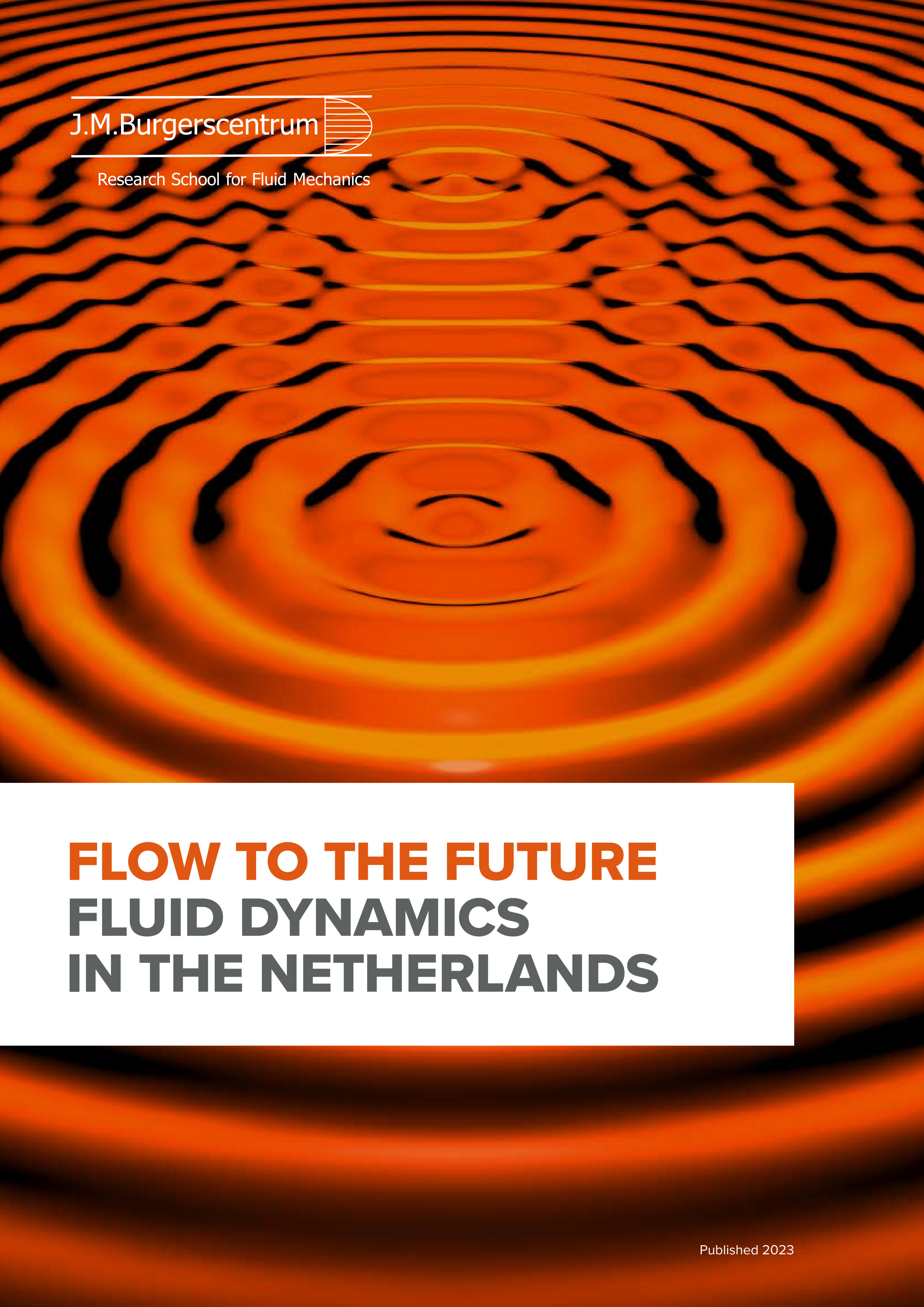


J.M.Burgerscentrum

Research School for Fluid Mechanics

FLOW TO THE FUTURE
FLUID DYNAMICS IN THE NETHERLANDS

Published 2023

Jos Benschop,
Corporate Vice President Technology,
ASML

Understanding and controlling how fluids behave is vital to all aspect of industry and for ASML in particular. From the early days until the latest generations EUV machines, fundamental understanding, prediction and control of Fluid Flows in our equipment is crucial importance for their performance. These capabilities have been developed in close collaboration with our academic and supply chain partners, often in PPS collaborative models support by the Dutch government. The value of having such research & innovation ecosystem infrastructure available for ASML is of vital importance for our next generation of innovations.

As this report demonstrates we are fortunate to have a wealth of expertise in understanding and application of fluid dynamics in the Netherlands. Our competitive and sustainable future will benefit when recognising and harnessing this capability for the next generation of industrial and societal challenges.

Annemieke Nijhof,
CEO,
Deltares Netherlands

Water management is of essential importance for developing and maintaining Dutch infrastructure in the Delta area. Fundamental understanding of fluid flows in combination with waves & tides, river (beddings) and draining systems are some of Deltares key assets to develop new sustainable infrastructure solutions. As illustrated by the flooding in Valkenburg, Limburg in 2021, fluid flows from heavy local rainfall in combination with insufficient local draining capacity can result in rapidly escalating situations.

At Deltares we are combining numerical fluid flow modelling with laboratory and field measurements to predict the impact of fluid flows. Further enhancement and investment in Fluid Flow science & technology in the Netherlands is of vital importance to face the environmental challenges of the future.

Fluid dynamics is the science and engineering of moving liquids, gases and particles. This includes predicting, controlling and measuring fluid flows at any speed and scale, from nano- to astrophysical. Applications range from blood flow and agriculture to lithography and industrial processes, to flow in buildings, the atmosphere, rivers, oceans, and stars.

EXECUTIVE SUMMARY

Fluid dynamics is all around us, underpinning the industries of today, and critical to solving the societal challenges of tomorrow. Yet fluid dynamics is hidden. For the first time, the impact of fluid dynamics on the Netherlands has been quantified, revealing the importance of future investment in this key enabling technology to protect our future.

Fluid dynamics contributes €11.5 billion annually to the Netherlands economy, and is critical to solving future societal challenges.

The Netherlands has been at the forefront of world-leading fluid dynamics research for decades, exemplified by the J.M. Burgerscentrum, the national research school for science and engineering in fluid mechanics. Industry has harnessed this expertise, hired its graduates and leveraged insights from fluid dynamics in a wide range of industries, from printing and semiconductor processing to agriculture, chemical production and water management.

Sustained industrial investment has created a fluid dynamics industry generating €11.5 billion in annual Dutch revenues, employing ~19,000 people in over 1,100 firms. With an annual gross value added to the economy of ~€130,000 per employee, fluid dynamics is one of the most productive manufacturing sectors in the Netherlands. Those employees are embedded in companies with a Dutch turnover of ~€125 billion and much more globally. Yet the societal reach of fluid dynamics is even greater.

Fluid dynamics will be a vital part of understanding and providing solutions to all major future societal challenges including:

Climate change. Predicting warming and impacts of greenhouse gas emissions on the oceans, sea levels and weather.

Environment. From water, river and flood management including pollution and water treatment. To the cooling, heating and air management in buildings.

Energy transition and energy security. Whether through tidal and wind energy, the hydrogen economy and biofuels, through to next generation batteries and high efficiency transport.

High-tech manufacturing and high-tech materials, from semiconductors to additive manufacturing, 3D printing and bio-compatible production.

Healthcare. From aerosol distribution of viruses, advanced micro-fluidic based diagnostics to personalised treatment and drug production.

Agriculture and food production. Such as next generation indoor vertical farming, food production and processing ideal for exploitation in the Netherlands.

Fluid Dynamics will thus be critical for the future of Dutch society and the economy. Neglecting the role of fluid dynamics risks that future, and makes us vulnerable and dependent on others to provide critical fluid dynamics expertise and innovation. **Together we can harness the power of fluid dynamics for a prosperous, healthy, sustainable future.**

The Netherlands urgently needs:

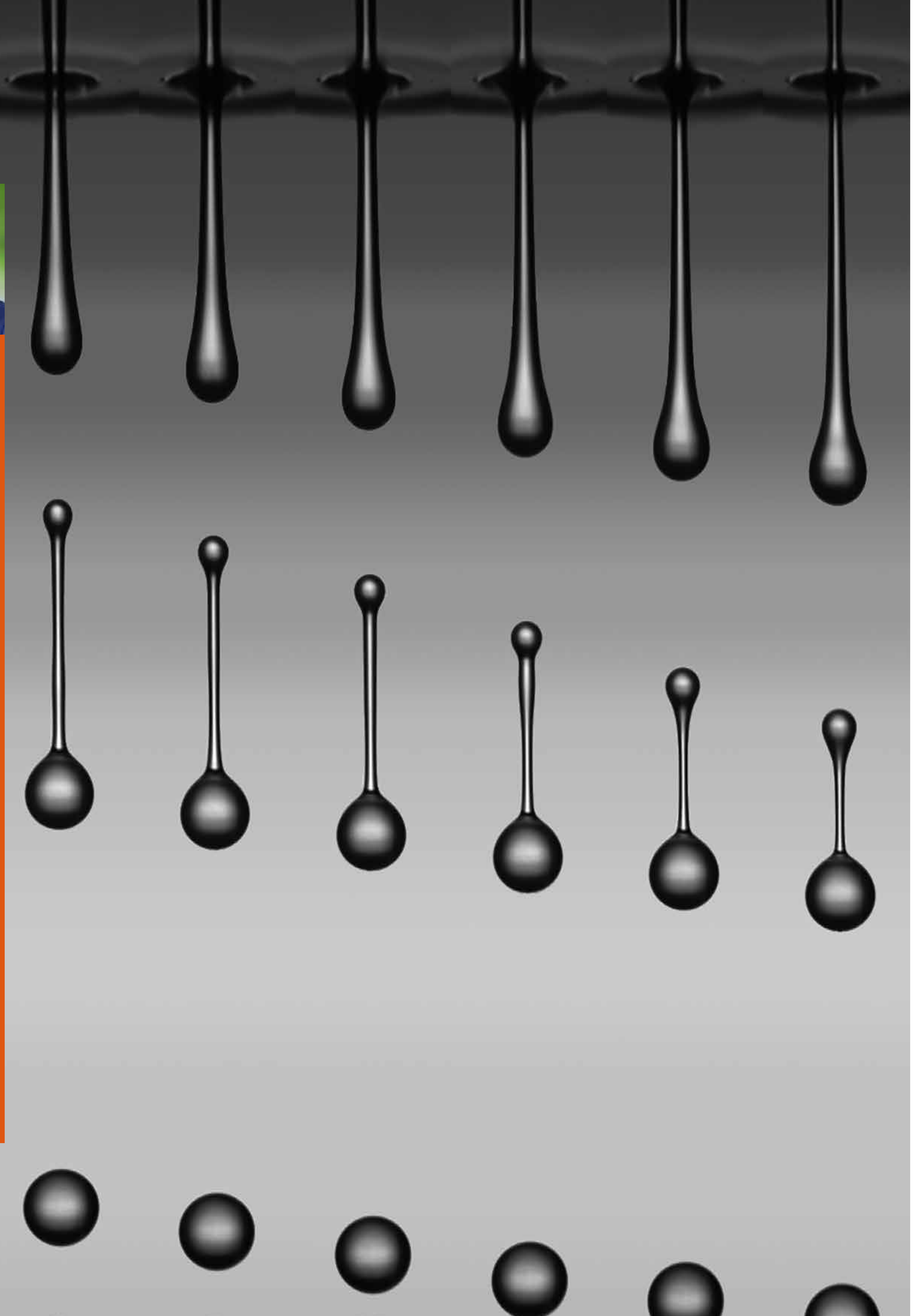
National recognition of cross-cutting roles of enabling technologies, especially fluid dynamics.

