UK FLUIDS NETWORK

OUR FLUID NATION

THE IMPACT OF FLUID DYNAMICS IN THE UK

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PROFESSOR PAUL S. MONKS FRSC FRMETS, CHIEF SCIENTIFIC ADVISER, DEPARTMENT OF BUSINESS, ENERGY AND INDUSTRIAL STRATEGY

The UK has a stated aim to be a science superpower. Innovative scientific research and development lies at the core of that. *Our Fluid Nation* highlights a major UK research and innovation strength in the broad area of fluid dynamics. It shows that fluid dynamics is an enabling technology that underpins many industrial sectors, as well as a wide range of societal applications built on a world-leading research core. One of the features of fluid dynamics is that it is not considered as a sector in its own right, therefore its importance and impact can be hidden.

Our Fluid Nation really brings to the fore the size and influence of fluid dynamics on UK industry. There is impressive economic value as well as key sectoral underpinning and an evidenced ability to support innovative UK industry and academic work. *Our Fluid Nation* challenges that in order to grow towards being a science superpower, there is a need to recognise where we have strengths and think about how to sustain and grow them.

PROFESSOR STEPHEN BELCHER, CHIEF SCIENTIST, MET OFFICE

Fluid dynamics is at the heart of a huge range of applications, ranging from the transmission of disease via liquid droplets, to fuel mixtures in engines and weather systems in the atmosphere. Fluid dynamics therefore underpins many scientific and technological breakthroughs, for example in health and engineering, and weather and climate forecasting. This huge range of real-world applications is what first attracted me to study fluid dynamics when I was looking for a PhD project.

The UK has huge expertise in fluid dynamics. We have been at the forefront of the fundamental work at the roots of the subject, but also at the cutting edge of applying fluid dynamics to understanding and solving real problems.

There is so much more potential for fluid dynamics, from novel drug delivery routes to simulating pathways through climate change. This report comes at a time when supercomputers and new technologies are revolutionising our ability to simulate and measure fluid dynamics in unprecedented levels of detail. I warmly welcome this report and look forward to a new generation of discovery in fluid dynamics.

EXECUTIVE SUMMARY

FLUID DYNAMICS IS A £13.9 BILLION UK INDUSTRY, EMPLOYING MORE THAN 45,000 PEOPLE IN 2,200 COMPANIES.

FLUID DYNAMICS IS THE SCIENCE AND ENGINEERING OF FLOWS OF ANY SORT - WHETHER LIQUIDS, GASES OR PLASMAS - IT INCLUDES MEASURING, MODELLING, PREDICTING AND CONTROLLING FLUID FLOWS. THIS INCLUDES FLOWS IN INDUSTRY, THE ATMOSPHERE AND OCEANS, GLACIERS, FLOWS IN THE BODY AND EVEN ASTROPHYSICAL FLOWS. FLUID DYNAMICS CAN BE AT ANY SPEED, TEMPERATURE RANGE, SPATIAL SCALE OR TIME SCALE.

Fluid dynamics is a major UK industrial and research strength, and is critical to many applications. Fluid dynamics is an enabling technology for industry sectors as diverse as transport, healthcare technologies, marine and energy. It plays a key role in the most important challenges facing today's society, including the drive to net zero, understanding disease and predicting weather and climate.

For the first time, the UK fluid dynamics industry has been analysed. Fluid dynamics generates £13.9 billion worth of output from over 2,200 firms and employs 45,000 people. The total UK turnover of firms engaged in fluid dynamics exceeds £200 billion and together they employ over 500,000 people, illustrating how fluid dynamics activity is often embedded in larger organisations. The gross value added (GVA) to the economy from fluid dynamics is estimated to be £3.4 billion. The industry is distributed across the UK with significant activity in Scotland, Wales and Northern Ireland and across England, supporting a levelling up of the economy.

The UK is a world leader in fluid dynamics research, including fundamental, computational, data-driven and experimental methods. The breadth and significance of the knowledge base is underpinned by consistent support from UK Research and Innovation (UKRI), including the STEM-facing research councils EPSRC, BBSRC, MRC, NERC and STFC. UKRI have invested in relevant research totalling over £2.3 billion over the last 10 years, and provided support for skills development via Centres for Doctoral Training and similar structures. The research strength in universities is spread both geographically and among many disciplines, including mathematics, physics, engineering, biophysics, and geo- and environmental sciences.

Fluid dynamics is a prime example of a deep, transformative technology. UK-led research has enabled the development of Computational Fluid Dynamics software, which is now a mainstay across all industry sectors. Advances in computational methods and investment in UK infrastructure underpin the pre-eminence of the UK in climate science and weather forecasting. Among many applications, these techniques are also now being used to increase the efficiency of renewable energy solutions and develop personalised medicine, including treating heart disease and infertility.

THE UK'S GLOBAL LEADERSHIP IN FLUID DYNAMICS IS UNDER THREAT. THERE IS AN IMMEDIATE NEED FOR:

A NATIONAL CENTRE IN FLUID DYNAMICS, BUILDING ON PRACTITIONER NETWORKS AND UK RESEARCH STRENGTHS

INCREASED SUPPORT FOR FLUID DYNAMICS TRAINING IN INDUSTRY AND ACADEMIA

THE APPLICATION OF NEXT-GENERATION DATA-DRIVEN FLUID DYNAMICS METHODS ACROSS SECTORS AND INTO INDUSTRY

GENERATION AND RETENTION OF FLUID DYNAMICS INTELLECTUAL PROPERTY AND EXPERTISE IN THE UK

Fluid dynamics is at the cusp of a new breakthrough, coupling exascale computing and big data to support the optimisation of processes and deep understanding of complex problems. It is vital that these advances propagate into a wide range of application sectors and companies of all sizes. A National Centre to foster collaboration and further growth is essential to retaining the UK's position as a world leader in fluid dynamics, thereby underpinning the growth of multiple sectors across the UK.

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INTRODUCTION

CREATING A SUSTAINABLE ENVIRONMENT, ADVANCING MEDICINE, DEVELOPING EFFICIENT INDUSTRIAL PROCESSES AND EXPLAINING THE BEAUTY OF THE NATURAL WORLD ARE ALL ENABLED THROUGH FLUID DYNAMICS.

Fluid dynamics influences all of our lives. We rely on fluid dynamics to design safe water supply systems, to prevent flooding, to enable comfortable buildings and to provide state-of-the-art treatment for cardiovascular and respiratory diseases. Harnessing fluid dynamics principles drives the transport and energy sectors, enabling international flight and worldwide shipping, delivering lower emission vehicles, and underpinning the development of battery technology, wind energy, biofuels and heat pumps that will power the next century. Across multiple sectors, fluid dynamics sits at the heart of manufacturing, enabling the production of a diverse range of products including filters, paints, glass, coated papers, personal care products and even chocolate.

The ability to measure, model and predict fluid flows is critically important to the innovation of processes and products across almost all industries, and to the monitoring, prediction and response to environmental processes, from managing urban air quality through to understanding changes to large scale atmospheric and geophysical flows. Applications of fluid dynamics range from simplified models through to complex computational simulations that utilise some of the world's largest supercomputers. New advances in real-time flow simulation, data-driven processes and machine learning are on the cusp of bringing a new revolution in fluid dynamics, enabling the next generation of optimised and efficient processes, as well as the ability to understand our world through immersive virtual reality models of the environment.

Although it is a vital component, the importance of fluid dynamics to the economy and society is often overlooked. As an enabling discipline, it is not a sector in its own right, yet understanding fluid dynamics is crucial to the safety, reliability and efficiency of a vast range of sectors. For example, investing in fluid dynamics enables new innovations and disruptive technologies to facilitate the transition to a green economy. Delivering this requires support for fundamental science and industry, the training and development of skilled people, and investment in experimental and computational facilities and software.

For the first time, this report evaluates the direct contribution that fluid dynamics makes to the UK economy, highlighting the breadth of industry sectors where fluid dynamics is a critical part of business. The analysis provides key metrics, including the revenue associated with fluid dynamics activities, the size and distribution of the workforce providing these essential skills, the gross value added (GVA) to the UK economy, and the scale of research investment.

The analysis is based on a proven methodology for quantifying the impact of transformative industries, which accommodates the diverse nature of the sector and accounts for the fact that fluid dynamics is frequently embedded within large, diversified companies.

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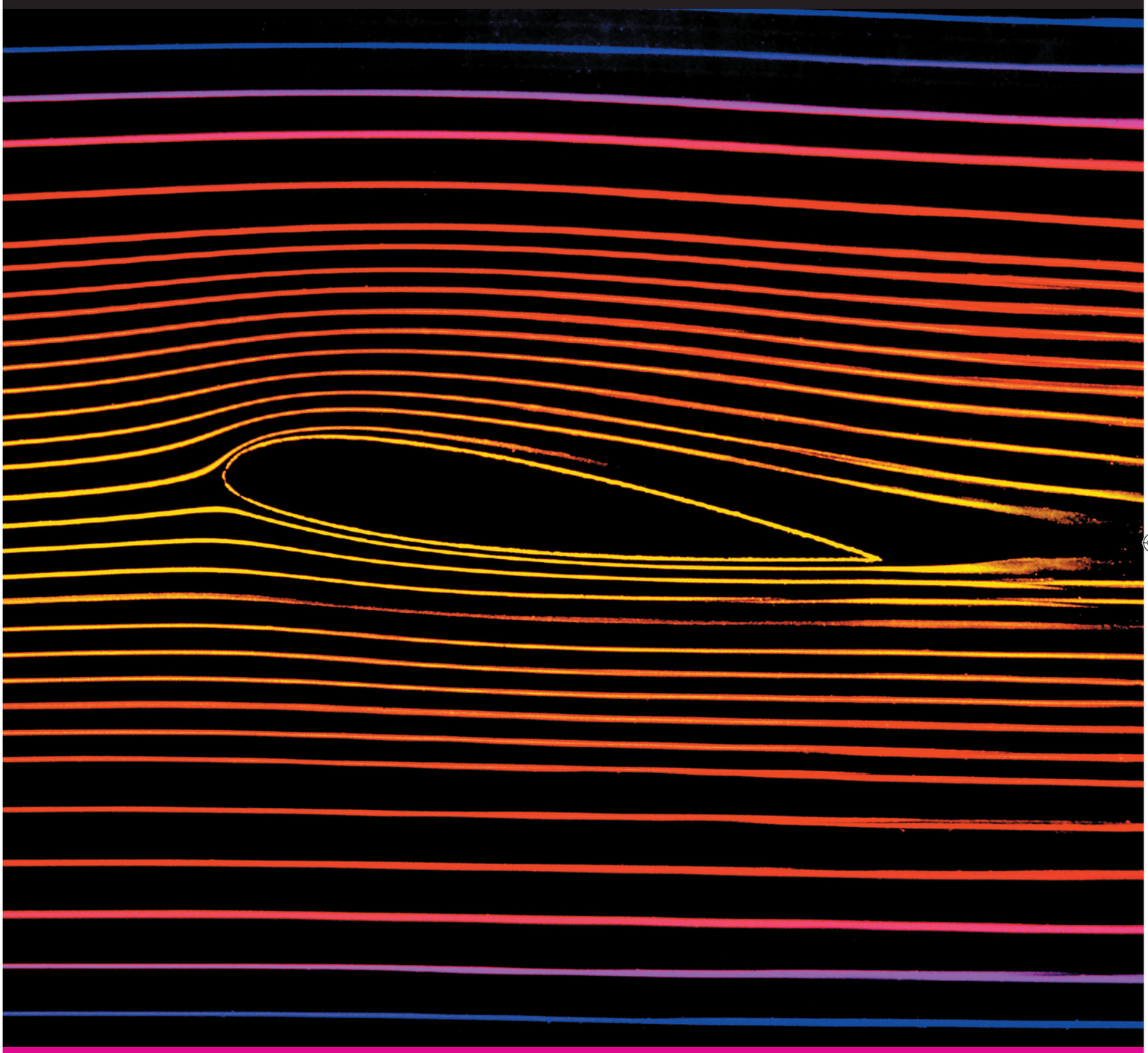

COLOURED WIND TUNNEL IMAGE OF AIR FLOW
OVER A MODEL AEROPLANE WING

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UK FLUID DYNAMICS INDUSTRY

£13.9 BILLION OF FLUID DYNAMICS GOODS AND SERVICES WERE DELIVERED IN THE UK FROM MORE THAN 2,200 COMPANIES IN 2019.

