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A review of hydraulic energy harvester designs – current practice and future improvements

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Abstract

This paper addresses the underexplored domain of hydraulic energy harvesters (HEH). Through a literature review, existing designs are identified, aiding in the categorisation of energy conversion technologies and fluid-mechanical interfaces. Recognizing a lack of standardized approaches to testing HEH, the paper proposes a re-configurable test platform. The platform, accommodating diverse configurations, operates at high pressures, aligns with existing hydraulic setups, and functions in static or dynamic modes. This tool aims to assist researchers further explore the implementation of HEHs.

Keywords: energy efficiency, energy harvester, prototyping, design review

1. Introduction

As the pursuit of sustainable energy solutions intensifies, energy harvesters have begun to garner increasing interest. Their ability to capture and convert otherwise unused and wasted ambient energy into electricity has piqued interest as an alternative to other, often more costly, efficiency measures (Alvarado *et al.*, 2012; Nechibvute *et al.*, 2012; Wang *et al.*, 2018). By generating power from otherwise wasted energy, energy harvesters align with environmental sustainability targets, contributing to reducing the reliance on traditional energy sources, lowering carbon footprints.

Energy harvesting is already making strides in a limited capacity across various applications. The Internet of Things (IoT) (Bakytbekov *et al.*, 2020), wearable electronics (Wang *et al.*, 2018), and passive monitoring of structures (Citroni *et al.*, 2019) represent key domains where energy harvesting has found practical use. However, the widespread adoption of energy harvesting faces challenges, prominently driven by the inherently low power generated by these systems. This limiting factor, in turn, impedes its application in scenarios where the demand for power is higher, such as in industrial settings or the deployment of Industry 4.0.

Industry 4.0 involves the integration and utilization of IoT to enhance industrial processes (Negri et al., 2017; Zhou et al., 2015). A continuous stream of data from sensors along a production line is required to allow for prompt responses to changing scenarios, be it through the use of a digital twin or other analytical models. Energy harvesting offers a solution in the context of IoT sensor deployment, where sensors can be strategically placed and powered without the need for cumbersome batteries, which periodically need charging and replacing contributing to e-waste. It can also facilitate sensor placement in remote locations thereby streamlining the implementation of Industry 4.0 initiatives.

The benefits of energy harvesting are amplified by the potential application towards monitoring of hydraulic systems. Vibrations and pressure variations occur in these systems during regular operation; providing an ideal environment for energy harvesting, and the need for continuous monitoring in hydraulic applications makes energy harvesters a natural fit for this domain. In essence, the convergence of energy harvesting and hydraulic systems holds promise for addressing the challenges posed by implementation costs and power limitations, fostering advancements in Industry 4.0 and beyond.

This paper therefore aims to provide an overview of existing designs for energy harvester applications evaluating their suitability for hydraulic systems and proposing a modular test platform that will empower researchers to test novel hydraulic energy harvester designs. To do so the paper is structured as follows: first a review of the literature (section 2) provides an overview of existing designs used to recover energy from hydraulic systems. The section additionally provides an analysis of existing designs. Thereafter (section 3) provides the details of a modular hydraulic test platform aimed at aiding researchers in exploring different hydraulic energy harvester designs and setups. The findings are discussed (section 4) to provide an overview of the implications of the analysis as well as the benefits of the test platform. Lastly, the paper concludes (section 5) with a summation of the findings as well as suggestions for future exploration for the improvement of energy harvesters.

2. Literature review

This section provides an analysis of existing work in the field of energy harvesters to lay the foundation of the analysis of said harvesters for hydraulic energy recovery, beginning with an overview of current energy harvester implementations. The section continues by cataloguing energy harvester designs. Finally, the section provides an overview of existing barriers to energy harvester adoption, with a specific focus on the challenges encountered in their application to hydraulic systems. This approach aims to provide an understanding of the current state of energy harvester applications and sets the stage for the subsequent analysis.