A directorate focused on industrial adoption in the national J.M. Burgerscentrum.

Strategic collaboration public platform funding of > €500 million over 5 years to expand industrial competitiveness.

Expansion of fluid dynamics research to ensure long term scientific leadership in fluid dynamics.

Increased fluid dynamics training at all levels to provide the expertise needed.



Eppo Bruins
Science and Innovation Lead, former member of Parliament

Eppo Bruins, Science and Innovation Lead, former member of Parliament

The flow of fluids has been one of the most challenging topics in science and technology since the nineteenth century, associated with great minds like Helmholtz, Kelvin and Rayleigh. Immense progress has been made since these early days, enabling present day technologies in many industrial sectors.

Up to this day, the Dutch fluid dynamics community is at the forefront of modern science. The challenges that lie ahead are mind-boggling, since flow is all around us. Turbulence is everywhere, in water, in the air and even in crowds of people. Multiphase flow is everywhere: in rivers and seas, in pipelines, and even in our own veins. Everything flows. Panta rhei.

Despite the abundance of flow in our world and its huge range of applications, the science of flowing liquids and gases is relatively hidden. However, its importance cannot be underestimated. Flow to the Future brings the Dutch fluid dynamics community to light. Its achievements as well as its potential. It is time to recognise the esteemed position of this community and its many contributions to science and technology. Flow to the Future does that in a convincing matter, focusing on the role of fluid dynamics in solving society's twenty-first century challenges.

I welcome this report, knowing that many new discoveries and solutions lie still ahead.

INTRODUCTION

Fluid dynamics is everywhere; enabling industry, solving societal challenges.

Fluids are ubiquitous. They are in every industrial process, home, hospital and ecosystem. Understanding, predicting and managing fluid flows is essential to maximise industrial value, keeping citizens safe, improving quality of life and protecting our future.

Water and air are the basics of life. How they are handled and harnessed is essential for all our futures. The transition to a sustainable economy requires moving from handling hydrocarbon fluids, to harnessing water, wind and solar. Feeding more people, more efficiently, depends on precision delivery of fluids.

The impact of climate change is understood through fluid dynamic models of weather. The mitigation of rising water levels and flooding is based on the mechanics of fluids.

Aerosol propagation drives the spread of COVID-19. Safe distances are determined by fluid dynamics. Blood flows are the core of cardiovascular health. Microfluidics will be the future of diagnostics and affordable personalised care.

Understanding fluid dynamics is critical to current industries and even more so to new ones, especially for addressing the societal challenges of today and tomorrow. Yet for such a critical technology it is mostly hidden from view and taken for granted.

The objective of this report is to highlight the importance of fluid dynamics on Dutch society and the economy, now and in the future. This first estimate of the size of the fluid dynamics sector in the Netherlands quantifies the current economic impact. Expert input further identifies the societal challenges most dependent on developments in fluid dynamics. The relative strengths and focus of current industry and research are identified. Forecasts of future growth and investment are based on direct community survey.

Our analysis is based on a proven process used internationally to quantify the impact of enabling technologies embedded deep within large diversified companies.

The conclusions lead to five clear recommendations for taking fluid dynamics in the Netherlands to the next level. Collectively these will protect and maximise societal and economic impact for the future. The Dutch are already world leaders in the application of fluid dynamics in traditional industries. Delivering on the recommendations made here will be critical to ensure that capability is leveraged to the full for tomorrow's economy.

MEETING SOCIETY CHALLENGES WITH FLUID DYNAMICS

Solving societal challenges depends on strength in fluid dynamics.

The compelling need to understand, predict and control fluid dynamics should be eminent for a country that has a large part of its land below sea level and is at the forefront of the transition to a sustainable economy. Fluid dynamics plays a vital role in three of the four major societal themes and missions identified by the Dutch government and is a key enabling technology required for sustainable growth (Kennis- en Innovatieconvenant 2020-2023, Den Haag 11 Nov. 2019).

Energy transition and sustainability

Transitioning to sustainable energy sources requires a solid understanding of fluid flows. Predicting air flows over wind farms and clouds above solar farms will have significant impact on the energy yield and hence impact on the power grid. With planned expansion in the share of sustainable energy sources, fluid dynamics modelling for predicting and managing output will be essential for the stability of the Dutch energy grid.

For more traditional sources of energy fluid dynamics plays an essential role, illustrated by the abrupt change in 2022 from pipeline gas transport to liquified natural gas (LNG) in Europe, for which fundamental fluid dynamics understanding in the processing of LNG was vital. With the transition to sustainable energy, the convertibility of LNG infrastructure for later use with renewable energy carriers, such as hydrogen, ammonia, or biofuels is of particular importance and dependent on detailed understanding of fluid dynamics and a strong local fluid management industry.

Agriculture, Water, Food and Advanced Manufacturing

The entire water management system, from coastal areas, to rivers and lakes, requires a fundamentally new approach to make them more resilient to climate change and the extreme weather events. Sustainable water management remains the starting point and will have to efficiently perform the core functions of freshwater supply, water transport, safety, and biodiversity.

The Netherlands has pioneered high density, high efficiency agriculture; skills that are increasingly critical to food security and which depend on the precision management of fluids.

The waters in the Dutch Delta have significant potential to play a role in the new challenges facing the Netherlands, such as energy supply, food supply, improving spatial quality or climate adaptation. Fluid flow measurements and modelling with Computational Fluid Dynamics (CFD) will be key for water management in the face of climate change.

Advanced manufacturing will be critical to delivering solutions to these challenges. Here fluid dynamics has a key cross-cutting role, vital to enabling efficient manufacturing of everything from advanced semiconductors, through to chemicals, pharmaceuticals, traditional materials such as steel and advanced 3D printing production techniques.

Health and healthcare

One of the key missions in the health and healthcare knowledge and innovation agenda is to ensure that by 2030, 50% more care will be provided in a citizen's personal living environment. Point-of-care diagnostics will be vital in achieving this mission, which often requires body fluids to be examined on the spot, as exemplified by the COVID-19 pandemic.

Fluid flow science and technology will be an enabler for the next generation of individualised care. From viably delivering personalised medicines, to depositing stem cells as a personalised test bench for new drugs.

Understanding fluids is essential to address Dutch grand challenges. The Netherlands has a unique ecosystem, leading scientific knowledge base and vibrant industry in fluid dynamics, which fully nurtured will be pivotal in addressing all the societal challenges ahead.

Impact of Fluid Dynamics on three of the major societal themes and missions (highlighted in orange) for the future identified by the Dutch government.

HIGH-TECH SYSTEMS ENABLED WITH FLUID DYNAMICS

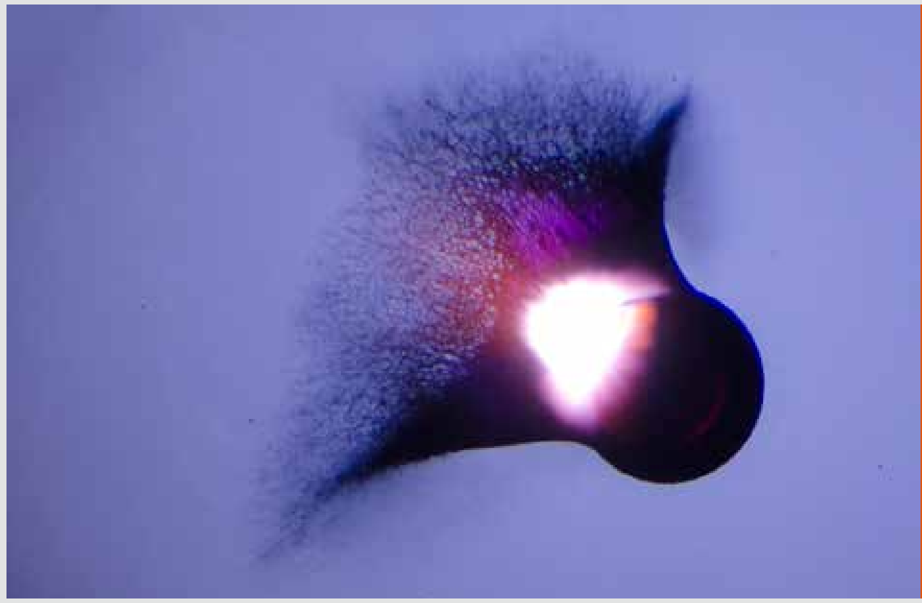
ASML Immersion Lithography case study.

ASML lithography tool with the fluid immersion stage highlighted

The microelectronics industry has been marching to the beat of Moore's Law for decades: doubling the number of transistors per chip every two years. Optical lithography has been the key enabler for this, printing smaller lines through a combination of decreasing the wavelength of light used and increasing the numerical aperture of the lens used to focus that light onto the patterned semiconductor. Fluid dynamics plays a significant role in the performance of ASML lithography equipment and has proven to be one of the key competitive advantages of the company.

It is well known to microscopists that adding a liquid between the last lens element and an object increases the resolution. The lithography industry exploited this application of fluids applying immersion technology in the early 2000s to achieve a higher density in wafer patterns. However, immersing lithography optics with a fast-moving wafer in liquid poses significant fluid dynamic challenges.

