Sustainable Energy Authority of Ireland

National Energy Research, Development & Demonstration Funding Programme 2018

FINAL REPORT TEMPLATE

SECTION 1: PROJECT DETAILS

Table 1.1 – Summary of Project Details

Project Title	Exergyn Heat Pump
Lead Applicant (Organisation)	Exergyn
Lead Applicant (Name)	Kevin O'Toole
Final Report Prepared By:	Kevin O'Toole
Total Project Duration (months)	9 months

Approved SEAI Funding	€88,858

	Name	**Organisation**
Partner Applicant(s)		
Collaborators		

Project Summary (max 500 words)
Exergyn has developed and demonstrated a small-scale prototype of a novel solid state heat pump ("Exergyn HP") based on its existing Exergyn Drive™ waste heat conversion system operated in a reverse cycle. The Exergyn HP concept utilises similar Shape Memory Alloy ("SMA") technology to the Exergyn Drive™ but is operated via stress cycling to enable thermal energy to be extracted. No refrigerants or materials with high GWP are required in the design. Testing of the prototype has demonstrated a CoP of 3.2 with a 11°C temperature lift in the fluid temperature achieved – surpassing the design targets, with the data gathered used to seed newly developed computation fluid dynamics models. These models demonstrate that the Exergyn HP can potentially outperform traditional vapour-compression based heat pump systems, whilst offering minimal impact on the environment – offering CoPs in excess of 7 in some circumstances.

Further work has also shown that the heat pump can be operated at different temperature to address a range of cooling and heating market segments, from refrigeration, to space heating. This can be achieved by changing the parameters of the SMA material utilised in the core.

From a cost perspective, the prototype testing has allowed for the evaluation of the quantities of SMA required, and therefore the expected system cost – considering the SMA costs make up approximately 40% of the total system cost with standard components making up the remainder. The expected cost is in-line with vapour compression/refrigerant based systems, and is significantly lower in cost than CO_2 based systems. This means that a scaled version of the Exergyn heat pump can provide a realistic alternative for heating and cooling applications.

Exergyn have filed 7 new patent families containing over 20 key innovations directly related to the work carried out during this project.

Keywords (min 3 and max 10)	Heat Pump, Shape Memory Alloy, Exergyn, Solid-state

SECTION 2: EXCELLENCE & INNOVATION (max 5 pages)

2.1 Innovation / Novelty – Beyond State-of-the-Art

Describe how your project has furthered the current state-of-the-art, current knowledge or current practice. Clearly highlight the degree of novelty and innovation demonstrated by your project.

Address each innovation in a bullet point below. Add as many bullet points as you need:

- *Innovation 1: An operating solid-state heat pump*

  A physical prototype of a solid state SMA heat pump has been developed and operated successfully. This is the first time this has been achieved in practice with large diameter SMA which is suitable for scaling. Exergyn can therefore be seen as world leaders in this technology sector.

- *Innovation 2: Novel, validated CFD models capturing SMA dynamics in heat pump applications*

  A novel CFD model that combines SMA thermomechanical behaviour within a thermofluid system has been successfully developed and validated for the first time. This allows for more advanced optimisation of future system designs and is an invaluable tool.

2.2 Project Objectives

In the Table below, list all project objectives as detailed in your application, and provide on update on their status. Have these objectives been achieved? What were the key outcomes or deliverables associated with each?

Table 2.1 – Summary of Project Objectives

No	Objective Description	Objective completed (Y/N) Justify your answer	Key Outcomes/Deliverables
1.	Optimisation of SMA selection criteria for HP, and construction of SMA wire into bundle format to maximise heating and cooling capability	[Y] SMA identified and bundles built. Latent heat maximised within available NiTi limits	A bundle of SMA optimised for testing within the heat pump prototype
2.	Development of a test bed capable of supplying a continuous flow of water to a bundle of SMA wires, whilst providing a method to control loading of the bundle	[Y] System developed and built. System utilises a high speed controller to direct the appropriate fluid to the SMA to accept and reject heat within the core. System in stable operation.	A physical test bed design that can be adapted as required. System is designed to test SMA solid state cores with different properties and seed CFD models with validated data
3.	Utilisation of the basic bundle testing results to develop a robust design for the demonstrator model	[Y] Solid state core designed using physical test data and integrated into the test bed design.	A SMA bundle capable of operating in heating mode, utilising room temperature fluid and providing a heat boost.
4.	Purchasing parts and manufacturing the prototype technology	[Y] All parts purchased.	Parts on-site ready for assembly
5.	Assembly of the demonstrator prototype	[Y] System assembled	Full system assembled and operated in the Exergyn lab
6.	Operation and analysis of the demonstrator technology	[Y] Testing & analysis complete and CFD models developed and validated. CFD models used to apply	Testing yielded an 11ºC temperature uplift with a CoP of 3.2.

