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Not all low-carbon energy pathways are environmentally “no-regrets” options

D.Dennis Konadu[a,*], Zenaida Sobral Mourão[a], Julian M. Allwood[a], Keith S. Richards[b], Grant M. Kopec[a], Richard A. McMahon[a], Richard A. Fenner[a]

[a] Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, United Kingdom
[b] Department of Geography, University of Cambridge, Downing Place, Cambridge CB2 3EN, United Kingdom

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ABSTRACT

Energy system pathways which are projected to deliver minimum possible deployment cost, combined with low Greenhouse Gas (GHG) emissions, are usually considered as ‘no-regrets’ options. However, the question remains whether such energy pathways present ‘no-regrets’ when also considering the wider environmental resource impacts, in particular those on land and water resources. This paper aims to determine whether the energy pathways of the UK’s Carbon Plan are environmental “no-regrets” options, defined in this study as simultaneously exhibiting low impact on land and water services resulting from resource appropriation for energy provision. This is accomplished by estimating the land area and water abstraction required by 2050 under the four pathways of the Carbon Plan with different scenarios for energy crop composition, yield, and power station locations. The outcomes are compared with defined limits for sustainable land appropriation and water abstraction.

The results show that of the four Carbon Plan pathways, only the “Higher Renewables, more energy efficiency” pathway is an environmental “no-regrets” option, and that is only if deployment of power stations inland is limited. The study shows that policies for future low-carbon energy systems should be developed with awareness of wider environmental impacts. Failing to do this could lead to a setback in achieving GHG emission reductions goals, because of unforeseen additional competition between the energy sector and demand for land and water services in other sectors.

1. Introduction

The need for low-carbon energy to curb greenhouse gas (GHG) emissions and combat climate change, coupled with the need to meet future demand and security of energy supply, presents a challenge for many governments. Transition to a low-carbon energy regime consistent with climate change mitigation aspirations will require significant changes to the whole energy system (Hoggett, 2014), including the deployment of new technologies, expansion of power generation capacity, and significant levels of demand-side management. However, the projected changes in the energy system will inevitably result in changes to the appropriation of other resources, and this will have wider implications for environmental impacts, and may affect other sectors of the economy.

Resource availability constraints do not feature significantly in energy policy development. Instead, the debate about the challenges to low-carbon energy transition has focussed on: the cost of low-carbon energy, and the rate at which it can be physically deployed (Kramer and Haigh, 2009); uncertainties about public acceptability and perceptions (Fischer et al., 2011; Engels et al., 2013; Butler et al., 2015); potential implications for biodiversity and maintenance of ecosystem services (Jackson, 2011); local and international politics (Droste-Franke et al., 2015) around issues such as emissions reduction (IPCC, EU targets). Thus, national policies have prioritised a mix of primary energy sources that would offer minimum cost, and feasible deployment rates (Torvanger and Meadowcroft, 2011). Energy system trajectories that meet these objectives are generally referred to as “no regrets” options. However, the question of whether these “no regrets” energy system options also present no-regrets in relation to environmental resource appropriation is rarely considered. For example, more land and water resources may be required if carbon capture and storage (CCS), nuclear power and crop-based bioenergy are deployed (McMahon and Price, 2011; Delgado

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[*] Corresponding author.
E-mail addresses: ddk24@cam.ac.uk, konadu@gmail.com (D.D. Konadu).

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et al., 2015; Schreiber et al., 2015; Milner et al., 2015), and this could trigger increased competition for these resources. This paper therefore aims to evaluate whether trajectories that are considered "no-regrets" options for the energy system are also "no regrets" policies for environmental resources. The paper uses the UK Carbon Plan (HM Government, 2011) as a case study, and considers the whole energy system including primary energy extraction, bioenergy crop production, refining, electricity and heat generation.

The UK Carbon Plan developed by the Department of Energy and Climate Change (DECC) presents potential pathways to achieving both 80% GHG emissions reduction, and energy security by 2050. The Carbon plan includes four pathways each consisting of a different mix of primary energy sources and technologies that achieve the 80% GHG reduction target by 2050, relative to 1990 levels, as enshrined in the UK Climate Change Act of 2008 (HM Government, 2008). The central pathway, "Core MARKAL", involves a combination of technologies and resources that minimise system cost by 2050, estimated by the UK MARKAL energy model (AEA, 2011). The other three pathways, "Higher Renewables, more energy efficiency", "Higher Nuclear, less energy efficiency" and "Higher Carbon Capture and Storage (CCS), more bioenergy", also achieve the GHG emissions reduction target, but do not offer absolute minimum-cost solutions. With the exception of the "Higher Nuclear, less energy efficiency", all pathways rely on decarbonisation of electricity in tandem with a range of energy efficiency measures, substitution of fossil energy by bioenergy, and introduction of CCS technologies. Given that around 86% of primary UK energy consumption in 2013 relied on fossil resources (DECC, 2015), these pathways require a significant departure from the current energy system, and imply substantial infrastructure replacement by 2050.

The connections of the energy system to land and water resources include cooling water used in thermal power generation, extraction and refining of primary fossil fuels, and land required for energy system infrastructure and growing bioenergy feedstock. These are water and land intensive and have the potential to trigger increased competition for water and land resources with other sectors of the economy, and with the need to maintain ecosystem services. It is therefore critical to assess the environmental resilience in determining whether a pathway has "no-regrets".

Recent studies including Konadu et al. (2015),HM Government (2010), Byers et al. (2014), Schoonbaert (2012) and EA (2010) have analysed individual natural resource (land or water) requirements of potential future energy system trajectories of the UK. These studies report significant changes in the water and land requirements by 2050 for all the UK Carbon Plan pathways, which points to the need for an integrated analysis of land, water and energy in order to identify potential environmental constraints to the development of future energy systems. Thus the aim of this paper is to simultaneously analyse the land and water impacts of the UK Carbon Plan under different scenarios of crop yield and composition, and future power plant locations.

A "no-regrets" low-carbon energy pathway is defined in this study as one that simultaneously exhibits low impact on land and water services resulting from resource appropriation for energy provision. Three broad analytical procedures are employed: (1) criteria are established for measuring environmental "no-regrets" based on the assumptions of sustainable limits of land and water resource appropriation in the UK; (2) the water and land requirements for each of the Carbon Plan pathways to 2050 are estimated; (3) the land and water requirements for each pathway are compared to the environmental "no-regrets" criteria.

2. Criteria for environmentally "no-regrets" low-carbon pathway assessment

Three categories of impact—Low, Medium and High—are defined to characterise the appropriation of land and the abstraction of water. These categories are related to sustainable resource appropriation and are described below.

2.1. Land use criterion

The criterion for assessing the land use impact of the carbon pathways is based the levels of land use change to bioenergy by 2050 according to the DECC Calculator (DECC, 2012), which sets 17% as the maximum limit of total UK land area that can be allocated for bioenergy crop production. The criteria for Low, Medium and High land use impact are described in Table 1.

2.2. Water use criterion

The criterion for assessing water use is based on the current UK abstraction licensing regime, in particular abstraction by the energy industry from surface water. This study considers only inland water resources, i.e. fresh and tidal water abstraction, which require licensing. Licences for water abstraction and impoundment

Table 1
Description of land impact criteria for "no-regrets" assessment.