Supported by Dutch research funding, ASML together with its partners from Industry & Universities developed a system based on partially wetting the wafer below the lens, while continuously refreshing the liquid during operation. Applying this principle to lithography meant finding a solution to constrain water under the lens while having a fast moving (> 0.5 m/s) and fast accelerating (> 1 g) partially wetted wafer. While the consortium led by ASML was able to introduce the first commercial scanners in 2003, it took the only remaining Japanese competitor two more years to introduce a less performing immersion scanner, a delay that enabled ASML to reach a market share of approximately 70%. This only has been growing to date turning it into a €20 billion company and one of the highest profile semiconductor equipment suppliers globally.



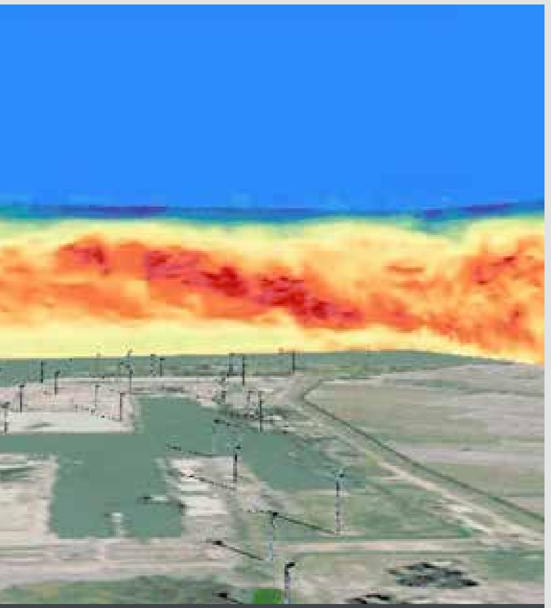
Immersion-based scanners are the backbone of integrated circuit production today. ASML shipped 68 immersion scanners in 2020 and 81 in 2021, with ongoing research programs to increase the wafer speed of immersion scanners further posing new fluid dynamics challenges.

The newest ASML lithography equipment is based on Extreme Ultra-Violet (EUV) technology for the very smallest 3 nanometer nodes. EUV scanners also incorporate many fluid dynamics fundamentals, since the EUV source is based on vaporising 50,000 tin drops per second to generate the light needed for patterning.

> **"A state-of-the-art fluid dynamics ecosystem and knowledge have proven and continue to be essential for ASML in the race to meet societies' insatiable desire for digital technology in support of the global digital economy."**
>
> **Jos Benschop**
> Corporate Vice President Technology, ASML

FLUID DYNAMICS POWERING THE ENERGY TRANSITION

Whiffle Case Study.



"In the current era of environmental and energy transformations the relevance of understanding and predicting advanced atmospheric fluid flows has been proved to be key essential for society and a unique Whiffle asset."

Harm Jonker
CEO Whiffle

Supported by the 2022 crisis in fossil energy, the need to transition to an energy system based on renewable sources has become even more pressing. Since the atmosphere is becoming one of our primary energy sources, understanding atmospheric fluid flow through wind farms has become an issue of large economic and societal concern.

The science of precisely predicting local weather patterns and atmospheric flows in wind and solar farms is the unique capability of Whiffle. This Dutch small enterprise, founded in 2015 as spin-out of Delft University of Technology, is using advanced 3D models of weather parameters to predict local conditions on a micro scale at a resolution of 100 metre or finer.

Whiffle's unique finecasting technology is based on Large Eddy Simulations, which have been used in academia to examine clouds and turbulence since the 1980s. As these complex fluid dynamics simulations require excessive computing power, even more than offered by supercomputers. Whiffle looked into the possibilities of translating the model to work on Graphical Processing Units (GPUs). The prediction accuracy of the in-house developed Computational Fluid Dynamics (CFD) software is amazing and obtained ~ 100 times faster than with regular supercomputers.

Wind turbines have been designed with an important objective: extracting kinetic energy from the atmosphere and converting it to electrical energy. They are very efficient in doing this and so behind a wind turbine there is a wake region with a significant reduction in wind speed. One of the challenges in understanding wind farm flow physics is the coupling between the micro-scale (say, turbine level ~100 m) and the mesoscale (100 km or more) which is relevant for atmospheric processes.

The key difference is the ultra-high resolution Whiffle uses for its finecasting. This facilitates an accurate and natural representation of small-scale fluid dynamic processes such as turbulence, surface interactions, cloud formation and precipitation at a certain location and time with unprecedented spatial and temporal detail. For wind farms this provides very accurate predictions on wind energy forecast. Also, the layout of new wind farms can be optimised by calculating the yield of wind farms and the interaction of wind turbines themselves with the wind in the farm.

Finecasting of local fluid flows is not only relevant for wind farms but can also be used for many other environmental applications. For example, accurately capturing the dispersion of air pollutants through the atmosphere, considering the impact of turbulence, obstacles, wind, weather phenomena and land-sea transitions on the dispersion of particles.

For further information: **www.whiffle.nl**

ENABLING THE ECONOMY: THE DUTCH FLUID DYNAMICS INDUSTRY

€11.5 billion of fluid dynamics based goods and services were delivered in 2021 from the Netherlands by more than 1,100 companies.

RENEWABLE POWER
PERFORMANCE SPORTS
METEOROLOGY AND CLIMATE
PHARMACEUTICALS AND DIAGNOSTICS
AGRICULTURE
HEALTHCARE
POWER GENERATION
CHEMICAL INDUSTRY
BUILT ENVIRONMENT
WATER MANAGEMENT
AEROSPACE AND DEFENCE
FOOD MANUFACTURING
OIL AND GAS
SIMULATION AND MODELLING
HIGH-TECH MANUFACTURING
LIQUID CONTROL
SHIPPING / MARINE

€11.5 BILLION OUTPUT

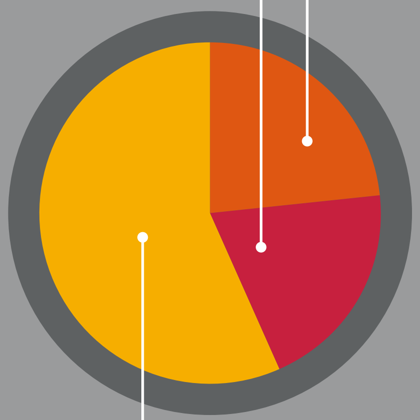
19,000 PEOPLE EMPLOYED

1,100 COMPANIES

€130,000 GROSS VALUE ADDED PER EMPLOYEE

> €2.4 BILLION TOTAL GROSS VALUE ADDED

Fluid Dynamics exports



The Dutch fluid dynamics industry directly generated €11.5 billion worth of output from over 1,100 firms employing over 19,000 fluid dynamics people in 2021. The industries' gross value added (GVA) to the economy is estimated to be €2.4 billion per year, equivalent to €130,00 GVA/employee. Over 75% of the industry export fluid dynamics products and services outside the Netherlands, with one quarter exporting over 75% of their output.

This fluid dynamics activity is often embedded in highly diversified businesses. The total Dutch turnover of firms where fluids make up a portion of their activity exceeds €125 billion, collectively employing over 200,000 people. The fluids portion of many businesses is therefore limited, but critical to enabling a much larger economic activity, considerably greater than the direct fluid dynamics output.

This breadth of fluid dynamics impact is further illustrated by the range of industries in which the top fluid dynamics companies operate. These cover renewable and traditional energy, drug and chemical production, high-tech manufacturing, marine design, environmental prediction/protection and construction.

Dutch multinationals also leverage fluid dynamics capability in the Netherlands to add value to their global businesses, suggesting that the overall economic impact is much greater than that credited here to fluid dynamics in their Dutch operations alone.

SELECTION OF THE LARGEST DUTCH COMPANIES ADDING VALUE WITH FLUID DYNAMICS

- Akzo Nobel N.V.
- ASML Netherlands B.V.
- Boskalis Nederland B.V.
- Canon Europa N.V.
- Chemours Netherlands B.V.
- DAF Trucks N.V.
- Dow Benelux B.V.
- DSM N.V
- Eneco N.V.
- Eriks B.V.
- ExxonMobil Chemical Holland B.V.
- Flowserve B.V.
- FrieslandCampina Nederland B.V.
- Fugro N.V.
- Heineken N.V.
- Lyondell Chemie Nederland B.V.
- Nobian Industrial Chemicals B.V.
- OCI N.V.
- Philips N.V.
- Schlumberger B.V.
- Sensata Technologies Holland B.V.
- Shell Nederland B.V.
- Stork B.V.
- Teijin Aramid B.V.
- Tata Steel Nederland B.V.
- Unilever Nederland B.V.
- Vattenfall B.V.

SUSTAINED FUTURE GROWTH

The Dutch fluid dynamics industry is investing €670 million annually and growing five times faster than rest of the economy.

Strong customer demand and new product introductions continue to drive growth in fluid dynamics.

The critical role fluid dynamics has in solving societal challenges means the industry is destined for strong growth. Three quarters of industrial respondents to our survey predict industrial growth of over 5% per year for the next 3 years, up to 5 times the near term growth forecast for the whole Dutch economy (OECD Nov. 2022).

