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Subsurface energy footprints

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Abstract
Anthropogenic climate change and energy security concerns have created a demand for new ways of meeting society's demand for energy. The Earth's crust is being targeted in a variety of energy developments to either extract energy or facilitate the use of other energy resources by sequestering emitted carbon dioxide. Unconventional fossil fuel developments are already being pursued in great numbers, and large scale carbon capture and sequestration and geothermal energy projects have been proposed. In many cases, these developments compete for the same subsurface environments and they are not necessarily compatible with each other. Policy to regulate the interplay between these developments is poorly developed. Here, the subsurface footprints necessary to produce a unit of energy from different developments are estimated to assist with subsurface planning. The compatibility and order of development is also examined to aid policy development. Estimated subsurface energy footprints indicate that carbon capture and sequestration and geothermal energy developments are better choices than unconventional gas to supply clean energy.

Keywords: carbon capture and sequestration, geothermal energy, unconventional gas, energy footprints

1. Introduction

A global energy transition has become necessary due to energy security concerns (Kruyt *et al* 2009) and the link between fossil fuel combustion and climate change (IPCC 2007). Meeting energy demands while reducing greenhouse gas (GHG) emissions will require a combination of exploitation of new energy resources or implementation of schemes that capture and store GHG emissions. Many proposals aimed at addressing these issues will utilize the Earth's subsurface, including unconventional gas production, carbon capture and sequestration (CCS) and geothermal energy. At this point, it is not clear which development strategies are optimal to address these global problems.

Exploitation of unconventional natural gas, specifically shale gas and coal bed methane (CBM), has the potential to address both aspects of this problem. Advances in drilling technology and reservoir stimulation techniques have led to a dramatic expansion in natural gas production in recent years (Connors *et al* 2010). Production of electricity from natural gas rather than coal has the potential to avoid a significant amount of GHG emissions (Connors *et al* 2010). However, there is significant overlap between the geological environments that host unconventional natural gas and potential CCS reservoirs (Elliot and Celia 2012, Nicot and Duncan 2012). Similarly, depleted oil reservoirs and deep saline aquifers are both targets for CCS and geothermal projects (Benson and Cole 2008, US Department of Energy 2010). Studies on the size of these resources and the possible mitigating impacts on climate change indicate that exploitation will need to be widespread in each case to strongly affect GHG emissions (Benson and Cole 2008, Connors *et al* 2010, Tester *et al* 2006).

2. Conflicts, synergies and order of developments

Oil and gas, CCS and geothermal energy projects exploit a wide range of depths within the Earth's crust (figure 1).

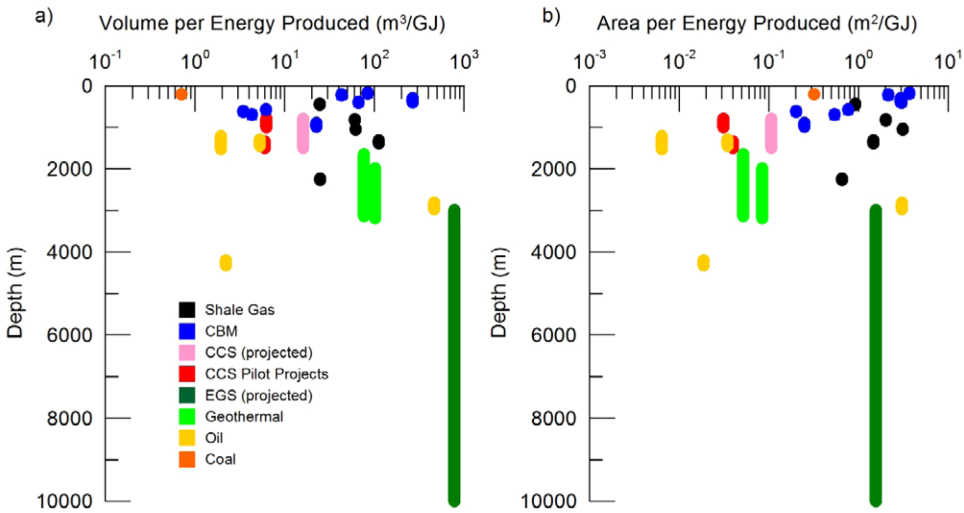

Figure 1. Footprints of various subsurface energy projects and their depths based on (a) volume and (b) area.

