DEXPAND PROJECT RESEARCH REPORT WITH EXPANDER PERFORMANCE AND FEASIBILITY MAPPING

Project partners:	CTU in Prague, NTNU, SINTEF, GT Progres
Project name:	Optimised expanders for small-scale distributed energy systems

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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.

This report presents a standalone work package 5 results (WP5) of performance mapping and feasibility mapping of different types of small-scale ORC expanders. The report is complemented by the data with models, resulting parameters, manufacturing documentation or experimental performance in the repository https://github.com/janspale/DEXPAND.

1 WP5 – Assessment and feasibility mapping

The first result belonging to the feasibility mapping is the cycle design point optimization from WP1, repeated below in Figure 1. 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.

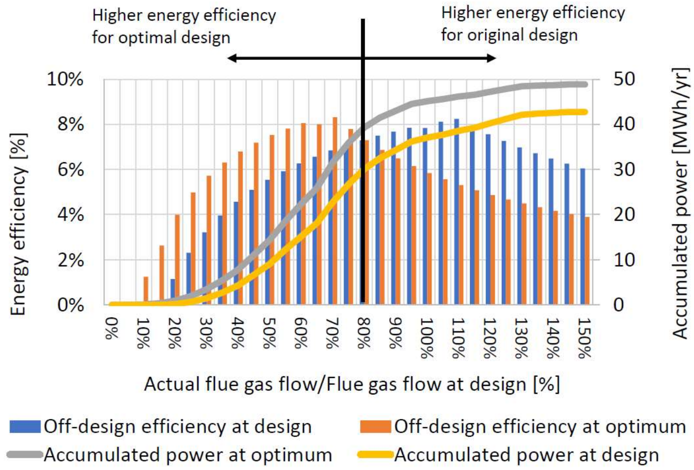

Figure 1. Energy efficiency and accumulated power output for the original and optimized designs based on the reference case study.

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 2 and can betaken as indicative results based on the models informed by engineering limits taken from our experimental experience. The efficiency values are indicative and detailed design may shift them by several (typically no more than 2) percentage points, in case of optimization works also into higher efficiency.

Note that for presented expanders there are several groups of boundary conditions and thus corresponding thermodynamic cycles. All MM expander results correspond to the CTU 120 kWth system design. Isobutane turbines are designed around low PR case of 400/160 kPa of the Expand isobutane test rig. RVE for isobutane at these conditions is, however, not feasible, as it would be prohibitively large and operation at higher pressures and slightly higher pressure ratio (1210/350 kPa) is used. Extensive experience from the RVE experimental design suggest unfeasible operation at expander length above 300 mm (largest RVE we built has 245 mm). Together with a L/D parameter maximal value at 2.5, i.e. stator diameter 120 mm, the results for RVE cannot be extended all the way to the 50 kW and entirely different approach to mechanical design would need to be developed for higher power outputs. RVE and Elektra turbine are considered always operating at 3000 rpm.

The RVE results show that there is a cap of efficiency, clearly depending on the pressure ratio (or even more expansion ratio) with higher values and lower pressure ratios, as well as size. Better pressure ratio and densities for the isobutane parameters result in significantly higher peak efficiency and larger maximal power output. Advantageous for the isobutane RVE efficiency are also relatively smaller leakages per unit of produced power.

However, high-speed turbines, unless we want to exceed extreme speeds, the efficiency drops significantly at small power output systems. The Elektra turbine comes out of our analysis as a possible techno-economic competitor of RVE at power output above about 10 kW. Despite mostly slightly lower efficiency, it enables dry operation and limits a servicing need, which the RVEs have after no more than 10 000 hours.

