# A PERSPECTIVE ON COSTS AND COST ESTIMATION TECHNIQUES FOR ORGANIC RANKINE CYCLE SYSTEMS

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## ABSTRACT

The potential of organic Rankine cycle (ORC) systems is acknowledged by both the considerable amount of ongoing research efforts and the increased occurrence of its applications in practice. A large share of research in this field strives to improve ORC systems by analyzing the performance of various cycle architectures and numerous working fluids. These technical feasibility and optimization studies are at the core of ORC development. Yet, when it comes down to considering practical instalments the economic feasibility of the project is often decisive. Complementary to research efforts on these technical issues this paper approaches the matter from an economic point of view. The costs-dimension of ORC systems is discussed from various perspectives. First of all, this paper provides a brief review of literature knowledge on ORC investment costs. Technical publications on ORC development increasingly include estimates of the costs associated with the system design, but knowledge on actual ORC module and project costs remains scarce. Secondly, this paper takes a closer investigation into the methods used to estimate ORC project costs from the bottom up and the expected accuracies associated with these estimates. Finally, these insights are used to estimate the costs of a known ORC system applied for waste heat recovery. The comparison of the estimated and the actual specific investment costs confirms the existence of a wide accuracy range. The purchased equipment costs obtained with the bottom-up estimate diverge from the actual costs by almost 44% and the deviation leads to differing interpretations on the share of equipment items in the total purchased equipment costs. The results of this analysis are not generalizable since only one real-life study is used for comparison. The main conclusion of the paper is to be cautious when interpreting estimated ORC plant costs.

## 1. INTRODUCTION

The interest for organic Rankine cycle (ORC) systems is growing increasingly. The concept of using an organic fluid instead of water dates back from right after the invention of the Rankine cycle in 1859, yet it was not until the 1960s and 1970s that ORC technology got more prominent research attention. By today, ORC systems constitute a flourishing research field and its practical possibilities have been proven. The reasons for this success are manifold. Rankine cycles operate with organic fluids, which allows conversion of energy sources in much lower temperature ranges than suitable for conventional steam cycles. ORCs can generate electricity from energy sources such as geothermal wells, biomass, solar and oceanic sources and industrial waste heat. Hence, ORC systems have potential to generate electricity from renewable energy sources as well as to enhance industrial energy efficiency. Both are essential in the transition of energy sectors to more streamlined, efficient, secure and climate-friendly systems. Research on ORC systems is very technical in nature and includes i.a. architecture design and optimization (e.g. Chen, Goswami, and Stefanakos (2010); Lecompte, Huisseune, van den Broek, Vanslambrouck, and De Paepe (2015)), the quest for suitable working fluids (e.g. Hung (2001); Lakew and Bolland (2010)) and the design of new expander types (e.g.

Declaye, Quoilin, Guillaume, and Lemort (2013)). Technical invention and optimization are a necessary first step in the technological innovation process. The subsequent steps are innovation (where the product goes from lab tests to real applications) and diffusion (gradual adoption by firms). The final degree of utilization may impact energy demand. Innovation processes typically follow an s-shaped figure: adoption occurs gradually in the beginning, then with increasing rapidity until the point of saturation. However, there is no guarantee for an invention to go through the entire innovation process and yield market success, even while interesting. For instance, the rate of technological invention and innovation of energy-efficient technologies is found to correlate with energy price increases. The gradual character of the diffusion process stems from the heterogeneity of (potential) adopters, which have a differing expected return. Those firms expecting the investment to be profitable will adopt first. Over time, more firms will adopt due to technology cost reduction, quality improvements and improved information availability. The adoption of energy-efficient technologies is likewise encouraged by higher energy prices, but decreased by adoption costs. Finally, energy-efficient technology adoption is found to be sensitive to the cost of equipment more than to the expected energy costs. (Jaffe, Newell, & Stavins, 2004) Seeing the importance of the economic perspective in technology development and diffusion, the aim of this paper is to complement the large body of literature on technical aspects with an economic viewpoint on ORC installations. A literature review gives insight in current knowledge on the investment costs of ORC systems (section 2). Section 3 elaborates on bottom-up cost estimation techniques and accuracies. In section 4 the investment costs of an actual ORC project are compared to those obtained from a bottom-up estimate. A final chapter discusses the results and conclusions.

