This presents the case for switching all energy investments from fossil fuels to renewable energy sources:

1) To limit climate change, world and national carbon budgets must come. These will cap the use of all fossil fuels.
2) The carbon intensity of both fossil fuel and renewable energy sources depends on their EROIs.
3) Of the low-carbon energy sources, the EROIs of wind turbines with Power-to-Gas conversion, may already exceed those of marginal high-carbon sources, such as ultra-deepwater, tar sands and shale oils. This may also be true after both the low-carbon and high-carbon sources are converted to gasoline.

**Carbon Budgets**

The starting point is: 'Greenhouse-gas emission targets for limiting global warming to 2 C', Meinshausen et al, Nature Letters, 2009. (https://www1.ethz.ch/iac/people/knuttir/papers/meinshausen09nat.pdf). It was among the first to suggest that, 'from a scientific point of view, burning all the world's proven fossil fuel reserves isn't an option'.

The above lead to: 'Global Warming's Terrifying New Math', Bill McKibben, 'Rolling Stone', 2012-07-19. (http://www.rollingstone.com/politics/news/global-warmings-terrifying-new-math-20120719). He was concerned that the message was not getting through, so published his interpretation of it in a popular journal. For an 80% chance of limiting global warming to 2 C, only 565 GtCO2 can be emitted (up to 2050). With carbon emissions increasing at about 3% a year, this would be reached in about 16 years, i.e. by 2028.

The above lead to: 'The Most Influential Climate Science Paper Today Remains Unknown to Most People', Katherine Bagley, 2013-02-14. (http://insideclimatenews.org/news/20140213/climate-change-science-carbon-budget-nature-global-warming-2-degrees-bill-mckibben-fossil-fuels-keystone-xl-oil). Describing the Meinhausen et al paper above, this includes:
'It is probably the most influential paper on climate science today. But few outside scientific circles even know it exists.

Though just six pages long, its dense, technical writing makes it largely incomprehensible to non-experts. And yet this paper is transforming the climate change debate—prompting the financial world to rethink the value of the world's fossil fuel reserves and giving environmental activists a moral argument for action.

That's because behind its complicated terminology is a simple question that affects every aspect of society and business: How much time do we have before the burning of fossil fuels pushes the climate system past tipping points? In a worst-case scenario, about 11 years at current rates of fossil fuel use, according to the paper'.

'After impressing scientists, it wasn't long before the findings rippled through the global financial world.

For years, investors had been hearing of carbon budgets and the 2-degree threshold—and they were growing concerned. As much as 30 percent of the value of some of the world's stock exchanges is in proven coal, oil and gas reserves, which energy companies are banking on mining and selling one day.

But what if governments buckled to activist pressure and decided to require firms to keep some of those reserves in the ground? What would that do to the market values of powerful energy companies? What would that do to the world's financial systems?

A newly formed group, made up of green-minded investors in London and called the Carbon Tracker Initiative, sought to assess those risks in a scientific way. They used Meinshausen's paper as the basis of their own report, "Unburnable Carbon," published in 2011.

The report tackled a question that Meinshausen had answered, but not in any depth: How much CO2 is in the world's fossil fuel reserves?'.

BP acknowledged that continuing use of fossil fuels would exceed even a high climate limit. 'BP Energy Outlook 2030 sees emerging economies leading energy growth to 2030; global CO2 emissions from energy well above IEA 450 scenario'. (http://www.greencarcongress.com/2011/01/bp-energy-outlook-2030-sees-emerging-economies-leading-energy-growth-to-2030-global-co2-emissions-fr.html and http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2008/STAGING/local_assets/2010_downloads/2030_energy_outlook_booklet.pdf).

'Unburned Carbon', The Carbon Tracker Initiative, 2011. (http://www.carbontracker.org/linkfileshare/Unburnable-Carbon-Full1.pdf).
Page 20 includes: 'Shell has a production-to-reserves ratio of 11.5 years, yet is still investing $25-27 billion CAPEX each year to develop more production.

BP has around 13 years of proven reserves at its current level of production and a CAPEX of around $17bn. However waiting in the wings for BP is a further 35 years of unproven reserves, waiting to be further developed and proven so they can be added to the official stockpile. This means there is an even larger unproven reserves bubble hidden on the capital markets'.

