Recycling Carbon: An outreach activity designed to introduce the general public to carbon capture, utilisation and storage

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Abstract

Anthropogenic emissions of carbon dioxide are causing unmeasurable damage to our planet. As well as rapidly decreasing annual carbon emissions we need to remove already-emitted carbon dioxide from the atmosphere, so-called negative emissions. However, public opinion is important when deploying new carbon capture technology and prior research has shown that it is more likely to be accepted when local residents have been introduced prior. In this paper we describe a new outreach activity, *Recycling Carbon*, to introduce the general public to negative emissions technologies. *Recycling Carbon* was designed by researchers active in the development of carbon capture and utilisation and has proven very versatile, appealing to audiences of 5-75 year olds in a number of settings including classrooms, science fairs and as a public science lecture. Preliminary feedback, in the form of a before-activity and post-activity questionnaire, indicates that engagement with *Recycling Carbon* improves people's understanding of negative emissions technology. Finally the paper discusses how engagement with *Recycling Carbon* is also an opportunity to discuss an individual's carbon footprint.

Keywords: Carbon capture and storage, carbon capture and utilisation, outreach, public acceptance, climate change education

1 Introduction

Global carbon dioxide (CO_2) levels have been increasing exponentially since the industrial revolution.[1] This increase is having, and will continue to have, an effect on every aspect of our lives; from the weather we experience, to the food we eat, to where we live. In 2018 the Intergovernmental Panel for Climate Change (IPCC) published a special report entitled "Global Warming of 1.5°C".[2] This report has led to policy change around the world with various countries, states and local councils declaring a "Climate Emergency".[3-6] In order to stay within 1.5 °C of global warming (above pre-industrial levels), determined as the "safe limit", the human race needs to 1) decrease worldwide carbon emissions[7] and 2) remove already-emitted CO_2 from the atmosphere and 3) capture CO_2 being emitted from heavy industry such as cement and steel production.[8]

Effective communication from media reports, peer-to-peer discussion, large-scale protests and government interventions have seen a dramatic increase in the awareness of climate change by the general public between September 2018 and December 2019.[9] People are aware of key personal changes that they can make to reduce their own carbon footprint such as decreasing flying, changing their diets, becoming more active, insulating houses and changing energy supplier to a 100% renewable supplier.[10-12] At a global scale, governments around the world are making a series of promises to cut carbon emissions.[13-16]
However, decreasing carbon emissions, will not be enough to keep the global temperature rise to 1.5 °C compared to pre-industrial levels. Heavy industry and aviation will also continue to

emit greenhouse gases which need to be captured at source or from the atmosphere to ensure that net-zero carbon emissions can be achieved by 2050.

The greenhouse gas carbon dioxide (CO_2) can be removed from the atmosphere using direct air capture (DAC). This technology has recently been commercialised by companies such as Climeworks,[17] Carbon Engineering[18] and Global Thermostat.[19] Industrial emissions such as those generated by steel or cement production, can be captured at the point of production, termed post-combustion capture.[20] This technique is being trialled by Petra Nova in Texas, USA,[21] where post-combustion capture was used to capture 1 million tonnes of CO_2 emissions in 10 months of operation of a coal-fired power plant. Carbon capture can also be used in conjunction with the burning of biomass for heat and/or electricity production. It's termed BECCS and is being pilot tested by Drax Power Plant in the UK, capturing 1 tonne of CO_2 from the burning of 100% biomass feedstock.[22] As well as pilot-testing the carbon capture technology Drax, like many other carbon capture companies, is also in discussions with a number of other companies to utilise the captured carbon. This could be in fizzy drinks, as synthetic fuels and even materials with incorporated CO_2.

