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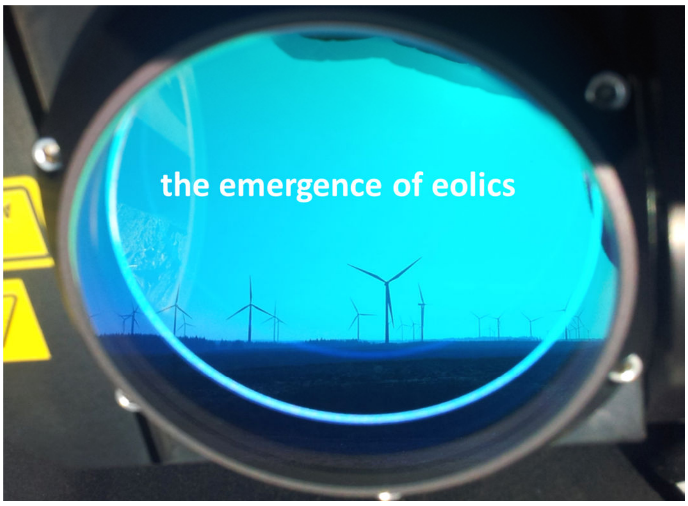


How does a "science" emerge?

How is it you find yourself in a classroom or a lecture theatre attending a lesson in

- Astronomy 101, or
- Introductory Equilibrium Thermodynamics,

or whatever course of study you have elected to pursue?

Who decided that this was how human knowledge should be

- subdivided, and
- presented to you, and eventually
- applied by you

once you have assumed a role like: mechanical engineer; or computer scientist?

The answer is that

- **The application of the science comes first**

At school we often encounter knowledge presented in a **well organised theoretical structure**, neatly arranged into **categories and silos of inter-related facts**, before we think about the **application** of that knowledge for **real world purposes.**

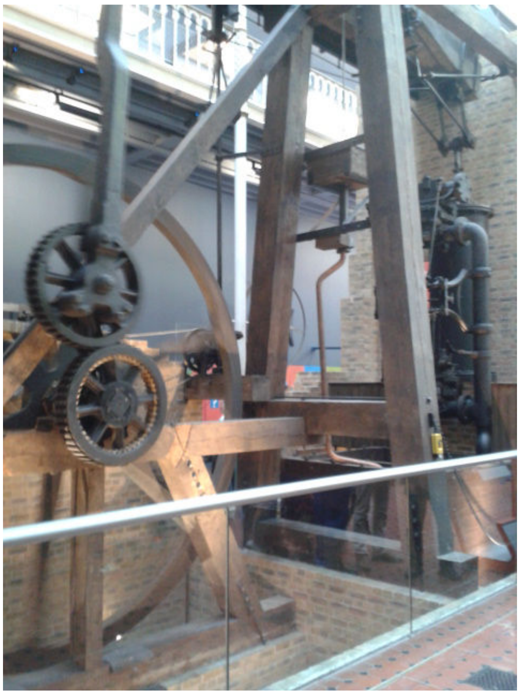
But that way of organising our knowledge only emerged as a result of the acquisition of **useful knowledge** while in the pursuit of **real world applications**.

The **application** of a science **precedes** the **codification** of the **useful knowledge** it represents into a "subject".

Like the kinds of subject that can be studied by you at schools such as this, the University of Strathclyde, founded in 1796 in accordance with the will of Professor John Anderson for the establishment of a “place of useful learning”.

Take, as an example the emergence of **thermodynamics**.

This owes a lot its application during the development of tools and techniques associated with industrialisation.



Here is a Boulton and Watt steam engine. This was a foundational technology for the Industrial Revolution.

Around half a mile from here, on Glasgow Green, in **1765**, James Watt was taking a walk, when he came up with the idea of a separate condenser for a steam engine.

- This idea radically enhanced the efficiency of steam engines, which
- Allowed them to make a crucial contribution to the emerging Industrial Revolution.
- This in turn stimulated the development of the science of **thermodynamics**, to describe how engines like these work.