For their second report, the Carbon Tracker Initiative joined up with the Grantham Research Institute on Climate Change and the Environment, LSE. The latter notably includes Sir Nicholas Stern. (See 'Nicholas Stern: 'I got it wrong on climate change – it's far, far worse', http://www.guardian.co.uk/environment/2013/jan/27/nicholas-stern-climate-change-davos).

This gave rise to: 'Unburned Carbon 2013: Wasted Capital and Stranded Assets'. (http://www2.lse.ac.uk/GranthamInstitute/publications/Policy/docs/PB-unburnable-carbon-2013-wasted-capital-stranded-assets.pdf).
Page 4 includes: 'Stress-testing the carbon budgets
Carbon Tracker, in collaboration with the Grantham Research Institute for Climate Change and the Environment at the London School of Economics and Political Science, has conducted new analysis to stress-test the carbon budgets. This analysis estimates that the available budget is 900GtCO2 for an 80% probability to stay below 2°C and 1075GtCO2 for a 50% probability, confirming that the majority of fossil fuel remains are unburnable'.

'Carbon capture and storage (CCS) doesn’t change the conclusions
CCS technology offers the potential for extending the budgets for the combustion of fossil fuels. Applying the IEA’s idealised scenario - which assumes a certain level of investment that is not yet secured – extends the budgets to 2050 only by 125GtCO2'.

'Listed companies face a carbon budget deficit
If listed fossil fuel companies have a pro-rata allocation of the global carbon budget, this would amount to around 125 - 275GtCO2, or 20 – 40% of the 762GtCO2 currently booked as reserves. The scale of this carbon budget deficit poses a major risk for investors. They need to understand that 60 - 80% of coal, oil and gas reserves of listed firms are unburnable'.

'Capital spent on finding and developing more reserves is largely wasted
To minimise the risks for investors and savers, capital needs to be redirected away from high-carbon options'.

Page 5 includes: 'New business models are required'.
'The conventional business model of recycling fossil fuel revenues into replacing reserves is no longer valid'.

Risk needs redefining'.
'More attention needs to be focused on the fundamental value at risk in the low-carbon transition'.

Page 16 includes: 'Wasted capital?
If CAPEX continues at the same level over the next decade it would see up to $6.74trillion in wasted capital developing reserves that is likely to become unburnable'.

**EROIs of Fossil Fuel Resources**

The EROI for global oil fell from 36 in the 1990s to 18 in 2008. The EROI of global crude oil was ~ 18, and of gasoline 10. Oil production costs are a function of the EROI. ('Energy return on investment, peak oil, and the end of economic growth'. http://www.ravennacapitalmanagement.com/mrr/wp-content/uploads/2013/01/Murphy_2011_End-of-Economic-Growth.pdf pp 63, 64, 68).

The EROI of US oil has fallen from around 18 in 1950 to around 10 in 1995. (http://www.theoildrum.com/node/9249).

The EROI of oil from Daqing, China: 10 in 2001, 6.5 in 2009, with 4.7 projected for 2015. ('Analysis of the Energy Return on Investment (EROI) of the Huge Daqing Oil Field in China'. http://www.mdpi.com/2071-1050/3/12/2323/pdf).

The EROI of oil from California: 6.5 in 1955, 3.5 in 2005. ('Oil Depletion and the Energy Efficiency of Oil Production: The Case of California'. http://www.mdpi.com/2071-1050/3/10/1833/pdf).

The EROI of Ultra-Deepwater Gulf of Mexico Oil and Gas, has been put at 7 to 4. ('Ultra-Deepwater Gulf of Mexico Oil and Gas: Energy Return on Financial Investment and a Preliminary Assessment of Energy Return on Energy Investment'. http://www.mdpi.com/2071-1050/3/10/2009/pdf).

'Traditional oil development is currently estimated to have an EROEI of about 15'. 'However, according to Peter Tertzakian, the chief energy economist at ARC Financial Corporation, the EROEI for tar sands amounts to 7:1 for extraction and drops to 3:1 after it has been upgraded and refined into something useful, such as gasoline'. (http://independentreport.blogspot.co.uk/2012/03/tar-sands-too-inefficient-energy.html).

The EROI of conventional oil is about 20 and that of gasoline therefrom about 4.5. The EROI of shale oil is about 2 'at the wellhead', and roughly 1.5 for the final fuel product. ('Energy Return on Investment (EROI) of Oil Shale'. http://www.mdpi.com/2071-1050/3/11/2307/pdf).