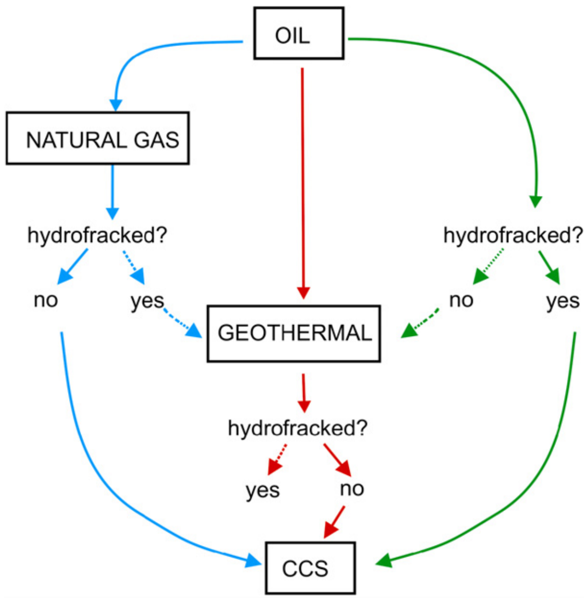

Figure 2. Suggested sequence of events where multiple developments are possible. CCS developments are unlikely in areas that have been subjected to hydrofracking.

While the optimal depths for each development differ, there is considerable overlap and the same geological units could have multiple possible uses. In other cases, use of one geological unit will rely on the integrity of the overlying units. To reduce GHG emissions while meeting global energy demands, some planning and prioritization will be necessary. Some developments can coexist or lend themselves to a logical progression in development. A possible framework for this could involve production of oil from a reservoir followed by later production of gas and ultimately CCS, which would be considered a terminal use (figure 2). Hydrofracking should be avoided in such a scenario because it might eliminate the possibility of using that same reservoir for CCS unless there is evidence to demonstrate the integrity of caprocks following stimulation (Nicot and Duncan 2012, Elliot and Celia 2012). Other scenarios involving geothermal development following oil production and then CCS or development of CCS immediately after oil production are also possible. Priorities have been legislated regarding the sequence of development for a few situations in some jurisdictions, such as oil and gas withdrawal in Alberta, Canada (Province of Alberta 2011), but are lacking in most instances (Dammel *et al* 2011, Tester *et al* 2006, EU 2009).

Oil and gas, CCS and geothermal projects will all exploit reservoirs with sufficient permeability and porosity when available. Oil has traditionally been extracted prior to considering other uses due to high energy densities (figures 1 and 2) and favourable economics. Both CCS and geothermal projects have been proposed for depleted oil reservoirs where appropriate temperature and pressure conditions exist (Benson and Cole 2008, US Department of Energy 2010). The optimal depths for CCS projects are usually between 800 and 1500 m (Benson and Cole 2008). Overlap between CCS and geothermal projects may occur in deeper formations where higher temperatures are present. Developing geothermal resources in areas adjacent to CCS reservoirs or in underlying geological units will also be difficult due to the potential to alter the hydraulics of these reservoirs and the potential for leakage associated with well installation. Utilization of a reservoir for CCS following geothermal energy production could be feasible in some cases. The possibility of formation damage during geothermal development and changes in temperature following geothermal production will need to be considered. If these changes are significant, then CCS might not be possible following EGS development (figure 2). Hybrid geothermal–CCS systems have been proposed for sedimentary basin environments (Randolph and Saar 2011) but the focus of research in that area to date has been on energy production rather than long-term sequestration of CO_2.