However, public opinion is important when implementing new carbon capture technology,[23] as public opposition has been a factor in the cancellation of carbon capture and storage (CCS) projects in Germany and the Netherlands.[24] Some of the concerns that individuals have about CCS are represented in a study by Thomas *et al.*[25] In this study, 12 UK residents living within 10 miles of Drax, a biomass- and coal-fired power station in the North of England, were surveyed for their views on CO_2 and CCS. The participants stated that CO_2 is a gas, a pollutant and contributes to climate change, which they were concerned about. However, when the idea of CCS was introduced, participants were wary in general and specifically concerned about leaks of CO_2 from the storage sites. In another study by Boyd and co-workers,[17] 1479 Canadians were surveyed to assess their perceptions of CCS. A key question was "How strongly would you support or oppose a carbon capture and storage projected being constructed within 25 kilometres of your home?" 61.4 % of respondents answered, "strongly oppose" or "oppose" and only 8.9% responded with either "support" or "strongly support". Boyd *et al.* found that "there was low familiarity with CCS, yet participants that were more familiar with CCS were more supportive of CCS projects". Fleishman *et al.* also showed that people were more likely to accept the idea of CCS once they "fully understood the benefits, cost, and limitations".[26] Dowd *et. al.* sampled 2,740 participants from Australia, Japan and the Netherlands to understand how participants' knowledge of CCS affected their perceptions of CCS.[27] They found that when participants didn't understand the properties of CO_2 or how CCS worked they were more likely to mistrust it. However, "providing information on CCS on the scientific characteristics of CO_2 reduced misunderstanding of CCS and mitigated some change in opinion formation on CCS implementation". Research by Ashworth, Boughen *et al.* and Ashworth, Bradbury *et al.* underlines this by showing how early engagement with the general public regarding a new CCS site is important for the technology to be accepted.[24, 28] A recommendation of the 2010 (*Ashworth, Boughen et al.)*[24] report was to "invest in developing education curricula which addresses the topic of climate change, the role of CCS and technological solutions for greenhouse gas mitigation." This was echoed by Duan, who suggested that "integrating public education and communication into CCS development policy would be an effective strategy to overcoming the barrier of low public acceptance".[29]

Despite a growing field of climate change education,[30-32] there is very little literature available describing educational activities or lessons that introduce CCS. Therefore, we have developed an interactive, engaging activity [called *Recycling Carbon]* that explores carbon capture. The activity expands beyond CCS to discuss what can be done with the captured carbon dioxide, namely converting it into useful products. This is termed carbon capture and utilization (CCU). The activity was originally designed for use at a science festival, where a broad demographic would be present to engage with the subject matter. Science festivals have been shown to be important for the dissemination of information[33-35] and there is a positive side-effect that diverse role models being present at science festivals inspire younger children into STEM subjects.[36-38] The aim of the *Recycling Carbon* activity is twofold:

1) To educate people that CCU is a viable technology and demonstrate that CO_2 needs to be controlled and looked after;
2) Impart information to and educate people to have them realise that they can also participate in climate change mitigation on an individual basis.

Since its conception, *Recycling Carbon* has been adapted from a science festival exhibit into an activity that can form part of a school lesson, a public lecture or a careers event. We present *Recycling Carbon* as something highly adaptable that will appeal to a broad demographic. We hope that it will be replicated and used to educate many more people on the importance of CCS and CCU in the future.

2 Methods

2.1 Language

The language used to explain the activity is adapted for each individual participant, taking age, enthusiasm & experience of science lessons into account. For example, with younger participants we would use terminology such as "burning", "power", "air" whereas for older participants, with beyond-primary school science education, we would use "combustion", "electricity", "atmosphere".
We use information sheets to support our activity (see supporting information Figs. 1-10). As the activity is primarily based in Wales, a bilingual country, for the sake of inclusivity the information sheets are bilingual (English and Welsh).

