# TECHNICAL (FACTUAL) REPORT REGARDING THE PROGRESS AND RESULTS IN YEAR 2024

Attachment of interim report of the project

| | |
|---|---|
| Project number: | TO01000160 |
| Project name: | Optimised expanders for small-scale distributed energy systems |

Submits:

**Organization**: Czech Technical University in Prague (ČVUT v Praze)

**Principal investigator**: Ing. Václav NOVOTNÝ, PhD.

# Publishable short 100 words non-technical summary (En)

Project DExpand aims at decentralized power production systems using a principle of organic Rankine cycle (ORC), converting heat to power. Applications are in decentralized and renewable sources such as biomass combustion, waste heat recovery, geothermal or solar thermal applications, eventually in novel storage systems as so called Carnot batteries.

The 4 months in year 2024 concluded the project by finalizing experiments, preparing models for full open access (OA) dissemination, preparing publications and general summarizing of project results. Project succesfully achieved the outlined results of four expander functional samples, scientific publications and overall OA project report and data.

# Publishable short 100 words non-technical summary (Cz)

Projekt DExpand je zaměřen na decentralizované systémy výroby energie využívající princip organického Rankinova cyklu (ORC), který přeměňuje teplo na energii. Aplikace jsou v decentralizovaných a obnovitelných zdrojích, jako je spalování biomasy, využití odpadního tepla, geotermální nebo solární tepelné aplikace, případně v nových akumulačních systémech, jako jsou takzvané Carnotovy baterie.

Během 4 měsíců v roce 2024 byl projekt ukončen dokončením experimentů, přípravou modelů pro plnohodnotné open-access (OA) sdílení, přípravou publikací a obecným shrnutím výsledků projektu. Projekt úspěšně dosáhl nastíněných výsledků - čtyř funkčních vzorků expanderů, impaktované vědecké publikace a shrnujícího OA reportu s daty z projektu.

# Actual progress (implementation) in 2024

The DEXPAND project successfully concluded in April 2024, meeting its objectives outlined at the project's onset. Throughout the year, the focus remained on conducting additional experiments, finalizing activities, and summarizing findings. Integration of the latest expander models into the cycle calculation tool, along with exploration of advanced heat exchanger models, took center stage. Additionally, case studies for ORC systems with new expanders were defined, contributing to the advancement of ORC technology.

The release of the multi-scale optimization tool and NTNU meanline turbine model as open-source code marked significant milestones, promoting collaboration and innovation within the academic and industrial sectors. The MM turbine's upgrade further enhanced the project's outcomes.

The culmination of these efforts was reflected in the generation of the open access report TO01000160-V4, providing a comprehensive summary of expander geometries, experimental data, and feasibility mapping. This resource serves both scientific and commercial communities involved in ORC technology.

The project's online presence, showcased through its website at https://dexpand.cz/en/, offers a platform for dissemination and engagement with stakeholders. While the Data Management Plan underwent a final update, project partners have opted to keep it open for future follow-up activities and additional data generation, ensuring ongoing relevance and impact beyond the project's conclusion.

# Project results in 2024

Within the project realization the originated results in this reporting period are:

Type "Jimp" Journal article

1. Streit P, Weiß AP, Stümpfl D, Špale J, Anderson LB, Novotný V, Kolovratník M. Concept and Design of a Velocity Compounded Radial Four-Fold Re-Entry Turbine for Organic Rankine Cycle (ORC) Applications. Energies. 2024 Mar 1;17(5):1185.

Type "O"

1. TO01000160-V4 "Summary report of geometries, experimental data and mapping of expanders' feasibility":
    a. Github repository https://github.com/janspale/DEXPAND containing the experimental data, design and manufacturing data and documents, design models and overall project report.
2. Conference presentation
    a. "Experimental Development of Various Types of Expanders for Small Scale Organic Rankine Cycle Power Systems", 9TH Thermal and Fluids Engineering Conference, Oregon State University, Corvallis, OR, USA, April, 21-24, 2024, presented by: Jan Spale

# Results dissemination

Selected results of the project were in 2024 presented and published by:

a) Journal article: Streit P, Weiß AP, Stümpfl D, Špale J, Anderson LB, Novotný V, Kolovratník M. Concept and Design of a Velocity Compounded Radial Four-Fold Re-Entry Turbine for Organic Rankine Cycle (ORC) Applications. Energies. 2024 Mar 1;17(5):1185
b) Conference presentation: J. Spale et al., Experimental Development of Various Types of Expanders for Small Scale Organic Rankine Cycle Power Systems. Presentation at the 9th Thermal and Fluids Engineering Conference, American Society of Thermal and Fluids Engineers (ASTFE), April 21-24 2024, Oregon State University, Corvallis, OR, USA
c) Summary report of geometries, experimental data and mapping of expanders' feasibility as a Github repository: https://github.com/janspale/DEXPAND
d) Final seminar – Took place on March 7 from 12:30 to 16:30 CET. Presentations are available on the project website.

e) Submission of two journal publications related to NTNU meanline turbine model:
1) Anderson LB., Agromayor R., Parisi S., Haglind F., Nord LO. Equation-Oriented Meanline Method for Axial Turbine Performance Prediction Under Choking Conditions. Journal of Turbomachinery. Submitted April 2024.
2) Anderson LB., Agromayor R., Haglind F., Nord LO. TurboFlow: Meanline Modelling of Axial Turbines. Journal of Open Source Software. Submitted June 2024.
f) Open source release of NTNU meanline turbine model in GitHub: https://github.com/turbo-sim/TurboFlow

## Involvement of project partners

During the 2024, as in previous years, there was very active continuous online communication and several physical project meetings between Czech and Norwegian partners. The project partners contributed based on their expected shares. CTU is responsible for project administration and coordination, technically then has main tasks in modelling, designing, and testing of impulse turbines (axial and "Elektra") for hexamethyldisiloxane (MM) working fluid which has been all performed. Design of rotary vane expander and results from experience with MM system, managing of the MM test rigs with primarily biomass cogeneration application. Also performing the tests air rigs were performed by CTU. NTNU has been working on commissioning the EXPAND test rig for natural refrigerants, primarily isobutane and corresponding turbine modelling and design. Different design approach taken by NTNU proceeds towards both impulse and reaction turbines and to cover larger range of working conditions and applications such as low temperature geothermal one. SINTEF is in charge and has performed most of the work on process modelling which includes development of a complex tool assessing both design and off-design performance, so that the optimization is performed at two fronts of the system, both expander and entire system. GT Progress as an industry representative with a responsibility for manufacturing and some design aspects has been assisting with the design and manufacturing analysis of the expanders as well as the experimental rigs.

## Steering Committee meetings

Project is managed on top level by a Steering Committee, which was meeting primarily via online communication. No notable issues were present for the Steering Committee in 2024.

## Budget utilization in 2024

In connection with previous approved change of project results and the project plan, minor transfers between the budget chapters and allowed transfers between project years, project partners had adjusted their budgets also in 2024 including unspent/transfer finance from previous year. CVUT fully utilized its budget as planned for 2024. NTNU fully utilized its budget as planned for 2024 including unspent/transfer from previous year.

GT Progress fully utilized its budget as planned for 2024 including unspent/transfer finance from the previous year. Unfortunately, GT Progres could not use up support in the amount of CZK 85, -- due to inaccuracies, respectively not using the maximum possible amount of support for 2021. GT Progres covered these costs/finance from its own resources.

SINTEF utilized 99,998% of its planned budget in the project. i.e., he did not spend costs in the amount of NOK 138 (according to the control of the audit authority).

Generally, the costs of Norwegian partners were reported in NOK. For reporting to TA CR, the balance between NOK and CZK were used these approaches:

a) if the entire planned budget was reported as a spent in NOK (as for NTNU), i.e. the total transferred subsidy, the accounting of costs in CZK then corresponded to the difference between reported costs in previous years and documented financial transfers between partners.

b) if the entire planned budget was not used up in NOK (as with SINTEF), then the calculation of the transfer of costs between NOK and CZK, or the drawdown, was carried out according to the principle of gradual drawdown of the budget according to the real exchange rate. More precisely, the unused subsidy was calculated and returned using the real exchange rate of 2024, i.e. with the 2.2190 CZK/NOK. The total unspent subsidy then amounted to NOK 138, i.e. CZK 315.84.