The UK fluid dynamics industry directly generated £13.9 billion worth of output from over 2,200 firms employing 45,000 people. The industry's gross value added (GVA) to the UK economy is estimated to be £3.4 billion, equivalent to £75,800 GVA per employee. Over 70% of the industry exports fluid dynamics products and services outside of the UK, with more than one quarter of firms exporting over 50% of their output.

Fluid dynamics activity is often embedded in highly diversified businesses. The total UK turnover of firms with fluid dynamics making up a proportion of their activity exceeds £200 billion, and collectively these companies employ over 500,000 people. The fluid dynamics portion of many businesses is therefore small but critical to enabling economic activity far in excess of their direct fluid dynamics output.

The breadth of fluid dynamics impact is further illustrated by the range of industries in which the top fluid dynamics companies operate. These cover aerospace, automotive, construction, defence, marine, pharmaceuticals manufacturing, and power production. Only ten companies are considered to contribute more than 1% to the overall fluid dynamics industry, reinforcing the distribution of fluid dynamics activity among a large range of companies.

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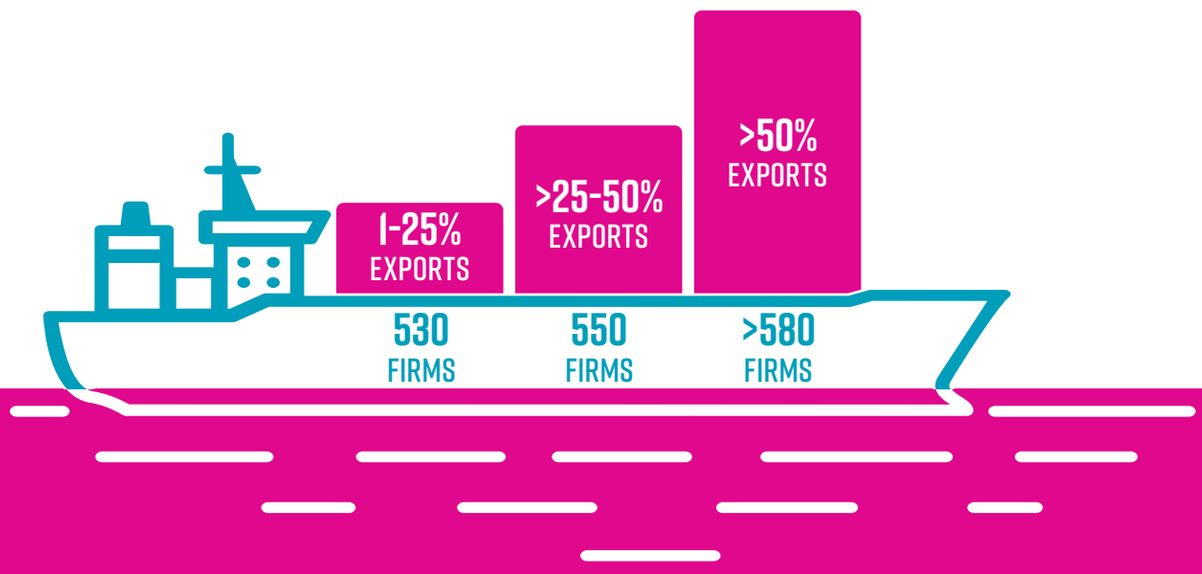
£13.9
BILLION OUTPUT

45,000
PEOPLE EMPLOYED

2,200
COMPANIES

£75,800
GROSS VALUE ADDED PER EMPLOYEE



UK FLUID DYNAMICS COMPANIES			
AIRBUS	BP	LEONARDO	SIEMENS
AKZO NOBEL	EXXON MOBIL	MBDA	TECHNIP
BABCOCK	FORD MOTOR	NATIONAL GRID	THALES
BAE SYSTEMS	JAGUAR LAND ROVER	PROCTER & GAMBLE	TI AUTOMOTIVE
BOMBARDIER	JOHN WOOD	ROLLS-ROYCE	UNILEVER

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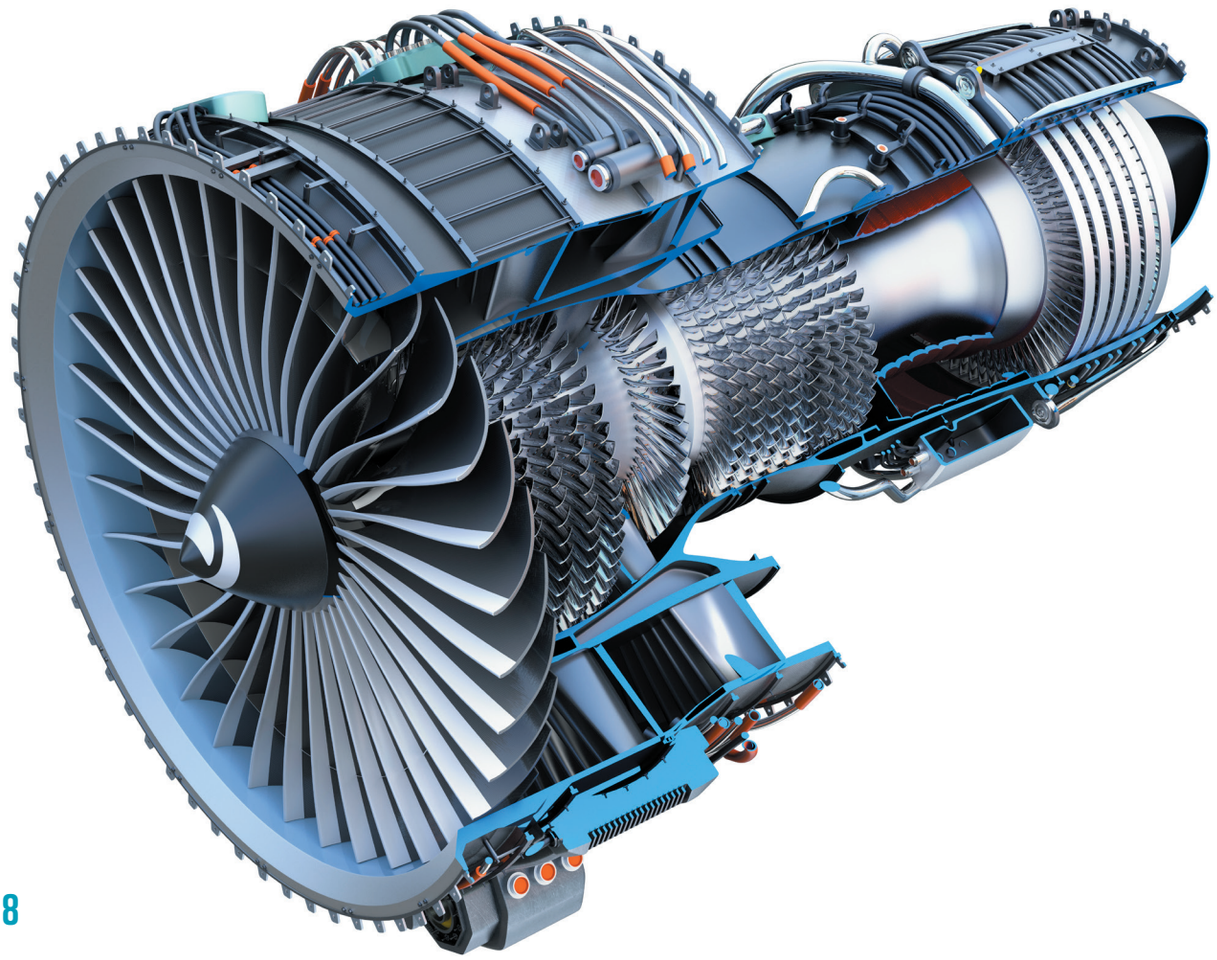

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ROLLS-ROYCE AND WHITTLE LABORATORY CASE STUDY

ACCELERATING THE DELIVERY OF NET ZERO CARBON FLIGHT

Achieving net zero carbon flight is possible but the size of the challenge is immense. This challenge combines aerodynamics, propulsion technologies, and new fuels, alongside rapid testing, and development. The existing aerospace research and development process cannot, however, achieve the throughput of technologies necessary to meet the challenge.

Over the past eight years, the Whittle Laboratory in Cambridge has focused on changing the technology development process applied to aerospace and propulsion technologies. Recent pioneering trials, undertaken in partnership with Rolls-Royce and funded by the Aerospace Technology Institute, have demonstrated a 10-to-100-fold reduction in the time required to design, build, test, and learn from a concept. This will support projects such as FlyZero in the UK, new aerospace SMEs, and the transition of large aerospace companies to zero carbon.

We are entering the fourth industrial revolution in which disciplines such as fluid dynamics and aerodynamics are combining with technologies such as machine learning, automation, and 3D printing to change the way that humans create value and solve problems. This revolution is allowing computers and humans to design in ways, and on timescales, that would not be achievable by humans alone.

The process established by the Whittle Lab involves a radical change in both the culture and the tools used to develop technology. It involves the use of in-house Computational Fluid Dynamics (CFD) software that is accelerated by graphics cards developed for the computer gaming industry. Design times have been cut from around a month to one or two days, using augmented and machine learning-based design systems. Manufacturing times have been reduced from two or three months to two or three days by directly linking the design systems to in-house 3D printing and rapid machining tools. Wind tunnel testing times have decreased from around two months to a few days by undertaking a value stream analysis of the experimental process and employing Formula 1 style pit teams. Test results are automatically fed back to the augmented design system so that it can learn from both the digital and physical data.

In the race to transform the aviation sector, time is the enemy. The aerospace companies are meeting this challenge by fundamentally changing the way fluid dynamics interacts with new technologies to speed up development times.

Further information at **www.re-tv.org/reinvigorate/reworking-innovation**

CASE STUDY SOURCE: PROFESSOR ROB MILLER, WHITTLE LAB, ENGINEERING DEPARTMENT, CAMBRIDGE UNIVERSITY, PROFESSOR MATTHEW JUNIPER, ENERGY GROUP, ENGINEERING DEPARTMENT, CAMBRIDGE UNIVERSITY

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MET OFFICE CASE STUDY

IMPROVED FLUID DYNAMICS MODELLING WILL HELP GENERATE £13 BILLION IN SOCIO-ECONOMIC BENEFITS FOR THE UK

Fluid dynamics is central to all the services provided by the UK Met Office, whether it's forecasting the weather over the next few days, projecting future climate change, or calculating the trajectory of atmospheric pollution. Fundamentally, weather and climate forecasts are fluid dynamical simulations of the movement of the air in the atmosphere and the water in the oceans. To capture their complexity and splendour, the Met Office simulates fluid dynamics within computer models run on one of the largest supercomputers in the world.

Increases in supercomputing power and advances in our understanding of fluid dynamics lead to more accurate forecasts of weather and climate. In turn, this results in more effective decision-making meaning that costs due to otherwise unforeseen extreme weather can be avoided, delivering economic benefits. Due to improved science, better observations and increased computing power, today's four-day weather forecasts are as accurate as the one-day forecasts of 30 years ago. These improvements have been brought about through increasingly realistic representation of real-world fluid processes within the models, for instance better simulations of atmospheric convection and the interactions between the ocean and atmosphere. Advances in our ability to observe the fluid dynamics of the atmosphere and oceans are also crucial to producing more accurate forecasts and require further research into new technologies.

The current Met Office supercomputer began operations in 2015. Over five years, the additional socio-economic benefit to the UK economy delivered through improvements in forecast quality is estimated to be ~£1.6 billion. This supercomputer is due to be replaced in 2022 with an increase in supercomputing capacity of ~18x. The upgrade is intended to deliver financial benefits to the UK economy of up to £13 billion over 10 years, representing a return on investment of £9 for every £1 spent. Future enhancements to the models, which better represent the fluid dynamics within the earth system, will realise even greater benefits.

CASE STUDY SOURCE: PROFESSOR STEPHEN BELCHER, MET OFFICE CHIEF SCIENTIST

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MEETING SOCIETY'S CHALLENGES

ALL 21ST CENTURY SOCIETAL CHALLENGES ARE IMPACTED BY FLUID DYNAMICS

Almost every natural and manufactured physical system involves fluid flow. Fluid dynamics therefore pervades all major societal challenges and should be integrated in policies designed to address those challenges and sustain long-term growth.

