The case for immediately powering down the CHP plant in Kings Buildings, installing heat pumps, and securing a power purchase agreement for 100% renewable electricity

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In this discussion paper, I outline a three stage process to reduce the carbon footprint of heating and power production in Kings Buildings campus from 11624 tonnes to ~0 tonnes, over the next two years. This is possible thanks to precipitous decarbonization of UK electricity in recent years.

The first stage involves simply powering down our CHP plant: this can -- and should -- be done immediately, with no associated construction, contractual obligation, disruption of service, or capital expenditure. This simple move will bring our carbon footprint down by more than 4600 tonnes, to 6932 tonnes.

The second stage involves replacing our remaining boilers with high temperature heat pumps, reducing our carbon footprint a further 3400 tonnes, to (at most) 3500 tonnes. This involves a capital expenditure of no more than £5mil.

The third stage – which can in fact be initiated in parallel to the first two – is to secure a PPA for renewable electricity with a local provider, such as Scottish Power. This involves a contract to buy renewable electricity at a fixed (heavily discounted) rate, but involves no capital outlay from the University of Edinburgh. This final stage will complete our transition to 100% renewable heat and power in Kings Buildings, while protecting us from future rises in electricity costs.

Indicative costs are given for each stage in three formats: total cost, cost per tonne reduction to our carbon footprint, and cost per tonne net emissions reduction.

These three proposals are consistent with the framework of the Energy Master Plan being developed; however they represent a much-needed acceleration of the goals there as regards Kings Buildings. Taken together, these three moves will **completely remove** our dependence on fossil fuels to power and heat the Kings Buildings at an **affordable price** and on a **very short timescale**. Instead of making our heat and power net zero by 2040, the plan outlined here will have our heat and power in KB net zero by 2023.

Section I: CHP plant

Electricity and heating in Kings Buildings is currently provided through a CHP – combined heating and power – plant. This plant burns natural gas to provide heat and electricity in a unified process to the entire campus. In the past, when electricity was primarily provided by coal plants, CHP was considered to be both green and cost effective, even supported by government incentives. However, Scotland is now producing its grid electricity almost entirely from renewable wind farms, bringing the UK grid's carbon intensity down precipitously. For these reasons, CHP plants can no longer be considered sustainable.

To underscore this point: our CHP plant in KB currently produces electricity at a carbon intensity of 366gCO2e/kWh, after adjusting for the heat produced in the cogeneration process. The national grid average delivers electricity at 113gCO2e/kWh[1] (dropping year on year).

Our CHP plant is therefore 3x as carbon intensive in its electricity generation versus the grid,

meaning that every kWh of electricity we produce in the CHP increases our carbon footprint by 253g.

Proposal I: Immediately power down the CHP plant in KB. Instead, purchase the required electricity directly from the grid, and produce the required heat directly from boilers.

Practicalities/logistics. It must be noted that we already are equipped to buy grid electricity and do this occasionally when required. We also have three industrial class boilers in place to provide backup heat, and these can easily take on the added heat requirement (combined they can produce 9x the heat capacity of the CHP). Hence there is *no capital expenditure or infrastructure work* required as part of this proposal, simply the flipping of a switch. This point has been confirmed with the Estates Energy office.

Costs and carbon footprint at present.
It is straightforward to determine our carbon footprint from the CHP plant:

- The CHP consumes **63177 MWh** natural gas annually, producing **11624 tonnes** carbon footprint (at 0.184tonne/Mwh).

This is a full 11% of our institution-wide carbon footprint.

- The CHP produces **18953 MWh** electricity and 28429 MWh heat (of which only **22014MWh** is actually used, the rest expelled to the atmosphere).
- On-site gas boilers displaced by the CHP convert natural gas into heat at 87% efficiency; hence **25503MWh** of our current natural gas expenditure provides for heating, with a carbon footprint of **4655 tonnes CO2e** (at 0.184tonne/Mwh).
- The remaining **37674MWh** of natural gas is expended to produce electricity, producing **6932 tonnes** CO2e, at a rate of **366gCo2e/kWh**.