The EROI of bioethanol made from corn is about 1.07. (See 'New Perspectives on the Energy Return on (Energy) Investment (EROI) of Corn Ethanol: Part 1 of 2'. http://netenergy.theoildrum.com/node/6760). Although the feedstock is renewable, it requires major (fossil) energy inputs and competes with food for land and water. This leads to Indirect Land Use Change, with a GHG payback time of 20 to 300 years. (See Edwards, R. 2004. 'What's Important in WTW Analyses'. http://www.sae.org/events/sfl/pres-redwards.pdf Slide 4).

**EROIs of Low Carbon Sources**

Renewable energy sources with high Energy Returns on Investment (EROIs) have low carbon intensities. For extensive deployment, they must also be ample, available worldwide, proven, scalable, and backed by credible companies.

Wind Turbines

The EROIs of Vestas 3.0 MW wind turbines are about 53 (offshore) and 54 (onshore). (http://www.vestas.com/Files/Filer/EN/Sustainability/LCA/LCAV90_juni_2006.pdf). Page 36 gives the energy payback times (EPBTs) as 6.8 and 6.6 months, and p 42 gives the lifetimes as 30 years. EROI = Lifetime/EPBT.

The EROI of an Enercon E-82 2/2.3 MW onshore wind turbine is about 35 to 51. (http://www.enercon.de/p/downloads/WB_02-2012_en_web.pdf). Page 14 gives the lifetime as 20 years and the 'harvest factors' (EROIs) for an inland site as 35.4, a near-coastal site as 40.8, and a coastal site as 51.

The lifetimes are 'design' values, but only time will tell. While there is good experience with old designs, equal or longer lifetimes are expected for the new, much larger designs.

The EROI of a wind farm is reduced due to the electricity output of the 'average' wind turbine being reduced by 'wake effects'. But it may be increased due to sharing of the cable to the (shore and) substation. Also, the new designs from the most experienced makers are highly optimised. For example, the Siemens 3.6 MW offshore wind turbines used to feed the Audi e-gas plant were introduced in 2009 and have geared generators, whereas their latest 6 MW offshore machine, launched in 2011, has a direct drive generator.

The EROI of wind turbines should also increase with the market size and the learning effect of cumulative production. This arises from the intense competition between the world-class suppliers. These include GE, Vestas, Siemens, Enercon, Suzlon (India) and several Chinese makers.

Even with the above caveats, the present EROIs of 35 to 50 for wind turbines are excellent. They also have a direct bearing on the monetary ROIs enjoyed by investors.

The GHG intensity of electricity from wind turbines for a lifetime of 20 years had a median of 11, and a range of 3.0 to 45gCO2e/kWh. ('Life Cycle Greenhouse Gas Emissions of Utility-Scale Wind Power, Systematic Review and Harmonization'. (http://onlinelibrary.wiley.com/doi/10.1111/j.1530-9290.2012.00464.x/pdf).

Solar PV

The Energy Payback Time of crystalline silicon solar PV arrays with an insolation of 1700 kWh/m2 (Southern Europe) is about 1.75 y. For a lifetime of 30 y, the EROI would be about 17. (See 'PV ENERGY ROI Tracks Efficiency Gains', (http://www.bnl.gov/pv/files/pdf/240_SolarToday%20June12_c.pdf).

The GHG intensity of electricity from crystalline silicon solar PV arrays with an insolation of 1700 kWh/m2 and a lifetime of 30 years has a median of 45gCO2e/kWh. ('Life Cycle Greenhouse Gas Emissions of Crystalline Silicon Photovoltaic Electricity Generation'. http://onlinelibrary.wiley.com/doi/10.1111/j.1530-9290.2011.00439.x/pdf).

Power-to-Gas conversion

Power-to-Gas conversion to methane may be used for renewable electricity balancing, transport fuels and heat. (http://www.etogas.com/fileadmin/user_upload/Paper_111027_P2G_CNG_ZSW_IWES_SolarFuel_final.pdf).
This is the best short paper I have found by Specht et al, and is in English. In particular, it shows that (save where hydro and pumped storage is available and sufficient) electricity in large amounts is best stored in chemical form, specifically as methane.