ROUTE TO NET ZERO

A net zero economy requires combining an understanding of climate change with innovations to reduce emissions and improve resource use. This relies on increasingly accurate fluid dynamics, starting with improved models for the climate and weather.

Wind power generates ~25% of UK electricity and will expand greatly by 2030. Fluid dynamics simulations, coupled with control algorithms, can increase wind farm efficiency by up to 20%. In the same vein, the prospect of zero carbon flight is only possible through a combination of improved aerodynamics and combustion or electro-chemical reaction of new fuels, all of which require advances in fluid dynamics.

PRODUCTIVITY AND RESILIENCE

Recent developments in fluid dynamics, measurement, and AI machine learning on big data enable the UK manufacture of high-value materials tailored to specific applications, for example, new high-performance batteries.

Fluid dynamics is central to cleaning and decontamination, with applications from domestic cleaning to removing hazardous chemical, biological, radioactive, or nuclear materials. Flooding is an increasingly common and catastrophic hazard in many regions. Fluid dynamics is used to manage the risk of floods, improve urban planning, and design for flood resilience.

> "FLUID DYNAMICS IS ESSENTIAL IN THE MATERIALS PROCESSING INDUSTRIES, REPRESENTING A FUNDAMENTAL BUILDING BLOCK FOR EXISTING AND INNOVATIVE UNIT OPERATIONS."
>
> DR KIERAN LOONEY, RESEARCH LAUREATE, DUPONT TEIJIN FILMS

LEVELLING UP

Fluid dynamics is central to the productivity and success of industries across the UK. Two out of three jobs in the sector are located outside London and the South East, with fluid dynamics making a transformative impact in multiple markets from pharmaceutical manufacturing to power generation.

Recent studies have highlighted how pollutant dispersal and building ventilation affect health, particularly in deprived areas. Fluid dynamics shows how to ventilate buildings and design towns where pollutants are diluted to safe, sustainable levels.

In healthcare, fluid dynamics has been central to understanding placenta dysfunction, sperm motility and eye disease, aiding cost-effective diagnosis, treatment and improved healthcare for all.

UK CAPABILITY AND GLOBAL REACH

The UK is a world leader in Computational Fluid Dynamics (CFD), pervasive in all aspects of engineering design. This drives global companies to engage UK expertise, giving the country a highly leverageable capability.

The UK is a world leader in aerospace and aeroengines, advances in which depend heavily on CFD. This brings significant economic benefits, with the value of commercial aircraft platforms expected to reach $7 trillion over 20 years, and capability benefits in unmanned aerial vehicles and micro-drones.

The UK is a global leader in the fluid dynamics of oil extraction. This is increasingly important as the UK depletes its easily accessible reserves and begins to use advances in fluid dynamics to acquire what remains whilst enabling time for shifting to a net zero economy.

Understanding fluids is vital to addressing the biggest challenges facing society. The UK has world leading capability in this area, ready to be leveraged into next-generation transformative solutions across all applications.

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NET ZERO THROUGH FLUID DYNAMICS

- Increasing wind and tide power efficiency
  Enabling safe nuclear fusion and fission
  Optimising carbon sequestration and storage
- Increasing aero-engine efficiency
  Reducing turbulent friction at surfaces
  Designing fluids and cycles for heat pumps
- Predicting weather and climate reliably
  Designing CO_2 capture and storage
  Investigating optimal direct capture of CO_2 from air

LEVELLING UP WITH FLUID DYNAMICS

- Generating high value regional manufacturing jobs
  Enabling high productivity in multiple industries
  Co-ordinating wind tunnels across the UK
- Understanding urban air quality
  Optimising building ventilation
  Reducing airborne viral transmission
- Visualising flows in the human body
  Understanding organ health
  Informing non-interventional reproductive health

PRODUCTIVITY AND RESILIENCE USING FLUID DYNAMICS

- Manufacturing functional materials
  Developing Digital Twins for flow processes
  Optimising design using advanced CFD
- Developing efficient and clean process engineering
  Dispersing and removing pollutants and microplastics
  Cleaning and decontaminating surfaces
- Managing rivers, coasts, and floods
  Modelling and predicting space weather
  Improving drought resistant agriculture

UK CAPABILITY IN FLUID DYNAMICS

- Leading globally in Computational Fluid Dynamics
  Maximising the impact of big data and AI in CFD
  Driving novel interfaces with physics-based modelling
- Supporting large-scale UK wind and tide power
  Optimising residual oil and gas recovery
  Designing future UK nuclear fusion capability
- Reducing aerodynamic drag in planes, cars and trucks
  Developing future propulsion and power devices
  Leading on hydrogen and fuel cell technology

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FLUID DYNAMICS GROWTH

FOUR OUT OF TEN FLUID DYNAMICS COMPANIES EXPECT TO GROW BY OVER 10% A YEAR.

Three quarters of fluid dynamics companies expect to grow by at least 5% per annum over the next three years, according to a survey of the industry, with 40% of firms predicting annual growth of over 10%.

Strong customer demand is almost universally cited as driving this growth, supported by introducing new products. This is underpinned by collaborations with universities and supply chain partners, with almost half of firms viewing access to public funding as a critical enabler for their growth.

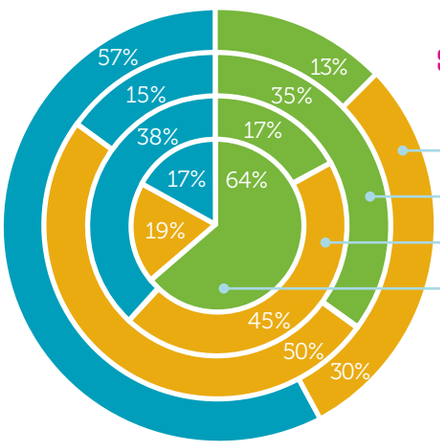
To support this growth, companies identify a strong need for research and development skills at post-graduate level, although they are divided over how easy it is to recruit skilled staff. Accessing staff with more than five years' experience is cited as a greater challenge, indicating a need to continue to foster, retain and expand the fluid dynamics future talent pool.

Exports are a significant focus for the UK fluid dynamics industry. Three quarters of firms report exporting over 20% of their output, with one third of these exporting over 50%. Europe and North America are the principle export destinations, closely followed by China and Asia (including Japan, Taiwan and South Korea).

The UK fluid dynamics industry is investing heavily in its growth, supporting the Government's target to increase the share of R&D expenditure to 2.4% of GDP by 2027. Half of all firms report having invested more than 2.5% of their turnover back into company growth over the last three years, with the number investing at this level projected to increase in the next three years.

Firms report that most of this growth has been funded from retained earnings, reflecting the ongoing strength of the industry. In addition, one third of firms indicate that they have also used public funding in the last three years (e.g. from Innovate UK), demonstrating its importance in leveraging private investment.

Half of firms reported a decline in sales and scaling back of expansion plans since January 2021, due to COVID-19. However, the groundwork for rapid recovery has been laid. Three quarters of firms reported no impact on their product development plans, with some even stating that their plans had accelerated during the pandemic, supporting their strong growth predictions for the next three years.



SKILLS REQUIRED IN THE NEXT 3 YEARS

Manufacturing staff at technician level (HND/HNC or below)

Research and development staff at postgraduate level (PhD, MSc)

Commercial / operations personnel (e.g. sales, HR, operations) at graduate level

Experienced staff with >5 years' industrial experience

REQUIRED & IN SHORT SUPPLY

REQUIRED BUT AVAILABLE

NOT REQUIRED

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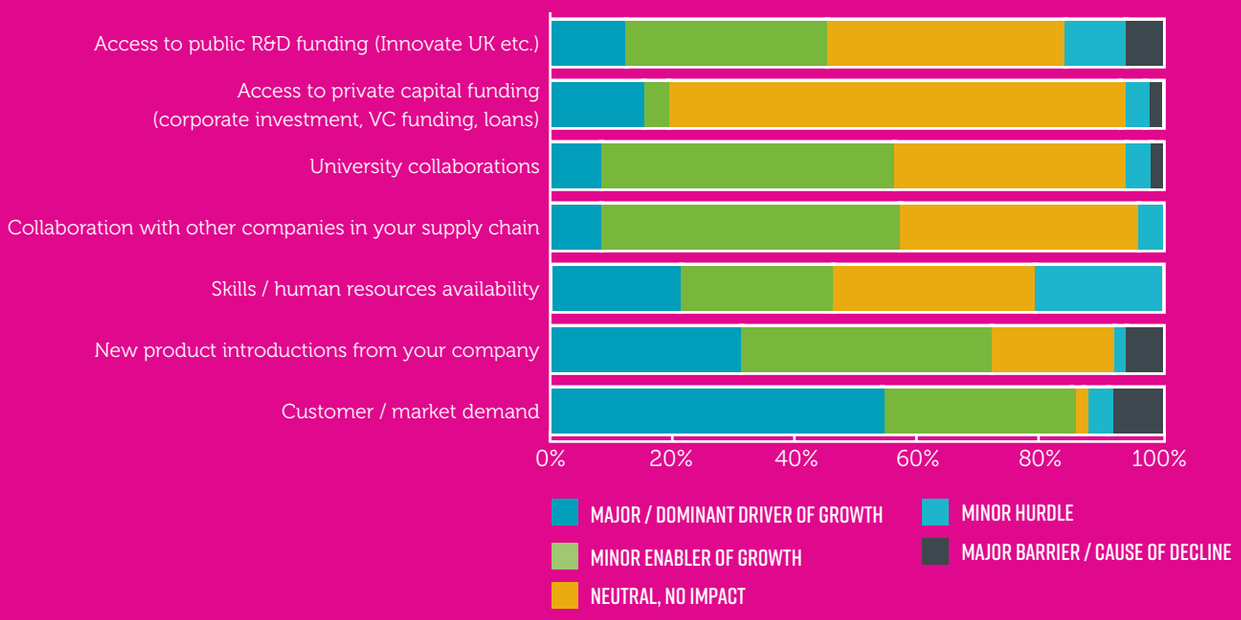
DRIVERS OF GROWTH / DECLINE

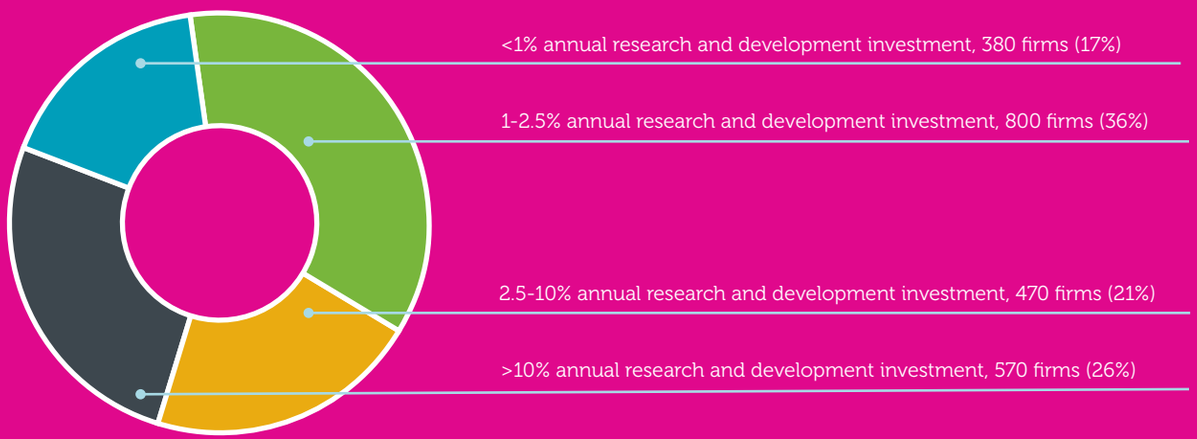


"WE SEE MASTERY IN FLUID DYNAMICS AS A STRATEGIC CAPABILITY AND A KEY ENABLER FOR INNOVATION IN THE FAST-MOVING CONSUMER GOODS (FMCG) SECTOR."