		learnings to larger scale industrial designs utilising the same physical principles of operation	Analysis in CFD indicates that CoPs in excess of 7 can be achieved in larger industrial scale designs
7.	Final report	[Y] Complete	

SECTION 3: RELEVANCE & IMPACT (max 6 pages)

3.1 Relevance to the needs of the Irish Energy Sector and to SEAI

The development of the Exergyn HP will have a major impact on both the Irish and international energy sector. As a result of its unique thermodynamic cycle and reliance on an internal solid-solid phase change of a SMA material, the developed system has been shown to have the potential outperform any existing heat pump technology, whilst maintaining a small footprint, low cost and utilises no toxic gases or refrigerants. The system would directly meet three of the four objectives of the SEAI, by accelerating the development of the technology, leading to the development of further high value intellectual property in conjunction with Exergyn's existing profile, and thus demonstrating Irelands national capacity to develop international class energy RD&D.

3.2 Project Impact

The heat demand which is of particular interest to Exergyn is split between industry and buildings. Some industrial applications require high temperatures which are not suited to heat pump technology. In buildings, the majority of the load is space heating or water heating. There is a small cooking load, but for the purposes of this assessment, 100% of the building load is assumed to be suitable. The existing load in buildings is 83.7EJ 23.2PWh, as the building stock only changes slowly. This is not expected to change significantly. High levels of insulation can increase cooling loads, so it is reasonable to assume that this will not change significantly. In industry, the total heat load is 78.8EJ/21.8PWh (although this excludes small heat pumps).

For the market potential, a reasonable, justifiable estimate is >90EJ / 25PWh across the 2 sectors. Assuming a conservative level of utilisation of 4,000hours/yr, this could be equivalent to 6.2TWth capacity installed. Note: hours may be lower and installed capacity is generally over-specified, so this is a conservative figure; an estimate 50% higher could be justified.

The three main areas for energy consumption are power, transport and heat. The schematics for Scotland and USA below show the split between emissions in these countries. Similar splits are seen in many countries. In warmer climates the heating element is replaced with cooling from air-conditioning systems.

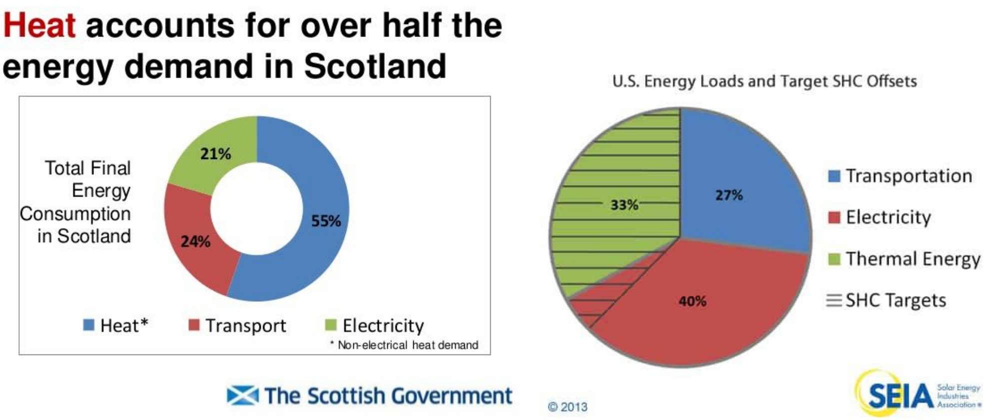

Figure 1. Heat Demand Example - Scotland

Heat is generally generated by combustion in boilers and furnaces. Combustion of carbon-based fuels (including bio-fuels) give off CO_2. Combustion of other fuels, including hydrogen, still gives off some pollutants with global warming potential (e.g. NO_x). The transition to biomass fuels causes an increase in actual CO_2 emissions at the source (the re-absorption of the CO_2 is slow), thus increasing atmospheric CO_2 in the short-medium term. Hence concerns exist around implementing biomass heating as the solution to decarbonising the heat load (since the CO_2 in the atmosphere must actually be reduced to meet the 2°C temperature rise target).