But it was not until **nearly a century later** that

- This science was formally defined by Lord Kelvin in **1854** as “the subject of the relation of heat to forces acting between contiguous parts of bodies." And
- The first textbook on the subject wasn’t written until **1859**, by William Rankine, across town at that other place, the University of Glasgow

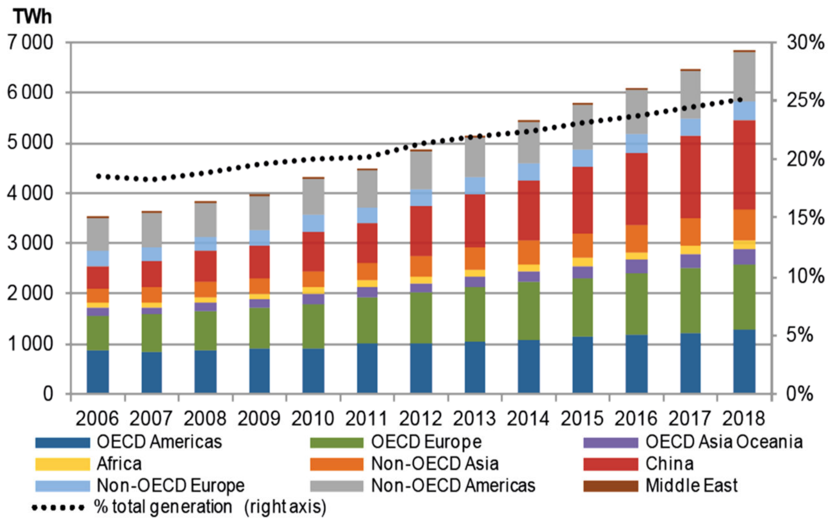
Nevertheless, our theme today is not “**where have we been**” but “**where are we going**”, so we should

- Look for **new disciplines** emerging **now** in response to **the needs of society today**, repeating this pattern I have described
- **What new applications** are stimulating **new investigations, measurements and analysis**, leading to **the development of a knowledge base** that may someday be **codified as a specific subject**?

And when we look for emerging disciplines one area we see is wind power.

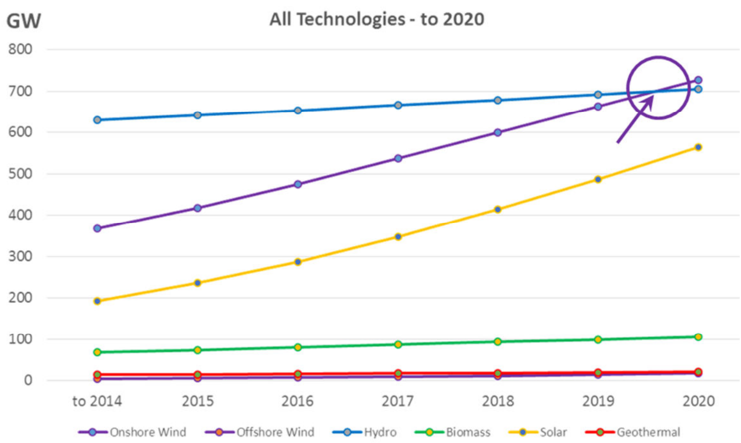
This is an increasingly important part of the economy.

Where steam power was an engine of change historically, wind turbines are the new engines of our sunrise industries. We see new high tech companies putting in place power purchase agreements with green energy companies, or investing directly in the construction of wind farms, as they try to be responsible consumers of electricity.



This chart shows the growth in the contribution renewable energy makes to our power generation globally as projected by the International Energy Agency.

It is projected to exceed one quarter of the total by 2018.



And wind power is making up an increasing proportion of that contribution, and is projected to overtake hydro power by 2020.

Indeed in many situations, wind is the cheapest form of generation.

But in many important respects wind power is not like other forms of generation. It is unique. We can't simply adopt the approaches we have used previously for other forms of generation. Entirely new tools and techniques are required. And why is this?