A more detailed calculation procedure is attached in Excel. The difference between the real costs of the planned budget in NOK and the planned ones was returned to TAČR as unconsumed support/profits from exchange rate conversions between NOK and CZK.

Specifically:

a) NTNU - CZK 374 630.95

b) SINTEF – CZK 86 295.42

The table of original costs in NOK and ones in CZK are included in DEXPAND_budget_spending_2024.

**Personnel costs**

**CVUT**

Key personnel of CVUT has not changed during 2024, minor changes were made in the “support team” in project management, technicians and young researchers (students).

Personnel of CVUT in 2024

| Name | man-year | position |
|---|---|---|
| Ing. Václav Novotný | 0,05 | Lead researcher |
| Ing. Jan Špale | 0 | Team key member |
| prof. Dr. Ing. Tomáš Vampola | 0,02 | Team key member |
| Prof. Dr. Andreas Weiß | 0 | Team key member |
| prof. Ing. Michal Kolovratník, CSc. | 0.03 | CTU senior researcher(s) |
| Ing. Jakub Maščuch, Ph.D. | 0,01 | CTU senior researcher(s) |
| Ing. Guk Chol Jun, Ph.D. | 0,12 | CTU researcher(s) |

| | | |
|---|---|---|
| Ing. Jan Pavlíčko | 0,01 | CTU researcher(s) |
| Ing. Daniel Suchna | 0,02 | CTU researcher(s) |
| Ing. Václav Vodička, Ph.D. | 0,02 | CTU researcher(s) |
| Ing. Zbyněk Zelený | 0,06 | CTU researcher(s) |
| Simandl Martin | 0,01 | CTU researcher(s) |
| Student | 0,03 | CTU young Researcher(s) |
| Mgr. Pilátová Lenka | 0.06 | Project management |
| Ing. Monika Vitvarová | 0,1 | Project management |

**GT Progres**

There has been only a minor change to the team of GT Progres in 2024.

| Name | man-year | position |
|---|---|---|
| Ing. Čeněk Vašák | 0,10 | Other solver |
| Ing.Jiří Hrubý | 0,13 | GT-Progres Tech. Researchers |
| Pavel Marek st. | 0,13 | Technician |

**NTNU**

Same technical team for NTNU as in 2023. Administrative personnel added for finalizing the project.

NTNU personnel in 2024:

| Name | man-year | position |
|---|---|---|
| Lars Olof Nord Ph.D. | 0,10 | Other solver |
| Lasse Borg Anderson | 0,33 | NTNU PhD candidate |
| Benjamin Mitterrutzner | 0,33 | NTNU researcher |
| Ida Antonsen | 0,02 | NTNU Project administrator |
| Tonje Kotte Fredriksen | 0,01 | NTNU Project economist |

**SINTEF**

SINTEF, as well as NTNU has engaged an extra researcher to help finalise the project and administration as described at previous annual report.

SINTEF personnel in 2024:

| Name | man-year | position |
|---|---|---|
| Ing. Luca Riboldi Ph.D. | 0,04 | Team member |
| Ruben Mocholi Montanes Ph.D. | 0,01 | Team member |
| Donghoi Kim | 0,03 | SINTEF Researcher category II |
| Magnus Kyrre Windfeldt | 0,07 | SINTEF Researcher category I |

# Changes in implementation

In 2024 were not performed any notable changes in implementation. The Gantt chart reflecting last minor adjustments from 2023 is shown below.

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# Factual progress report

For 2024

Written by: Dexpand project team

# Introduction

Efficient, reliable and cost-effective expanders are the key enabling components for many distributed energy systems, such as organic Rankine cycles (ORC) and other thermodynamic cycles for waste heat recovery (WHR), biomass-fired power generation, or low-temperature geothermal resources based on deep energy wells. ORCs are the unrivalled technical solution for generating electricity from low to medium temperature heat sources of limited capacity; therefore, this project aims specifically at the development of expansion machines for these technologies. Current expanders for small systems (1–50 kW electrical power output) are either not in the market, are too expensive, or don't provide satisfactory performance and most of the possible energy sources are not utilised. Cost-effective expanders could enable a significant market for this type of distributed energy systems and offer a large potential for overall CO2 savings. This project focuses on the development and testing of cost-effective expanders for power generation in distributed energy systems, reporting expanders' data and mapping of the technologies over the power range 1–50 kW based on cost, application feasibility, and performance.

The report is further divided to chapters according to the work packages. Details can be found in an overall project report, attached separately (Appendix 2 – Extended report) or as a part of the overall summarizing report in GitHub.

# 1. WP1 – System modelling and simulation

The DEXPAND project WP1 in the first phase included a methodology to translate process performances into expander design parameters through system modelling, simulation, and optimization. The main focus of the work was to develop a universal off-design optimization tool of the cycle to assess the best performance for fluctuating parameters. This work is interlinked with the expander modelling activities. The year saw the successful integration of an expander model into the system design platform. This integration was a breakthrough, enhancing the tool's ability to manage multi-scale optimization for ORC systems with fluctuating heat sources and sinks.

Significantly, the team made strides in refining and expanding the capabilities of the off-design optimization tool. This development was critical for assessing performance under varying operational conditions, thereby allowing for a more accurate and dynamic modelling of the ORC systems. The application of this tool in real-world scenarios, such as biomass-fired micro-cogeneration systems, showcased its practical effectiveness. The successful running of the tool on a reference case study using long-term experimental data demonstrated a potential 10% increase in produced electricity compared to base case models, while supplying the required heat demand.

The reference case study is biomass-fired micro-cogeneration of heat and power via ORC. The case study is representative of an existing unit operating at the Czech Technical University (CTU) in Prague for supplying heat (design 120 kWth) and electricity (design 6.2 kWel) to the university research center. The working fluid is MM (hexamethyldisiloxane). The unit is woodchips-fired.

In 2024, WP1 finalized the multi-scale optimization tool, updating it with latest expander models. In particular, the design optimization tool was tested using the single-stage axial turbine model developed by NTNU. The model is based on a based on mean line method and incorporate an advanced loss model, critical to reflect incidence losses at off-design conditions. In additions, an off-design heat exchanger (HX) model was developed in-house to enhance the capability of the optimization tool to realistically capture off-design system performances. The HX model was developed to represent a generic counter-current HX estimating local heat transfer and pressure drop from end to end. Case studies were defined to examine ORC systems' flexibility with these expanders. The project's findings will be documented in a journal article, with planned publication early within the sustainability phase of the project (late 2024/early 2025). Consistent with our commitment to open research, the tool will be made open source, broadening its impact in the energy field together with the journal article publication.

The main objective within WP1 was to design three different heat-to-power conversion cycles by means of system modelling, simulation and optimisation. This objective was achieved in early phases of the project as documented in the memo "DExpand Case Studies: WP1 System modeling and optimization", where three case studies were established and, accordingly, three heat-to-power cycles were optimized. The simulation work provided a basis of design and boundary conditions for the detailed design of the expanders.

The secondary objective of WP1 was to explore further the potential application and flexible operation of the resulting process from the case study applications by means of steady-state off-design modelling and simulation. Also this objective was achieved by developing a multi-scale optimization tool to guide the design of heat-to-power cycles at variable conditions typical of relevant applications of the technological solutions developed in the project. This work was broadly disseminated and the tool will be made open source.

Demonstration of the developed tool and framework is presented in Figure 12. With a tailor-made design of the expander, it was how the design nominal point of the expander and whole cycle can affect the operational efficiency and thus cumulative power production. In this specific case a potential for 10 % increase in accumulated power production was demonstrated.