Zero-emission heat options include:

- Electrical (resistance) heating
- Heat pump running off renewable electricity
- Cogeneration using heat from a zero-carbon power generation such as fuel cells or nuclear (nuclear is only zero-carbon at point of generation; the total carbon footprint for the overall process is greater than zero)
- Solar thermal (not suitable for space heating as there is no sun in many locations when there is a heat demand)
- Seasonal thermal storage is also an option (although this may store waste heat, potentially from a carbon-emitting process).

In the UK for example, the ETI has used complex, cost-benefit modelling to forecast scenarios where carbon emissions can be reduced. The ETI forecasts that in the UK alone, 170TWh heat will be delivered by heat pumps, with a similar amount to come from heat networks (which could be fed by heat pumps). Assuming 250TWh and 4,000 hours/yr, Exergyn could deploy over 300,000 units in the UK alone. A similar trend for increased demand for heat pumps is being observed elsewhere e.g. US (from CAH)).

Cooling Demand

The above focus has been on heating, as the heat pump is displacing a combustion technology. In cooling, the heat pump would only replace existing technologies if efficiency & cost-effectiveness are increased. The Exergyn HP would replace chillers which are electrically driven (there are absorption chillers which utilise waste heat, but these account for a fraction of the chiller market and are a low-efficiency technology). Cooling and refrigeration are major issues, and a major consumer of electricity. Radically increasing the efficiency of cooling will cut energy consumption (and reduce emissions, where fossil fuels are in use) by reducing consumption in buildings and reducing total power generated. Cooling is a significant part of the electrical load in the USA in residential, commercial and, to a lesser extent, industrial sectors (see below). It is also a major load in Middle East, Asia etc.

The key sectors of interest are residential and commercial. It could reasonably assumed that all the gas & biomass used in these applications go for space heating and if 50% of the electrical load goes into cooling, then the thermal load is around 11Quads (3,200TWh), equivalent to the total energy load in the residential sector. If we include the rejected energy, then 33quads (9,600TWh) of fuel was required to satisfy this demand.

The heating, ventilation & air conditioning (HVAC) market is expected to be worth $117 billion in 2019. The global heating equipment market is forecast to be $49 billion p.a. by 2025. The HP heating products market was worth $6.5b in 2016.

3.3 Communication, Dissemination and Exploitation

Please provide details of all dissemination activities undertaken throughout the project, providing references and links where applicable.

Dissemination Summary Tables

Please list details of any scientific publications in Table 3.1 on the next page. Please mention papers published in peer-reviewed journals or papers disseminated at conferences (e.g., on the conference website, etc.).

Due to the novel nature of the work and the need to secure the relevant IP upfront only one poster presentation has been completed outlined.

Please list details of all dissemination activities in Table 3.2 on the next page (e.g. publications, conferences, workshops, websites/applications, press releases, flyers, articles in press, videos, presentations, exhibitions, thesis, interviews etc.).

Exergyn are working with the Technical University of Dublin on a joint MPhil project directly related to this work

3.4 Intellectual Property Management & Exploitation

If applicable, please provide details of any patents or IP generated as a result of this research award, or patents/IP which you think may eventuate as a result of the project.

Title	Application No.
System and method for Maximising heat output and temperature delta in a SMA heat pump/refrigeration system	GB1911073.3
System and method for Supporting SMA Material and Optimising Heat Transfer in a SMA Heat Pump	GB1911093.1
System and method for heat recovery in a hydraulically actuated SMA/solid-state heat pump to increase system efficiency	GB1911101.2
System and method for heat Pump/refrigeration using Heat Pump Load Control	GB1911107.9
A Housing for a Shape Memory Alloy (SMA) Heat Pump	GB1911108.7
Elastocaloric Heat recovery in a Heat Pump / Refrigeration system using a Pump Mechanism	GB1911112.9
System and Method for Work Recovery in a SMA Heat Pump	GB1911109.5