ZAYEED ALAM, CORPORATE DIRECTOR, DATA AND MODELLING SCIENCES, PROCTER & GAMBLE, EUROPE

INDUSTRIAL RESEARCH AND DEVELOPMENT INVESTMENT

Next 3 years (2021-2023 inclusive)



Annual research and development by UK fluid dynamics companies based on survey responses for forecast investment from 2021-2023

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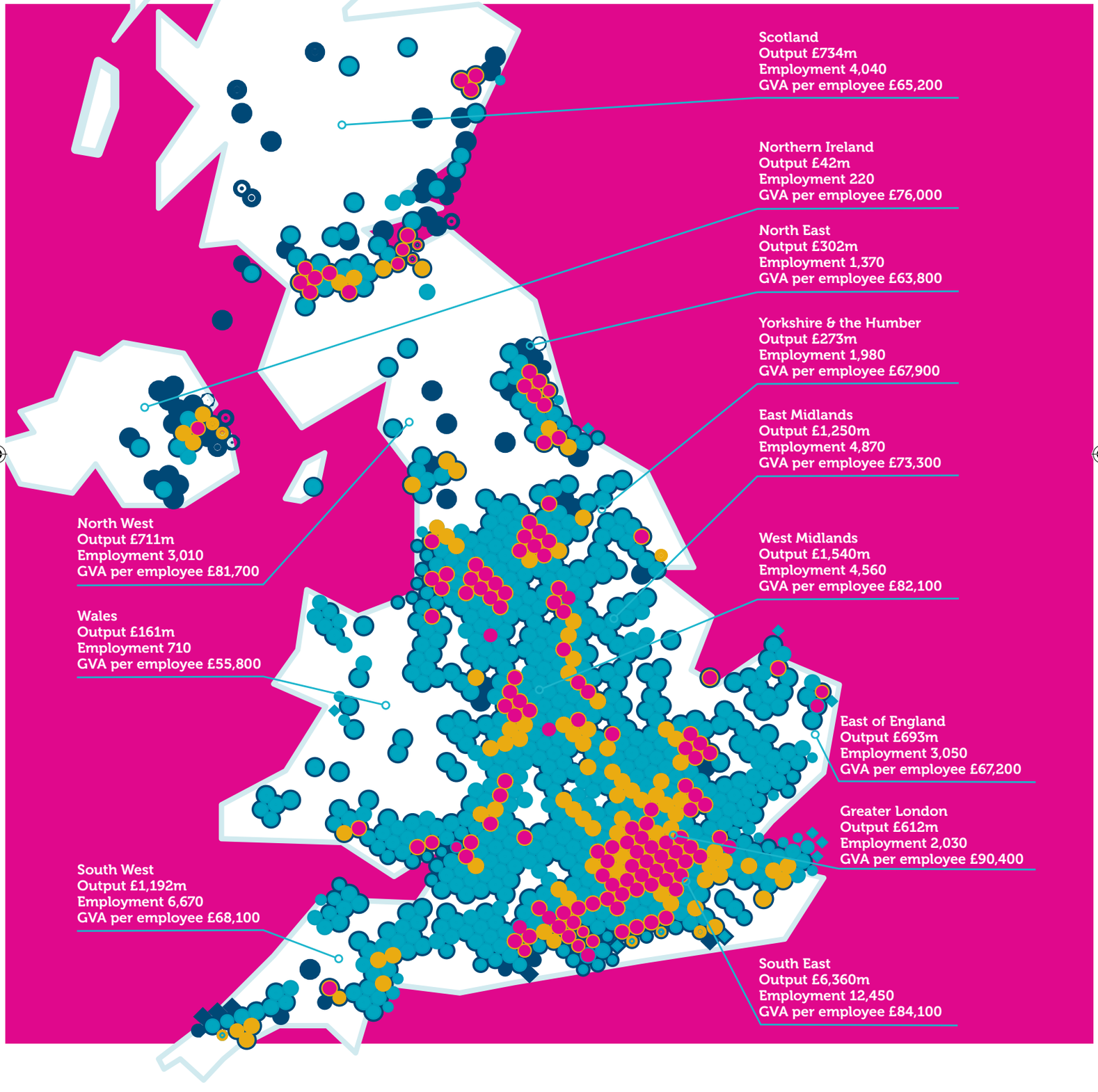
REGIONAL DISTRIBUTION



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The fluid dynamics industry is widely distributed geographically. Over 3,300 addresses were recorded for the 2,200 companies contributing to the UK fluid dynamics industry, indicating that many firms operate in multiple locations within the UK. The overall distribution broadly follows the UK's industrial base, with greater activity on the east coast of Scotland due to the critical role of fluid dynamics in the oil and gas sector, and a high concentration on the south coast of England owing to marine applications. Notably, fluid dynamics companies can be found at the extreme ends of the UK, from Shetland to southern Cornwall.

Four regions, including the East and West Midlands, the South East and South West, host over £1 billion of fluid dynamics activity. The South East region records the largest fluid dynamics activity, partly due to the location of BP's substantial global R&D facility.

Productivity, as estimated from the gross value added per employee, exceeds £80,000 per employee in four regions, including the North West, West Midlands, South East and London. Unlike many other industries, this shows that some of the most productive fluid dynamics activity occurs outside the South East.

FLUIDS ARE SO UBIQUITOUS THAT WE TEND TO TAKE THEM FOR GRANTED. BUT THE ABILITY TO ENHANCE OR CONTROL FLUID MOTION IS CRUCIAL IN MANY BUSINESSES, FROM AVIATION, TO THE MATERIALS AND PROCESS INDUSTRIES, TO BIOENGINEERING.

PROFESSOR DAME ANN DOWLING, OM, DBE, FRENG, PAST PRESIDENT OF THE ROYAL ACADEMY OF ENGINEERING

The lower productivity observed in Wales is due to the influence of the steel industry, where fluid dynamics makes a small but critical contribution to production. The high losses recently incurred by the steel industry mean that even when only a small fraction of an operation is associated with fluid dynamics, it negatively impacts the local fluid dynamics GVA.

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ANSYS CASE STUDY

PUSHING BACK BOUNDARIES WITH COMPUTATIONAL FLUID DYNAMICS SOFTWARE

Computational Fluid Dynamics (CFD) software enables simulations of flows, ranging from microscale, such as blood vessels, to medium-scale, such as vehicle aerodynamics, to large-scale, such as environmental impact from chimney plumes. From academic origins, it has been commercially transformed to become an essential tool for engineers, scientists and researchers. With global revenues of over $1.6 billion, Ansys delivers CFD software as part of the core technology of its simulation suite. As well as being the historical birthplace of our industry-leading CFD tools, Fluent and CFX, the UK continues to be an important commercial centre for the development and application of fluids simulation methods to solve common and complex problems. This allows engineers to bring technologies to market against an increasingly competitive and technically demanding environment. Ansys customers in the UK are using CFD software to solve a range of problems, for example:

POWER GENERATORS - TO DETERMINE THE BEST LAYOUT OF AN ARRAY OF WIND TURBINES OVER COMPLEX TERRAIN

FORMULA I TEAMS - TO OPTIMISE THE VEHICLE AERODYNAMICS IN ADVANCE OF EVERY TRACK ON WHICH THEY RACE

AUTOMOTIVE OEMS - TO ENSURE THEIR ELECTRIC VEHICLE BATTERIES AND MOTOR SYSTEMS ARE AT OPTIMAL OPERATING CONDITIONS THROUGHOUT THE DRIVE CYCLE

ENERGY COMPANIES - TO BE CERTAIN THAT THEIR COMPONENTS AND ASSEMBLIES WILL DELIVER UNDER DEMANDING OPERATING CONDITIONS

DOMESTIC APPLIANCE MANUFACTURERS - TO PROVIDE MAXIMUM PERFORMANCE WHILST ACHIEVING THE BEST ENERGY EFFICIENCY

BUILDING SERVICES DESIGNERS - TO IMPLEMENT NOVEL, LOW-ENERGY SOLUTIONS TO DELIVER IMPROVED VENTILATION AND OCCUPANT COMFORT

AERO-ENGINE DESIGNERS - TO MEET EVER-GROWING DEMAND FOR EFFICIENCY AND ALTERNATIVE GREEN FUELS

The UK has leveraged its strong background in fundamental fluid dynamics to generate internationally-leading brands and expertise in the global market for CFD software. Ansys is part of this UK success story and continues to work with its UK customers to design, develop, innovate and deliver with the latest methods and technology.

CASE STUDY SOURCE: ANSYS UK LTD.

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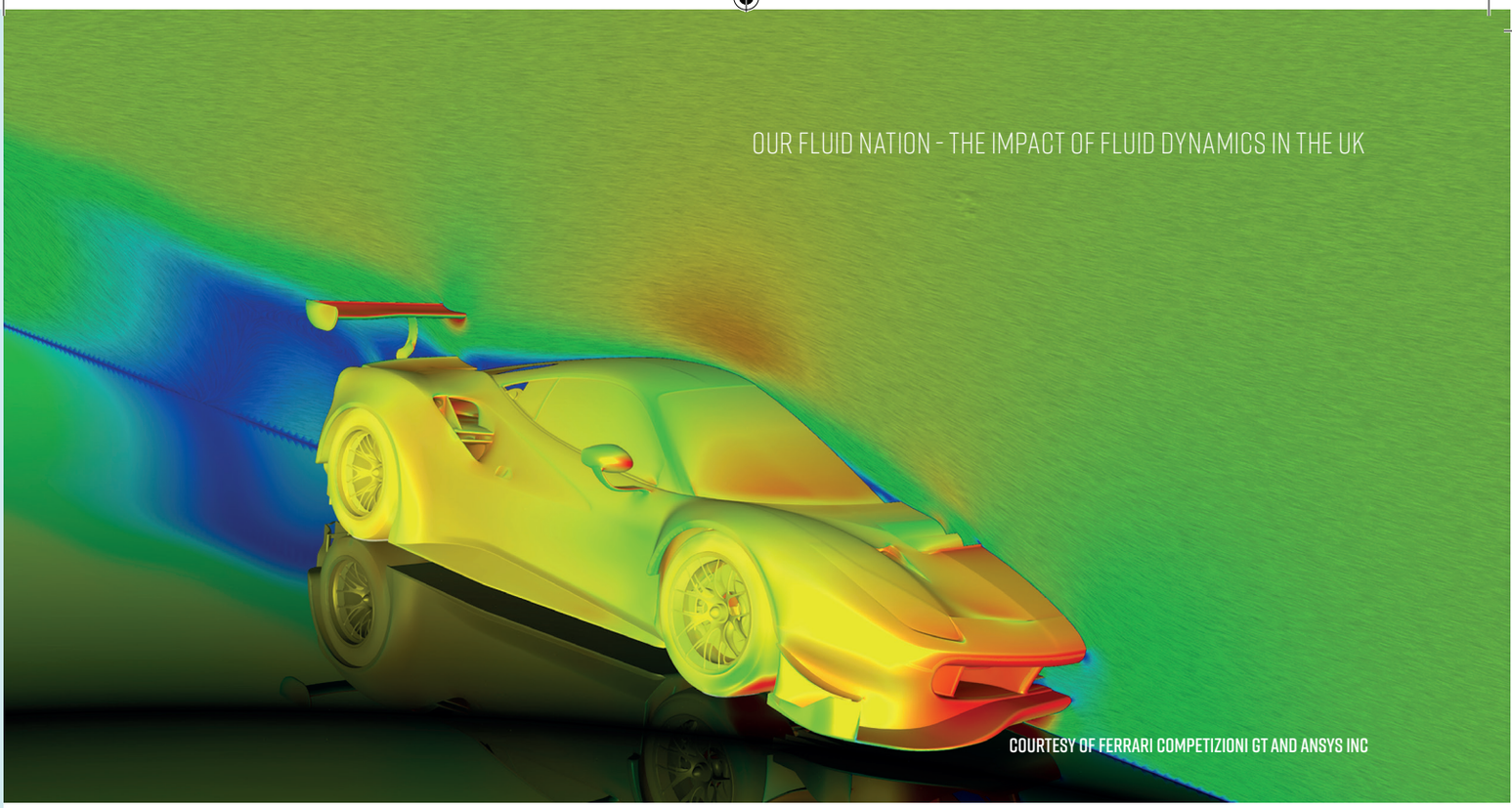
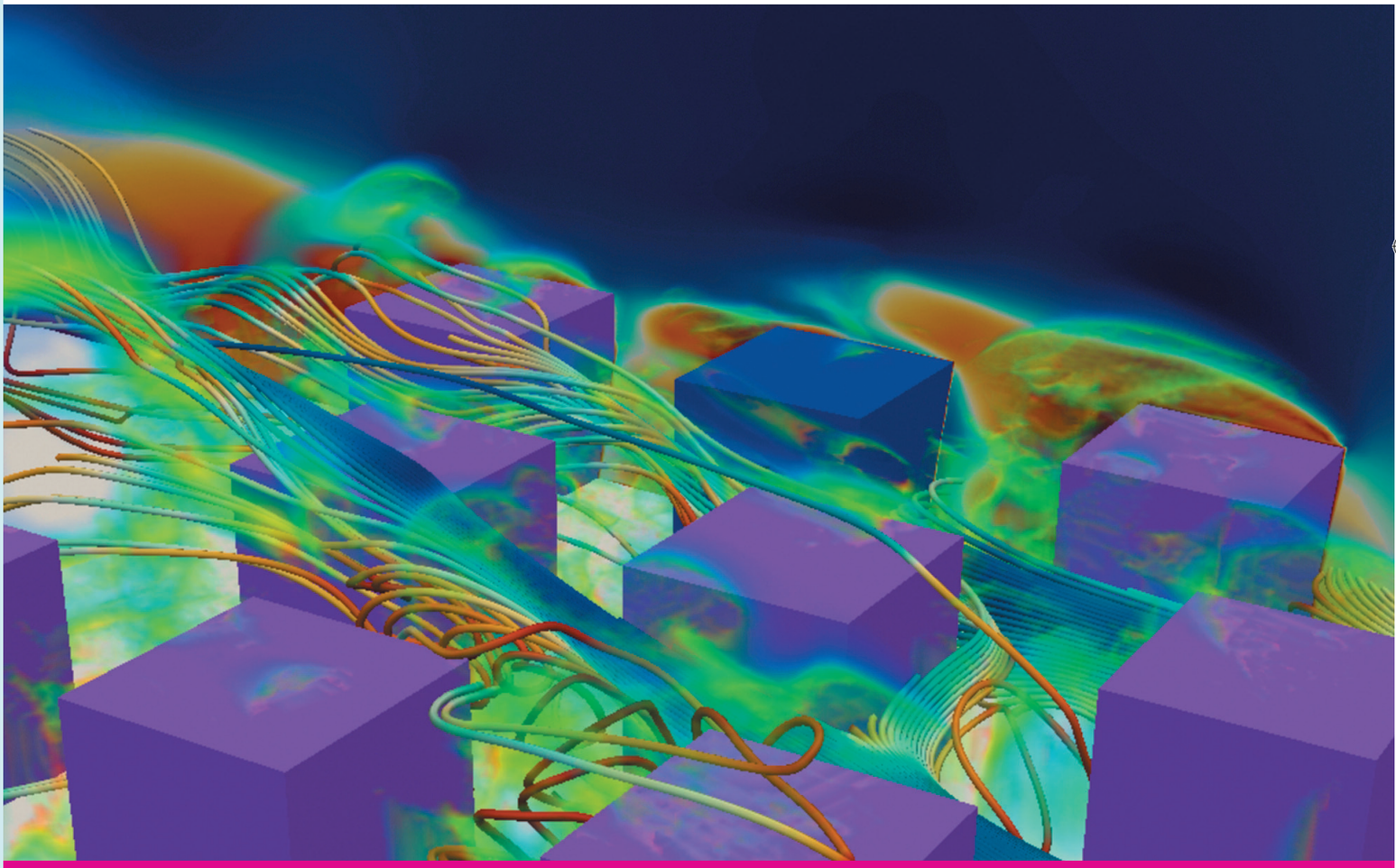


