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SmallFLEX GOMS

Small Hydro Flexibility and Complementarity with Photovoltaic Production in Goms Region

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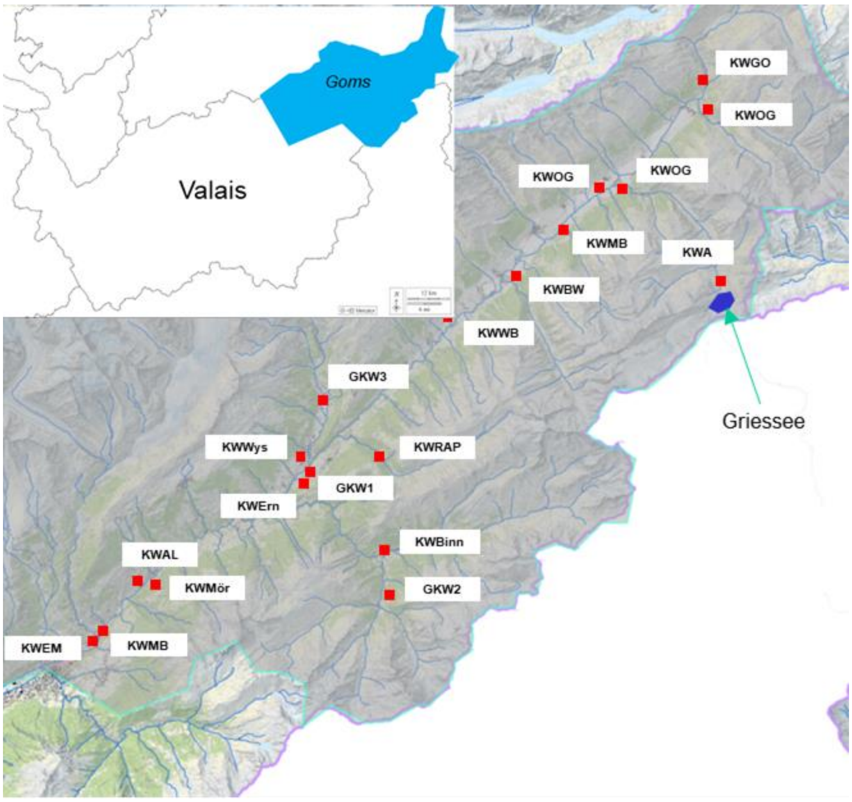

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Rue de la Dixence 9, CP 506, CH-1951 Sion
www.fmv.ch
ALPIQ
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Subsidy recipients:
HES SO Valais
Rue de l'industrie 23, 1950 Sion
www.hevs.ch
HEIG-VD
Route de Cheseaux 1, 1400 Yverdon-les-Bains, CH
www.heig-vd.ch
PVE - Power Vision Engineering Sàrl
Rue des Jordils 40 1, CH-1025 St-Sulpice
www.powervision-eng.ch/
WSL - Swiss Federal Institute for Forest, Snow and Landscape Research
Zürcherstrasse 111, CH-8903 Birmensdorf
www.wsl.ch
ETHZ - Versuchsanstalt für Wasserbau (VAW)
Hönggerbergring 26, 8093 Zürich, Switzerland
www.vaw.ethz.ch
Authors:
Line Moret, Jean Decaix, Cécile Münch-Alligné, HES SO Valais, cecile.muench@hevs.ch
Rayati Mohammad, Mokhtar Bozorg, HEIG-VD, mokhtar.bozorg@heig-vd.ch
Florent Gauye, FMV, florent.gauye@fmv.ch
Matthieu Dreyer, Christophe Nicolet, Powervision Engineering, christophe.nicolet@powervision-eng.ch
Massimiliano Zappa, WSL, massimiliano.zappa@wsl.ch@wsl.ch
Clara Streule, Adriano, Lais, Frederic Evers, Robert Boes, ETHZ VAW, boes@vaw.baug.ethz.ch
Bernard Valluy, ALPIQ, bernard.valluy@alpiq.com
SFOE project coordinators:
Karin Söderström, karin.soederstroem@bfe.admin.ch
Michael Moser, michael.moser@bfe.admin.ch

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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 de-sander 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.

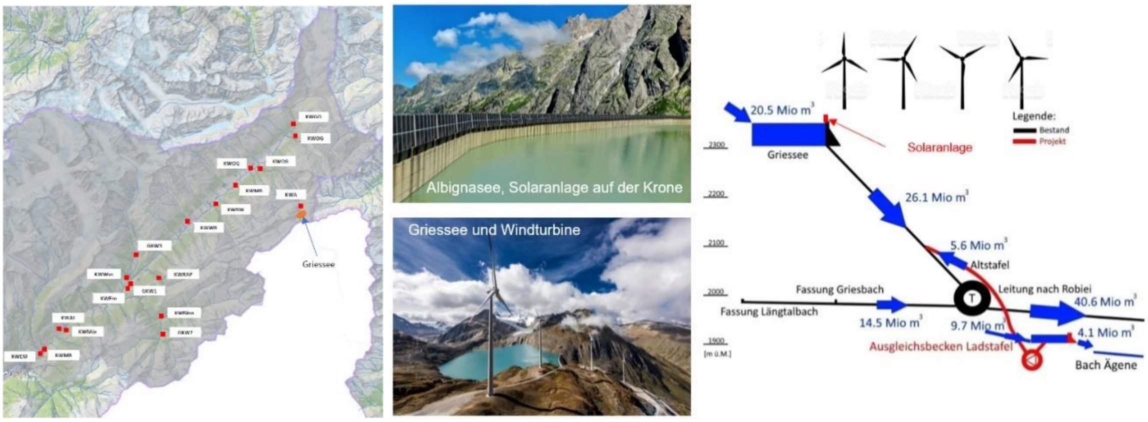


Figure 1: Hydrological map of Goms region with some existing hydro power plants and possible combination of hydro, solar, and wind generation close to Griessee lake.

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.

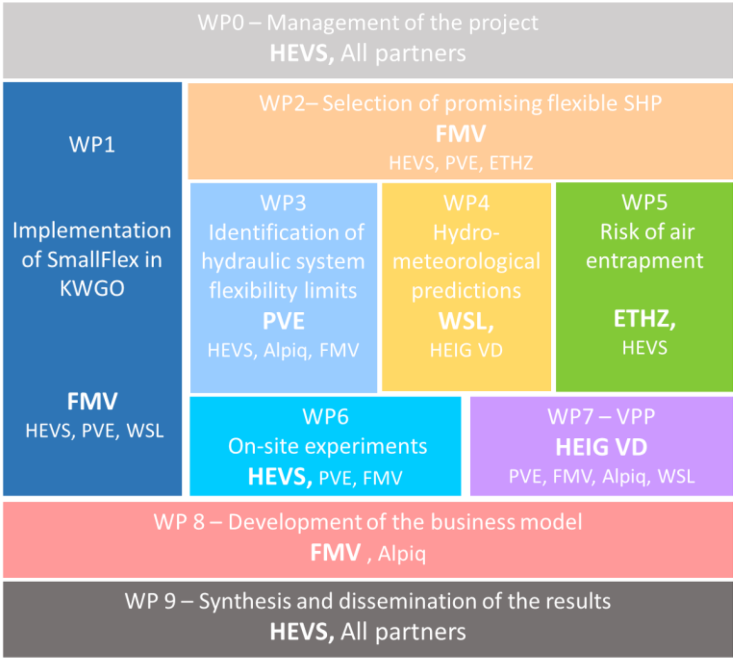


Figure 2: Project organisation

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 entrapment
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:

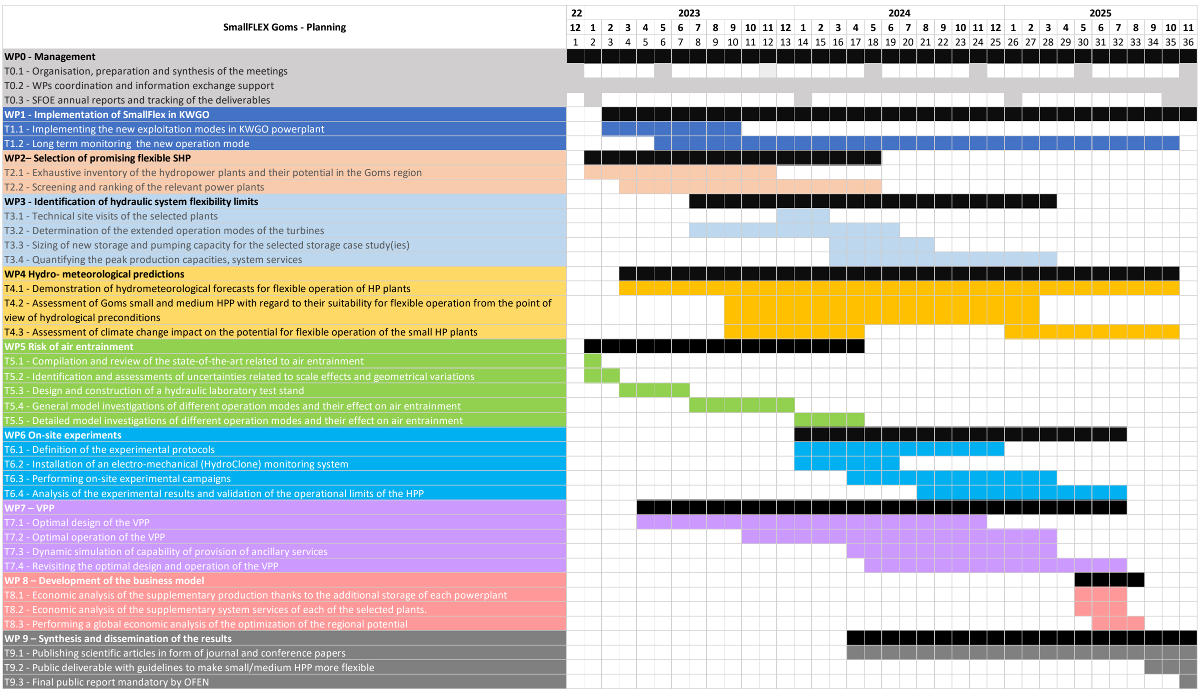


Figure 3: Initial project planning

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
WP0	HEVS	D0.2 – Annual reports (HEVS)	yearly
WP1	FMV	M1.1 – Implementation of the flexible operation mode at KWGO (FMV)	30/09/2023

		D1.1 – Optimized flexibility (booklet)	30/11/2025
		D1.2 – Analysis of the 3-years monitoring.	30/11/2025
WP2	FMV	M2.1 - Intermediate inventory of the hydropower plants	31/07/2023
		M2.2 – Selection of the two power plants	30/08/2023
		M2.3 - Exhaustive inventory of the hydropower plants	31/11/2023
		D2.1 – Screening and ranking of the hydro powerplants based on the criteria and the methodology of selection.	30/04/2024
WP3	PVE	D3.1 – Detailed analysis of the flexibility of the selected power plants	30/04/2025
WP4	WSL	M4.1 – Setup of catchment completed - real-time operations ready	31/07/2023
		M4.2 – Climate change scenarios computed	30/04/2024
		M4.3 – Framework for-flexible-operations analysis ready	31/08/2024
		D4.1 – Analysis of flexible real-time operations with hydrological forecasts	28/02/2025
		D4.2 – Analysis of flexible real-time operations with hydrological scenarios	30/09/2025
WP5	ETHZ	M5.1 – Initial operation of the laboratory test stand	30/06/2023
		D5.1 – Review report on air entrainment	31/05/2023
		D5.2 – Report on detailed model investigations	31/04/2024
WP6	HEVS	M6.1 – On-site measurements achieved (PP2)	31/03/2025
		M6.2 – Hydro-Clone in operation	31/08/2024
		D6.1 – Analysis of the on-site measurements.	31/08/2025
WP7	HEIG-VD	D7.1 – Preliminary design of the VPP	30/06/2024
		D7.2 – Final report on optimal design, operation and simulation performance of the VPP	31/05/2025
WP8	FMV	D8.1 - Assessment of the economic benefits of the demonstrators	30/11/2025
		D8.2 – Added value of new storage and pumping	30/11/2025
WP9	HEVS	M9.1 – Share of the deliverable 9.2 with HPP actors	30/11/2025
		D9.1 – List of the dissemination activities	30/11/2025
		D9.2 – Guidelines to make small/medium HPP more flexible	30/11/2025

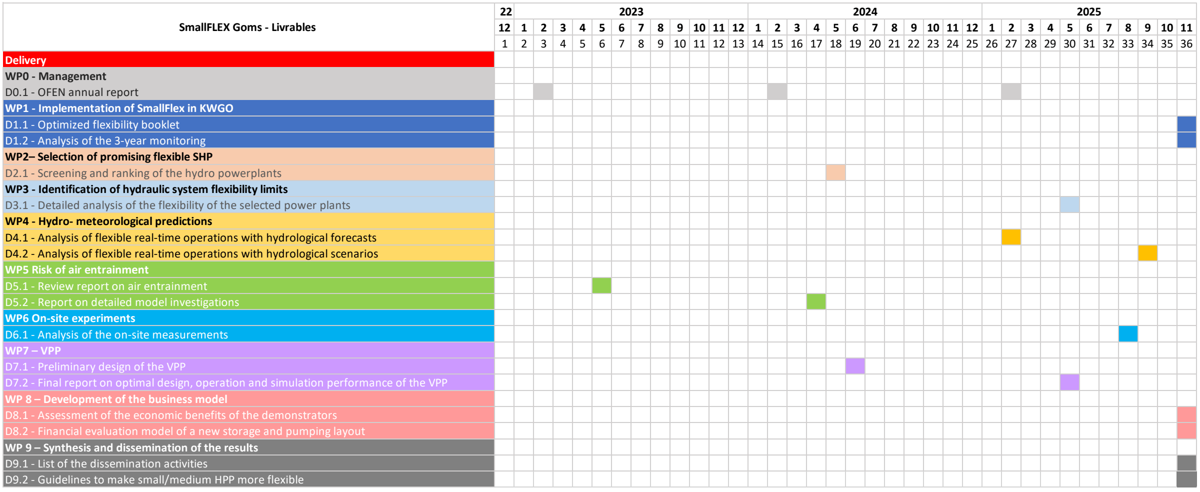


Figure 4: Planning of the deliverables

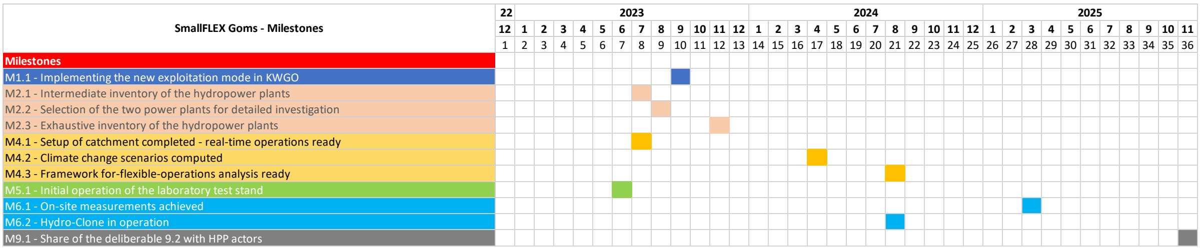


Figure 5: Planning of the milestones

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. Two **bi-annual meetings** have then been held on **May 9th** and **September 25th** to share the progress of the activities will all the partners. In addition to these meetings, other discussions were organised to launch the WPs which started this year and to collaborate:
4 WP Kick off in 2023:

- Kick off WP1: January 13th.
- Kick off WP2: January 16th.
- Kick off WP3: August 25th.
- Kick off WP7: June 29th.

10 Meetings in 2023:

- WP1 – WP2: January 31st, April 5th, April 12th, April 17th, May 1st, July 18th.
- WP2 – WP5: March 30th, August 23rd, September 1st.
- WP4 – WP7: September 25th.

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.

The first flexibility mode is the use of the settling basin in winter when the flows in the river are low. This allows to reduce the number of starts and stops of the group in operation. It also avoids the loss of water during this period. This operating mode is implemented. Over the three winters of the project, it will be possible to analyse the use of this operating mode and quantify the added value of this flexibility mode.

The second flexibility operating mode is the implementation of active primary control. This flexibility mode is implemented. The Gletsch Oberwald power station is now certified by Swissgrid for a positive and negative primary control capacity of 0.8 MW. Discussions are under way to increase this capacity to 1.6 MW. This control power is integrated into a pool of power plants from FMV SA to market this primary control capacity.

The third flexibility operating mode is the use of the volume of the upper part of the inclined headrace tunnel to make hydropeaking. This flexible mode is not yet in operation. It is planned to put it into operation in the coming months.

Technical Monitoring:

Technical monitoring is carried out via two channels. Firstly, data from the plant's sensors is extracted from the plant's SCADA for analysis. Secondly, a hydro clone has been installed at the Gletsch-Oberwald power plant to measure additional parameters. Both systems are in operation and recording data. When sufficient data has been collected, it will be possible to carry out the first analyses.

Environmental analysis:

An environmental analysis is planned to monitor changes in the watercourse downstream of the power station. Initial contact has been made with Pronat. The specifications are currently being drawn up.

4.3 WP2 – Selection of promising flexible SHP

Lead: FMV, partners: HEVS, PVE, ETHZ

To obtain the most accurate information possible on each power plant, all the owners have been contacted. Some of them do not wish to respond to this request, so the information was found in another way and may therefore be incomplete. Table 3 gathers the main known information useful for assessing the flexibility of each power plant.

Table 3: Main characteristics of the power plants in the Goms region.

