Imperial College
London

From: Ajay Gambhir, Jeremy Woods and Matthew Hannon (Grantham Institute and Imperial College London).

Subject: Peer review of: "Review of renewable electricity generation cost and technical assumptions"Select this text and type your own letter here.

Objective: Imperial College's Grantham Institute was requested to peer review Arup's report, "Review of Renewable Electricity Generation Cost and Technical Assumptions" and provide feedback on five areas:

- Assumptions and methodology: a check of the assumptions developed with best practice and the methodology applied.
- Values stated: a view on whether the evidence from Imperial's perspective are of the 'correct' order and accurate.
- Completeness of analysis: based on experience of whether there are any gaps in the analysis and reporting.
- External perspective: whether the findings are consistent with Imperial's experience and knowledge of international approaches

Uncertainty and ranges: provide a view on the approach for calculating values and reporting uncertainty around estimates.

Reviewer background: The Grantham Institute at Imperial College London undertakes analysis on long-term low-carbon pathways, using energy systems modelling and research into the performance and cost improvement potential of a range of low-carbon energy technologies. The Grantham Institute has been a core partner in the DECC and Defra-funded avoiding dangerous climate change research programme since 2009, with a focus on exploring the feasibility of achieving greenhouse gas emissions pathways which would avoid dangerous levels of climate change.

Other analysis by the institute, frequently in collaboration with other departments and institutes at Imperial College London, requires an understanding of the literature on future technology costs in the power generation sector.

Summary of review, Ajay Gambhir:

Methodology: For the most part the methods are clearly described. One area where greater clarity would be useful is a more detailed description of which learning rates and which deployment figures have been taken from the literature, and how these have been combined/contrasted with the stakeholder survey results to arrive at component cost reduction indices.

Quantity of analysis: Several data points have been gathered, enabling a representative view of costs, with the (acknowledged) exception of solar PV.

Values generated: The cost reduction paths of onshore wind and solar PV look reasonable in light of other literature sources, but offshore wind cost reduction projections do look on the conservative side. Some more elaboration of why this might be the case would be useful.

Specific comments

Literature Review: IEA World Energy Outlook is given as a source for deployment data for key renewables technologies, but it is not stated what year's outlook and which particular scenario's deployment figures are used. This is critical to driving cost reductions.

Cost forecast model: Following from the above comment on the specific scenarios used to generate cost reduction factors, it should be clarified what learning rates were used and how specifically these were combined with the views of stakeholders to generate a component cost index. Currently it is not clear how much relative weight was given to stakeholders' views where they differed from the cost reductions resulting from the learning rate and deployment levels used in the literature sources.

Correlation analysis: It would add clarity to the description and justification of the correlation analysis if some examples could be given of what correlation might be expected between specific variables, whether this is the case for the four technologies for which this analysis was performed, and therefore why further analysis was not undertaken.

Onshore wind: The reductions in capital cost for onshore wind over the period 2015 to 2030 look modest though reasonable in comparison to other sources. The medium projections suggest that the cost will fall from £1,527/kW (2015) to £1,395/kW (2030), a fall of 9% over 15 years.

By comparison, the International Energy Agency's World Energy Investment Outlook (2014) – for its "450 scenario" has onshore wind in Europe falling from $1,790/kW (2012) to $1,600/kW (2035) – a fall of 11% over 23 years.

Offshore wind: As with onshore wind, capital cost reductions look modest. The Arup medium figures show costs falling £2,879/kW (2015) to £2,432/kW (2030), a fall of 16% over 15 years. By comparison, the International Energy Agency's World Energy Investment Outlook (2014) – for its "450 scenario" has offshore wind in Europe falling from $5,180/kW (2012) to $3,030/kW (2035) – a fall of 42% over 23 years.

This discrepancy seems high. The International Energy Agency tends to be on the more conservative end of technology cost reduction ranges, so some explanation of differences would be beneficial, notwithstanding that the estimates are for round 3, in deeper waters with higher construction costs.

Solar PV: Given that the PV costs data relies more heavily on other published sources, unsurprisingly these cost reduction pathways look in line with the other literature.

The Arup report estimates costs falling 31% over the period 2015-2030. This compares to a cost reduction of 48% over the period 2012-2035 in the IEA's World Energy Investment Outlook's "450 scenario", for both building and large-scale ground mounted PV.

A recent survey of building and utility scale PV by the Grantham Institute indicates that the current cost estimates, at around £1,000/W, are reasonable for utility scale projects, although building scale projects from Arup's collected survey data seem quite low (see table below). This may be explained by the larger scale building installations that Arup's survey has included, compared to the data in the table which is a combination of household and commercial buildings.

Summary of review: Jeremy Woods

LCOE does not include system costs e.g. grid reinforcement etc (not from definition in Exec Summary). This should be clearly stated in the Exec summary.