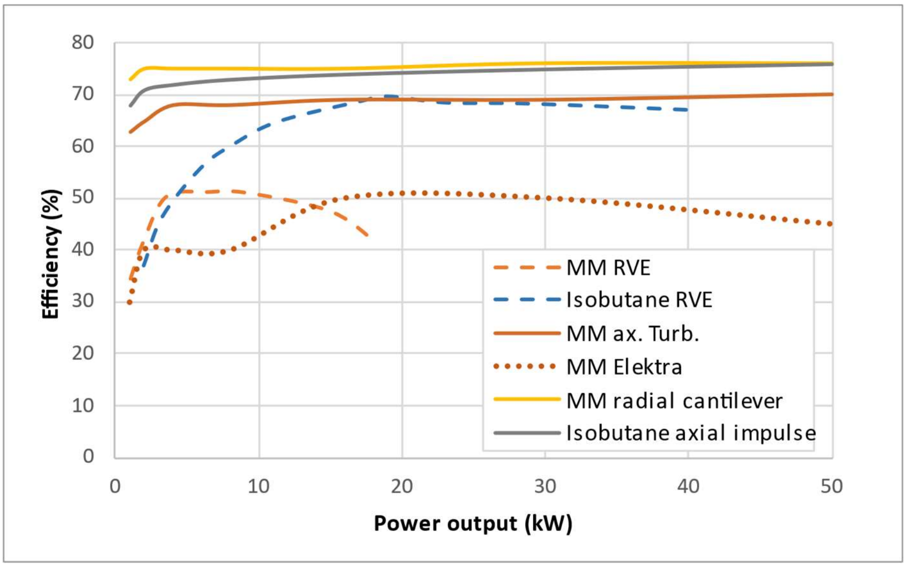

Figure 2. Efficiency mapping for considered expander types (assuming impulse turbines).

Nominal design speed needs to be also considered when selecting the expanders. Figure 3 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.

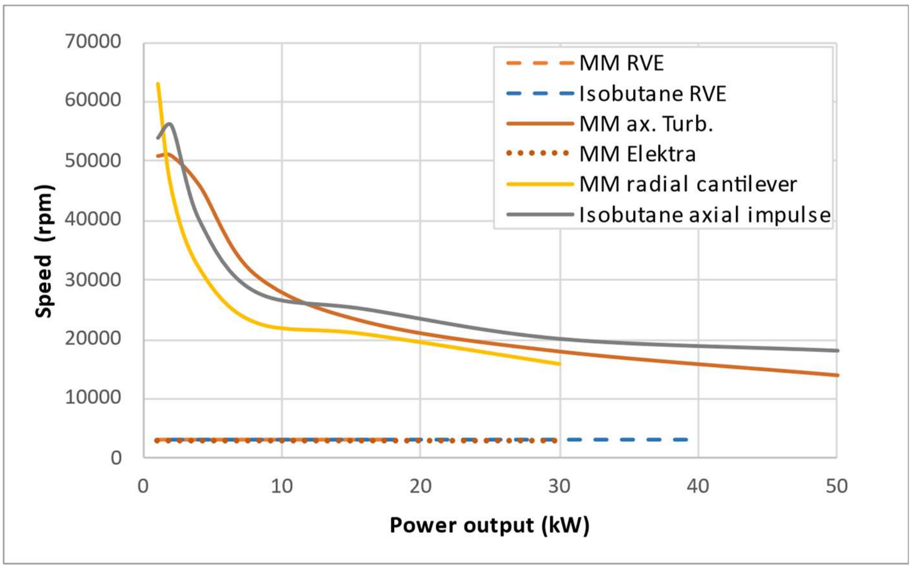

Figure 3. Expander mapping regarding speed for considered expander types.

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 4. 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.

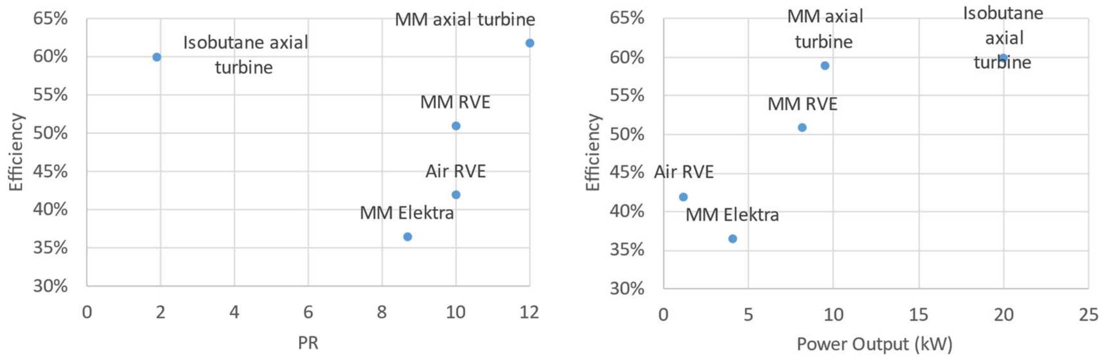

Figure 4. Performance maps of the experimentally explored expanders regarding the PR, power output and efficiency.

Clear disadvantage of the axial turbines is the necessary high speed, documented then in Figure 5. 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.