It is also straightforward to determine the operating costs associated to running the CHP plant:

- The cost of buying 63177 MWh natural gas is **£1.33mil** (at 2.1p/kWh).
- CHP plants carry a significant maintenance cost, estimated at £95k per year (at an estimated £5/MWh electricity produced[2]).

1 See Data Table 1 at https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal, reproduced in Section IV below.

2 See UK Government Data in https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/961322/Part_5_CHP_Finance_BEIS_v03.pdf

- Hence the cost of running the CHP plant is £**1.42**mil.

Costs, carbon footprint, and emissions reductions under Proposal I.
It straightforward to determine the carbon footprint to produce the same heat and power under Proposal I:

- The carbon footprint of 18953MWh electricity from the grid is **2141 tonnes CO2e** (at 0.113tonnes/MWh). This is 4827 tonnes lower than the status quo.
- The carbon footprint of 25303MWh natural gas is **4655 tonnes CO2e** (at 0.184tonne/Mwh). This is unchanged from the status quo, as we simply shift the heating burden to the boilers, and do not decarbonize the heat production (however, see Proposal II).
- Combining the above, our total carbon footprint for heat and power under Proposal I is **6797** tonnes, which is **4827** tonnes fewer than at present.

It is also straightforward to determine the costs associated with Proposal I:

- The cost to buy 25303 MWh natural gas is **£531k** (at 2.1p/kWh).
- The cost to buy 18953 MWh electricity from the grid is **£2.37mil** (at 12.5p/kWh).
- Hence the total annual expenditure on heat and electricity if we power down the CHP is **£2.90mil**. This is **£1.48mil** more than the status quo.

It is slightly more complicated to estimate the net emissions reduction achieved under Proposal I:

- The UK long-run marginal emissions factor (LRMEF) for electricity production is presently 258g/kWh. While grid average carbon intensity is used for carbon footprinting, the LRMEF more accurately determines the carbon intensity of the power plants which the CHP is currently displacing (computed as a weighted average of those power sources with spare capacity), which are typically more carbon intensive than the grid average. Energy analysts use LRMEF to determine net emissions reductions involving changes in energy production.
- This means that each kWh of electricity purchased from the grid instead of produced by the CHP will result in a net emissions reduction of 108g CO2e.
- Hence, the net emissions reduction resulting from Proposal I is **2047 tonnes** CO2e.
- Marginal emissions factors have also fallen precipitously in the last decade, and will converge to zero by 2040 as the grid completes its decarbonization.

Conclusion on Proposal I: Without any capital expenditure or disruption to service, we can cut the carbon footprint of our electricity from 6932tonnes CO2e to 2141 tonnes CO2e immediately, reducing our footprint by 4827tonnes CO2e each year, at an additional operating cost of ~£1.48mil annually.

The annual cost per tonne reduction to our carbon footprint is therefore £307/tonne. The cost per tonne net emissions reduction (factoring LRMEF) is £723/tonne.

Powering down the CHP plant is a necessary first step in decarbonizing heat and power as part of our Energy Master Plan. It is an easy step which we can take today, with immediate and profound consequences on our carbon footprint. There is no reason to delay.

Section II: Heat pumps

In addition to increasing the carbon footprint of our electricity consumption in KB as outlined above, the CHP plant poses a major obstacle to our most important challenge: decarbonizing our heat provision.

Proposal II: Install high temperature air source heat pumps extracting the waste heat from the data centre to heat Kings Buildings campus, supplementing with outside air as required.

Heat pumps are considered the future of UK home and commercial heating, although the technology is very simple and over one century old. The reason for such an established technology to shoot to prominence is the rapid decarbonization of the electrical grid, in contrast to the immutable carbon content of natural gas: in order to decarbonize heating, we must move to electric heating solutions. The district heating system in Kings Buildings provides a textbook application of heat pumps, and they will allow us to sever our dependence on natural gas for heating entirely.