You can consider three categories of generation.

Resource		Technology		Challenge	Example
Simple	x	Simple	=	Simple	
Simple	x	Complex	=	Complex	
Complex	x	Simple	=	Complex	

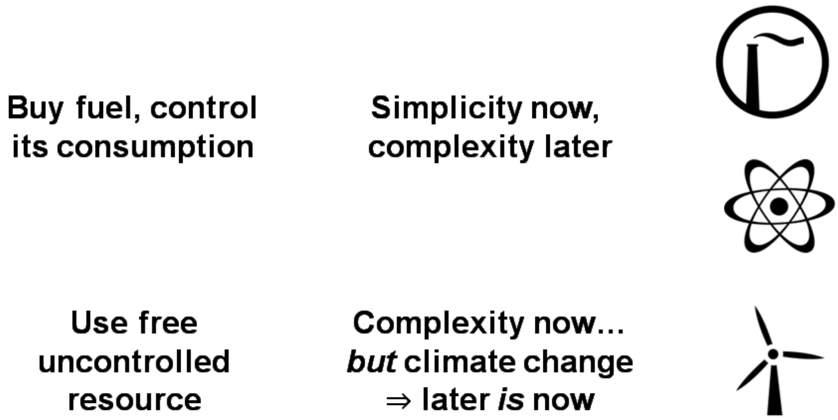
- In the first, you are exploiting a **relatively simple resource**, possibly some **fuel** you are burning, and the technology required to do this is also **relatively simple**, so the overall challenge is itself **relatively simple**
- In the second category **the technology required is complex**, for example a nuclear power plant, and so this entails **complex challenges**
- Wind turbines are **relatively simple objects** by comparison and so **historically** there was an **assumption** that the **challenges were simple**, however
- **We now appreciate** that in fact **wind belongs to a third category** in which the **resource** itself is **highly complex**.

The wind is uncontrolled, unlike the resources in the other two categories.

We are **not** exposing our assets to a **well regulated resource** being **consumed at a constant rate** under **highly controlled conditions but** to a **highly variable** and **intermittent** resource, directly exposing wind turbines to an **energy flux** which varies over **3 or 4 orders or magnitude**.

The wind is always trying to break your turbine

So why bother? Well, wind power exploits a renewable resource. It has no fuel costs.



Indeed, when we consider the other categories of generation - ones that rely on purchasing fuel whose consumption can be regulated and controlled - we see that what is really being purchased is, in a sense, **not fuel, but simplicity**, or rather, the **illusion of simplicity**, since the complex challenges of dealing with the environmental impacts of consuming that fuel are deferred, for example,

- to the **end of the project life cycle** when nuclear power stations have to be **decommissioned**,

- or **beyond**, when we all ultimately have to deal with **climate change**.

We buy a fuel and control its consumption to enjoy **simplicity now at the expense of complexity later**.

Wind power requires us to tackle complexity up front, head on, **now rather than later**, as we use a free but uncontrolled resource. But if we acknowledge anthropogenic climate change and attempt to mitigate its effects, later **is** now.

So if we cannot **control** the wind then we have an urgent need to **understand** it with precision and detail,

- so we can design turbines that withstand the loads it imposes,

- so that we can operate them as efficiently and reliably as possible, and

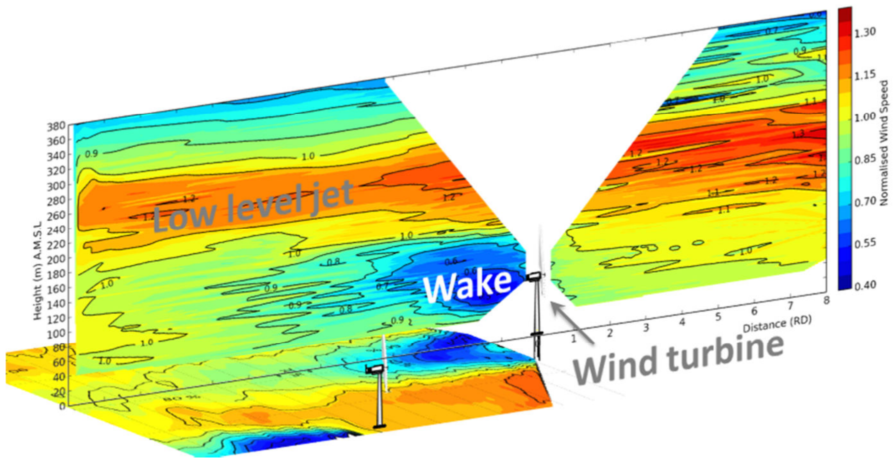
- so that we can predict as accurately as possible the energy generated.

