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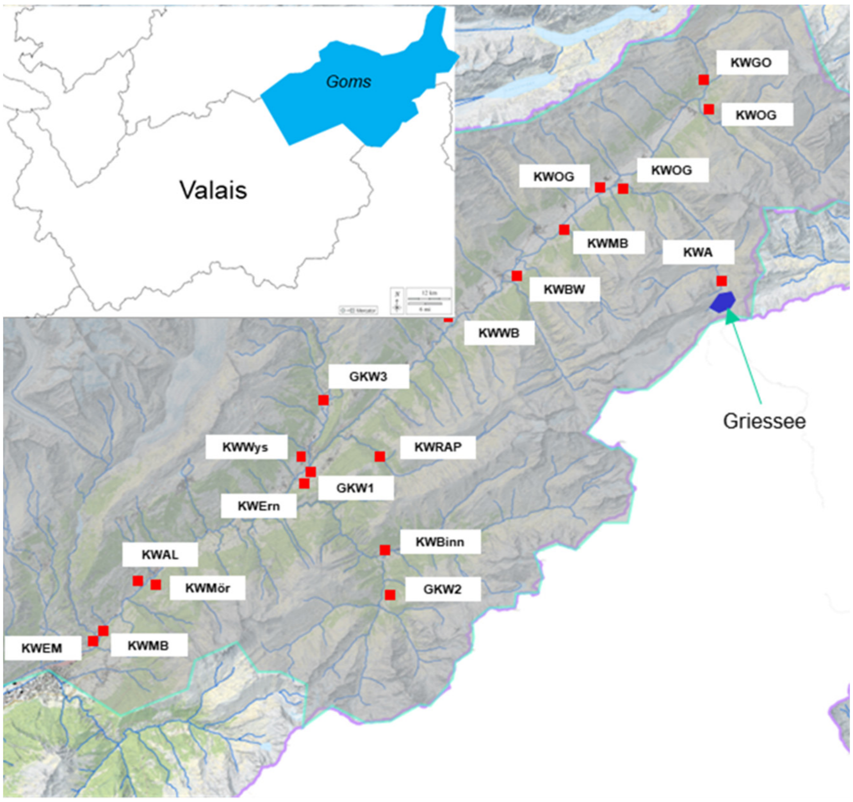
Interim report dated 29 10 2024

SmallFLEX GOMS

Small Hydro Flexibility and Complementarity with Photovoltaic and Wind Production in Goms Region



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The authors bear the entire responsibility for the content of this report and for the conclusions drawn therefrom.

Zusammenfassung

Das Projekt SmallFlex Goms sieht zunächst vor, die im Rahmen des SmallFLEX-Projekts identifizierte Flexibilität der KWGO-Anlage durch die Langzeitüberwachung dieser neuen flexiblen Betriebsarten zu bestätigen (WP1). Unter Anwendung der für KWGO entwickelten Methodik wird eine umfassende Bestandsaufnahme der Kleinwasserkraftwerke in der Region Goms durchgeführt, um Auswahlkriterien zu definieren (WP2). Für die geeignetsten Standorte wird eine hydraulische Analyse der technischen Grenzen dieser Anlagen (WP3) sowie eine kurzfristige Prognose der Zuflüsse und des Solarpotenzials (WP4) durchgeführt. Parallel dazu wird das Lufteintragsrisiko bewertet (WP5), bevor Feldmessungen durchgeführt werden, um diese Ergebnisse zu bestätigen (WP6). Ausserdem wird das Interesse an der Integration flexibler Laufwasser- oder Pumpspeicherkraftwerke in ein virtuelles Kraftwerk (Virtual Power Plant, VPP) verbunden mit anderen Quellen der Stromerzeugung und -speicherung in der Nähe des Kraftwerks bewertet (WP7). Schliesslich wird ein Geschäftsmodell entwickelt, um die wirtschaftlichen Vorteile der Einführung dieser neuen Betriebsarten zu bewerten (WP8).

Résumé

Le projet SmallFlex Goms vise d'abord à confirmer la flexibilité de la centrale KWGO identifiée dans le projet SmallFLEX avec un suivi de l'exploitation de ces nouveaux modes flexibles cette fois sur le long terme (WP1). En appliquant la méthodologie mise en place pour KWGO, un inventaire exhaustif des petites centrales hydroélectriques de la région de Goms sera effectué afin de définir des critères de sélection (WP2). Pour les sites les plus prometteurs, une analyse hydraulique des limites techniques de ces centrales sera réalisée (WP3), ainsi qu'une prédiction à court-terme des débits d'apports et du potentiel solaire (WP4). En parallèle, le risque d'entraînement d'air sera évalué (WP5) avant de réaliser des campagnes d'essais sur site pour confirmer ces résultats (WP6). L'intérêt d'intégrer des centrales au fil de l'eau flexibles ou à accumulation avec pompage dans un VPP associé à d'autres sources de production et de stockage électrique à proximité de la centrale sera évalué (WP7). Enfin un business model permettra d'évaluer les gains économiques par la mise en place de ces nouveaux modes d'exploitation (WP8).

Summary

The SmallFlex Goms project aims first to confirm the flexibility of the KWGO plant identified in the SmallFLEX project with a monitored long-term operation of these new flexible modes (WP1). Applying the methodology developed for KWGO, an exhaustive inventory of small hydro power plants (SHP) in the Goms region will be carried out to define selection criteria (WP2). For the most promising sites, a hydraulic analysis of the technical limits of these plants will be carried out (WP3), as well as a short-term prediction of the inflow and solar potential (WP4). In parallel, the risk of air entrainment will be evaluated (WP5) before carrying out on-site test campaigns to confirm these results (WP6). The interest of integrating flexible run-of-river or pumped storage plants in a Virtual Power Plant (VPP) associated with other sources of electricity generation and storage in the vicinity of the plant will be evaluated (WP7). Finally, a business model will be developed to evaluate the economic gains from the implementation of these new operating modes (WP8).

Contents

1 Introduction

1.1 Background information and current situation

The main motivation for launching the ‘SmallFlex Goms’ project is to build on the successful experience gained from the ‘SmallFlex’ project, which was conducted between 2018 and 2020. The results of the latter have clearly revealed the great potential of small run-of-river hydro power plants (SHP) in producing energy in peak hours as well as providing system services while maintaining the safety of the power plant and at the same time minimizing the environmental impacts related to hydropeaking.

Small Hydropower in Switzerland represents 10% of the hydroelectricity production with 3400 GWh per year (around 5% of the annual electricity production of Switzerland) and an existing potential of 770 GWh/year (rapport de l’OFEN - Potentiel hydroéléctrique de la Suisse - Août 2019) has been estimated. More than 70% of this potential concerns the so-called “large” small hydropower plant with a mean installed power between 1 MW and 10 MW. The proposed project aims specifically at this type of hydro power plants and will try to increase their annual productions (mostly in winter) by employing a smart combination of the available additional resources. These could include using un-conventional spaces such as the desander and the upper part of the penstock as supplementary accumulation volumes (as in SmallFlex project), coupling hydro generation with solar and wind energies, or even using pumping stations to save energy for peak production.

In addition to peak production, the mentioned actions could also help the plant owners to better plan their assets and use them for ancillary services as well. In fact, provision of grid services by hydroelectric power plants is a key factor associated with the energy transition. These services are vital for a stable operation of the grid, and thus, for the security of electricity supply in Switzerland. The massive integration of renewable energies such as solar and wind, which are intrinsically intermittent, results in a higher need for ancillary services. Hydropower energy is considered as a safe backup for such services. Traditionally, this task has been undertaken by large hydro power plants. However, with the emergence of the smart and local grids, the role of small hydro power plants becomes more crucial. Moreover, the need for flexibilities (ancillary services) is increasing year by year while the possibility for installing new large hydro power plants is limited. Many of the small hydro power plants might have a very small capacity that does not make them eligible for ancillary services, however, by integrating a number of small power plants (a pool of hydro power plants or a combination of hydro, wind and solar assets), the asset managers could call for these services, too. This definitely brings additional profits to the companies and also contributes to a better grid stability in the national level. These operations, however, require much higher levels of flexibility in the hydro section. The turbines must be ready to operate in off-design conditions and undergo fast transitions. To guarantee that these demands could be borne safely, further analysis and tests must be performed on each machine to define its limits in terms of operating modes.

Concretely, the proposed project of ‘SmallFlex Goms’ aims at addressing the following issues:

- How will the proposed actions in SmallFlex project respond in real operations?
- How could the SmallFlex project experience be transposed to other powerplants?
- How could we widen the production and flexibility possibilities beyond the SmallFlex out-comes? In other words, how could we integrate additional sources like solar, wind, pumping, and so on into the previously approved approach to improve the performance of the plants?
- What would be the associated risks (technical, environmental, etc.) with the new functionalities and operation modes of the integrated systems and how could we address them?

- What will be the outcome of the proposed actions in terms of economic paybacks?

A particular attention will be paid to the following objectives:

- Demonstration of the flexibility of KWGO for a long-term operation.
- Definition of the main criterion and limits for a given run-off power plant to determine its flexibility.
- Evaluation of the complementarity of flexible medium and small power plant (run-off and storage) with new renewable production.

The obtained results through the proposed project will be of high value for the whole fleet of the Swiss hydropower production, as the potential for small hydro is quite high and demand for this sector is rising to answer to the long-term energy policies and decarbonization. The results and recommendations are believed to be directly applicable to many hydro power plants in Switzerland. This clearly shows the usefulness and the necessity of conducting the proposed project.

1.2 Purpose of the project

The SmallFlex Goms project aims to discover new production and flexibility opportunities for small and medium hydropower, including these three main research paths:

- Applying the flexibility solutions to a region with several hydro power plants. This requires the evaluation of the potential of each plant at the first place, and then, leads to new challenges regarding connecting the plants together and having a virtual pool of small hydro power plants that can work together for peak production and system services.
- Integration of new solutions such as solar, wind, pumping stations, etc. to further increase the production capacity and flexibility. This brings in several new challenges in terms of coordination between the assets and choosing the optimal combination/solution in real time. This also requires preparing the system for being resilient against unforeseen events such as unpredicted cloudy skies and instantaneous peaks in energy demand.
- Implementation of the proposed actions in real practice and evaluation of the actual benefits and risks in place; and at a later stage, applying the solutions to other power plants and evaluating the economic profits in Goms region thanks to new operation modes

1.3 Objectives

The above-mentioned goals are divided to the following tasks, which will be followed and evaluated during the project:

- Implementing the results of the ‘SmallFlex’ project to the KWGO hydro power plant and evaluating the outcomes of such modifications in a realistic manner over a three-year horizon.
- Evaluating the existing potentials in the Goms region based on the methodology developed through the ‘SmallFlex’ project.
- Improving (short-term) weather predictions and including the results for optimizing the exploitation program.
- In-depth analysis of air entrainment risks in penstock due to flexible operations of small hydro power plants.
- Design of Virtual Power Plants (VPP’s) by aggregating all the available potentials in a region including hydro, solar, wind, pump-turbine cycles, etc in order to optimize the utilization of these potentials in energy and ancillary service markets.
    - Performing on-site experimental campaigns to evaluate the proposed scenarios and solutions in practice and ensure that these actions do not threaten the installation safety.
    - Evaluating the economic benefits of the selected scenarios for the whole region of Goms.

2 Description of facility

The project focuses on the Goms region, situated in the northwest of Canton of Wallis. This region includes many small hydro power plants and holds a considerable potential in terms of solar energy production. This makes this region a great candidate for the proposed project. Figure 1 (left) shows the hydrological map of the region with a non-exhaustive list of the existing hydro power plants.

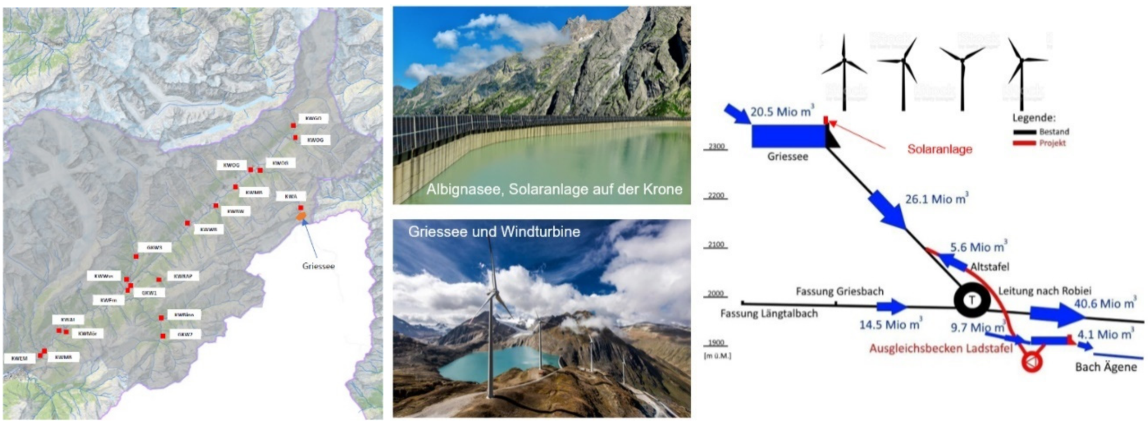

Figure 1: Hydrological map of Goms region with some existing hydro power plants and possible combination of hydro, solar, and wind generation close to Griessee lake.