Roughly speaking, a heat pump works in the reverse of an air conditioner or refrigerator: it cools outside air and in turn heats up inside air. As the name suggests, the heat pump is able to collect heat energy at a low temperature, and output heat at a higher and more useful temperature. This process violates fundamental thermodynanic principles, and therefore costs electrical energy to run; however because the electrical energy is not devoted to heat itself (as in a resistance heater), but rather entropy reversal, the process produces between 3 and 6 kWh of heat energy output per 1kWh electrical energy input, and so is a very promising replacement for carbon-based heating. This ratio, between 3 and 6 typically is called the "coefficient of performance" and typically abbreviated as COP. Given the low carbon intensity of grid electricity available in the UK, heat pumps produce drastically lower emissions, while competing on cost (see the computations below), even with relatively low COP.

Revisiting past assumptions and consequent timelines regarding heat pumps. Heat pumps were already explored in a 2019 energy audit, where their proposed implementation was attached a £43mil capital expenditure (to retrofit buildings to use their output optimally), and also an increased expenditure on electricity. The 2021 Energy Masterplan which grew from those recommandations commits the University of Edinburgh to a refabrication project over the coming decades to enable this retrofit, and to move us towards low-temperature heat pumps.

It is highly commendable that the University has committed to net zero by 2040. However, the next ten years are by all scientific consensus absolutely crucial to mitigating the climate crisis.

In this proposal we are arguing – based on a straightforward and transparent cost and carbon analysis – to jump-start the University's conversion to heat pumps, by deploying high temperature heat pumps to replace our current heat provision **without** the associated requirement to refabricate the buildings (which can still happen subsequently if desired). This step will provide significant carbon savings immediately, with a far lower capital expenditure and a comparable operating expense, while providing substantial carbon savings immediately. Here are the key points:

1. Traditional radiator systems such as in KB work on a 60/80 system: spent water cycled into the boiler is 60C, and heated water put out to radiators is 80C. Heat pumps traditionally work most efficiently (i.e. with the optimal COP) instead at 45/60, hence are not apparently useful in the 60/80 paradigm. Heating offices with heat pumps therefore traditionally must also be paired with increasing radiator sizes, and insulation efficiencies to accommodate the 45/60 paradigm. This type of retrofit was the rationale for the £43m pricetag on heat pumps in the 2019 energy audit.
2. The timeline for such refabrication is highly unclear presently, given both the construction complications and building disruptions, as well as the considerable administrative lift required to walk such work from conception to completion. It would be reasonable to anticipate it will take many years to complete, given both the administrative and logistical hurdles it will face.

3. To avoid precisely such costly retrofits and extended timelines, several mainstream heating firms are marketing high temperature heat pumps; these are able to operate in the 60/80C range, typically at a reduced COP of ~2. Even this sub-optimal COP produces massive reduction in carbon footprint at an affordable cost (see estimates below).
4. However, the reduced COP of 2 assumes that the air source for heat pumps is outside (cold) air. We propose instead to exploit the heat rejected from the data centre (consistently in the range 27-40C) as a source. The COP is a function of the *differential* between source and sink (i.e, the hot air required), so applying a heat pump to the air from the data centre could potentially restore the desired COP of 3-6. At a COP of 3, heat pumps produce drastic reduction in carbon footprint and are even less expensive to run than gas boilers.
5. Even if heat pumps cannot economically produce heat at 80C, any temperature they obtain above 60C would allow us to preheat the water for boilers in a 60/80 system, thereby proportionally reducing their consumption of natural gas. For instance, if spent water is preheated to 70C by a heat pump, then the boiler needs to consume only one half the fuel previously required in order to return it to radiators (as the differential 80-60 is adjusted to 80-70).
6. As a related point, it will be entirely feasible to immediately begin introducing heat pumps *incrementally*, to thereby precisely gauge their COP, running cost, and carbon footprint, and to subsequently build a strong case for their expansion.
7. Moreover, we presently spend considerable electricity *cooling off* the data centre to prevent servers overheating. Heat pumps, by design cool the source while heating the sink, so they would bypass (or at least significantly reduce) the need for cooling in the data centre.
8. Finally, we note that high temperature heat pumps can be subsequently recalibated to run in a low-temperature regime and thereby recover the additional COP. Hence an investment now in high temperature heat pumps is entirely consistent with a use case in the future for low temperature heat pumps.

As the computations below illuminate, early action now can get us very close to our 2040 goals already by 2024, without in any way impeding the strategic goals for 2040.