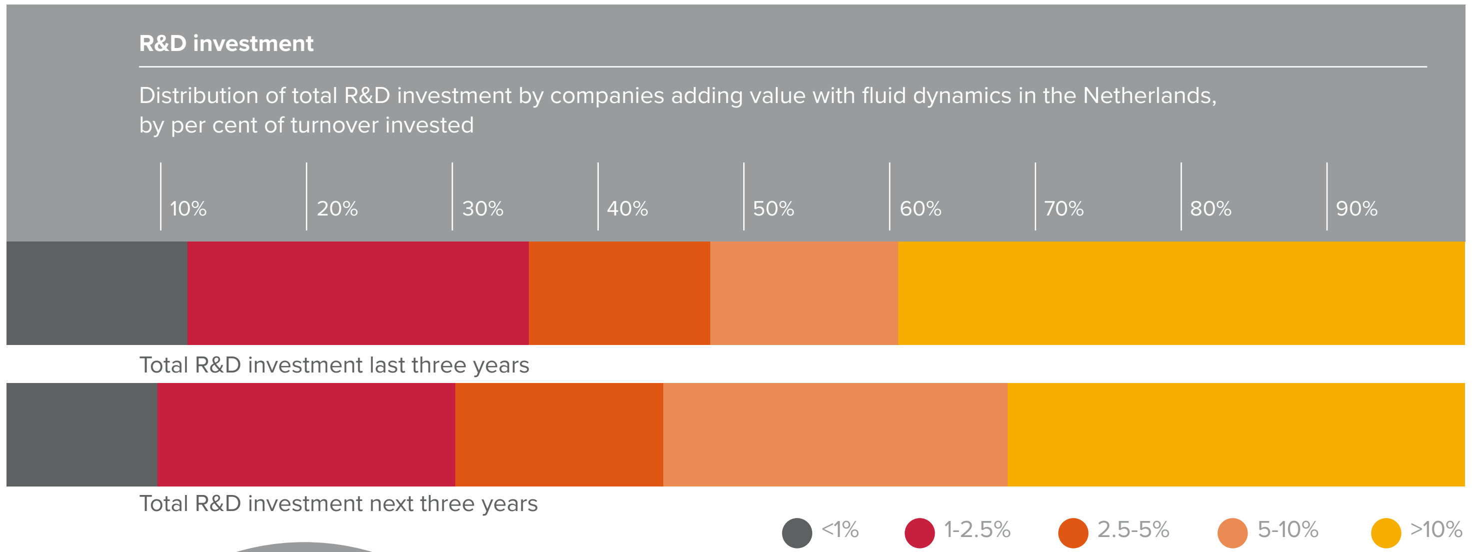
Industrialists describe strong customer demand and new product introductions as the key drivers of that growth, illustrating the strength of market pull for more fluid dynamics innovation. Over half of all industrialists also indicate public funding will help enable that growth.

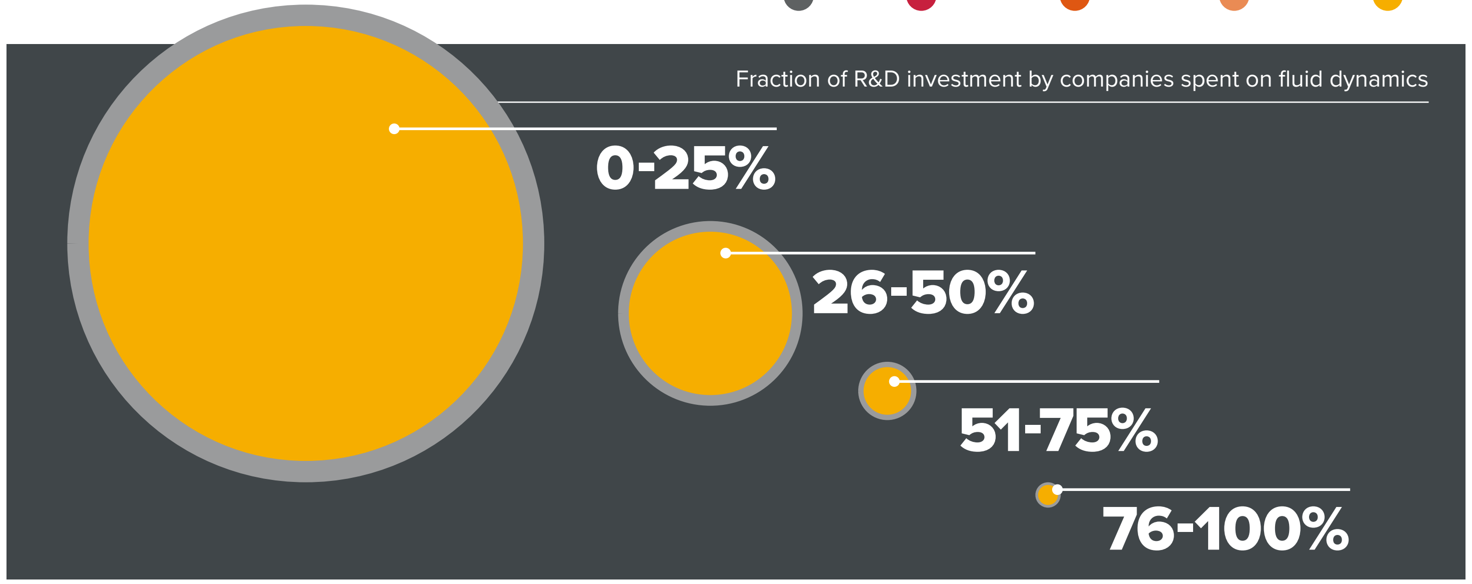
Additional staff, to sustain and support growth, are identified as most needed at postgraduate level (PhD / MSc) and/ or from those with more than five years' experience. This reflects the key role fluid dynamics has in product and process design across a wide range of applications. Experience takes time to accumulate and indicates the need for a long term fluid dynamics skills strategy in the Netherlands.

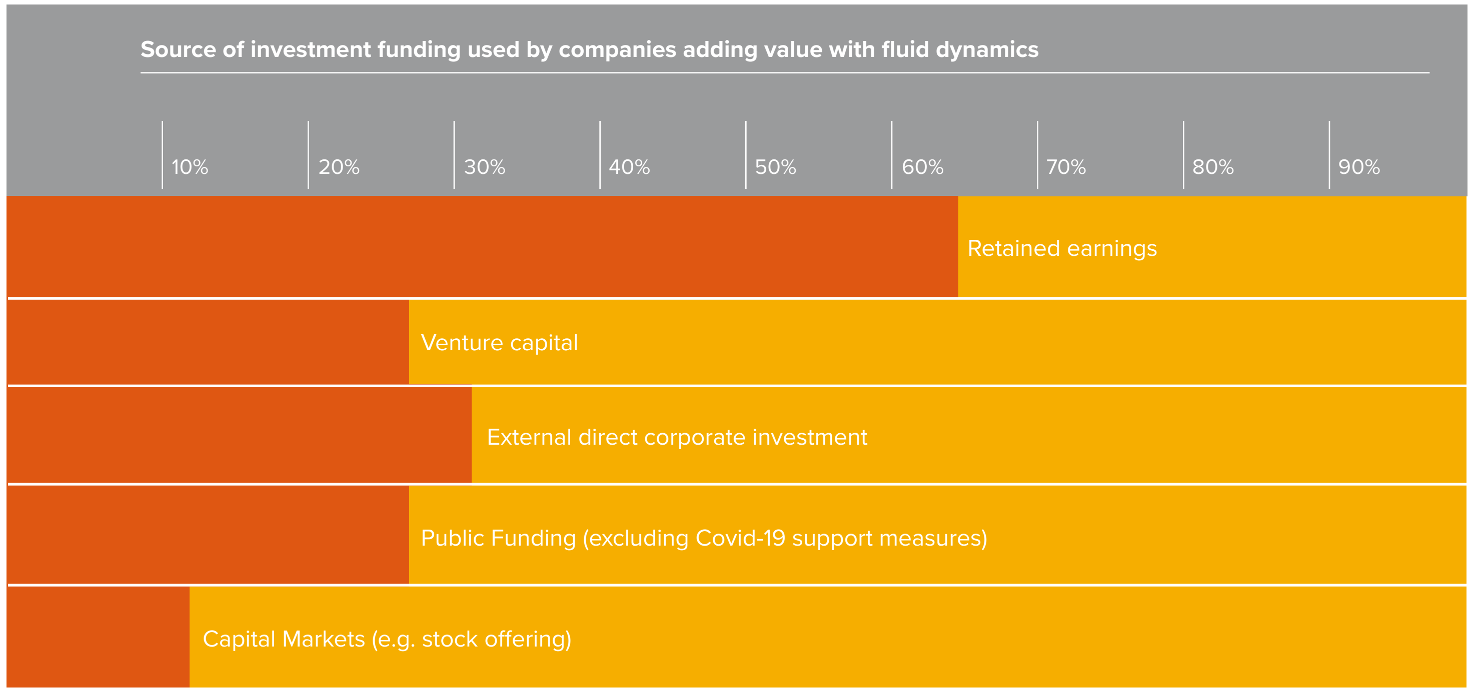
Reflecting their forward focus, companies adding value with fluid dynamics are major investors. A third of those fluid dynamics organisations surveyed invest more than 10% of their turnover back into research and development, with over half investing more than 5% across all areas of their business. Given the scale of this industry, this conservatively indicates an annual R&D investment of more than €670 million by companies working with fluid dynamics in the Netherlands. This is a sustained long term investment, with little change reported between investments made in the last three years and forecast for the next three.

The importance of fluid dynamics in supporting transformational innovation is underscored by provisional survey responses indicating that one third of those investing more than 5% in R&D will put more than half of that investment into fluid dynamics in the next three years. This amounts to direct investment into fluid dynamics by Dutch industry of at least ~€100 million per annum.

Industry indicates that overwhelmingly the source of this investment is retained earnings, and external corporate investment. This supports the sustainability of investment financed by sales of existing products. Using retained profits also points to fluid dynamics being heavily leveraged inside established firms, driven by real customer demand. Venture investment was cited as almost irrelevant. Wider sampling may change this, or it may indicate the venture community is less aware of the underpinning nature of fluid dynamics and the returns it can bring, providing opportunities to crowd in more investment.