An example of the ideas explained earlier related to creating an optimal combination of hydro, wind and solar generation is depicted on the right of Figure 1. This figure shows the Griessee lake as well as the installed wind turbines at its vicinity and highlight the potential of installing additional photovoltaic solar panels in the region to boost the production. The possibility to refurbish the Altstafel power plant, KW Aegina AG, as a pumped storage facility will be investigated in the project. Apart from this site gathering hydro, wind and solar, the following hydro power plants have been identified in the Goms region, at the beginning of the project, as potential candidates to be operated in a more flexible way.

Table 1 – List of the power plants in the Goms region.

- KW Gletsch-Oberwald
- KW Merezenbach
- KW Wannebode (Blinnenwerk AG)
- KW Walibach / Grafschaft
- KW Mörel (Aletsch AG)
- KW Bitsch (KW Massaboden)
- KW Bitsch (Electra Massa)
- KW Münstigertal
- KW Binn

Rhonewerke AG

- KW Ernen
- KW Mörel

KW Obergoms AG

- KW Gere
- KW Ulrichen
- KW Niderbach

Gommerkraftwerke AG

- KW Rappental (GKW1)
- KW Saflisch (GKW2)
- KW Heiligkreuz (GKW2)
- KW Fieschertal (GKW3)
- KW Wysswasser
- Neubrigg / Mubisa (GKW1)

A wide variety of power plants are available, with outputs ranging from less than 200 kW to over 300 MW. Some power plants have a storage basin, others are run-of-river. From an electromechanical point of view, some power plants are equipped with Pelton turbines, others with Francis turbines.

3 Procedures and methodology

In order to provide concrete answers to the issues raised, 9 work packages in total have been structured for the SmallFlex Goms project, which are explained in detail in Figure 2 below.

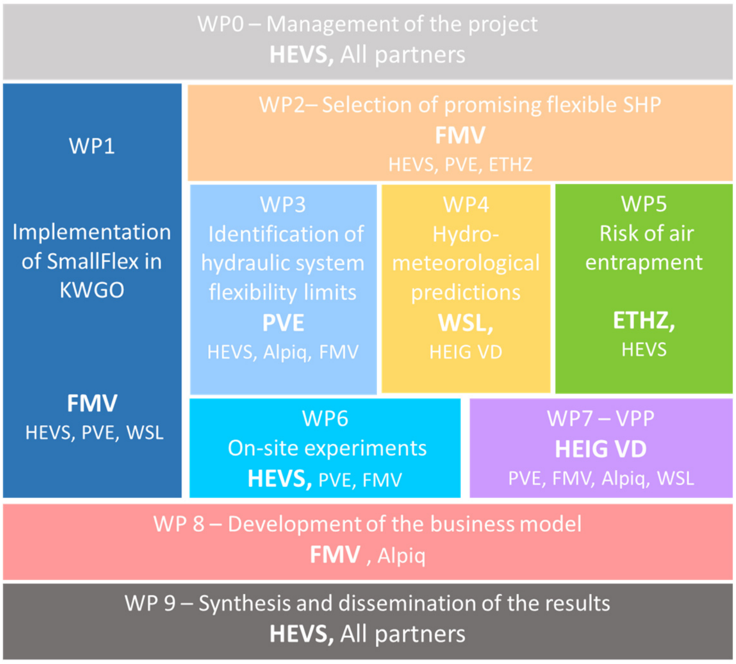

Figure 2: Project organisation

Hereafter are described in detail, the activities planned in the different WPs.

WP0 – Management of the project
Lead: HEVS, **partners:** all
This WP includes the fundamental actions required to guarantee the correct execution of the project throughout its lifecycle. This WP is led and handled by HEVS acting as the coordinator between partners and convene regular progress meetings to guarantee successful communication between the partners and the WP as well as the execution of the project. Three tasks have been defined:

- T0.1: Organisation, preparation, participation, and synthesis of the meetings
- T0.2: WPs coordination and information exchange support
- T0.3: SFOE annual reports and tracking of the deliverables.

WP1 – Implementation of SmallFlex in KWGO
Lead: FMV, **partners**: HEVS, PVE, WSL
This work package deals with the implementation of the flexible operating mode based on the use of the upper part of the head race tunnel as an additional storage volume, demonstrated in the SmallFlex project, at the Gletsch Oberwald (KWGO) hydropower plant. The following activities have been considered for this purpose: Two tasks have been defined:

- T1.1: Implementing the new exploitation modes in KWGO power plant following the conclusions of the previous SmallFlex project (HEX, HEVS VS)
- T1.2: Long-term monitoring of the new operation mode (FMV, HEVS, PVE)

WP2 – Selection of promising flexible SHP
Lead: FMV, **partners**: HEVS, PVE, ETHZ

This work package deals with the selection of power plants for which, the implementation of the results and the developed methodology in the SmallFlex project KWGO could be applied. The following activities have been considered for this purpose: Two tasks have been defined:

- T2.1: Exhaustive inventory of the hydropower plants and their potential in the Goms region: data availability, relevance, potential (FMV, HEVS)
- T2.2: Screening and ranking of the relevant power plants based on specific criteria and methodology to select the most promising plants. (FMV, HEVS, PVE, ETHZ)

WP3 – Identification of hydraulic system flexibility limits
Lead: PVE, **partners**: HEVS, ALPIQ, FMV

The aim of this work package is to perform an extensive hydraulic analysis of the flexibility potential of a selection of promising hydropower plants, via the following tasks:

- T3.1: Technical site visits of the selected plants (HEVS, PVE, FMV, Alpiq)
- T3.2: Determination of the extended operation modes of the power plants available and new storage capacity both in volume and energy, risk of air entrainment, turbine flexibility, variable speed) (HEVS, PVE, Alpiq, FMV)
- T3.3: Sizing of new storage and pumping capacity for the selected storage case study(ies) (Alpiq, PVE, FMV, HEVS)
- T3.4: Quantifying the peak production capacities, system services (SDL), etc. (PVE in coordination with WP4. HEVS, FMV, Alpiq)

WP4 – Hydro-meteorological predictions
Lead: WSL, **partners:** HEIG-VD

The aim of WP4 is to assess the suitability of the current FMV hydropower plants in the Goms valley for flexible operation from the point of view of the hydrological characteristics of the corresponding catchments. A second goal is to investigate how water discharge at selected HP intakes (e.g., Griesbach), and ultimately HP production, matches with the production of wind and solar electricity at corresponding HP infrastructures in order to optimize a joint operation. To this end, we will further develop and operate our hydrometeorological forecast system based on the hydrological model PREVAH and the corresponding operational information platform (https://hydro.slf.ch/sihl/gletsch/), which was created during SmallFlex Gletsch. The following subtasks are planned:

- T4.1 Demonstration of hydrometeorological forecasts for flexible operation of small HP plants (WSL, HEIG-VD)
- T4.2 Assessment of FMV small hydropower plants in the Goms valley with regard to their suitability for flexible operation from the point of view of hydrological preconditions (WSL, PVE)
- T4.3 Assessment of climate change impact on the potential for flexible operation of the small HP plants (from a hydrological point of view) (WSL)

WP5 – Risk of air entrainment
Lead: ETHZ, **partners:** HEVS

WP5 extends the work conducted within the preceding SmallFLEX project and aims at reducing the uncertainties related to the assessment of the limitations to the flexible operation of existing hydropower facilities in terms of air entrainment. In addition, the work package aims at minimizing the necessity to conduct tests of different operation modes at the selected facilities. The work package includes hydraulic laboratory tests at the VAW hydraulic laboratory at ETHZ. The experimental setup consists of an approximately 10 m-long acrylic glass pipe with D=0.484 m, adjustable in a range of inclination angles from 0° to 45°. The work plan involves the following tasks:

- T5.1: Compilation and review of the state-of-the-art related to air entrainment and transport in hydraulic systems similar to the investigated facilities; (ETHZ)
- T5.2: Identification and assessments of uncertainties related to scale effects and geometrical variations as well as gaps in the state-of-the-art; (ETHZ, HEVS, PVE)
- T5.3: Design and construction of a hydraulic laboratory test stand representing a penstock with a scale between 1:5 and 1:10; (ETHZ)
- T5.4: General model investigations of different operation modes and their effect on air entrainment and transport within the penstock; (ETHZ)
- T5.5: Detailed model investigations of different operation modes and their effect on air entrainment and transport within penstock systems representing KWGO and the two selected facilities (WP2); (ETHZ)

WP6 - On-site experiments
Lead: HEVS, **partners:** PVE, FMV

The goal of this work package is to validate the predicted potentials in the previous work packages in real action for two hydro power plants and verify that the new operation modes will respect the security guidelines of each plant. In order to answer to these questions, the following tasks have been defined:

- T6.1: Definition of the experimental protocols (instrumentation, program, identification, and limitation of the risks) (HEVS, PVE)
- T6.2: Installation of the Hydro-Clone system on 1 hydro power plant (PVE)
- T6.3: Performing on-site experimental campaigns in 2 hydropower plants (HEVS)
- T6.4: Analysis of the experimental results and validation of the operational limits of the power plan with respect to the identified storage potentials (HEVS)

WP7 – VPP
Lead: HEIG-VD, **partners:** PVE, ALPIQ, FMV, WSL

This work package deals with the optimal design and operation of a Virtual Power Plant composed by a set of distributed resources connected to a distribution grid in the vicinity of small-scale hydro power plants in order to optimize energy and flexibility (ancillary service) exchanges. Finally, to ensure secure operation of the VPP and validate provision of ancillary services, we perform a dynamic analysis and simulation of the VPP including dynamic model of the resources as well as the electric grid model. The optimization process will be formulated in two stages. The first stage deals with design of the components of the VPP (i.e., selection of possible resources including PVs, battery energy storage systems, wind turbines, pump-turbines, etc as well as optimal size and location of each resource connected to the grid). The second stage deals with optimizing the operation of the VPP components within various time horizons (weekly, daily, intra-day) with respect to market conditions, and uncertainties related to renewable generations and natural water discharge. In particular, the following activities are envisaged:

- Task 7.1 Optimal design of the VPP (HEIG-VD)
- Task 7.2 Optimal operation of the VPP (HEIG-VD, Alpiq)
- Task 7.3 Dynamic simulation of capability of provision of ancillary services regarding power system constraints (e.g., primary frequency control) (HEIG-VD, PVE). Physical emulation of the reduced-scale local grid in the ReIne reconfigurable distribution grid laboratory of HEIG-VD.
- Task 7.4 Revisiting the optimal design and operation of the VPP (HEIG-VD, FMV, PVE) and optimal design of VPP regarding the results of optimal operation (Task 7.2)

WP8 – Development of the business model
Lead: FMV, **partners:** ALPIQ

This work package investigates the economic aspects of the project and examines how the proposed flexibility potential will reflect in the real economic situation. This is realized via:

- T8.1: Economic analysis of the supplementary production thanks to the additional storage of each power plant (including KWGO) (FMV, Alpiq)
- T8.2: Economic analysis of the supplementary ancillary services of each of the selected plants. (FMV, Alpiq)
- T8.3: Performing a global economic analysis of the optimization of the regional potential. (FMV, Alpiq)

WP9 – Synthesis and dissemination of the results

Lead: HEVS, **partners:** all

This work package is structured to gather all the project results under the same umbrella and disseminate them in an appropriate manner. To achieve this goal, the following activities have been foreseen.

- T9.1 Publication of scientific articles (journal and conference papers).
- T9.2 Public deliverable with guidelines to make small/medium HPP more flexible.
- T9.3 Final public report mandatory by OFEN.

The initial planning for all these activities is described below:

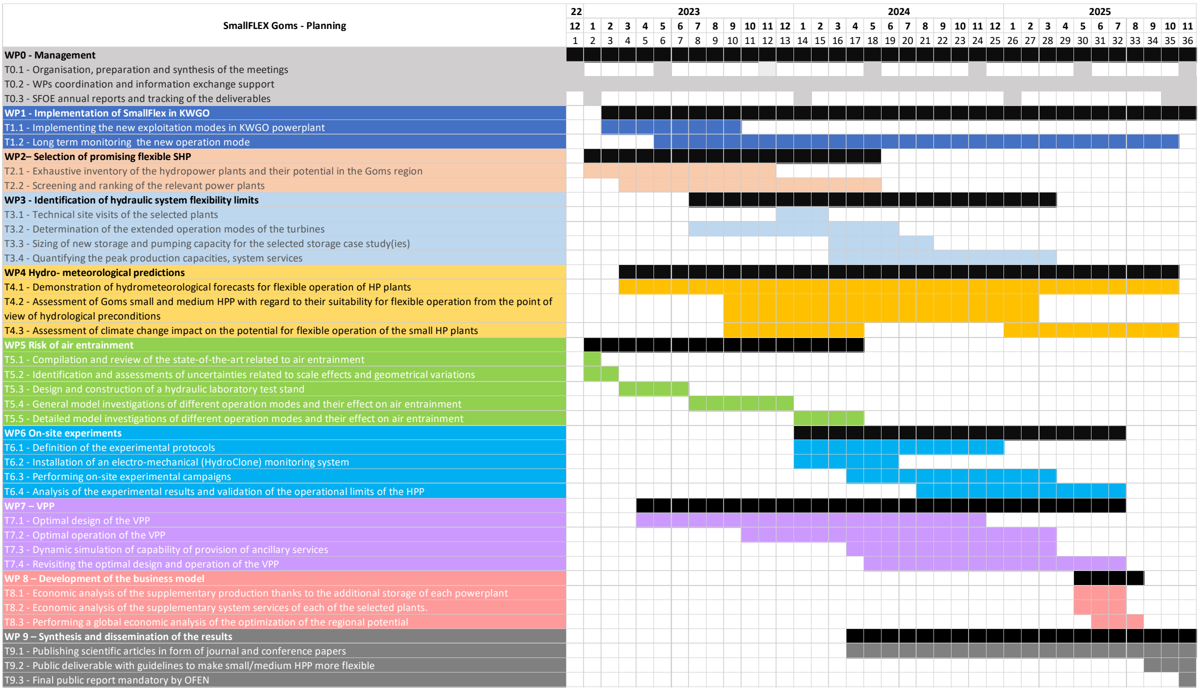

Figure 3: Initial project planning

The deliverables and milestones planned are described in Table 2 as well as in Figure 4Table 2 and Figure 5.