The thermal efficiency of the Power-to-Gas conversion to methane at industrial scale should be over 60%, (http://www.solar-fuel.net/en/home/the-solution/the-beta-plant-is-currently-being-planned/).
'Commercial SolarFuel plants will be available to the industry from 2015 with a connected electric load of 20 MW and an efficiency of over 60 percent'. Incidentally, from a 6.3 MWe plant in 2013 to a 20 MWe plant in 2015 is a very rapid scale-up.

Methane (as Compressed Natural Gas - CNG) is already used in Internal Combustion Engine Vehicles (ICEVs). They have a second tank for gasoline. Such vehicles are in series production in Europe and elsewhere and sell in significant numbers.

Reiner Mangold of Audi (the Project Director of Audi e-gas) gave a presentation at the DENA 'Power-to-Gas' meeting, dated 2011-11-22. 'Das e-gas Projekt von Audi: Power-to-Gas im Verkehrssektor'. (This is no longer online, but I can supply a copy).
a) Slide 13 shows the life cycle GHG emissions for an ICEV with e-gas (renewable synthetic methane) are lower than those for a Battery Electric Vehicle (BEV) with electricity from wind power.

Reinhard Otten of Audi (the Project Manager of Audi e-gas) gave a presentation at IRED, Berlin in December 2012. 'Mobility: A Driver for Power-to-Gas-Technology, The Audi e-gas project'.
(http://www.conference-on-integration-2012.com/fileadmin/user_upload_COI-2012/RE_PDF/Otten_Reinhard.pdf).
This is outstanding, and in English. The points I find especially interesting are:

a) Slide 4 includes: 'GHG reduction [in transport] costs about 10 times higher than in other sectors'.

b) Slide 6 introduces 'Life Cycle Analysis'.

c) Slide 8 shows that BEVs offer no advantage over ICEVs unless the grid is substantially decarbonised. Then see Slide 16.

d) Slide 10 is the rationale for e-gas/Power-to-Gas. Moreover, at 78% renewable electricity, the 'excesses' are much larger than the 'deficits', so the round-trip efficiency is not critical. For deficits of 43.5 and excesses of 187.7, the round trip efficiency need be only 23%. By luck or judgement, this is close to that for the PtG and GTCC conversions.

e) Slide 11, showing the storage capacities: this shows that the oft-suggested (e.g. by UC Davies) Vehicle-to-Grid is next to useless.

f) Slide 16 shows that Audi has included the wind turbines and e-gas plant in the Life Cycle Analysis (LCA). It also shows that 'a vehicle fuelled with e-gas is just as environmentally friendly as one using electricity from wind power'.

g) Slide 17 shows how Audi (and hence VW Group) are minimising risk by developing e-gas, which could well win out over both BEVs and hydrogen FCEVs so that all the Internal Combustion Engine production plants are not 'stranded'. Also, ICEVs could continue to be sold worldwide, requiring no new fuel infrastructures.

There is also:'Press release, Ingolstadt/Werlte, 2012-12-13, 'Topping-out ceremony for the Audi e-gas plant'. (https://www.audi-mediaservices.com/publish/ms/content/en/public/pressemitteilungen/2012/12/13/topping-out_ceremony.standard.gid-oeffentlichkeit.html). This includes a picture of the plant complex, complete with a Visitor Center.

When comparing a ICEV running on fossil CNG and e-gas, Mangold Slide 13 shows a CO2 reduction of 85% (without including that of the construction of the wind turbines and e-gas plant), while Otten Slide 16 shows it as 75%, when including that of the construction of the wind turbines and e-gas plant. I believe that the difference - 10% - implies that the wind turbines and e-gas plant have an EROI of 10. [This value could be affected by differing carbon intensities, but I believe that it is still broadly correct. Audi and SolarFuel would have better data]. This value has several very important implications. (See 'Comparisons' below).

Since the EROI of large wind turbines on good sites is around 50, that for wind turbines and Power-to-Gas conversion of around 10 is highly plausible. Moreover, it will increase with learning and scale. (The potential numbers are in the Appendix). Furthermore, the EROI would increase by using the Power-to-Gas reject heat for district heating of buildings.

As well as balancing renewable electricity from wind and solar over time, Power-to-Gas etc could provide all transport fuels and some heat. Much of the required CO2 can be provided from clean sources, such as biogas plants, breweries and cement plants. More could be captured from gas-fired power plants, but it may be necessary to capture some CO2 from the air.