Land impact	Criteria description/assumptions
Low: *Lower than or up to 2010 level of unused arable land area*	Area of land used for energy crops is lower than the available unused arable land in 2010. As only unused high quality arable land is put to bioenergy cropping, a minimal amount of fertiliser would be required for cultivation. Additionally, this would not require significant changes in agricultural land use and management policy. Moreover, bioenergy occupied only 0.4% of UK agricultural land in 2010, which is comparatively very low.
Medium: *Above total 2010 unused arable land area and up to 10% UK land area*	In addition to unused arable land, some improved grassland would also be converted to bioenergy cropping. This is equivalent to the medium ambitions of the 2050 Pathways Analysis report (HM Government, 2010). As land appropriation for bioenergy nears the 10% limit, all the unused arable land, and a significant share of improved grassland would have to be converted to bioenergy crops, leading to some level of competition between bioenergy cropping and other land services, particularly livestock grazing/feed production. Due to the scale of land use change involved, this may require some land use/agricultural policy changes to incentivise adoption of bioenergy cropping, for example.
High: *Above 10% of UK land*	Above 10% land appropriation for bioenergy production effectively competes with other land services, such as land for livestock grazing, feed and fibre production. This would present a highly challenging situation for bioenergy deployment due to the unprecedented level of land use change. Semi-natural grasslands could be allocated for bioenergy cropping in addition to improved grasslands and unused arable land, with the potential loss of undesignated high biodiversity areas. Moreover, a significant amount of the land used beyond this level would be of low quality and for some energy crops, there would be a requirement for significant application of fertiliser and irrigation in some regions of the UK. Significant land/agricultural policy changes are required, including regulations to ensure that there is no net loss of high biodiversity areas.

in the UK, as defined in the Water Act 2003 (HM Government, 2003), are issued with the intention of maintaining an efficient and sustainable use of water; of particular importance is the preservation of the ecological quality of aquatic environments (Poff and Zimmerman, 2010). However, not all licensed abstractions are actually withdrawn. For example in England and Wales, actual abstraction levels average 45% of all permitted abstractions, and 40% of all electricity-related permits (SI Fig. 3, SI Table 8) (EA, 2013a; DEFRA, 2013a,b). Therefore, although some catchments in the UK are already either over-licensed or over-abstracted, according to the Environment Agency (EA) (EA, 2008), the current average national-scale abstraction for electricity is largely within the overall regulated abstraction levels.

However, water availability in the UK is a regional problem. For example, power stations providing about 70% of total UK inland generation capacity in 2010 were clustered within a few major river basins – the Severn, Humber, Trent, Mersey and Thames – as shown in Fig. 1. Some of these river basins are already experiencing some degree of water stress (e.g. the Thames catchment). Thus, any incremental water demand for the energy infrastructure on the national level is likely to translate into additional demand within these regional clusters. Future changes such as population growth; and future demand for irrigation and additional non-energy industrial infrastructure within these river basins could exacerbate the pressure on available water resources. Thus, to provide a method for assessing water stress related to the national energy pathways, this study aggregates national abstraction for thermal generation to define thresholds of stress. Three criteria—Low, Medium and High, as for land stress—are defined in Table 2.

3. Estimation of land and water requirement for the Carbon Plan pathways

The pathways of the Carbon Plan project changes to the current UK energy system that deliver 80% GHG emissions reductions by 2050. To analyse their land and water requirements, material flow analysis (MFA) was used to predict resource reserves or deficits (Rowse, 1986). The analysis is based on scenarios of land use associated with different compositions and yields of second-generation (2Gen) energy crops, and water abstraction levels predicated on power plant locations.

The analysis starts by establishing the connections between the national energy system and the land and water systems. The projected technologies of each of the Carbon Plan pathways to 2050 are then related to land and water resource use. The analysis of the land—energy connections cover the entire UK land use system using different scenarios for crop yield and energy crop composition. The analysis of the water system focuses only on water used in the energy system for primary extraction (e.g. coal, oil, gas extraction) and transformation processes (e.g. electricity generation, oil refining), using scenarios to assess the impact of different technologies and locations for future energy infrastructure (see Fig. 2). The predicted land and water requirements are compared with sustainable use limits based on the criteria defined in Section 2, to assess the environmental "no-regrets". Details of the data and methods used to analyse the connections of the energy, land and water systems are covered in the following subsections.

