by the research partners SINTEF, NINA and NTNU, answer to this challenge? The ValueFlex pre-project organized a workshop with the project group, where also the management was invited, to give their best advice on how to establish a systematic methodology for putting a value on hydropower flexibility. Based on the summary for the four technical research topics, the challenge to the group of scientists were: Given that the methodology must incorporate the best available methods and current state of knowledge for the different fields, as well as provide reproduceable results: where should we start?

The result from the workshop is summarized in Figure 1, shown below. The pyramid defines the objective and scope at the top ("Målsetting"), before going into main aspects and topics to be included ("Hovedtema"), subtopics ("Undertema") and competences/building blocks ("Puslespillbrikker") required that are either already available in HydroCen, work in progress or missing.

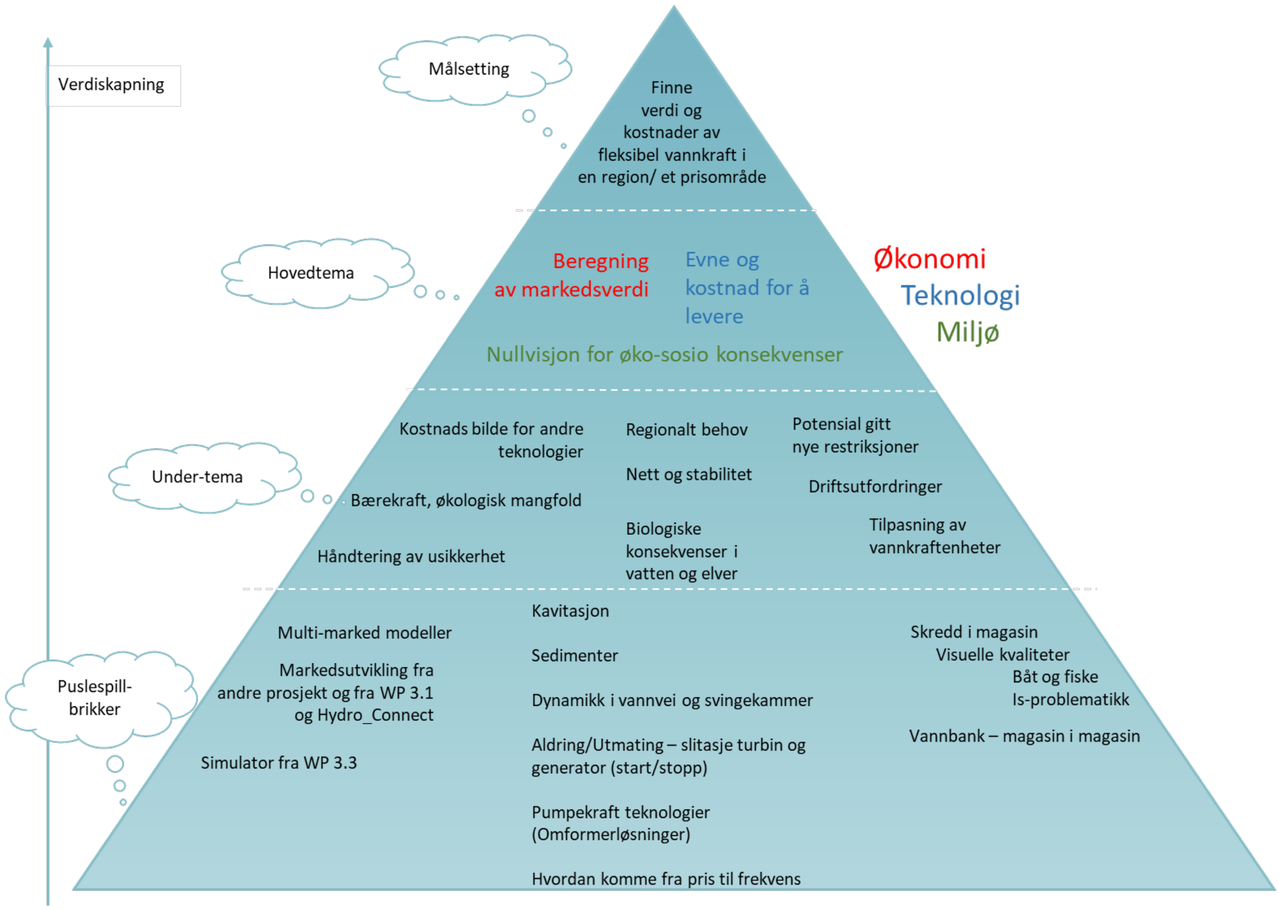

Figure 1: Summary of findings from workshop

A conclusion from the workshop and collection of materials was that there is a need for a systematic approach to valuing flexibility and that the methodology of most value to FME HydroCen and partners is a bottom-up approach starting with assessing the flexibility of a single watercourse or the value of flexibility within a limited area, such as within a price zone.

A working group consisting of Ellen Krohn Aasgård, Arne Nysveen, Arild Helseth, Tonje Aronsen and Michael Belsnes compiled the results from the workshop into a project proposal called "Metrics for sustainable flexibility from hydropower", which propose an assessment system that will define and collect comparable metrics for the different aspects of flexible hydropower and present them in a common framework. The new project extends an ongoing Open Calls project in HydroCen called "Flexibility Metrics" that will develop metrics using the hydropower scheduling model ProdRisk. The new proposal will extend the approach in Flexibility Metrics to include environmental, technical and socioeconomic aspects also. The assessment system will be applied to case studies of individual watercourses.

The draft-proposal was also discussed and further elaborated in the multi-disciplinary group for flexibility that HydroCen has started up this fall. This group has a broad basis of participants from all the research areas in HydroCen. The resulting proposal for a common assessment system for sustainable flexibility from hydropower was sent to HydroCen 2021-09-25 as an OpenCalls proposal. The full proposal can be found in App. 5.

3 Findings

This Chapter summarises the findings from the different research fields contributing to ValueFlex.

3.1 Recommendations for Electric Machinery

From the information collected it seems that the knowledge base and research in Norway and HydroCen is concentrated on improving and solving specific technology challenges. While it shows a deep understanding and contribution to the technology frontier of pumped storage hydropower and its connection to the power grid, there is little information that connects it to the other aspects in HydroCen, such as environmental design and economic feasibility and potential, operation strategies and the role of variable speed solutions in the future energy system.

The aspects of traditional machines also have potential of improvements, cost reductions, increased robustness, etc. Suppliers of hydropower generators has worked with improving the design for more flexible operation. The improvements have the same benefits for both constant and variable speed designs and are related to the mechanical design of stator housing as well as how windings are fastened.

Some research questions regarding the concept of 'flexibility' are:

- What value (revenue potential) will hydropower get in return for flexibility services? This will inform the decision on if/when/how to invest in flexible machinery.
- What is the potential for integrating RES in a hydro-dominated energy system (like the Nordic), compared to other systems?
- How will new operation patterns impact maintenance cost and fault probability?
  What can be done to drive down costs and become more competitive? Especially what can be done in parallel to cost reductions on frequency converters, which WP 2.1 is currently working on.
- Will new solutions have other benefits that should be counted with respect to emissions, durability, circularity?