2.1. Existing energy harvester designs

An analysis of Scopus was performed to collect information on existing designs of energy harvesters. A search for documents containing the term "Energy Harvester*" anywhere in the text returned a total of 48,522 documents, the oldest one published in 1982. As such it was necessary to restrict the search parameters in order to perform a more detailed analysis of the designs of harvesters. The following search parameters were used to narrow down the search:

> (((ALL ("Energy Harvester*") AND AUTHKEY (pressure)) AND PUBYEAR > 2017 AND PUBYEAR < 2025)) AND (hydraulic) AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "re")) AND (LIMIT-TO (EXACTKEYWORD , "Energy Harvesting") OR LIMIT-TO (EXACTKEYWORD , "Energy Harvester")) AND (LIMIT-TO (LANGUAGE , "English"))

The search performed looked at any documents containing the term "Energy Harvester*" (where the asterisk represents an unknown letter i.e.: 's') anywhere within its text. Of these documents, only the ones with at least one author or publication specified keywords (viz.: Pressure, Hydraulic, Energy Harvesting, and Energy Harvester) were selected. Additionally, the search specifies that only documents published between 2017 and 2025 are to be included, in order to allow for the analysis to be reflective of current energy harvester design. Lastly, the search limits the types of documents to be returned to only journal, conference, or review papers that were published at the time of the search in English.

This narrowed the results found to twelve papers. One interesting finding of the search performed is how limited the research into the development of hydraulic energy harvesters is. Performing the exact same search while omitting the requirement for the keywords "Pressure" and "Hydraulic" returned 12,465 documents, over a thousand times the number of search results for papers pertaining to hydraulic energy recovery. The titles and authors of each of the papers found in the search for hydraulic energy recovery are listed in Table 1.

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Table 1. List of recent papers pertaining to hydraulic energy recovery. Asterisk denotes the presence of a force amplifier

Nr	Title	Authors	Energy conversion technology (ECT)	Fluid-mechanical interface (FMI)
1	Design, simulation and experiment for a piezoelectric energy harvester based on fluid pressure pulsation in water hydraulic system	(Shi, Yang, et al., 2023)	Piezoelectric (PE) Disk	Flexible Diaphragm
2	Experimental and simulation study of a hydraulic piezoelectric energy harvester under different connection modes	(Shi, Chen, et al., 2023)	PE Disk	Flexible Diaphragm
3	Design and Experimental Investigation of a Novel Piezoelectric Energy Harvester in Pneumatic System	(Yang et al., 2022)	PE Disk	Direct Action
4	Hydraulic Pressure Ripple Energy Harvesting: Structures, Materials, and Applications	(Xiao et al., 2022)	PE Stack & Triboelectric	Flexible Diaphragm & Piston *
5	Self-powered wireless sensor using a pressure fluctuation energy harvester	(Aranda et al., 2021)	PE Stack	Piston *
6	Modelling of the circular edge-clamped interface of a hydraulic pressure energy harvester to determine power, efficiency and bandwidth	(Xiao et al., 2021)	PE Stack	Flexible Diaphragm
7	Design and performance enhancement of a force-amplified piezoelectric stack energy harvester under pressure fluctuations in hydraulic pipeline systems	(Cao et al., 2020)	PE Stack	Flexible Diaphragm *
8	Simulation and theoretical Analyses of the Impact of Velocity, Pressure and Kinetic Energy during Damping in a Shock absorber	(Sob and Pita, 2020)	No technology/design proposed	No technology/design proposed
9	A space-coiling resonator for improved energy harvesting in fluid power systems	(Lechuga Aranda et al., 2019)	PE Stack	Piston *
10	Modelling and experimental validation of a controllable energy harvester for pressure regulation	(Ko et al., 2019)	Alternator	Turbine
11	An Apparatus for the Performance Estimation of Pressure Fluctuation Energy Harvesters	(Aranda et al., 2018)	PE Stack	Piston
12	Development and modeling [sic] of an electromagnetic energy harvester from pressure fluctuations	(Ren and Wang, 2018)	FPLG	Direct Action

There are a number of salient observations to be made on the on the papers listed in Table 1, namely:

- (Sob and Pita, 2020): This paper primarily theorized about an application without presenting an actual energy harvester design. It lacks detailed information on how an energy harvester could be constructed to meet their use case, rendering it less useful for the analysis.
- (Yang *et al.*, 2022) and (Ren and Wang, 2018): While these papers were aimed at pneumatics rather than hydraulics, their discussions on energy harvesters are intriguing as both their energy harvesters could be reconfigured to function in a hydraulic setting.
- (Xiao et al., 2022): This was a review paper that provided an insightful overview of various energy harvester designs currently in use. It proved helpful in identifying designs that might not have been found in the literature review performed in this paper, offering valuable reference points for further analysis. When the design was found through Xiao et al. (2022) they are cited, otherwise the original source is used.
- (Aranda et al., 2018): This paper focused on the design of a test rig for testing energy harvesters rather than presenting a design for an energy harvester itself. While not directly contributing to the collection of energy harvester designs, it highlights the importance of developing standardized testing methodologies.