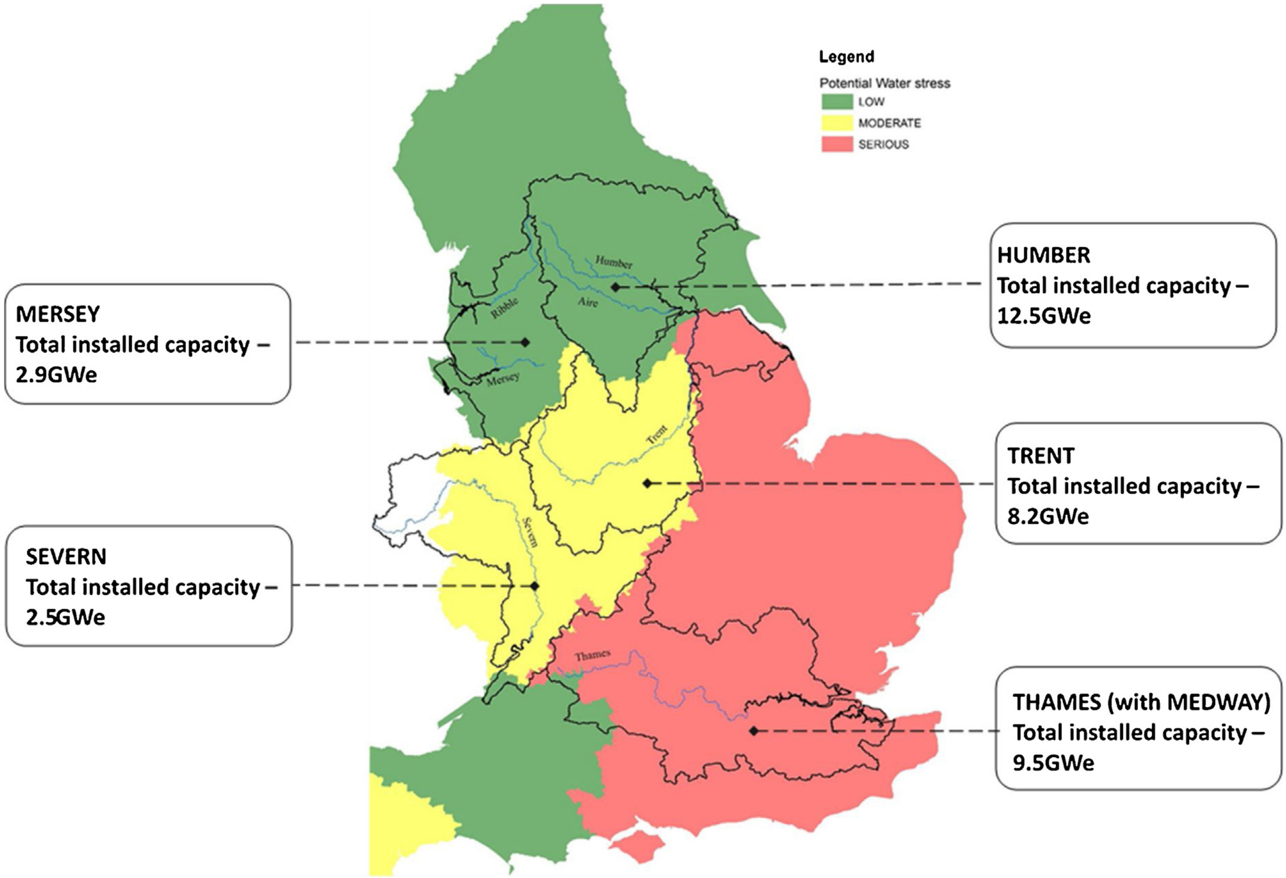


Fig. 1. Inland electricity generation capacity along major UK river basins in 2010 and the potential water stress risk. Source: Digest of UK Energy Statistics (DUKES) (DECC, 2011), Environment Agency (EA) areas of water stress: final classification (EA, 2007), EA CAMS dataset (2010).

Table 2
Description of tidal and fresh water abstraction impact criteria.

Water impact	Criteria description
Low: *Lower than or up to current actual abstraction level*	Water abstraction reduces or remains at current levels. No need for change in current licensing regime for the energy industry, as current abstraction averages 40% of licensed volumes. It is assumed that this would leave ecologically acceptable headroom for abstraction.
Medium: *Up to 100% increase in current abstraction levels for thermal generation*	Up to 100% increase in future abstractions for thermal generation relative to current actual abstraction levels. Actual abstraction would still remain within current licensed volumes, as current actual abstraction for thermal generation averages 40% of the licensed volumes (SI Fig. 3 and SI Table 8)
High: *More than 100% increase in current abstraction levels for thermal generation*	More than 100% increase relative to current actual abstractions for thermal generation could be considered environmentally unsustainable, as this would be nearing or surpassing the licenced volumes which are based on sustainable ecological limits. This level of abstraction could lead to competition with other essential water services, and could necessitate significant changes to the licensing regime.

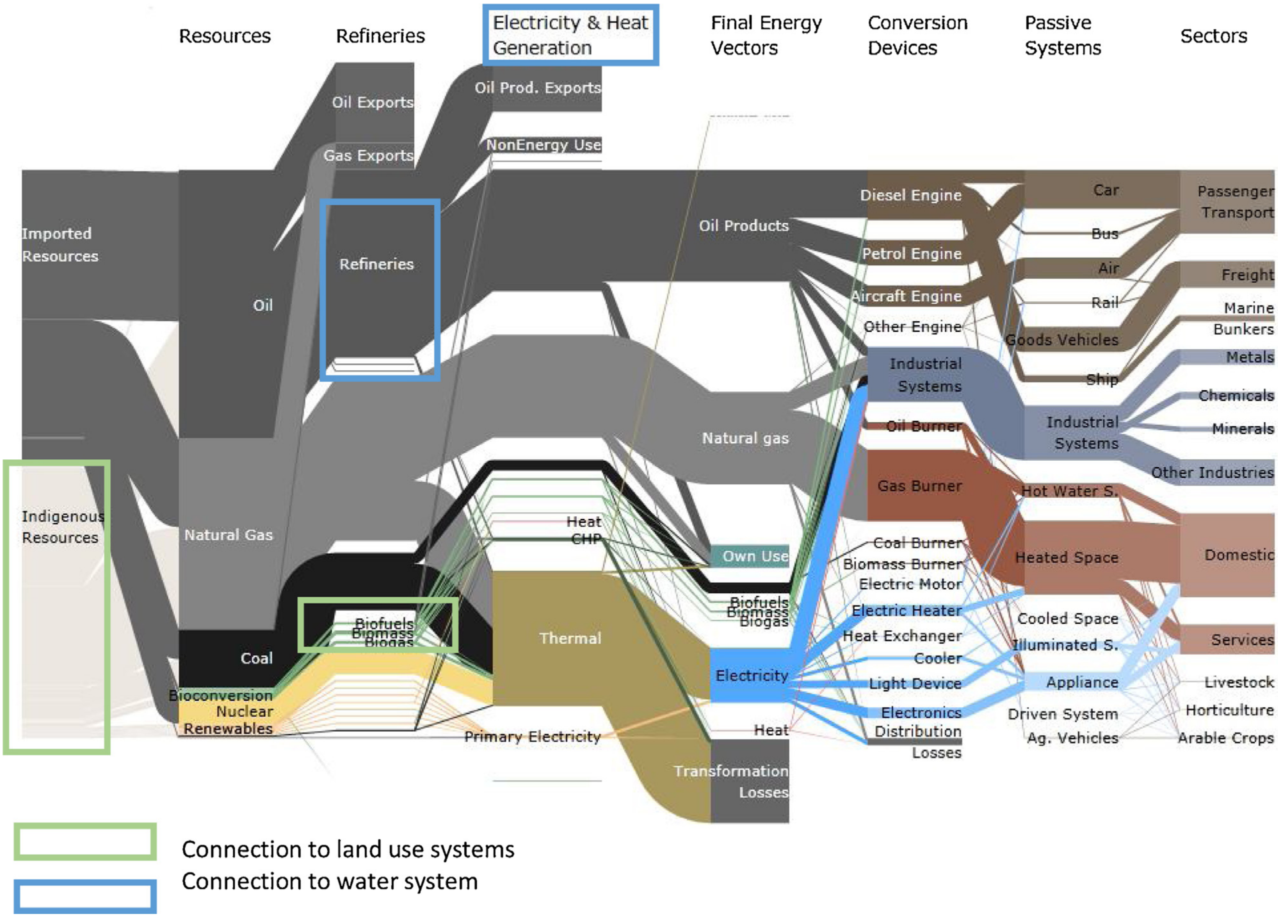


Fig. 2. Illustration of the UK energy system with the connections to land and water systems analysed in this study, highlighted in green and blue rectangles respectively for 2010 (Allwood et al., 2014).

3.1. Land and water connections to the UK energy system to 2050

The current (2010) connections of land and water to the UK energy system are shown as a Sankey diagram in Fig. 2. This diagram maps the flow of energy from primary sources through transformations involving conversion devices and passive systems to final energy consumption in 2010 in different sectors (transport, buildings, industry and agriculture), using statistical data from the Digest of UK Energy Statistics (DUKES) 2013 (DECC, 2014) and the Energy Consumption in the UK (ECUK) dataset (DECC, 2013).

The main connections of the energy system to land and water systems are highlighted in the green and blue rectangles respectively in Fig. 2. The primary resources were grouped into imported and indigenous sources. Onshore oil and gas and coal exploration mainly influence water use, while bioenergy crop production affects land use. The transformation of primary resources into final energy vectors, such as electricity and liquid fuels, affects the water system. The main processes that require water are coal washing, biofuel and crude oil refining, and thermal electricity generation. Since crop production in the UK is predominantly rainfed (Richter et al., 2008), this study does not consider water abstraction for bioenergy crop production. However, bioenergy production may have significant impact on water resources in other regions of the world where crops are mainly irrigated (Gerbens-Leenes et al., 2009, 2012). Additionally, this study does not consider land use for ground mounted PV, Onshore wind and other energy infrastructure such as power plants and oil refineries, as these are insignificant (see DECC Calculator—DECC, 2012) compared to the scale of land use change required for bioenergy crop production for the energy pathways analysed in this study.