The investigations and analyses we undertake to achieve this are examples of applied science. The question is do we see a science of the wind emerging from this application?

Do we see the emergence of eolics?

One place to look for clues is in the kinds of measurements that are required. There is no science without measurement.

Just as the favoured instrument of the astronomer is the telescope, so the instrument of choice for the **eolicist** is the **lidar**.



Where the astronomer infers the velocities associated with the expansion of the universe by making observations of distant stars and galaxies using a telescope, the **eolicist** infers the wind velocity by observing the motion of tiny microscopic dust particles called aerosols that are present in the lower atmosphere, and are entrained with this wind.

If an astronomer is a star-gazer, then an eolicist is a dust-gazer.

However, the astronomer observes objects that shine with their own light. The eolicist must illuminate the aerosols to observe them.

This is done using lasers. The system that delivers the laser emissions for this is a **lidar**.

Here is an offshore wind turbine and here are lidars installed on it to measure the wind as it encounters and interacts with the wind turbine.

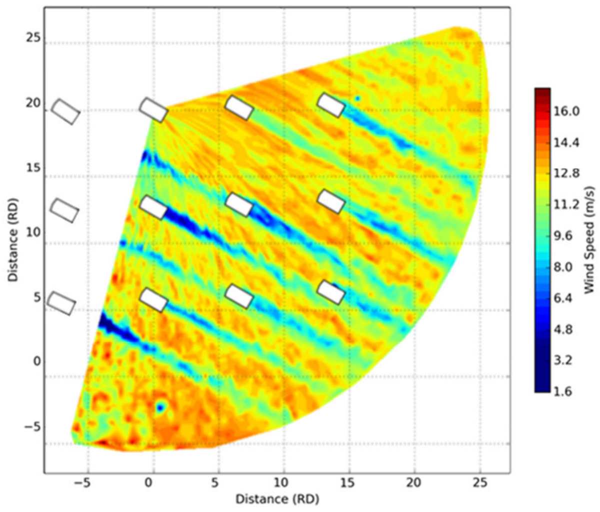
These effectively allow us to see the wind.

We can use this to deal with key questions, such as

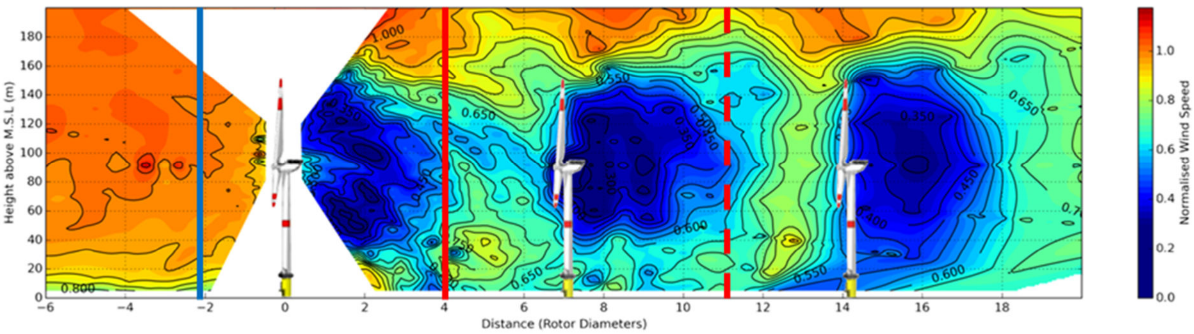
- How efficiently does a wind turbine extract energy from the wind?
- How much energy does it leave in its wake for the next turbine downwind?
- How do the varying wind conditions affect the wind turbine?