CO2 capture from the air could be scaled up beyond that required for synthetic fuels to 'rollback' the CO2 concentration of the atmosphere. Because the plant is on land and deployed incrementally, this is the only safe method of geo-engineering.

Gas to Liquid conversion

The thermal efficiency of converting methane to methanol at scale approaches 75%. (http://two.web-dms.net%2Fdms%2Fuploaded_files%2Fzerom%2FZeroMDMS.mdb%2Fdocuments%2FRoutes%2520for%2520making%2520methanol%2520new.pdf )

The thermal efficiency of a methanol to gasoline process is 92-93%. (http://nzic.org.nz/ChemProcesses/energy/7D.pdf Page 17).

So the methane to gasoline efficiency should be 0.75 x 0.92 = 0.69 and the EROI of Wind Turbines with Power-to-Liquids (gasoline) plants might be about 10 x 0.75 x 0.92 = 6.9.
(This omits the embedded energy of the methane to methanol and methanol to gasoline stages. However, unlike the wind turbines and electrolysis stage of the Power-to-Gas process, they would run at full capacity almost continuously (i.e. save for maintenance).

Energy Saving and Energy Efficiency

Energy savings and increased energy efficiency measures are essential accompaniments to renewable energy supply solutions, such as renewable electricity, Power-to-Gas and Power-to-Liquids. Such measures should also be judged by EROI, where the energy output is not supplied but saved. They would reduce the energy demands for given energy services, and reduce or slow the expansion of renewable energy harvesting into less favourable areas (e.g. of wind resource), which would otherwise reduce the EROI. Many such measures can reduce GHG emissions at zero or negative life-cycle cost. ('Vattenfall's Global Climate Impact Abatement Map'. http://www.iea.org/media/workshops/2007/egrd/Nelson.pdf Slide 12). They can be monetized by Energy Service Companies (ESCOs).

**Comparisons**

Minimum EROI required

The EROI values of high-carbon and low-carbon energy sources must be compared with the minimum EROI required by a sustainable society. When the energy for transporting and using the fuel is included, this is about 3. (http://netenergy.theoildrum.com/node/6356 and http://www.mdpi.com/1996-1073/2/1/25/pdf).
This includes: 'Thus we introduce the concept of "extended EROI" which includes not just the energy of getting the fuel, but also of transporting and using it. This process approximately triples the EROI required to use the fuel once obtained from the ground, since twice as much energy is consumed in the process of using the fuel than is in the fuel itself at its point of use. Any fuel with an EROImm less than the mean for society (about 10 to one) may in fact be subsidized by the general petroleum economy. For instance, fuels such as corn-based ethanol that have marginally positive EROIs (1.3: 1) will be subsidized by a factor of about two times more than the energy value of the fuel itself by the agricultural, transportation and infrastructure support undertaken by the main economy, which is two thirds based on oil and gas. These may be more important points than the exact math for the fuel itself, although all are important.

Of course the 3:1 minimum "extended EROI" that we calculate here is only a bare minimum for civilization. It would allow only for energy to run transportation or related systems, but would leave little discretionary surplus for all the things we value about civilization: art, medicine, education and so on; i.e. things that use energy but do not contribute directly to getting more energy or other resources. Whether we can say that such "discretionary energy" can come out of an EROImm of 3:1, or whether they require some kind of large surplus from that energy directed to more fundamental things such as transport and agriculture was something we thought we could answer in this paper but which has remained elusive for us thus far'.

The same authors also wrote 'EROI, Insidious Feedbacks, and the End of Economic Growth'. (http://www.theoildrum.com/node/6961 and http://www.esf.edu/outreach/sure/2010/documents/Murphy_SUREpresentation-11-4-2010.pdf). This should give pause for thought to all those calling for 'growth'.

For any energy source, an energy profit (EROI > 1) is essential for there to be a money profit. However, obeying the energy budget dictated by global warming of 2 C would constrain oil, gas and coal more than the sources having EROIs > 1.

Aspects of the Switchover

There are many who believe in sustainable solutions, based on 100% renewable energy. (E.g. 'Pathways to 100 Percent Renewable Energy'. http://www.renewableenergyworld.com/rea/news/article/2013/04/pathways-to-100-percent-renewable-energy?cmpid=WindNL-Thursday-May2-2013 and http://www.renewables100.org/pathways-to-100/ and https://www.dropbox.com/sh/n7z26gx3nrqhl2f/bG7U5g4yhG).