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In addition to the points above, which related directly to the papers found as part of the literature analysis performed as part of this paper, two key observations were made. These observations pertain predominantly to the overall state of adoption of hydraulic energy harvesters and the literature which surrounds the design and implementation of energy harvesters in hydraulic applications. These are:

- That, despite the considerable body of research on energy harvesting in general, information related to energy harvesting for hydraulic systems specifically is notably limited. The scarcity of research in this specific domain underscores the need for further exploration and development.
- Additionally, at present, there are no established best practices or methodologies for designing energy harvesters for hydraulic applications, integrating existing energy harvesters into hydraulic systems, or conducting tests on these energy harvesters. The lack of standardized approaches poses a challenge for the advancement and widespread adoption of hydraulic energy harvesters.

This analysis sets the stage for the subsequent sections, where the identified energy harvester designs will be further evaluated, and potential improvements and recommendations will be explored.

2.2. Analysis of existing designs

The papers listed in Table 1 were analysed to provide an overview of existing hydraulic energy harvesters. Five distinct energy conversion technologies (ECTs) and four fluid-mechanical interfaces (FMIs) were identified across all the papers analysed and shown in Table 1. Table 2 attempts to summarise the power density of the technologies within each of the papers as well as their operating principle and the general size of the ECT. Of the five ECTs used to transform changes in hydraulic pressure into other forms of energy, piezoelectric (PE) disks and stacks are the most popular approaches, being used in three and five of the papers respectively. The edge in popularity of PE stacks over disks is likely linked to their ability to generate more energy for the same deflection as highlighted by the power density values in Table 2. In contrast, triboelectric, alternators, and Free Piston Linear Generators (FPLG) only appear once each. The pervasiveness of PE based systems for energy recovery can likely be associated both to the ease with which they can be implemented and the relative maturity of the technology. Indeed, triboelectric setups, when applied to energy recovery, are a novel approach that is still being investigated (Chittibabu *et al.*, 2022; Fan *et al.*, 2012; Xiao *et al.*, 2022). Alternators and FPLG's are even more esoteric approaches to the harvesting of energy (Ko *et al.*, 2019; Ren and Wang, 2018) and indeed their adoption seems limited. This can likely be linked to either the complexity of including a turbine and attaching it to an alternator (as in Ko et al. (2019)) while minimally disrupting the flow of hydraulic fluid; this requires precision machined parts made bespoke for the hydraulic system. In addition, as highlighted in Table 2 it is difficult to present a fair comparison between alternators and the other technologies due to them being inextricably linked to a turbine and to the vast difference in the size and scale of the technology. Similarly, there are drawbacks to the use of an FPLG (as described by Ren and Wang (2018)). For example, it is necessary to build and calibrate and FPLG for the specific hydraulic circuit (to guarantee it will function with the circuit's operating pressures and flow rates). Additionally, there are risks if the piston is allowed to travel further than the designed stroke length by prolonged flow in one direction as this can cause damage when the piston hits the casing. This is in contrast to piezo- and tribo-electric approaches, which can be implemented with off the shelf components.