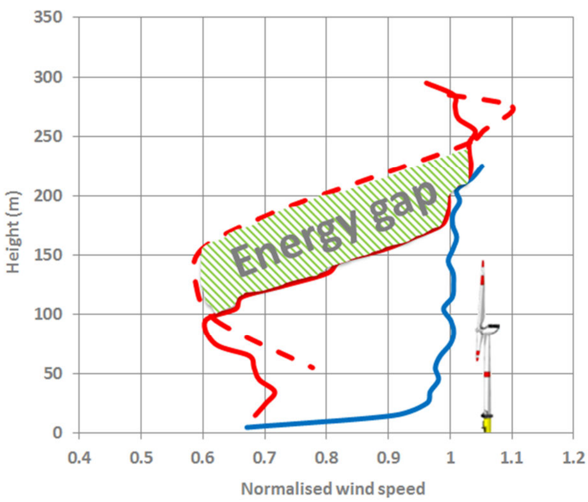
So here is a plan view of the wakes of many wind turbines in a wind farm.

This was acquired by a lidar on the nacelle of the wind turbine I showed you a moment ago.



And here is a side elevation.



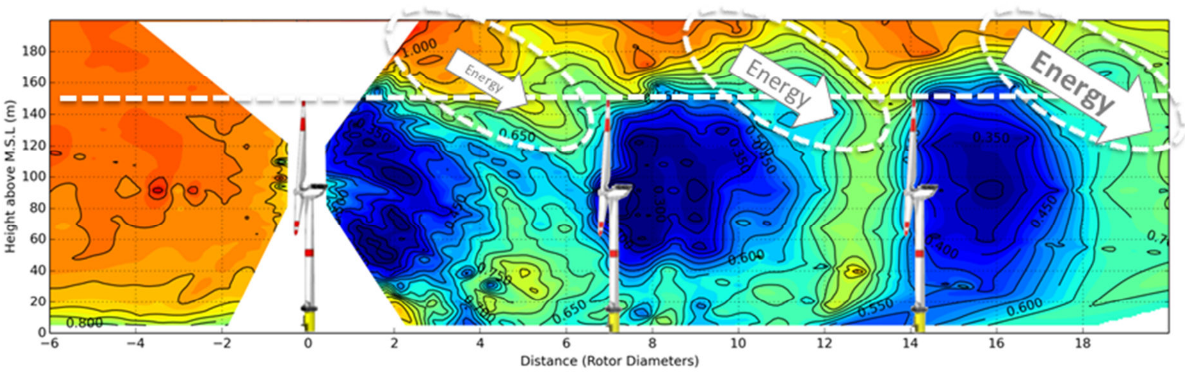


If we look at how the wind speed changes with height at different points in this plot as we move downwind we obtain some interesting results.

We see the wind in front of the first turbine, behind the first turbine, and behind the second turbine.

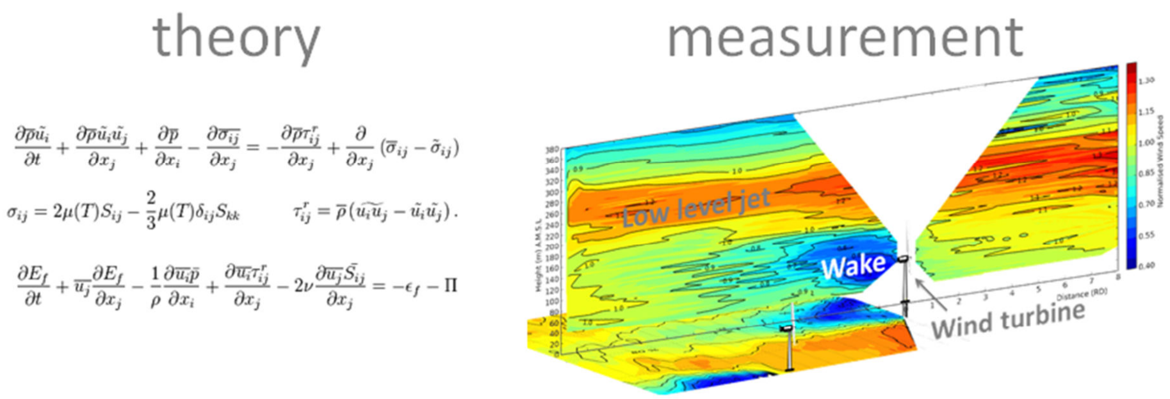
When we compare these different profiles we see an energy gap that develops as we move further and further into the wind farm.