Costs and carbon footprint of heat pumps (very rough estimates). It is difficult to precisely estimate installation costs and running costs; an expert manufacturer of high temperature heat pumps will need to be consulted for a careful study. However, let us do some simple estimates:

- I have obtained a quote from Pure Energy, for ~£2million for a high energy heat pump capable of providing all KB's heating needs (as detailed in Proposal I). This number should be taken roughly, but certainly we may cap the capital expenditure at £5mil for sake of discussion.
- Assuming a COP of 2 (a theoretical worst case in the high temperature regime), a heat pump could meet our current heating demand of 22014MWh heat with 11007MWh electricity. This would cost £1.36mil, and produce 1243 tonnes CO2. This is approximately £845k more annually than we currently spend on heating via CHP (or via boilers under Proposal I), and it reduces our carbon footprint (starting from Proposal I) by a further 3411 tonnes CO2e, a cost of £247/tonne reduction in our carbon footprint. The net emissions reduction (factoring in LRMEF) is 1595 tonnes, at a cost of £530/tonne.
- Assuming a COP of 3 (a likely acheivable case if we recycle heat), a heat pump could meet our current heating demand of 22014MWh heat with 7338MWh electricity. This would cost £880k, and produce 829 tonnes CO2e. This is approximately £350k more annually than we currently spend on heating via CHP (or via boilers under Proposal I), and reduces our carbon footprint (starting from Proposal I) by a further 3826 tonnes CO2e, a cost of £91/tonne reduction in our carbon footprint. The net emissions reduction (factoring in LRMEF) is 2615 tonnes, at a cost of £133/tonne.

It is very important here to stress: the actual, quantifiable difference between a COP of 2 and a COP of 3, in terms of emissions and cost is quite small. No matter what COP we obtain, moving our provision of heat to electricity rather than natural gas gets us most of the way towards our carbon goals, and buys us time for building refabrication. To underscore this point, let us consider three scenarios:

- Scenario I: the University commits to a refabrication program for its buildings, culminating in 2030 with the installation of low-temperature heat pumps (COP=3) being installed.
- Scenario II: instead, the University installs high temperature heat pumps in 2022 (COP=2), and does not refabricate buildings and does not move to low-temperature heat pumps in 2030.
- Scenario III: the University installs high temperature heat pumps (COP=2) in 2022, commits to refabrication by 2030, and moves to low temperature heat pumps (COP=3) in 2030.

Let us analyze the cost and carbon impact of the three scenarios through to 2040 (all assuming the CHP is non-operational). For simplicity, we may assume that the carbon content of electricity will stay fixed at present rates; in fact it will not stay fixed and will continue to decrease to zero by 2030, which will only amplify the conclusions coming below, reducing both the costs and the emissions associated to each potential move.

- In Scenario I, we continue producing 4655 tonnes CO2e at annual operating expense of £531k until 2030, and then 829tonnes CO2e annually at operating cost of £880k for the decade 2030-2040. By 2040 we have emitted 45550 (=8x4655+10x829) tonnes CO2e, and spent £13.05mil (=8x£531k + 10x£880k) on operating expenses, in addition to £43mil to refabricate KB and install low-energy pumps in 2030. In total, this amounts to ~£56mil spent and 45550 tonnes emmited by 2040.
- In Scenario II, we produce 1243 tonnes CO2e from 2022, at an operating cost of £1.36mil annually for the period 2022-2040. We incur a £5mil capital expenditure to install high-temperature heat pumps in 2022. In total, we spend £29.5mil (=£5mil + 18x£1.36mil) between now and 2040, and we emit 22374 tonnes CO2e, **fully half** the emissions under Scenario I, at just over **half** the total cost.
- In Scenario III, we incur £43mil capital expenditure (because we can repurpose the high-temperature heat pumps to low temperature ones after refabricating). Our emissions through 2040 are 18234 (=8x1243 + 10x829) tonnes CO2e, and our operating expenses are £22.6mil (=8*£1.36mil + 10*£880k); our total expenditure is therefore ~£62.7mil.

These headline numbers underscore that if our goal is to reduce not only our emissions from 2040 onwards, but our **total emissions between now and 2040**, then it is imperative to move quickly to installation of high temperature heat pumps in the short term, to be reconfigured to low-temperature heat pumps at the points that buildings works are completed.