3.2 Recommendations for Machinery

With the respect of the HydroCen's ambition of increasing the value potential there seems to be a gap between the technology research and the economic research:

- HydroCen and related projects have provided several advancements of technical and mechanical equipment, but the research needs to be more tightly linked to economical modelling so that future technical research can be more focused on solving challenges that are important for ensuring and increasing future revenue streams from hydropower operations. Economical modelling is needed to determine what those revenue streams are and thus further what those challenges are.
- Economic research should to a larger extent capture the true cost of hydropower operation when switching from a stationary to a flexible operation. Inclusion of wear and tear in daily operation will to a larger extent be important for the future operational decisions.

3.3 Recommendations for Scheduling

With respect to HydroCen's ambition of increasing the value potential for hydropower from optimal utilization and scheduling of hydropower, the most important areas for future research within this field is:

- Continuing to pursue improved modelling of hydro and other technologies (including transmission, market coupling, thermal units, increased uncertainty, and generation variation from intermittent renewables as well as flexibility from alternative energy technologies and demand side) in fundamental market models for hydro-dominated power and energy systems. Including variability and flexibility on shorter time scales and with more detailed characteristics will give tools that are better suited to analyse the value/cost of flexibility from hydropower.

- Continue to improve the precision and speed of scheduling models both for individual hydro operators (producer perspective) and investment/system analysis (system/market perspective), potentially also utilizing new algorithms and hardware. For daily planning there is a need to develop planning tools and methods that are precise enough to be used in automatic and autonomous scheduling processes, and fast enough to be used for scheduling and re-scheduling in markets with shorter-time resolutions. For system/market and investment analysis, more efficient or new methods could allow for more detailed modelling of alternative technologies and demand-side response which will give better quality results for prices of electricity and related flexibility products, and therefore also the value of flexibility from hydropower.
- Establish consistent data sets and scenarios that represent the future power and energy system and pathways for the transition. This includes data for relevant energy producing technologies and interconnectors as well as climate and weather patterns relating to inflow, wind and solar irradiance at various regional/local resolutions. Data sets must also represent the demand side, i.e., expected future energy use in different sectors including the available flexibility from demand-side response. These high-quality data sets should be used together with efficient mathematical models to produce scenarios for future prices that will serve as the basis for analysis, investment decisions and operations.

3.4 Recommendations Ecosystem and Environmental impact

Recent research, also research within HydroCen, have shown that it is possible to quantify loss and gain in environmental conditions and outcomes, such as number of salmon smolts, square meters of available spawning grounds for fish, increased number of days suitable for kayaking, decreased flood risk or increased recreational use of rivers. However, it has so far not been many studies that are able to quantify this in monetary values. With respect of HydroCen's ambition of increasing the value potential from hydropower for ecological and environmental aspects, the most important areas for future research within this field are:

- Continuing to pursue an integrated, holistic approach to the management and regulation of hydropower rivers.
- Developing systematic methods, tools and knowledge and apply them to specific case studies in order to quantify loss and gain in environmental conditions and outcomes.
- Advancements in methods for combining, representing, and retrieving knowledge such as Bayesian networks and other data-driven approaches. Expand the holistic view with socioeconomic aspects.
- Consider aspects of climate change mitigation with respect to flood control and draught management.

4 Discussion

The ValueFlex pre-project has collected and summarized relevant work from HydroCen on the topic of valuation of flexibility, and identified knowledge gaps and "building blocks", i.e. existing knowledge. The expert group in ValueFlex has proposed a methodology for valuating flexibility from hydropower which gave the foundation for development of a new, interdisciplinary Open Calls project, "Metrics for sustainable flexibility from hydropower".

However, the project has not answered all the questions and aspects of valuating hydropower flexibility. In this part of the report, we will therefore discuss the relation between the work done in the pre-project and the questions originally asked by user partners in HydroCen, as well as current and proposed future work in HydroCen to further answer these questions.

In the summary of questions from the user partners as of 2019, the objective was to find the value of flexible hydropower. It was proposed that this could be done by the following activities:

1. Mapping the current state of knowledge: what do we have of relevant models, knowledge, and scenarios for the development of the power system towards 2050?
2. Build realistic scenarios for future power systems and markets in Europe and Norway's integration in this.
3. Run models to study the role of Norwegian flexible hydropower in such scenarios, as well as further develop suitable models and / or point out new development needs for the models.
4. Study the sensitivity of concession restrictions on operations of Norwegian hydropower plants, e.g., reservoir restrictions, up/down and minimum water flows.
5. Study the price effects of new interconnector cables
6. Optimize operational patterns for flood mitigation and power generation
7. Identify and prioritize topics that needs more research, i.e., in topics such as market, technology, environment, hydrological forecasting, etc.

It was verified during the ValueFlex project that finding the value of flexible hydropower is a large and complex challenge that requires almost all research efforts in HydroCen and several related projects to set up a methodology that can be proved and repeated. Flexibility has been and is a strategic research area in HydroCen which has been emphasized in the updated strategy HydroCen developed just before the mid-term evaluation. Therefore, in the autumn of 2021, an interdisciplinary group of researchers has been established that will work specifically towards flexibility, under the heading "Norwegian hydropower in Norway and Europe". The aim is that the research done in HydroCen can contribute to the competence base on these issues to provide better answer during the remaining time of the centre and in new related projects.

We do not believe that the solution is to gather all aspects of flexibility valuation into the same project, as this will be too large, both within the framework HydroCen exemplified by Open Calls, but also requires increased focus on finding additional funding from NFR, the power industry or other instruments. Therefore, we must divide the topic and the list of questions into smaller activities, building blocks as we have referred to them in ValueFlex. If we can define relevant and concise projects and activities that work towards common goals, we will be able to provide better quantification of the flexibility value. The interdisciplinary group on flexibility will also ensure that HydroCen develops a coherent project portfolio that together provides answers to the question of the value of flexibility - and that the results from these projects are compiled in a way that makes actors see the benefits across several projects.

The list of activities that EnergiNorge set up in 2019 is a good starting point for defining new activities that will address several aspects of flexible hydropower. We already have significant activity in HydroCen that answers some of the points as well as proposals for new Open Calls, see the list below:

1. Mapping the current state of knowledge: what do we have of relevant models, knowledge, and scenarios for the development of the power system towards 2050?

As described in this report, the ValueFlex pre-project has reviewed results from the various work packages in HydroCen and searched for results that focused specifically on the value of flexibility. We have found few results that directly assess the value, and it has also been challenging to summarize results from each individual field into something holistic. We believe that it is a good approach to involve experts in the review to reveal the most important key topics to investigate and the trends in the ongoing research.

2. Build realistic scenarios for future power systems and markets in Europe and Norway's integration in this.

This task is particularly challenging, as it requires deep insights in energy and power market/system dynamics period to create consistent pathways and assess their impact on the power system, and the uncertainty is large. Work on future power system/market scenarios is carried out and presented publicly on a regular basis by companies such as Statkraft, Statnett, NVE and the European commission and the Member states through their national energy and climate plans (NECP's). SINTEF adapted scenarios from CEDREN Hydrobalance for the Northern-European power system at the stage 2030 within HydroCen WP3.1. This work was completed in 2019 and has been extensively used within HydroCen for price prognosis. This fall, an Open Calls proposal was submitted, which aims to update some of what was done in WP3.1 in HydroCen. This open call project aims at providing price forecasts that include a more realistic description of uncertainty, enabling better price prognosis, and consequently a more correct valuation of hydropower flexibility. This will add relevance to the calculation with the tools developed in WP 3.3 and WP 3.4.

3. Run models to study the role of Norwegian flexible hydropower in such scenarios, as well as further develop suitable models and / or point out new development needs for the models.