Table 2 Deliverables of the project and deadlines

WP	WP Leader	Deliverables/Milestones (responsible partner)	Due date	Updated due date
WP0	HEVS	D0.2 – Annual reports (HEVS)	yearly	yearly
WP1	FMV	M1.1a – Implementation of the flexible operation mode at KWGO **without** the headrace channel (FMV)	30/09/2023	30/09/2023
		M1.1b – Implementation of the flexible operation mode at KWGO **with** the headrace channel (FMV)	30/09/2023	31.01.2025
		D1.1 – Optimized flexibility (booklet)	30/11/2025	30/11/2025
		D1.2 – Analysis of the 3-years monitoring.	30/11/2025	30/11/2026
WP2	FMV	M2.1 - Intermediate inventory of the hydropower plants	31/07/2023	31/07/2023
		M2.2 – Selection of the two power plants	30/08/2023	30/08/2023
		M2.3 - Exhaustive inventory of the hydropower plants	31/11/2023	31/11/2023
		D2.1 – Screening and ranking of the hydro powerplants based on the criteria and the methodology of selection.	30/04/2024	30/04/2024
WP3	PVE	D3.1 – Detailed analysis of the flexibility of the selected power plants	30/04/2025	30/04/2025
WP4	WSL	M4.1 – Setup of catchment completed - real-time operations ready	31/07/2023	31/07/2023
		M4.2 – Climate change scenarios computed	30/04/2024	30/04/2024
		M4.3 – Framework for-flexible-operations analysis ready	31/08/2024	31/08/2024
		D4.1 – Analysis of flexible real-time operations with hydrological forecasts	28/02/2025	28/02/2025
		D4.2 – Analysis of flexible real-time operations with hydrological scenarios	30/09/2025	30/09/2025
WP5	ETHZ	M5.1 – Initial operation of the laboratory test stand	30/06/2023	30/09/2024
		D5.1 – Review report on air entrainment	31/05/2023	30/06/2025
		D5.2 – Report on detailed model investigations	31/04/2024	30/06/2025
WP6	HEVS	M6.1 – On-site measurements achieved (PP2)	31/03/2025	30/11/2025
		M6.2 – Hydro-Clone in operation	31/08/2024	31/03/2025
		D6.1 – Analysis of the on-site measurements.	31/08/2025	30/11/2025
WP7	HEIG-VD	D7.1 – Preliminary design of the VPP	30/06/2024	31/11/2024
		D7.2 – Final report on optimal design, operation and simulation performance of the VPP	31/05/2025	31/05/2025
WP8	FMV	D8.1 - Assessment of the economic benefits of the demonstrators	30/11/2025	30/11/2025

		D8.2 – Added value of new storage and pumping	30/11/2025	30/11/2025
WP9	HEVS	M9.1 – Share of the deliverable 9.2 with HPP actors	30/11/2025	30/11/2025
		D9.1 – List of the dissemination activities	30/11/2025	30/11/2025
		D9.2 – Guidelines to make small/medium HPP more flexible	30/11/2025	30/11/2025

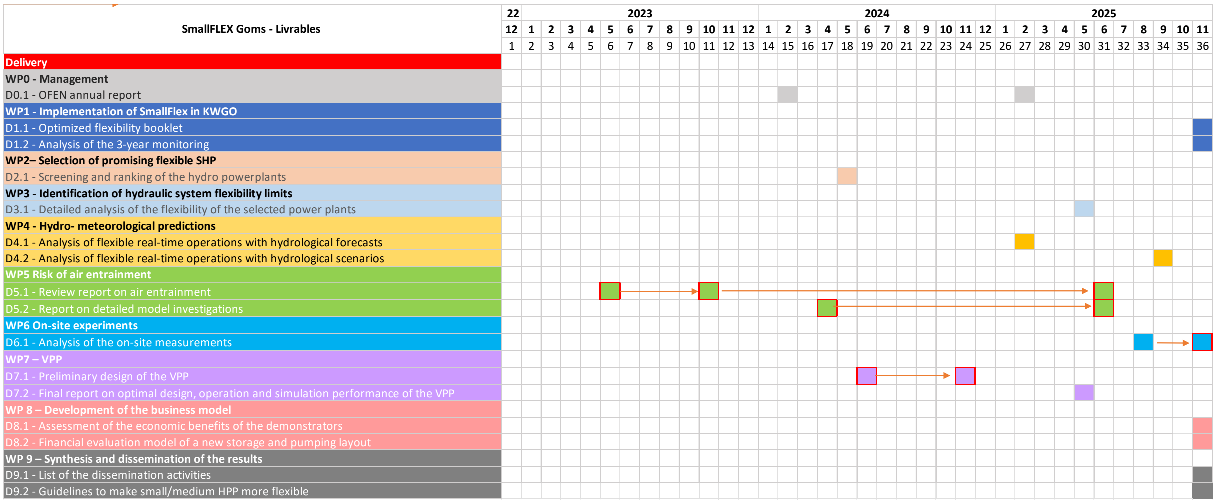

Figure 4: Updated planning of the deliverables

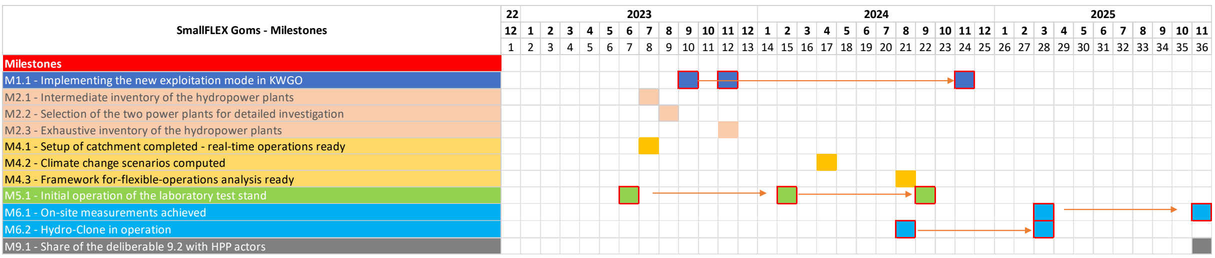

Figure 5: Updated planning of the milestones

4 Activities and results

4.1 WP0 – Management of the project

Lead: HEVS, partners: all

The project started in December 2022 with a hybrid **kick-off meeting** organized on **December 14th** to officially launch the activities. In 2023, two **bi-annual meetings** have then been held on **May 9th** and **September 25th** to share the progress of the activities with all the partners. The annual meeting with SFOE was organized in Sion on **November 15th**. In 2024, a bi-annual meeting was held in Brig on **June 24th** in the framework of the visits of Merezenbach and Aegina power plants organized for the consortium by FMV. A common visit of the Mörel power plant from the intake to tailrace channel was held on **July 17th**. ETHZ VAW organized the second bi-annual meeting in Zürich with SFOE experts on **November 5th**, with a visit of the test-rig developed for the project. The project has been delayed primarily due to the difficulty in collecting data from regional power stations, followed by the difficulty in implementing the complete flexibility at the Gletsch Oberwald power station through the use of the penstock.

4.2 WP1 – Implementation of SmallFlex in KWGO

Lead: FMV, partners: HEVS, PVE, WSL

The goal of this work package is to implement in operation and to monitor the three modes of flexibility identified during the SmallFlex project. An analysis of the data since 2019 have been performed to find the occurrences of some dewatering of the desander, the forebay tank and eventually the penstock. These occurrences are linked to some specific operations. Two of them have been considered:

- The opening of the gates between the desander and the forebay tank allowing switching from winter mode to summer mode and vice-versa, which requires the dewatering of the upper part of the penstock.
- The PRL (Primärregelleistung) service that requires the use of a fraction of the water volume stored in the desander and the forebay tank.

Figure 6 shows the time history of the runner rotational speed, the water level in the desander and the forebay tank, the pressure at the group valves and the vibration level monitored by the sensor set on the turbine shafts during the dewatering event of the 26th of May 2023 for switching from the winter mode to the summer mode. The group 1 is used for dewatering the penstock since the rotational speed of the group 2 goes to zero. The process last approximately one hour and the desander and the forebay tank are empty. The pressure drop measured by the pressure sensors at the group valves is close to 1 bar, which means that the water level decreases by approximately 10 m. This is higher than the height of the forebay tank. Consequently, a part of the penstock is also dewatered. During this operation, the vibration level is not changed for any sensor.

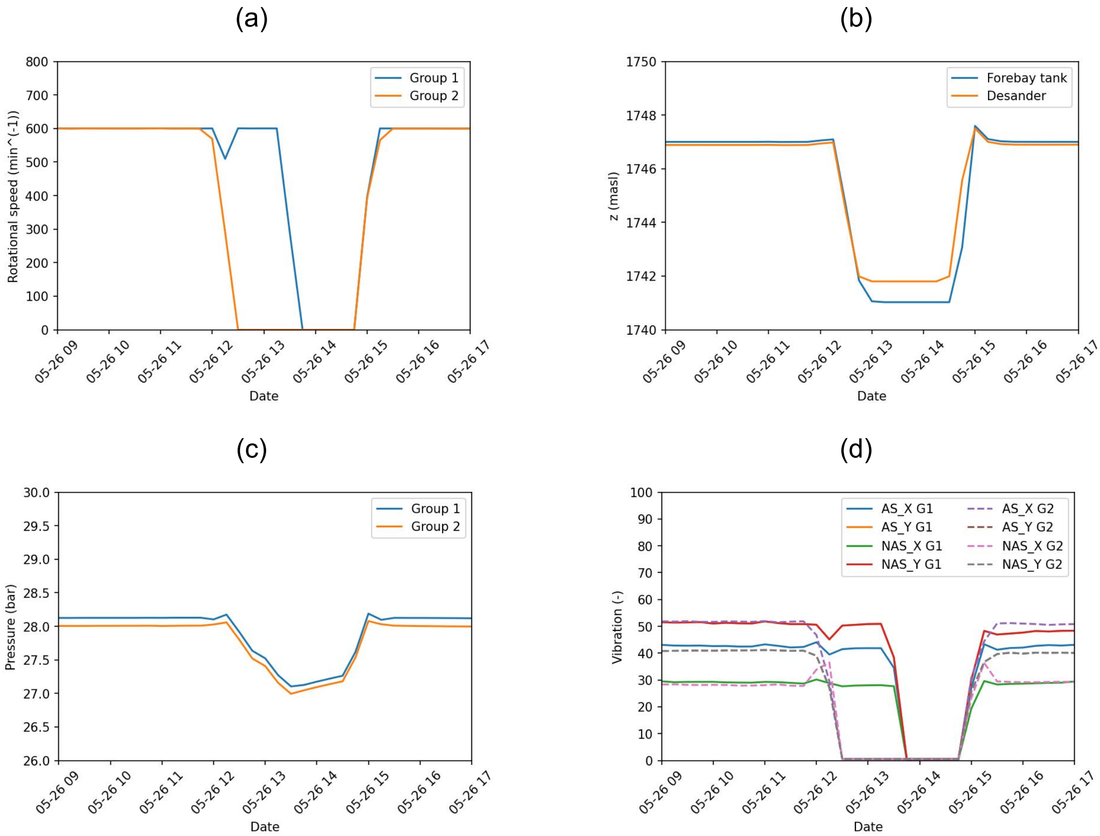

Figure 6: Time history of (a) the runner rotational speed, (b) the water level in the desander and the forebay tank, (c) the pressure at the group valves and (d) the vibration level for each sensor set on the turbine shaft. Dewatering event of the 26th of May 2023 between 9am and 17pm. The values are averaged over 15 minutes.

For all the dewatering events considered, the vibration level does not change compared to the normal operating conditions. However, these events are often carried out at low powers. Therefore, additional data at higher powers should be considered.

Figure 7 shows the time history of the power and the frequency the Tuesday 17th of October 2023 during two PRL events: one from 09:00 to 09:15 and a second from 10:00 and 10:15. For both cases, the power is increased by 0.3 MW consecutive to a drop in frequency of about 150 mHz. The increase in power goes hand in hand with a small decrease in the water level in the forebay tank. During these two events, the vibration level is not changed as shown in Figure 8.