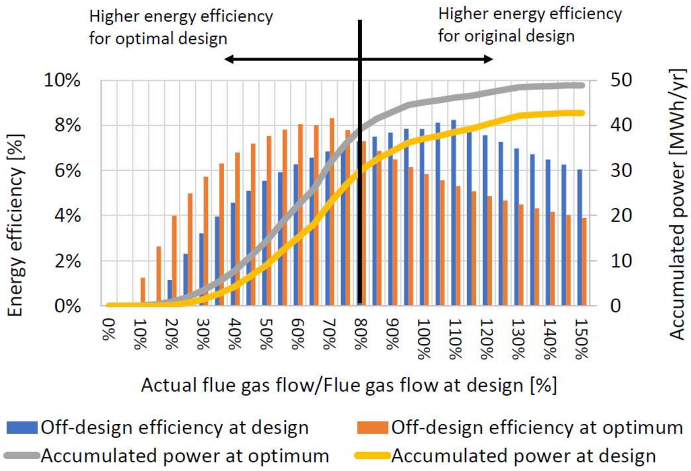


*Figure 1. Energy efficiency and accumulated power output for the original and optimized designs based on the reference case study.*

# 2. WP2 - Expander modelling, design and optimisation

Modelling and optimization included three types of the expanders applied for two different ORC working fluids and air, according to the test rigs at NTNU and CTU, i.e., rotary vane expander, axial single stage turbine for working fluids isobutane and MM and "non-orthodox" turbine. Within the task of providing the fluid dynamic design for further mechanical design and manufacturing in following WP were some models progressed further, while other used to adjust previous designs to new conditions.

## *2.1. Single stage axial turbines*

An axial impulse turbine is considered for the MM fluid and the CTU rig, while both impulse and reaction turbine are considered for the isobutane and NTNU rig as the pressure ratios are lower and the project covers larger range of turbine types.

Activities in 2024 in impulse turbine models of both CTU and NTNU focused primarily on improving the models code structure and generating documentation for their publications. The CTU axial impulse supersonic turbine model was coded in Python (previously Excel VBA) in order to easily implement optimization algorithms and also to make it available to broader public, as Python is the most adopted programming language. The main logic of the code remains the same as within the previous years, but the code now has a robust documentation and is more approachable by someone who is not familiar with turbomachinery design. It still uses REFPROP 10 for thermodynamic and thermophysical fluid properties; it allows for easy change of boundary conditions and design variables such as vapor inlet/outlet properties, mass flow rate or working fluid.

TurboFlow, developed at NTNU, is a Python package for mean-line modelling of axial turbines. It aims to offer flexible and reliable simulations for both performance prediction and design. It has been released as open-source software. It supports a broad range of axial turbine configurations and offers user control over various modelling options such as loss, deviation correlation, and blockage factors due to boundary layer development. The model introduces a novel method for predicting critical states and automatically detects whether cascades are choked. It can predict various combinations of choked stator/rotor scenarios. Validated against experimental results, the model successfully predicts flow regimes, mass flow rates, torque, and rotor exit flow angles with a high degree of accuracy. This robustness makes it ideal for preliminary axial turbine design, focusing on efficiency over diverse operating conditions to enhance yearly power output and investment returns for ORC systems.

In summary, within the project were developed two 1-D models of axial turbines. One as a higher accuracy design model specifically for small impulse turbines. While the second model doesn't provide such accuracy for the design of these specific small impulse turbine, it is fully applicable also for reaction turbine type and off-design conditions. The models were then applied to develop the functional samples of axial turbines. Both models are within the open access repository.

The 1-D models were further complemented by 2D and 3D CFD models serving for further precision level in performance prediction and additional geometry optimization, which goes beyond the 1D model capabilities. Detailed description of the CFD models in order to ensure replicability is also within the OA repository. Below in Figure 2 is illustration of CFD sensitivity study on rotor edges shape, a feature highly affected by manufacturability and the results od a CFD sensitivity study of off-design performance. Both are for MM turbine.

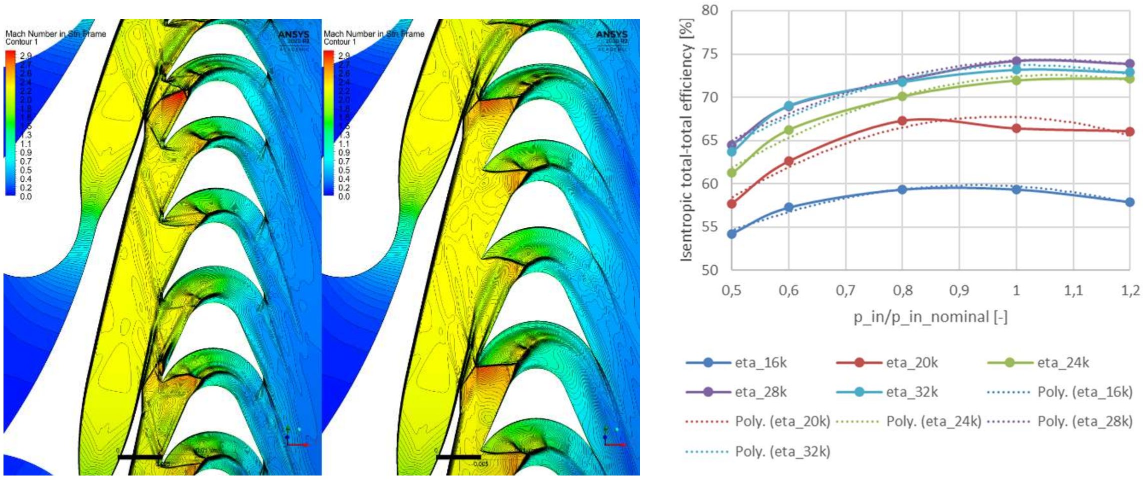


*Figure 2. Midspan Mach contours in stationary frame - effect of sharpened rotor edges contra easily manufacturable design (left) and off-design performance map of the v1 axial MM turbine based on 3D high fidelity CFD (right)*

## 2.2. Elektra turbine (velocity compounded)

Within the Elektra modelling, the activities were also largely focused on summarizing and finalizing. Large parts of the activities were dedicated to revisions within the journal publication focusing specifically on Elektra turbine model.

In summary, within the project was previous deign 1D model successfully extended to include organic fluids. The model was then applied in design of the functional sample. Similarly as for the axial turbines, CFD was then employed for further geometry optimization and increased accuracy of performance prediction and were an essential step before full mechanical design of the Elektra turbine. The process of optimization via CFD study is illustrated in Figure 3  These ORC Elektra models are, apart from the journal paper, also described in full detail for replicability within the open access repository.

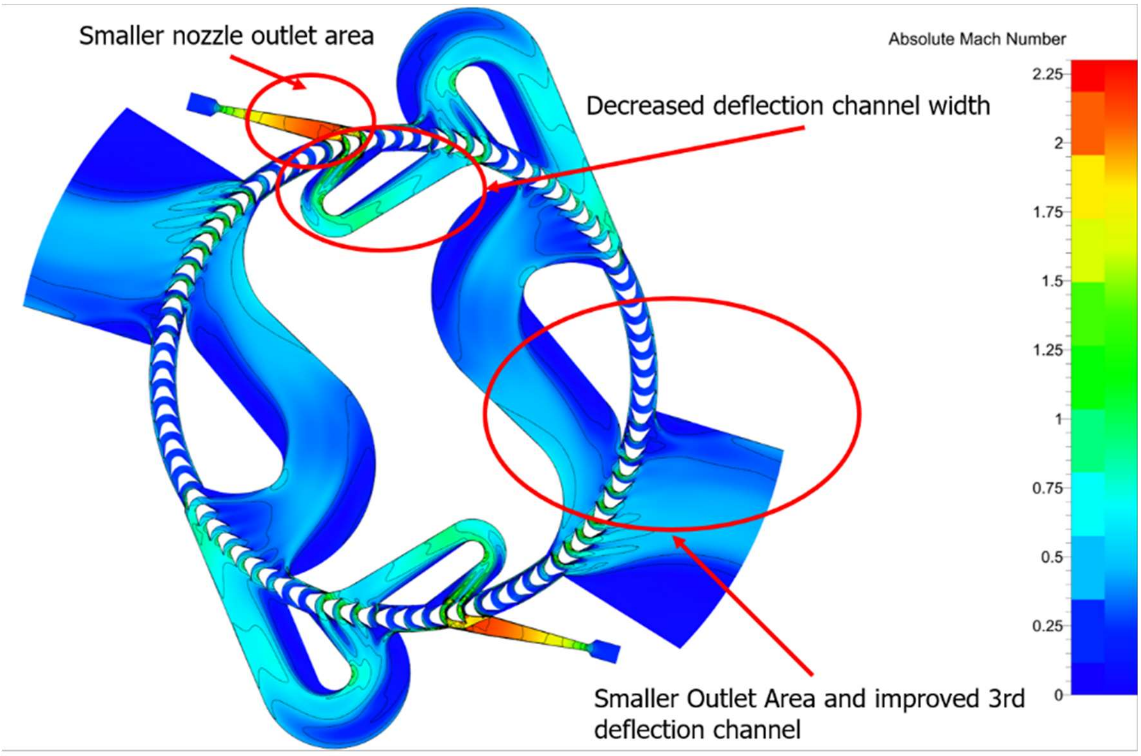


*Figure 3. Absolute Mach number plot of the Elektra turbine (V2) with highlighted optimization points.*