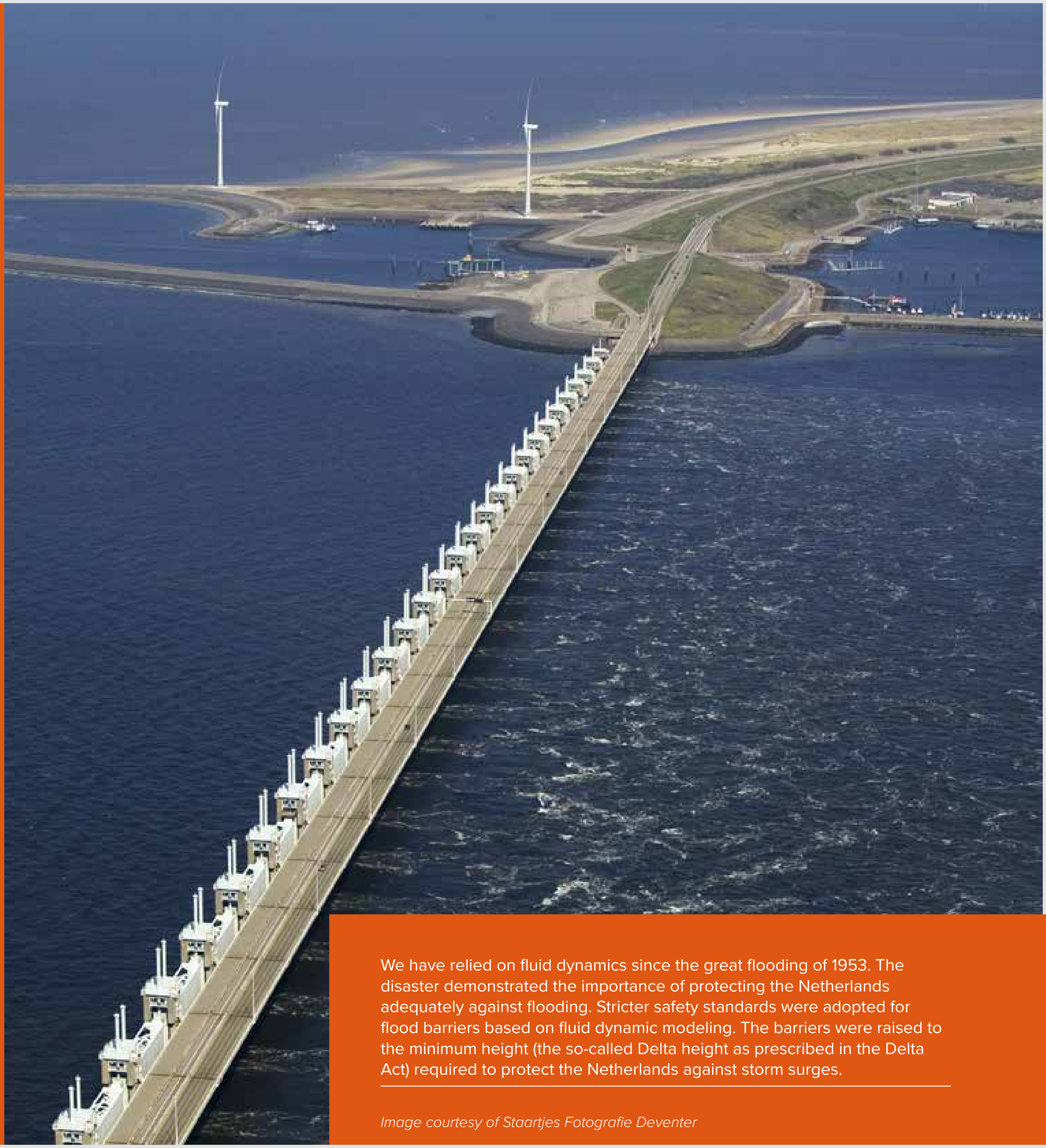






WATER MANAGEMENT

Fluid mechanics at Deltares case study



We have relied on fluid dynamics since the great flooding of 1953. The disaster demonstrated the importance of protecting the Netherlands adequately against flooding. Stricter safety standards were adopted for flood barriers based on fluid dynamic modeling. The barriers were raised to the minimum height (the so-called Delta height as prescribed in the Delta Act) required to protect the Netherlands against storm surges.

Image courtesy of Staartjes Fotografie Deventer

Expertise in fluid mechanics is key to ensuring life in the Dutch Delta is safe and sustainable, both now and in the future. Understanding flow behaviour has made it possible to build many different water structures. The Delta Works are a prime example, as is the recently completed (2022) IJmuiden Sea Lock, which maintains a complex balance between fresh and salt water. This specialised knowledge is also important for the design of hydraulic structures that contribute to strengthening the ecosystem, also known as nature-inclusive design. Often, fluid mechanics can help to find an optimal solution between ecological impact, construction, and water quality aspects.

Deltares has nearly 100 years' experience in designing innovative solutions to societal challenges. Key to this is their expertise in water and subsurface. The knowledge of fluid mechanics forms part of this expertise. In the past, they mainly used large physical scale models to simulate flows. Today, they use numerical modelling in addition to physical scale models. Using these models of complex flows, the experts provide insight into the effects of flows on the environment. From global flood forecasts, (sea)bed morphodynamics, the prediction of (sea)bed changes, to scour around offshore wind foundations.

A good understanding of flows is also essential to finding solutions for problems resulting from the salinisation of groundwater, caused by climate change and sea level rise. New measurement techniques and simulations are needed to minimise saltwater intrusion at dams, locks, and storm surge barriers, and to optimise the design. This requires well-trained fluid mechanicists. Significant challenges also remain in understanding fluid mechanics in (tidal influenced) harbours. Sediment balance and deformations in the riverbed are important for navigation and vessel safety, and for optimising dredging operations in a nature-inclusive way whilst restoring the balance.

Technological developments - such as the robotisation of (optical) physical measurements, free surface field measurement methods, autonomous vessels for surveying, and the continuous development and validation of numerical models of free surface flows around structures - are part of Deltares' 'future of flow'.

For further information:
www.deltares.nl

Flow patterns of tidal energy turbines in the Eastern Schelde storm surge barrier

"Expertise in fluid mechanics is essential for the design of resilient, sustainable, and climate-proof infrastructure for the coming decades."

Annemieke Nijhof
CEO
Deltares Netherlands

FLUID FLOW FOR THE ENERGY TRANSITION

Shell case study

"The Netherlands was created and developed by utilising wind and managing water for many centuries. This continues into the future. It is a fluid flow country at its core. World class expertise in fluid flow science and technology provides an exciting opportunity to support governments, industries, and societies with the required knowledge to make the energy and circularity transitions happen, at home and abroad. For the Netherlands, fluid flow technology is an export product with purpose."

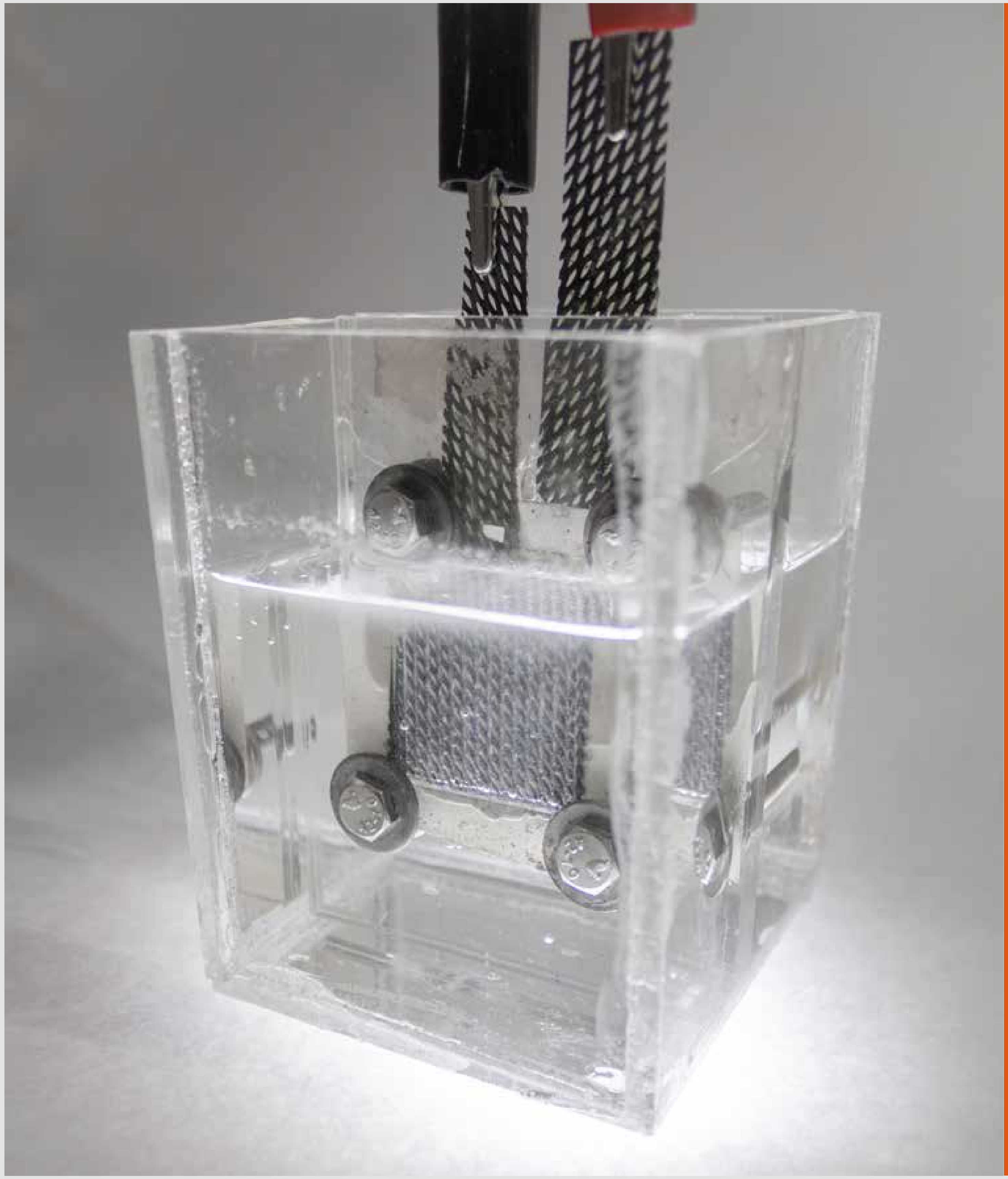
Yuri Sebregts
Executive Vice President Technology and Chief Technology Officer, Shell

The landscape and water architecture of the Netherlands demonstrate the Dutch world class leadership in the science and engineering of fluid flow. We all recognise the historical wind mills and their role in reclaiming land. The same fluid flow principles are also applied in Shell's process industry, involving the transport and conversion of gasses, liquids and solids via complex pipelines, separators, pumps, compressors, and reactors.

As it is time for change, collaboration among all stakeholders is required to develop the know-what and know-how to obtain a worldwide clean and sustainable energy system. Fluid flow is at the heart of the hydrogen value chain (production, transport and use), manufacturing of synthetic fuels (like kerosine for aircraft), and carbon capturing and storage.

Shell sees great potential in hydrogen production. Electrolysis of water to make hydrogen is a well-known principle, with significant opportunities for further optimisation. The electro-chemical process in a low temperature electrolyser generates a flow of hydrogen and oxygen bubbles in the water solution between the electrodes. What is the optimum design of the flow configuration that gives minimum energy losses? And how to convert the lab testing into pilot testing, and scale up to industrial sizes, including storage and transport? The fundamental knowledge at the interface between materials, electro-chemistry and fluid flow will be required for new breakthroughs like high-temperature high-pressure electrolysis.