Biomass fuel price is a key parameter with fuel costs typically comprising 1/3 to 2/5 of the LCOE where 'waste' and dedicated (Pellets) fuels are used. There are real risks (and uncertainty) in projections of future prices which are not properly addressed in the report.

There are inconsistencies across all the biomass categories in terms of assumed energy contents in particular that should be resolved.
Should be clear about the uncertainty in projected costs for construction materials e.g. particularly steel, not least because of the uncertainty in the projected costs time frame of the energy prices for energy intensive material production / provision.

Occasionally the term 'negative impact on LCOE' is used and I find this 'negative impact' terminology to be confusing. I would suggest changing it to 'reduction' or 'increase' in LCOE.

LCOE calculation

- Hurdle rate definition required
- Might mention the impact of lower fossil fuel prices on material costs and delivered costs for materials?
- What about exogenous impacts e.g. lower fossil fuel and material costs?
- Use of system cost explain acronyms
- This 'negative impact' terminology is confusing. I would suggest changing it to 'reduction' or 'increase' in LCOE.

ACT: The technology description is confused- I would advise a major re-write

- Gasification is used to produce syngas
- Pyrolysis is used to produce bio-oil
- How was the assumed GCV of the fuel chosen? (Gate Fee section)
- This is inconsistent with the other biomass fuel energy contents- how was the figure of 17.3 GJ/tonne chosen?
- What source was used to provide this temperature range? Gasification usually takes place between 800 and 900 deg C.

Biomass CHP: I have concerns about the assumed energy content of the biomass fuel which is stated to be 'waste wood'. Whittaker and Murphy (2009) assume a moisture content for waste wood of 10% (wet basis). The GCV for 10% moisture wood is 16.56 GJ/tonne. They provide an average moisture content for all biomass waste of 29% which would have an energy content of c. 12.5 GJ/t. In practice, some of the material for producing the fuel could come from forest harvest residues which are c. 50% moisture when produced but are often left in the field to dry to 20% to 30% moisture. 50% moisture content material would have a GCV of less than 10 GJ/t.

Should also include estimates of the MWth capacity.

I would think obtaining planning consent is a key component of this cost and v variable between projects.

Emissions abatement has been an important component in dedicated biomass CHP as far as I know- did any of the stakeholders mention this?

I would use the 'fuel' suffix to indicate that this value is not per unit output e.g. electricity (also need to be consistent with heat output values)

A GCV 12.5 GJ/tonne This seems OK to me but must be based on a relatively high moisture content for the waste wood supplies e.g. 20%+. In practice this is extremely variable with the GCV for biomass at 15% moisture = 16 GJ/tonne. I would expect the moisture content of waste wood supplies to increase as the resource undergoes greater exploitation.

I calculate this to be £33.54 per tonne waste wood. Whilst this is probably OK at the moment I think you should put in a statement that says the quantities of waste wood biomass available at this quality and price are possibly quite limited. I could point you to Whittaker & Murphy (2006) and might be able to find a more recent ref if useful?

LHV efficiency: Should specify these to be 27.7% c.f. DECC's 20%. This seems reasonable as the 20% was a real guestimate based on old US plant efficiencies i.e. from the late 80s and 90s.

Comparison of DECC and Arup LCOE values: This seems quite reasonable to me with the proviso that future fuel prices are likely to be quite sensitive to the anticipated overall scale of demand and it might be worth generating a cost-supply curve for biomass fuel feedstocks?

Biomass Conversion: Drax's website states 'The third unit is expected to be converted in 2015/16.' - See more at: http://www.drax.com/biomass/our-biomass-plans.

A GCV of 17GJ/tonne: This is fine, perhaps a little low. I would have used 17.5 GJ/t or 16.9 GJ/t NCV (LHV) for SE US wood pellets. I note the Lynemouth State Aid application uses 17.2 GJ/t GCV.

LHV Efficency: This seems correct- I understand DRAX's thermal efficiency is nearly 39% and Lynemouth reports 36.9% in the State Aid application.

EfW: Need to check the GCV value used of 16.99 - I think this should be closer to 10-11 GJ/t e.g. for MSW (Cheeseman, 2014)

Risk in the composition of the fuel should be explicitly stated

+100% LCOE seems extremely high and probably needs further justification than provided here.

Dedicated Biomass: Should be clear that this refers to conventional dedicated biomass (have inserted in text in intro) to distinguish from ACT.

Similar issues with the assumed use of 'waste wood' as the feedstock, including the GCV used of 12.5 GJ/t. I would think each plant will use a different mix of fuel feedstocks but mostly sawmill residues (e.g. sawdust and off-cuts) and forest residues (branches, off spec wood). This will result in a v wide range in potential energy densities for the fuel and in pre-processing infrastructure, particularly with regard to drying and comminution.

A GCV of 12.5GJ/tonne: Whittaker and Murphy (2009) assume a moisture content for waste wood of 10% (wet basis). The GCV for 10% moisture wood is 16.56 GJ/tonne.

Add conventional to distinguish from ACT.