## 2. ORC COSTS: A LITERATURE REVIEW

The body of literature on ORC systems and applications is extensive. The importance of the economic perspective is recognized and increasingly taken along in the engineering studies. At the basis of the economic analysis are the capital costs, particularly important for ORC projects since the annual costs are fairly low. Figure 1 displays the specific investment costs (SIC) estimated for various types of ORC input sources: solar, waste heat recovery (WHR), biomass and geothermal. The references are not included in the figure for clarity, but are included in the reference list. The values in the graph stem from literature and have been adjusted to 2013 Euros to allow for comparison. Geothermal ORC systems are most reported in the larger power output ranges. Figure 2 displays the same values but without the geothermal systems to provide a better view on the other costs. Similarly, Figure 3 limits the graph to smaller size (< 1.2 MW) ORC units. Solar ORC systems appear to be more costly, but most of the other costs are within the 2000 to 4000 €/kW range. Figure 1 suggests lower SIC values for higher power output systems, but additional references would be needed for a more detailed analysis.

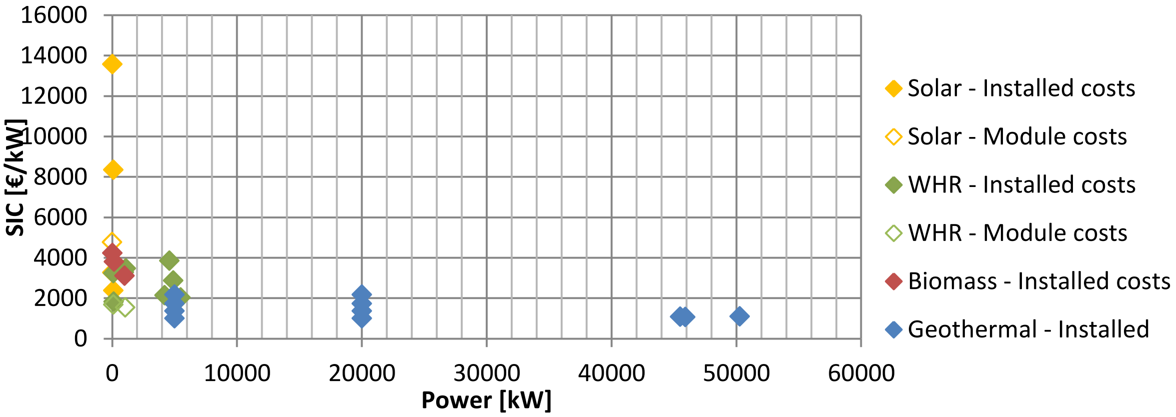

**Figure 1:** ORC costs in literature

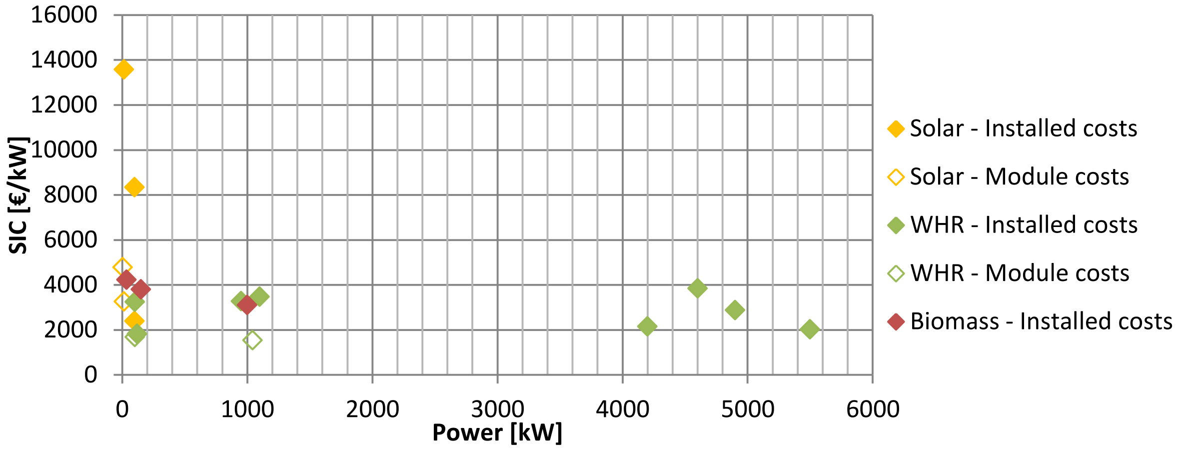

**Figure 2:** ORC costs in literature - without geothermal references

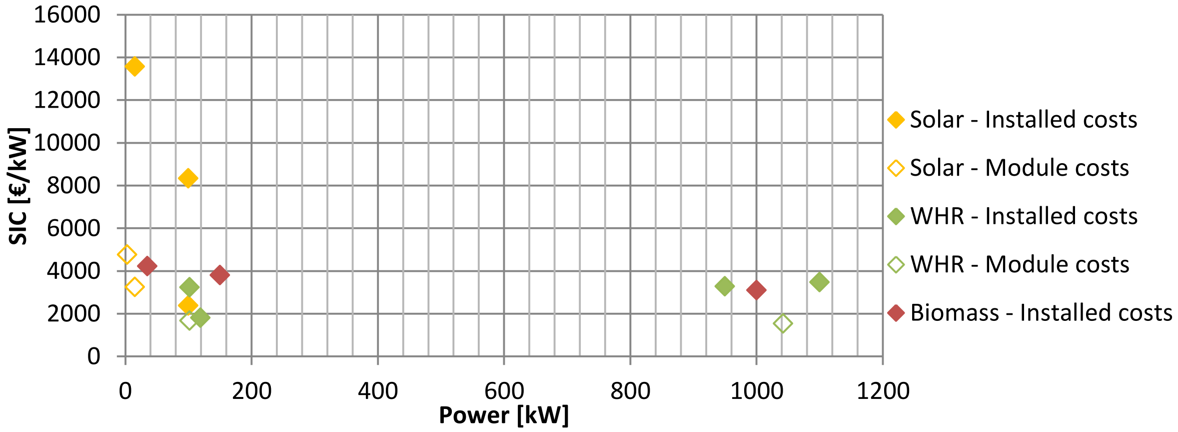