Power Plant	H_n [m]	Q_{BEP} [m^3/s]	P [MW]	Winter production	Turbine	Penstock (diameter, length, and slope)
1 KW Altstafel (KW Aegina AG)	417	2.8	9.2	78%	1 x Francis	ø: 700 mm L: 800 m slope: 51%
2 KW Gletsch-Oberwald	287	5.7	14	10%	2 x Pelton	ø: 2800 mm L: 2117 m slope: 13%
3 KW Merezenbach	504	0.5	1.9	27%	1 x Pelton	ø: 450 mm L: 1114 m slope: 45%
4 KW Wannebode (Blinnenwerk AG)	147.5	1.625	2.1	20%	1 x Pelton	ø: 711 mm L: 475 m slope: 39.2%
5 KW Walibach / Grafschaft	772	0.53	2 x 1.8	20%	2 x Pelton	ø: 500 mm L: 3637 m slope: 22%
6a GKW1 / Rappental (Gommerkraftwerke AG)	62	2	0.5 + 0.8	20%	2 x Francis	
6b GKW1 / Neubrigg (Gommerkraftwerke AG)	720	4.5	25	24%	2 x Pelton	ø: 990 mm L: 1826 m slope: 41% (max 61%)
7 GKW2 / Saflisch (Gommerkraftwerke AG)	341	0.5	1.2	32%	1 x Pelton	ø: 500 mm (estimation) L: 1480 m slope: 27%
8 GKW2 / Heiligkreuz (Gommerkraftwerke AG)	680	6.6	3 x 13	16%	3 x Pelton	ø: 1400 mm L: 3100 m slope: 23%
9 GKW3 / Fieschertal (Gommerkraftwerke AG)	509	15	2 x 32	9%	2 x Pelton	ø: 1650 mm L: 1500 m slope: 35% (max 41%)
10 KW Wysswasser (Gommerkraftwerke AG)	37	10	2 x 1.55	20%	2 x Francis	
11 KW Ernen (Rhonewerke AG)	269	14	2 x 16	30%	2 x Francis double	ø: 1850 mm L: 571 m slope: 55% (max 59%)

12 KW Mörel (Rhonewerke AG)	250	24	3x17 + 0.3	29%	3 x Francis double + 1 x Pelton	ø$_1$: 3100 mm L_1: 28 m (estimation) slope$_1$: 85% ø$_2$: 2460 mm L_2: 397 m slope$_2$: 80%
13 KW Aletsch (Aletsch AG)	675	7.5	38	19%	3 x Pelton	
14 KW Massaboden (Bitsch)	44	21.5	2 x 4	31%	2 x Francis doubles	L: 70 m slope: 54%
15 KW Gere (KW Obergoms AG)	244	3	4.6 + 1.5	27%	2 x Pelton	L: 2720 m
16 KW Ulrichen (KW Obergoms AG)	273	1.1	2.3	15%	1 x Pelton	L: 2100 m
17 KW Niderbach (KW Obergoms AG)	653.5	0.15	0.8	15%	1 x Pelton	L: 2200 m
18 KW Münstigertal (KW Obergoms AG)	220	0.1	0.18		1x Pelton	
19 KW Binn (Rhonewerke AG)	23	1.5	0.25		2x Francis	
21 KW Bitsch (Electra Massa)	718	55	340	78%	3x Pelton	slope: 70%

**Blank box indicates that the information is missing*.

Despite the strong diversity of the layout of the plants' hydraulic systems, some common features can be identified. The following main types of waterway design can be distinguished (Figure 6): (1) All water ways are pressurized, (a) without surge tank and (b) with surge tank connecting a gently inclined headrace tunnel to the strongly inclined penstock; (2) The waterways consist of one or several free surface headrace tunnels and the pressurized penstock (a) without and (b) with surge tank. Figure 8 provides an overview map of the considered plants and indicates the location of specific parts of their hydraulic system.

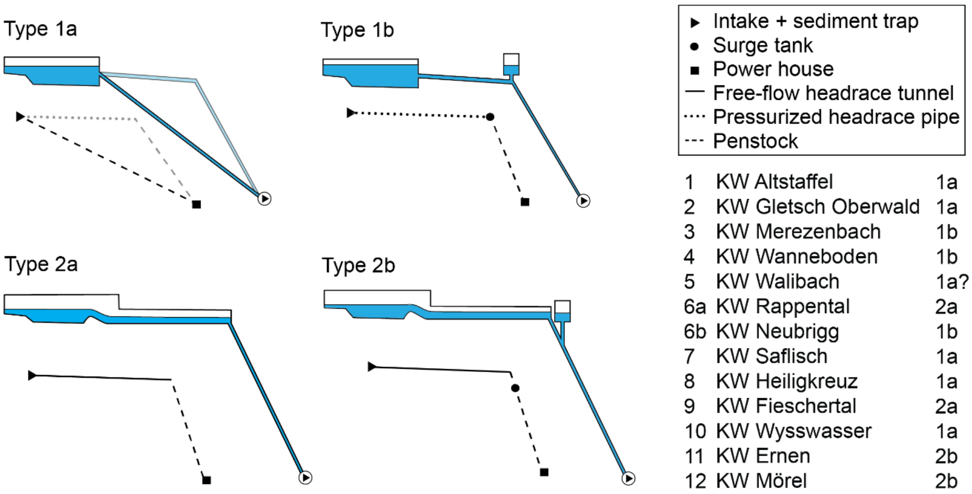


Figure 6: Main types of waterway designs of the HPP fleet considered in the SmallFLEX Goms project.

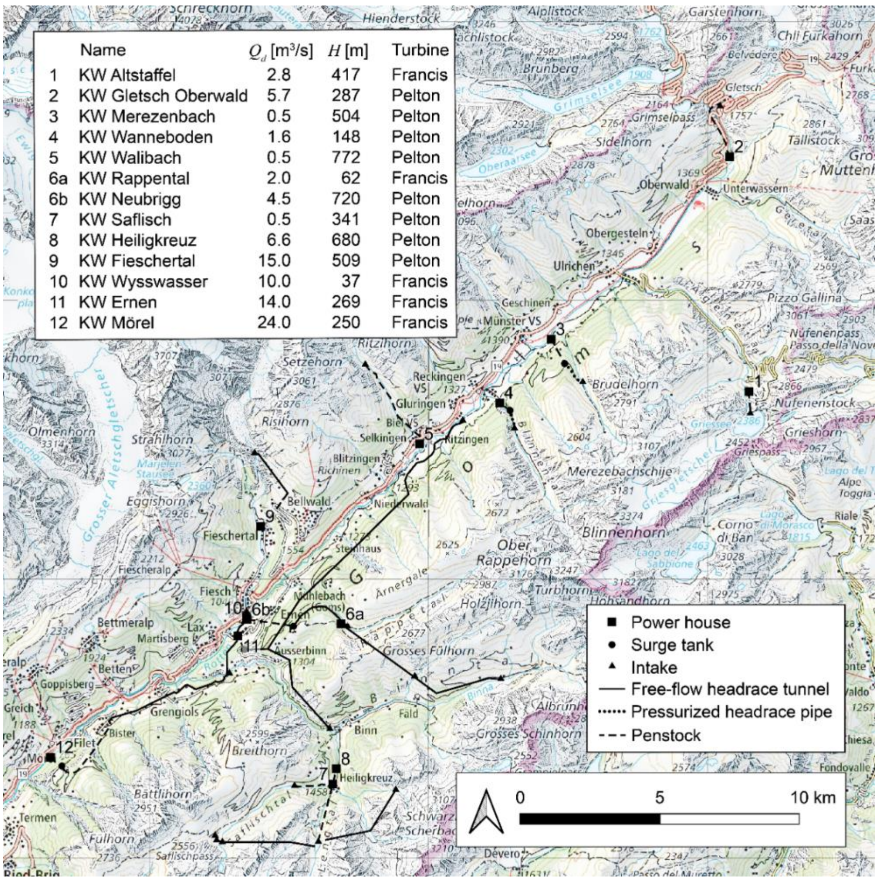
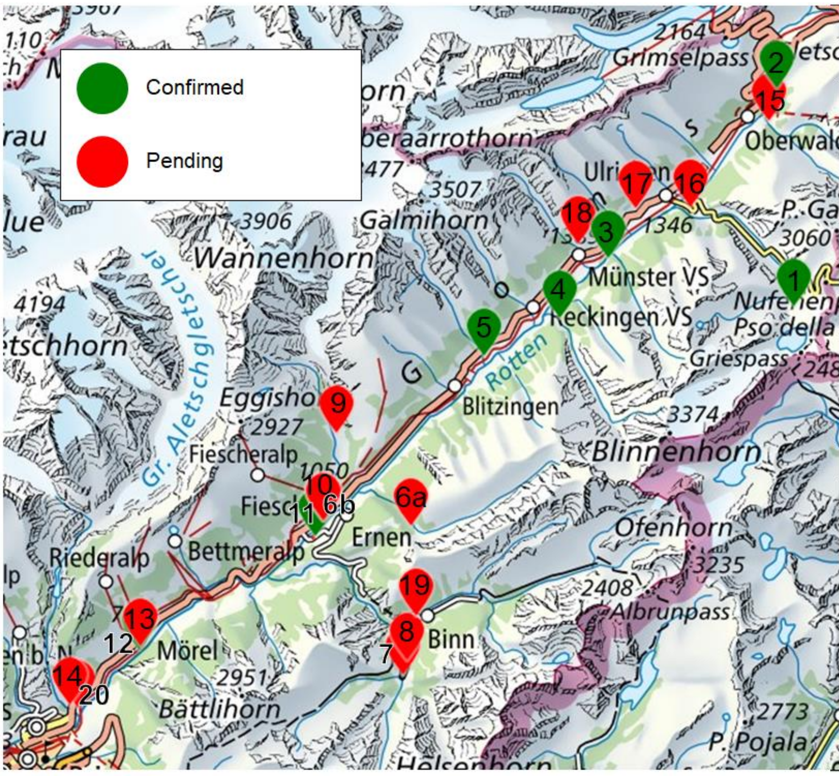


Figure 7: Localization of the HPPs considered in the SmallFLEX Goms project, and their design characteristics: design discharge Q, head H and turbine type, as well as the main construction elements of the hydraulic system.