Table 3.1 – List of Scientific Publications

Title	Main Author	Journal Title	Number, Date or Frequency	Publisher	Year of Publication	Is/Will open access be provided? If you marked "will", provide an estimate of the date	Peer-reviewed (Y/N)?
Analysis,Characterisation and modelling of the heat pumping performance of a Nitinol Elastocaloric Cycle	K.Warren (Exergyn)	TU Inspire (conf)	n/a	n/a	2019	yes	Y

Table 3.2 – List of Dissemination Activities

Type of Activity	Main Leader	Title	Date/Period	Location	Type of Audience*	Size of Audience
Joint MPhil Thesis	TUD	Nitinol Elastocaloric Heat Pumping	Ongoing	Dublin, Ireland	Academia, Industry, Policy Makers	unknown

**Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).*

SECTION 4: WORK PLAN

4.1 Work Plan

Please provide your list of work packages in Table 4.1 below, as detailed in your original Application Form, and include a status update for each.

Table 4.1 – List of Work Packages

No.	Title	Status Update
WP1	SMA Selection & Bundling	*Complete*
WP2	Test Bed Development	*Complete*
WP3	Design, Manufacture & Assembly	*Complete*
WP4	Testing & Analysis	*Complete*

In Table 4.2, please include details for each work package (copy and replicate the Table for each work package as required). Please provide an update on the progress achieved, the specific milestones and deliverables achieved, and clearly identify any deviations from the original proposed work packages.

Table 4.2 – Summary of Work Packages

WP No. & Title	WP1 SMA Selection & Bundling		
Start Month No.	0	**Finish** Month No.	2
WP Lead:	Kevin O'Toole		
WP Contributors	Jan Pilch Gary O'Sullivan		
Objective(s)	WP1-O1: Optimisation of SMA selection criteria for HP, and construction of SMA wire into bundle format to maximise heating and cooling capability	Status: Complete	
Description (max 200 words)	The Exergyn HP relies on using a parallel bundle arrangement of optimised SMA's. The temperature profile must be configured in the wire via a series of thermal and mechanical treatments in order to minimise the phase change temperature band and maximise the latent heat of transformation. Once finalised, the SMAs must be bundled into a parallel arrangement that is capable of withstanding the applied load. It is envisaged that the bundling arrangement and technology will be similar to the Exergyn Drive™ system, but with minor modifications to operate in lower temperature environments.		
Milestones	WP1-M1: Selected SMA wire blend and treatment for desired temperature band WP1-M2:	Status: Complete Status: Complete	

	Assembled bundle of SMA wires ready for insertion into HP prototype	
Deliverables	WP1-D1: Completed and assembled bundle of SMA wire optimised for the selected temperature band	Status: Complete
Deviations from planned WP (if applicable)	N/A	
Key Outcomes	• A bundle of SMA optimised for testing within the heat pump prototype	

WP No. & Title	WP2 Test Bed Reconfiguration		
Start Month No.	0	**Finish** Month No.	3
WP Lead:	Kevin O'Toole		
WP Contributors	Gary O'Sullivan Keith Warren		
Objective(s)	WP1-O1: Development of a test bed capable of supplying a continuous flow of water to a bundle of SMA wires in bundle format, whilst providing a method to control loading of the bundle	Status: Complete	
Description (max 200 words)	An existing test bed must be modified to continually flow a fluid stream (water) into the Exergyn HP. The test bed will require a number of new sensors to measure temperature, pressure, flow rate and SMA wire displacement during the phase transformation. These factors will allow for the full assessment of performance during the testing phase. The test bed will be controlled using a high performance controller, which will perform data logging duties at rates higher than 25Hz to ensure the dynamic behaviour of the system is fully captured.		
Milestones	WP1-M1: Completed test bed	Status: Complete	
Deliverables	WP1-D1: Test bed capable of supplying fluid up to 5l/s at a desired temperature, and capable of data logging at a rate of 25Hz when connected to the Exergyn HP	Status: Complete	
Deviations from planned WP (if applicable)	N/A		
Key Outcomes	• A physical test bed design that can be adapted as required for multiple tests. System is designed to test SMA solid state cores with different properties and seed CFD models with validated data		