Table 2. ECT parameter overview based on papers from Table 1

ECT	Operating Principles	Power Density Range μW/mm³	Size
PE stack	Compression and decompression	0.11 - 19.39	5mm × 5mm × 9mm - 6.8mm × 6.8mm × 30mm
PE disk	Deflection (compression and decompression)	1.34 - 8.06	φ25 × 0.2 mm³
Triboelectric	Deflection (internal friction) (Fan et al., 2012)	10.4 (Fan et al., 2012)	0.345mm×45mm×12 mm
Alternator	Rotation	Not available in source. Only peak power output: 100w	Not available in source. Only diameter: 152.4mm
FPLG	Reciprocation	0.145	φ21 × 40 mm³

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In addition to the ECTs used in each paper, Table 1 highlights the FMIs used to convert the hydraulic pressure into mechanical force for actuating the energy converter. The four identified FMIs are:

- Flexible Diaphragms: Here the hydraulic pressure forces a thin flexible piece of material, often a polymer or shim steel, to flex. The energy converter is placed against the diaphragm.
- Direct Action: In this type of FMI the hydraulic fluid acts directly on the energy converter, exerting mechanical force without any intermediary.
- Pistons: Here a solid cylinder constrained within a bore moves to convert the hydraulic pressure.
- Turbines: A device that turns the hydraulic fluid's flow into rotational motion.

It should be noted that, despite using a FPLG the design proposed by Ren and Wang (2018) was categorised as a direct action type as the piston in the FPLG is considered to be an integral part of the energy converter itself, rather than a means to convert pressure into mechanical force which then acts on the energy harvester. It is also interesting to note that various authors chose to include a force amplifier within their design, these took different forms depending on the type of FMI but were all aimed at increasing the energy output from the energy harvester.

As shown in Table 3, it appears the most popular FMI/ECT combination is the piston with the PE stack. Pistons can operate at a wide range of pressures, limited mostly by the effectiveness of their seals (Aranda et al., 2018). However, the installation of a piston requires a corresponding bore to be machined. This adds complexity and cost to the installation. Additionally, the seals require periodic maintenance to guarantee their integrity, adding an additional point of failure and making them less suitable for applications where maintenance cannot be performed regularly.

The flexible diaphragm, in combination with multiple ECTs, was the most common FMI (Table 3). This is likely due to the ease with which they can be made and implemented. Additionally, when working at lower pressures, it is possible to utilise polymer diaphragms with lower Young's moduli, which improves the efficiency of the transfer of energy from the fluid to the energy converter (Kottapalli *et al.*, 2019; Shi, Yang, et al., 2023; Xiao *et al.*, 2021).

Diaphragms capable of operating at high pressures are possible (Skow *et al.*, 2014); this is achieved by stiffening the diaphragm. This, however, results in a reduction of the diaphragm's ability to transmit mechanical force when operating at lower pressures. This limits the use of flexible diaphragms to a preestablished and limited range of pressures.

The direct action approach presents another interesting FMI; allowing the hydraulic fluid to act directly on the energy converter. It relies entirely on the strength of the energy converter to contain the fluid within the hydraulic system. Maintaining the seal so as to avoid leakage as well as guaranteeing that the energy converter is never stressed until failure present the largest challenges to this approach.

The use of turbines as an FMI presents multiple challenges. Hydraulic systems, characterized by variable and intermittent fluid flows rates, pressures, and flow directions, present challenges for turbines, which perform optimally under steady conditions. The mechanical complexity of turbines further complicates maintenance. It is likely for this reason that the use of turbines was seen in only one of the analysed papers.

Table 3. Categorisation of FMIs from papers from Table 1

	PE Disk	PE Stack	Triboelectric	Alternator	FPLG
Flexible Diaphragm	2	3	1	0	0
Direct Action	1	0	0	0	1
Piston	0	4	1	0	0
Turbine	0	0	0	1	0

3. Proposed test platform

The analysis of the literature revealed a notable gap: while a substantial body of knowledge exists with regards to energy harvesters, their integration into hydraulic systems remains relatively unexplored. The absence of established best practices or widely accepted methodologies underscores the nascent stage of this field. Determining an optimal design for a hydraulic energy harvester is challenging as each

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method comes with its set of compromises, particularly concerning FMIs. The lack of a standardized methodology impedes the identification of the most effective technologies.
In response to this gap, this paper introduces a novel re-configurable test platform, aimed at supporting researchers in testing energy converter technologies, novel hydraulic sensors (e.g.: for pressure and flow), and FMIs. The goal is to provide a controlled environment that facilitates systematic experimentation, enabling researchers to assess the performance, advantages, and limitations of different approaches. By doing so, the proposed test platform aims to contribute to the establishment of benchmarks, aiding researchers in making informed decisions about the most suitable technologies for their specific hydraulic energy harvesting applications.
The design of the test platform aligns with the technologies and FMIs identified in Table 3. By covering the most common combinations of ECT and FMIs, the test platform aims to allow researchers to explore a wide spectrum of possibilities in the realm of hydraulic energy harvesting. This approach lays the foundation for a more systematic and comparative analysis, offering insights that can drive advancements in the field and contribute to the eventual establishment of standardized methodologies and best practices.