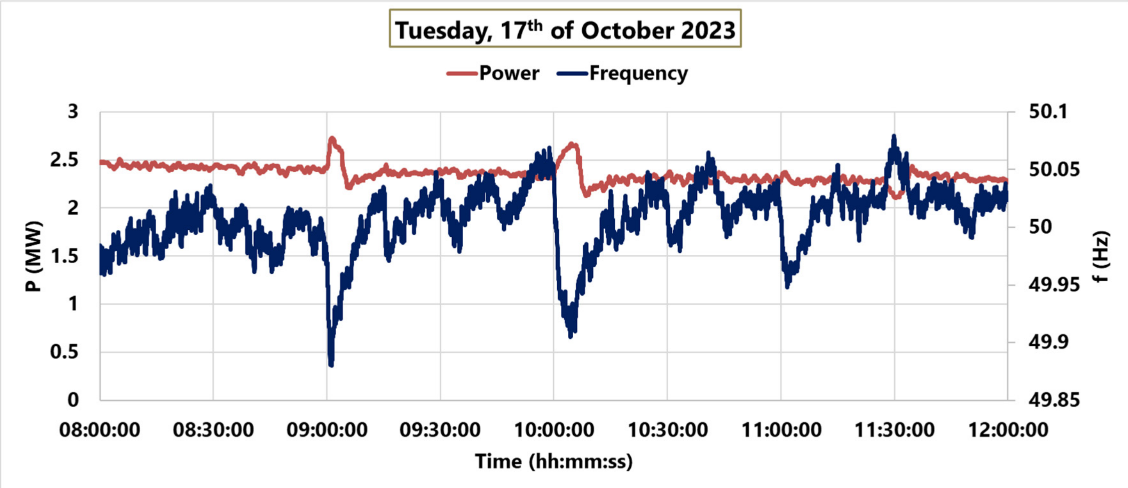

Figure 7: Time history of the power (left axis) and the frequency (right axis) the Tuesday 17th of October 2023 with two PRL services activated between 09:00 and 09:15 and 10:00 and 10:15.

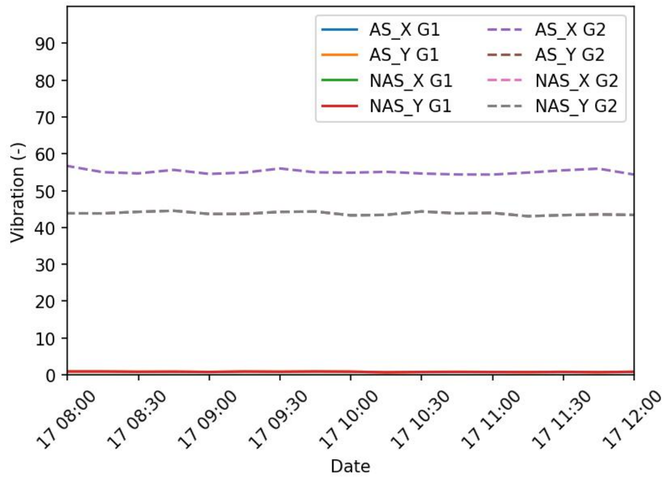

Figure 8: Time history of the maximum vibration level the Tuesday 17th of October 2023 with two PRL services activated between 09:00 and 09:15 and 10:00 and 10:15.

From the available data, the dewatering of the desander, the forebay tank and eventually of the upper part of the penstock does not lead to an increase in the vibration level monitored along the turbine shafts. This conclusion must be supported by additional data that will be acquired at higher powers and during longer times of operation.

The implementation of the last flexible mode at the Oberwald power plant had to be postponed prioritising other activities linked to the operation of the region's power plant facilities. It is planned to bring this mode into operation by the end of January 2025.

The latest inspection of the hydraulic tunnel revealed some cracks in its upper section. This is an additional point of attention to be considered in the monitoring of the final flexible mode.

Regarding to environmental monitoring, an initial discussion has taken place with an environmental office. The final monitoring concept will be fixed before the last flexible mode is implemented (Q4-2024).

4.3 WP2 – Selection of promising flexible SHP

Lead: FMV, partners: HEVS, PVE, ETHZ

Following the preliminary selection of the 5 interesting power plants performed last year, a final ranking of these power plants has been carried out.
The ranking is based on five criteria:

i. The storage volume.
ii. The power peak.
iii. The duration of the power peak.
iv. The energy produced.
v. The risk of air entrainment.

The value of the first four criteria are given in Table 3 for each power plant, whereas the risk of air entrainment is plotted in Figure 9 for the power plant located in the Goms region.

Table 3: Evaluation of the potential energy flexibility of the hydropower plants with a small storage capacity.

	KW Gletsch-Oberwald	**KW Merezenbach**	**KW Wannebode**	**KW Walibach**	**KW Mörel**
Storage volume (m^3)	6 909	1 195	2 811	234	1 076
Inflow discharge (m^3/s)	4.9	0.45	1.5	0.5	21.6
Turbined discharge (m^3/s)	5.4	0.5	1.6	0.5	24.0
Duration of the power peak (min)	213	398	288	74	7
Power peak (MW)	0.8	0.1	0.1	0.2	3.1
Energy (MWh)	38	11.5	8	3.5	5

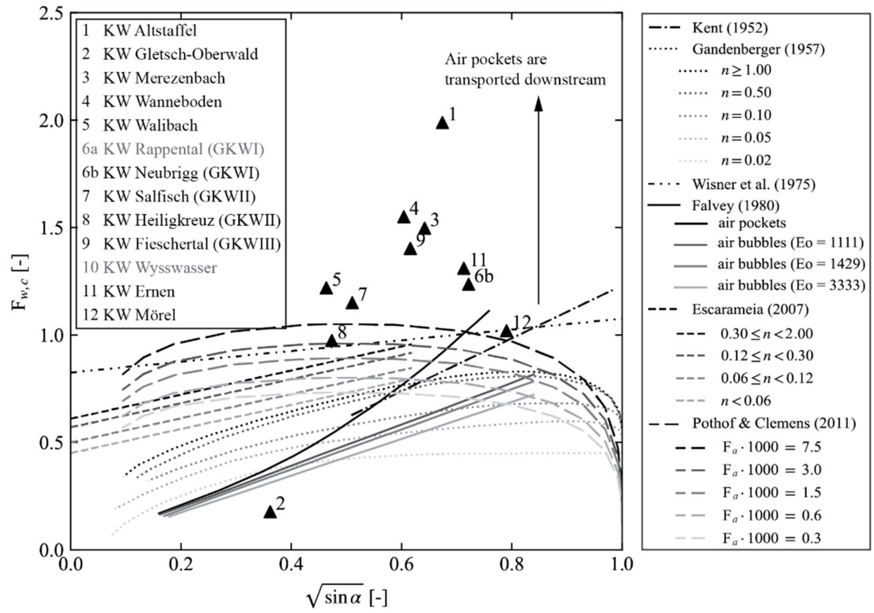

Figure 9: Comparison of different studies on the clearing flow number $F_{w,c}$ of air pockets in pipes, depending on pipe inclination *a*, dimensionless air velocity F_a or relative air pocket sizes n. For $F_{w,c}$ above the lines, air pockets are cleared from a pipe system, thus the entire air is transported downstream. For the considered plants in the Goms region, $F_{w,c}$ in the penstocks at design discharge ($Q = Q_d$) are indicated. Figure from WP5 led by ETHZ.

For each criterion, the hydropower plants are ranked from the best rank, 1, to the worst rank, 5. Then, the sum of rank is calculated. Lower is the sum, better is the flexibility potential.
For the storage volume, the power peak, the duration of the peak and the energy produced, the best rank is for the highest value. For the risk of air entrainment, the best rank corresponds to the lowest clearing flow number (see Figure 9). Table 4 shows the ranking of the hydropower plants for each criterion and the sum. KW Gletsch-Oberwald is the power plant with the highest flexibility potential with a sum of rank equal to 8, followed by KW Merenzenbach with a sum of 14, KW Mörel with a sum of 16, KW Wannebode with a sum of 17 and finally KW Walibach with a sum of 20.

Table 4: Ranking of the potential flexibility by criterion.

	KW Gletsch-Oberwald	KW Merezenbach	KW Wannebode	KW Walibach	KW Mörel
Storage volume (m3)	1	3	2	5	4
Power peak (MW)	2	4	5	3	1
Duration of the power peak (min)	3	1	2	4	5
Energy (MWh)	1	2	3	5	4
Risk of air entrainment and transport according to ETHZ	1	4	5	3	2
Sum of rank	8	14	17	20	16

The selection of the hydropower plants for the WP3 and WP6 is based on this ranking. Since KW Gletsch-Oberwald is the topic of the WP1 and has been already studied in the previous SmallFlex project, the two selected hydropower plants are KW Merenzenbach and KW Mörel.

4.4 WP3 – Identification of hydraulic system flexibility limits

Lead: PVE, partners: HEVS, ALPIQ, FMV

The aim of this work package is to perform an extensive hydraulic analysis of the flexibility potential of a selection of promising hydropower plants identified in the WP2, which will serve as a basis for WP6, WP7, WP8 and WP9. The kick-off meeting was successfully held on August 25, 2023, bringing together key collaborators from FMV, Alpiq, HES SO Valais, ETH, HEIG-VD, and WSL. The initial discussions during the kick-off meeting helped shape the project's direction, especially regarding the selection of potential hydropower plants for evaluation. Based on the work carried out in WP2, the HPP of KW Merenzenbach, KW Mörel and KW Altstafel were selected in order to carry out a more detailed assessment of the flexibility potential of these plants.

A critical aspect of this work package involves conducting technical site visits to the selected plants, see Figure 10, to provide valuable insights into the operational aspects and general layout, which is a fundamental step in the evaluation process. The site visit at the KW Merezenbach hydropower plant took place on the 24th of June 2024, and the visit of KW Altstafel took place on the next day, the 25th of June 2024. The visit at the KW Mörel hydropower plant took place on the 17th of July 2024. FMV managed and coordinated the scheduling of these visits, ensuring efficient organization.

Figure 10: Photos of SmallFLEX Goms teams during the visits of KW Merezenbach and KW Mörel in June and July 2024.

After collecting data for the selected plants, the new storage capacity of the selected HPP was assessed first in terms of both volume and energy. Full 1D-models of the KW Mörel, Altstafel and Merezenbach power plants were created using the SIMSEN software, based on available detailed drawings. These models are illustrated in Figure 11, Figure 12 and Figure 13. At this stage, only the Altstafel model in turbine mode has been validated with on-site measurements. The models of KW Mörel and KW Merezenbach were not yet validated for lack of on-site measurements. However, based on commissioning tests, the 4-quadrant characteristic of the KW Mörel turbine has been validated with good agreement between measurement and simulation, as shown in Figure 14.