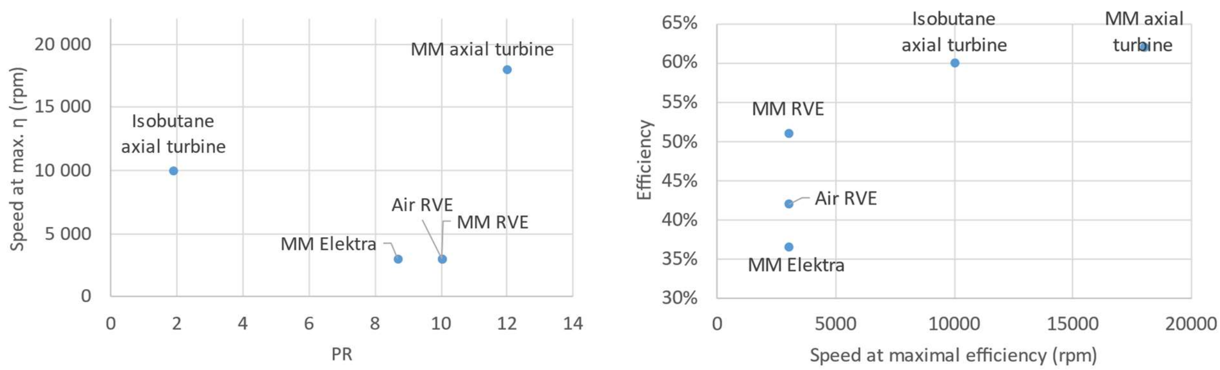

Figure 5. Performance maps of the experimentally explored expanders regarding the PR, nominal speed and efficiency.

In order to complement the technical parameter of speed, Figure 6 shows the rotor diameters of the turbines (eventually stator bore diameter for RVE) for the explored expanders. As expected, diameter must increase, rotational speed decrease with power rating. Furthermore, efficiency increases also with power rating. This effect is most probably underestimated, because the modelling tool does not take into account:

- Reynolds number dependency of friction losses
- Gaps and the corresponding (tip) leakage losses
- Trailing edge thickness and trailing edge losses

All these issues are getting worse if reducing power rating (= smaller turbine). In particular, if partial admission Is necessary (1 kW, 2 kW).

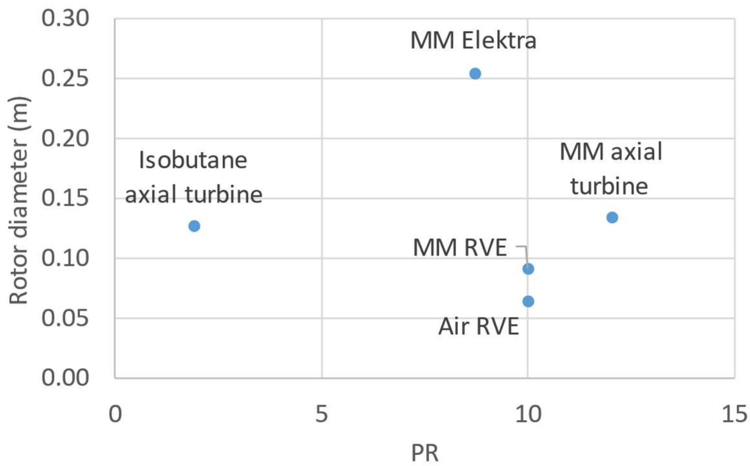

Figure 6. Parameter map of the experimentally explored expanders regarding the PR and rotor (or stator bore for RVE diameter).

As a final result of the mapping are the economic parameters, specifically cost per kW of power output plotted against the efficiency in Figure 7. 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.

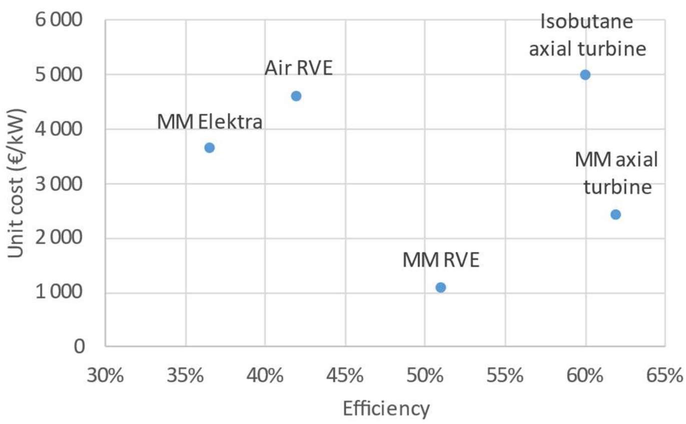

Figure 7. Performance maps of the experimentally explored expanders regarding the PR, nominal speed and efficiency.

For the experimental data for the analysis, please refer to the repository:

https://github.com/janspale/DEXPAND/blob/main/README.md