Clearly the points above are *complicated, site specific, and data-dependent.* They require expert guidance and consultation, whereas above I am providing only rough estimates. The College of Science and Engineering should insist that heat pumps sourced (at least in part) to the data centre be explored in-depth and if necessary, independently from the energy adviser, given the possibility for oversights and simplifications in a cursory analysis. I have obtained a quote of £4250 (at £850/day) for a desktop study by Pure Energy, a UK company who manufacture high temperature heat pumps for precisely such uses. This cannot replace an independent consultation, but it should proceed immediately, to allow next steps to take place by 2022.

Conclusion on Proposal II: Even a cursory estimate of the utility of high temperature heat pumps with conservative COP estimate of 2 indicates a reduction of our heating carbon footprint from 4655 tonnes to 1243 tonnes, versus CHP and boilers for heating as in the status quo and Proposal I. This reduction comes at an even more affordable price per tonne reduced than Proposal I.

The carbon emission to be achieved by acting quickly now far outweigh the benefits to waiting until buildings are refabricated. We should act now, to jumpstart the implentation of our energy masterplan.

Section III: Renewable electricity PPA

Power purchase agreements (PPAs) are in large part behind the explosion of renewable energy production in Scotland. Client-side “sleeved” or “corporate” power purchase agreements, in particular, allow a client such as the University of Edinburgh to engage a manufacturer of renewable electricity stations – typically wind or solar – to build and maintain renewable energy facilities and deliver the power directly to us. These bring four very desirable advantages:

1. The cost of grid electricity has risen 48% since 2010, largely due to government tariffs separate from production and provision costs (see Figure 2 in the Appendix). PPA’s give stability to both producers and consumers of electricity, by negotiating a fixed price and rate of consumption of power over a 15-year period.
2. By definition, 100% of the electricity produced through a PPA is renewablly sourced and regionally provided, ending altogether any dependence on carbon for heating and power and providing a boost to the local renewables economy.
3. PPAs guarantee **additionality –** the power supplier uses the PPA to underwrite bank financing for **new** production of renewable electricity. This makes the University a partner in producing renewable electricity, without requiring capital investment or risk exposure that would come with us building our own renewable energy production.

This form of PPA is not a new idea. A consortium of 20 UK universities made national headlines in 2019 by signing onto a PPA to provide them with 100% renewable energy through 2035. This is an established, safe, and effective way to simultaneously drive down costs of electricity and heat, while guaranteeing the generation of new renewable energy resources in Scotland.

Note: these are distinct from “direct wire” or “onsite” PPAs, which provide far better cost incentives, by operating behind the grid to avoid network charges and government tariffs. However, these require the source of the energy to be within 1-2km of Kings Buildings, which we presume to be impractical.

Proposal III: Arrange a sleeved power purchasing agreement with a Scotland-based company to provide 100& renewable electricity at a fixed rate.

Impact on Proposals I and II under a PPA agreement.

Concerning Proposals I and II, this brings two essential changes:

1. The cost of buying electricity through a PPA is protected against inflation and re-indexing for the duration of the contract. Given historical UK rates of inflation at ~3% annually, this

implies massive cost savings on a 20-year timescae, however, we will not attempt to estimate this factor at this time as it involves unknowns involving future market behavior, and hence large error bars.

2. Meanwhile, the power provided is 100% renewable, meaning that the reduction in carbon footprint is equal to the reduction computed by LRMEF, is equal to the entire current carbon footprint of our heating and power provision, at 11650 tonnes annually.

Assuming a worst-case COP of 2 in Proposal II, the combined additional annual operating expense of both moves is £2.84mil (= £1.48mil for Proposal I + £1.36mil for Proposal II). This eliminates our entire carbon footprint, resulting in a net emissions reduction of 11650 tonnes CO2e annually, at a cost of £244/tonne reduced.

Conclusion on Proposal III: We can supplement Proposals I and II with by securing a PPA with a Scottish firm, completely eliminating the carbon footprint of our power and heating, an annual cost per £244/tonne reduced. Our carbon saving can start immediately, resulting in a savings of 207,000 tonnes CO2e emissions by 2040, at a total cost, including capital and operating expenses, of £56mil spread evenly from now through 2040.