In several of the ongoing projects between HydroCen and the US, the topic is to compare different models and modelling tools for hydropower operations and power markets. This work will provide insights into alternative model formulations and opportunities/challenges for further development of tools applied in Norway and HydroCen.

SINTEF has developed a toolchain of prototype models, including the Fansi and Primod models, that has promising properties for performing system studies and price forecasting in the future power market. This toolchain is actively employed in existing SINTEF-led research projects, such as HydroConnect, SumEffekt and Vannfly. Activities where the modelling tools are used to analyse scenarios and the consequences for hydropower can defined as separate projects, possibly in connection to the updates to the prices from 3.1 described in point 2. This is however not part of the submitted proposal in this stage.

4. Study the sensitivity of concession restrictions on operations of Norwegian hydropower plants, e.g. reservoir restrictions, up/down and minimum water flows.

The study of new environmental constraints following renewed hydropower concessions is the topic of HydroCen WP3.4. Both the mathematical modelling within hydropower scheduling tools and the assessment of the impact of such constraints on the producers' revenues are addressed in WP3.4.

The project proposal "Metrics for sustainable flexibility from hydropower" mentioned earlier in this report aims to provide answers to this as part investigating the trade-off between various indicators. This work will analyse how new regulations impact operating patterns and reserve capability, in other words, the effect of different environmental restrictions on the ability to deliver flexibility.

5. Study the price effects of new interconnector cables
This topic is addressed within the recently initiated and SINTEF-led HydroConnect project. The Hydro-Connect project will build on data developed in earlier projects as well as within HydroCen and will apply the prototype fundamental market models Fansi and Primod to analyse the effects on prices. It focuses on the price and environmental impacts of new interconnectors between Norway and the European continent.

6. Optimize operational patterns for flood mitigation and power generation
We are also in the process of starting up IPN SamVann, which is a continuation of the work on flood costs in HydroCen WP 3.5. This project looks at the value of flood mitigation provided from hydropower and will work mostly on finding cost functions for different types of land use and infrastructure that are affected by floods. The project does not contain development of production scheduling tools to reduce floods, because the power producers wanted to have this as a separate project. The knowledge about costs/value of flood mitigation that SamVann will provide will be an important input for planning and scheduling as well. EnergiNorge is leading this project.

7. Identify and prioritize topics that needs more research, i.e., in topics such as market, technology, environment, hydrological forecasting, etc.
This is done continuously in all forums in HydroCen: in the WPs, Executive Management Team (EMT), strategy meetings, etc. The four strategic research areas, defined in the current strategy, are a result of this type of work. The strategy are further operationalized in the new interdisciplinary groups that are established. The project proposal "Metrics for sustainable flexibility from hydropower" will also contribute directly to this. By defining various indicators and putting them together, it will be possible to identify where there are knowledge gaps and which connections that are not fully understood. The work with the HydroCen "Kunnskapsbank" will also contribute this, as it will facilitate sharing of knowledge across HydroCen and to stakeholders.

To conclude, we have found that there is a lot of knowledge in HydroCen that constitute specific building blocks for making a methodology for integrated valuation of the flexibility of hydropower. However, there are some knowledge gaps and also a need for more coherent methods for presenting results from the different WPs and topics towards valuation of hydropower. There is a need to make the research and new knowledge that is created assessable for user partner and other stakeholders. The common frameworks and tools that are currently being developed in HydroCen is a good start, i.e., TwinLab (data management platform), Kunnskapsbanken and the new proposed project on metrics.

5 References

[1] Statnett, "Verdien av regulerbar vannkraft -Betydning for kraftsystemet i dag og i fremtiden", Mars 2021 Dok. 20/00565
[2] NOU, “Skattlegging av vannkraftverk, Norges offentlige utredninger”, 2019:16, ISBN 978-82-583-1413-1

Appendices

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ValueFlex – Electric Machinery

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APPENDICES

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1 Material

Material uploaded to the ValueFlex folder on NVKS Teams is listed below

CFSM Vibration TMAG'17.pdf	31. juli 2020	Liv Randi Hultgreen
Gov11 Electric Norway_11844 Pro.pdf	31. juli 2020	Liv Randi Hultgreen
Variable-speed_IAS Magazine-no5_2018.pdf	31. juli 2020	Liv Randi Hultgreen

2 Summary of the material

2.1 Document 1: Influence of Converter Topology and Carrier Frequency on Airgap Field Harmonics, Magnetic Forces, and Vibrations in Converter-Fed Hydropower Generator

This is a journal paper in IEEE transactions on industry applications.

The paper states the importance of understanding the airgap field harmonic with respect to appliance of power electronics in variable speed hydropower units. The argument is that variable speed technology can help the system accommodate more variable renewables such as wind and solar power because of the broader operation intervals for this technology. The conclusion is that although converter design impact on airgap harmonics hence vibration and short-term dynamics of the unit this manageable due to the larger inertia in the hydropower unit.

There is no translation from the technical aspects to the cost aspects on building maintaining and operation hydropower plants with variable speed compared to standard technology. The publication says nothing about potential of the technology neither technical or economical.

2.2 Document 2: Electricity for the Future

This is a two-page flyer giving a popular science introduction to the importance of electricity in the future power system, followed by an introduction to initiatives in NTNU such as the smart grid centre and HydroCen as well as the Department of Electric Power Engineering. There is no quantification regarding value of hydropower flexibility in the flyer.

2.3 Document 3: Variable-Speed Operation of Hydropower Plants

Article in the IEEE Industry Applications Magazine

The paper points to three benefits from variable speed technology:

- Load control of power in pumping mode allowing units in pumping mode to participate in primary and secondary control.

- Increasing efficiency in turbine mode providing better part-load efficiency.
- Drive down cost for small scale hydro by enabling less complex turbine design.

With respect to the system benefit the paper points to:

- Adding flexibility in pumping mode faster than alternatives such as multi-pump applications.
- Improving grid stability especially in week grids.
- Pumping capability will reduce the amount of wind curtailment.

The paper also quantifies the technical improvement of variable speed technologies:

- The improvement in the plant operation is estimated to between 3-10% efficiency gain compared to fixed speed installations.
- Variable speed will increase the typical operation area of the pump operation from 1.25 between minimum and maximum pumping head to as much as 1.45.
- The pump power variation capability with variable speed technology is 30-40%

It is estimated that the additional investment cost of a pumped storage project with variable speed is plus 7-15% of the total investment cost. The lower rate is connected to DFIM (Double Fed Induction Machine) configuration with about a converter size around 30% rated unit capacity compared to CFSM (Converter Fed Synchronous Machine) where the rating of the power electronics must match the rating of the unit.

Despite the higher cost of CFSM solution this is expected to be the main technology used due to its superior performance and cost reduction on power electronics in general

The business case for the technology, the ability to cover the cost and make a profit delivering energy and ancillary services is not quantified and discussed.

The market mechanisms needed to boost application of the technology is not discussed, and the technology is not compared to other technical solutions that can deliver similar services to the grid

3 Future challenges

From the information collected it seems that the knowledge base in Norway and HydroCen is tied to the technology research. While it shows a deep understanding and contribution to the technology frontier of pumped storage hydropower and its connection to the power grid there is little information that connects it to the other axis in HydroCen, environmental design and economic feasibility and potential, operation strategies and the role of variable speed solutions in the future energy system.