COURTESY OF FERRARI COMPETIZIONI GT AND ANSYS INC



PRESSURE FIELD AROUND A CAR AND
AIRFLOW AROUND AN ARRAY OF BUILDINGS CALCULATED WITH ANSYS FLUENT

IMAGE COURTESY OF DR MARCO
FELIPE-KING, RESEARCH FELLOW, CIVIL
ENGINEERING, UNIVERSITY OF LEEDS

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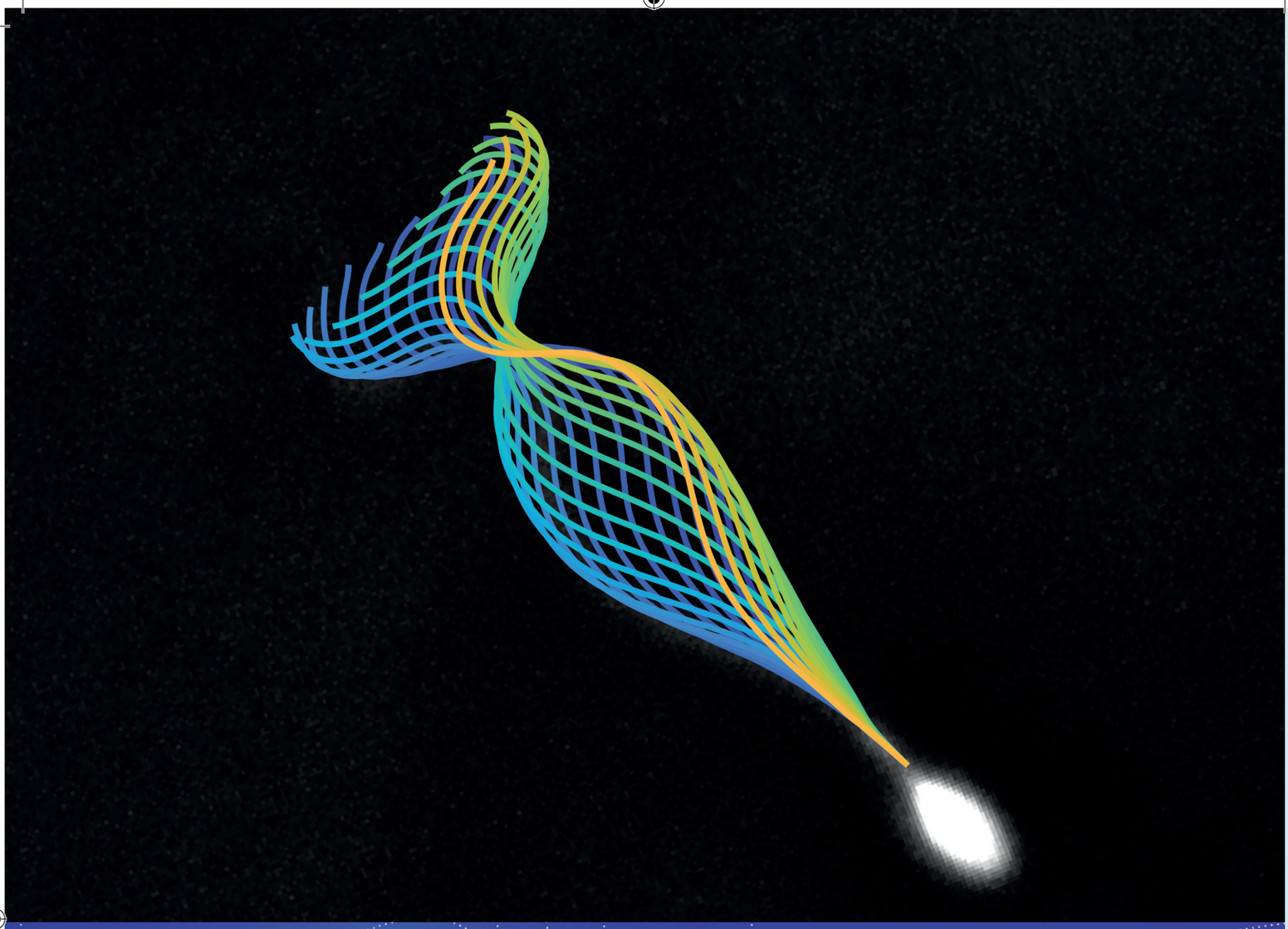

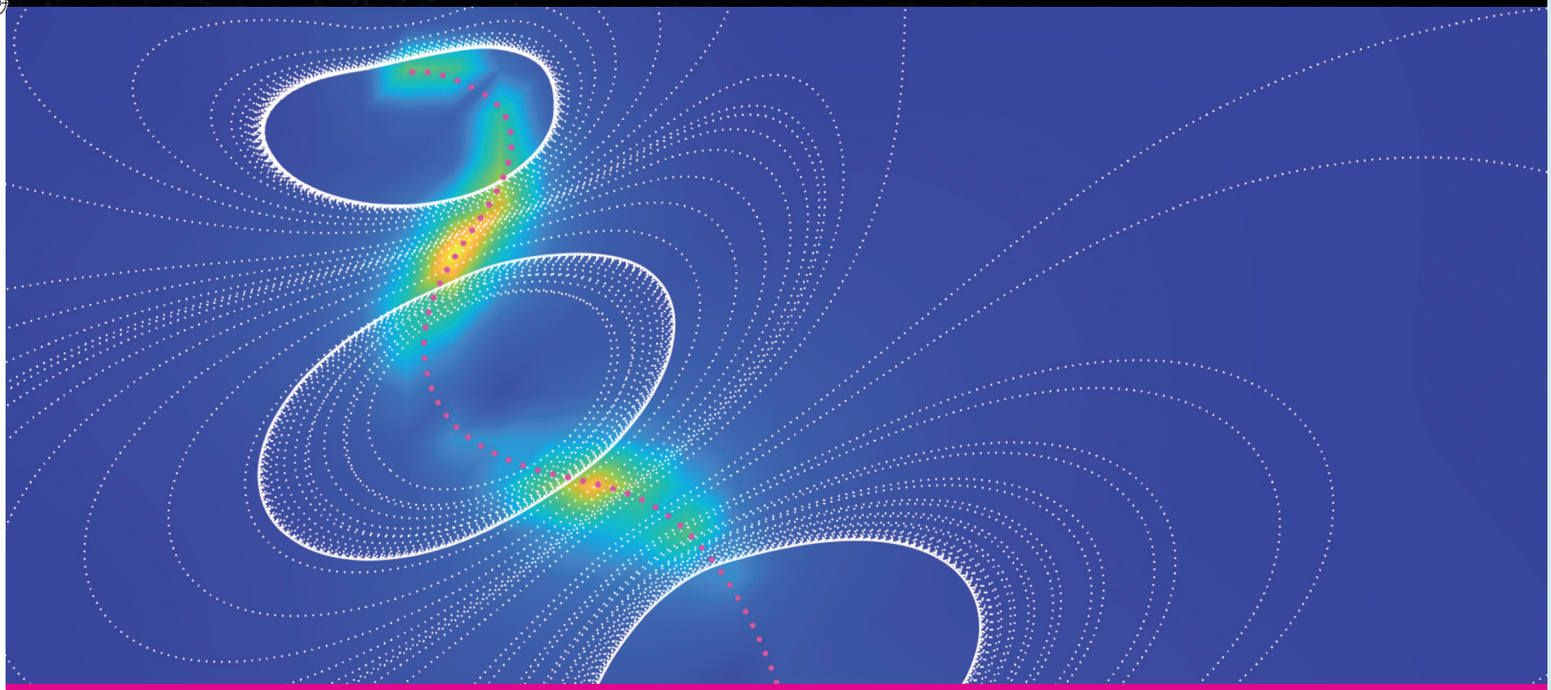

MICROGRAPH OF SPERM ALONGSIDE FLOWFIELD
IMAGE COURTESY OF DAVID J. SMITH AND MEURIG GALLAGHER

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REPRODUCTIVE HEALTH CASE STUDY

FLUID DYNAMICS IS ENABLING ESSENTIAL NEW INSIGHTS TO SUPPORT ADVANCES IN REPRODUCTIVE MEDICINE

Pre-term and stillbirths affect up to 10% of all deliveries, and pregnancy complications cost the NHS over £1.2 billion each year. Issues with fertility affect large numbers of people and there are over 75,000 IVF cycles every year in the UK. Two collaborations between academic research teams and the NHS are harnessing fluid dynamics to support new approaches for assessing placental blood flow and sperm quality.

Knowledge of the structure of the human placenta and the mechanisms of blood flow and transport of solutes is essential for understanding placental function in high-risk pregnancies. A collaboration between academic and clinical centres of excellence across the UK is using experimental and Computational Fluid Dynamics expertise to help transform obstetrics and neonatal critical care into technology-enabled precision medicine.

With the support of the MRC and EPSRC, the teams in Manchester and Edinburgh are using the UK national imaging facilities at the Diamond Light Source, informed by a combination of ex-vivo physiological perfusion and biomimetic microfluidics experiments, to build and validate a set of computational models. These have already helped integrate the anatomy and physiology of the human placenta into novel biometrics which can serve as signatures of pathology for the fetal medicine of the future. Further iterative testing, refinement and validation will enable model-based clinical diagnostics and therapies for placental dysfunction, as well as design optimisation of an 'artificial placenta' for the support of extremely premature babies.