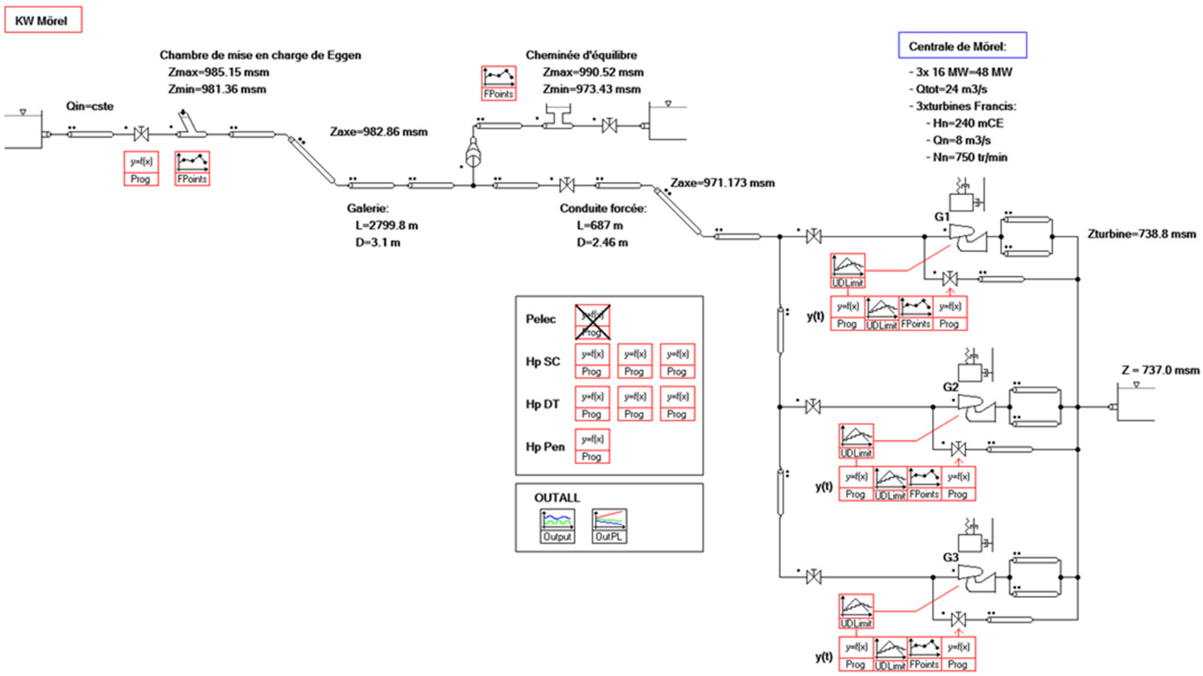

Figure 11 SIMSEN model of KW Mörel

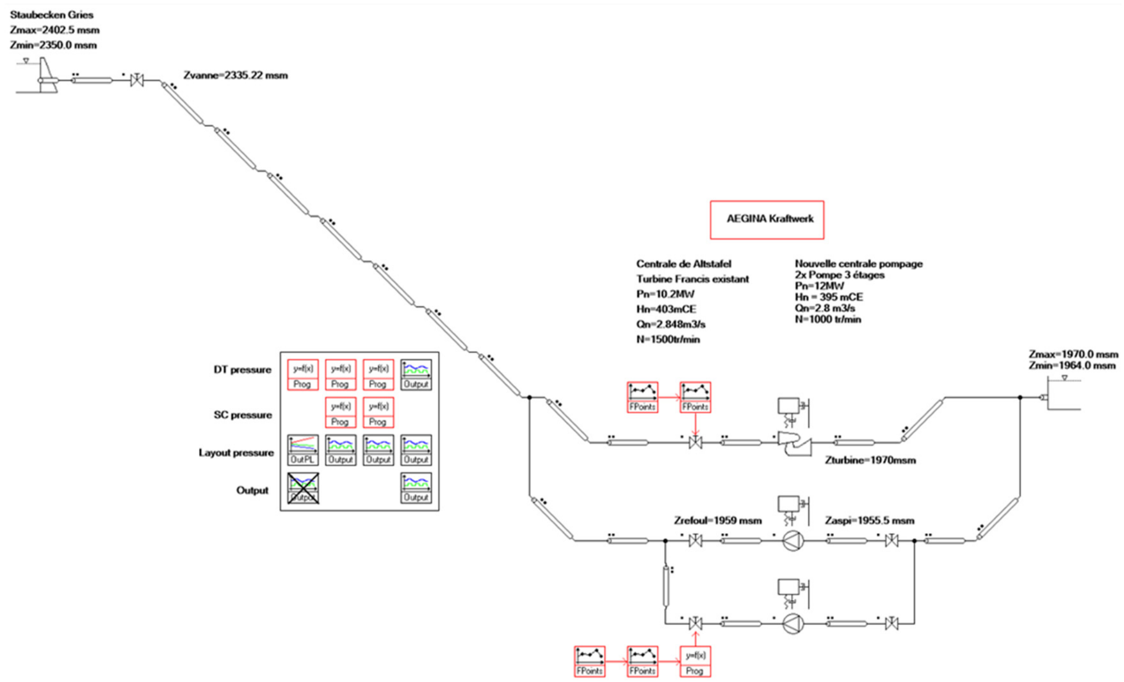

Figure 12 SIMSEN model of KW Altstafel.

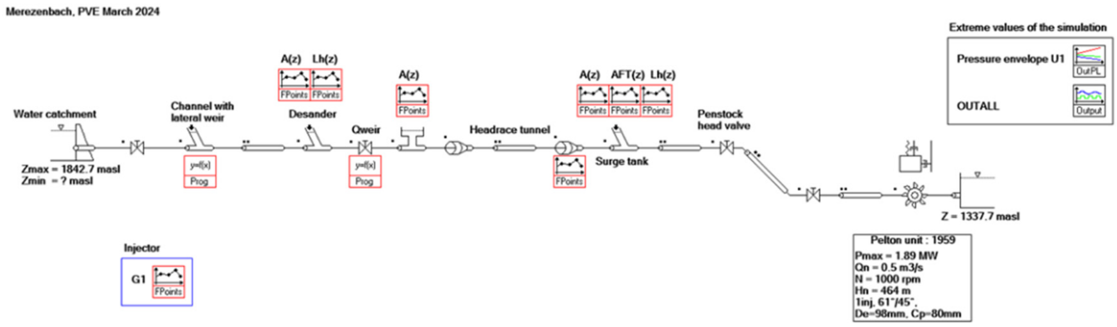

Figure 13 SIMSEN model of KW Merezenbach.

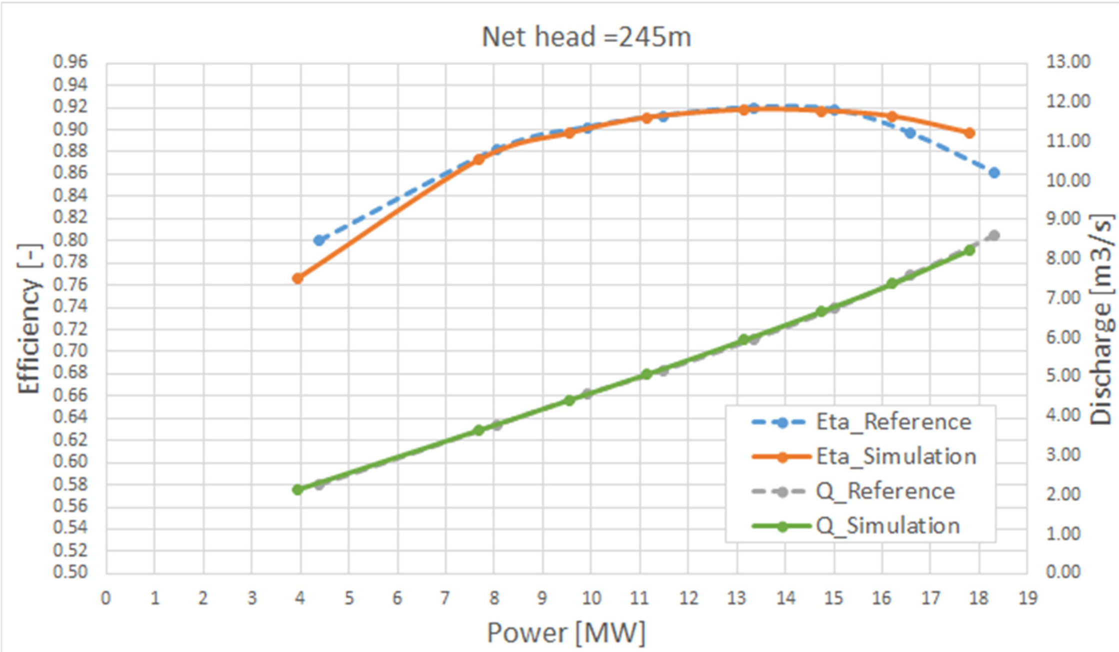

Figure 14: KW Mörel – Adjustment of the 4-quadrant characteristic.

In the feasibility study for the pumping station variants of KW Altstafel, three types of pumps were considered. The standard industrial pump, from the catalog, was found to be unsuitable for the site's requirements. According to manufacturers, the required flow rate (Q=2 m³/s for a head of 400m) would lead to a high number of pumps, limited operational stability, and low efficiency. The customized standard industrial pump, designed to meet the site's specific needs, offers a solution like Sulzer's HPDM model, with a configuration of three pumps (3x Q=0.8 m³/s @ H=400m). Finally, a prototype pump with a specific design, fully adapted to the site's needs, could achieve very high efficiency, up to 90%. A study on prototype pump variants was conducted to determine the optimal combination of pump quantity and stage configuration needed to achieve a specific speed greater or egal than Nq > 25 and a submergence level above -10m. Meeting these criteria would allow for either two three-stage pumps with a power output of 6 MW each or three three-stage pumps with a power output of 4.2 MW each to be proposed (see Table 5).

Table 5: Prototype design pump variants based on preliminary civil engineering feasibility study.

			1x Pump				2x Pump			3x Pump	
Characteristic of pump stage											
Mechanical power	Pm	[MW]	10	12.5	12.5	12.5	6.3	3.2	2	4.2	1.4
Nominal head	Hn	[m]	400	400	400	400	400	200	133	400	133
Nominal discharge	Qn	[m3/s]	2.28	2.81	2.87	2.87	1.4	1.4	1.4	0.92	0.96
Rotational speed	Nn	[rpm]	1500	1000	1500	750	1000	1000	1000	1000	1000
Specific speed	**Nq**	**[-]**	**25**	**18.7**	**28.4**	**13.9**	**13.2**	**22.7**	**30.1**	**10.7**	**25**
Mechanical time constant	Taum	[s]	3.9	3.9	4.1	3.8	3.3	2.8	2.5	3	2.3
Submergence	**Hs**	**[m]**	**-28**	**-19**	**-32**	**-12**	**-11**	**-7.6**	**-5.4**	**-7.2**	**-3**
Characteristic of pump											
Number stage	**e**	**[-]**	**1**	**1**	**1**	**1**	**1**	**2**	**3**	**1**	**3**
Mechanical power	Pm	[MW]	10	12.5	12.5	12.5	6.3	6.4	6	4.2	4.2
Nominal head	Hn	[m]	400	400	400	400	400	400	400	400	400
Characteristic of pumping station (total)											
Number pump	**Zp**	**[-]**	**1**	**1**	**1**	**1**	**2**	**2**	**2**	**3**	**3**
Total mechanical power	**Ptot**	**[MW]**	**10.0**	**12.5**	**12.5**	**12.5**	**12.6**	**12.8**	**12.0**	**12.6**	**12.6**
Total discharge	**Qtot**	**[m3/s]**	**2.3**	**2.8**	**2.9**	**2.9**	**2.8**	**2.8**	**2.8**	**2.8**	**2.9**
Efficiency	**eta**	**[%]**	**90%**	**88%**	**89%**	**86%**	**86%**	**89%**	**90%**	**86%**	**90%**

Concerning KW Mörel, the partner ETHZ calculated the water level in the Eggen loading chamber for different discharges. The SIMSEN model was used to simulate emergency shutdowns for each calculated setpoint, and the results were transmitted to ETHZ. ETHZ will use these results for their model tests to be performed within work package WP5. The transient behavior for the case where Q=24m^3/s is shown in the Figure 15 below.

(a) (b)

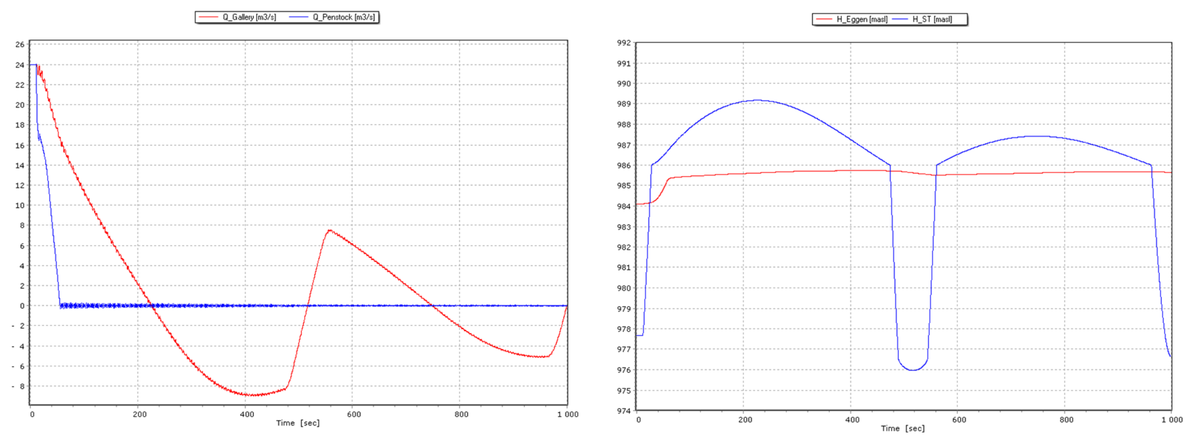

Figure 15 : Simulated transient behaviour of discharges (a) in the headrace tunnel (red) and penstock (blue) and water levels (b) in the Eggen chamber (red) and surge tank (blue) in the case of an ESD from Q=24m3/s at the Mörel hydropower station.

Hydraulic transients were also simulated using the SIMSEN model of KW Merezenbach. The model was adapted to simulate hydraulic transients with dewatering of the headrace tunnel and penstock.

Regarding the risk of air entrainment during the dewatering of the head race pipe, the simulation of the flow has been carried out by HEVS on a domain including the forebay tank, the head race pipe (shortened in order to reduce the computational cost), the surge tank and the upper part of the penstock (see Figure 16). During the first 100 seconds, the discharge at the intake is set to 100 l/s and the discharge at the outlet of the penstock is set 500 l/s. Consequently, the head race pipe dewaters as well as the upper part of the penstock. Then during the next 350 seconds, the outlet is closed, mimicking an emergency shutdown. Therefore, a wave goes back to the intake and the pipes fill in water progressively. After 450 seconds, it is observed that a thin sheet of air is still present at the top of the head race pipe (see Figure 17). This feature suggests that some air is trapped in the pipe, which could be risky for the operation of the power plant. However, this simulation must be considered as the most critical scenario with a closure of the group valve that is instantaneous. By adding a time delay, the trapped air in the pipe may be removed. Therefore, additional investigations are still needed.