Next to the potential of hydrogen, CO2 capturing, transport, and storage at large scale is part of the strategy to reach net-zero emissions in line with the Paris Agreement on climate change. How can CO2 most efficiently be captured from the air, from water, from process gases? Single phase transport and multiphase transport under turbulent flow conditions is a mature field for many fluid types. However, the complex thermodynamic properties of CO2 have initiated new Shell research, with lab testing, computer simulations, field testing and deployment to unlock the full potential of CO2 storage for the future ahead.



Optimising electrolysis for hydrogen production

DUTCH FLUID DYNAMICS IN THE WORLD

Nationally and globally significant

> **"It is evident that The Netherlands are among the leaders worldwide in fundamental and applied fluid mechanics research. For instance, the number of grants from the European Research Council and international awards prove the considerable success of the fluid mechanics community in the Netherlands"**
>
> **Professor Howard A. Stone**
> Member of the 2021 International Evaluation Panel, Burgerscentrum
>
> Professor in Mechanical and Aerospace Engineering at Princeton University

The Dutch fluid dynamics industry is globally significant. With annual revenues of €11.5 billion the Dutch fluid dynamics industry is three-quarters of the size of the equivalent UK industry, twice the size it so would be if scaled according to the relative GDP of the two countries.

Whilst there are no estimates of the global size of the fluid dynamics industry, if it scaled according to other enabling technologies (e.g. photonics) fluid dynamics would be ~ €65-130 billion European industry and more than €400-800 billion globally. This would indicate the Netherlands makes up 9-18% of the global fluid dynamics industry.

Looking at key fluid dynamic segments, the global market for fluid flow control devices alone in 2021 was €47 billion, forecast to increase to €67 billion by 2027 (Global Pumps and Valves Market, Maximize Market Research, 2022), approximately evenly split between agriculture, building services, oil and gas, metal and mining and power generation. Indicating the vibrancy of fluid dynamics driven industries, historical reports indicate that the Netherlands exports over €1 billion worth of valves alone and is the 5th largest importer of valves in Europe (CBI, 2016).

Fluids dynamics firms, or the fluid dynamics portion of larger companies, would overwhelmingly count as Small to Medium Enterprises (SMEs). The portion that would be considered larger operations, with more than 250 staff directly engaged in fluid dynamics, is ~2%

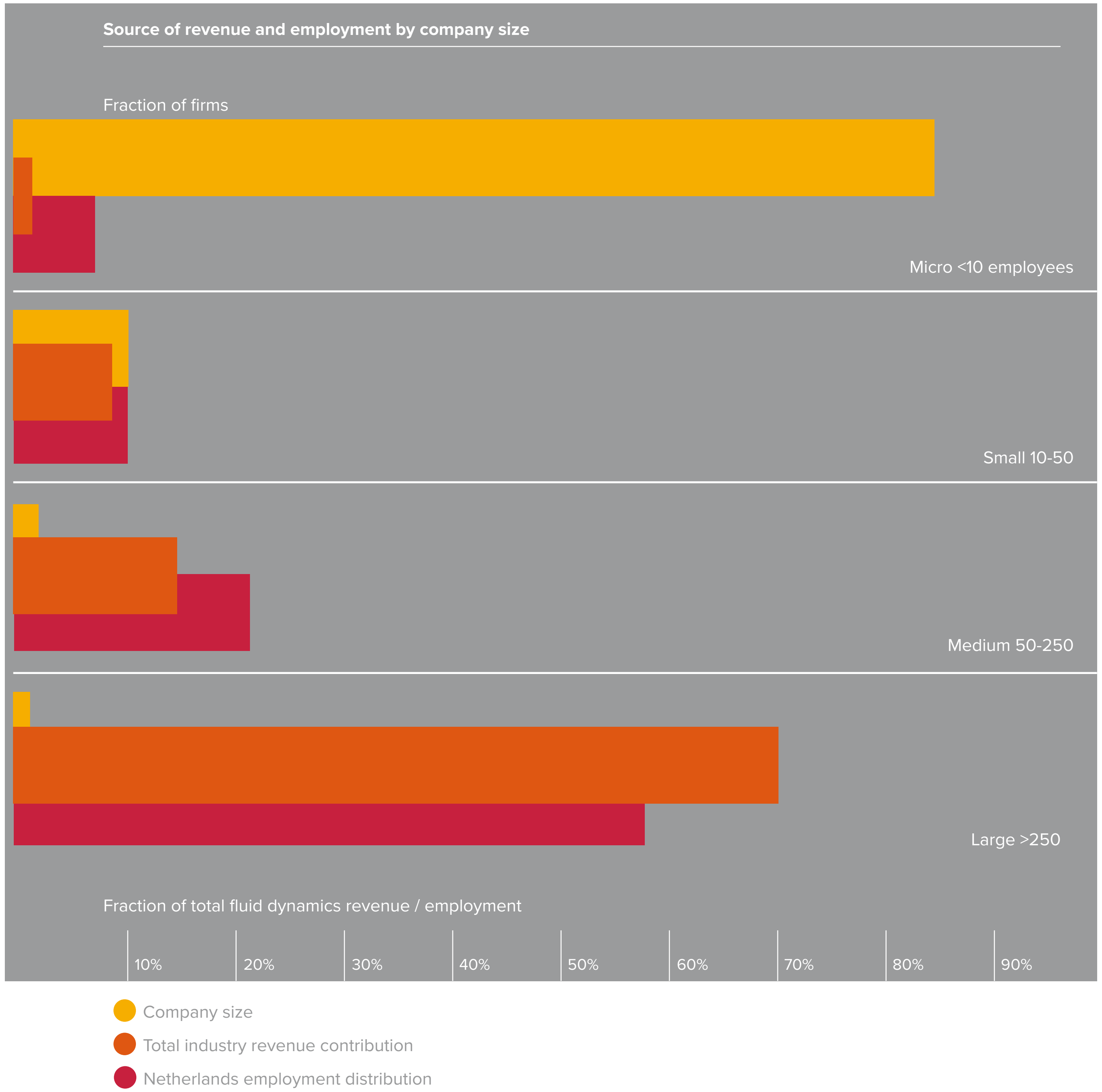
Although the fluid dynamics sector is mostly made up of SMEs, the majority of the revenue and employment comes from the small number of larger firms.

This is a common feature of most manufacturing industries. Indeed, the distribution of employment and revenues according to company size is barely different to that of fluid dynamics in UK, and has been shown to be the same between industries as diverse as photonics and acoustics. (*Our Fluid Nation 2021*).

Relative to other key industries fluid dynamics is also a significant contributor to the Netherlands economy. For example, the Dutch photonics industry, another key enabling technology, consists of ~ 200 companies with an annual turnover of ~ €5.5 billion. Two photonic powerhouses, Philips and ASML, together contribute approximately 70% of this revenue.

When comparing Fluid Dynamics with the automotive industry in the Netherlands we see the significance of the Fluid Dynamics ecosystem. With large OEMs such as DAF & VDL the automotive industry has a total annual turnover of €20 billion, less than double the size of Fluid dynamics industry in the Netherlands.

Dutch Aeronautics industry has an annual investment of about €50 million, including investments from the main public stakeholders such as NLR, TNO and Universities that accumulate to about 40% of this amount (Topsector HTSM, roadmap Aeronautics 2020-2025). The estimated investment of Dutch Industry only in Fluid dynamics of about €100 million shows the significant importance of this technology for both industry and society in general.



NETHERLANDS KNOWLEDGE BASE

Strength, depth and diversity in research knowledge underpinning industry

The Netherlands has long been a leader in fluid dynamics research. For 30 years the J.M. Burgerscentrum (JMBC) has been the national research school for fluid mechanics, hosting over 250 research staff, 350 PhD-students and 40 postdocs in multi-disciplinary research groups with fluid flow in the universities of Delft, Eindhoven, Twente, Wageningen, Groningen, Amsterdam, and Utrecht. The JMBC partners generate over 650 peer reviewed journal publications every year and have a global reputation for outstanding fundamental and applied fluid dynamics research. As a whole, Dutch authors published almost as many papers (77% in 2022) as the whole of Germany in the Journal of Fluid Mechanics, the leading academic journal in the field.

The focus of fluid dynamics research in the Netherlands covers the full spectrum of fundamentals and applications. Computational Fluid Dynamics is at the heart of the research providing the core simulation tools for predicting fluid behaviour. Next generation applications in microfluidics and renewables are naturally a focus for research. Given the strengths of Dutch chemical industry, research into industrial liquid, powder, gas and air flows features highly in research activity. As do the significant challenges in understanding multiphase flows when, for example, liquids and gases are combined. Aerodynamics is also a key research area, which reflects the importance in transport efficiency, renewable power generation, and high performance sports.