Unconventional oil and gas target geological units that occur in the upper 2000 m of the crust (Jenkins and Boyer 2008). These formations generally have poor permeability and porosity and would not normally be considered targets for CCS. However, conflicts may arise in these situations as

Table 1. Energy densities for natural gas, oil, geothermal energy and carbon dioxide. Energy density for CCS is calculated using the amount of electrical energy generated during production of CO_2 by combustion of coal. CCS efficiency considers the additional energy required for sequestration. Energy density for coal was calculated using a density of 1400 kg m^{-3} (Morcote *et al* 2010) and an energy density per mass of 28 GJ t^{-1} (National Energy Board of Canada 2012).

Energy source	Energy density (GJ m^{-3})	Efficiency of conversion at power plant (%)	Lifecycle GHG emissions (g CO_{2eq} kWh^{-1})	References
Natural gas	0.037	45	466	National Energy Board of Canada (2012), Taylor *et al* (2008), Sovacool (2008)
Oil (light)	39	37	778	National Energy Board of Canada (2012), Taylor *et al* (2008), Sovacool (2008)
Geothermal	0.026	11	38	Tester *et al* (2006), Pehnt (2006)
CCS	2.6	80	217	Benson and Cole (2008), Metz *et al* (2006), National Energy Technology Laboratory (2010)
Coal	20	37	931	National Energy Board of Canada (2012), Taylor *et al* (2008), National Energy Technology Laboratory (2010), Morcote *et al* (2010)

some of these formations are important caprocks. Hydraulic stimulation may compromise caprock integrity and the possibility of CCS in any underlying reservoirs (Benson and Cole 2008, Elliot and Celia 2012, Nicot and Duncan 2012) (figure 2). Extensive shale gas development could put up to 80% of the USA's CCS capacity at risk for this reason (Elliot and Celia 2012).

Subsurface planning is necessary to ensure optimal development of the Earth's crust to support energy security and climate change interests. Calculation of land-use footprints has been proposed as a method of examining the environmental impact and efficiency of various energy projects (Fthenakis and Chul 2009). Here a similar concept is used to determine the subsurface footprints of energy projects to facilitate comparison and management.

3. Energy footprints

3.1. Methods

Electricity generation is chosen as a metric to evaluate the amount of energy that could be produced using a volume or area of the Earth's crust over the lifetime of a project. This allows for direct comparison of natural gas, oil, CCS and geothermal energy and follows the idea that electrical energy will be increasingly important to society in the future as we attempt to address climate change (Williams *et al* 2012). CCS does not generate electricity but could facilitate the continued use of fossil fuels, notably coal, to generate electricity while reducing GHG emissions. The treatment provided here considers the amount of electricity that can be generated from fluids produced from the crust or, in the case of CCS, sequestered in the crust. Energy consumed in well installation, fuel extraction and transport, power plant construction and decommissioning activities are not considered in the calculations presented here.

The ability to produce electrical energy from heat or hydrocarbons contained in the crust was assessed on a per unit volume basis. Calculations were performed using volumetric energy contents of produced fluids and typical conversion factors (table 1) along with estimates of the volume of crust required to produce those fluids. This volume was computed as the product of developed areas and thicknesses (table 2). The footprint of CCS projects was calculated by estimating the volume of crust required to sequester the CO_2 produced from the generation of a unit of electricity. This volumetric treatment allows for comparison of projects that compete for the same pore space. Similar calculations were done to determine the energy produced by an area of the Earth's crust to allow for comparison of developments at different depths that might impact each other. Examination of case studies was necessary to determine the amount of crust involved for different developments due to the differences in porosity, extraction and injection efficiencies and the presence of multiple fluids within the pore spaces of different geological environments. These calculations are based on both production data as well as estimates of reserves and contingent resources. Oil and gas are dealt with in terms of reserves, which must be discovered, recoverable, commercial, and remaining (as of a given date) based on the development project(s) applied (Society for Petroleum Engineers 2011). CCS and EGS developments are assessed based on the in place contingent resources because they are generally not commercially viable at the present time due to one or more reasons (Society for Petroleum Engineers 2011). Footprints for conventional geothermal systems were calculated in a somewhat different manner. The exploited volumes at these facilities were divided by the powerplant capacities, assuming a 30-year period of operation.