According to the Carbon Plan the primary energy mix is projected to change significantly to 2050, with a significant decrease in the share of fossil fuel resources and increase in the share of bioenergy and nuclear resources. Additionally ambitious energy efficiency and demand reduction measures are deployed across all pathways, leading to a reduction in the overall primary energy demand compared to current levels. Fig. 3 shows the projected changes in primary energy mix for each pathway by 2050. This also highlights the different impact of energy efficiency measures on the overall primary energy demand, with the highest and lowest levels of demand reduction for the “Higher renewables, more energy efficiency”, and the “Higher nuclear, less energy efficiency” pathways respectively.

The contribution of bioenergy to the primary energy mix increases significantly by 2050, ranging from 17% to 40% for the “Higher Renewables, more energy efficiency” and the “Higher Nuclear, less energy efficiency” pathways, respectively (Fig. 3). Land use change related to bioenergy depends on the level of primary energy demand met by indigenous crops. The “Higher Renewables, more energy efficiency” pathway has the lowest contribution from indigenous crops, while the “Higher Nuclear, less energy efficiency” has the highest. This is mainly due to a combination of ambitious energy demand reduction and higher share of wind and PV resources in the “Higher Renewables, more energy efficiency” pathway, as shown in Fig. 3. Additionally Konadu et al. (2015) have shown that the decarbonisation of the transport sector via use of bioenergy in the “Higher Nuclear, less energy efficiency” pathway in lieu of mainly using these resources in electricity and heat generation is directly linked to the high use of bioenergy in this pathway.

In all four pathways, the use of fossil resources is projected to decrease, so the extraction sector should have a relatively low requirement for tidal and freshwater. The main water demands are thus from refining liquid fuels and from electricity generation. The impact of electricity generation is particularly critical for pathways that include new thermal centralized electricity generation and CCS technologies, since electricity demand increases for all the trajectories to 2050. All pathways show an initial decrease in thermal generation as legacy power plants (mainly coal and nuclear) are shut down and are substituted by new wind capacity (both onshore and offshore). The pathways then diverge from 2025 onward: with the “Higher Renewables, more energy efficiency” pathway deploying mostly new wind capacity (with a focus on offshore wind); the “Higher Nuclear, less energy efficiency” deploying mostly new thermal nuclear capacity; the “Higher CCS, more bioenergy” pathway deploying mostly new thermal with CCS, with a mix of fossil and bioenergy, and some increase in nuclear; and the “Core MARKAL” pathway with similar growth rates for new wind, nuclear and CCS capacity, and a higher share of new wave and tidal capacity than the remaining pathways in 2050. Further details of the energy system configuration for each of the pathways to 2050 are presented in the supplementary information (Appendix 1–SI), and also in the UK Foreseer^{TM} tool (Allwood et al., 2014). The land and water requirements associated with the UK energy system to 2050 are presented in the following subsections.

3.2. Estimation of current and 2050 land requirements for bioenergy

The connections of the energy system to the land resource are mainly associated with crop-based bioenergy feedstock production, and are constrained by the availability of suitable agricultural land. Currently an estimated 0.4% of UK agricultural land is used for bioenergy crops (DEFRA, 2014), which provides ~10% of the total feedstock (DECC, 2014). Even though imports form ~70% of the current and up to 50% in 2050 bioenergy feedstock (excluding feedstock from waste) (DECC, 2014), the study focuses only on indigenously produced feedstock. The energy crops considered in this study are Miscanthus (grassy) and Short Rotation Coppice (SRC) (woody).

The 2010 analysis used a similar approach to that by Konadu et al. (2015), based on crop production data for UK agriculture, and

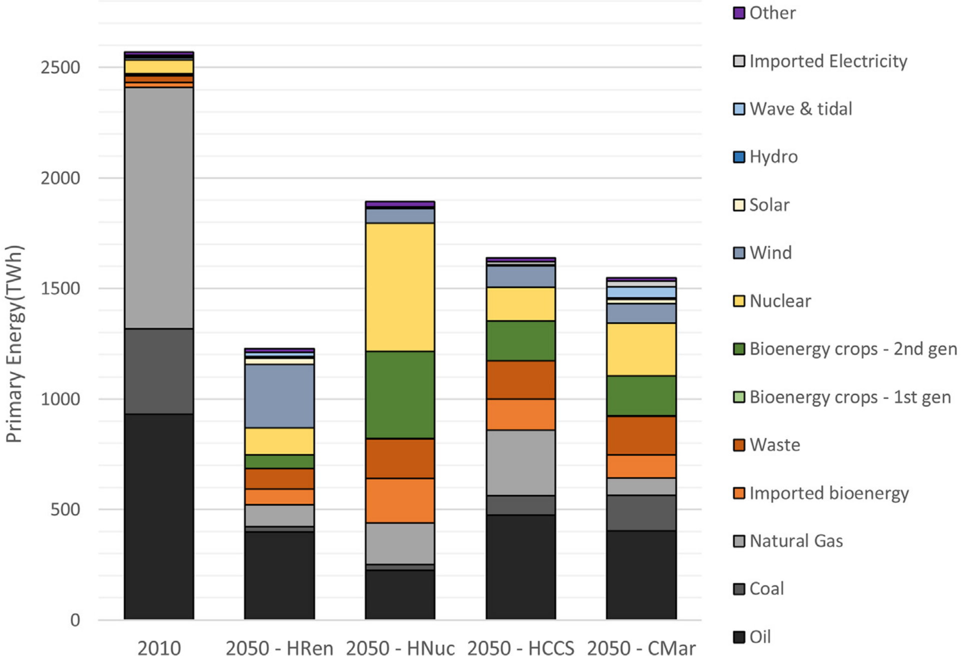


Fig. 3. Primary Energy mix to meet UK energy demand in 2010, based on national energy statistics, and projections to 2050 under each of the Carbon Plan pathways (with HRen—“Higher Renewables, more energy efficiency”, HNuc—“Higher Nuclear, less energy efficiency”, HCCS—“Higher CCS, more bioenergy”, “CMar”—Core MARKAL).

energy statistics (DECC, 2014; DEFRA 2013a,b). The land area required in 2050 was estimated based on different scenarios of both energy crop mix and crop yield projections. This study considers the two predominantly grown second generation energy crops in the UK—Miscanthus (grassy) and Short Rotation Coppice (SRC). Two energy crop mix options were considered: Business-As-Usual (BAU), which assumes that the composition of indigenously-produced energy crops remains as in 2010; a '50-50' scenario which assumes a mix of 50% of Miscanthus and 50% Short Rotation Coppice (SRC). Two scenarios of crop yield were also analysed: "Business-As-Usual (BAU) yield", which assumes no yield improvements after 2010; and "High Yield" which assumes a very ambitious and challenging yield improvements of 30% by 2050, based on DECC projections (DECC, 2012). The area of land required under each of the Carbon Plan pathways for indigenously sourced bioenergy were estimated based on these yield and crop composition scenarios, the amount of projected bioenergy, and the energy density (heating value) factors of the energy crops considered (based on US DOE/ORNL, 2011).