The aspects of traditional machines are also have potential of improvement, cost reductions, increased robustness, etc.Suppliers of hydro power generators has worked with improving the design for more flexible operation. The improvements have the same benefits for both constant and variable speed designs and related to the mechanical design of stator housing as well as how windings are fastened.

Some research questions are:

- What will the value hydropower will get in return for these services?
- What are the RES integration potential of hydropower?
- How will operation patterns impact on maintenance cost and fault probability?

- What can be done to drive the cost down and become more competitive? Especially what can be done in parallel to cost reductions on frequency converters which WP 2.1 is currently working on.
- Will this solution have other benefits that should be counted with respect to emissions, durability, circularity.

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APPENDICES

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1 Material

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	Navn	Endret	Endret av	TeamSite
	Dynamic loads in Francis runners and their i...	11. juni	Ole Gunnar Dahlhaug	Rommal
	Impact from flexible operations on High He...	26. juni 2018	Ole Gunnar Dahlhaug	Rommal
	Pressure Pulsation and Stresses in a high he...	27. juni 2018	Ole Gunnar Dahlhaug	Rommal

1.1 Summary of the material

1.1.1 Document 1

Conference contribution to Earth and Environmental Science: Dynamic loads in Francis runners and their impact on fatigue life

The paper states the fatigue mechanisms and show how better management of start-ups of the turbine can reduce the fatigue. This work is very relevant for investigating how design and operation schemes together can mitigate fast changes in turbine operation ex. how fast a Francis turbine can respond to start-ups and changes load and how fast robust Francis runners should be designed. This paper also gives an estimation on the refused lifetime for of design operation which can be used to estimate the time for a replacement runner and its cost.

There is no translation from the technical aspects to the cost aspects on building and operation hydropower plants.

1.1.2 Document 2

Master Thesis: Impact from flexible operations on High Head Francis turbines
This is a master thesis from the hydropower laboratory and the focus is how wear and tear is going to impact on the cost of hydropower operation.

The thesis contains a very useful summary of UK, DE and Nordel power and system service markets and points to resent published literature regarding possible designs of future power markets. This is a good introduction to where hydropower might receive revenues today and in the future. The actual revenue streams are not assessed because this would typically require dedicated optimization software.

After this introduction the thesis describes the mechanisms that result in wear and tear in the turbines how this can be modelled and the consequence for the lifetime of the equipment. The lifetime reduction for different operation schemes is translated to operation cost in net present values NPV and shows a factor 4+ from the current operation scheme to a the most aggressive future operation scheme. This is also reflected in expected lifetime of the Francis runner where lifetime is reduces from expectantly 30 years to 7 years just by applying a more aggressive operation scenario. This illustrates that the impact on long-term revenues from different operation strategies can be expected to be large and should be included in daily operational decisions and in the bids and the reimbursement from the markets

1.1.3 Document 3

Master Thesis: Pressure Pulsation and Stresses in a Francis Turbine Operating at Variable Speed

This is a master thesis from the hydropower laboratory. There is no direct reference to the value of hydropower or future value of hydropower in the document but it points the extra stress for running the turbine away from the designed best point operation, and how the stresses are reduced when a variable speed design is applied. This information is relevant for the activity in HydroCen 3.2 assessing the start-up cost and cost from extra weir due to more stressed turbine operation.

2 Future challenges

With the respect of the Hydrogen's ambition about increasing the value potential there seems to be a gap between the technology research and the economic research:

- The technical research can to a larger extent focus on solving challenges that are important for ensuring and increasing future revenue streams from hydropower operation.
- Economic research should to a larger extent capture the true cost of hydropower operation when switching from a stationary to a flexible operation. Inclusion of wear and tear in daily operation will to a larger extent be important for the future operational decisions.

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Project memo

ValueFlex – Value from improved scheduling of hydropower

Subtitle

VERSION	DATE
1	2021-06-21

AUTHOR(S)
Ellen Krohn Aasgård

CLIENT(S)	CLIENTS REF.
HydroCen	Client's reference
PROJECT NO.	**NO. OF PAGES AND APPENDICES:**
HydroCen 5.5.2	8

ABSTRACT
This document summarizes the material that was given as background documents for the topic of optimal scheduling of hydropower in the ValueFlex repository.

ISO 9001 = ISO 14001
OHSAS 18001

PREPARED BY	SIGNATURE
Ellen Krohn Aasgård	
APPROVED BY	SIGNATURE
Michael Belnes	
PROJECT MEMO NO.	**CLASSIFICATION**
Project Memo No.	Restricted

Document history

VERSION	DATE	VERSION DESCRIPTION
1	2021-06-21	First

Table of contents

1 Material

Material uploaded to the ValueFlex folder on HydroCen Teams is listed below.

1 Skjelbred_Best_Profit.pdf	17.06.2021 10:32	Adobe Acrobat D...	392 KB
2 PhD thesis Unit-based short-term scheduling.pptx	18.06.2021 07:55	Microsoft PowerP...	1 331 KB
3 SHARM.pdf	17.06.2021 10:32	Adobe Acrobat D...	590 KB
4 Reserve.pdf	17.06.2021 10:32	Adobe Acrobat D...	228 KB
5 PhD Thesis Stochastic short-term bidding and scheduling.pdf	17.06.2021 10:32	Adobe Acrobat D...	7 649 KB
6 Short-term_hydro_scheduling_of_a_variable_speed_pu.pdf	17.06.2021 10:32	Adobe Acrobat D...	718 KB
7 Skjelbred-Calculationofpowercompensationforapumpedstorageh...	18.06.2021 08:05	Adobe Acrobat D...	979 KB
8 Sediment management.pdf	17.06.2021 10:32	Adobe Acrobat D...	1 204 KB
9 Pressure system operation.pdf	17.06.2021 10:32	Adobe Acrobat D...	208 KB
10 Project proposal - FloodSupport.pdf	17.06.2021 10:32	Adobe Acrobat D...	263 KB
11a Project proposal_iSPaM.pdf	17.06.2021 10:32	Adobe Acrobat D...	239 KB
11b MonitorX final report - L12_incl appendixes_DRAFT 2019_06_30....	17.06.2021 10:32	Adobe Acrobat D...	3 962 KB
12 link.txt	17.06.2021 10:32	Text Document	1 KB
13 Operational Hydropower Simulation in Cascaded River Systems f...	17.06.2021 10:32	Adobe Acrobat D...	377 KB
14 ES656078_full.pdf	17.06.2021 10:32	Adobe Acrobat D...	2 511 KB
15 IPN_PROMISE_final_project_proposal.pdf	17.06.2021 10:32	Adobe Acrobat D...	512 KB
16 faktaark - iScheduling 1.0.pptx	18.06.2021 07:59	Microsoft PowerP...	498 KB
17 EEM18_final.pdf	17.06.2021 10:31	Adobe Acrobat D...	212 KB
18 EEM20_final.pdf	17.06.2021 10:31	Adobe Acrobat D...	571 KB
19 EPEC19_final.pdf	17.06.2021 10:31	Adobe Acrobat D...	342 KB
20 Final report_2019_00649.pdf	17.06.2021 10:32	Adobe Acrobat D...	2 735 KB
21 TR A6890 Hydro scheduling with transmission transfer limitation...	17.06.2021 10:32	Adobe Acrobat D...	1 334 KB
22 TR A7164 Samnett – The EMPS Model with Power Flow Constrain...	17.06.2021 10:32	Adobe Acrobat D...	814 KB
23 TR S7375 Stochastic optimization model with individual vater val...	17.06.2021 10:32	Adobe Acrobat D...	2 300 KB
24 TR A7618 SOVN implementation.pdf	17.06.2021 10:32	Adobe Acrobat D...	1 245 KB
25 Assessing the benefits of exchanging spinning reserve capacity ...	18.06.2021 07:23	Adobe Acrobat D...	1 138 KB
26 TR_HydropowerSchedulingToolchains.pdf	18.06.2021 08:11	Adobe Acrobat D...	3 180 KB

1.1 Summary of the material

Because there is relatively more material uploaded to the repository for "Scheduling" compared to the other aspects of hydropower (Eco-values, Efficiency and maintenance, Strategies and Scenarios), a choice is made to only summarize some selected results in this report. However, to give an overview of the material, the results are analysed according to different dimensions, as listed in the table on the next page.