Although it was possible to find information on power plants whose owners do not wish to participate, their interest is of prime importance to be selected as demonstrator for WP6, since their agreement is required in order to carry out any tests at the plant. Figure 8 is a map showing the different sites and the interest of the owners. Over twenty-one power plants, seven (*i.e.*, one third) agreed to share information and will be considered for the final selection of two power plants where on-site measurements will be carried out for WP6.



1	KW Altstafel
2	KW Gletsch-Oberwald
3	KW Merezenbach
4	KW Wannebode
5	KW Walibach
6a	KW Rappental
6b	KW Neubrigg
7	KW Saflisch
8	KW Heiligkreuz
9	KW Fieschertal
10	KW Wysswasser
11	KW Ernen
12	KW Mörel
13	KW Aletsch
14	KW Massaboden
15	KW Gere
16	KW Ulrichen
17	KW Niderbach
18	KW Münstigertal
19	KW Binn
20	KW Bitsch (Electra Massa)

Figure 8: Map of the power plants and whether they intend to participate in the project or not.

For the power plants selection for WP6, the objective is to investigate hidden flexibility by using for instance a part of the volume of the penstock, the KWGO power plant, already studied in the SmallFLEX project, being considered as a reference. Regarding the seven remaining power plants, the KW Altstafel and KW Ernen power plants have reservoirs of 18 million and 150 000 m^3 respectively, which already provide a large flexibility. Therefore, these power plants are not considered for investigating hidden flexibility by using for instance a part of the volume of the penstock. The power plants that could be considered are therefore KW Merezenbach (type 1b), KW Wannebode (type 1b), KW Walibach (presumably type 1b) and KW Mörel (type 2b).

For each power plant, the hidden storage volume is estimated by considering the volumes of the water intake, the desander, the headrace tunnel and the upper part of the penstock. It is important to note that KW Mörel is a special case since a part of the penstock has a negative slope, which makes the calculation of the available volume not trivial compared to the other power plants.
The potential flexibility is calculated as the time required to use the estimated hidden volume when the power plant is operated at its nominal power and without any inflow. The results are displayed in a time/power graph in Figure . The KW Mörel power plant can provide a power of 42.5 MW in less than a minute, which means that this power plant can be eligible for ancillary services, *i.e.*, for peaks of power of few MW (for instance ±1MW) during a short period (around 15 minutes). The power plants of KW Merezenbach and KW Wannebode can provide a relatively small power (less than 5 MW) over a period larger than 25 minutes, which means that the production (mainly during winter period) could be smoothed to reduce for instance the number of starts and stops and to provide energy adjustment.

These two power plants can be considered as smaller versions of the KW Gletsch-Obserwald demonstrator studied in the SmallFlex project.

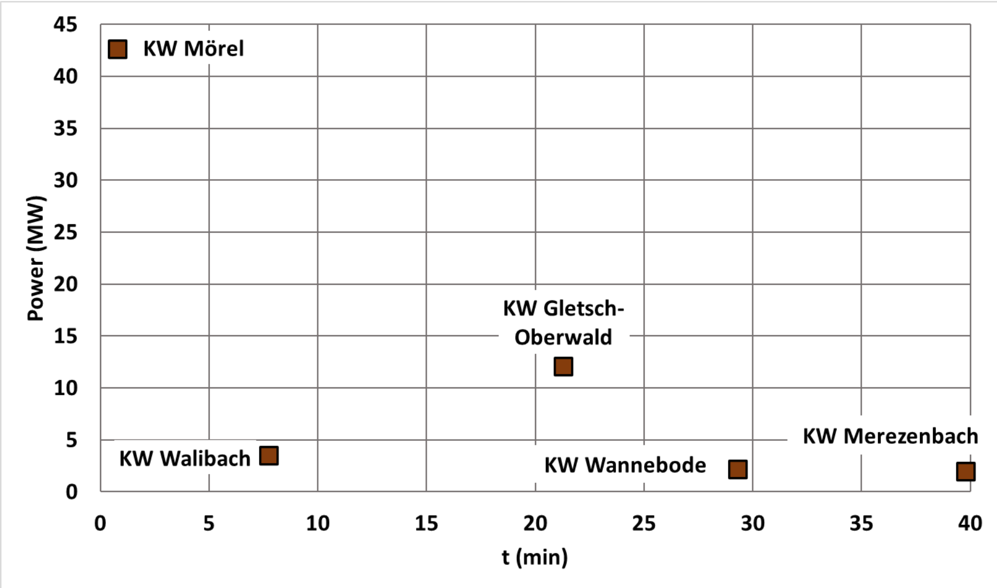


Figure 9: Potential flexibility represented as a power production versus operated time of the power plant.

Beyond the potential flexibility, additional information is also considered for the final selection of the two most promising power plants with mainly the type of power plant according to ETHZ (see WP5) and the surface of the catchment area according to WSL. Table 4 summarizes the main information used for the ranking and the selection of the power plants. Except the KW Gletsch-Obwerwald, a risk of air entrainment and transport is expected for all the other power plants, which will require detailed investigations and a possible limitation of the storage volume identified.
Due to the lack of some information, a ranking has not yet been performed (this will be done in the deliverable D2.1 due to for May 2024). However, the power plants of KW Merezenbach and KW Mörel have been preselected since they present extreme case of flexibility according to Figure 9 and a different type of penstock. For KW Mörel, the increased flexibility could be used to provide system services, which is an additional motivation. For KW Merezenbach, the available drawings show the presence of long headrace tunnels that could be used as a storage volume although air-related phenomena need to be carefully investigated. For KW Wannebode such information is still missing but the power plant is considered as a back-up to KW Merezenbach. KW Walibach is not taken on because the estimated storage volume and the catchment area are too small.

Table 4: Information and data considered for the estimation of the potential flexibility of each power plant.

	KW Gletsch-Oberwald	KW Merezenbach	KW Wannebode	KW Walibach	KW Mörel
First volume assessment (m3)	**6 909**	**1 195**	**2 811**	**248**	**1 076**
Power peak (MW)	**12**	**1.9**	**2.1**	**3.4**	**42.5**
Flow rate (m3/s)	**5.4**	**0.5**	**1.63**	**0.53**	**24**
Duration of the power peak (min)	**21.3**	**39.8**	**29.4**	**7.8**	**0.7**
Energy (MWh)	**4.26**	**1.26**	**1.03**	**0.44**	**0.53**
HPP Type according to ETHZ	**1a**	**1b**	**1b**	**?**	**2b**
Surge tank	**no**	**yes**	**yes**	**?**	**yes**
Risk of air entrainment and transport according to ETHZ	**no**	**yes**	**yes**	**yes**	**yes**
Provision of system services	**yes**	**?**	**?**	**?**	**no**
Catchment area according to WSL	**enough**	**too small**	**enough**	**too small**	**enough**
On site measurement possible	**yes**	**yes**	**?**	**?**	**yes**

For WP3, WP4 and WP7, the KW Altstafel will be considered to investigate the possibility of adding a pump in the powerplant, to develop on hydro-meteorological model and to be integrated in the VPP. The Gletsch-Oberwald power plant will also be considered in WP4 and in WP7.

Finally, after the investigations performed in WP2 and WP5, the preliminary selections of the power plants for the different WPs are listed in Table 5.

Table 5: Pre-selected power plants

Selections of HPPs	WP1	WP3	WP4	WP5	WP6	WP7
KW Altstafel		x	x			x
KW Gletch-Oberwald	x		x			x
KW Mörel		x	x	x	x	
KW Merezenbach		x	x		x	
KW Wannebode*		?	?		?	

*****KW Wannebode could replace KW Merezenbach.*

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 Wannebode (Blinnenwerk AG), 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, to provide valuable insights into the operational aspects and general layout, which is a fundamental step in the evaluation process. The initial site visit will focus on the KW Altstafel (KW Aegina AG) hydropower plant and is foreseen to take place end of 2023 or in Spring 202. FMV will be responsible for coordinating the scheduling of this visit through a distributed doodle poll.