## 2.3. Rotary vane expander

Efforts regarding RVE modelling were largely concluded in 2023. In summary, a previously validated 1D model for RVE development was within the project modified for alternative working fluids and to include predictions of change of performance when operating under oil-free conditions. First, using isobutane as a working fluid and parameters of the Expand rig, model was optimized for originally planned RVE with isobutane. After the issues with the isobutane test rig came, first on delays with commissioning and eventually its breakdown prevented isobutane RVE tests within the project timeline, and following project change, RVE model was modified to a different scale and air as a working fluid. As so, the 1D model under new conditions was used to provide an optimized design basis for the RVE functional sample, oil-free RVE operating with air, as a way for emulation similar conditions that would be present in operation with other ORC working fluids under dry conditions.

Note, that CFD analysis has not been performed for this volumetric expander type, as it does not bring notable benefits. Based on the underlaying principle of the RVE, the performance is based on tribological and mechanical parameters and manufacturing tolerances, rather than on aerodynamic parameters analysed in CFD.

# 3. WP3 - Expander Manufacturing, Assembly, Commissioning

In summary, within the project were successfully developed four functional samples of expanders and test rigs. That means the fluid dynamics design was converted to mechanical design, manufactured, assembled and successfully commissioned. This was achieved for the project obligatory results which are axial MM turbine, axial isobutane turbine, radial velocity compounded MM turbine and oil-free rotary vane expander. Within the project were also developed small supporting testing systems like an air nozzle test rig or vane durability testing system. Lastly, the project assisted also with the main test rigs. Apart from maintaining the systems, the 200 kWth MM testrig has been renovated, partially modernized and re-commissioned as a result of fire incident and the EXPAND isobutane test rig for expander testing has been built and commissioned, both with assistance of the Dexpand project.

While all the expanders were successfully commissioned in 2023, MM Axial supersonic impulse turbine got a redesign to allow for low-vibration high-efficiency operation at higher rotational speed than the initial version while the nominal speed was, for the same reason, reduced. The mechanical assembly was described in the progress report of the Year 2023. The implementation of the modifications has been performed in 2024.

## *3.1. Expander mechanical design, manufacturing and assembly*

At the turn of the year, adjustments to the design of the axial MM turbine based on operating experience were made. In the last months of the project, the components of the modified design were manufactured and in the process of assembly. Note that the obligatory result was achieved in 2023 and this modification is an initial step to ongoing efforts to be performed within the sustainability phase of the project with finalization of assembly and new experimental tests. The Elektra turbine was upgraded with a new casing to better accommodate for the large sealing O-ring and avoid aluminium frame damage that was identified before. No other activities within this point were performed in the 4 months of the project in 2024.

In summary, the within the project were successfully designed, manufactured and assembled four different ORC expanders, axial turboexpanders for MM and for isobutane working fluids, “Elektra” velocity compounded radial turbine and oil-free rotary vane expander. Models of each are illustrated together in Figure 4. Manufactured expanders are then shown in Figure 5.  The project further took advantage of previous experimental development and data with several sizes of rotary vane expanders.

At the end of the project, design modifications were proposed to the MM turbine based on the experimental performance.

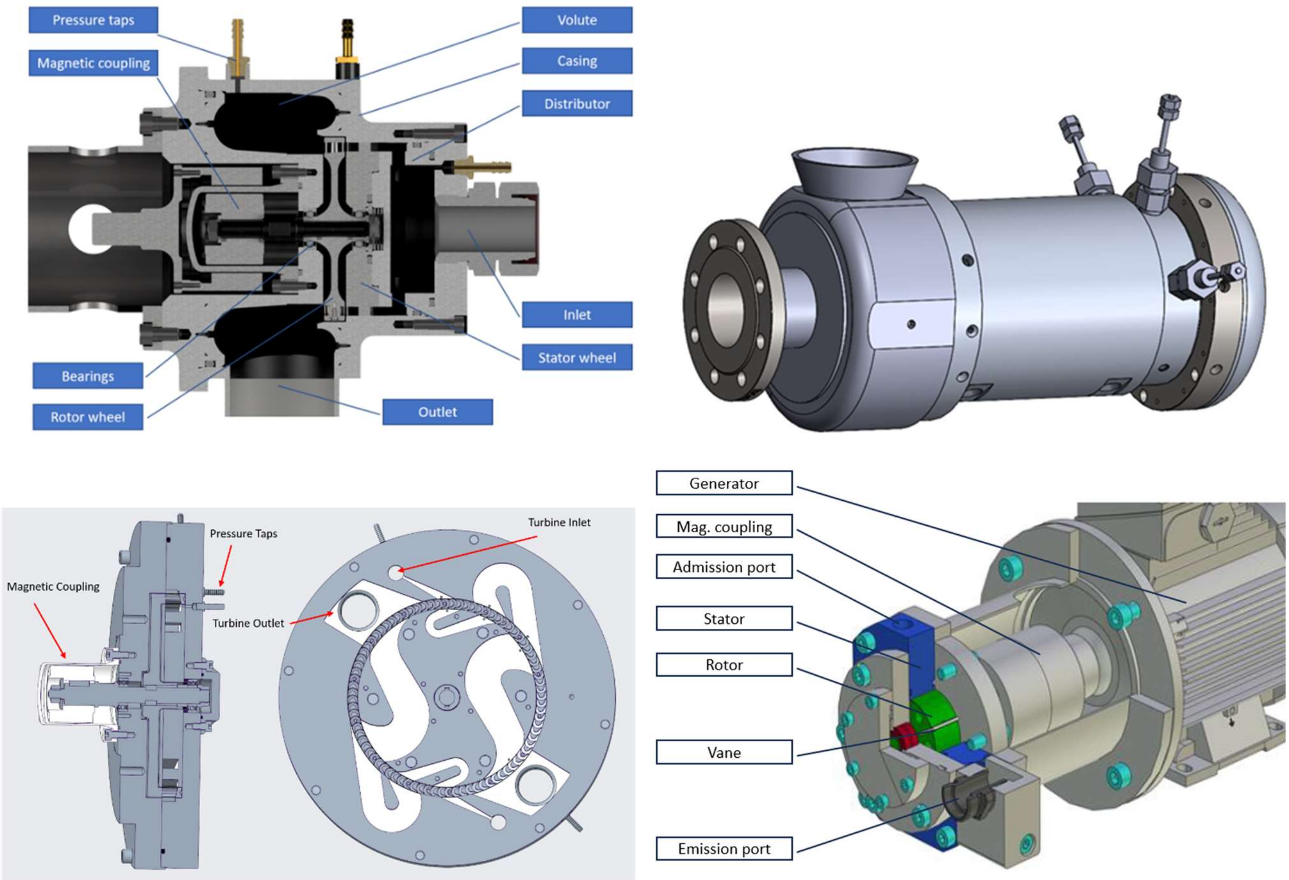


*Figure 4. Mechanical design of four explored expanders – MM axial turbine, isobutane axial turbine, MM Elektra turbine and air RVE.*


*Figure 5. Photos of manufactures expanders – MM axial turbine, isobutane axial turbine, MM Elektra turbine and air RVE.*

## *3.2. Rotordynamics and stress analyses*

Rotordynamic analysis performed in past years are crucial in turbine development to ensure mechanical integrity and operational safety by evaluating dynamic characteristics, resonance frequencies, and deformation behaviours.