Combining Proposals I, II, and III completely eliminates our carbon footprint from heating and power, yielding a dramatic reduction of carbon emissions as compared to the longer-term proposals of the energy master plan, and at a fraction of the total cost.

Section III: Discussion

It is no longer acceptable for the University to look for carbon reductions holding a tight line that all reductions must be costed to be cost neutral or cost beneficial: we must be prepared to spend in order to reduce our carbon footprint.

The costs computed for each proposal are done at a macro level, and all estimates are designed to **over-estimate** the cost of implementation. The operating costs of Proposal I are very small in the context of the university budget, and it will not be possible to obtain such a sizable emissions reduction at that price point. Moreover, if the heat pump installation, working with the data centre heat, is able to achieve a COP of 3 despite its high temperature regime, then the combination of all three proposals becomes *cost neutral.*

While cost neutrality cannot be held as a litmus test for moves to reduce our institutional carbon footprint, nevertheless the proposals in this document are as close to cost-neutral as one can conveivably hope for.

Historical context:
Does the analysis in Proposal I mean that installing CHP was a bad idea? No! Typically CHP plants have a lifespan of approximately 15-20 years, which means our current plants have served their role already. At the time of their installation and for most of their lifespan, grid electricity was primarily coal-fired, and the numbers were in favor. In most of the world, CHP is still preferable to grid electricity. Only in the last five years has electricity in Scotland, and the UK more widely, been so dramatically decarbonised (indeed, the crucial determining threshold of 366gCO2e/kWh for grid electricity was passed in 2016). So, this is not about questioning past decisions, but acting now to capitalize on our rapidly decarbonizing electricity sector.

College of Science and Engineering context:
[[This part of the report should be determined in future ongoing discussions with colleagues in the CSE, who are essentially the "customers" and stakeholders of the district heating operation in KB]]

University of Edinburgh context:
Currently, the University's CO2e emissions across Scopes 1 (estates), 2 (procurement), 3 (travel) are estimated at around 100k tonnes CO2e, of which approximately 25k tonnes CO2e are tied to heating and power across all campuses. This means that the CHP plant at KB is contributing a full 11% of our total institutional CO2e emissions, equal to more than a third of our total heating and power related emissions.

Proposal I would therefore cut our institutional carbon footprint by a full 4%, effective immediately, while Proposal II would drop it another 4%. It must be stressed that such substantial and immediate emissions reductions, without any impact on core business, are not acheivable by any other means. Moreover, a parallel rationale applies to Pollock Halls and George Square CHP as well, providing even more opportunity to slash emissions a further 4-8%.

These is a huge reduction to be obtained immediately, with a relatively small monetary opex cost, no capex cost in Proposal I, and a relatively small capex cost in Proposal II, and which does not require any changes to how we conduct our core business.

Broader context:
The University of Edinburgh has an enormous opportunity to redirect its spending to support wind farms (by buying grid electricity instead of natural gas), to reduce its carbon footprint dramatically, and then to champion other institutions around Scotland to make the same move. We have an opportunity to lead, and to make a splash, and to encourage other institutions to follow us. We must sieze it.

Section IV: Technical points

Note: indicative unit costs for electricity and fuel quoted throughout this report are taken from https://www.gov.uk/government/statistical-data-sets/gas-and-electricity-prices-in-the-non-domestic-sector.

Note: Annual maintenance costs for running a CHP plant are taken from UK government website https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/961322/Part_5_CHP_Finance_BEIS_v03.pdf
However, it would be helpful to have precise historical data produced by the Estates Energy office.

Note: Ofgem's Targeted Charging Review, which will become effective in April 2022, will have two significant impacts on this report, both speaking in favor of shutting down the CHP. Firstly, the "Triads" program will be eliminated as of April 2022. This program has provided the University with additional subsidies tied to their CHP generation.

Secondly, balancing charges going forward will be charged *per kWh consumed* and no longer *per kWh drawn from the grid*. This means that our standing charges will increase significantly based on our estimated total consumption, while our per kWh charge for electricity will drop significantly. This should provide modest decrease to the cost per kilowatt hour of Proposal I (also II and III), increasing the financial viability of those options.