**Figure 3:** ORC costs in literature – small to medium sized

Not all references reporting ORC costs can be included in such summary graphs, e.g. because only SIC values are given and not the power output. For instance, Quoilin et al. (2011) perform a thermo-economic optimization of ORCs for waste heat recovery. They obtain SIC values between 2136 €/kW and 4260 €/kW, depending on the fluid operated, for small scale (< 5 $W_{net}$) systems. An important conclusion from their work is that the operating point yielding maximum power does not coincide with that of minimal SIC. Similarly, Imran et al. (2014) utilize thermo-economic optimization to compare cycle setups. The SIC values are in the range of 3274 to 4155 €/kW for the basic ORC, 3453 to 4571 €/kW for the single stage regenerative ORC and 3739-4960 €/kW for the double stage regenerative ORC, depending on the working fluid operated. Unfortunately no indication was given on the power range. Walraven, Laenen, and D'Haeseleer (2015) investigate air-cooled geothermal ORC systems. No exact specific investment costs numbers are presented, but the impact of various factors, such as brine inlet and outlet temperatures, pressure levels, electricity prices, discount rates and electricity price evolutions, on the economics of the ORC project are demonstrated. Other studies are not included here because the economic values are expressed in €/kWh rather that €/kW, such as in Meinel, Wieland, and Spliethoff (2014) who perform a considerate comparison of architecture designs at various sizes. The results were calculated for heat sources of 0.5 $MW_{th}$, 1 $MW_{th}$ and 5 $MW_{th}$.