The research project investigates the rotordynamics and stress analyses of the developed ORC turbine systems. Initial studies on different shaft configurations, including single-shaft with two bearings and magnetic coupling, used Finite Element Method (FEM) analyses. Results showed that natural frequencies should be well-separated from nominal rotational speeds, reducing the risk of torsional oscillations. Further studies on the turboexpander assembly aimed to determine resonance bands and system deflections under unbalance. Simplified mathematical models and FEM revealed that axial, bending, and circular oscillation frequencies are significantly higher than the theoretical speed limit, ensuring safe operation. However, bearing stiffness was found to alter these frequencies, necessitating sensitivity analyses.

The v1 axial impulse supersonic MM turbine faced excessive vibrations, limiting speed to below 18000 rpm. Campbell diagram analysis (Figure 6) identified a critical speed at 13901 rpm, where resonance could induce significant vibrational stress. Expert recommendations led to design improvements for dynamic stability.

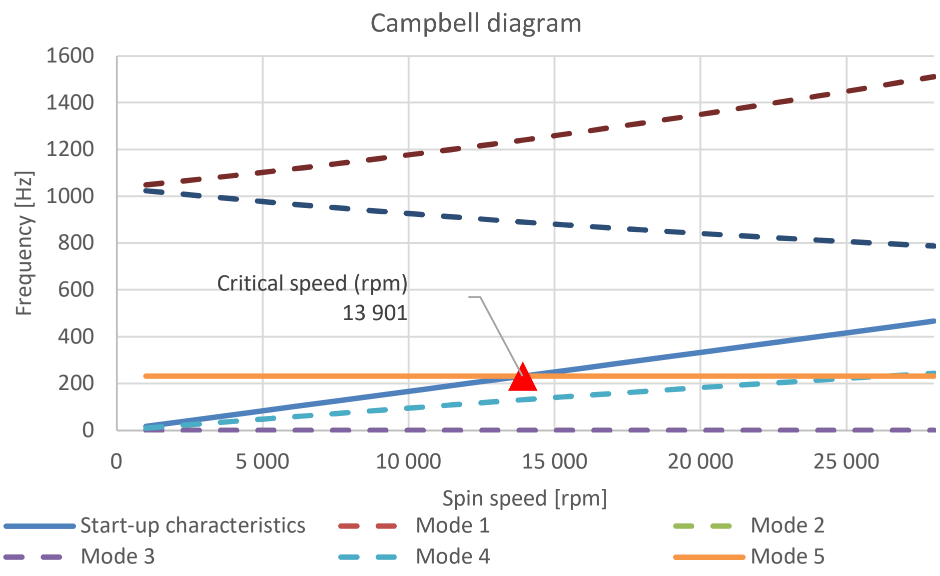


*Figure 6. Campbell diagram of the axial turbine, identifying the potentially critical speed for resonance operation, v1 MM turbine.*

For the Elektra turbine, stress and displacement analyses at 3000 rpm and 200°C showed safe maximum displacement and stress levels. Modal analysis confirmed that none of the vibrational modes are near the operational speed, ensuring mechanical integrity.

Overall, the research provides vital insights into turbine dynamic behaviours, highlighting the need for both careful design but also experimental feedback to avoid resonance and ensure safe, efficient operation. The findings support further optimization of turbine configurations in ORC units and other applications.

## 3.3. Commissioning

Commissioning of the expanders and test rigs is an essential step to ensure reliability and general operation functionality before further experimental campaigns. As such, it has been an integral part of the project's experimental activities.

The axial MM turbine was initially tested using compressed air to check mechanical stability and efficiency across various pressure ratios and rotational speeds. These tests identified excessive shaft vibrations, leading to damage to the sealing canister. Iterative design improvements were made to enhance robustness.

The axial isobutane turbine test rig succesfully complied its Factory Acceptance Test (FAT) but faced problems during the Site Acceptance Test (SAT). Damage to the low-pressure compressor shaft and bearings required extensive refurbishments, including valve replacements and power cable upgrades, delaying further tests into the sustainability phase of the project.

The Elektra turbine's commissioning revealed design optimization needs, such as easier handling of large housing plates and improved O-ring grooves. Despite these challenges, the turbine operated smoothly under typical conditions. Some oil condensation reduced efficiency but did not cause a damage. Successful commissioning of the Elektra turbine, which was in this regard the smoothest of all turbines, has been documented by a photo in Figure 7.


*Figure 7. Part of the Czech-German-Norwegian project team after successful measurements of the Elektra turbine at CTU UCEEB.*

The Air RVE turbine was tested for torque and volumetric flow rate using pressurized air. Initial issues with vane sealing at low rotational speeds were resolved at higher speeds, confirming the design model's predictions.

These commissioning activities have been crucial in identifying and addressing design and operational issues, ensuring the expanders' reliability and functionality for subsequent experimental campaigns.

# 4. WP4 – Experimental results

Additional experiment to complement the 2023 campaigns were performed also in 2024 along with works in data processing and analysis and these are in more detail described below. Generally, experimental works are essential for validating the theoretical models and design, while feedback for improvements is provided back to the design activities. Obtaining an analysing the experimental data is also the essential step towards the final project result on mapping expander performance, which is then shared in the open access philosophy to wide professional community. Note that the team is dedicated to continuing with experimental works into the sustainability phase of the project with prospect of later utilizing the data for high level academic publications.

## *4.1. MM turbine data analysis tool*

New Python script for automatic experimental data evaluation from the CTU MM test rig was developed and published in the GitHub open access repository. It reads the raw CSV data exported from the PLC of the ORC unit, parses them using the time string in *pandas* library, and using time ranges for steady states, it evaluates the time-averaged steady state measured data. Example of automatically evaluated experimental dataset can be found in following section.

## *4.2. Axial MM turbine tests*

As a second version (Mark II) of the axial assembly was developed, a new experimental campaign within the MM CTU ORC test rig was conducted. The results are presented in Figure 8 below. The second version was designed to operate at a lower nominal rotational speed. Even though the bearing housing subassembly was more stable and resistant to vibration, the maximum speed was capped at the design speed (18 000 rpm) for these experiments. Maximum isentropic efficiency achieved was just below 62 %, which is a value slightly lower than the prediction of the design tool (72 %) which can be considered as a major success and confirmation of the good aerodynamic performance of the functional sample in its lower TRL phase of development. A great achievement is the turbines low sensitivity to off-design pressure ratios which could be accounted for the supersonic nozzle design by the method of characteristics. This is especially important for expander machines that will operate in applications with fluctuating heat sources such as waste heat recovery. The design tool underpredicts certain losses such as the tip leakage in the stator nozzles, compromised for easy assembly of the machine, secondary losses caused by the increased thickness of the leading and trailing edges due to machinability of the small turbine blades. Moreover, it does not take into account dissolved oil in the working fluid of the organic Rankine cycle, which impedes the leading edge and causes damage to the rotor blades. This will be avoided in the next campaign with further modifications.