Projections for future non-energy cropland demand were also estimated based on assumptions that diet composition and food import would not change from 2010, and on UK population projections (ONA, 2014), and crop yield changes (as for the yield scenarios described above). Other land demand projections including for forestry and settlement were based on DECC's 2050 Pathways Analysis (HM Government, 2010). Details of the analysis and data sources and outputs can be accessed online (www.foreseer.group.cam.ac.uk/foreseer-tool/) (Allwood et al., 2014).

3.3. Estimation of current and future water requirements in the energy sector

Water demand was estimated for each stage of energy transformation, from primary fuel extraction, through refining processes, to electricity and heat generation. Water abstraction for bioenergy crop irrigation was not considered in this study, as most of UK agriculture is rainfed. Currently water abstraction for irrigation of crops in England and Wales constitutes less than 1% of all water abstractions (DEFRA, 2015). Even though second generation energy crops could have potential hydrological impacts on catchments where they are grown (Rowe et al., 2007), irrigation may only be required under drought conditions, in the relatively drier regions of the UK (e.g. the Southeast of England) (see Richter et al., 2008), and favorable market price for feedstocks (Biomass Energy Centre, 2007). However, the analysis of water requirements and abstractions under these conditions is beyond the scope of this study.

Water use was tracked from source of water (tidal or freshwater), through abstraction and consumption to discharge stages, with abstracted volumes dependent on location, the type of primary fuel, and/or the technology deployed. For primary fuel extraction, water used in indigenous coal mining and onshore oil and gas extraction was considered. It was assumed that offshore oil and gas extraction require no demand for freshwater or tidal water. Water demands in fossil fuel treatment and refining include coal washing and preparation, as well as petroleum and biofuel refineries. Water used in electricity generation is mainly associated with thermal cooling, with volume dependent on fuel type and the generation and cooling technology used (e.g. once-through, wet cooling, dry cooling). The next sub-sections describe the methodology and data sources used in the estimation of water demand for the extraction and refining processes, and thermal electricity and heat generation.

3.3.1. Water for primary energy extraction and refining processes

Water abstraction and consumption factors for each process are presented in SI Tables 4 and 5. For the base year, data for indigenously mined coal (categorised into surface and deep mines) and onshore oil and gas extraction were combined with the associated water abstraction and consumption factors to estimate the overall water use. The water required for each energy pathway in the future was estimated similarly by combining the projected indigenous coal, oil and gas extraction with the water abstraction and consumption factors.

Two categories of water use in refining were estimated—for coal washing and for oil refining. In the absence of published data, it was assumed that all indigenously deep-mined coal requires washing. Thus, data for indigenously mined coal (DECC, 2011) were combined with water abstraction and consumption factors for coal washing (from US DOE, 2006), to estimate water required in 2010 and beyond. Water use for crude oil and biofuels refining were estimated using the abstraction and consumption factors for once-through cooling technology for refineries (Williams and Simmons, 2013).

3.3.2. Water for electricity generation

Water use for electricity generation is the largest component of industrial water demand in England and Wales (EA, 2013b). Abstractions for hydropower and pumped storage generation account for over 90% of this use (EA, 2011), but this water is returned immediately to the source at almost the same level of quality. This study therefore excludes these applications to focus on thermal generation, which constituted up to 90% of UK electricity generation capacity in 2013 (DECC, 2014). The analysis begins with estimation of the base year abstraction and consumption volumes for different generation and cooling technologies involved in the energy system. This follows similar approaches adapted by Schoonbaert (2012), Byers et al. (2014) and the Environment Agency (EA, 2013c), and is based on the primary fuel used, cooling technology and cooling water sources.

Analysis of future water demand for electricity generation is complex because neither the location of future power stations nor the cooling technologies to be deployed are known. Therefore, this

Table 3
Description of the power station location scenarios.

Scenario	Narrative/assumptions
PAU	*Progress-As-Usual; no significant change to cooling technology composition and location of plants*—Assumes the composition of cooling technologies and location of power stations remains as today.
HC	*High Coastal—predicated on widespread over-licensing and abstraction of freshwater*—Driven by future reduced freshwater abstraction licensing for electricity generation due to over-licensing/abstraction within major catchments after 2030.
HI	*High Inland*; *increased coastal and marine protection* - Driven by increased protection of marine and coastal environments and the need to avoid potential long term consequences of extreme coastal flooding and tidal/storm surges on power generation. Additionally, in consonance with marine protection objectives, soft engineering approaches to coastal and sea level rise management are adopted.
Int-CCS	*Integrated electricity and industrial Carbon Capture and Storage*—Assumes the deployment of CCS technology in power generation and industry, with CCS infrastructure planned and built to accommodate both sectors after 2025. As power stations with CCS are more water intensive compared to similar technologies without CCS, and these would be clustered together with industrial CCS, this could have significant impacts on the inland water resources

study uses four scenarios of power plant location and cooling technology, using the same estimation approach as noted above (Schoonbaert, 2012; Byers et al., 2014; EA, 2013c). The four scenarios considered are: “Progress-As-Usual (PAU)”; “High Coastal (HC)”; “Higher Inland (HI)” and “Integrated electricity and industrial carbon capture and storage (Int-CCS)”. These scenarios are presented in Table 3. The assumed composition of cooling technologies and the mean water abstraction and consumption factors associated with each technology, are presented in the SI Tables 6 and 7, respectively.

4. Results

Results of this study are presented as tables and Sankey diagrams showing the percentage of UK land required for bioenergy in 2050 and the volume of water abstraction (million cubic meters) required for both primary energy extraction and thermal electricity generation. The outcomes of the environmental “no-regrets” assessment are presented as a color matrix of resource use impacts of the different Carbon Plan pathways (see Fig. 5).

4.1. Current and 2050 land use and energy connections

The land use changes associated with each of the Carbon Plan pathways resulting from the different yield and crop composition scenarios to 2050 have been developed in the UK Foreseer^{TM} online tool as dynamic Sankey diagrams (Allwood et al., 2014). In 2010 (the base year), the total area of land used for energy crop production was estimated at 108kha, ~0.4% of the total UK land area. Table 4 shows the land area required for indigenous bioenergy crop production under the different scenarios for crop yield and composition, as a percentage of total UK land. The “Core MARKAL” and “Higher CCS, more bioenergy” pathways have the same land requirements, as they require the same volumes of second-generation indigenous energy crops. The “Higher Nuclear, less energy efficiency” and “Higher Renewables, more energy efficiency” pathways have the highest and lowest projected land demand for bioenergy crop production respectively, across all yield and crop composition scenarios. The highest demand—41% of the total UK land area—is required if yields and energy crop composition remain the same as today, and the “Higher Nuclear, less energy efficiency” path is pursued. The lowest demand (5% of total UK land area) occurs under the “Higher Renewables, more energy efficiency” pathway, assuming a significant improvement in energy crop yields and a diversified energy crop composition. However, this combination of scenarios i.e. “50/50 composition & Increased yield” is rather ambitious, and may be difficult to achieve. This is because in order to avoid increased competition for high quality arable land for food production, large-scale bioenergy deployment would have to rely on marginally productive agricultural land (Wilson et al., 2014; Lovett et al., 2014). Thus, achieving high yield increase could be very challenging without extensive application of fertilisers and irrigation in some regions of the UK. Additionally, the diversification of second-generation energy crop production is predicated on the emergence of a competitive and profitable market for indigenous bioenergy (Wilson et al., 2014).