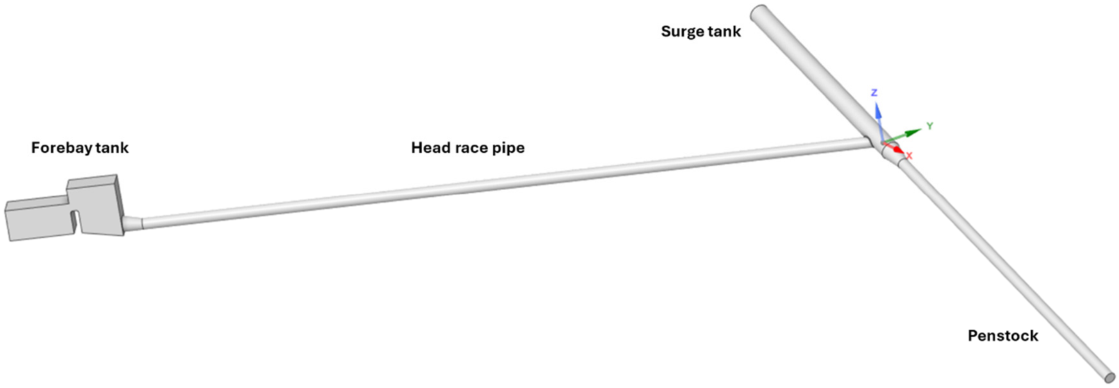

Figure 16 : Computational domain considered for the simulation of the flow in the pipes during a dewatering event. The length of the head race pipe is shortened compared to the real length.

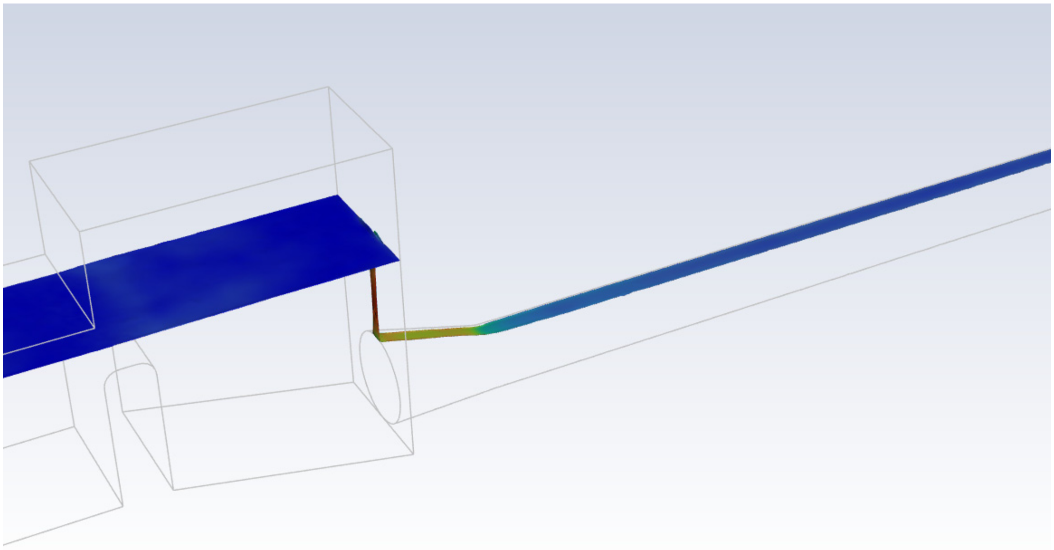

Figure 17: View of the free surface at the intake after 450 seconds during a dewatering/filling sequence of the head race pipe.

4.5 WP4 – Hydro-meteorological predictions

Lead: WSL, partners: HEIG-VD, PVE

In 2024 WP4 set the basis for providing operational 5 days forecasts for selected power plants of the project. A major effort had to be completed to setup the operational data flow and configure the system with the new ICON models by MeteoSwiss, which replaced the COSMO models. Prior to June 2024 COSMO forecasts were implemented for the Small Flex area of Gletsch. This experiment is on place since several years now. The ICON forecasts were put into operations by MeteoSwiss end of May 2024. The first forecasts for Small Flex WP4 have been run on June 10, 2024. Beside KW Gletsch, forecasts are available for KW Altstafel (including 4 sub-areas), KW Merezenbach and KW Wannenboden. Figure 18 presents one of the first forecasts published.

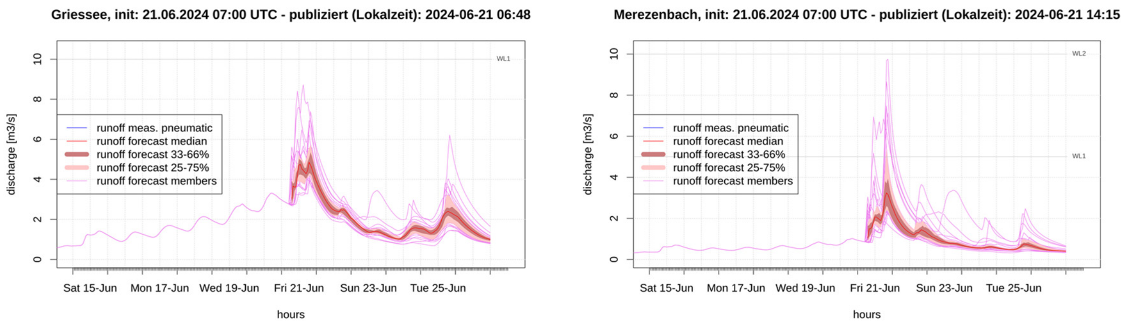

Figure 18 (left) 5 Days forecasts for the discharge at Längtalbach of KW Altstafel and (right) 5 Days forecasts for the discharge at Längtalbach of KW. The forecast has been started on June 21.

The forecast hinted at a possible runoff event on that day. Some kilometres downstream a debris flow was recorded at the WSL Illgraben site. Further, severe damages have been recorded in Zermatt (Figure 19).

Figure 19 (left) Debris Flow at the WSL Illgraben on June 21 (photo by WSL). (right) Flood impacts in Zermatt, with no connections by train from Zermatt to Visp (https://www.baerntoday.ch/)

Next to discharge information, WP7 of Small Flex require further meteorological information to setup flexible management of a virtual station including hybridization of hydropower with solar and wind energy.

The first forecasts for wind and incoming solar radiation were produced on June 21st. These are displayed in Figure 20.

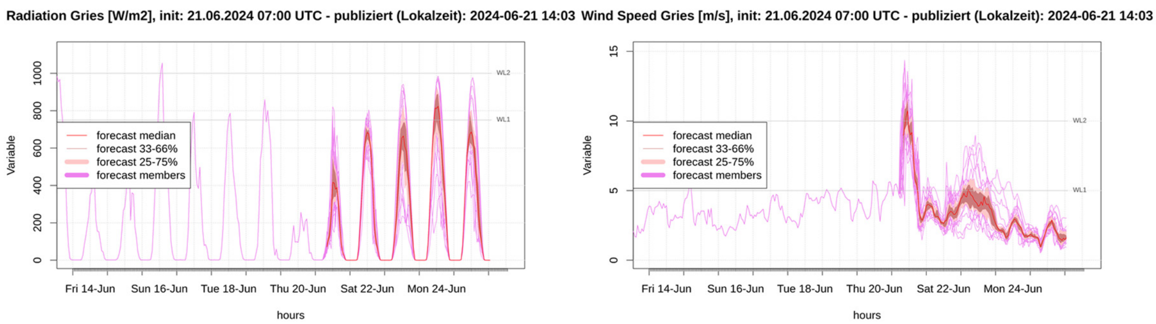

Figure 20 (left) Forecast for solar radiation at the lake Gries dam. (right) Wind speed forecast for the lake Gries dam.

Since June 21 files for data exchange with WP7 have been generated and archived. This data archive will be evaluated and integral part of D4.1 due in early 2025.

The data format is compatible with the requirements of WP7. Historical data in same format based on actual observations have been also prepared for the period 2006-2023 and delivered to WP7 in early October 2024. The latest forecasts for scheduling energy production are available at about 6 a.m. This is about two hours earlier than the old COSMO-based forecasts.

Currently the same data are in preparation at daily time scale for future scenarios. The data downscaling for the four basins providing operational forecasts should be completed in November 2024. The hydrological scenarios will be ready by early 2025. This will be the basis for the D4.2, due in fall 2025. The results presented in 2023 for an idealized plant in the Binntal are currently being prepared as manuscript to be submitted by the end of 2024.

Finally, WP4 wants to promote here a possibly relevant new data set that WSL presented in Summer 2024. In Switzerland, hydropower plants (HPPs) with a capacity of more than 300 kW are systematically recorded and collated in the national hydropower statistics (WASTA). A newly compiled data set for Swiss micro-hydropower plants includes 1,682 locations with a capacity of less than 300 kW. The two datasets WASTA (> 300 kW) and CH small hydropower plants (≤ 300 kW) currently include 2,388 wind turbines. The 1,682 small hydropower plants account for around 70% of all recorded hydropower plants in Switzerland, but with less than 600 GWh/year they only contribute around 1.5% to Swiss hydropower production. The data sets include more than 250 plants in the Canton of Valais and several micro plants in the Small Flex target area of Goms.

Wechsler, T., Zappa, M. (2024). CH-Kleinstwasserkraftwerke - ein schweizweiter Datensatz zu Kleinstwasserkraftwerken. *EnviDat.* https://www.doi.org/10.16904/envidat.523.

The documentation can be downloaded here:
https://www.dora.lib4ri.ch/wsl/islandora/object/wsl%3A37066

4.6 WP5 – Risk of air entrainment

Lead: ETHZ, partners: HEVS

The aim of this work package is to assess the risk of air entrainment and transport in the waterways resulting from the partial lowering of the water level to use this storage volume in flexible operation. In the first year of the project, the flow conditions during water level lowering were studied, and a literature review was carried out to identify relevant processes, and knowledge gaps related to air entrainment and transport. It was found that the clearing flow number $F_{w,c}$ offers a simple criterion to exclude, at an early stage of the project, those hydropower plants (HPPs) where the transport of large air pockets is expected when lowering of the water level in the penstock. In this regard, the flow conditions in KW Gletsch-Oberwald (KWGO) were found to be unrepresentative of the entire Goms region. Except for the pilot plant, all sites exceeded $F_{w,c}$ under design discharge conditions, indicating that entrained air would be transported to the turbines, posing operational risks. For evaluating other sites, the exceedance of $F_{w,c}$ can serve as a criterion for exclusion, but sites where $F_{w,c}$ is not exceeded still need more detailed investigation.

In the second year, the literature review was extended to additionally include the effects of dissolved air. When air is entrained and transported within the penstocks, increased pressure dissolves more air into the water, as gas solubility rises with pressure (Henry, 1803). Once the pressurized water is released downstream, the rapid pressure drop causes the dissolved air to exceed equilibrium levels, creating total dissolved gas (TDG) supersaturation. Prolonged exposure to elevated TDG levels downstream of a hydropower plant can be harmful to aquatic organisms, leading to gas bubble disease (GBD), a condition similar to human decompression sickness. GBD in fish involves the formation of free gas bubbles in blood vessels and various body tissues, such as fins, the loose connective tissue of the eyes, or the gills (Weitkamp and Katz, 1980; Fidler, 1988).

Pulg et al. (2024), assessing the potential for TDG supersaturation (TDGS) downstream of hydropower plants in Norway, found that plants characterized by secondary intakes and Francis or Kaplan turbines are prone to generating TDGS. The secondary intakes are characterized by steep shafts, where the water flows as a free surface flow to a level determined by the pressure line of the system, where the transition to pressurized flow occurs. The hydraulic conditions are equivalent to those in a partially emptied penstock. Air is thus entrained into the pressurized system, transported to the power station, and dissolved due to the increasing hydrostatic pressure. In contrast to Francis and Kaplan turbines, Pelton turbines aerate the supersaturated water, triggering degassing and mitigating TDGS downstream of the hydropower plant. All three selected HPPs (KW Altstaffel, KW Ernen, and KW Mörel) are equipped with Francis turbines.

Based on the findings of the literature review, it was decided that the physical model investigations shall focus on air entrainment and specific countermeasures at selected plants. At the selected KW Mörel, air is expected to enter the pressurized headrace tunnel during water level lowering at the pressurization chamber. It was decided to model the relevant section between the pressurization chamber and the upper section of the refurbished headrace tunnel, consisting of a mild and a steep downward inclined section (Section 1: S = 0.0036, D = 3.1 m, $L \approx$ 67 m; Section 2: S = 0.85, D = 3.1 m, $L \approx$ 27 m). The main objectives of the physical model investigations include:

1. Verifying two-phase flow patterns in headrace tunnels and penstocks.
2. Quantifying air entrainment caused by vortices, surface instabilities, and hydraulic jumps.
3. Investigating transient conditions and pressure surges during emergency shutdowns.

Based on the literature review, it is appropriate to apply the Froude scaling law to model air entrainment and transport processes, ensuring geometric and kinematic similarity. The implied overestimation of viscous forces diminishes for pipe diameters D > [0.15, 0.19] m. A scaling factor of 1:16, corresponding to D = 0.19 m was therefore chosen to minimize scale effects. The model construction at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at ETH Zurich was completed in September 2024 (Figure 21). The physical model consists of an inlet tank, the free-flow headrace tunnel, and the pressurization chamber constructed from PVC and acrylic glass. The adjacent pressurized headrace tunnel is made of acrylic glass pipes. Air can be injected immediately downstream of the pressurization chamber, and emergency shutdowns can be simulated with a manual valve and a secondary water inlet to simulate surge tank oscillations. The measurement equipment includes several magnetic-inductive flow meters (MID), relative pressure sensors, a de-aeration shaft equipped with an absolute pressure sensor, allowing for the quantification of air transport, and capacitance wave gauges for detecting surge waves in the event of transients. The model tests are planned to take place between Q4 2024 and Q2 2025, with the literature review being updated in parallel.