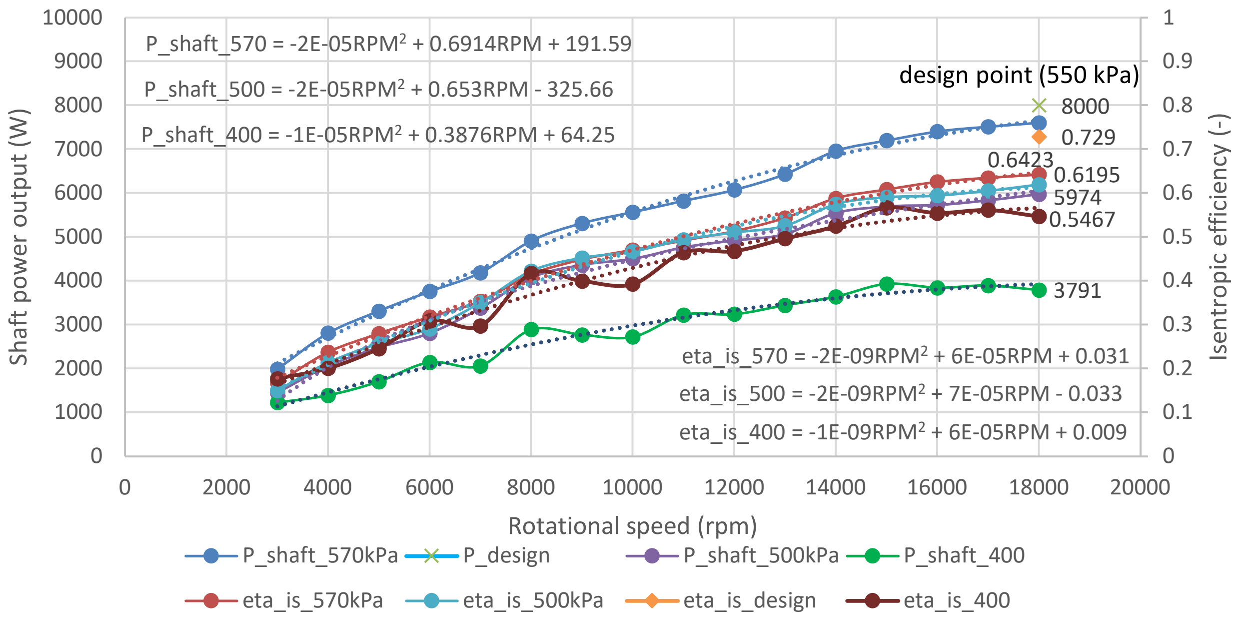


*Figure 8 Results (shaft power output and isentropic efficiency) of the experimental campaign of Mark II assembly of the MM Axial impulse turbine*

A future experimental investigation will be done within the project sustainability phase to complete the measurements at different off-design conditions and to prepare summarized results for a prestigious Q1 journal publication (Renewable Energy / Energy journal). At the same time, thanks to the open access nature of the GitHub repository, as more experimental data will be collected, they will be continously shared with the academic and professional community using the DEXPAND repository. In summary, the turbine tests validated the aerodynamic design as a success, though they also prompted changes in design to address encountered vibrations issues.

## 4.3. Elektra MM turbine tests

In 2024 further measurements of the Elektra Turbine with pressurized air have been carried out to investigate, if it is reasonable to compare off-design, off-medium measurements with off-design, off-medium CFD calculations for turbine performance analyzation and optimization. Table 1 shows the comparison of the boundary conditions of the design point of the turbine and the off design/medium boundary conditions for the CFD calculations and the measurements.

*Table 1. Comparison of the boundary conditions of the design point and the off design/medium CFD/Measurements of the Elektra Turbine.*

| | Design Point | Off design/medium CFD/measurements | Unit |
|---|---|---|---|

| Medium | Hexamethyldisiloxane (MM) | Air | - |
|---|---|---|---|
| Inlet pressure (absolute total) | 6.5 | 3 - 6 | bar |
| Inlet temperature (total) | 463 | 293 | K |
| Outlet pressure (static) | 0.55 | 1 (atmospheric) | bar |
| Rotational speed | 3000 | 1000-3000 | rpm |

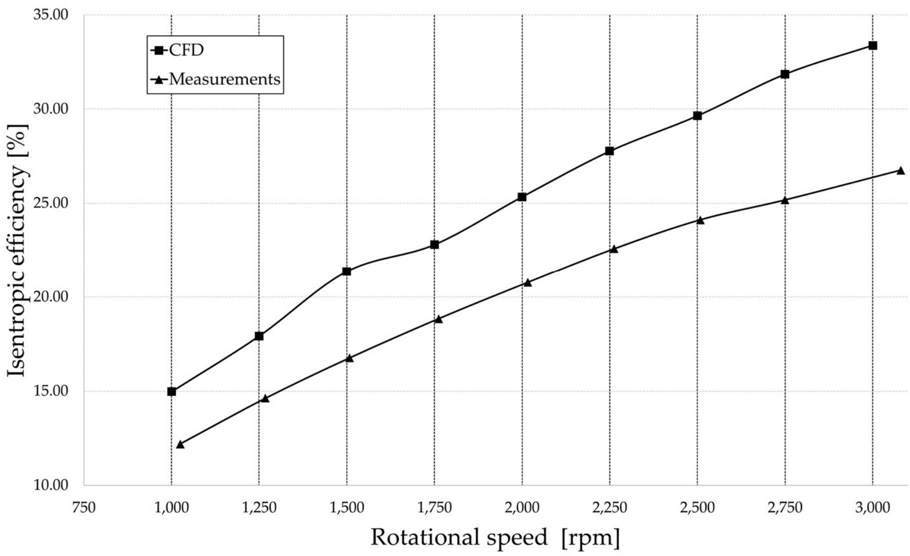


*Figure 9. Comparison of the performance map of the Elektra turbine from CFD calculations and measurements for 6 bar inlet pressure and air as working fluid.*

Figure 9 shows the comparison of the performance map of the Elektra turbine measurements and CFD Calculations for pressurized air. It becomes immediately clear, that there is a deviation of the isentropic efficiency from around 3 %-points at 1,000 rpm to around 5 %-points at 3,000 rpm, which the CFD calculation is above the measurements. The deviations slightly increase from lower to higher rotational speeds. These deviations can be explained by the rather simple CFD-model of the Turbine (no axial gaps, less leakages) and the missing bearing friction.

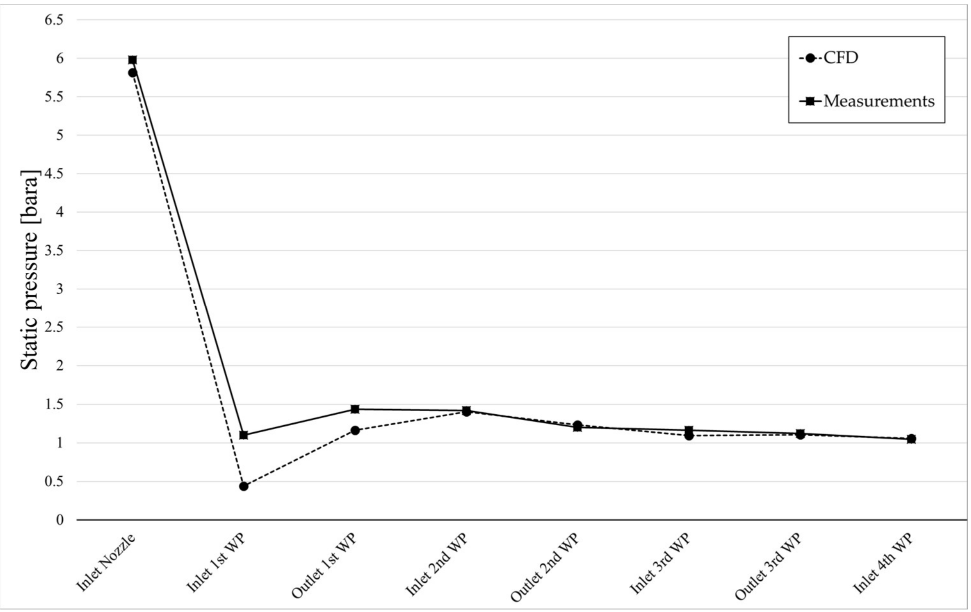


*Figure 10. Comparison of the streamwise static pressure distribution over the Elektra turbine from CFD calculations and measurements for 6 bar inlet pressure (WP = wheel pass).*

Figure 10 shows the comparison of the streamwise static pressure distribution of the measurements and the CFD Calculations of the Elektra Turbine with pressurized air. The results show that the pressure distribution over the turbine almost overlap over a wide range (Inlet 2nd WP to Inlet 4th WP) and only deviate from each other by approx. 0.5 bar at the Inlet 1st WP – which is also the outlet of the nozzle. This deviation could be explained by the strong shockwaves, that are in the region of the nozzle outlet/wheelpass inlet. The pressure measured in this area strongly depends on the actual position of the pressure probe. If the positioning of the probe is slightly displaced, the pressure measured in this position could be strongly different. The CFD value in comparison shows a surface averaged pressure in this area and therefore, the deviation can be larger.