The references in Figure 1 all concern estimates of ORC costs rather than reporting of real ORC costs. Real ORC costs are provided by e.g. Leslie et al. (2009) who report the findings of a 5.5 MW ORC system applied for heat recovery from a gas turbine driving a natural gas pipeline compressor. The system was monitored extensively for one year, the capital costs of the system constitute approximately 2500 €/kW. Prices for biomass fuelled ORC systems are published in the range of 4500 €/kW for a 1803 kW system to 10,200 €/kW for a 345 kW system in 2009 (Duvia, Guercio, & Rossi di Schio, 2009).

## 3. COST ESTIMATION FOR ORC PLANTS

The up-front estimation of the costs of a new plant is a challenging task. Capital costs, or capital investment, refer to the one-time costs occurring at the beginning of the project. These total investment costs include the costs directly associated with the system (equipment, materials, labor etc. required for the equipment and the installation thereof), indirect costs (engineering, construction costs and contingencies) and other outlays (such as startup costs, working capital, etc.) (Bejan, Tsatsaronis, & Moran, 1996). The estimate of plant capital costs is a practice iterating as the design evolves to increased detail. Plant estimates are classified according to their level of detail and thus their accuracy (Table 1). The accuracy ranges indicate variations regarding technological complexity of the project, suitable reference information, and an appropriate determination of project contingencies (AACE International, 2005). The ranges represented in Table 1 are applicable for process industry projects (AACE International, 2005). Underestimation of capital costs occurs mainly due to incomplete listing of all the equipment needed in the process (Turton, Bailie, Whiting, Shaeiwitz, & Bhattacharyya, 2013, p. 160). An increasing level of detail implies a smaller accuracy range, but similarly an increasing amount of effort and labor hours to make the estimate. Estimates performed in research are generally order-of-magnitude, study and preliminary design estimates.

**Table 1:** Classification of capital cost estimates (AACE International, 2005; Turton et al., 2013).

| Class | Type of estimate | Description | Accuracy ranges |
|---|---|---|---|
| 5 | Order-of-magnitude estimate<br>(also Ratio / Feasibility) | Based on limited information.<br>Concept screening. | Low: -20% to -50%<br>High: +30% to +100% |
| 4 | Study estimate<br>(also Major Equipment / Factored) | List of major equipment.<br>Project screening, feasibility assessment, concept evaluation, and preliminary budget approval. | Low: -15% to -30%<br>High: +20% to +50% |
| 3 | Preliminary Design estimate<br>(also Scope) | More detailed sizing of equipment.<br>Budget authorization, appropriation, and/or funding. | Low: -10% to -20%<br>High: +10% to +30% |
| 2 | Definitive estimate<br>(also Project Control) | Preliminary specification of all the equipment, utilities, instrumentation, electrical and off-sites.<br>Control or Bid/Tender. | Low: -5% to -15%<br>High: +5% to +20% |
| 1 | Detailed estimate<br>(also Firm / Contractor's) | Complete engineering of process and related off-sites and utilities required.<br>Check Estimate or Bid/Tender. | Low: -3% to -10%<br>High: +3% to +15% |

The equipment needed for construction of the plant is at the core of most cost estimates. The best approach for the purchase cost of a piece of equipment is a current vendor's price quote. Data from previously bought but similar equipment is next best. (Turton et al., 2013) When the costs of a component are known but its capacity differs from that of the to-be-estimated component, the costs can be roughly estimated using the correlation

$$\frac{c_a}{c_b} = \left(\frac{A_a}{A_b}\right)^n \tag{1}$$

where $c$ and $A$ respectively represent the purchase costs and the equipment cost attribute of the required component ($c_a$ and $A_a$) and the known component ($c_b$ and $A_b$) and $n$ is the exponent used to correlate the costs. This exponent $n$ differs per type of equipment, but it is often close to 0.6 for the chemical industry and therefore sometimes referred to as the six-tenths rule. This extrapolation method provides only rough approximations of the actual costs. In case no purchased equipment costs are known, but technical details are available, the costs can be estimated using equipment cost correlations. Guidance, exponents and correlations for various types of process equipment are provided by i.a. Bejan et al. (1996), Couper, Penney, Fair, and Walas (2012), Smith (2005), Towler and Sinnot (2008), Turton et al. (2013).