Overall, the results show that future improvement in energy crop yields and a diversification of energy crop composition would significantly reduce the overall land requirement for delivering the bioenergy component required in all the Carbon Plan pathways. The actual projected land areas required under each of the pathways for the scenarios are presented in SI Tables 3a–d.

4.2. Current and 2050 water abstraction for energy

The water demands of the UK energy system in 2010 are presented in Fig. 4 as Sankey diagrams illustrating the different sources, uses and final sinks of water use in the (a) extraction, and (b) refinery and electricity generation sectors. This excludes water used in hydropower and pumped storage electricity generation. The output results show that ~90% of all abstraction for the energy industry is from tidal sources with ~75% used for energy transformation, mainly in electricity generation and crude oil refining. Overall, ~80% of all abstracted water is returned to surface water systems, ~6% is recycled and ~14% is evaporated (consumed). Also, all the accompanying discharged water of onshore oil and gas extraction is assumed to be re-injected into exploration wells.

Future water abstraction by the UK energy sector is mainly associated with oil refining and electricity generation. This is as a result of the projected decline in on-shore fossil fuel extraction in the UK. The evolution of water abstraction and consumption levels in this analysis is presented in the Foreseer UK online model (Allwood et al., 2014) and in SI Fig. 4, SI Tables 8 (abstraction) and 9 (consumption).

Table 5shows projected water abstraction requirements for electricity generation as analysed in this study. In 2010, abstraction from tidal and fresh water sources is estimated at $\sim 5.6 \times 10^9 m^3$. The results show that if the current spatial distribution of power generation is maintained (i.e. PAU scenario), only the “Higher Nuclear, less energy efficiency” or “Higher Renewables, more energy efficiency” pathways would avoid significant impact on fresh and tidal water systems. However, changing the spatial distribution has mixed impacts: water abstraction generally decreases under the “Higher Nuclear, less energy efficiency” and “Higher Renewables, more energy efficiency” pathways; however, the “Higher Inland” scenario leads to increased abstraction for all pathways (SI Fig. 4c), far above the maximum projected abstraction for the other scenarios.

4.3. Environmental “no-regrets” assessment

The output of the environmental “no-regrets” assessment is presented as a color-coded matrix of impacts in Fig. 5. The impacts on land and water are assessed against limits to sustainable land appropriation and water use. The “Higher Renewables, more energy efficiency” pathway presents the only environmentally “no-regrets” option, as long as high deployment of inland power

Table 4
Percentage of UK land required by 2050 for bioenergy as a percentage of UK land area under different crop composition and yield scenarios for each of the carbon plan pathways derived from the UK Foreseer^{TM} analysis (Allwood et al., 2014; Konadu et al., (2015)), compared to 2010 levels.

Pathway	2010	BAU composition & BAU yield	BAU composition & increased yield	50/50 Composition & BAU yield	50/50 Composition & increased yield
Core MARKAL	0.4%	19%	10%	15%	8%
Higher Renewables	0.4%	7%	6%	5%	5%
Higher CCS	0.4%	19%	10%	15%	8%
Higher Nuclear	0.4%	41%	23%	32%	18%