WP No. & Title	WP3 Design, Manufacture & Assembly

Start Month No.	2	**Finish** Month No.	6
WP Lead:	Kevin O'Toole		
WP Contributors	Gary O'Sullivan Neil Dwyer Liam McBreirty		
Objective(s)	WP1-O1: To design & build a mechanical heat pump prototype using SMA bundles that can deliver an increase in output fluid temp of >10ºC at a COP of >3. WP1-O2: To design & build the electrical and control system for a mechanical heat pump using SMA bundles	Status: Complete Status: Complete	
Description (max 200 words)	Once the bundle has been selected and optimised, it must be integrated into a physical demonstrator model of the system. The design will be developed using 3D solid modelling software and various computational fluid dynamics simulations will be conducted to assess the theoretical performance of the design. In conjunction with this, a series of finite element analysis simulations will be conducted to ensure the system is capable of withstanding the forces required during operation. Once approved, the drawings will be sent to manufacturers who are on Exergyns approved suppliers list for manufacture. It is expected that the largest cost item will be the SMA material since it is a once off unique production run. Once in house, the system ill be assembled by members of the Exergyn R&D team, and prepared for testing		
Milestones	WP3-M1: Utilisation of the basic bundle testing results to develop a robust design for the demonstrator model in 3D CAD WP3-M2: All purchase orders issued and manufacturing the prototype technology WP3-M3: Parts delivered, inspected and assembled	Status: Complete Status: Complete Status: Complete	
Deliverables	WP1-D1: Mechanical and electrical heat pump prototype fully assembled	Status: Complete	
Deviations from planned WP (if applicable)	N/A		
Key Outcomes	• A SMA bundle capable of operating in heating mode, utilising room temperature fluid and providing a heat boost. • Parts on-site ready for assembly • Full system assembled and operated in the Exergyn lab		

WP No. & Title	WP4 Testing & Analysis		
Start Month No.	7	**Finish** Month No.	9
WP Lead:	Kevin O'Toole		
WP Contributors	Gary O'Sullivan Keith Warren		
Objective(s)	WP1-O1: To assess the performance of the Exergyn HP when connected to the modified fluid delivery rig	Status: Complete	
Description (max 200 words)	A series of tests will be conducted on the developed test bed to assess the performance of the Exergyn HP. The net requirement from testing will be an observable increase in fluid temperature by >10ºC, with a CoP of >3.0. Data will be analysed using customised scripts developed in MATLAB to allow for fast interpretation and presentation of the results.		
Milestones	WP1-M1: 1 full cycle of the Heat Pump WP1-M2: Continued operation of the heat pump for 100 hours in the lab environment	Status: Complete Status: Complete	
Deliverables	WP1-D1: Operating heat pump within desired output range WP1-D2: Technical Report	Status: Complete Status: Complete	
Deviations from planned WP	N/A		
Key Outcomes	• Testing yielded an 11ºC temperature uplift with a CoP of 3.2. • Analysis in CFD indicates that CoPs in excess of 7 can be achieved in larger industrial scale designs		

ANNEX 1 – CASE STUDY TEMPLATE

As well as the above Final Project Report, please also complete the SEAI Case Study Template below. The details below may be used for SEAI promotional activities, e.g. project dissemination on SEAI Website or SEAI Twitter account.

Project Title	
Exergyn Heat Pump	
Project Summary – Please provide a brief and high-level summary of your project. (Max 3 sentences)	
A novel solid state heat pump prototype using the shape memory effect. This heat pump does not require refrigerants and thus is carbon neutral. Performance and cost effectivenessy can potentially outcompete traditional refrigerant based heat pumps.	
Three key statistics: **If applicable, please provide three key statistics related to your RD&D Project:** e.g. X kW generation capacity; X Papers Published; X Communities/Users involved; X potential energy/cost savings	
1.	**7 patent families filed**
2.	**CoP of >3 achieved in a first proof of concept solid state heat pump**
3.	**Zero refrigerants & zero CO2 emissions**
What has this SEAI funding enabled for you/your organisation? (e.g. building capacity, developing a product, opening new markets, growth in revenue). Please be specific and quantify your responses where possible.	
Build and test a new type of heat pump, allowing for further development to commence with confidence in the concept capability	
How has this or will this research project be of benefit to Ireland? In the latter case, please provide an estimate of when the project will benefit to Ireland	
2022 onwards. On the back of the work conducted with this funding, Exergyn have just recently secured the Carrier Corporation as a development partner for the large scale roll out of the technology. Pending the success of the collaboration, Carrier have confirmed that Ireland will be a key trialling area for the technology and a priority roll out territory. The development will also take place in Ireland leading to further technical jobs being created in R&D and Engineering	
What would you regard as the three most significant achievements or impacts enabled by this SEAI funding?	
1.	**Allowing us to prove the technologies capability**
2.	**Securing partnership with a large multinational to enable roll out**
3.	**Potentially facilitating a refrigerant free cooling industry, thus tacking one of the biggest contributors to climate change – refrigerants**
Other	
What challenges did you face? Challenges can be technical (e.g., sensor failure), managerial (e.g., delay in the hiring process), financial (e.g. unexpected costs), etc.	
Mostly technical. This is a brand new concept and technology so the lack of peer reviewed papers to reference meant that we needed to do it all ourselves.	
What advice would you give to other researchers?	
Ensure the theory makes sense before committing to further work. Spend time here working everything out. If the theory stacks up, then you will find a way to develop it with strong team behind you.	
If you wish, please provide below additional comment or quote below.	