3.1. Test platform development

As shown in Table 3, the most common types of FMIs are the diaphragm and the piston with six and five citations respectively and as such the test platform will focus primarily on enabling researchers to explore the potential afforded by these technologies. Similarly, the most common ECT was the PE stack, followed by the PE disk, and the triboelectric. As the PE stack is so dominant in the literature, the design of the test platform will focus primarily on enabling researchers with exploring its implementation. The ability to explore other technologies will be considered a useful, if secondary, addition. Additional criteria for the platform are listed in Table 4.

Table 4. Test platform development specifications

	Criteria	Must/Wish	Target Value/Range
1	Accommodate diaphragm FMIs	Must	0.01-5mm thickness diaphragm
2	Accommodate piston FMIs	Must	10-50g piston weight
3	Accommodate PE Stacks	Must	2x 2.5x5mm-5x5x20mm PE stack size
4	Operational safety	Must	Safe at pressures 33% higher than operating pressure
5	Easy to integrate	Must	2 points for hydraulic connection: input and output.
6	Simple FMI replacement	Must	Single tool needed. Task complete in under 5min
7	Simple ECT replacement	Must	Single tool needed. Task complete in under 5min
8	Accommodate other ECTs	Wish	Be able to integrate PE disk (or other ECT)
9	Low service requirements	Wish	2 year regular service interval
10	Wide pressure range	Wish	Operating pressure of 100 bar max

3.2. Test platform design

The platform was designed using established design knowledge, predominately based on mathematical analysis of the components to guarantee that they would meet the criteria laid out in Table 4. Additionally, the expertise of technical and manufacturing staff was sought out to verify the manufacturability and safety of the test platform was in line with established standards.
The proposed re-configurable platform is shown in Figure 1a and Figure 1b. As can be seen from the figures, the platform consists of a hydraulic block with an inlet and outlet channel which allows the unimpeded flow of hydraulic fluid. A dedicated tube leads hydraulic fluid away from this channel and towards a cavity where the ECT can be housed. In the example shown in Figure 1a and Figure 1b, a collet is used to ensure a PE stack is held firmly against either the diaphragm plate or the piston. However, the space within the expansion cavity is sufficiently large to accommodate other FMIs, e.g. PE disks.

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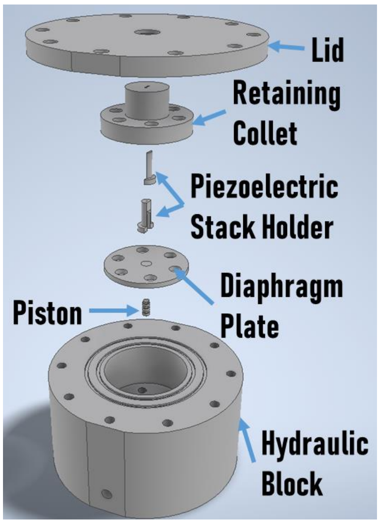
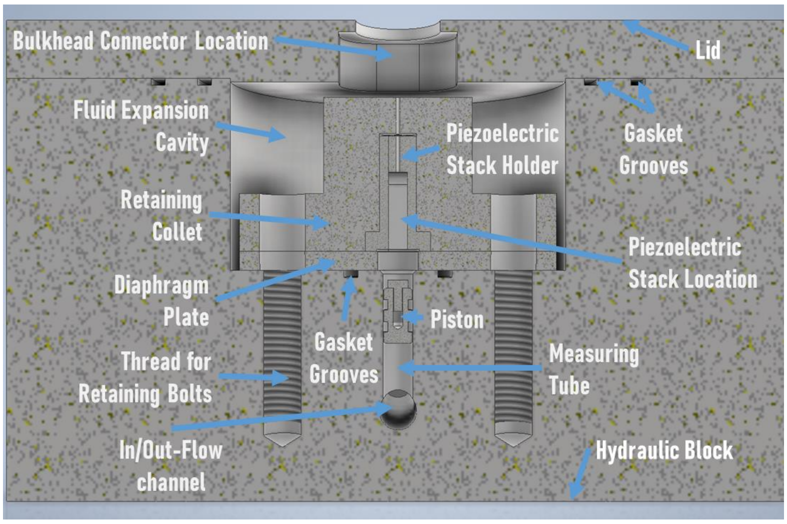
The advantage of this platform lies with its reconfigurability. The measuring tube is designed to accept a removable piston. By using the thread cut into the piston, it is possible to remove it allowing the fluid to press directly on the energy converter or on an optional diaphragm plate. The modularity and ease of assembly allow for diaphragm plates with differing diaphragm thicknesses to be experimented with, without having to adjust the setup of the other components. Additionally, the test platform is designed to allow testing at high pressure ranges, the use of double seals and an expansion cavity to capture potential leaks are all aimed at improving the safety of the platform when in experimental use.