AD: A GCV of 16.99GJ/Tonne: Again this is too high- see comments in the EfW section. I would use a GCV of c. 10 GJ/t unless dedicated feedstocks are assumed such as maize sillage.

Biomass co-firing: A GCV of 17 GJ/tonne: See comments on GCV of pellets in biomass conversion section.

Marine: Reference the AMEC and Carbon Trust report on wave energy resource. Analogous report for tidal too by them I think: https://www.carbontrust.com/media/202649/ctc816-uk-wave-energy-resource.pdf

Which projects were these? Also makes a difference about which technologies they were. Was it Pelamis 'Sea Snake' or Aquamarine 'Oyster' for example? Different techs represent diff costs on basis of: 1) different levels of development and 2) fundamentally different engineering challenges

Any details on how the internal review was performed and who performed it? Assuming this is within Arup.

Greater explanation of differences observed in DECC and ARUP modelling needed. I'm unclear why there is such a dramatic difference between some of the results e.g. OPEX costs for 2020 & 2025

Important to explain why an increase in costs is expected from 2016 to 2020

Summary of review: Matthew Hannon

- Clarification required on, "reputable source of information".
- "Published report", should be referenced.

Do you mean 'geothermal heat-only' projects? (There are, of course, in other regions geothermal 'power-only' projects) so this is potentially ambiguous and misleading.

"For the analysis Arup engaged with Ricardo-AEA to review the efficiency of geothermal CHP", from where? Germany? If you used examples from high-enthalpy volcanic regions these might be misleading.

Data collection; again, the geographical provenance needs to be mentioned.

"For the average ('medium') project construction cost is equal to around £6.9m/MW". What is the origin of this figure? Gold-plated govt-funded projects in Germany? This is very high compared to costs I have experienced drilling the UK's only deep geothermal boreholes in recent decades, where costs were more like £1.5M per borehole. How many boreholes is this assuming? 2 or 3? (Need to mention reinjection boreholes are necessary.

Cost and availability of onshore drilling rigs is probably THE big issue - certainly in my first-hand experience. When oil is cheap, so is drilling; when oil is dear, then geothermal is disadvantaged as it struggles to justify top rig rates.

There has been a very detailed study on this by IFC, which you should read and cite:http://www.ifc.org/wps/wcm/connect/7e5eb4804fe24994b118ff23ff966f85/ifc-drilling-success-report-final.pdf?MOD=AJPERESs.

These learning rates seem rather conservative: If we figured out how to reduce dry holes by 30%, for example, that would save a lot more than 2% by 2020.

"A comparison of the DECC assumptions and the Arup 2015 update indicates a large overall increase in construction cost of around 50%." Is this an artefact of the methodology being used? Clearly drilling costs (= construction costs in geothermal) have not done this. In fact they are probably falling.

"Construction costs, the 2015 estimate of £6,907/kW is significantly higher than the external cost estimate range. It should be noted that the external benchmarks are more likely to reflect international construction costs where geothermal CHP is an established", Your reasoning on which construction cost figure to use (the high one) is that the lower numbers come from places 'where geothermal is an established technology'. This begs the question: where did the previous numbers came from then?

Summary of cost projections:

Source and geography	Current / near-term cost	2025 cost projections
Fraunhofer (2013) - Germany	Utility: $1.4/W (2013) Building: $1.7/W (2013)	Utility: $0.85/W Building: $1/W
Lazard (2014) - USA	Utility: $1.6/W (2014) Building: $3/W (2014)	n/a
IEA (2014) – Global average	Utility: $2/W (2015) Building: $4/W (2015)	Utility: $1/W Building: $1/W (for cheapest)
GTM (2014) - USA	Utility: $2.2/W (2014) / $1.2/W (2017) Building: $3/W (2014) / $2.3/W (2017)	n/a
NREL (2014) - USA	Utility: $3/W (2013)/ $1.8/W (2016) Building: $4.5/W (2013)/ $2.2/W (2016)	n/a
ITRPV (2015) - China	Utility: $1.3/W (2015) / $1.1/W (2017)	Utility: $0.8/W

In section 6.5 it is notable that by 2030, Arup's reported capex estimates are higher (in one case – 1-5MW ground-mounted PV shown in table 32 - significantly so) than DECC's current costs. Given that Arup's reported data is broadly in line with the literature, it would be useful to know why DECC's previous estimates were relatively optimistic.

References:

Fraunhofer: https://www.ise.fraunhofer.de/en/publications/studies/cost-of-electricity
GTM: http://www.greentechmedia.com/articles/read/Its-Solar-Balance-of-System-Innovation-That-Will-Drive-Cost-Reduction
ITRPV: http://www.itrpv.net/Reports/Downloads/2015/
NREL: http://www.nrel.gov/docs/fy14osti/62558.pdf
IEA: https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapSolarPhotovoltaicEnergy_2014edition.pdf
Lazard: https://www.lazard.com/media/1777/levelized_cost_of_energy_-_version_80.pdf