Key challenges for IVF are its high cost, relatively low success rate, and high physical and emotional burden for the patients. Male factors contribute to around half of all cases of infertility but diagnostics remain relatively rudimentary, focusing on sperm counting. However, as sperm are continually produced, they provide an excellent avenue to improve a couple's chances of conceiving through lifestyle interventions and less invasive procedures, such as intra-uterine insemination.

Through EPSRC and NIHR funding, a team at the Centre for Human Reproductive Sciences in Birmingham have developed a computer algorithm (FAST) to track the high speed, complex beat pattern of sperm as they propel themselves through fluid and to analyse the energy output required of the cell. This free-to-use software represents a step change in how sperm are examined and is currently in the early stages of clinical translation, with data being collected routinely from IVF cycles. This integration of knowledge has the potential to unlock major benefits. If even 5% of IVF cycles taking place each year could be moved to IUI, this would save £15M annually alongside protecting thousands of patients from the associated physical risk and emotional stress.

CASE STUDY SOURCE: THE UNIVERSITIES OF BIRMINGHAM, EDINBURGH, MANCHESTER AND SOUTHAMPTON (UK), AND MCMASTER (CANADA); NHS MANCHESTER TOMMY'S MATERNAL AND FETAL HEALTH RESEARCH CENTRE; DIAMOND LIGHT SOURCE; AND ROSALIND FRANKLIN INSTITUTE (UK)

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NATIONAL COMPARISONS

The UK fluid dynamics industry predominantly comprises micro- and small-sized operations. When considering the number of employees apportioned to fluid dynamics, only 1% of operations would be considered large, with more than 250 employees, and 5% medium-sized. This distribution is very similar to the overall UK engineering and manufacturing sectors. At 24%, there are fractionally more small than micro-sized operations.

Illustrating how fluid dynamics operations are frequently embedded in larger organisations, the distribution of company size by total employees prior to any allocation to fluid dynamics, shows 6% are large organisations and 9% medium. This underpins how fluid dynamics is embedded in many large UK engineering and manufacturing organisations, delivering a key enabling function.

"THE UK HAS AN ENVIABLE POSITION IN FLUID DYNAMICS ANALYSIS, FROM THE EARLY CONTRIBUTIONS OF REYNOLDS, FROUDE AND RAYLEIGH TO BEING THE ORIGINAL SOURCE OF MUCH OF THE COMPUTATIONAL FLUID DYNAMICS SOFTWARE USED AROUND THE WORLD TODAY. THE RAPID CHANGES WE FACE IN THE TRANSPORT, ENERGY, AND CHEMICALS INDUSTRIES AS WE MOVE TO NET ZERO WILL DRAW HEAVILY ON THIS EXPERTISE; FLUID DYNAMICS HAS NEVER BEEN MORE IMPORTANT."

SIMON REES, PROJECTS DIRECTOR, NORTON STRAW CONSULTANTS LTD.

Whilst there may be far more micro and small fluid dynamics companies and operational units, the majority of the industry's revenue and employment comes from the larger organisations. 70% of overall fluid dynamics revenues are generated by just 1% of large firms, which in turn employ 45% of people in the industry. This is not unusual and other enabling technologies, e.g. photonics, show revenues and employment figures similarly dominated by large firms, both in the UK (Photonics Leadership Group, 2019), and internationally (SPIE, 2021).

45,000 people are directly employed in the UK fluid dynamics industry. This is similar to employment in the UK nuclear sector, significantly more than the UK steel industry employs and stands at around two thirds of the number employed in FinTech. However, unlike in FinTech, fluid dynamics employs more than 30,000 people (70% of its workforce) outside of London and the South East.

Crucially, more than 500,000 UK jobs are estimated to depend on the direct application of fluid dynamics expertise and technology. This is the total number of people employed in diversified firms which have internal fluid dynamics capability. However, it does not include the many more people employed in the sale, distribution and installation of fluid dynamics products, ranging from air and pumping installation to water treatment. Indeed, so pervasive is the use of fluids of one form or another in society that the majority of economic activity relies on fluids, and thus the understanding of fluid dynamics, at some level.

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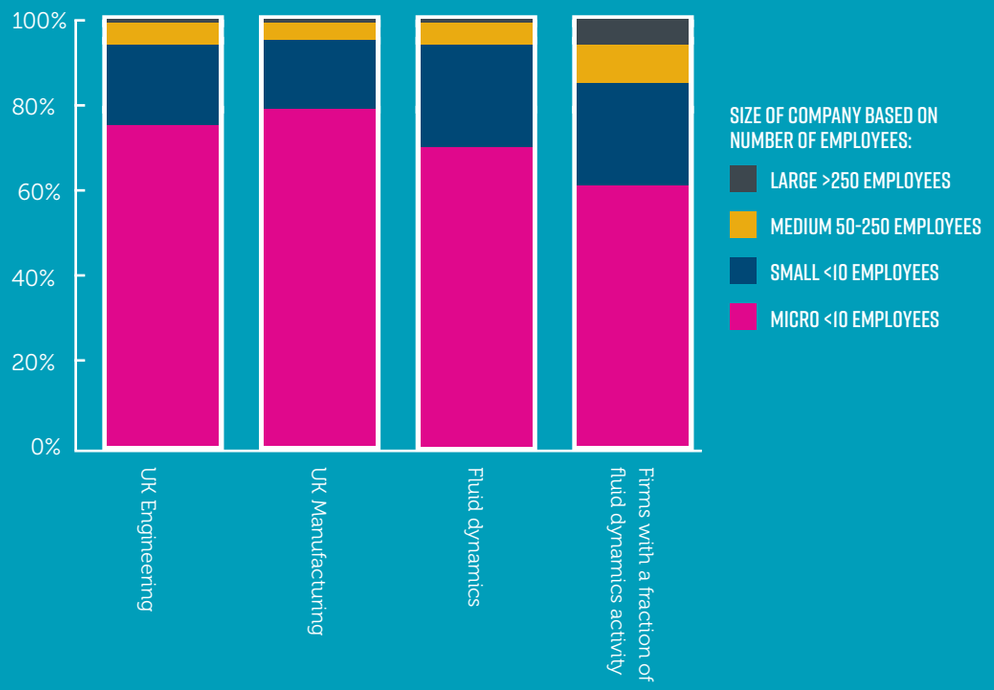
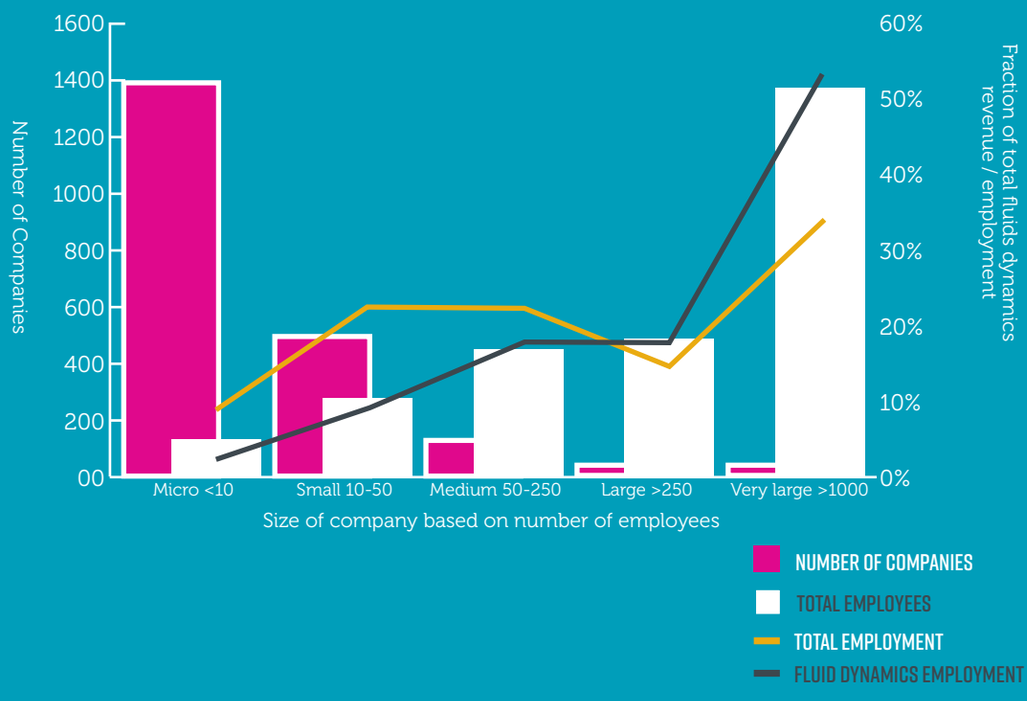
SIZE OF FLUIDS FIRMS RELATIVE TO UK ENGINEERING, MANUFACTURING & OTHER ENABLING, CROSS-CUTTING SECTORS



REVENUE BY SIZE OF OPERATION



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METHODOLOGY SUMMARY

WIDESPREAD APPLICATION OF FLUID DYNAMICS ACROSS A VAST ARRAY OF MARKETS CHALLENGES QUANTIFYING ITS ECONOMIC CONTRIBUTION.

Companies active in fluid dynamics use a huge range of 'Standard Industry Classification' (SIC) codes, with no differentiation from other industries. As a result, an alternative approach to using SIC based sector figures was necessary.

A combination of two approaches was used: first, a focused industry survey to obtain unreported data; second, an adaption of the methodology previously used to size the photonics and acoustics industries in the UK and internationally, which involved apportioning a fraction of the firms' reported activity to fluid dynamics.

The survey was conducted in Q1 2021 and had separate questions for industrial and academic respondents. Industrial participants were requested to report on growth, growth drivers, exports, investment and sources of funding, both over the last three years and also forecasting for the next three. Academics were asked for sources of funding as well as interaction with and level of funding from industry. Both groups were asked to comment on the impact of COVID-19, their regional location and topic of fluid dynamics focus/ expertise.

The process of sizing the fluid dynamics industry comprised five key steps:

1. A comprehensive list of companies delivering fluid dynamics products and services in the UK for internal or external customers was constructed. Over 2,200 companies were identified using a machine learning (ML) algorithm from The Data City, trained using a set of known fluid dynamics companies and applied to descriptions from the websites of ~900,000 UK companies.

2. For the largest and most diversified companies and key sub-sectors, a panel of industry experts was asked to estimate the proportion of output attributable to fluid dynamics activity.

3. The apportioned fraction was applied to the turnover, profit and employment figures for those companies, based on their latest annual fillings at Companies House, obtained from Dun and Bradstreet. This yielded the output, profit and employment directly attributable to fluid dynamics.

4. Gross value added for the sector was calculated from profit plus the total employee benefits paid. The latter was based on the average benefit paid per employee for fluid dynamics in the UK (£53,708), taken from a sample of 20 companies with 13,000 employees, where employee benefits had been reported to Companies House.

5. The regional distribution was based on 3,300 operational addresses recorded for UK fluid dynamics firms. The financial and employment figures were split uniformly between sites where firms operate in more than one location, unless evidence was available that the fluid dynamics activity took place preferentially in one location.
(For further details, see Appendix.)

The use of machine learning enabled the first comprehensive list of UK companies working in fluid dynamics to be built. When combined with expert apportioned financial data and a comprehensive survey, this approach has enabled unique insights into the contribution of fluid dynamics to the UK economy.