(a) Test platform exploded view showing all major components



(b) A cross section of the test platform with all the components in their respective places

Figure 1. Exploded (a) and cross section (b) views of the platform

The re-configurable test platform presented in this section offers a versatile framework for researchers to explore various configurations in both energy converter types and FMIs. Its adaptability is a key strength, allowing for the accommodation of different ECTs, such as PE stacks, disks, or triboelectric setups. All these technologies can be installed within the fluid expansion cavity and the retaining collet modified or exchanged to suit the energy recovery technology being investigated. For example, if wanting to investigate a PE disk, it would be possible to remove the PE stack holder and clamp the disk using the retaining collet alone against either the diaphragm plate or the piston. Simultaneously, the modularity of the platform facilitates the testing of distinct FMIs, enabling researchers to experiment with diverse configurations to better understand the associated trade-offs.

Importantly, the test platform is designed to withstand high pressures, ensuring that experiments can be conducted under conditions representative of real-world hydraulic systems. This capability is crucial for assessing the performance and reliability of energy harvesters in scenarios where hydraulic pressures are substantial, such as in industrial applications.

Furthermore, the versatility of the platform extends to its compatibility with existing hydraulic setups. The design allows the platform to seamlessly integrate into various hydraulic systems, offering researchers the flexibility to conduct experiments in line with their specific applications. The platform can be operated under a combination of static and dynamic pressure conditions, depending on the hydraulic circuit configuration. This adaptability is paramount for researchers seeking to replicate and assess the performance of energy harvesters in different operational scenarios, ensuring a comprehensive understanding of their potential applications. The re-configurable test platform introduced in this section serves as a valuable tool for researchers, offering a controlled environment to systematically explore and evaluate different facets of hydraulic energy harvesting. Its design considerations, encompassing multiple configurations, high-pressure testing capabilities, and integration flexibility, position the platform as a catalyst for advancing the understanding and implementation of energy harvesters within hydraulic systems.

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4. Discussion

The exploration of existing energy harvesters applied to hydraulic systems presented in this paper revealed a critical gap between general energy harvester literature and that aimed specifically at hydraulic applications. This emphasises the limited exploration of energy harvesters within hydraulic contexts. This discussion aims to delve into key findings and existing challenges to the adoption of hydraulic energy harvesters.

One prominent finding of the literature analysis was the lack of established best practices or widely accepted methodologies for deploying energy harvesters into hydraulic systems. This void presents a clear opportunity for researchers to pioneer standardized approaches that can guide the implementation of these technologies in diverse hydraulic applications. The absence of a benchmark or comprehensive comparison framework also complicates the determination of optimal ECTs and FMIs. In particular it is currently unclear what FMIs are best suited to which application (Xiao et al., 2022).

This lack of standardization is captured in Table 1 and Table 3 where a diverse array of technologies are categorised, highlighting the breadth of possibilities in hydraulic energy harvesting. Deciphering the trade-offs associated with each ECT and FMI is essential for informed decision-making in real-world applications and adoption of energy harvesters both in promotion of Industry 4.0 as well as for improved efficiency and reduction in energy usage. To support this goal, the proposed re-configurable test platform positions itself as a contribution to assist with these evaluations. Its design, aligned with the ECT and FMIs that have been identified as currently in use for the advancement of hydraulic energy harvesters, provides a valuable tool for researchers to conduct systematic experiments.