Currently, efforts are focused on collecting data for the selected plants, which will serve as the basis for a detailed assessment of flexibility. This includes assessing new storage capacity of the selected HPP in terms of both volume and energy, while evaluating the risk of air entrainment, examining turbine flexibility, and exploring variable speed capabilities. In addition, the feasibility and potential opportunities for pumping will also be addressed. The estimation of the available power/energy for ancillary services of each HPP will be evaluated by means of a complete 1D-Model of the power plant, using the SIMSEN software. This includes the simulations of primary control scenarios, the estimation of water level variations at the inlet & outlet of the plant, as well as the estimations of the pressure fluctuations in the waterways. Two preliminary SIMSEN models for the HPP of KW Mörel and KW Altstafel are already available as illustrated in Figure 4 and Figure 5. Based on ongoing data collection, these models will be updated to include Francis turbine models and turbine regulators. If needed, these models can be further enhanced to include potential pumping capacity or technological changes such as variable speed. In addition, their accuracy will be assessed based on existing data or new on-site measurements.

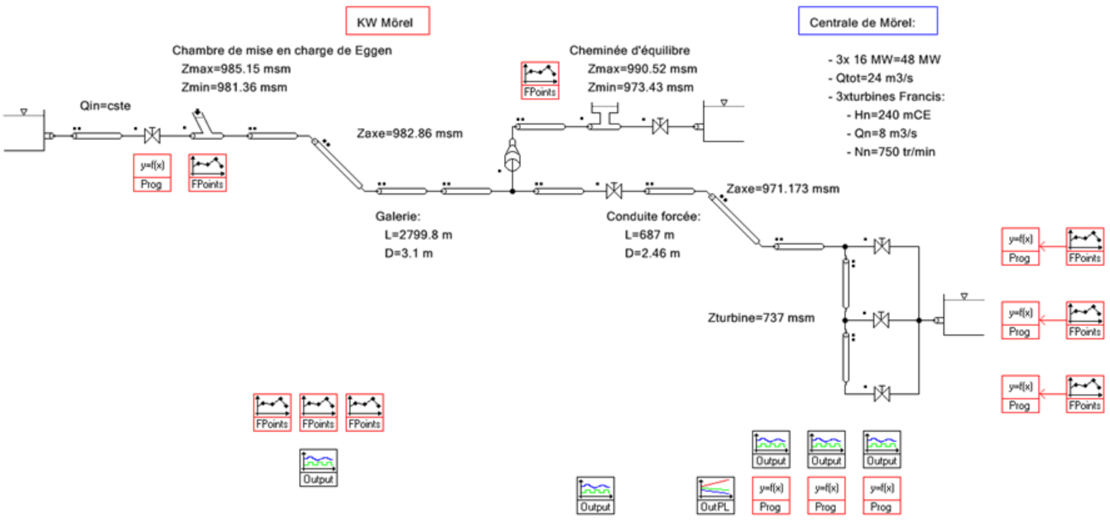


Figure 10 Preliminary SIMSEN model of Mörel HPP

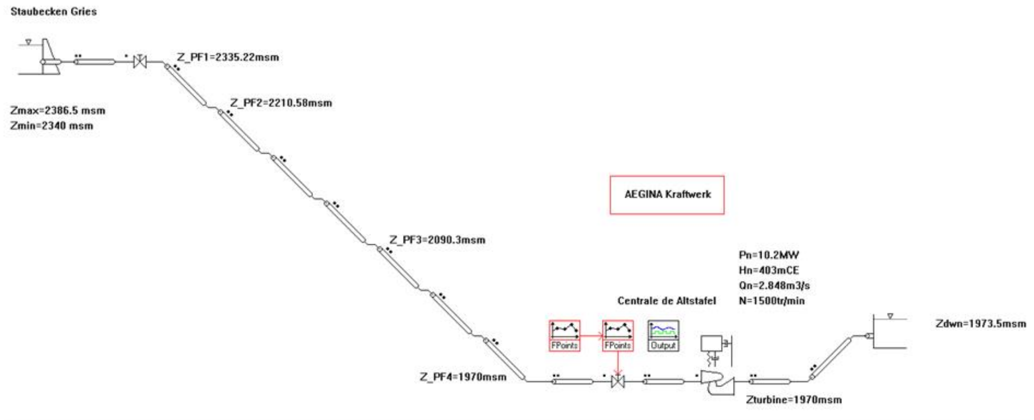


Figure 11 Preliminary SIMSEN model of Aegina HPP.

4.5 WP4 – Hydro-meteorological predictions

Lead: WSL, partners: HEIG-VD, PVE

The kick-off meeting of WP4 was held online on June 29, 2023, jointly with WP7.

The first objective of WP4 is to provide short-term predictions (up to 5 days) of discharge upstream of the hydropower plats that are selected in WP2. Further predictions and projections of solar radiation and wind speed are provided to the project partners. The hydrological predictions and future projections of discharge at the water intake of the selected hydropower plants aims to demonstrate the suitability of these powerplants for a joint operation of hydropower production and the production of wind and solar electricity.

In late summer 2023, the KW Altstafel, KW Merezenbach and KW Wannenboden (as back-up) were selected within WP2. This was the actual start of action in WP4.

Meteorological data for KW Altstafel was provided to WP7 and the latest PREVAH forecast data for Small-Flex Gletsch were uploaded on the SharePoint.

Based on the hydrometeorological model PREVAH KW Altstafel was successfully modelled. The calibration of the model is still ongoing (Figure 10 and 11).

KW Merezenbach and KW Wannenboden both have small catchments of less than 15 km^2, which would be too small for modelling individually with the semi-distributed modelling system PREVAH that operates with a spatial resolution of 500x500 m^2. The tentative solution for this problem is to model these two neighbouring catchments together.

In 2024 MeteoSwiss will deploy a new weather prediction model (ICON-CH1-EPS and ICON-CH2-EPS will replace COSMO-1E and COSMO-2E). Thus, the predictions for the SMALL-FLEX Goms target areas will be directly implemented in operational mode with the new ICON-models. This is scheduled for late Winter 2023/2024.

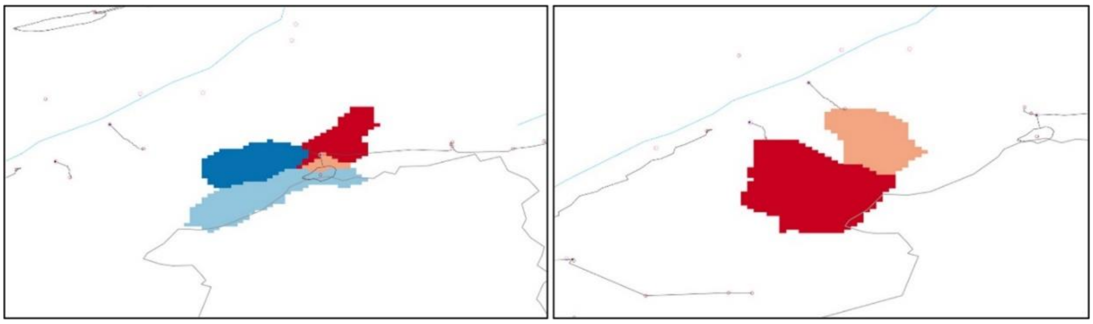


Figure 10: (left) Implementation of the Altstafel and (right) implementation of the KW Merezenbach and KW Wannenboden plant within the PREVAH-Framework. The coloured areas correspond to the sub-catchments. The lines correspond to pipelines. The intakes and centrals are represented with pink circles.

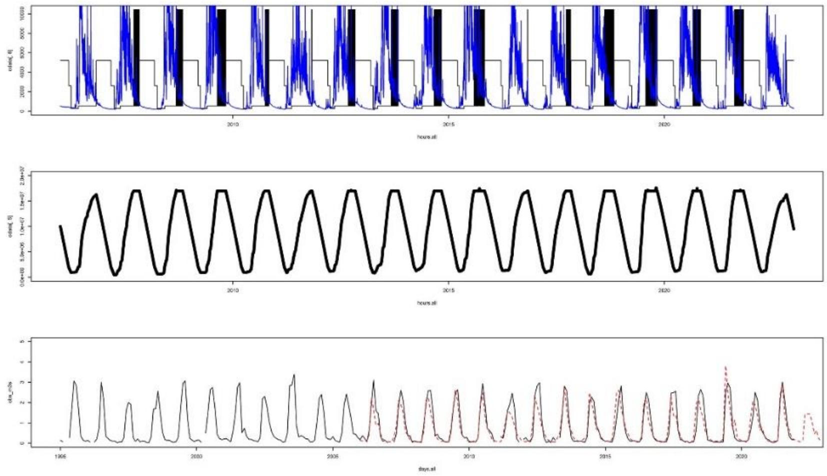


Figure 11: First simulations with PREVAH for the Altstafel area. (top) Inflows and approximated turbination from the Gries-Dam. (Centre) Storage in the dam. (bottom) Monthly lake inflow (model in black, observation in red).