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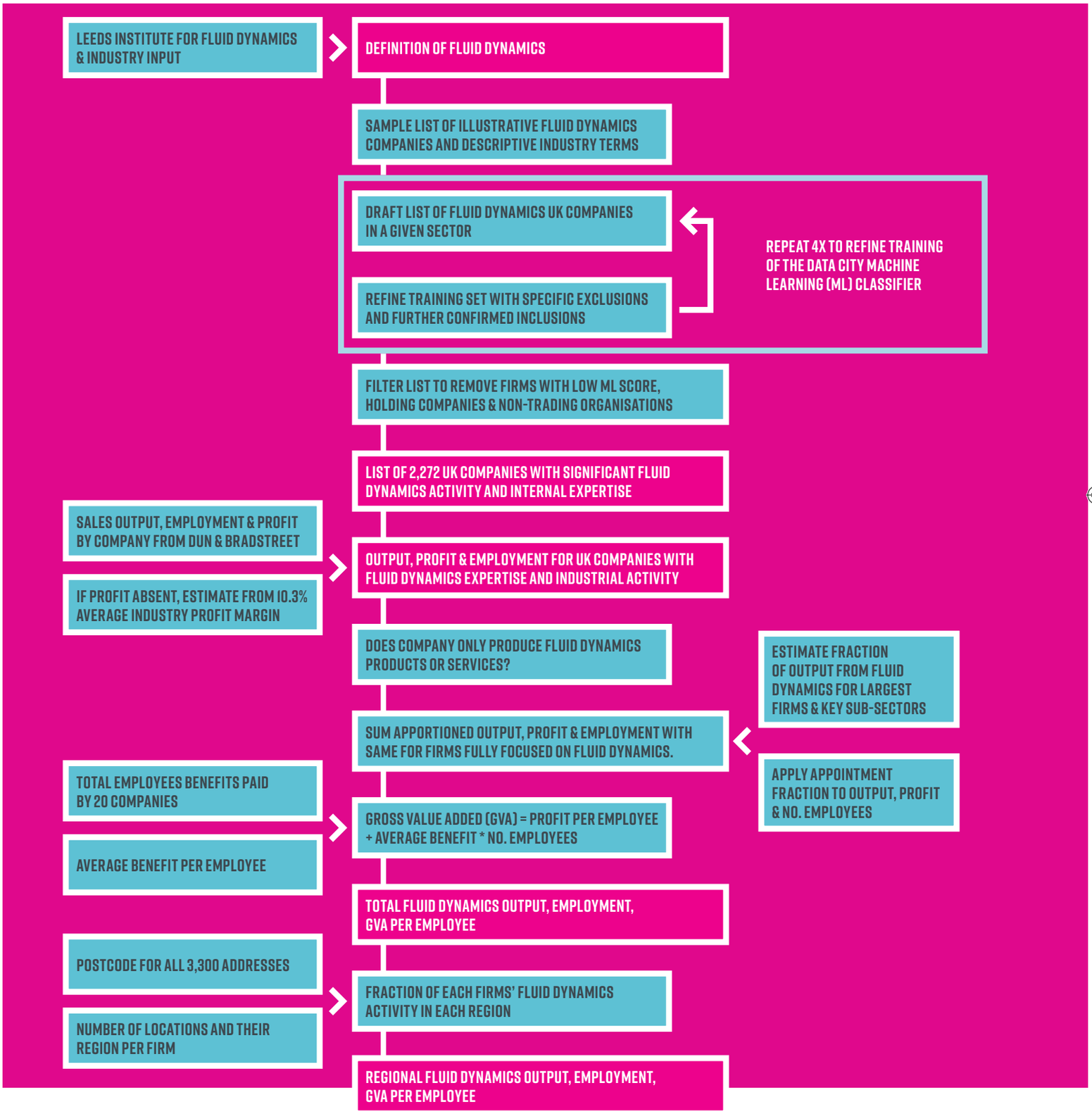

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FLUID DYNAMICS KNOWLEDGE BASE

FLUID DYNAMICS RESEARCH IN THE UK IS WORLD-LEADING, WITH STRONG SUPPORT FROM UKRI, EUROPE AND INDUSTRY.

The UK has historically been, and continues to be, a world leader in fluid dynamics research. This includes leading breakthroughs in fundamental, computational, data-driven and experimental methods in fluid dynamics. Research strength in universities is spread both geographically and among many disciplines, including mathematics, physics, engineering, biophysics, and geo- and environmental sciences.

An analysis of data from UKRI shows that since 2012, over 3,600 fluid dynamics-related grants have been funded by UKRI with a total value exceeding £2.3 billion. Of these, approximately half the awards and half the value can be attributed to EPSRC for research in fundamental and engineering fluid dynamics. Nevertheless, fluid dynamics research is supported broadly, with considerable investment from NERC (over 1,000 grants with a total value exceeding £400 million) for research in geophysical fluid dynamics (applied, for example to the atmosphere, ocean or the Earth's fluid interior), STFC (over 400 grants valued above £200 million) for research in astrophysical fluid dynamics, and Innovate UK (over 350 grants valued above £0.4 billion). The strong support from all research councils as notable sources of funding indicates the importance of fluid dynamics to the full range of scientific disciplines and problems, spanning fields as diverse as climate modelling, medical research, engineering to net zero, and astrophysics.

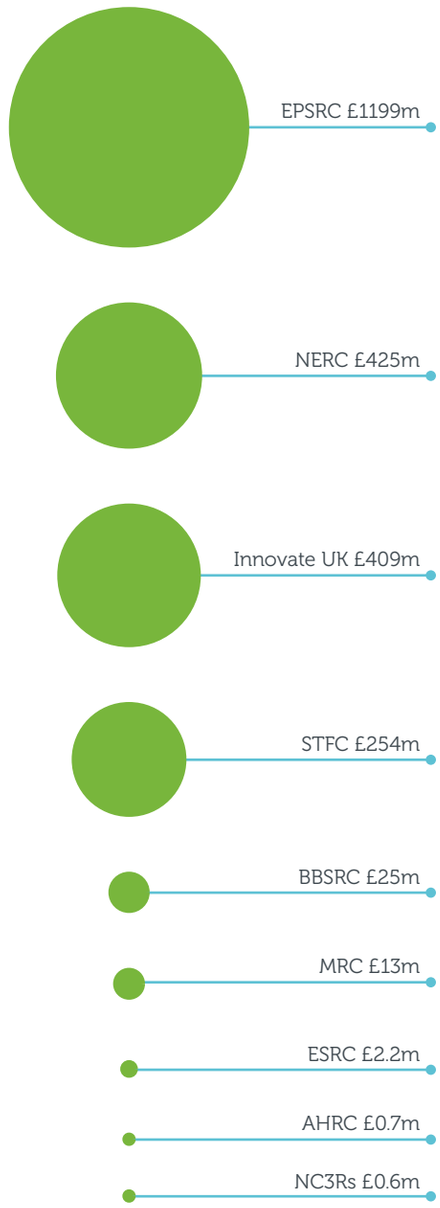
The fluid dynamics knowledge base is also geographically dispersed across the UK. UKRI funding was received by over 75 universities and 300 companies, broadly spread across England, Scotland, Wales and Northern Ireland. This speaks to the importance of fluid dynamics at a local as well as a national level.

Fluid dynamics research is associated with 17 UKRI-funded Doctoral Training Partnerships (DTPs) and 15 Centres for Doctoral Training. Each DTP/CDT provides funding for around 10-20 PhD students per year, demonstrating a significant transfer of advanced fluid dynamics knowledge to the next generation.

An analysis of survey responses indicates that Europe has also been a major source of funding for at least one quarter of researchers. The continued access to Horizon Europe funding for UK researchers is therefore extremely welcome and it is vital to maintain this funding source in the future.

The survey results also demonstrate that industry was also seen as a significant source of research funding for one quarter of academics, with modest size projects (<£0.5m) being the most common. Industry income is also expected to increase over the next 3 years, with the strongest growth anticipated in £0.5-2 million scale industrial projects.

VALUE OF GRANTS RELATING TO FLUID DYNAMICS FROM UKRI DATA 2012-2021



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"THE UK HAS BUILT A SIGNIFICANT REPUTATION FOR EXCELLENCE AND INNOVATION IN FLUID DYNAMICS THAT HAS PROVEN TO BE CRUCIAL TO THE PRODUCTIVITY AND SUCCESS OF MANY INDUSTRIES, INCLUDING CHEMICALS, BIO-TECH AND AEROSPACE ACROSS MANY REGIONS OF THE UK."

KEDAR PANDYA, DIRECTOR, CROSS-COUNCIL PROGRAMMES, ENGINEERING AND PHYSICAL SCIENCES RESEARCH COUNCIL

PRINCIPLE SOURCE OF GRANT FUNDING FOR RESEARCH

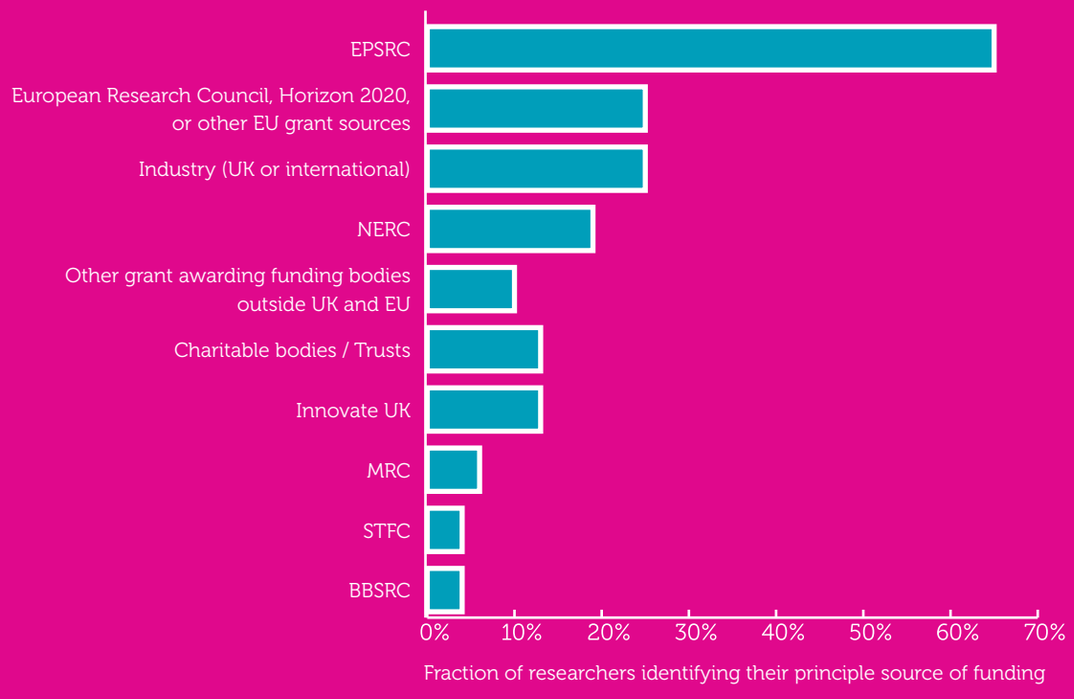

IMAGE COURTESY OF CHRIS HOWLAND

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SUMMARY AND RECOMMENDATIONS

FLUID DYNAMICS IS VITAL FOR OUR HEALTH, OUR ENVIRONMENT AND OUR ECONOMY.

Fluid dynamics is all around us and is integral to the products and processes we rely on every day. It underpins numerous industries and is critical to solving major societal challenges. Yet fluid dynamics is complex and often hidden from the public eye. For the first time, the influence and impact of fluid dynamics has been uncovered, revealing the importance of continued investment in this discipline.

The UK's success in fluid dynamics stems from harnessing the impact of fundamental research through to innovations in industry. The UK has been at the forefront of world-leading research in fluid dynamics for decades and expertise is embedded in multiple departments throughout academic institutions across the country.

Sustained investment in fluid dynamics expertise has led to the substantial economic impact uncovered by this report. Over 2,200 firms, with a total of 45,000 people working in fluid dynamics, generate £13.9 billion worth of output across multiple industry sectors. This is only a small fraction of the reach of fluid dynamics - the total UK turnover of companies with a portion of activity involving fluids dynamics exceeds £200 billion.

Furthermore, the societal impact of fluid dynamics is immeasurable. An understanding of fluids is vital for our health, our environment and our climate. Achieving net zero and managing pandemic disease will only be possible through understanding fundamental fluid dynamics processes.