It looks like this is where energy is coming down from above the wind farm to balance the cumulative effects of the wakes of the wind turbines which are extracting energy from the wind within the wind farm.



As we move into the wind farm it interacts with and modifies the wind conditions around it, pulling more and more energy down from above as shown here.

This may look like a computer simulation, but it is important to remember that these images represent measurements, not simulations, **and in a sense this is the point**.



In simulations we can capture the physics and the theory of the situation in the models and equations that we solve numerically.

The computer models we use embody what we know about

- gravity, mass and momentum;
- how buoyancy supports or suppresses different wind conditions – for example, the wake recovery results we looked at a moment ago;
- how energy dissipates from large turbulent structures down to heat at the molecular scale;
- and many other considerations.

The equations that represent this are solved numerically using computer models and simulations to provide us with predictions.

What these lidar measurements provide are **observations** whose level of detail and precision **for the first time** matches the sophistication of the theory.

This allows us to select between accurate and inaccurate predictions **more effectively than ever before**.

theory + measurement = science ⇒ eolics

And when theory and measurement come together in this way the result is **science** – in this instance, a science of the wind, **eolics**.

So, just as we saw in the case of thermodynamics, **eolics** is emerging as a result of its application as the wind industry strives to understand the wind resource and the best way of exploiting it.

So we see the distinctions we make between different sciences are artificial.

- They don't reflect an intrinsic underlying structure to knowledge
- They arise from the use we make of the knowledge they embody

At a deeper level all sciences are connected.

This interconnectedness finds an immediate and compelling manifestation at a local level and an urgent timescale.

Recently the Intergovernmental Panel on Climate Change has issued reports warning in the starkest terms so far about the hazard posed to human society by anthropogenic climate change.

The concentration level of carbon dioxide in the atmosphere is now the highest it has been for 800,000 years, and this is changing the climate.

We are confronted with a significant rise in global temperatures which can only be limited with an immediate expansion of renewable energy generation that consumes **no fuel** and emits **no carbon dioxide** as a result.

Where

- the development of thermodynamics was stimulated by the **needs** arising from the **narrow imperatives of nascent industrial capitalism** as it accelerated the rate at which we consume resources and short-circuited the carbon cycle,

- the emergence of eolics is stimulated by a **wholly more comprehensive** set of needs that have arisen as a consequence.

The needs we must now respond to transcend

- short term commercial interests, or
- class interests or
- national interests, or even
- our species' interest.

The **needs of the planet as a whole** are now paramount.

Industrialisation has catapulted us into a situation where we exceed the carrying capacity of our environment and we can no longer recklessly and unsustainably exploit it.

Indeed, recent mathematical models have suggested that the only way to avert disaster is to

- restore the sustainability of our environmental impacts and
- reduce the economic inequalities of our societies.

If we want to continue as a society we have to become **responsible stewards** of the planet we share with each other and temper the trespass we inflict on its habitats.

And in this

- **eolicists**, that is, the **engineers** and **scientists** engaged in collaborative inter-disciplinary endeavour of making wind power a success, and

- the **investors** and the **policy makers** and you the **consumers**,

have an important role to play.

A science exists because it is needed. And now we need eolics.