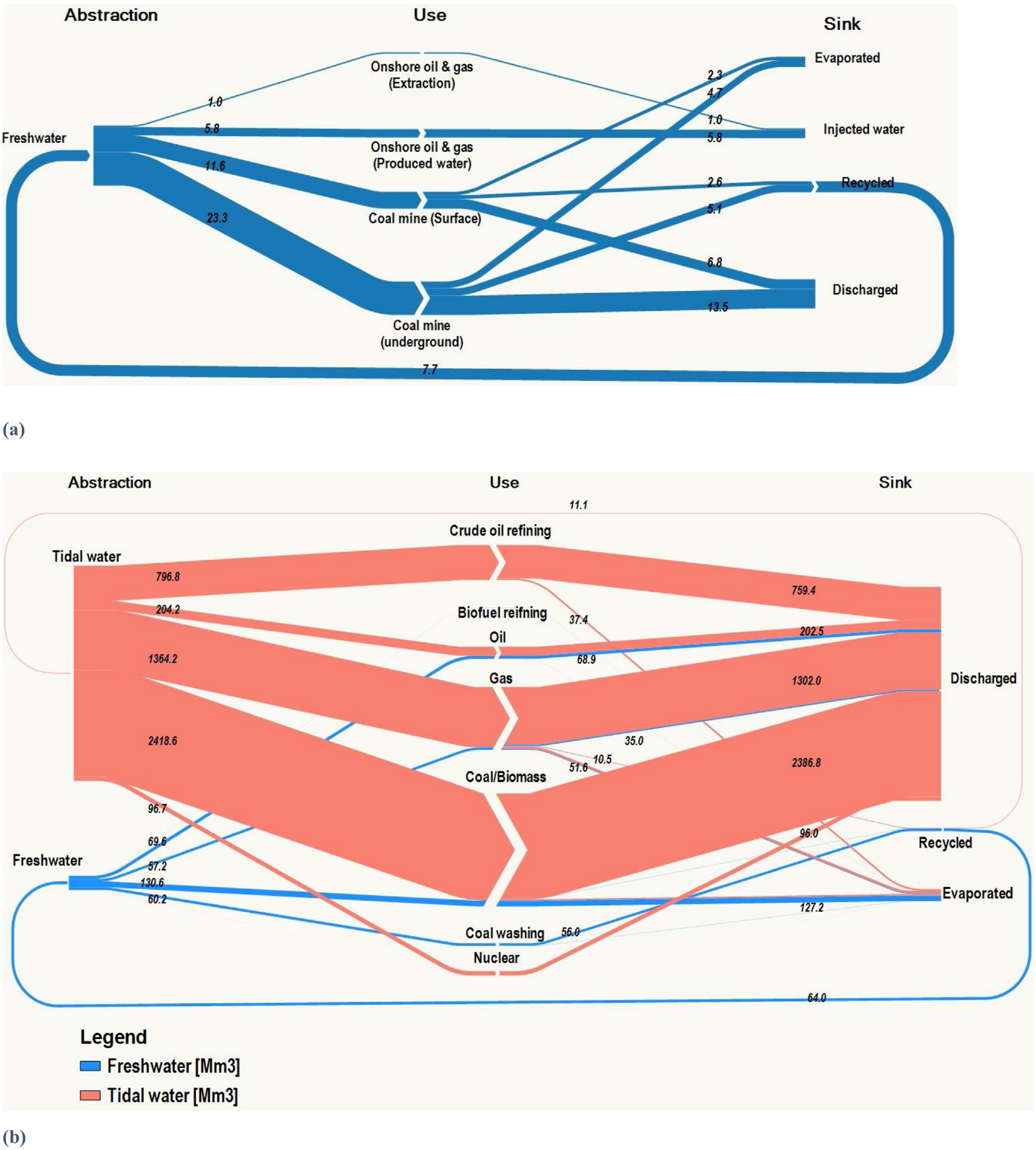
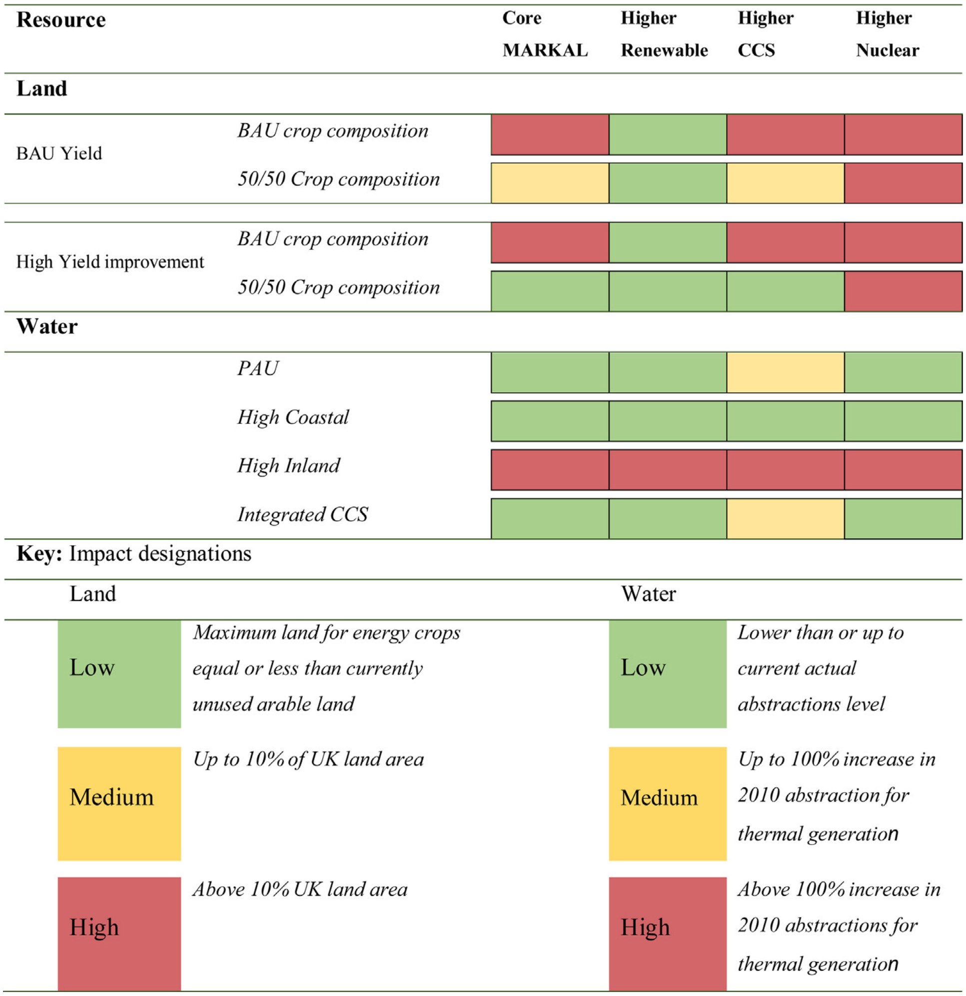


Fig. 4. Illustration of fresh and tidal water use in the UK energy industry in 2010: (a) for extraction of primary fossil resources; (b) for refining and electricity generation. These are exclusive of hydropower generation. The water abstraction and consumption factors by technology for electricity generation are based on: Macknick et al. (2011, 2012); Electric Power Research Institute Inc. EPRI (2002); National Energy Technology Laboratory NETL (2009); Tzimas (2011); and Williams and Simmons (2013) (Appendix C—SI Table 6).

stations is avoided. This pathway leads to low resource use in all the land appropriation and water abstraction scenarios. The "Core MARKAL" pathway exhibits a low to high impact on both water and land. A high impact is only avoided provided there is a high yield increase with crop composition diversification, and inland power generation is limited. The "Higher CCS, more bioenergy" pathway has higher impact unless high yield improvement is combined with diversification of energy cropping, and a preference for coastal power stations. The "Higher Nuclear, less energy efficiency" pathway never meets the "no-regrets" criteria although it generally has the least impact on fresh and tidal water resources (provided inland power station siting is limited).

5. Discussion and conclusions

The results of this study show that the environmental impacts of the low-carbon pathways of the Carbon Plan are not always "no-regrets". Even though most of the pathways avoid significant



Resource		Core MARKAL	Higher Renewable	Higher CCS	Higher Nuclear
Land					
BAU Yield	*BAU crop composition*	🟥	🟩	🟥	🟥
	50/50 Crop composition	🟨	🟩	🟨	🟥
High Yield improvement	*BAU crop composition*	🟥	🟩	🟥	🟥
	50/50 Crop composition	🟩	🟩	🟩	🟥
Water					
	PAU	🟩	🟩	🟨	🟩
	High Coastal	🟩	🟩	🟩	🟩
	High Inland	🟥	🟥	🟥	🟥
	Integrated CCS	🟩	🟩	🟨	🟩

Key: Impact designations

Land		Water	
Low	*Maximum land for energy crops equal or less than currently unused arable land*	Low	*Lower than or up to current actual abstractions level*
Medium	*Up to 10% of UK land area*	Medium	*Up to 100% increase in 2010 abstraction for thermal generation*
High	*Above 10% UK land area*	High	*Above 100% increase in 2010 abstractions for thermal generation*

Fig. 5. Environmental no-regrets matrix. The categories of impacts on land and water presented here are independently assessed based on different metrics of identifiable limits of sustainable land appropriation and water use.

Table 5
Comparison between 2010 and projected total water (tidal and freshwater) abstraction requirements for electricity generation for each of the Carbon Plan pathways in 2050 under the different scenarios of power station infrastructure location (units in $10^9\,m^3$).

Pathway	2010	PAU	High Coastal	Int CCS	High Inland
Core MARKAL	5.6	6.8	2.9	2.8	31
Higher CCS	5.6	7.9	4.6	5.7	19
Higher Renewables	5.6	3.1	2.1	2.4	15
Higher Nuclear	5.6	0.9	0.9	0.9	77

potential impacts on fresh and tidal water resources, the impacts on land use can be significant. An example is the "Higher Nuclear, less energy efficiency" pathway, which has a high impact on land use, because bioenergy plays a major role in substituting fossil fuels in transport and industry. Compared to previous studies including HM Government (2010), and Byers et al. (2014), Schoonbaert (2012), EA (2010), the land and water requirements for the Carbon Plan pathways estimated in this study are shown to be in the same order of magnitude. However, there are significant differences in the absolute values due to differences in assumptions regarding water cooling technologies, cooling water sources, future location of power plants and crop composition and yields.