Of the renewable energy sources, solar, wind and biomass are in principle large enough and available worldwide. However, biomass feedstocks compete with food for land and water, whereas the wind resource – at about 72 TW - is many times the total world energy demand of about 10 TW. ('The CAST Proposal, Compatible Affordable Sustainable Transportation'. http://www.energypolicy.co.uk/CAST_52c.pdf Appendix C). Also, the UK wind resource is several times the UK energy demand. ('Coalition & wind: can the UK be a net exporter of Renewable Electricity?'. http://www.cambridgeinvestmentresearch.com/uploads/Delany.pdf Slide 9). So UK-based companies such as BP and others could produce more renewable electricity and synthetic fuels than the UK requires, and sell them overseas.

Conventional oil sources with high EROIs are no longer available for leasing and development. So the low-carbon sources need only exceed the EROIs of ultra-deepwater and Arctic oils, which are hugely expensive, and prone to very costly disasters.

If the EROI for Wind Turbines with Power-to-Gas (methane) plants is about 10, it would be higher than for ultra-deepwater oil (7), tar sands oil (7) and shale oil (2). If the EROI for Wind Turbines with Power-to-Liquids (gasoline) is 6.9, it would be higher than for gasoline derived from ultra-deepwater oil (4), tar sands oil (3) and shale oil (1.5).

Also, while the EROIs of high-carbon (depletable) sources will continue to fall, and their carbon intensities to rise, the EROIs of low-carbon (renewable) sources will increase due to learning and scale. This will in turn reduce their CAPEX requirements (for a given magnitude of energy source). The low-carbon sources also reduce water requirements and - being indigenous – increase national energy security and employment.

A 'first-mover advantage' of switching CAPEX from high- to low-carbon sources would be the opportunity of cost-sharing R&D with e.g. the UK Government and the EU in Europe and the US Government in the USA.

Early switching of CAPEX would also give the competitive advantage of early delivery from preferred suppliers. While most components are mature, and available from several world-class suppliers, their combined production capacity is still far below that required for a complete worldwide switchover.

Switching CAPEX from high- to low-carbon sources should reduce OPEX for fuel imports, and hence currency risk. As well as reducing carbon emissions, it would also reduce exposure to future price rises.

Only 20 to 30 years of conventional oil are left. Yet any major energy transition would take 2 to 10 decades. ('Energy return on investment, peak oil, and the end of economic growth'. http://www.ravennacapitalmanagement.com/mrr/wp-content/uploads/2013/01/Murphy_2011_End-of-Economic-Growth.pdf pp 63, 64, 67). Delaying the switchover would condemn humankind to overshoot and collapse, followed by a lower world population and/or standard of living. ('The Limits to Growth'. http://web.ics.purdue.edu/~wggray/Teaching/His300/Illustrations/Limits-to-Growth.pdf and 'Energy Criteria for Sustainable Energy Solutions'. http://www.energypolicy.co.uk/Gordon_Taylor8e.pdf Slides 3, 4). Despite repeated warnings, humankind has lacked the political will to make the switchover. It is now vital, while some low cost energy remains to effect the transition.

**Conclusions**

For an 80% chance of limiting global warming to 2 C, only 565 GtCO2 can be emitted (up to 2050). With carbon emissions increasing at about 3% a year, this would be reached in about 16 years, i.e. by 2028. This means that about 80% of the fossil fuel reserves must not be burnt. The switch from high-carbon fossil to low-carbon renewable energy sources will have to take place sooner or later. For example, BP has around 13 years of proven reserves at its current level of production and a CAPEX of around $17bn (a year). By switching sooner, energy companies would reduce the size of fossil reserves as stranded assets.

The EROI of high-carbon conventional oil is about 15, ultra-deepwater oil 7 to 4, tar sands oil is from 7 to 3, and shale oil is from 2 to 1.5. However, the EROIs of low-carbon Wind Turbines producing electricity are around 50 to 35, and with Power-to-Gas conversion producing methane, may be about 10, and with further conversions producing gasoline, may be about 7.

As the high-carbon sources are replaced by low-carbon sources, the carbon intensity of energy would reduce, eventually to zero. Such zero-carbon sources would impose zero risk to the climate so such investments would incur zero climate risk.