Further analysis was done to determine the amount of the subsurface required to cause a unit reduction greenhouse reductions. This was calculated by dividing the energy footprints (figure 1) by the difference between the global average emissions per unit of electrical energy produced (International Energy Agency 2012) and those associated with natural gas, geothermal energy and CCS (table 1). These assessments were calculated on the basis of both volume and area (figure 3).

Table 2. Thicknesses, areas and energy contents of subsurface projects analysed in this study. Amount of recoverable energy does not consider conversion efficiencies in this table. Volumes were calculated as the product of thickness and area.

Resource type	Field	Thickness (m)	Area (km^2)	Basis of area	Recoverable energy (GJ)	Footprint (m^3 GJ^{-1})	Reference
Shale gas	Antrim	27	0.38	Well spacing	4.73×10^5	25	Jenkins and Boyer (2008)
Shale gas	Ohio	20	0.40	Well spacing	1.42×10^5	62	Jenkins and Boyer (2008)
Shale gas	New Albany	30	0.32	Well spacing	1.77×10^5	61	Jenkins and Boyer (2008)
Shale gas	Barnett	38	0.49	Well spacing	8.27×10^5	25	Jenkins and Boyer (2008)
Shale gas	Lewis	76	0.81	Well spacing	6.14×10^5	112	Jenkins and Boyer (2008)
Coalbed methane	CBM-Wyodak	23	0.32	Well spacing	9.88×10^4	85	Jenkins and Boyer (2008)
Coalbed methane	CBM-Big George	91	0.32	Well spacing	1.25×10^5	268	Jenkins and Boyer (2008)
Coalbed methane	Ignacio Blanco	17	0.77	Well spacing	4.25×10^6	3	Jenkins and Boyer (2008)
Coalbed methane	Drunkard's Wash	8	0.65	Well spacing	1.30×10^6	4	Jenkins and Boyer (2008)
Coalbed methane	Cedar Cove	8	0.32	Well spacing	4.73×10^5	6	Jenkins and Boyer (2008)
Coalbed methane	Recluse Rawhide Butte	20	0.32	Well spacing	1.65×10^5	43	Jenkins and Boyer (2008)
Coalbed methane	Horseshoe Canyon	22	0.49	Well spacing	1.77×10^5	67	Jenkins and Boyer (2008)
Coalbed methane	Fairview	91	0.32	Well spacing	1.42×10^6	23	Jenkins and Boyer (2008)
CCS	Theoretical	1	0.000 001	Unit estimate	0.062	16	Benson and Cole (2008), Metz *et al* (2006)
CCS	Weyburn	150	4.00	Measured plume	1.00×10^8	6	Jensen *et al* (2011), Wright *et al* (2009)
CCS	Sleipner	200	2.00	Measured plume	6.40×10^7	6	Wright *et al* (2009)
Geothermal	Geysers	1480	78.00	Developed area	1.50×10^9	77	Goyal and Conant (2010)
Geothermal	Dixie	1200	5.00	Developed area	5.90×10^7	102	Bertani (2012), Reed (2007)
Geothermal	Theoretical EGS	500	0.25	Stimulated area	1.60×10^5	781	Tester *et al* (2006)
Oil	Ghawar	118	2800.00	Field size	1780×10^{11}	2	Al-Anazi (2007)
Oil	Burgan	305	830.00	Field size	1.55×10^{11}	2	Desai *et al* (2012)
Oil	Prudhoe Bay	153	864.00	Field size	2.89×10^{10}	5	BP (2006)
Oil	Elm Coulee	153	1170.00	Field size	4.44×10^8	466	Sonnenberg and Pramudito (2009)
Coal	US average	2.2	0.000 001	Unit estimate	1.40	0.7	Robeck *et al* (1980)