The study shows that energy system policies should be evaluated across all environmental resource systems. As well as environmental stress, the impact on other environmental resources could hinder attainment of GHG emission reduction targets. For example, restrictions placed on the water system could lead to deployment of thermal generation technologies with low water intensity, such as air-cooling. This can affect the efficiency of generation, and require more primary fuel consumption and thus increase emissions. Moreover, restrictions in water abstraction for electricity generation could delay the construction and deployment of some low-carbon, water-intensive electricity generation infrastructure. This could result in a prolonged life span of unabated fossil generation, and thus delay the timelines of GHG emissions reduction targets.

The results are subject to uncertainties, mainly related to the underlying assumptions. The availability of land for indigenous energy crop production has been shown to be a strong determining factor for bioenergy deployment which suggests that, unless crop yields significantly improve, land demand for bioenergy production could compete with food production—in particular livestock production.

The results also depend on the assumption that dietary characteristics and food import levels will be similar in the future. Any deviation from "Business-As-Usual" for the projections of diet and food imports might result in changed land use competition. For example, increases in future food imports could release more high quality land for bioenergy production although this is likely to increase GHG emissions associated with transport. On the contrary, a reduction in food imports would result in increased indigenous food production, which could result in greater land competition associated with bioenergy. Moreover, changes in diet have implications for land use (Kastner et al., 2012; Haberl et al., 2011; Gerbens-Leenes and Nonhebel, 2002; Bajželj et al., 2014), but the degree of dietary change and its implications for UK land use change remains uncertain.

The study also assumes that second generation perennial crops (Miscanthus and SRC) will dominate future bioenergy supply. However, with current conversion efficiencies of energy crops to liquid fuels (Tyner and Taheripour, 2014), it could be more efficient to use bioenergy for heat and electricity generation, than for liquid fuel use in transport. This is shown in the contrasting land use of the “Higher CCS, more bioenergy” and the “Higher Nuclear, less energy efficiency” pathways (Table 5), which are, respectively, dominated by high levels of bioenergy crops for heat and electricity and liquid fuels for transport. Future advances in second-generation energy crop conversion to liquid fuels could therefore reduce competition for land-use. However, other changes such as increases in anaerobic digestion systems that use first generation energy crops, could further increase competition for agricultural land.

The impact of the energy system on fresh and tidal water use is limited, unless there is an increase in the number of inland power stations. However, extreme weather conditions witnessed along parts of the UK coastline in the last decade suggest that future power station siting decisions must consider tidal surges and flooding as well as sea level rise. Additionally, future siting of power stations on the coast should take into account the potential adverse effect on marine ecosystems. This is especially critical for scenarios with high nuclear capacity, such as in the case of the “Higher Nuclear, less energy efficiency” pathway, which projects approximately a seven-fold increase in nuclear capacity (Fig. 3), since the current eligible sites are located on the coast.

The study also shows that locating new generation infrastructure further inland (high inland water scenario), possibly in tidal reaches, would have a high impact on fresh and tidal water resources, particularly if nuclear and CCS technologies are used.

The study has mainly focussed on water abstraction, but not all water withdrawn by the energy industry is consumed at the point of use. Most water withdrawn for electricity generation is returned to source, but at a different quality (usually at a higher temperature). The amount of water consumed (evaporated) depends on the type of cooling technology and the primary fuel used (Fig. 4). Additionally, the Future Flows and Groundwater Levels dataset developed for Great Britain by Prudhomme et al. (2012) based on UKCP09 projections (Murphy et al., 2009) suggests increased hydrological variability, increased summer-time air temperature and decreased summer rainfall by 2050. This is likely to exacerbate the potential pressure from the energy sector on water resources (and vice versa). For example, increased air temperatures reduce the thermal efficiency and cooling of closed-loop, hybrid and air-cooled power generation systems (Byers et al., 2014). Moreover, increased air temperatures would inevitably increase the temperature of surface water (van Vliet et al., 2012), which would further reduce the cooling efficiency of power generation systems, and potentially lead to increased GHG emissions. In extreme cases, and in particular for air-cooled and once-through cooling, this could even result in power-station shut down, as has occurred in several recent cases in France, Germany and Spain (Förster and Lilliestam, 2010).

This study has not considered reciprocal relationships between water and the energy systems (that is, estimation of the energy requirements of the water system, in pumping water transport, and in water treatment); or between the land and energy systems (e.g. energy to produce fertilisers when land use is changed from grassland to energy crops), since these contributions are typically small in the UK. However, potential future increases in water demand from increased population and reduced river flow levels, could also lead to significant changes in the water industry, including trans-regional bulk water transfers from the North to the drier and more populated South-East/East, and deployment of more desalination plants. These changes are energy intensive and could therefore result in additional environmental impacts from the energy system, as well as increased competition for water services between industries. Other potential wider environmental consequences of future energy systems trajectories that have not been considered in this study include impacts on water, land and air quality, eco-toxicity and biodiversity. These impacts have been analysed by Stamford and Azapagic (2012, 2014) for other energy system scenarios using life cycle analysis (LCA). The authors concluded that future changes in the UK energy system could pose significant environmental impacts in this regard.

In conclusion, this study shows that analysis of changes in the energy system to meet GHG emissions targets should consider the wider impacts of energy supply on land and water system. Different low-carbon energy pathways have significantly different impacts on environmental systems. Failing to consider these inputs could lead to a setback in achieving GHG emission reductions goals, because of additional land use change and increased competition for resources between the different land and water services. It could also lead to “lock-in” of long term energy infrastructures which may not be able to cope with future changes in the land and water systems. For example, energy system pathways with high proportions of large-scale thermal electricity and heat generation, CCS technologies, and allocation of bioenergy resources (if indigenous) to biofuels for transport have been shown in this study to have the highest impacts on land and water systems. Low-carbon pathways, with high proportions of renewable primary electricity in combination with ambitious targets for energy demand reduction across all sectors, have been shown to have the lowest impacts on water and land resources in the UK.

Whist the analyses in this study have primarily focused on the UK, the approach used is applicable to other countries—both developed and developing. In countries where energy demand is expected to increase significantly along with increased demand for land and water resources for other services, for example China and Southeast Asia regions (Qin et al., 2015; Rasul, 2014), integrated analysis of energy, land and water resources is critical. This would prevent the development of conflicting energy and resource use policies, and ensure the protection of biodiversity and maintenance of ecosystem services. Also given the need for global GHG emissions reduction, with several countries committing to ambitious reduction targets by 2050, low carbon technologies including bioenergy, nuclear and CCS have been projected to form a significant part of the future mix (IEA, 2014). As has been shown in this study, these technologies could be land and water intensive. In countries with other services competing for and policies limiting resource use, this change in the energy system could constrain the deployment rate and overall capacity of these technologies, and lead to high impact on the wider environmental system. Thus, an integrated analysis, such as the approach presented in this study and the Foreseer^{TM} tool (Allwood et al., 2014), would highlight the potential conflicts and trade-offs in resource allocation. This would help decision makers to narrow down options that meet different development objectives in a robust and sustainable manner while minimizing the impacts across the land and water systems.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2015.10.002.

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