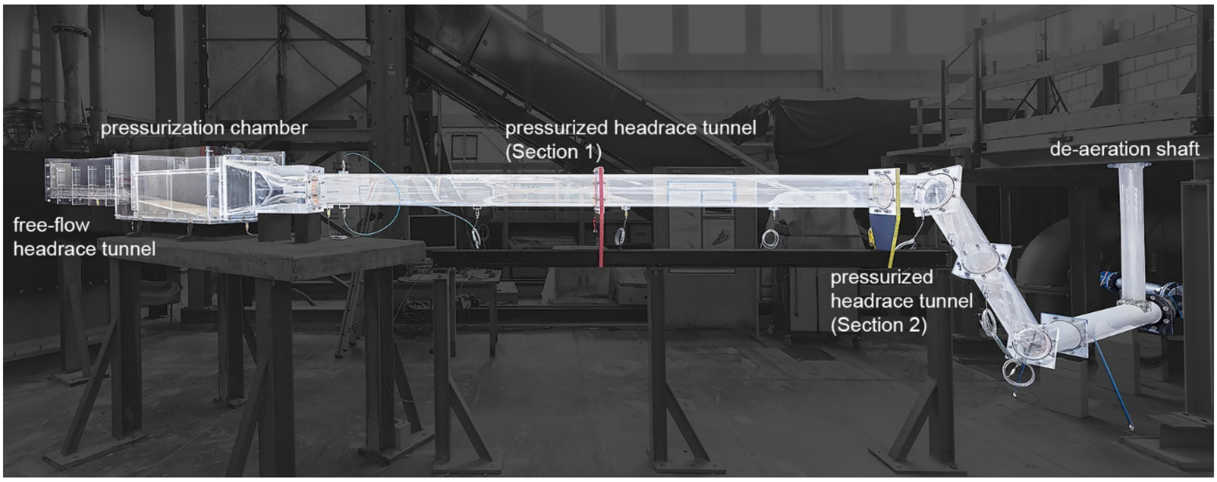

Figure 21: Foto of the physical model (scale 1:16)

4.7 WP6 - On-site experiments

Lead: HEVS, partners: PVE, FMV

One of the objectives of WP6 is to deploy the Hydro-Clone system at KW Mörel. Initially scheduled for deployment in autumn 2024 to support the experimental measurement campaign conducted by HES, this task has now been postponed to spring 2025. However, preliminary tasks such as the establishment of the SIMSEN model and signals description have been completed. The reason for the delay is due to delays in ordering the IT components needed to deploy Hydro-Clone system, such as the PLC and the availability of on-site operators.

Hydro-Clone is a "Real-Time Simulation Monitoring" system that uses a validated SIMSEN model of a hydropower plant to ensure proper operation by simulating its dynamic behavior based on on-site boundary conditions transmitted via the SCADA system. The system aims to detect and prevent equipment malfunctions or anomalies that could impact hydraulic transients, thereby reducing the risk of major accidents. The digital twin provides insights into difficult-to-measure quantities, such as pressure fluctuations, allowing for early identification of potential issues. Additionally, long-term monitoring of transient regimes helps optimize operating parameters, reducing equipment loads and enhancing service life while minimizing accident risks.

The on-site measurements will be carried out according to the schedule in year 2025.

4.8 WP7 – VPP

Lead: HEIG-VD, partners: PVE, ALPIQ, FMV, WSL

Approach and Problem Formulation

A preliminary version of the VPP design problem formulation (including the objective function, decision variables, and key constraints) was formulated in 2023 following several meetings and discussions among the partners of WP7. An appropriate solution algorithm is also developed to solve the proposed problem formulation. The following are the main assumptions underlying the problem formulation and proposed solution algorithm:

A) The VPP will focus on three distinct electricity markets: day-ahead, intraday balancing, and flexibility (*i.e.*, ancillary service).
B) The number of VPP design schemes is limited. As a result, we can calculate the profit and risk of each design scheme individually.
C) The VPP might consist of several existing and potential small hydro power plants, pumps, PVs, wind turbines, and battery energy storage systems.
D) There could be a hydrological link constraint between small hydro power plants and pumps. FMV must be contacted for additional information on the configuration of hydro power plants.
E) Small hydro power plants, pumps, and energy storage systems will participate in the flexibility market to provide flexibility products. Because of practical reasons, PVs and wind turbines do not curtail their power to participate in the flexibility market.
F) The VPP will optimize its resources in day-ahead and flexibility markets knowing the forecast with lead time of 24h. Furthermore, the VPP will participate in intraday balancing market knowing the short-term forecast with lead time of 1h.

When we combine small hydro power plants, PVs, wind turbines, energy storage systems, and pumps into a single portfolio and centrally manage them within a VPP, there are several advantages.

- *Firstly*, by integrating small hydro power plants into a VPP scheme, it is possible to optimize their production and increase their potential profit in the day-ahead market.

- *Secondly*, the less reliable flexibility of the hydro power plants with small reservoir capacity can be combined with the more reliable flexibility of the battery energy storage systems, allowing them to meet the requirements of the flexibility market as well as environmental constraints (*e.g.*, limits related to hydropeaking).

- *Thirdly*, the flexibility of the small hydro power plants can be used to compensate for PV and wind turbine production imbalances due to forecast errors, resulting in increased profits in the day-ahead and intraday markets. Figure 22: Proposed algorithm for the VPP design problem. Proposed algorithm for the VPP design problem.

- *Fourthly*, the pumps can be used to transfer water multiple times to higher altitude hydro power plants, allowing them to provide and sell more flexibility if the price of flexibility is higher than the cost of energy in the day ahead.

In the following, a brief description of problem formulation and proposed algorithm is presented. To optimally design the VPP, we must determine the optimal operation of the VPP components over various time horizons, considering the three mentioned markets. However, if we consider all time horizons in one optimization problem, it would be so large that it would be impossible to solve in a tractable manner. We employ a hierarchical approach to resolve the issue of tractability by estimating the optimal operation and designing the VPP components, keeping in mind that the number of VPP design schemes is limited. The flowchart in Figure 22 describes the process of designing the VPP.

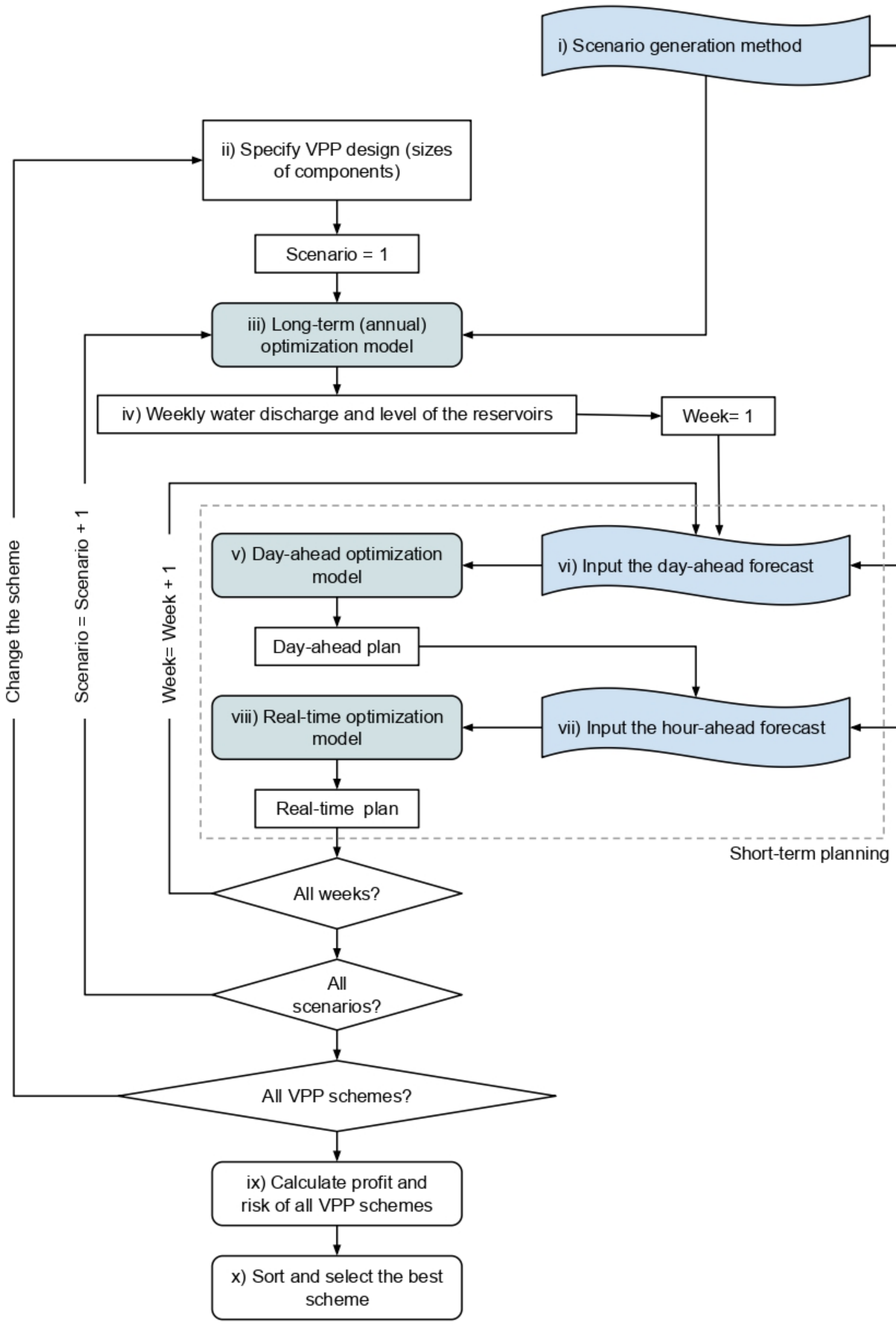

Figure 22: Proposed algorithm for the VPP design problem.

The process begins by generating a set of long-term annual scenarios, each of which represents a different possible hydro-meteorological condition (this will be done in WP 4). The next step is to optimize the VPP operation for each scenario. This is done using a three-level optimization framework including a long-term (annual) optimization model, a day-ahead optimization model, and a real-time optimization model. The long-term optimization model takes an annual scenario and determines the optimal weekly water discharge and average head of each reservoir for each week. The day-ahead optimization model determines the optimal power output of the VPP for the next day, given the forecast for the day. The real-time optimization model determines the optimal power output of the VPP for the current hour given the hour-ahead forecast. The process is repeated for all scenarios. We will use aggregation and parallelization techniques to reduce computational time. Aggregation is accomplished by combining day-ahead and real-time problems from one week into a single problem, and parallelization is accomplished by running long-term problems from various scenarios on multiple parallel processors.

Once the VPP has been optimized for all scenarios, the profit and risk of all VPP schemes are calculated. The best scheme is then selected. The overall objective of the proposed algorithm is to identify the following:

(a) The optimal VPP design scheme, including the optimal capacity of its generation and storage units.

(b) The optimal trade-off between profit and risk level of the VPP.

(c) The optimal operating schedule for each generation and storage unit regarding various scenarios.

In 2024, the mathematical problem formulation has been refined to better represent the technical and economic constraints for development of VPPs in the GOMS region following further advances in the project. In the revised formulation the feedback from the partners is integrated and additional constraints are modelled such as the financial risk of the VPP operation.

In step ii of the proposed algorithm in Figure 4, we define several VPP design schemes. These schemes are defined based on the geographical and technical limitations that exist for the renovation of small HP units and the building of other distributed resources.

The models and formulations for steps iii, v, viii, ix, and x of Figure 4 are presented in the draft document, including the long-term (annual), day-ahead, and real-time optimization models. These three optimization problems can be combined to form a larger problem. We will address the scalability and numerical issues by addressing these three problems with two long-term and short-term optimization problems for various scenarios and VPP design schemes, which can be solved in parallel.

Each short-term and long-term optimization problem has its own objective and set of constraints. Specifically, the following constraints are considered:

- The flow rates of small hydroelectric power plants and pumps limit their capacity for production. Additionally, the flow of small hydro power plants must respect environmental constraints (e.g., hydropeaking and limits on the amount of stored water), which depend on input discharge and unit turbined flow. Small hydro power plant minimum and maximum head (or minimum and maximum volume), ramp-rate restrictions for flexibility, and water flow dependence of cascaded units and pumps are also taken into consideration.
- The charging and discharging power of a battery energy storage system, as well as the minimum and maximum charging/discharging power, all have an impact on the state of energy of the battery energy storage system. The battery's ramp-rate for supplying flexibility is also considered.
- The production of PVs and wind turbines is limited by the irradiation and wind speed considering their production efficiencies.
- The VPP follows the rules and regulations of the power exchange and the ancillary service markets.

The constraints for the small hydro power plants and pumps are complex due to the non-linear relationship between production and flow. We used a stepwise linearization technique to approximate them. The constraints for the battery energy storage systems and PVs and wind turbines are more straightforward.
A full description of the mathematical formulation as well as linearization techniques for the solution algorithm is presented in the annex document (VPP Design Problem Formulation Document)

Implementation The formulated optimization problem has been implemented in a Python environment. In addition, a simple scenario generation procedure is implemented in Python using naive ARIMA forecasting method as a benchmark. Figure 23 below shows the flowchart of implemented scenario generation procedure.