3.2. Results

The amount of energy production supported by a volume of the Earth's crust has a large range from <2 m^3 GJ^{-1} for large conventional oil fields and coal to >800 m^3 GJ^{-1} for projected EGS projects (figure 1). CBM projects examined ranged from 3 to 270 m^3 GJ^{-1} and shale gas projects from 25 to 112 m^3 GJ^{-1}. The projected value for CCS projects was 16 m^3 GJ^{-1} for coal-fired power plants and pilot projects at Weyburn, Canada and Sleipner, Norway both had values of approximately 6 m^3 GJ^{-1}. Note that footprints for CCS could be reduced by as much as 45% if CCS were applied to a natural gas power plant rather than a conventional coal plant (Metz *et al* 2006). Factoring in the footprint of coal mining operations changes the situation somewhat, requiring an additional volume of approximately 0.7 m^3 GJ^{-1}. Current geothermal projects had values of approximately 77–100 m^3 GJ^{-1}, while a typical EGS project is expected to require nearly 800 m^3 GJ^{-1}. The Elm Coulee Field, an unconventional oil field within the Bakken Formation, has a footprint of over 470 m^3 GJ^{-1}.

The footprints are slightly different when examined on the basis of area rather than volume. Shale gas and CBM resources require 0.25–3.7 m^2 GJ^{-1} and the unconventional oil of the Elm Coulee Field exceeds 3.0 m^2 GJ^{-1}. CCS footprints are 0.03–0.11 m^2 GJ^{-1} and EGS becomes more competitive with other developments at 1.6 m^2 GJ^{-1}. The estimated additional impact of coal to CCS projects is 0.3 m^2 GJ^{-1} on the basis of area.

Projects with small energy footprints are also the most effective in reducing GHG emissions if they allow for generation of electricity with emission lower than the global average of 565 g CO_{2eq} kWh^{-1} (International Energy Agency 2012) (figure 3). Some deviations from this trend are present, most notably when energy and emissions are examined on the basis of volume of crust (figure 3(a)). Geothermal energy and CCS require larger volumetric energy footprints than shale gas and coal bed methane developments for equivalent

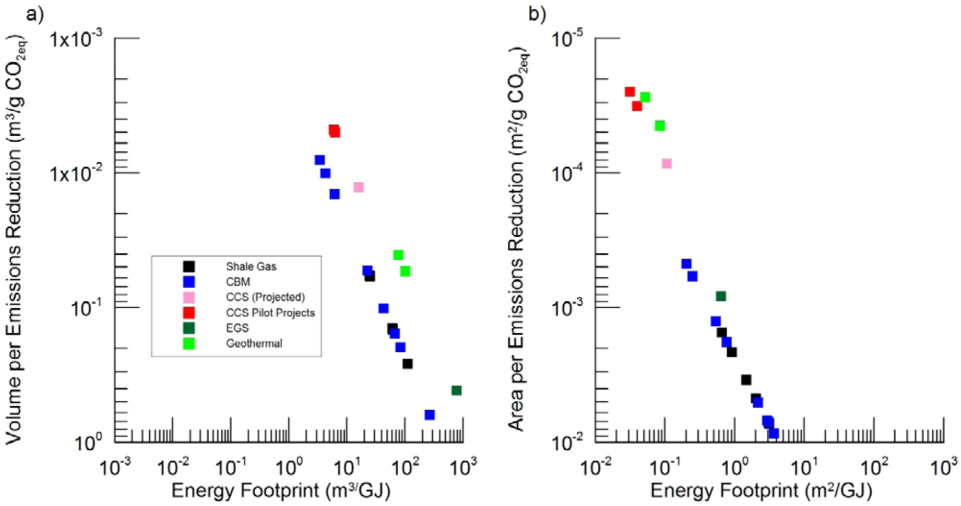

Figure 3. Electricity generation possible using a unit (a) volume and (b) area of the Earth's crust compared to the emissions avoided relative to the global average emission of 565 g CO_{2eq} kWh^{-1} (International Energy Agency 2012). Emission footprints are calculated by dividing the energy footprints (figure 1) by the emissions per unit energy produced (table 1).