Fluid dynamics has the power to transform sectors but its complexity requires sustained investment in training and infrastructure. It is essential that we advance the training of graduates in the mathematical and engineering skills to develop new products, processes and software, and to harness the opportunities that the combination of exascale computing and an increasingly data-led economy will bring. Fluid dynamics will be a critical enabling technology for the UK's Industrial Strategy and future economic success. A National Centre in Fluid Dynamics will drive collaboration and knowledge transfer between industry and academic partners to rapidly advance innovation across multiple sectors

RECOMMENDATIONS:

- A NATIONAL CENTRE IN FLUID DYNAMICS, BUILDING ON PRACTITIONER NETWORKS AND UK RESEARCH STRENGTHS
- INCREASED SUPPORT FOR FLUID DYNAMICS TRAINING IN INDUSTRY AND ACADEMIA
- THE APPLICATION OF NEXT-GENERATION DATA-DRIVEN FLUID DYNAMICS METHODS ACROSS SECTORS AND INTO INDUSTRY
- GENERATION AND RETENTION OF FLUID DYNAMICS INTELLECTUAL PROPERTY AND EXPERTISE IN THE UK

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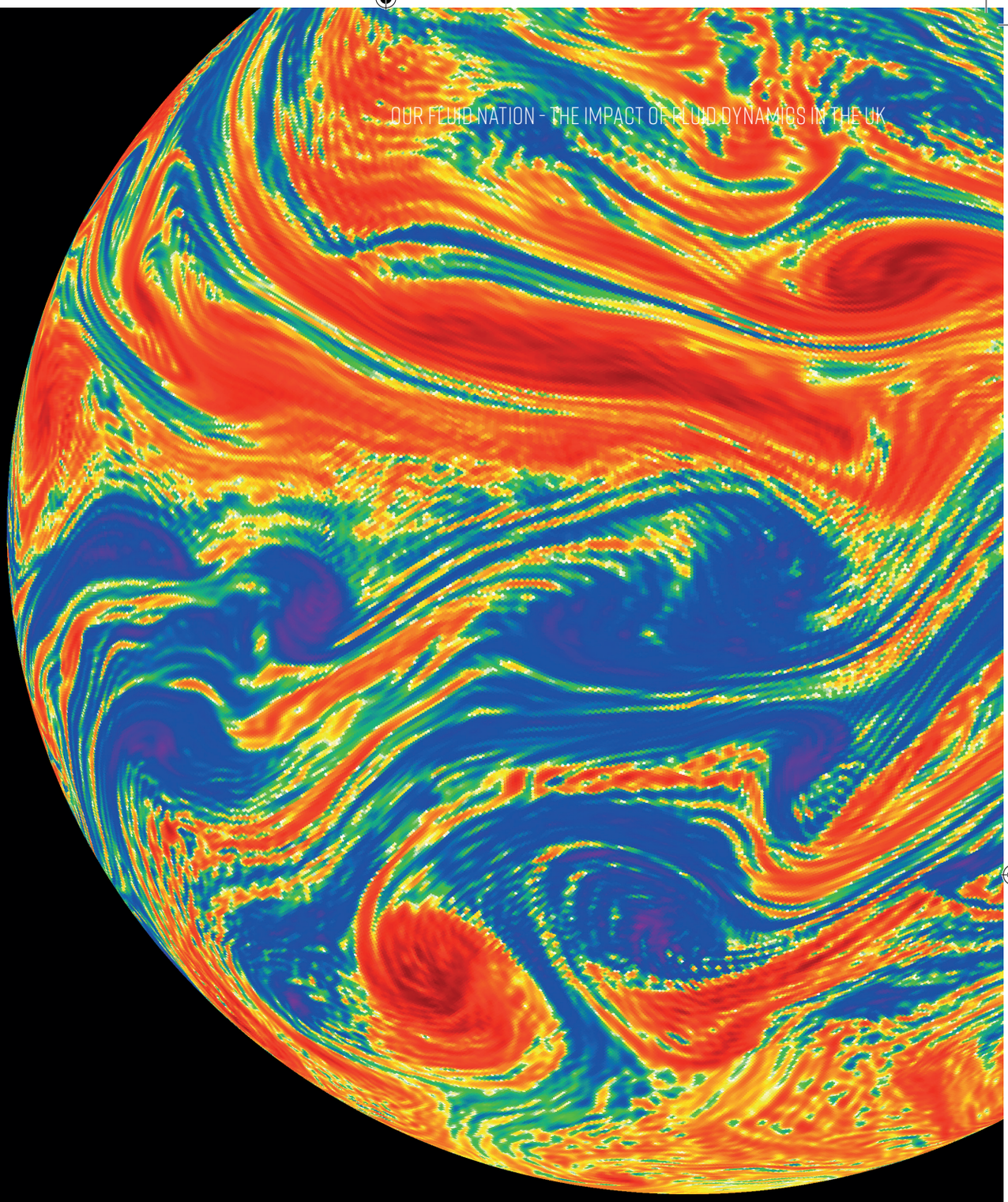

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- UK FLUIDS NETWORK
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IMAGE COURTESY OF BRAD MARSTON & STEVEN TOBIAS

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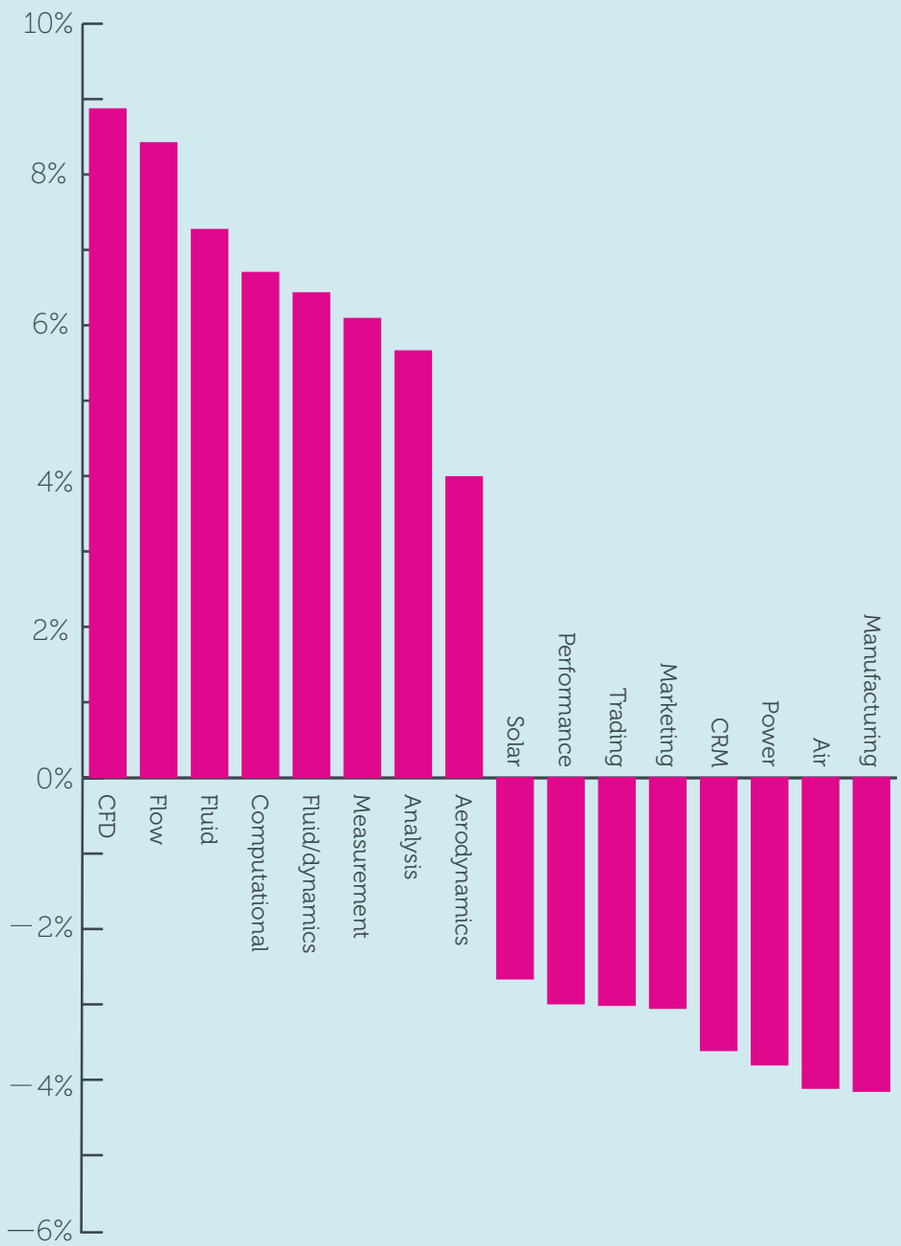
APPENDIX: SIZING METHODOLOGY

MACHINE LEARNING CLASSIFIED TERMS



COURTESY OF THE DATA CITY

Accurately sizing the fluid dynamics industry requires identifying those organisations which add distinct value with their fluid dynamics expertise, and identifying the portion of their business activity that can be fairly considered part of the fluid dynamics industry, when this is only part of their operations.

STEP I: IDENTIFY UK COMPANIES ACTIVE IN FLUID DYNAMICS

This began with forming a clear definition of fluid dynamics companies: those that add value through using the description of flows of any sort, whether in liquids, gases or plasmas, and including the ability to measure, model, control and predict fluid flows over any spatial or temporal scale, volume, temperature or speed. A number of sub-sectors became apparent as the definition covers the control of liquids, for example through pumps and valves, including blood flow, air handling and air flows (e.g. aerodynamics); and also extends to the interaction with fluids in the marine environment, as well as air and wind in the built environment.

To facilitate the identification of relevant companies over such a diverse space, a machine learning (ML) approach from The Data City was applied. The ML algorithm was trained from a set of known fluid dynamics companies and those easily confused with the sector (e.g. Contract for Difference (CfD) trading). The ML looks for common positive 'classifier' terms based on how the fluid dynamics companies describe themselves on their own websites, and also uses negative terms from companies not associated with

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the industry. Once taught, the ML engine identified similar companies from descriptions extracted from the websites of over 900,000 UK companies, ranked by fit to the classifier terms.

The process was iterated adding companies to the training set. The final top classifier terms indicated strong alignment with expected terms, such as 'cfd', 'aerodynamics', 'flow' and 'fluid'. A manual review showed that the first 1,600 ML identified companies were clearly aligned to fluid dynamics. A small number of relevant companies were also identified within the next 400 firms. Companies installing fluids technology and wholesalers, e.g. air-conditioning installation and plumbers, were removed.

To this initial group, a further 265 companies were identified in the fields of valves, pumps and fluid controls, following the same iterative ML process, filtered to include only manufacturing organisations. An additional ~200 firms were identified in the marine sector, which uses different descriptions, e.g. hydrodynamics, not apparent in the initial classifier. Finally, a number of diversified engineering, automotive, food and pharmaceutical companies were added, which were known to use fluid dynamics as a small, but essential, part of their business. Such firms were found not to use fluid dynamics terms in their online descriptions and thus were not identified by ML.

The final result was a list of 2,227 companies working in fluid dynamics in the UK.

STEP 2: APPORTIONMENT

A panel of experts, formed by Leeds Institute for Fluid Dynamics (LIFD), was consulted on the fraction of output from diversified companies that should be apportioned to the fluid dynamics industry.

To facilitate this process, companies turning over >£20m were grouped into 13 sectors. The expert group recommended a default apportionment value of either 1, 5, 10, 20 or 50% of output to be assigned to fluid dynamics for each sector, according to the level of fluid dynamics expertise commonly found in those firms. Any outliers were also identified to be treated individually.

STEP 3: OUTPUT, PROFIT AND EMPLOYMENT

The appointment fraction was applied to the turnover, profit and employment figures for the identified companies based on their latest annual fillings at Companies House, obtained from Dun and Bradstreet. Where profit figures were not available, these were estimated from the average profit margin for the industry of 10.3%. This calculated the profit and turnover of 53 firms producing fluid dynamics products only, each turning over >£1m.

STEP 4: GROSS VALUE ADDED (GVA)

Calculation of gross value added requires an estimate of employee benefits. The total employee costs reported in annual returns by the 20 largest companies with fluid apportionment of >50% was averaged over their combined 13,000 employees. This yielded an average of £53,708 per employee, including wages, pensions contributions and other direct benefits.

Gross value added to the economy was taken as the sum of profit and total employee benefits paid, with the latter being the product of average benefit and number of employees. GVA per employee was taken as the sum of profit per employee and average benefit.

STEP 5: REGIONAL DISTRIBUTION

3,300 addresses were identified for UK fluid dynamics companies, including registered and operational addresses. By default, revenue, employment and profit was split uniformly among the number of addresses recorded for each organisation and the associated region, unless any other information was available from the expert group.

The exception was organisations with a registered addresses in London, typically used only for financial reporting. If an address outside London was available for such firms, the portion of business allocated to the London office was reallocated to the other company locations.

The final figures represent a best effort economic estimate of the size of the industry, with any errors in the treatment of any individual organisation averaging out over the complete dataset.

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UK FLUIDS NETWORK

LIFD
Leeds Institute for Fluid Dynamics

IF YOU ARE INTERESTED IN LEARNING MORE ABOUT THE UK FLUIDS NETWORK, PLEASE VISIT:

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