The dimensions are:

- Higher security of supply
- Increased flexibility
- Reduced cost for flexibility
- More renewable energy
- Reduced cost for renewable energy
- Competitiveness abroad
- Improved environment
- Improved modelling
- Transmission restrictions

As evident from the table, the research represented by the results in the repository represents significant value along all of the dimensions.

Research topic	ID	Ref	Realized	Potential	Higher security of supply	Increased flexibility	Reduced cost for flexibility	More renewable energy	Reduced cost for renewable energy	Competitiveness abroad	Improved environment	Improved modelling	Transmisson restrictions
Marginal cost identification	1	MC paper	1		1	1	1						
Deterministic STHS	2	HI PhD	1		1			1	1	1	1		
Stochastic STHS	3	SHARM paper		1	1			1	1		1		
Deterministic multi-market operations	4	Reserve paper	1		1		1		1	1			
Stochastic multi-market operations	5	E PhD		1	1		1		1				
Varspeed pump optimization	6	Japan paper	1		1	1	1			1			
Hydraulic short-circuit optimization	7	Seville paper	1		1	1	1	1					
Sediment and cavitation protection	8	Panama paper	1				1		1				
Pressure system optimization	9	Stavanger Per paper	1		1	1		1					
Optimal flood damping	10	Project proposal FloodSupport		1				1	1		1		
Maintenance optimization	11	Project proposal ISPAM, Monitor X		1	1		1		1				
Unified multi-term optimization	12	Prodrisk SHOP simula	1	1	1		1	1		1	1		
Digital twin of watercourse	13	Simulator paper	1	1	1	1		1		1	1		
Simulation-based optimization	14	Project proposal Go Hydro		1	1		1		1				
Real-time data in optimization	15	Project proposal Promise		1		1		1		1	1		
Autonomous scheduling	16	iScheduling in brief		1	1	1	1	1	1	1	1		
Pricing of reserves in fundamental market models	17	EEM18_final	1		1	1		1		1		1	
Pricing of reserves in fundamental market models	18	EEM20_review		1	1	1	1	1		1			
Pricing of reserves in fundamental market models	19	EPC19_final	1		1	1				1		1	
Representation of hydro in power system models	20	Final report_2019_006	1									1	
Including transmission constraints	21	TR A6890 Hydro sched	1		1							1	1
Coupled market and transmission in hydro scheudling and	22	TR A7164 Samnet - Th	1		1							1	1
Coupled market and transmission in hydro scheudling and	23	TR A7375 Stochastic o	1		1							1	1
Coupled market and transmission in hydro scheudling and	24	TR A7618 SOVN Imple	1		1							1	1
Flexibility and reserve capacity	25	Assessing the benefit	1		1	1	1					1	1
Modelling tool chain	26	Modelling tool chains	1		1	1	1	1	1	1	1	1	1

1.1.1 Document 1 (Ref 19)

Paper titled "On the Importance of Detailed Thermal Modeling for Price Forecasting in Hydro-Thermal Power Systems" published in the proceedings of the 2019 IEEE Electrical Power and Energy Conference (EPEC).

The paper presents a framework for long-term price forecasting in hydro-thermal power systems comprising two modelling layers. A long-term hydro-thermal model expresses the expected future cost as a function of hydro reservoir levels to a short-term operational model. The short-term model re-optimizes the weekly decision problem with more details and a finer time resolution.

The paper argues that as a consequence of more interconnectors between Norway and the European continent as well as introduction of more intermittent renewables in the system, fundamental long-term scheduling models need to better account for the flexibility in the system and all short-term markets when calculating the price forecasts and the value of water. It is necessary to develop or adapt existing models to account for how fundamental price drivers influence the prices in both the day-ahead market and the subsequent physical short-term electricity markets. This is done in the paper by adding detailed constraints on the operation of thermal power plants that affect their capability of delivering products in the various markets. This gives a more realistic price formation for the different products (energy and reserve). A case study of the Nordic power system shows more detailed thermal modelling causes less flexible production from thermal power plants and greater variation in power prices, increasing the value of flexible production from hydropower.

1.1.2 Document 2 (Ref 24)

SINTEF-report on the implementation of the SOVN model.

The SOVN project ("Stokastisk optimaliseringsmodell for Norden med individuelle vannverdier og nettrestriksjoner") aimed at creating a new fundamental hydro-thermal market model with detailed representation of the hydropower system. New tools are needed since existing models, such as the EMPS model [1], include too many simplifications in important parts of the solutions procedure, and heavily rely on calibration in order to show the real value of e.g. pumped-storage plants in the future Nordic power system with more new renewables and stronger couplings to Europe. The goal of the SOVN project was therefore to develop a new fundamental market optimization and simulation model able to solve the hydro-thermal scheduling problem with detailed description of all relevant constraints, including constraints given by individual hydro storages and plants using a formal optimization method. The model is based on a combination of optimization and simulation and does not rely on any aggregation of the hydropower system. It is suitable for both operational planning and expansion planning studies. The report documents the theoretical foundation, implementation and functionality available in the SOVN model at the end of the SOVN project in 2017. Development of the model has since been continued in Fansi.

1.1.3 Document 3 (Ref 25)

Paper titled " Assessing the benefits of exchanging spinning reserve capacity within the hydro-dominated Nordic market" published in Electric Power Systems Research in 2021.

The paper presents a hydrothermal scheduling toolchain suitable for detailed studies of procurement of spinning reserves in the hydro-dominated Nordic power system. The toolchain combines a long-term model to find the expected marginal value of water in the hydropower reservoirs and initial states for thermal generators, and a short-term model to optimize the daily unit commitment and dispatch. The short-term model has a detailed description of both hydro and thermal generation technologies to realistically constrain their capabilities as reserve capacity providers. The toolchain is applied on a data representing a 2030 scenario of the Northern European power system to quantify the benefits of exchanging spinning reserve capacity both between bidding zones and between countries within the Nordic market. By allowing 10% of the transmission line capacity for exchange of reserves, it is found that the daily average economic benefit is 290 k€ and 102 k€ for reserve exchange between bidding zones and countries, respectively.

The case study also demonstrates the importance of detailed modelling of both the hydro and thermal generation. In particular, the detailed representation of the hydropower is crucial to accurately capture the flexibility of the Nordic system to deliver spinning reserve capacity. By relaxing the integrality requirement for the unit commitment decision variables in the hydropower system, the economic benefit of reserve capacity exchange was on average reduced by 22%.

1.1.4 Document 4 (Ref 26)

Report on "Scheduling Toolchains in Hydro-Dominated Systems" co-authored by researchers at SINTEF and the Brazilian Electric Energy Research Centre (CEPEL).