This comparison ensured that the off-design, off-medium measurements and CFD simulations can be compared well with each other. The CFD simulations show the basic course of the efficiency curve and reproduce the pressure curve in the turbine well. Based on these results, it can be assumed that further optimization of the turbine is possible using this approach.

## *4.1. RVE vanes durability tests*

A testing stand for long term durability tests of vanes was assembled using the RVE functional sample with asynchronous motor (normally used as generator), programmable frequency converter and a pipe to dampen the noise as seen in Figure 11. This set-up then by running the motor emulates the long term expander operation.

*Figure 11. Experimental stand for long term vane durability testing.*

This experimental analysis yields after nearly 100 hours of operation some mixed results. Positive aspect is that the vanes did not fail but minor signs of wear were already visible and the friction between. A further investigation is recommended for follow-up activities. Currently recommended solution for oil-free operation is in regular supply system of a very small amount of a dry lubricant such as MoS2. Note that this dry lubricant has been tried in the initial phase of the test and the data on friction resistance (power consumption) do indicate a transfer point between stable operation as long as the lubricant is present and slightly increased resistance once the lubricant wears off.

# 5. WP5 – Assessment and feasibility mapping - Summary report

A concluding activity of the Dexpand project has been development of the *Summary report of geometries, experimental data and mapping of expanders' feasibility*, which has been published as a Github repository at: https://github.com/janspale/DEXPAND. It is a summary of the project analyses and results throughout the project duration including the design models, mechanical design models or manufacturing documentation and finally experimental data and results and analysis. An introductory document then helps users to navigate within the repository and a document summarizing project activities, models and results further adds to the description and understanding of the data in the repository. Note that the repository is set-up to be a living plattform with possible and expected updates by new data and results from follow-up activities and will also serve as a go-to location for supporting data of considered future publications.

The first result belonging to the feasibility mapping is the cycle design point optimization from WP1, repeated below in Figure 12. With a tailor-made design of the expander, it was how the design nominal point of the expander and whole cycle can affect the operational efficiency and thus cumulative power production. In this specific case a potential for 10 % increase in accumulated power production was demonstrated.

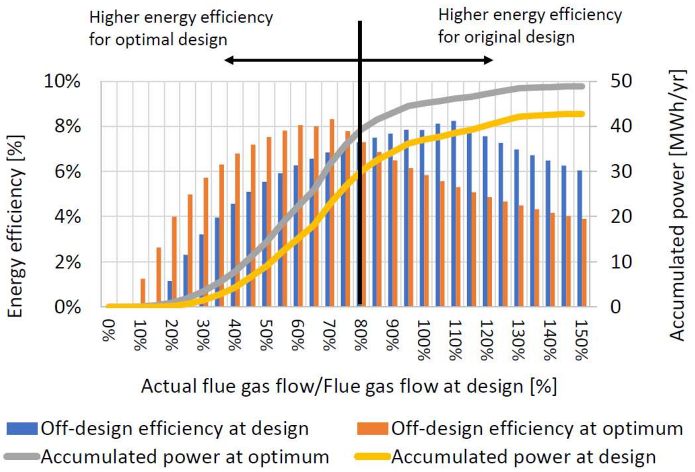


*Figure 12. Energy efficiency and accumulated power output for the original and optimized designs based on the reference case study.*

As a next phase, feasibility of expanders was looked at in detail using the developed models and experience from our experimental development. These results are shown in Figure 13. It shows that the RVE has a cap of efficiency, clearly depending on the pressure ratio (or expansion ratio) with higher values and lower pressure ratios, but also a cap in power output within the design limits (see full project report for details). However, turbines, unless we want to exceed extreme speeds, the efficiency drops more significantly at small power output systems. Elektra appears to be a good solution for MM microcogenration systems above about 10 kW power output.

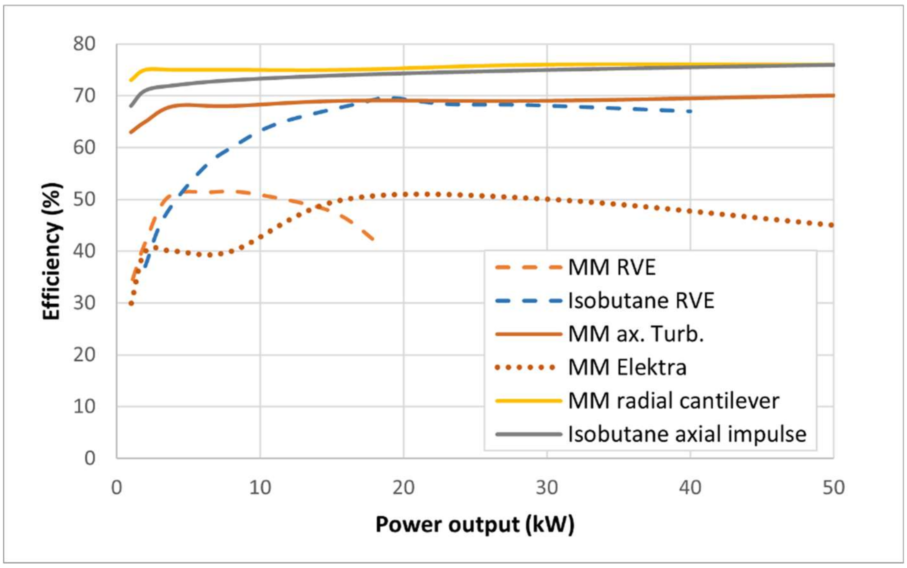


*Figure 13. Efficiency mapping for considered expander types assuming impulse turbines*

Nominal design speed needs to be also considered when selecting the expanders. Figure 14 shows, that while the RVE and Elektra are considered always at constant 3 000 rpm, the other turbines are not only operating at high speed, but a suitable speed differs largely based on the power output.

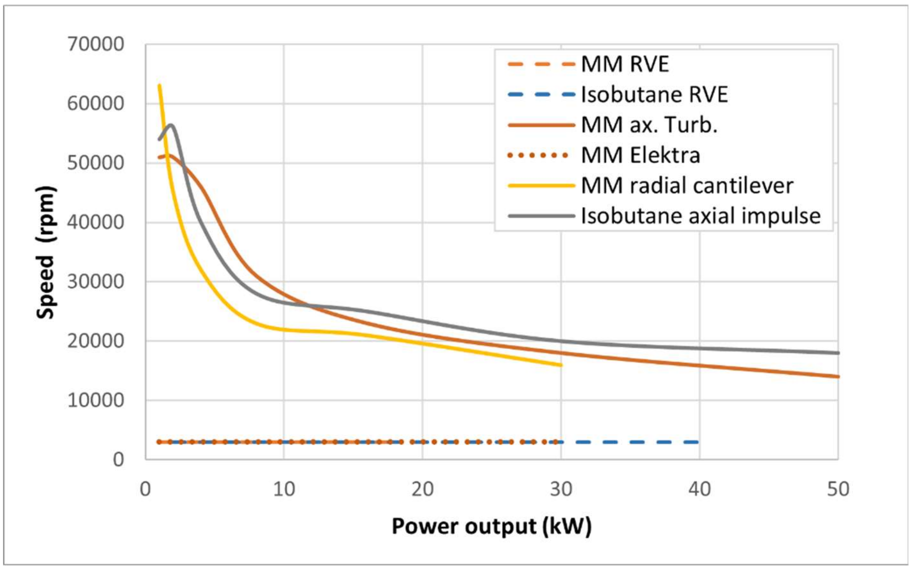


*Figure 14 Expander mapping regarding speed for considered expander types.*

Highly important are however feasibility maps from the experimental data. An overview of performance at nominal (or maximal if nominal parameters were not achieved) regarding the PR, power output and efficiency is in Figure 15. Note for the further results the low PR and highest power output of the isobutane turbine. This makes the high PR axial turbines performance way more challenging when these two turbines are compared against each other. The axial turbines achieve the highest efficiency, while for the Elektra turbine should be mentioned that this is the first reported ORC trial of this type of turbine and there is a space for improvement, while previous results suggested that it might have the most competitive performance at higher power outputs than used here.