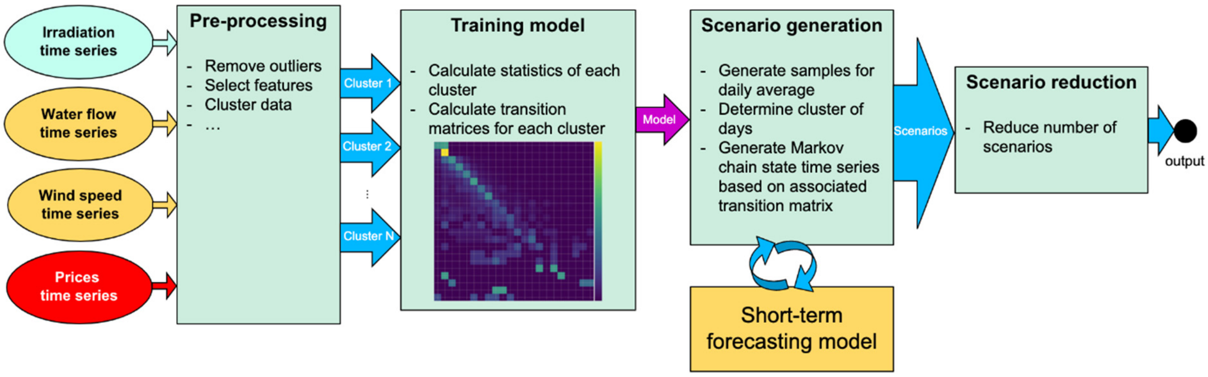

Figure 23 Scenario generation procedure

A pipeline for processing the input data linked to the scenario generation procedure, forecasting benchmark, and optimization model is developed as depicted in Figure 24 below.

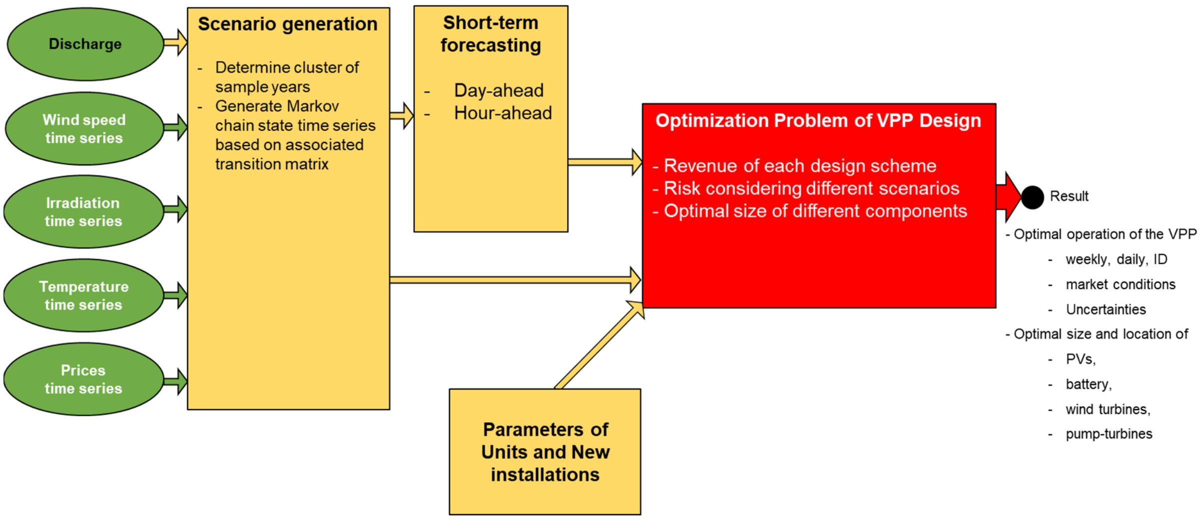

Figure 24 Implemented pipeline

Case studies and Collected data

Regarding various considerations for availability of input data and flexibility of hydro power plant units in the region, three initial plants are considered, namely, KW Merezenbach, KW Mörel, and KW Aegina – Alstafel.

PVE has provided a set of hydraulic performance table for different level of the head for the above-mentioned power plants.

WSL has provided a set of historical and current measurements of hydro-meteorological variables from 2006 to 2022 related to the KW Aegina – Alstafel.

- discharge for each sub-basin of Gries.
- Temperature Surface (°C)
- Global Radiation (W/m2)
- Wind Speed (m/s)

FMV has provided geometrical information of the reservoirs as well as nominal data of the existing wind power plant and planned PV power plant in the region.

Finally, for the market and the economic data, first HEIG-VD extracted data from the Swissgrid website. Then, Alpiq has considerably enriched this data set by providing a set of historical energy and ancillary service market data for Switzerland and the neighboring countries including Germany, France, Austria and Italy.

At HEIG-VD, a data schema is developed to federate all the input data with a unique platform (which is integrated to the pipeline presented in Figure 24). At this stage, the focus has been on the KW Aegina – Alstafel power plant and the wind and photovoltaic installations and projects in its vicinity. An example of solar irradiation data is depicted in and an example of market data (day-ahead and spot market prices) are illustrated in Figure 25 and Figure 26.

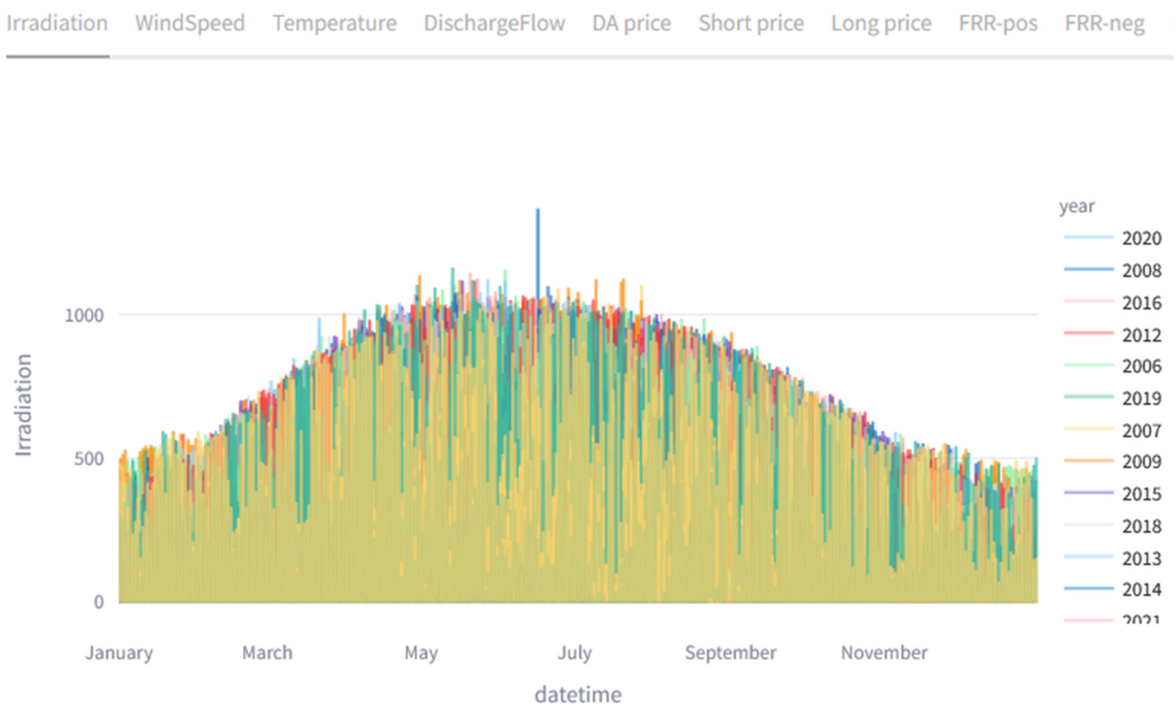

Figure 25 Data platform with historical solar irradiation data

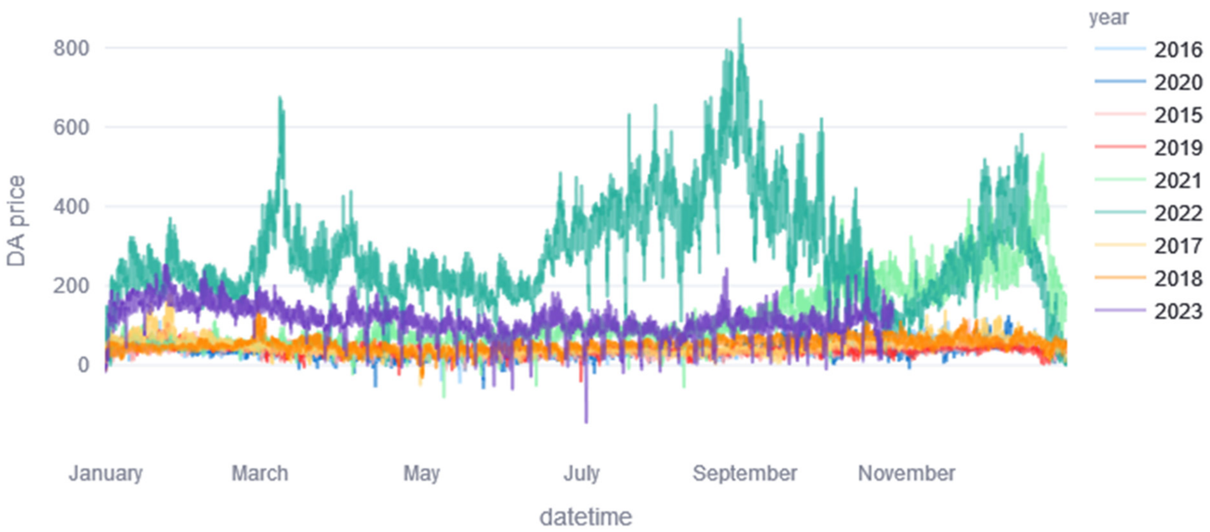

Figure 26 Data platform - historical day-ahead energy prices

4.9 WP8 – Development of the business model

Lead: FMV, partners: Alpiq

This WP has not started according to the planning.

4.10 WP9 – Synthesis and dissemination of the results

Lead: HEVS, partners: All

This WP has not started according to the planning.

5 Evaluation of results to date

Regarding the initial planning, some activities have been delayed or modified. Regarding WP1, the flexible mode has been implemented partially at KWGO with the start of the long-term monitoring. Nevertheless, the headrace tunnel has not been yet used, this should be done by beginning of 2025. In WP2, the inventory has been performed with the development of ranking methodology allowing to identify the best case studies in the Goms region. Regarding WP3, the site visits have been organised during the summer of 2024. The collection of data from selected plants (KW Merezenbach, KW Mörel, and KW Altstafel) has allowed to develop the corresponding SIMSEN models, to start the sizing of new pumping capacity for Altstafel and to predict the risk of air entrainment at KW Merezenbach with CFD simulations. For WP4, the new ICON models by MeteoSwiss have been implemented to provide hydrometeorological forecasts for the selected power plants. In WP5, the state-of-the-art report related to air entrainment has been compiled while the hydraulic scale model to investigate air entrainment has been constructed and is ready to perform the first experiments. For WP6, following the site visit and the first results from WP3, the definition of the experimental protocols for the field tests just started. The mathematical problem formulation of the VPP has been refined to better represent the technical and economic constraints in the GOMS region following further advances in the project in WP7. The formulated short-term and long-term optimization problems have been implemented in a Python environment. At this stage, the focus has been on the KW Aegina – Alstafel power plant and the wind and photovoltaic installations and projects in its vicinity. WP8 and WP9 did not started yet.

6 Next steps

In the coming months, the last flexible exploitation mode will be implemented in KGWO in the framework of WP1 with the first part of the environmental monitoring. WP2 has been closed with the final selection of the power plants for the other WP. In WP3, specific measurements should be performed on site to validate the developed SIMSEN model and provide the peak production and SDL capacity for the selected power plants. In parallel, more CFD simulations will be carried out to investigate the risk of air entrainment for KW Merezenbach. A review on the extension of operating range of hydraulic machines will be performed. For WP4, the hydrometeorological forecasts for the selected power plants will be assessed as well as the investigation of the climate change impact on the potential flexible modes. In WP5, different operation modes and their effect on air entrainment and transport within the penstock of the developed test bench will be investigated. For WP6, the Hydro-Clone system will be installed in the Mörel power plant at the beginning of the next year. Free-run and specific on-site experimental campaigns will be performed in KW Merezenbach and KW Mörel to explore the operational limits of the power plants using the identified potential storage. For WP7, a benchmark optimal design and operation will be compared with existing data of annual operation of KW Aegina – Alstafel. Moreover, dynamic simulation of capability of provision of ancillary services regarding power system constraints will be carried out, while a physical emulation of the reduced-scale local grid in the ReIne reconfigurable distribution grid laboratory of HEIG-VD will be investigated. WP8 will be launched to investigate the economic aspects of the project and the dissemination of the first results will start within WP9.

7 Publication

Streule, C., Lais A., Evers F., Münch-Alligné C. & Boes R. (2024). Flexibilisierung der Kleinwasserkraft durch Stollenspeicherung – Lufteintrag und -transport als limitierende Faktoren. In G. Zenz (Ed.), Wasserbausymposium Graz 2024 (9-17).

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Pulg, U., Lennox, R. J., Enqvist, M., Stranzl, S. F., Espedal, E. O., Schwarz, M., ... & Velle, G. (2024). Assessing the potential for gas supersaturation downstream of hydropower plants in Norway, Austria and Germany. *Science of the Total Environment*, *948*, 174645.

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