With respect to the task of assessing the impacts of climate change a thesis has been completed from February to September 2023. For this an idealized setup in the Goms region has been evaluated (Figure 12, left). For a combination of existing water intakes an idealized hydropower central was defined. The hydropower production of that central was estimated under current and future climate conditions (Figure 12, right). In the thesis also the interplay between hydropower and energy from fictive wind and solar power plants in the region was evaluated. The results have been shared with the partners.

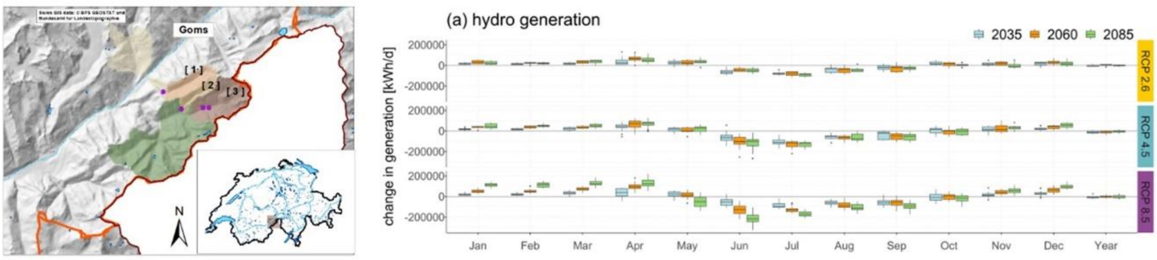


Figure 12: (left) subregions of the Goms valley selected for the study of R. Schenk. (right) Difference in the electricity generation potential in the future periods (2035 = early, 2060 = mid, 2085 = late) compared to the reference period (1991-2020) for an idealized power plant in the Goms region. The results are shown for three emission scenarios (RCPs) with RCP2.6 being an optimistic and RCP8.5 being a pessimistic future scenario. Results for wind and solar power can be found in the Thesis of Schenk (2023).

4.6 WP5 – Risk of air entrapment

Lead: ETHZ, partners: HEVS

The aim of this work package is to assess the risk of air entrainment and transport in the waterways caused by the lowering of the water level during flexible operation. First, the flow conditions at water level lowering were studied. Then, a literature review was carried out to identify relevant processes, scale effects and knowledge gaps regarding air entrainment and transport as a basis for planning further investigations. The main findings on air transport in the penstocks are summarized below, more detailed information will be provided in the review report on air entrainment (deliverable D5.1). Finally, the implications for the planned physical model investigations are discussed.

Flow conditions at water level lowering

A risk of air entrainment into the hydraulic system arises at the transitions of free surface to pressurized flow. Under normal operational conditions this transition is located at the downstream end of the settling tank for type 1 plants and at the junction of the headrace tunnel to the penstocks for type 2 plants (typology according to the classification provided in Chapter 4.3). Air entrainment is structurally avoided under these conditions. If the outflow is higher than the inflow, *e.g.*, for power generation at peak times or for providing system services, the water level decreases, thus the transition of free surface to pressurized flow is displaced and the risk of air entrainment changes. This process is described below for the different types of waterway designs.

Type 1a	First, the water level in the settling volume decreases. If a critical submergence of the outflow is exceeded, an air entraining vortex may form. Depending on the air transport capacity flow in the penstock, the air might reach the turbines. At a further decrease of the water level, the water table comes to lie within the penstock. Then the supercritical flow, which occurs in the upper, drained area of the penstock, hits the filled penstock, and causes a hydraulic jump with air entrainment.
Type 1b	The lowering of the water level in the settling volume can lead to an air entraining vortex if the critical submergence of the outflow is exceeded. The entrained air is transported by the water flow in the headrace tunnel as smaller or elongated bubbles. If possible, it vents through the surge tank; if the air transport capacity in the downwardly inclined penstock is insufficient, it may accumulate in the penstock, resulting in stratified flow conditions. As soon as the air accumulation spreads along the soffit to the end of the penstock, the air reaches the turbine. Further lowering of the water level leads to a gradual transition from pressurized to free surface flow in the headrace tunnel. Air entrainment by vortex formation may occur at the junction between the headrace tunnel and the penstock once the critical submergence of the penstock is exceeded. As the water level reaches the penstock, an air entraining hydraulic jump forms at the transition from free surface to pressurized flow.
Type 2a & Type 2b	The water level in the settling volume and the free-surface head race tunnel decreases simultaneously. An air entraining vortex may form at the junction between the headrace tunnel and the penstock if the critical submergence of the latter is exceeded. Once the water level lies in the penstock, an air entraining hydraulic jump is formed between the free surface inflow and the pressurized outflow.

All considered plants have a steep penstock with the slope S and a circular cross-section with the inner diameter D. If the water level is lowered into the penstock, the transition from free surface to pressurized flow provokes a hydraulic jump. Thus, the flow conditions upstream and downstream of the water level are of great importance and are described in the following.

For the pressurized flow below the water level the dimensionless water velocity in the pipes (pipe Froude number) is defined as:

$$\mathrm{F}_w = \frac{Q}{A\sqrt{gD}}$$

Where Q is the discharge, A is the cross-sectional area of the pipe and g is the gravitational acceleration. During flexibility operations, it is expected that the turbines operate at design discharge Q_d. The dimensionless water velocities F_w for these conditions are provided in Table 6: Table 6.

The free surface flow above the water level corresponds to the inflowing discharge and is thus not dependent on the turbine operation, but on the availability of water. For three potential inflow discharges Table 6 provides the Froude number F at normal flow depth y_n. The Froude number is defined as:

$$\mathrm{F} = \sqrt{\frac{Q^2}{gA_w^3} \cdot \frac{dA_w}{dy}}$$

Where A_w is the cross-sectional area occupied by water, which is a function of the flow depth y.

Table 6: Slope S and diameter D of the penstocks, as well as the dimensionless water veloicty F_w under pressurized condtions and the Froude number F under free surface flow conditions for three different discharges.

					Pressurized flow	Free surface flow		
					Q_d	Q_d	$0.5Q_d$	$0.1Q_d$
		Q_d	S	D	F_w	F	F	F
		[m³/s]	[-]	[m]	[-]	[-]	[-]	[-]
1	KW Altstaffel	2.8	0.51	[0.7, 0.9]	[2.8, 1.5]	[15.9, 16.7]	[16.3, 16.7]	[15.9, 16.0]
2	KW Gletsch-Oberwald	5.7	0.132	2.8	0.2	9.3	9.1	8.6
3	KW Merezenbach	0.5	0.45	0.45	1.5	14.6	14.6	13.9
4	KW Wanneboden	1.625	0.392	0.711	1.5	14.2	14.3	13.8
5	KW Walibach	0.53	0.22	0.5	1.2	10.2	10.3	9.9
6a	KW Rappental	2.0	1.00					
6b	KW Neubrigg	4.5	0.61	[0.99, 1.34]	[1.9, 0.9]	[18.8, 19.0]	[18.5, 18.9]	[17.8, 17.9]
7	KW Salfisch	0.5	0.27	0.5*	1.1*	11.4*	11.4*	10.9*
8	KW Heiligkreuz	6.6	0.23	[1.4, 1.6]	[1.2, 0.8]	[11.6, 11.9]	[11.7, 11.8]	11.3
9	KW Fieschertal	15	0.41	[1.65, 1.95]	[1.7, 1.1]	[15.8, 16.1]	[15.9, 16.1]	[15.4, 15.5]
10	KW Wysswasser	10						
11	KW Ernen	14	0.59	1.85	1.2	19.3	19.2	18.4
12	KW Mörel	24	0.80	2.46	1.0	23.1	22.9	21.8

*estimation

Table 6 shows that the flow conditions in the penstock of the KW Gletsch-Oberwald exhibit much lower dimensionless water velocities F_w than the other plants. Under free surface conditions Froude numbers F in the KW Gletsch-Oberwald are also lower than in the other plants, however the difference is smaller. There are only minor differences at the various inflow discharges.

Literature review

The review report of the literature on air entrainment and transport, which will be available at the end of 2023, summarizes the expected air entrainment processes, characterizes the air-water flow patterns, and provides design equations of air transport. The most important findings include the transport of single air bubble or pockets in downwardly inclined pipes, which is described below.

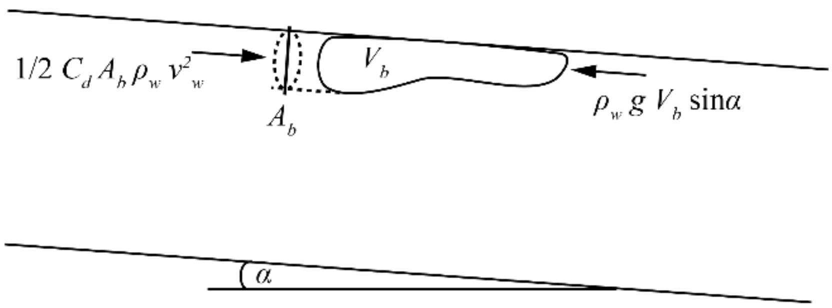


Figure 12: Forces acting on a bubble with volume V_b and projected bubble front area A_b: Drag force and buoyancy force.