The report elaborates on the toolchains applied for generation scheduling in the two countries with hydropower-dominated power systems: Norway and Brazil. Both countries have vast hydropower resources, with numerous geographically widespread and complex reservoir systems. Although the underlying objective of the scheduling is essentially the same, the systems are operated in different market contexts, where the different stakeholders' objectives clearly differ. This in turn leads to different uses of the scheduling models and information flow between the models. The report reviews the main operational scheduling models and their overarching toolchains developed and maintained by the two research institutions SINTEF Energy Research and the Brazilian Electric Energy Research Centre (CEPEL). Similarities and differences are identified and the original ideas that motivated the creation of the models and toolchains are discussed. The report also discusses the current state of the models and how they are being developed through R&D.

1.1.5 Document 5 (Ref 2)

Power-point presentation that summarizes the development and papers that make up Hans Ivar Skjeldbred's PhD Thesis at NTNU in 2019. The thesis gives an overview and details of the development of the SHOP model for short-term hydropower scheduling in since 2013.

The thesis details the fundamental modelling principles behind unit-based short-term hydro scheduling and the scientific development of this, as well as the model's industrial applications in competitive electricity markets. Flexibility and the need to understand the true capabilities of hydropower is increasingly important as the level of wind and solar power increases. There is an increased need for precise calculation of energy conversion and available capacity for each unit to deliver reserves and other products, not just energy. Precise and efficient algorithms for hydropower scheduling will contribute to hydropower's role as an enabler for the future zero-emission energy system.

1.1.6 Document 6 (Ref 16)

Power-point presentation that summarizes the iScheduling project led by Skagerak Energi.

The iScheduling project is the first granted project that SINTEF Energi/NTNU has on automatization of the hydropower scheduling process. At present, hydropower operators manually set up the executive commands before running the hydro scheduling optimization tools. These commands are only set up once and valid for all the hydraulic objects and the entire scheduling horizon. The project aims at replacing the current manual setup of commands with the automatic allocation of commands depending on the specific operating and market conditions of the given hydro system. This automation will be achieved by integrating modern machine learning techniques with a comprehensive understanding of the hydro systems and optimization models. The focus is on short-term scheduling, but the methods developed in the project might also be relevant for other horizons.

1.1.7 Document 7 (Ref 14)

Full application of the GoHydro project proposal sent to the Research Council in 2019. The project was not funded but still represent significant ideas for future development of hydro scheduling tools, utilizing new GPU hardware for massive parallelization of calculations.

The GoHydro project proposal describes how hydro power scheduling is a complex combinatorial optimization problem, and that current models are not precise or efficient enough to handle flexible operation of hydropower in a future setting with increased exchange of power between countries, more dynamic markets, and the need to incorporate data uncertainty. The project applications argues that there is therefore an urgent need for optimization methods that are both faster and solve a more realistic problem description.

GoHydro seeks to capitalize on recent developments in hardware technologies, specifically general-purpose Graphics Processing Unit (GPU), to develop simulation-based optimization algorithms for hydropower scheduling, integrating a more physically correct simulation of the production system and multi-market products and prices. The proposed technology has the potential to be faster than current methods and algorithms due to the massive parallelization that is obtainable by using GPU hardware.

2 Future challenges

With respect to HydroCen's ambition of increasing the value potential for hydropower from optimal utilization and scheduling, the most important areas for future research within this field is:

- Continuing to pursue improved modelling of hydro and other technologies (including transmission, market coupling, thermal units, increased uncertainty and variation due to intermittent renewables as well as flexibility from alternative energy technologies and demand side) in fundamental market models for hydro-dominated power and energy systems. Including variability and flexibility on shorter time scales and with more detailed characteristics will give tools that are better suited to analyse the value/cost of flexibility from hydropower.
- Continue to improve the precision and speed of scheduling models both for individual hydro operators (producer perspective) and investment/system analysis (system/market perspective), potentially also utilizing new algorithms and hardware. For daily planning there is a need to develop planning tools and methods that are precise enough to be used in automatic and autonomous scheduling processes, and fast enough to be used for scheduling and re-scheduling in markets with shorter-time resolutions. For system/market and investment analysis, more efficient or new methods could allow for more detailed modelling of alternative technologies and demand-side response which will give better quality results for prices of electricity and related flexibility products, and therefore also the value of flexibility from hydropower.
- Establish consistent data sets and scenarios that represent the future power and energy system and pathways for the transition. This includes data for relevant energy producing technologies and

interconnectors as well as climate and weather patterns relating to inflow, wind and insolation at various regional/local resolutions. Data sets must also represent the demand side, i.e., expected future energy use in different sectors including the available flexibility from demand-side response. These high-quality data sets should be used together with efficient mathematical models to produce scenarios for future prices that will serve as the basis for analysis, investment decisions and operations.

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Project memo

ValueFlex – Ecosystem and environmental value from hydropower

Subtitle

VERSION 1	**DATE** 2021-06-18
AUTHOR(S) Ellen Krohn Aasgård	
CLIENT(S) HydroCEen	**CLIENTS REF.** Client's reference
PROJECT NO. HydroCen 5.5.2	**NO. OF PAGES AND APPENDICES:** 6

ABSTRACT
This document summarizes the material that was given as background documents for the topic of ecosystem and environmental value of hydropower in the ValueFlex repository.

PREPARED BY Ellen Krohn Aasgård	SIGNATURE
APPROVED BY Michael Belsnes	SIGNATURE
PROJECT MEMO NO. Project Memo No.	**CLASSIFICATION** Restricted

Document history

VERSION	DATE	VERSION DESCRIPTION
1	2021-06-18	First

SINTEF

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1 Material

Material uploaded to the ValueFlex folder on HydroCen Teams is listed below:

Hydrocen rapport Demovassdrag 12042020.docx		21.06.2021 09:41	Microsoft Word D...	40 063 KB
Rapport_Nea_Nr9.pdf		21.06.2021 09:20	Adobe Acrobat D...	4 926 KB
Flomdempingstjenester i utvidet miljødeesign_HydroCen rapport oktober 2020.pdf		21.06.2021 09:19	Adobe Acrobat D...	3 629 KB
TR A7600 MiljødesignKavfossenUtløpBjelland.pdf		17.06.2021 10:32	Adobe Acrobat D...	3 230 KB
SusWater_bok_100720 fra Kari.pdf		17.06.2021 10:32	Adobe Acrobat D...	4 652 KB
Barton et al_MCDA in Bayesian networks_2020.pdf		17.06.2021 10:32	Adobe Acrobat D...	2 896 KB
Harby et al_Socio-environmental integration of hydropower facilities_La Houille Blanch...		17.06.2021 10:32	Adobe Acrobat D...	425 KB

1.1 Summary of the material

1.1.1 Document 1

Paper titled "Multi-criteria decision analysis in Bayesian networks - Diagnosing ecosystem service trade-offs in a hydropower regulated river" published in *Environmental modelling and software* in 2020.

The paper demonstrates a formalized multi-criteria decision analysis (MCDA) for evaluating the trade-offs between hydropower production and cultural ecosystem services of recreational salmon fishing and riparian landscape aesthetics; and the supporting service of habitat quality for salmon smolt in the Mandalselva River in Norway. Multi-criteria here mean that interactions between physical mitigation measures, environmental flow requirements and loss of hydropower production are considered together. Not considering the synergistic interactions between environmental compensation measures means that the costs of achieving good ecological potential are likely to be overestimated. By considering interaction between measures, the study finds that physical river restoration can reduce e-flow requirements and thereby reduce the loss in hydropower production, while at the same time gaining satisfactory conditions for angling and landscape aesthetic interests.