The total capital investment of a project can be estimated using various techniques. A simple method is to use a capacity exponent ratio, similarly as previously described for equipment costs estimates. The costs of a planned plant are estimated using the known costs of a similar previously constructed plant. The accuracy of this method is rather low. It should be used for order-of-magnitude or study estimates only. (Peters, Timmerhaus, & West, 2004) Step Count methods take a different approach and utilize the number of functional units or plant sections as a basis to estimate total investment costs. This method is designed for use in the chemical process industry and not so suitable for usage in other manufacturing fields. The accuracy would be in the range of order-of-magnitude estimates. (Towler & Sinnot, 2008) Thirdly, factorial estimation techniques are based on the costs of the major purchased equipment items and apply multiplication factors to obtain the total capital investment. The Lang Factor method is probably the first factorial method. Lang suggested to multiply the total delivered costs of the major equipment parts with a factor that differs according to the type of process. The factors are available for solid, fluid and mixed fluid-solid processing chemical plants. (Towler & Sinnot, 2008) The Lang Factor technique utilizes only one multiplication factor and is therefore expected to yield lower accuracies, it is suggested to use for order-of-magnitude estimates (Peters et al., 2004, p. 252). The Lang Factor method has been adapted numerous times since then. For instance, Hand suggested to utilize multiplication factors for the equipment types instead of the plant type. (Towler & Sinnot, 2008) The utilization of multiple factors implies more detail, but this method would probably still not provide very good accuracies. The detail of the estimate can be improved further using cost factors for different items related to direct costs (erection of equipment, piping, electrical, instrumentation and control, buildings and structures, ancillary buildings, storage, utilities, site preparation). Dividing the process into subunits and applying factors per subunit function improves the estimate's accuracy and reliability. (Towler & Sinnot, 2008) An even more detailed estimate is suggested by Guthrie and accounts the installation, piping and instrumentation costs of each equipment item individually. Inclusion of a factor for the equipment materials used would improve accuracy even more. (Towler & Sinnot, 2008) Still, these estimates would remain within the accuracy of preliminary estimates. Another, somewhat different, factorial method calculates the direct fixed costs and total investment costs as percentages of the delivered-equipment costs. The factors used depend i.a. on the process type, design complexity, location, experience. This percentage of delivered-equipment method is suitable for study and preliminary estimates. (Peters et al., 2004) When the goal is to achieve more detailed estimates than the ones formerly described, this requires more detailed information and engineering effort. For instance, the unit cost method is used for preliminary and definitive estimates. The method requires accurate information on costs from previous projects, detailed estimates of equipment prices, installation labor, instrumentation, electrical and other miscellaneous items. Also engineering hours, drawing efforts, construction, contractor's fee and contingencies are included. This can yield relatively accurate results but requires sufficiently detailed information and engineering time. (Peters et al., 2004) Detailed item estimates, with high accuracies, generally concern advanced project plans. At this stage most details of the project are known, the drawings are finished and the estimates are based preferably on delivered quotations. For most research and development projects, both definitive and detailed cost estimates would range beyond the scope of the project and the information available. Preliminary estimates are feasible, but the accuracy of the results relies strongly on the quality of the information (i.a. factors) used.

Finally, the costs of materials and labor are subject to inflation which implies cost figures from different years are not directly comparable. The most straightforward manner to update historical data is by means of composite cost indices, using equation

$$c_j = c_i * \left(\frac{I_j}{I_i}\right) \tag{2}$$

where $c_j$ and $c_i$ refer to the costs in year $j$ and $i$ respectively, and $I_j$ and $I_i$ are the cost indices for the respective years. These composite indices are a weighted average index of various components costs commonly used in a particular industry. Updating cost data using cost indices is acceptable for only shorter periods of time, some say four to five years (Jelen & Black, 1983, p. 339). The accuracy of the results decreases when longer time periods are used.