The movement of single bubbles or air pockets in horizontal and downward inclined pipes is mainly determined by inertial forces and gravity forces. Air bubbles can thus move downstream with the water flow or upstream against the water flow, depending on their shape and size, and the velocity of the water v_w. The velocity of the water at which the air remains stable is often referred to as the clearing velocity $v_{w,c}$, because when it is exceeded, the air pockets are cleared from the pipe. The equilibrium of forces of a stationary bubble can be written as:

$$\frac{1}{2} C_d A_b \rho_w v_{w,c}^2 = \rho_w g V_b \sin\alpha$$

Where C_d is the drag coefficient that considers the bubble shape, A_b is the projected bubble front area, $v_{w,c}$ acts on the bubble front, ρ_w is the water density, V_b is the bubble volume, and α is the slope angle of the pipe ($S = \tan\alpha$). The simplified equations found in the literature rely on two assumptions:

1. $C_d = \mathrm{const}$
2. V_b/A_b also referred to as d_b, the equivalent bubble diameter, increases linearly with the pipe diameter, hence $d_b/D = \mathrm{const}$.

These two assumptions allow to simplify the force equilibrium to the following equation for the clearing Flow number:

$$\mathrm{F}_{w,c} = \frac{v_{w,c}}{\sqrt{gD}} = C \cdot \sqrt{\sin\alpha}$$

Where C is a constant, which might be empirically derived. However, the available descriptions of the flow patterns include a complex range of bubble shapes and sizes for different flow velocities and pipe inclinations. It is therefore likely that neither of these assumptions is fulfilled.

Various model tests investigating the removal of individual air pockets in downward sloping pipes have been reported in the literature and are summarized in Table 7 and Figure 13. In these experimental investigations air was injected at the soffit of the fully filled pipes to form large air pockets. Kent (1952) suggested a relationship for air pockets with $L_B/D > 1.5$ (Table 7, [1]), where L_B is the length of the bubble. However, it should be noted that his experimental results systematically deviate from his own formula as shown by Wisner et al. (1975). Gandenberger (1957) did not suggest a design equation, but presented his results of $\mathrm{F}_{w,c}$ for different relative air pocket sizes $n = (4V_b)/(\pi D^3)$. Wisner et al. (1975) compared their data with Kalinske & Robertson (1943) and Kent (1952), and defined a conservative envelope curve (Table 7, [2]) as a lower limit for the clearing Flow number $\mathrm{F}_{w,c}$. Falvey (1980) combined several literature sources to obtain two distinct expressions for $\mathrm{F}_{w,c}$ for air bubbles and air pockets. The design equation (Table 7, [3]) suggested by Escarameia (2007) includes a set of parameters for different relative air pocket sizes n. On the basis of a momentum balance Pothof & Clemens (2010) analytically derived a criterion for air pocket removal (Table 7 [4]) that agrees well with their own data from a large-scale model test. Based on this criterion Pothof & Clemens (2011) proposed a formulation (Table 7, [5]) of the clearing flow number $\mathrm{F}_{w,c}$ including an air-discharge-dependent factor. The dimensionless air velocity F_a, is defined in analogy to the dimensionless water velocity as:

$$\mathrm{F}_a = \frac{Q_a}{A\sqrt{\frac{(\rho_w - \rho_a)}{\rho_w} gD}}$$

with Q_a the volumetric air discharge, A the pipe cross section, ρ_w the density of water and ρ_a the density of air respectively.

Table 7: Studies investigating the clearing velocity of air pockets.

Authors	Equation	No.	Dimensions
Kent (1952)	$\mathrm{F}_{w,c} = C_0 \cdot \sqrt{\sin\alpha}$ $C_0 = 1.23$	[1]	D = 0.1 m, α = [15, 75]°
Gandenberger (1957)	-		D = 0.045 m, α = [0.5, 90]
Wisner et al. (1975)	$\mathrm{F}_{w,c} = C_0 \cdot \sqrt{\sin\alpha} + C_1$, $C_0 = 0.25$, $C_1 = 0.825$	[2]	D = 0.245 m, α = 18.4°
Falvey (1980)	-		Literature study
Escarameia (2007)	$\mathrm{F}_{w,c} = C_0 \cdot \sqrt{\sin\alpha} + C_1$, $C_0 = 0.56$, $C_1 = \begin{cases} 0.45 & \text{for } n < 0.06 \\ 0.50 & \text{for } 0.06 \leq n < 0.12 \\ 0.57 & \text{for } 0.12 \leq n < 0.30 \\ 0.61 & \text{for } 0.30 \leq n < 2.00 \end{cases}$	[3]	D = 0.15 m, α = [0,22.5]°
Pothof & Clemens (2011)	for $\mathrm{F}_a = 1.51 \cdot 10^{-3}$: $\mathrm{F}^2(\alpha) = \frac{2 \sin\alpha}{\lambda} \frac{D_h}{D} \left(\frac{A_n}{A}\right)^2 = \cdot \frac{A}{A_b} \frac{\cos\alpha}{\pi} \left[\frac{2}{3}\sqrt{\frac{4y_n}{D} - \left(\frac{2y_n}{D}\right)^2} \cdot \left(\frac{2y_n}{D} - 3\right) \cdot \left(\frac{2y_n}{D} - \frac{1}{2}\right) + \arcsin\left(1 - \frac{2y_n}{D}\right) + \frac{\pi}{2}\right]$ with λ the friction factor, D_h the hydraulic diameter and A_n the water cross-sectional area at normal depth	[4]	D = 0.22 m, α = [5, 90]°
	$\mathrm{F}_{w,c} = \mathrm{F}(\alpha) \left[\ln\left(\frac{\mathrm{F}_a \cdot 10^7}{1.87}\right)^{\frac{1}{9}}\right]$	[5]	

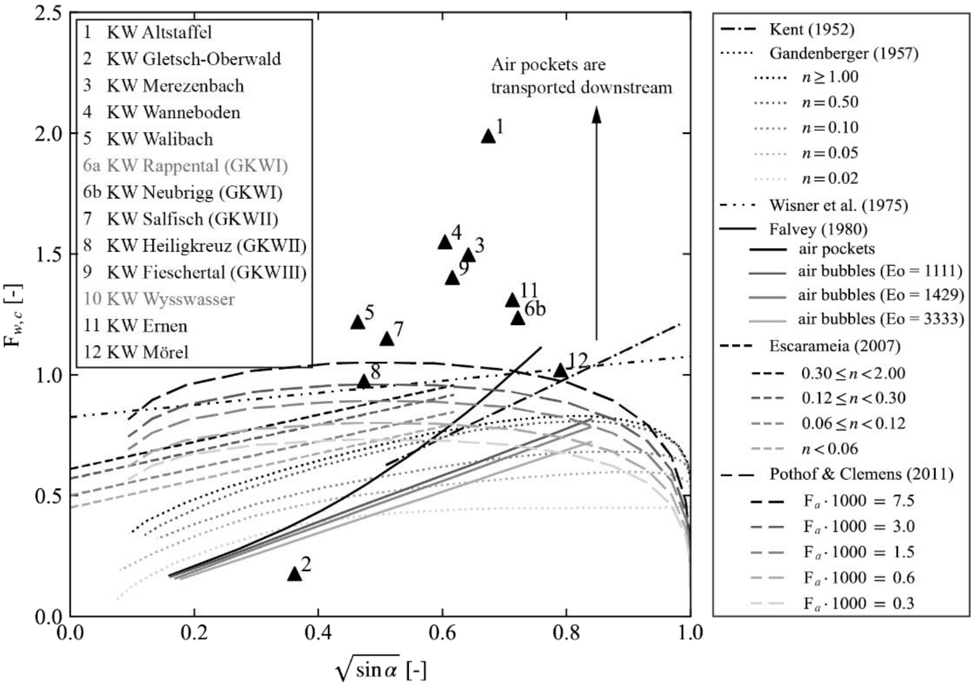


Figure 13: Comparison of different studies on the clearing flow number $F_{w,c}$ of air pockets in pipes, depending on pipe inclination α, dimensionless air velocity F_a or relative air pocket sizes n. For $F_{w,c}$ above the lines, air pockets are cleared from a pipe system, thus the entire air is transported downstream. For the considered plants in the Goms region, $F_{w,c}$ in the penstocks at design discharge ($Q = Q_d$) are indicated.

Figure 13 shows the dimensionless velocities in the penstocks of the considered plants at dimensioning discharge. Under these conditions, the flow numbers in most plants exceed the maximum estimation of the clearing flow number. Even large air pockets are thus expected to be transported downstream. The flow number in KW Mörel lies in the scatter of the different design equations. Only KW Gletsch-Oberwald reveals a flow number clearly below all estimations of the clearing flow number. With a reducing discharge, the water flow number decreases linearly. Thus, at $Q = 0.5\ Q_d$ for example, the clearing flow number will not be reached in certain plants. However, even under these circumstances the transport of small air bubbles cannot be excluded and is likely to occur.