The study is the first environmental application of MCDA using a Bayesian network approach that we know of in the literature.

1.1.2 Document 2

Paper titled "Socio-environmental integration of hydropower facilities" published in *La houille blanche* in 2017.

This paper gives a short summary of the future challenges and opportunities for hydropower, and how future licensing processes should take into account different aspects. Hydrological as well as market and grid situations are changing, leading to a need for re-design of many hydropower facilities. Further, modern requirements to include environmental and social aspects of hydropower re-design, re-licensing and expansions will lead to new solutions.

As a way of dealing with these new challenges, steps could be taken to establish a data bank of knowledge aiming at some kind of standardisation of insights and data gained from the assessment of the various hydropower projects. Such an informational resource could also contribute to a higher degree of transparency and legitimacy of the licensing processes. However, given the predominantly case-by-case approach to hydropower development, a more coherent knowledge basis will not necessarily change the priority between different interests and concerns in a general manner. Even so, the possibility of drawing on knowledge and experiences from comparable cases and reviewing the underlying knowledge and documentation by third parties, could constitute an important step towards a strengthening of the overall legitimacy of the licensing system.

1.1.3 Document 3

Book titled "Ulike vannveier til god kraft - Mot bedre kunnskapsforvaltning i vassdrag med vannkraft" to be published as the final product from the SusWater project. SusWater is based on previous research projects at the Center for Environmental Design of Renewable Energy (CEDREN) which has linked social sciences with natural sciences and technical issues.

The different chapters of the book all have valuable contributions to the knowledge on ecological and environmental aspects of hydropower, but a summary of the main messages can be related to

- Formal processes
- Knowledge acquisition and data base
- Dialogue and cooperation

Regarding formal processes, there are clearly defined legislative processes for how environmental measures can be implemented in regulated watercourses, for instance via revisions of terms. The Water Resources Act also provides an opportunity to implement new environmental measures. What is important is that there is a common standard for management of water bodies aiming to establish natural or near-natural conditions.

Regarding knowledge acquisition, there is always a local component since all watercourses and hydropower plants are unique, and both natural and man-made changes are site-specific. Hydropower differs from many others forms of energy production precisely through this locality, and it is difficult to make general recommendations and suggestions for methods, processes and indicators that fit everywhere. Common to all suggestions and examples in the book is therefore that careful assessments must be made of how different methods, processes and indicators can be adapted to the relevant watercourse or the relevant license. Nevertheless, there are also many similarities and many conditions that are very similar across watercourses, so there is potential for learning by acquiring and using data in a systematic way.

Regarding dialogue, there exists different stakeholders who are affected by watercourse regulations at national, regional, and local level. All these interests should be taken into account, and ideally be in dialogue with each other, to achieve a less conflict-ridden implementation of environmental measures in regulated watercourses.

1.1.4 Document 4

Technical rapport titled " Miljødesign Mandalselva – Fysiske biotoptiltak på strekningen fra Kavfossen til utløpet av Bjelland kraftverk" published by SINTEF Energi in 2016.

This report considers possible measures on a minimum flow river stretch in the Mandalselva river in Norway. Specifically, removal to two concrete weirs is considered. A hydraulic model is set up and a simulation of different minimum flow levels is performed with and without the weirs present. It is found that the removal of the weirs and some smaller habitat measures can increase smolt production by between 35 and 60 % depending on the water discharge. This will improve the salmon habitat, increase the salmon population and the river's suitability for salmon fishing.

1.1.5 Document 5

Draft HydroCen report “Utvidet miljødesign i demovassdrag Nea”, summarizing HydroCen work in test case Nea for extended environmental design.

HydroCen WP4.3 has used Nea River as case study for developing methods and applying “extended environmental design solutions” to an inland river. The study has shown how new methods like remote sensing of hydro-morphological parameters and environmental DNA can help in assessing environmental conditions and possible mitigation measures in a regulated river. Impacts and mitigation measures for trout, invertebrates and recreational interests have been assessed. The resulting solutions to improve conditions will not compromise hydropower production, as the volume of released environmental flows will not increase. Instead, the method has shown there are significant gains for both the trout population and the recreational interests in adjusting the construction of weirs combined with changing the regime and timing of water release to the bypassed reach of Nea.

2 Future challenges

Recent research, also research within HydroCen, have shown that it is possible to quantify loss and gain in environmental conditions and outcomes, such as number of salmon smolts, square meters of available spawning grounds for fish, increased number of days suitable for kayaking, decreased flood risk or increased recreational use of rivers. However, it has so far not been many studies that are able to quantify this in monetary values. With respect of HydroCen's ambition of increasing the value potential from hydropower for ecological and environmental aspects, the most important areas for future research within this field are:

- Continuing to pursue an integrated, holistic approach to the management and regulation of hydropower rivers.
- Developing systematic methods, tools and knowledge and apply them to specific case studies in order to quantify loss and gain in environmental conditions and outcomes.
- Advancements in methods for combining, representing and retrieving knowledge such as Bayesian networks and other data-driven approaches. Expand the holistic view with socioeconomic aspects.
- Consider aspects of climate change mitigation with respect to flood control and draught management.

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1. Project title and short title

Metrics for sustainable flexibility from hydropower

2. Norsk prosjekttittel

Måltall for bærekraftig fleksibilitet fra vannkraft

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Ellen Krohn Aasgård, Arild Helseth, Michael Belsnes, Tor Inge Reigstad – SINTEF

Tonje Aronsen, Markus Majaneva – NINA

Arne Nysveen – NTNU ELK

7. Which work package (s) will the project belong to thematically?

Interdisciplinary

8. Which user partners support the project?

The proposal has received positive feedback from several researchers, but we have not been able to discuss it with user partners. We need to have support from user partners that can supply case studies for the project, and we will seek to do this in the time leading up to the final decision for open calls later this fall.

9. What is the budget of the suggested project in Cash?

2 MNOK over 2 years.

10. How is the budget (Cash) distributed between the partners?

At the onset of the project, we will start with a relatively small working group consisting of SINTEF (Ellen, Arild, Michael, Tor Inge), NINA (Tonje, Markus) and NTNU (Arne) that will define the first set of metrics. Additional research groups will be included as we develop the system and spread information about the project in HydroCen. Feedback from stakeholders will also be taken into account when considering which metrics and fields of expertise we include in the project. Due to this incremental development process, we wish to not set a final distribution of cash between partners at this stage. A preliminary distribution is 1 MNOK to SINTEF, and approx. 500 KNOK each to NINA and NTNU.

11. What is the time frame of the project (start date, expected last day of the project)?

Project period of 2 years. Start Jan 2022, end Dec 2023**.**

12. Have other sources of financing been considered?

No, but we might seek other funding opportunities for extensions or spin-off projects.

13. Describe the overall objective/topic of the project (30 words maximum)

Develop metrics for relevant aspects of hydropower operations and aggregate these in a common framework that will help stakeholders assess how flexibility can be supplied in a sustainable way.