Table 5 describes how each of the criteria previously described in Table 4 has been achieved. With the notable exception of point 10, all other criteria have been met. A higher operating pressure could be achieved through the use of a different lid incorporating a bulkhead connector that is resistant to higher pressures. However, this aids in showing how the platform is modular only one component (the bulkhead connector) needs replacing to increase the pressure operating range of the platform.

Table 5. Test platform evaluation

1	The fluid expansion cavity is large enough to accommodate diaphragms up to 5mm in thickness. The gasket grooves and the retaining collet used to apply pressure mean that a diaphragm of 0.1mm can be used safely without failure as verified through experimental tests at 50 bar for 5min
2	The depth of the measuring tube is sufficiently long to accommodate multiple piston sizes and weights.
3	The PE stack holder in the collet is large enough to comfortably house a 5x5x20mm stack. The use of shims allows for smaller stacks to be fitted into the stack holder without issue. Alternatively, only changing the size of the PE stack location within a new holder gives the opportunity to make the platform reconfigurable without changing any other components.
4	Entire platform has been set up to withstand up to ca. 400 bar. However, the bulkhead connector is the singular part that is only rated to 100bar, causing this to be the limiting factor and limiting maximum operation of the platform to ca. 70 bar. This has been experimentally tested by pressuring the platform for 10 min and checking for leaks.
5	Only two connections were used for connecting to a hydraulic system.
6	One 10mm hex key is sufficient to undo and redo all the bolts on the platform and change the ECT or the FMI. The procedure can be undertaken in less than 10min based on tests with multiple users.
7	One 10mm hex key is sufficient to undo and redo all the bolts on the platform and change the ECT or the FMI. The procedure can be undertaken in less than 10min based on tests with multiple users.
8	The fluid expansion cavity is large enough to accommodate PE disks up to 5mm in thickness. The gasket grooves and the retaining collet used to apply pressure prevent leakage into the expansion chamber.
9	Only perishable components are the O-rings with an average life stated by the manufacturer of ca. 15 years. Stainless steel construction of the platform is corrosion resistant and the lack of rotating parts means little stress will be placed on the O-rings.
10	Due to the limitations of the bulkhead connector, only a max pressure of 70bar can be safely maintained.

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5. Conclusion

This paper has examined the relatively unexplored intersection of energy harvesters and hydraulic systems. The literature analysis highlighted the abundance of knowledge surrounding energy harvesters in general but pointed towards a need for solutions tailored to hydraulic systems. The ambiguity surrounding the superiority of various technologies and the inherent compromises associated with FMIs underscore the challenges researchers face in this evolving field.

To address these gaps, this paper proposed a re-configurable test platform, designed to assist researchers in conducting comprehensive experiments on different FMIs and ECTs. By accommodating the ECTs and FMIs identified in Table 1 and Table 3, and allowing researchers the flexibility to reconfigure the platform to suit their research needs, the test platform serves as a versatile tool for systematic experimentation. The principal aim of the platform was to provide a controlled and (re)configurable environment for assessing the performance, advantages, and limitations of various hydraulic energy harvester approaches, thereby contributing to the establishment of benchmarks and informed decision-making that would further the field of hydraulic energy harvesters.

Looking forward, future research in this field should focus on refining and expanding the proposed test platform to accommodate more and newer technologies, both for ECTs and for the FMIs. This would allow the exploration of additional ECTs and FMIs, thereby addressing identified compromises of existing approaches, and conducting real-world validations to provide datasets that can assist the advancement of the field. In addition to expanding the capabilities of the platform, it goes without saying that new datasets should be created to evaluate existing FMIs as well as ECTs. Through the development of these datasets, it will become increasingly apparent which ECT or FMI is best suited to which scenario. This will aid in increasing the adoption of hydraulic energy harvesters. By building on the research presented in this paper, future researchers have the opportunity to aid in the adoption of hydraulic energy harvesters, thereby supporting more sustainable and efficient approaches to energy and industry.

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