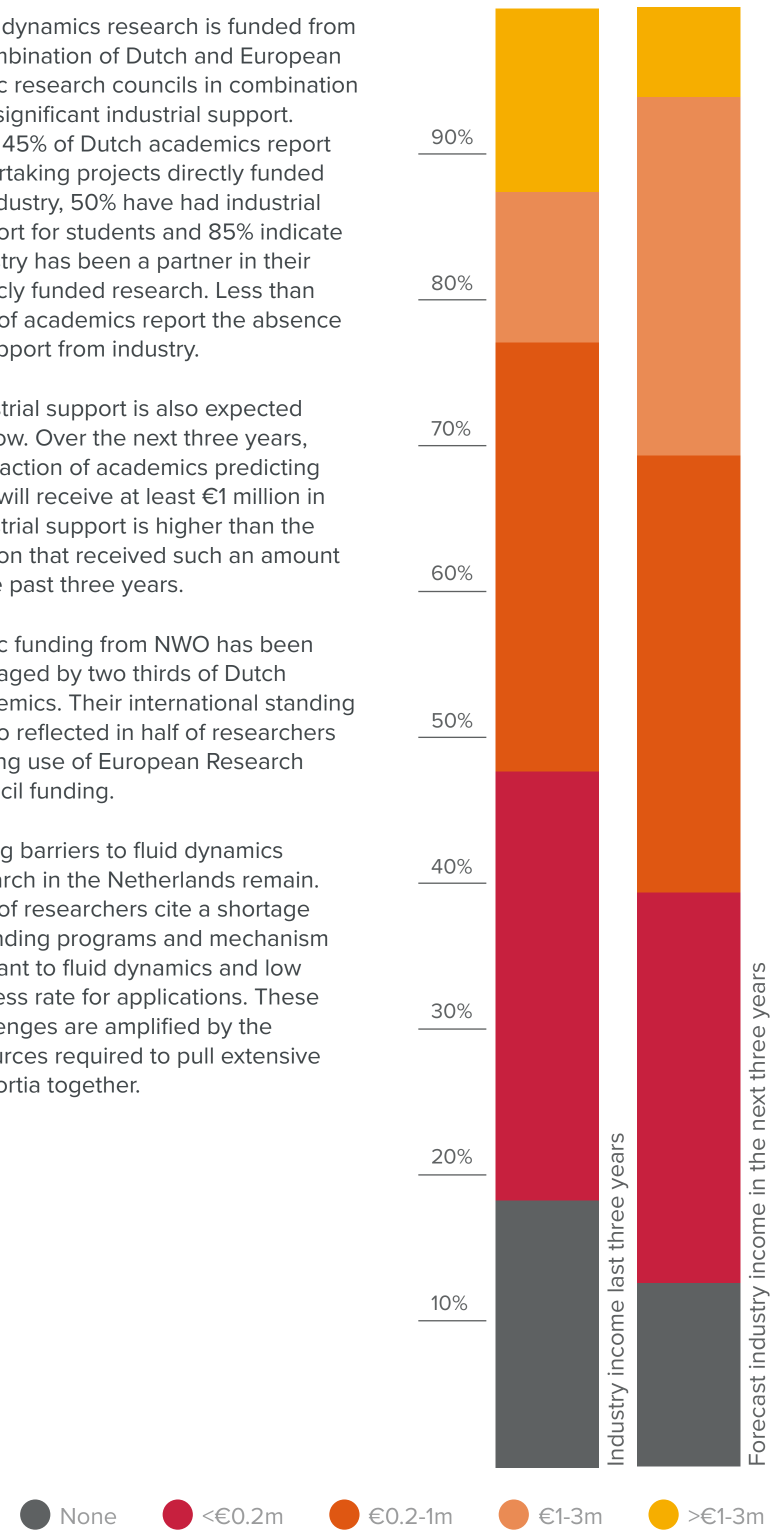
Fluid dynamics research is funded from a combination of Dutch and European public research councils in combination with significant industrial support. Over 45% of Dutch academics report undertaking projects directly funded by industry, 50% have had industrial support for students and 85% indicate industry has been a partner in their publicly funded research. Less than 20% of academics report the absence of support from industry.

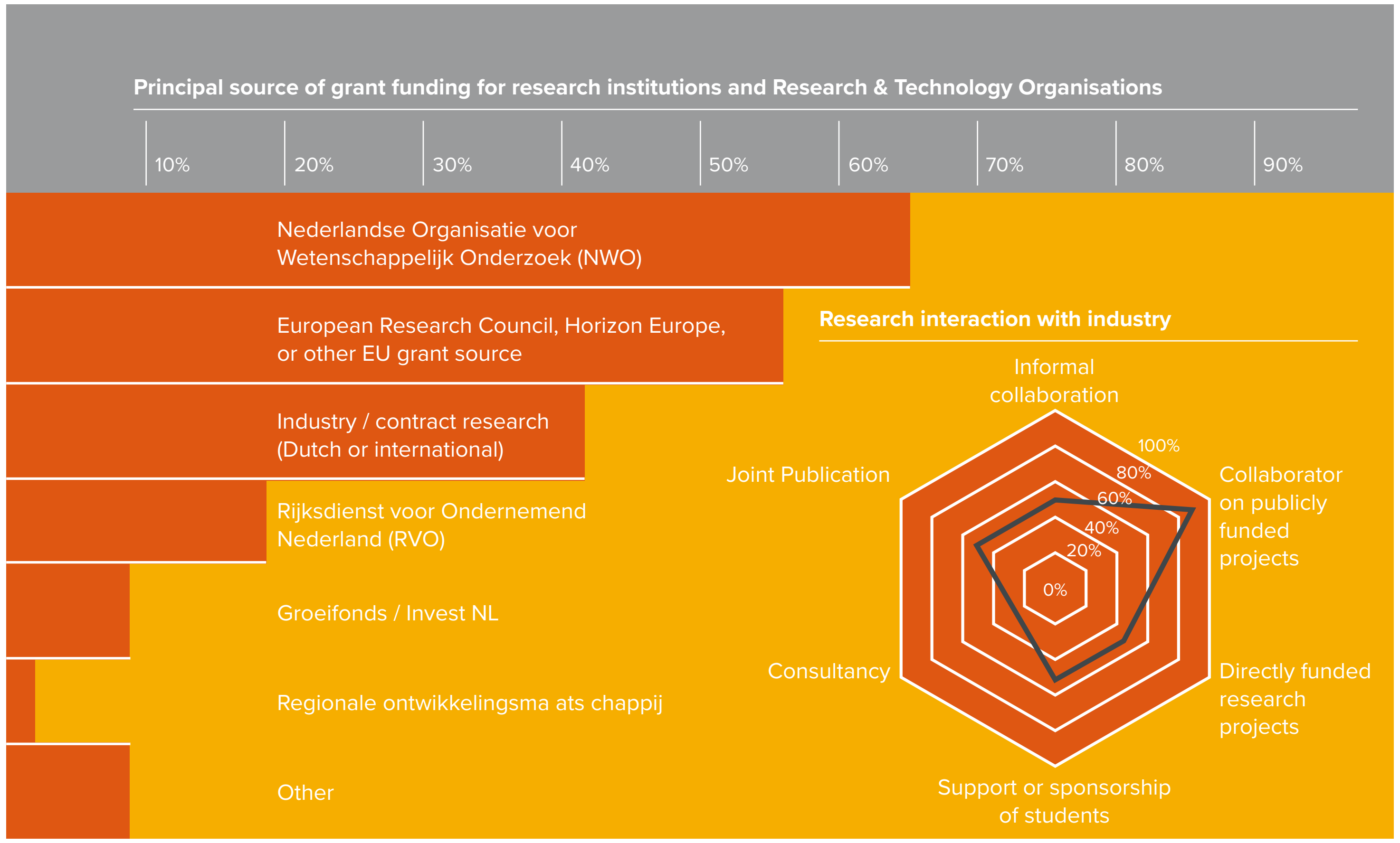
Industrial support is also expected to grow. Over the next three years, the fraction of academics predicting they will receive at least €1 million in industrial support is higher than the fraction that received such an amount in the past three years.

Public funding from NWO has been leveraged by two thirds of Dutch academics. Their international standing is also reflected in half of researchers making use of European Research Council funding.

Strong barriers to fluid dynamics research in the Netherlands remain. 60% of researchers cite a shortage of funding programs and mechanism relevant to fluid dynamics and low success rate for applications. These challenges are amplified by the resources required to pull extensive consortia together.

Industry income to academia and Research & Technology Organisations (past and future)





METHODOLOGY SUMMARY

Systematically quantifying enabling technologies.

Companies active in fluid dynamics are hugely diverse. No single industry classification code (SBI, SIC or NACE) is associated with fluid dynamics and the classification code based statistics are not a viable method to size the industry.

To accurately quantify the fluid dynamics industry in the Netherlands a methodology previously applied to sizing the photonics, acoustics and fluid dynamics industries in the United Kingdom and internationally was used. The process consists of eight key steps (further detailed in the annex):

1. Develop a clear definition of fluid dynamics and a taxonomy of common terms by which companies adding value with fluid dynamics describe themselves.

2. Construct a list of candidate companies using on place based internet search using above terms. Extract data on company location and business type.

3. Identify relevant business types e.g. manufacturer. Filter list to remove irrelevant types and duplicates. Assign companies to one or more sub-sectors based on search origin. 1,100 companies were identified adding value with fluid dynamics to products and services in the Netherlands.

4. Annual revenue, profit and employment figures for those companies, was sourced from international credit agency Dun and Bradstreet. Where global financial figures were returned e.g. for large multinationals, a fraction of business activity was attributed to the Netherlands based on either capacity (e.g. in power generation), or by employment.

5. For the largest, and most diversified companies and key sub-sectors, a panel of industry experts was asked to assign a fraction of such firms output to fluid dynamics according to the value they considered added by fluid dynamics.

6. This appointment fraction was applied to revenue, profit and employment yielding the corresponding figures directly attributable to fluid dynamics.

7. The average €61,300 benefit paid per employee was estimated from the reported total benefits paid and employment numbers for a sample of 8 working with fluid dynamics employing over 84,000 people in total. Gross value added for the sector was calculated from profit plus the total employee benefits paid.

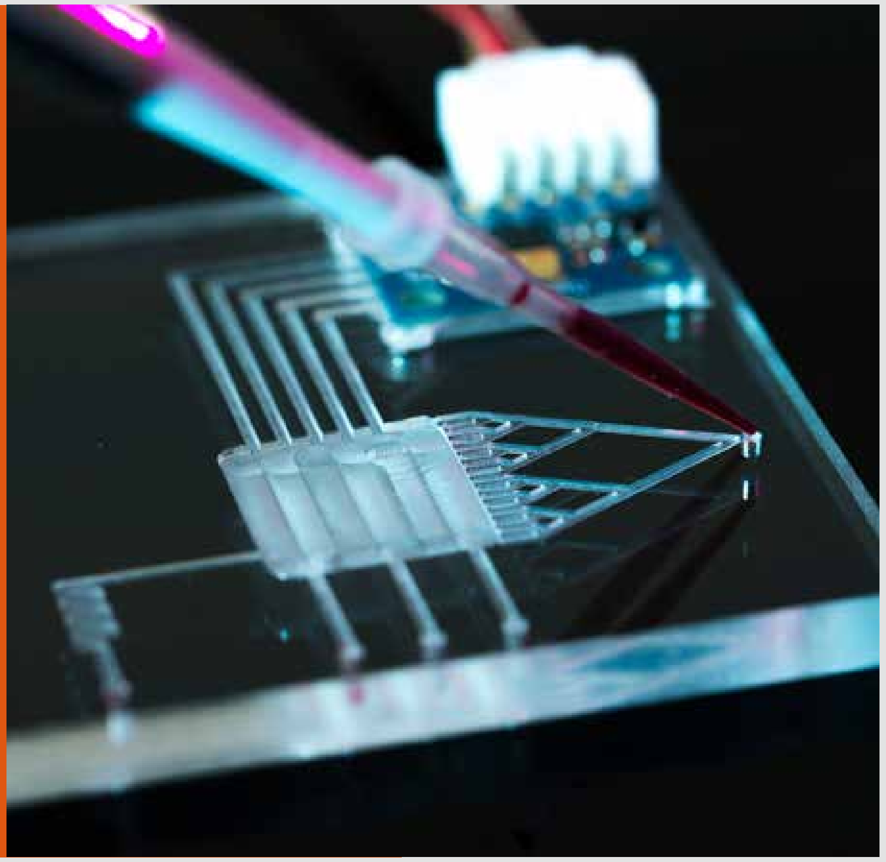
8. Additional forward looking data was gathered through a survey conducted in Q4 2022. Industry input was requested on growth, growth drivers, exports, investment and sources of funding, in the last three and forecast for the next three years. Separately academics were asked for sources of funding, interaction and level of funding from industry.