14. Which strategic research areas are relevant for this project?

Norwegian Hydropower in Norway and Europe (flexible operation)

Environmental design and environmental technologies

How does suggested project meet the criteria for the use of Open calls funding? Describe how the project will:

15. Stimulate international collaboration?

To begin with, the project will focus on case studies for Norway and Sweden. However, the metrics developed in the project may also be relevant for hydropower in other areas. The project will seek to disseminate results in international channels, i.e. scientific and popular science articles, various conferences and EERA groups. If during the project it is decided to follow up the open call project with a larger, externally funded research project, we will seek to include international collaborators and case studies. While defining the metrics we will seek input from already established international partners in HydroCen and related projects.

16. Contribute to value creation in and from the hydro power sector?

The project will develop a framework for systematic quantification of the regulation capabilities of hydropower in terms of metrics, while also taking into account other important aspects such as impact on nature and ecosystems, multi-purpose use of reservoirs, costs, wear etc. The framework will consider trade-offs between operational patterns and profits from flexible operation, environmental effects and increased costs and wear on equipment. Together, the system of trade-offs between indicators/metrics for different aspects of flexible operation will be a tool to assess how regulation and flexibility can be obtained from hydropower systems with the least impact on other factors such as ecosystems and costs. Regulation, flexible operation and hydropeaking is of most socio-economic value when technical and economical aspects are balanced against other impacts, and the results from the project will help identifying these cases. The assessment system will also give information about the sensitivity of different regulatory constraints (reservoir levels, e-flows, ramping etc) on the ability to provide flexibility from hydropower systems. The assessment system and the individual metrics can be a valuable knowledge base for revision of terms and refurbishment of hydropower systems because it will give insights into the drivers behind capabilities and costs for delivering flexibility and regulation from hydropower.

17. Contribute to the Sustainable Development Goals (be as specific as possible, preferably on target level)?

SDG 7 – Clean Energy for All. Targets 7.1, 7.2. SDG 13 – Climate action. Targets 13.2, 13.3.SDG 15 – Life on Land. Targets 15.1, 15.4, 15.6, 15.9

18. Facilitate implementation and utilization of the project results?

The project will present and discuss the indicator and metrics with user partners throughout the project. It is vital that the metrics that are developed are well-funded within their field while at the same time being understandable for non-experts. Similarly, the metrics need to be relevant and measurable for the end-users of the system, i.e., power companies, TSO etc. Close dialogue with user partners throughout the project, especially related to case studies, will facilitate efficient utilization of the project results. Even though we will develop the system around case studies, we will not necessarily publish the results for individual watercourses if this is not wanted by the power companies due to confidentiality or other concerns. There will still be a value in defining new indicators and a common framework for presenting them, and the power companies can use the results internally in their organization.

19. Abstract (150 words maximum) (Note that the abstract will be available for the technical committees during the technical committee meeting primo October.)

Flexible hydropower is of critical importance for the power system by contributing to system stability. Hydropeaking and flexible operation to deliver balancing and system services may however also entail significant negative environmental and ecological consequences for the affected watercourses. The capability of flexible operation is therefore a trade-off between increased revenues and system stability against environmental impact and sometimes also increased costs due to additional stresses on equipment. Flexible operation is of most socio-economic value when these aspects are balanced against each other, but this balance is difficult to assess and often location- or case-dependent. The project will therefore develop a framework of metrics that can be used to assess how balancing and system services can be delivered from hydropower systems in a cost-effective and sustainable way. The result will be a framework for systematic quantification of regulation capabilities of hydropower in terms of a set of metrics.

20. Project description (1000 words maximum):

The ongoing project Flexibility Metrics (FlexMet) aims at developing indicators/KPIs/metrics that define the regulating capabilities of hydropower systems. Whereas traditional metrics for flexible operation are based on technical criteria such as ratio storage/yearly inflow and duration time of the power plants, FlexMet aims to develop new metrics by analysing new operational patterns obtained from ProdRisk model runs of flexible operation. The new proposed project will extend the work in FlexMet to also account for metrics/indicators that includes other aspects of flexible operation, especially focused on environmental/ecosystem impacts and costs. Combined, the metrics for regulation capability, environmental effects and costs will provide a wider perspective on the concept of flexibility from hydropower.

The result from the project will be the foundation of an assessment system that can aid power companies and other stakeholders (such as TSO, regulator, environmental agencies) to plan for effective, robust, and sustainable delivery of regulation services from hydropower. The assessment system and the individual metrics can be a valuable and easy-understandable knowledge base for revision of terms and refurbishment of hydropower systems because it will give insights into the drivers behind capabilities and costs for delivering reserves from hydropower. Throughout the project, existing knowledge will be extended and concretized through defining the metrics for the various fields of expertise, and further insights will be obtained when the metrics are systemized and shared across an interdisciplinary research and stakeholder group. The research challenge in this project is to define, analyse and verify metrics that give meaning within each field and also as part of the system as a whole.

The specification and definition of the various metrics will be based on current state-of-the-art knowledge from relevant fields (structures, turbine and generators, market and environmental) and then united in a common framework that will give a holistic view on hydropower systems' ability to deliver regulation in a sustainable way. Flexible operation of hydropower is of most socio-economical value when technical and economic aspects are balanced against adverse environmental impact. The system of indicators that will be developed in this project will shed light on this trade-off. Similarly, flexible hydro operation may also have adverse effects on costs, especially related to more frequent start/stop-sequences and wear on equipment that leads to increased need for maintenance. Indicators will be developed to assess the balance between increased costs and profits from flexible operations.

The project will work to present the indicators and their trade-offs in an intuitive way, so that the results can be easily understood and utilized by stakeholders. This involves innovative synthesis and visualization of data, e.g., comprising time series of market prices, simulated hydropower generation, water flows and reservoir trajectories. An initial idea is to illustrate the indicators and their trade-offs by radar plots similarly to the Hydropower Sustainability Assessment Protocol (HSAP) framework recently developed by IHA. The HSAP includes criteria for more than 20 sustainability topics, covering all stages of a hydropower project's life cycle and includes both social and technical aspects as well as national and global impacts. This will serve as an inspiration, but the scope of the proposed project is more narrowly focused on the operational phase of hydropower systems and local conditions for the regulated watercourses. We might also look for other methods to graphically display the metrics during the project.

The project will work with a set of case studies, and the different metrics and their consequences for revenues and operational patterns will be analysed using production scheduling software similarly to what is now done in FlexMet. For some of the metrics it might be relevant to also utilize the more detailed modelling that is included in the ProdRisk-SHOP simulator developed in HydroCen WP3.

The project will invite user stakeholders to workshops in order to discuss and define the metrics. The metrics should be relevant, understandable, and measurable as well as being founded on proven best practice within each field. We seek to develop metrics that are applicable to hydropower systems worldwide but will focus on case studies for HydroCen user partners as a starting point. It is possible to extend the project scope by applying for external funding for a spin-off project later on, and we will build the system and method in a way that opens up for inclusion of additional metrics as they are developed. In this way, the system of indicators developed in this project can serve as a common ground and display for various other research activities in HydroCen. Combining the metrics and their scientific background into a common framework will also help to identify which areas needs new knowledge, which will serve as a basis for defining new research projects.

The project will be led by SINTEF Energy, who will also be responsible for the hydropower production scheduling analysis (ProdRisk, ProdRisk-SHOP Simulator) and combining the metrics into a common framework. The other partners will contribute with developing metrics for their specific field of expertise as well as giving feedback on the other metrics. All research partners as well as industry partners in HydroCen and other relevant stakeholders will be invited to discussions and workshops in the project so that an interdisciplinary, holistic approach is maintained throughout the project.

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