Please submit *a separate e-copy of any* ***<u>pictures / maps / images / graphics</u>*** *inserted into the text above, as individual .jpeg, .tiff, .csv files to ensure good quality printing.* *Please also submit 3* ***research project cover pictures*** *(e.g., team photo, site photos, prototype photos, research lab photos etc). Please ensure the below picture requirements are met:* • *Pictures must be of high quality to ensure good quality printing* • *Layout: Landscape* • *Format: Jpeg* • *Size: Minimum 1200 x 1200 pixels*

ANNEX 2 – PROJECT COMPLETION SURVEY

Workforce Statistics *Please indicate in the table below the number of people who worked on this project*		
Position	**Number of Women**	**Number of Men**
Research Coordinators		
Total	0	1
Of which, indicate the number in Academia		
Experienced Researchers		
Total	0	6
Of which, indicate the number in Academia	0	
PhD Students		
Total	0	0
Of which, indicate the number in Academia	0	0
Research Assistants		
Total	0	0
Of which, indicate the number in Academia	0	0
Other (please specify)		
How many researchers were recruited specifically for this project?		
Of which, indicate the number of men	**0**	
Employment Statistics *Please indicate whether your project is likely to have a potential impact on employment, in comparison with the situation before your project (tick as appropriate)*		
□ Increase in employment, **or** □ Safeguard employment, **or** □ Decrease in employment, **or** □ Difficult to estimate/quantify *(select **one** of the above answers only)*	□ In Small & Medium-sized Enterprises □ In large companies □ None of the above / not relevant to project	

Engagement – Civil Society and Policy Makers	
Did your project involve working with students and/or school pupils (e.g. open days, participation in science)?	
Yes – Please specify	
No	
Did your project engage with societal actors beyond the research or industrial community?	
Yes – Please specify	
No	
If yes, did you engage with citizens or organised societal groups (select from the below options)?	
No	
Yes – in determining the research to perform	
Yes – while implementing the research	
Yes – in communication/dissemination of research results	
Did you engage with government / public bodies or policy makers (including international organisations)?	
No	
Yes – in framing the research	
Yes – while implementing the research	
Yes – in communication/dissemination of research results	

If you marked yes above and engaged with international organisations, please specify which organisation and which country here:	
Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?	
Yes – as a primary objective	
Yes – as a secondary objective	
No	
If you marked yes above, please add details here	
If yes, at which level?	
Local / Regional Level	
National Level	
European Level	
International Level	

Dissemination	
How many articles were published/accepted for publication in peer-reviewed journals?	**0**
How many articles were presented and published in conference proceedings?	**1**
How many new patent applications have been made?	**7**
How many spin-off companies were created/ are planned as a direct result of this project. **If you marked "are planned", please give an estimation of the date of creation.**	**0**

Communication Statistics	
Which of the following have been used to communicate information about your project? (tick as appropriate)	
□ Press Release □ Communication via social media (Twitter, Linkedin, Applicant website, etc.) □ Media Briefing □ TV coverage / report □ Radio coverage / report □ Brochures / posters / flyers □ DVD / Film / Multimedia □ Other (please specify):	□ Coverage in specialist press □ Coverage in general press □ Coverage in national press □ Coverage in international press □ Website for the general public □ Event targeting general public (Festival, conference, exhibition) □ Scientific conferences □ Other (please specify):

SEAI National Energy RD&D Funding Programme - Feedback
If you have any feedback or suggestions in relation to the SEAI National Energy RD&D Funding Programme, please provide below:
- **-**