## 4. A NUMERICAL EXAMPLE

To demonstrate the precarious exercise of bottom-up cost estimation for ORC-plants, this paper compares the costs of an actual case study with the costs obtained from a rough bottom-up estimate. The case study concerns a waste heat recovery ORC installation. The heat source is a low-medium temperature (range 150 – 250°C) flue gas stream from an industrial plant. The ORC system was integrated into the plant using an intermediate thermal oil circuit including a flue gas heat exchanger. The ORC itself has a gross power output of 375 kW and is composed of a centrifugal pump, a one-step radial expander and a generator. The evaporator is a plate heat exchanger and condensation occurs air-cooled. The project has a SIC of 4216 €/kWgross, including installation (in 2013). The partitioning of the costs for this project (Figure 4) demonstrates a major share stems from the ORC unit itself, including pump, expander and generator. The intermediate thermal oil circuit represents about 11% of total investment costs.

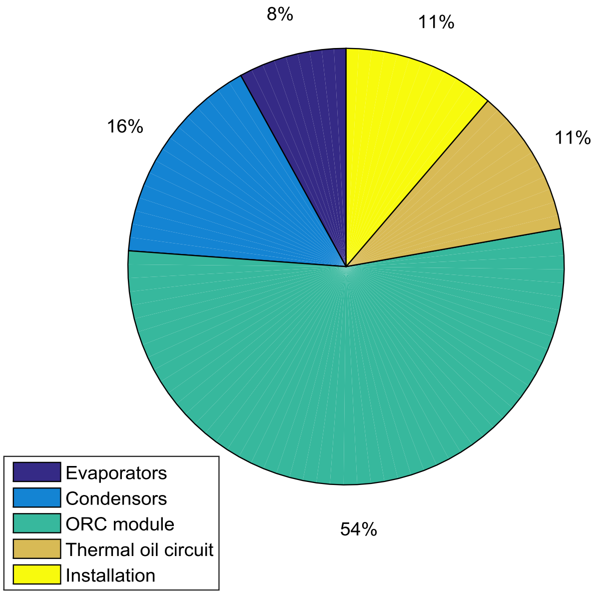

**Figure 4:** Diagram of the real ORC project costs

Knowing most technical details of the real plant, a rough bottom-up cost estimation was performed using the module costing technique. The module costing technique is a commonly used factorial cost estimation method based on the approach of Guthrie. (Turton et al., 2013). This technique is suitable for preliminary estimates in the range of -20% to +30% accuracy. The costs of the major purchased equipment parts are estimated using available correlations. These base costs are multiplied with the bare module cost factor, that accounts for operating pressures and specific materials of construction, as well as direct and indirect project expenses. This yields the bare module costs. To obtain the total module costs, estimated for integration of the plant into an existing facility, the bare module costs are adapted with another multiplication factor. (Turton et al., 2013) All estimates are converted to 2013 Euros to allow for comparison with the real system. The cost correlations published in Turton et al. (2013) are utilized to estimate most purchased equipment costs, the correlation by Smith (2005) for estimation of the fan costs and the generator costs stem from the correlation given by Toffolo, Lazzaretto, Manente, and Paci (2014). The results obtained from Turton et al. (2013) are in $\mathrm{USD}_{2001}$, they are converted to EUR using a 1.1162 exchange rate (average 2001) and updated to 2013 using the Chemical Engineering Plant Cost Index (CEPCI), with $\mathrm{CEPCI}_{2001}$ and $\mathrm{CEPCI}_{2013}$ values of 397 and 587.3 respectively. Results obtained from Smith (2005) are converted from $\mathrm{USD}_{\mathrm{Jan},2000}$ to $\mathrm{EUR}_{2013}$

using an exchange rate of 0.9857 (average Jan 2000) and $CEPCI_{2000}$ equal to 394.1. The correlation from Toffolo et al. (2014) was first published in 1993, so a $CEPCI_{1993}$ of 359.2 was used.