**Appendix: The Potential Scale of Low-Carbon Sources**

To produce renewable methane for use in GTCC power plants to 'balance' electricity from renewable sources for Germany, I assumed that the number required would be the total 'excesses' of electricity available at 78% renewable electricity, divided by the electricity input to the Audi e-gas Werlte plant. From the Otten presentation, Slide 10, the former is about 188 TWh/y = 188,000 GWh/y, and from Slide 13, the latter is 27,600 MWh/y = 27.6 GWh/y.

I believe that the Audi e-gas Werlte plant is the smallest that requires a 'full size' methanation reactor. This is 5.8 by 3.6 by 16m long, which I guess is the largest that can be moved fairly easily by truck. (http://auto-geil.de/2013/01/25/audi-e-gas-anlage-methanisierungsreaktor-erreicht-werlte/). So larger e-gas plants would use multiple methanation reactors. For the plant at Werlte, the methanation reactor was made and delivered by MAN, a member company of the VW Group.

So the number of methanation reactors required for 'balancing' renewable electricity for Germany would be about 188,000/27.6 = 6812. This would be very good business for Germany, with MAN having an inside track. Then there is the catalyst inside the reactor. The IPR on this is probably owned by ZSW and SolarFuel, since the latter paid for both the 25 kW 'two-container' plant and the new 250 kW plant near ZSW, to be used for process development.

With 4 offshore wind turbines of 3.6 MWe feeding the Werlte plant, the number required for Germany could be 6812 x 4 = 27,248. Since the size of offshore wind turbines is still increasing to 6 and even 8 MWe, this can also be expressed as 6812 x 4 x 3.6 = 98,093 MWe = 100 GWe. As suppliers to the Werlte plant, Siemens would have an inside track. However, it would still be very good business, even if Germany (e.g. Siemens, Enercon, Nordex) has to compete with other wind turbine suppliers, such as GE, Vestas and several Chinese companies.

More plant would be required to meet the total demand for gaseous and liquid fuels in transport. Otten Slide 3 shows the total energy for Germany as 3440 TWh/y and transport fuels as 21%. So transport fuels for Germany are about 3440 x 0. 21 = 722 TWh/y. Assuming that the energy efficiency of producing liquid fuels is about 60% x 69%, this would require about 722/0.41 = 1760 TWh/y input electricity. Assuming a capacity factor of about 0.40 for offshore wind turbines, this implies offshore wind turbines of 1760/(8.76 x 0.40) = 502 GWe. This implies additional Power-to-Liquids capacity of 502/100 ≈ 5 times, with wind turbines, electrolysers, methanation reactors, methane to methanol stages and methanol to gasoline/kerosene/diesel stages.

With the English name 'Power-to-Gas', coined I guess by DENA, Germany clearly aims to sell this solution worldwide. It uses 'right-sized' components that can be built in series in factories, and assembled and commissioned in a year. Also, by harnessing indigenous renewable energy sources, it reduces worldwide resource conflicts and increases energy security in the long term.

The UK's oil imports for 2010 cost about $ 56bn. (http://www.indexmundi.com/united_kingdom/oil_imports.html). Germany's oil imports for 2011 cost about $ 71bn. (http://www.reuters.com/article/2012/02/13/germany-oil-imports-idAFL5E8DD82F20120213). So large CAPEX for renewable fuel plants could be justified by import savings, as well as reduced GHG emissions.

Using Reject Heat for Heating

For Germany, the 'heating' demand is about 41% of 3440 = 1410 TWh/y. (See Otten presentation, Slide 3). Assume that reject heat is about 65% of 'balancing energy' (due to losses in two conversions), and 35% of 'transport fuels' (due to losses in one conversion). Assume the recoverable losses for 'balancing' = 100 – 0.25 (round trip efficiency) – 0.10 (unrecoverable) = 0.65. Assume the recoverable losses for Power-to-Liquids = 100 – 0.41 (overall efficiency) – 0.10 (unrecoverable) = 0.49. Hence (from above) (188 x 0.65 = 122) and (1760 x 0.49 = 862) = 984 TWh/y. So reject heat from the 'balancing energy' and 'transport fuels' processes could meet about 984/1410 = 70% of the 'heating' demand.

In addition, the 'Industry' demand is about 20% of 3440 = 688 TWh/y. Assume that about half is high temperature heat (using electricity or methane) and half is low temperature heat. This would require additional renewable electricity.

Both the heating and industry demands could be reduced by energy savings and increased energy efficiency.