Interesting question: Could the emissions reduction proposed herein be achieved in cheaper ways? This is a good question, and an important question, but one which is very difficult to answer convincingly. There are a number of carbon offsetting and/or sequestration programs, which sell offsets ranging from £1/tonne of CO_2e to £600 tonnes CO_2e. Unsurprisingly, the cheaper options are considerably more dubious and unverified/uncertified, the more expensive options are more methodologically sound. Tree-planting is a verifiable and promising offset, falling in the range of £20/tonne, but with a 30 year time until fruition (for the tree to grow).

Our central argument is that the imperative must be on sustained elimination of CO_2e emissions streams, and that a natural gas burning power plant is simply unsustainable. It is comparing apples to oranges to weigh the cost of this move against an abstract offsetting promise, and it should only be compared to other moves which actually reduce the CO_2 emitted.

Interesting question: What about hydrogen CHP, should we wait for that? No. Hydrogen CHP is not appropriate when renewable electric is directly available from the grid. Heat energy, such as is provided by burning hydrogen or natural gas is low-quality energy, as compared to electricity. The process of electrolysing hydrogen is inefficient in this sense, because it converts high-quality electricity into low-quality hydrogen stores. Its advantage, however, lies in its transportability and stability: electricity meets wire resistance when travelling long distances, and cannot easily be stored. Hydrogen CHP is therefore appropriate in remote locations, in transport and construction, or other settings where grid electricity is unavailable or insufficient, such as in industrial applications like steel plants, factories, etc.

Grid carbon intensity data referred to in the document: The table below shows grid carbon intensity (average and long-run marginal) for 2010 through 2030, as quoted from: https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal.

Highlighted in purple is the precipitous fall of carbon intensity of grid electricity over the past decade, as wind farm capacity in Scotland has **tripled.**

Year	Long-run marginal				Grid average			
	Consumption-based			Generation-based	Consumption-based			Generation-based
	Domestic	Commercial/ Public sector	Industrial		Domestic	Commercial/ Public sector	Industrial	
2010	0.389	0.382	0.375	0.357	0.501	0.492	0.483	0.460
2011	0.384	0.377	0.370	0.350	0.485	0.476	0.467	0.443
2012	0.377	0.370	0.363	0.343	0.532	0.523	0.513	0.485
2013	0.367	0.361	0.354	0.336	0.495	0.486	0.477	0.452
2014	0.360	0.354	0.347	0.328	0.441	0.433	0.425	0.402
2015	0.350	0.344	0.337	0.320	0.369	0.363	0.356	0.337
2016	0.340	0.333	0.327	0.311	0.291	0.285	0.280	0.266
2017	0.330	0.324	0.318	0.301	0.247	0.243	0.238	0.226
2018	0.319	0.313	0.307	0.291	0.180	0.177	0.174	0.165
2019	0.308	0.302	0.296	0.281	0.146	0.143	0.141	0.133
2020	0.296	0.290	0.285	0.270	0.141	0.138	0.135	0.128
2021	0.283	0.278	0.272	0.258	0.115	0.113	0.111	0.105
2022	0.269	0.264	0.259	0.246	0.107	0.105	0.103	0.098
2023	0.255	0.250	0.246	0.233	0.112	0.110	0.108	0.102
2024	0.240	0.236	0.231	0.219	0.104	0.102	0.100	0.095
2025	0.224	0.220	0.216	0.205	0.105	0.103	0.101	0.096
2026	0.207	0.203	0.200	0.189	0.099	0.097	0.095	0.090
2027	0.189	0.186	0.182	0.173	0.105	0.103	0.101	0.096
2028	0.171	0.167	0.164	0.156	0.100	0.098	0.096	0.091
2029	0.151	0.148	0.145	0.138	0.092	0.090	0.088	0.084
2030	0.130	0.127	0.125	0.118	0.083	0.081	0.080	0.076

Contact: This proposal was prepared by David Jordan, in the School of Mathematics. Please contact me at djordan@ed.ac.uk with any inputs, corrections, or ideas how to move this forward.