In case only the essential ORC components are considered, and the thermal oil circuit is not accounted for, the estimate yields a result of 1843 €/kW for the purchased equipment costs. In the module costing technique, the purchased equipment costs are used to estimate the total plant costs. An intermediate step is the calculation of the bare module costs. These costs include the direct (equipment, installation materials and labor) and indirect (freight, insurance, taxes, overhead and engineering expenses) costs associated with the project. Accounting for these expenses additional to the purchased equipment costs yields a bare module cost of 4390 €/kW. Finally, the total module costs include also contingencies and contractor fees and auxiliary facilities and are estimated at 5180 €/kW. Note that these estimated costs do not yet include the costs of the thermal oil circuit. Simply adding the costs of the thermal oil system (real costs, not estimated) gives a total module cost of 5642 €/kW. The costs of the thermal oil system are taken as such and not manipulated with bare module or total module factors. Manipulation of the costs for the thermal oil system with a bare module factor of 1.5 and a 1.18 multiplication factor to obtain the total module costs would give a SIC of 5997 €/kW. The bare module factor given for this latter estimate was not given by any reference but expected in line with other bare module factors, a 1.5 factor seems not unreasonable knowing the amount of piping involved with the installation of the system.

Figure 5 displays the real (a) and the estimated (b) purchased equipment costs of the components of the ORC system, excluding installation and thermal oil circuit. The partitioning of purchased equipment costs differs strongly from that of the actual costs. Whereas the evaporators constitute only 10% of purchased equipment costs in reality, the cost estimation leads to a 45% share. The ORC module (expander, generator and pump) represents 69% of actual purchased equipment costs but is estimated at 47%.

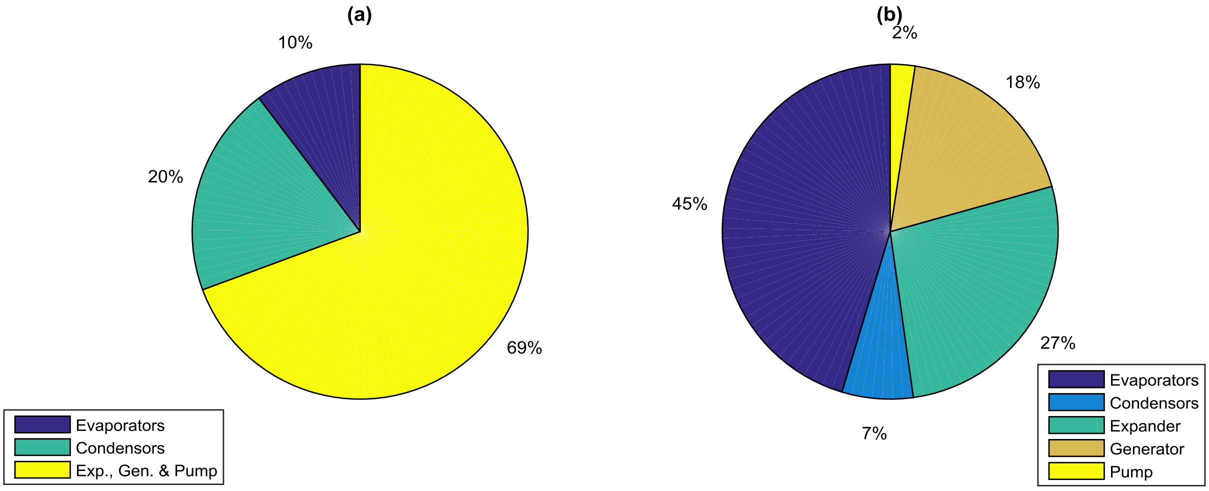

**Figure 5:** Real (a) and estimated (b) purchased equipment costs

The estimated PEC of 1843 €/kW is significantly lower than the actual PEC of 3280 €/kW (-44 %). If the total module costs are estimated, including the thermal oil circuit but with no adaption of the real costs of the thermal oil system, the obtained costs (5642 €/kW) are 34% higher than the actual total project costs (4216 €/kW). If the thermal oil circuit is included and adapted with bare and total module factors, the estimated cost (5997 €/kW) is even higher and deviates more from the actual costs.