Implications and next steps

The above considerations show that the flow conditions in KW Gletsch-Oberwald are not representative of the entire Goms region but are rather an exceptional case. Based on the findings of the SmallFLEX project and the present study, air pockets are not expected to be transported in this SHP penstock. For all the other SHPs, the dimensionless water flow velocities in the penstocks are higher and even large air pockets are expected to be transported. Consequently, the systematic experiments originally envisaged (see Chapter 3) are not to be carried out as a priority. Instead, physical model investigations shall focus on air entrainment and specific countermeasures at the selected plants. Consequently, the model tests in the VAW laboratory were postponed to 2024 and the time schedule of WP5 was adapted according to Figure 14.

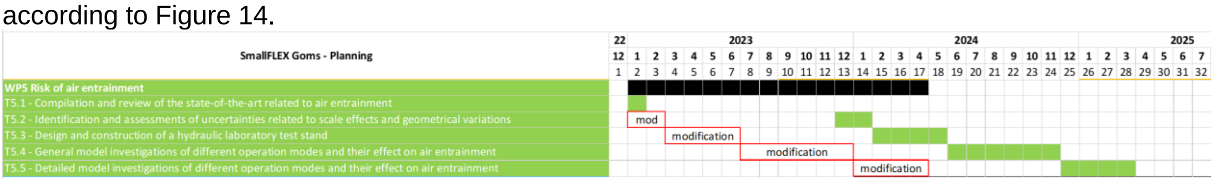


Figure 14: Adapted time schedule of WP5.

4.7 WP6 - On-site experiments

Lead: HEVS, partners: PVE, FMV

This WP has not started.

4.8 WP7 – VPP

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

The work package's kick-off meeting took place on June 29, 2023, with collaborators from HEIG-VD, WSL, PVE, and ALPIQ in attendance. During the meeting, a preliminary version of the VPP design problem formulation (including the objective function, decision variables, and key constraints) was presented. Based on the feedback received, a draft document describing the VPP design problem formulation and the algorithm for solving was created and sent out to the partners. The following are the main assumptions underlying the problem formulation and proposed 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.

In the following, a brief description of problem formulation and proposed algorithm is presented:
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.

- *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.

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 4 describes the process of designing the VPP.

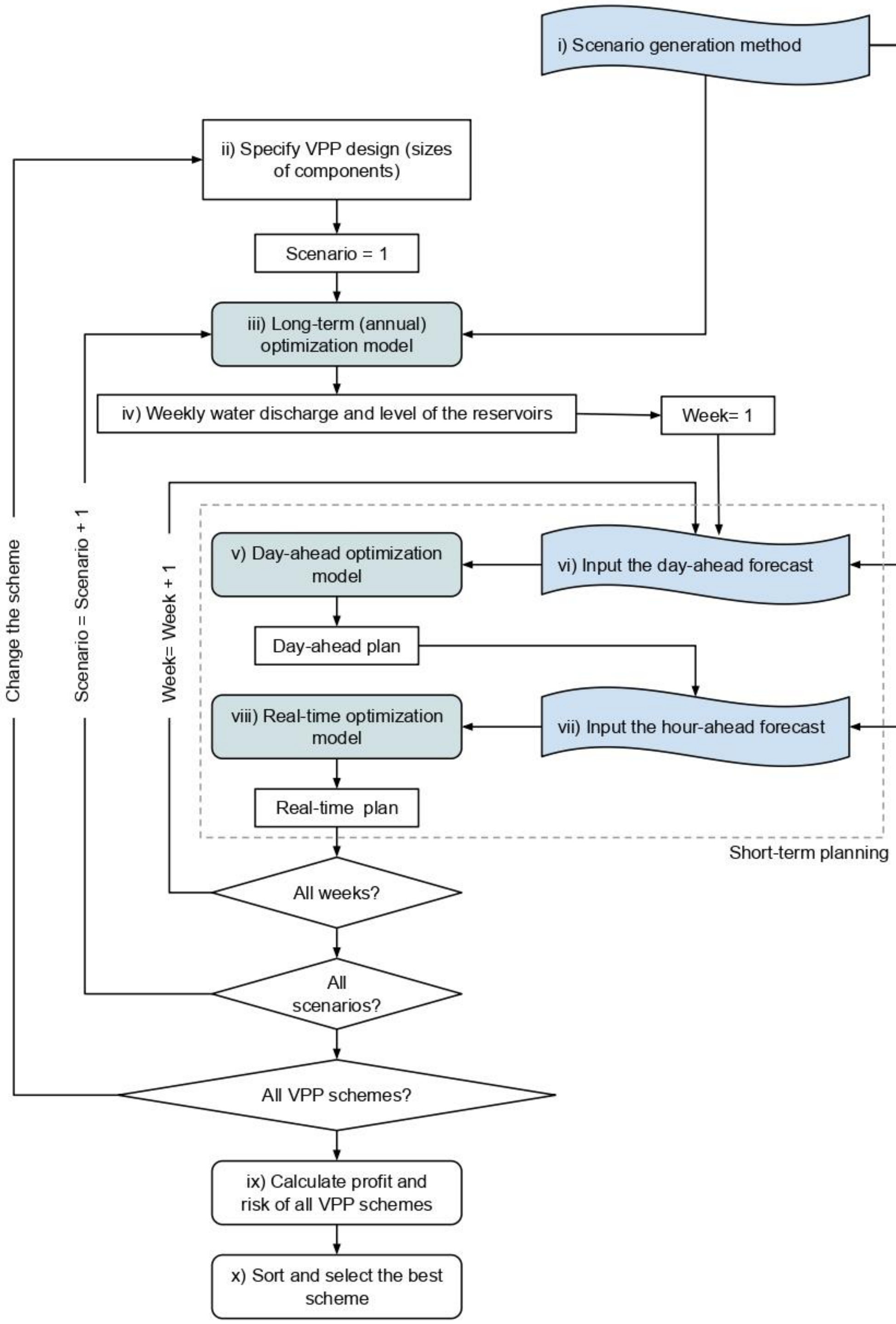


Figure 15: Proposed algorithm for the VPP design problem.

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 step ii of the proposed algorithm in Figure 4, we must define several VPP design schemes. These schemes will be defined based on the geographical and technical limitations that exist for the renovation of small HP units and the building of other distributed resources. We will consider at least the following four schemes for the VPP design.

- Case 1: All interested small hydro power plants in the Goms region (at least 7 units) will be integrated.
- Case 2: One small HP “KW Gletsch-Oberwald” will be integrated with a PV like “Griessee Solaranlage auf der Krone” and a wind turbine like “Windpark und Griessee”.
- Case 3: One small HP “KW Gletsch-Oberwald” will be integrated with other distributed resources, including a PV like “Griessee Solaranlage auf der Krone”, a wind turbine like “Windpark und Griessee”, and a battery energy storage system with a predetermined capacity.
- Case 4: All interested small hydro power plants in the Goms region (at least 7 units) will be integrated with distributed resources, including a pump like “Altstafel” (10 MW), a PV like “Griessee Solaranlage auf der Krone”, a wind turbine like “Windpark und Griessee”, and a battery energy storage system with a predetermined capacity.

This is a preliminary list of case studies. It will be extended or modified throughout the project by analysing real-world data and hydro and meteorological historical time series related to the resources of the VPP.

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.

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 implementation of the flexible mode has some delays and the tasks T1.1 and T1.2 will start end of 2023. In WP2, we encounter some issues to collect information regarding the identified small hydropower plants in the Goms region. The list of candidates for WP3 and WP6 was shortened due to the lack of information gathered, and the parametric study initial planned in WP5 had also to be redesigned. The model test at ETHZ will now focus on one power plant to investigate the risk of air entrainment.

6 Next steps

In the coming months, the last flexible exploitation mode will be implemented in KGWO and the analysis of the long-term monitoring of the power plant production during the first year will start in the framework of WP1. In WP2, the methodology to screen and rank the power plants will be described in a deliverable (D2.1) and the final selection of the power plants for the other WP will be done. In WP3, the technical site visits will be organized and the collection of additional input data for detailed flexibility assessment will be performed. In parallel, the evaluation of pumping feasibility in Alstafel will start. For WP4, the hydrometeorological forecasts for the selected power plants will be set up by preparing the spatial and meteorological data and calibrating the models. In WP5, the first deliverable will be finalized and ETHZ will start to plan the physical model investigation considering one of the power plants selected. WP6 will start beginning of next year with the preparation of the experimental campaigns according to the first results of WP3. The focus for WP7 will be on implementing the proposed algorithm for designing the VPP structure. Additionally, efforts will be directed towards collecting the necessary data and subsequently sharing the results with our project partners. WP8 should start in 2025, once most of the results from the other WPs will be available.

7 Publications

Master Thesis related to WP4:

Schenk, Rona. 2023: “Complementing a hydropower plant with solar and wind power plants: a conceptual study in the canton of Valais”. MSc Thesis at WSL and ETH Zürich. 32 pp. + Appendix.

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