reductions in greenhouse gas emissions. A different picture arises when footprints are considered on the basis of areas due to the differences in the typical thicknesses of these developments (table 2). Using area as a metric, little overlap occurs between the energy footprints and CCS will produce far greater reductions in emissions than unconventional gas (figure 3(b)).

4. Discussion and conclusions

CCS should be prioritized over other crustal uses in terms of its subsurface energy footprints and its effectiveness in reducing GHG emissions. Previous studies drawing attention to the overlap between shale gas and underlying CCS candidate reservoirs suggest that further development of unconventional gas should consider the impact of hydrofracking on caprock integrity (Elliot and Celia 2012, Nicot and Duncan 2012). The situation changes slightly if the energy footprint of coal production is considered in the footprint of CCS. The additional footprint of coal mining by area estimated here is approximately 0.3 m^2 GJ^{-1}. Fthenakis and Chul (2009) conducted a similar analysis and arrived at a footprint of 0.05–0.1 m^2 GJ^{-1}. The coal mining footprint by area is nearly an order of magnitude greater than CCS pilot projects. However, the shallow depth of coal developments makes the possibility of conflict with other activities discussed here remote. Consideration of coal mining associated with CCS is more relevant in terms of the overall environmental impacts, which can be quite problematic (Banks *et al* 1997). To evaluate such impacts fairly, a comprehensive comparison of coal mining impacts with those associated with natural gas extraction (Osborn *et al* 2011, Van Stempvoort *et al* 2005) and geothermal energy (Giardini 2009) would need to be conducted. The need for setbacks in CCS projects was not considered here. Buffer zones will likely be required to isolate CCS projects from other subsurface developments. This will increase the footprint of CCS developments but the magnitude of this increase is not clear at this point.

Geothermal energy is somewhat problematic to assess relative to the other developments because of its renewability (Tester *et al* 2006). Conversely, fossil fuels are not renewable and the CCS capacity of the crust will be used up within a few centuries (Benson and Cole 2008). With the 30-year lifespan considered here, EGS does not appear to be an optimal use of the Earth's crust due to its relatively large crustal requirements. Allowing for longer reservoir lifetimes or multiple cycles of development could make EGS more competitive with CCS, particularly on the basis of crustal area, where an EGS development would extend vertically beyond the boundaries of a potential CCS reservoir. In cases where competition exists for the same volume of crust, geothermal energy production would have to extend over millennia to create similar energy footprints to those achieved by CCS. Conventional geothermal energy projects are competitive with CCS developments, particularly on the basis of area, but overlap of these sites is expected to be rare. EGS will be possible in a wide range of environments (Tester *et al* 2006) and many opportunities will exist to pursue geothermal developments at sites that do not conflict with CCS. Such developments could be very important in the long-term.

Development of the subsurface has significant potential to address energy security and climate change issues. The current rapid expansion in unconventional natural gas resources does address this issue to some extent because of the relatively low emissions associated with natural gas combustion. However, this is not an optimal method to address either of these issues in terms of energy produced per unit of the Earth's crust and GHG emissions. Hydraulic stimulation required in natural gas developments may preclude CCS developments, which have greater potential to address greenhouse gas emissions while facilitating production of larger amounts of energy per unit of crust. Long-term sustainability and the current urgency to address GHG emissions will need to be considered when determining whether CCS or geothermal developments should be prioritized where both are possible.

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