## 5. DISCUSSION AND CONCLUSIONS

The aim of this paper is to give insight into ORC systems from an economic point of view. Technical invention and innovation are key for evolution to more streamlined and renewables-based energy sectors, but the adoption and diffusion processes of innovative technologies are strongly influenced by economic factors. There is still not much published information about the actual costs of ORC systems. A brief review of literature knowledge on the investment costs of ORC modules and ORC projects reveals most are in the 2000 – 4000 €/kW range. Geothermal projects tend to be larger with lower SIC values, solar projects are mostly small and can have very high specific investment costs. An increasing number of references utilize thermo-economic and techno-economic optimization techniques and apply bottom-up estimation techniques to estimate the costs of ORC modules or projects. Component cost estimates can simply be made using scale exponent methods, more detailed estimates use factorial estimation techniques. In any bottom-up estimate it is important to consider the expected accuracy range. Simpler methods require less effort but yield lower accuracy. High accuracies are possible making definitive and detailed estimates, but these require a level of plant detail which is commonly not achieved in research estimates. The precariousness of using factorial techniques to approach real plant costs is demonstrated and confirmed for an existing ORC applied for waste heat recovery. The estimated specific purchased equipment costs deviate from the actual project costs by almost 44%. The purchased equipment costs distribution differs largely between the actual and the estimated costs of the components. There are many potential reasons for this deviation. First of all, factorial estimation methods are suitable for preliminary estimates. A deviation of -20% to +30% is therefore not uncommon. The accuracy of factorial estimation methods depends strongly on the quality of the information that was used to establish the multiplication factors. Additional inaccuracies and uncertainties may stem from treatment of costs over time periods. Extrapolation of costs over large periods of time decreases the accuracy of the results. Most of the open-source correlations available in text books are at least nine years old and thus provide less accurate results. Additionally, some of these references refer back to original factors and correlations published in by Guthrie in 1969 or 1974 and updated with few recent data points or using cost indices. This makes these correlations less reliable. Finally, also the choice of indicator for cost escalation and local conditions may have an influence and create additional deviations. This implies that results in such settings should not be interpreted as final, but rather as giving an idea on the expected range of investment costs. This type of estimate can be useful to mutually compare various system designs, where the proportional comparison is more important than the exact outcomes. Finally, it is important to take the difference between costs and prices into consideration in this type of studies. Costs reflect the amount that is required to produce a certain item, the price is the amount you pay to purchase it. The costs associated with producing an ORC system will thus differ from the price paid to acquire that system. Many correlations used to estimate costs are obtained using vendor prices. In case the ORC developer would purchase most equipment instead of developing it this is not a problem. For innovative system designs (e.g. expanders) this method would be less suitable. The main conclusion from this study is to be careful when interpreting results obtained from preliminary bottom-up cost estimates. This is also the case for the results obtained from the estimates in this study. The results confirm a wide accuracy range. Rather than being used as exact results, these estimates could give guidance when comparing several alternatives, estimated with the same method.

## NOMENCLATURE

| | | |
|---|---|---|
| $A$ | equipment cost attribute | |
| $c$ | cost of component | (€) |
| CEPCI | Chemical Engineering Plant Cost Index | |
| ORC | organic Rankine cycle | |
| $n$ | exponent for cost correlation | |
| SIC | specific investment costs | (€/kW) |
| WHR | waste heat recovery | |

**Subscript**

| | |
|---|---|
| $a$ | required component |
| $b$ | known component |
| $i$ | year i |
| $j$ | year j |

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