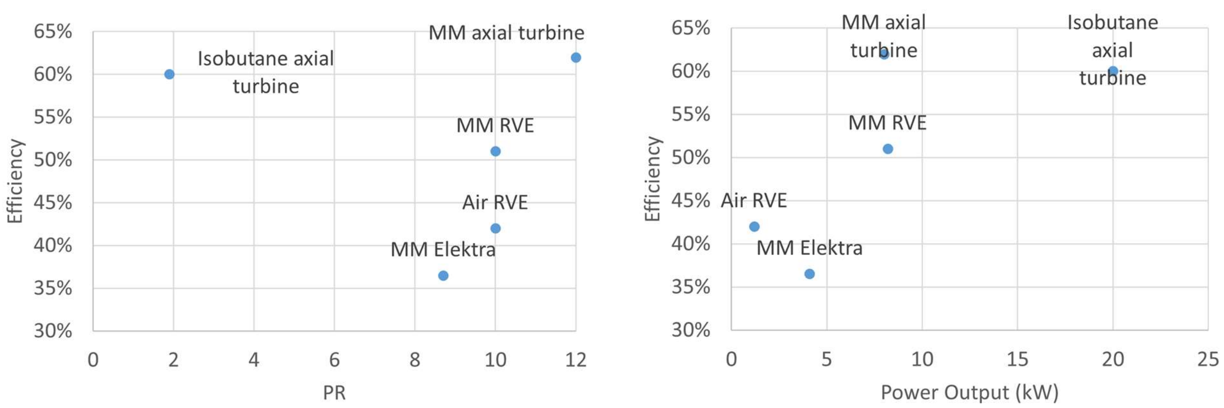


*Figure 15. Performance maps of the experimentally explored expanders regarding the PR, power output and efficiency.*

Clear disadvantage of the axial turbines is the necessary high speed, documented then in Figure 16. This is particularly represented in achieved performance, where both axial turbines reached only below-nominal speeds. This was 10 000 rpm for the isobutane turbine (nominal 17 – 20 000 rpm) while the

MM turbine during the ORC operation did was for safety reasons due to vibrations operated below 20 000 rpm (nominal 28 000 rpm). This prompted a modified design of a 18 000 rpm axial isobutane turbine operating also at higher mass flowrate at slightly lower PR, as shown on the first graph. The document version on the repository will be updated once the experimental performance is obtained.

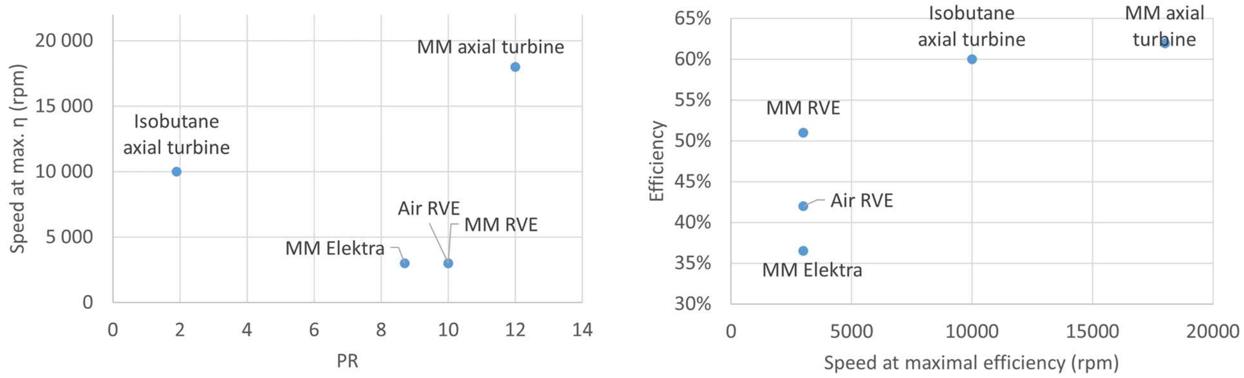


*Figure 16. Performance maps of the experimentally explored expanders regarding the PR, nominal speed and efficiency.*

As a final result of the mapping are the economic parameters, specifically cost per kW of power output plotted against the efficiency in Figure 17. There are several specific points to take into account. The air RVE has a high cost due to being only 1 kW unit. Yet, isobutane axial turbine with external manufacturing has still higher unit cost even though having the highest power output, reason why the in-house procured manufacturing and in-house assembly has much lower cost. Lastly, the MM Elektra turbine is somewhat costly as a result of currently limited efficiency and thus low power output.

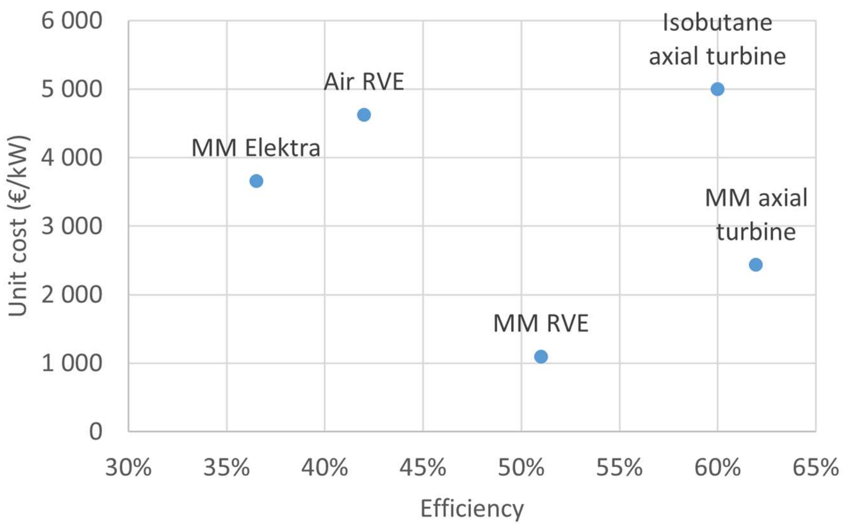


*Figure 17. Performance maps of the experimentally explored expanders regarding the PR, nominal speed and efficiency.*

# 6. Conclusion

In 2024 were performed remaining activities of the project towards its successful conclusion. The main activities in 2024 consisted of finalizing, publishing and reporting project results. Additional experimental activities complemented the achieved results in performing additional experimental runs and modifying expander functional sample for better performance.

The project achieved the outlined goals with a single major and approved change during the investigation, which consisted of experimentally pursuing the Elektra turbine in addition to experimental development of axial turbines. The experimental oil-free rotary vane expander was then developed for air working fluid due to unforeseen issues with isobutane testrig. By publishing the project results in a scientific journal and developing an open access report and repository the project successfully provided all deliverables and provides a major step forward to the whole ORC scientific and commercial community.

In 2024, the DEXPAND project successfully concluded, achieving all its outlined objectives. The primary activities this year focused on finalizing experiments, publishing results, and preparing models for open access dissemination.

Key activities and achievements were focused on finalizing and release of the open-source code for multi-scale optimization tool, the meanline turbine models or experimental data analysing tool, promoting collaboration and innovation within academic and industrial sectors. The MM turbine's upgrade further enhanced the project's outcomes. The culmination of these efforts was documented in the open access report and repository of documents TO01000160-V4, which provides a comprehensive summary of expander geometries, experimental data, and feasibility mapping. This resource serves both scientific and commercial communities involved in ORC technology.

The project's online presence, showcased through its website at dexpand.cz, offers another platform for dissemination and engagement with stakeholders. While the Data Management Plan underwent a final update, project partners have opted to keep it open for future follow-up activities and additional data generation, ensuring ongoing relevance and impact beyond the project's conclusion.

The project has successfully met its goals, advancing ORC technology significantly. The development and optimization of various expander types, extensive experimental validations, and collaborative efforts have paved the way for more efficient and flexible small-scale ORC systems. Future efforts will focus on utilizing the data and tools developed during the project for further research and practical applications, ensuring the project's long-term impact on sustainable energy technologies.

# 7. Appendices

Appendix 1 – DEXPAND costs - DEXPAND_budget_spending_2024

Appendix 2 – *dexpand_final_report_full.pdf* - A summary report of the whole project with specific sections on feasibility and parameters mapping (whole report with data and documents present on Github repository: https://github.com/janspale/DEXPAND)