Publicly funded research institutes were excluded from the analysis to focus on private industry's contribution to the economy. These are a significant source of additional employment. The allocation of revenues for Dutch multinationals is also a conservative estimate, as the fluid dynamics expertise in Netherlands based design centres informs the global business and thus has a much higher revenue impact than that calculated on the fraction of employees based in the Netherlands.

Methodology summary

FLUID DYNAMICS FOR HEALTHCARE

University of Twente Lab-on-a-Chip diagnostics case study



> **"Fluid dynamics plays an essential role in developing new methods that could ultimately be implemented in mass screening programmes for lung, bladder, colon, and endometrium cancer."**
>
> **Professor Loes Segerink**

Point-of-Care (POC) healthcare testing is a rapidly fast-developing field in clinical diagnostics and is expected to define the future of diagnostics in healthcare. The most well-known POC tests are the COVID self-test packages used during the pandemic that proved to be a strong tool for outbreak control, although they still were inaccurate in some cases. Fluid dynamics play an essential role in POC testing since in all cases body fluids are examined in a small user-friendly and equipment free setting, ranging from simple fluid capturing devices to microfluid management for lab-on-a-chip POC testing.

POC sensors such as the handheld glucose sensors for diabetes patients are widely known, but rapid development now also enables sensors for detecting proteins, small (inorganic) molecules, and nucleic acids. Access to rapid and reliable detection methods of nucleic acids is critical in many fields, such as life sciences, environmental monitoring, biotechnology, and maybe most notably, health care. Sensing pathogens based on their genetic information, for instance, by monitoring circulating cell-free DNA/RNA particles related to various (cancerous) diseases, makes early diagnosis and treatment possible. However, this depends on methods that allow the detection of ultralow concentrations of nucleic acids with high sensitivity and specificity, in this case from urine samples.

The University of Twente focuses on the development of new techniques that can measure these ultra-low concentrations of nucleic acids in urine. Although the volume of urine is not the limiting factor, the throughput and volume of a microfluidic chip is a technological challenge. In the case of surface-bound sensors, the urine can be flown over the sensor, but the high throughput of these volumes will be challenging for microfluidic applications. Furthermore, the chance of all molecules binding to the surface also depends on reaction kinetics between the target and probe and mass transport towards the sensor, influencing the time it takes for the sensor to equilibrate.

The most well-known POC testing are the COVID self-test packages used during the pandemic

SUMMARY AND RECOMMENDATIONS

With full support, the Netherlands has the strength in fluid dynamics to address the burning societal challenges.

Fluid dynamics is a vital, but mostly unknown, technology that influences all the major Dutch societal challenges for the future. We have relied on fluid dynamics since the great flooding of 1953 and the subsequent Delta works to control water flow on the macro level, but fluid dynamics also affects all our daily lives on the micro level. For the first time, the influence and impact of fluid dynamics in the Netherlands has been uncovered, revealing the substantial industry that already exists and the importance of continued investment in science & technology and expanding adoption of this discipline across all applications.

The Netherlands has been at the forefront of world-leading fluid dynamics research for decades, exemplified by the J.M. Burgerscentrum as the national research school for science and engineering in fluid mechanics. Industry has harnessed this expertise, hired its graduates and leveraged insights from fluid dynamics in industries, from printing and semiconductor processing to agriculture and chemical production to water management. Sustained industrial investment and application of fluid dynamics has created an industry worth an annual €11.5 billion to the Netherlands economy, employing 19,000 people in over 1,100 firms.

Fluid dynamics is driving many of the grand societal challenges as prioritised by the Dutch government. The urgently needed transition to sustainable energy requires more detailed climate and weather knowledge, from advanced wind farm simulations and atmospheric fluid flow models to the design of new tidal energy turbines. For health, the COVID-19 pandemic has clearly demonstrated the need to understand, predict and control viral aerosol spreading and rapid (self) testing. Looking ahead, more health challenges need fluid flow knowledge, from advanced lab-on-chip tools for Point-of-Care diagnostics of diseases, to personalised medicine manufacturing and printing stem-cell based organoids such as personal drug discovery test banks.

Fluid dynamics technology has the potential to transform societal challenges, but its complexity and hidden presence makes it relatively unknown to the general public and policy makers. It is essential to create more visibility and have national recognition of fluid dynamics as a key enabling technology to solve important societal problems.

To protect our future, and continue to grow the economy, it is vital to have strategic research and innovation funding (>€500 million) for fluid dynamics, to leverage the network from the J.M. Burgerscentrum to new Public-Private projects with a major industrial-societal focus. This would ensure long term Dutch scientific leadership in fluid dynamics and drive collaboration between industry and academia, whilst boosting training in fluid dynamics at all levels essential to support the ever-expanding industrial application across all markets.

Recommendations

- **National recognition of cross-cutting role of enabling technologies, especially Fluid Dynamics.**
- **A directorate focused on industrial adoption in the national J.M. Burgerscentrum.**
- **Strategic collaboration public platform funding of > €500 million over 5 years to expand industrial competitiveness.**
- **Expansion of fluid dynamics research to ensure long term scientific leadership in fluid dynamics.**
- **Increased fluid dynamics training at all levels to provide the expertise needed.**

Valkenburg Aan De Geul, Netherlands. Damage caused by extreme flooding on July 15, 2021 in Valkenburg, Netherlands. Heavy rains overnight left multiple places in the province of Limburg flooded.

ANNEX: FULL METHODOLOGY

The methodology applied to quantify the impact of fluid dynamics in the Netherlands has four principal components.

a) Quantifying the current direct economic impact of the existing fluidics dynamics industry in the Netherlands.

b) Understanding the impact on future societal challenges.

c) Understanding the scale and drivers of future growth.

d) Capturing representative case studies to illustrate impact now and in the future.

Quantifying size and scale.

The previous methodology flowchart illustrates the eight step process for quantifying the current scale of the Dutch fluid dynamics industry. It builds on the principal of taking known and report data on financial output, employment and gross value added and apportioning a fraction of this to fluid dynamics based on expert panel input.

The process is dependent on a number of critical factors. Firstly, identification of the correct companies to include. Placed-based search was used to identify companies located in the Netherlands associated with terms commonly linked with either fluids dynamics focused products e.g. pumps, valves, seals or HVAC manufacturers, or vertical markets using fluid based inputs e.g. wind power, chemical processing. Down selection on business type e.g. manufacturing organisations was vital to focus on only those with direct economic impact.

Accuracy of financial data was ensured by using respected estimates from Dun and Bradstreet, carefully annotated to ensure figures related only to Dutch rather than global business outputs. The financial data applied were one to two years old, covering a range of financial year end dates in 2021. Impact is therefore likely from variations in industrial recovery rates from the COVID-19 pandemic. However, figures should also not have been impacted by the energy price increases seen in 2022. Given the central role of fluid dynamics in energy generation and intensive consumption industries, the presented figures are likely to be highly conservative and already have grown significantly.

Relevant apportionment is vital to accuracy of the presented figures. The consensus view of a panel of fluid dynamics experts was therefore used to assign a fraction of business activity to fluid dynamics. In some areas significant variation in expert opinion was noted. This was highest when an industry's current output is strongly dependent on historically applied fluid dynamics expertise and /or empirical fluid dynamics knowledge.

Application of common apportionment to output (turnover), employment and profit and a single employee benefit are also top level assumptions that mask the impact of high value fluid dynamics jobs, e.g. in design with greater employee benefits and profit impact. Gross Value Added figures should therefore be seen as particularly conservative.

Survey

Whilst the above methodology provides vital information on the size and direct economic impact of the fluid dynamics industry in the Netherlands today, it does not provide information on the future prospects for the industry, or key metrics such as investment. A survey was therefore used to gather this additional information.

The principal survey questions for industry were:

- Which sectors do you see as the principal applications areas for your business?
- What do you forecast the compound annual growth (or decline) will be in the fluid dynamics portion of your business in the next 3 years?
- What impact will the following factors have on the growth of the fluid dynamics based portion of your business over the next 3 years?
- Where will you need additional staff and skills to sustain and/or support the growth of your company over the next 3 years ?
- Please indicate the share of fluid dynamics related output (products or services) from your organisation that is normally exported & export region?
- Please indicate the approximate total value of R&D investment over the last 3 years and forecast for the next 3 years as a percentage of turnover?
- What portion of your total R&D investment relates to fluid dynamics?

The survey was bifurcated according the type of organisations respondents selected; industrial or academic. The following questions were presented to academic respondents:

- What are the principal focus areas of your fluid dynamics research?
- What are your principal sources of research funding?
- How has your research group interacted with industry or external organisations?
- What level of funding has your research group received from industry over the last 3 years and forecast for the next 3 years?
- What are the main barriers you encounter in securing research funding for fluid dynamics in the Netherlands

Type of organisations, size (Micro, Small Medium Large) & geographic locations were also requested.

All survey responses were anonymous, with no individual or organisation identifiers requested and all questions being optional. This supports survey participation at the risk of more than one response being received from the same organisation. Responses were in the form of selection from a given list of options in broad groups e.g. 20-49%, 50-75% supporting anonymity and analysis.

The total number of survey responses received was less than ideal (<100 total). The uncertainty in some survey based conclusions e.g. exports, is therefore relatively high. Follow-on surveys targeting greater response rates and focused on major Dutch application sectors for fluid dynamics are therefore recommended.

Overall the methodology is intended to provide broad estimates designed to inform economic understanding. Their accuracy relies on averaged over a large number of firms and responses. The quantitative impact of any single organisation, sub-sectors or application to a specific societal challenge would benefit from further analysis.

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The contribution of many industrial and academic leaders in responding to the survey and suggesting companies and sectors for inclusion is gratefully acknowledged.

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