2.2 Power plant

The activity starts from the "Power plant" table, where the concept of burning fossil fuels to produce energy is introduced. A range of examples is given, with the aim of finding at least one with which the participant is familiar. Examples include the use of coal and natural gas in power plants to produce electricity, petrol and diesel fuel in cars, natural gas in boilers for household heating. We explain that these processes are chemical reactions that lead to the production of CO_2. The participant is then provided with an information sheet where the chemical reaction between methane (CH_4) and oxygen (O_2) to produce carbon dioxide (CO_2), water (H_2O) and energy is illustrated (Figure 1). Methane was chosen as a “model” fossil fuel because it is the simplest hydrocarbon and the main component of natural gas, which is a common energy source. The participant is also provided with molecular models of CH_4 and O_2 made of Bunchems (velcro-type balls that stick together): CH_4 is made of one black Bunchem, representing the carbon atom, and four white Bunchems, representing hydrogen atoms; O_2 is made of two red Bunchems, representing oxygen atoms (Fig.1). The participant is asked to reproduce the chemical reaction illustrated in the information sheet. This involves taking apart the molecular models and building new ones, which provides an idea of the bond breaking and formation process involved in a chemical reaction. Emphasis is then put on the formation of CO_2, a gas, as an unavoidable waste product of the combustion of fossil fuels. The participant is asked to keep the CO_2 molecule they just produced with them and move to the “Lucky dip” table.

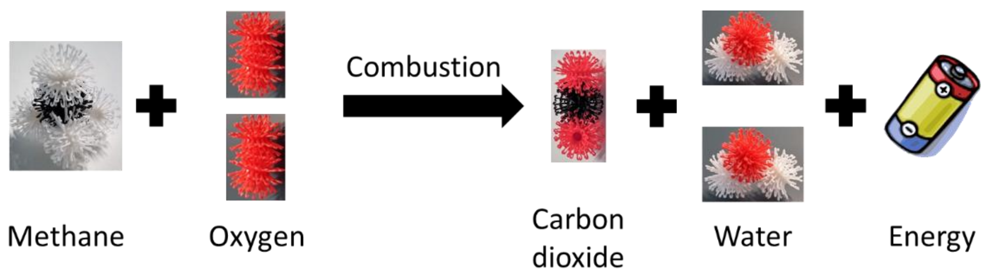

Figure 1. Depiction of the bunchem models and chemical reaction for the combustion of methane in oxygen.

2.3 Lucky dip

At this stage, the issues related to the release of CO_2 into the atmosphere are introduced, explaining that the accumulation of CO_2 prevents dissipation of heat from the atmosphere and leads to global warming and climate change. The CO_2 molecule carried by the participant is then hidden in a box filled with packing peanuts and the participant is asked to retrieve it. This “lucky dip” is intended to provide an idea of the extreme dilution of CO_2 in the atmosphere (415 ppm, i.e. about 4 molecules of CO_2 every 10,000 molecules in the air) and the challenges associated with its removal. The concept of carbon capture is then introduced, explaining that there are two main options: direct air capture and capture from point sources, such as power plants. The focus is on the use of nanoporous materials as a sorbent for carbon capture represented by a sponge, which the participant is invited to hold and explore. The participant is encouraged to reflect on how the sponge is used to soak up water and “regenerated” by squeezing it. The importance of the porosity of the sponge for the process is emphasised and the participant’s attention is directed towards visualisation of the pores. At this point, a ball-and-stick model of an ideal nanoporous material is used to provide an idea of how the CO_2 Bunchem model can be “soaked up” within the pores. By comparison with the sponge, we discuss how the nanoporous material can be regenerated and reused for several cycles. The discussion then moves onto the question “What do we do with the captured CO_2, once it is recovered from the sorbent?”. The two options of geological storage and utilisation are both mentioned, but the focus is kept on the latter, which leads to the “Catalyst” table.

2.4 Catalyst

The choice of focusing on utilisation is justified by the fact that conversion of CO_2 into fuels is a form of recycling waste, a concept with which most of the audience is familiar and that fits within the scope of circular economy. For this reason, the target fuel of the activity is methane. The participant, still carrying their CO_2 molecule, is provided with an information sheet where the chemical reaction between CO_2 and hydrogen (H_2) to produce CH_4 and H_2O is illustrated (Fig.2). Again, the participant is asked to reproduce the reaction depicted on the information sheet.

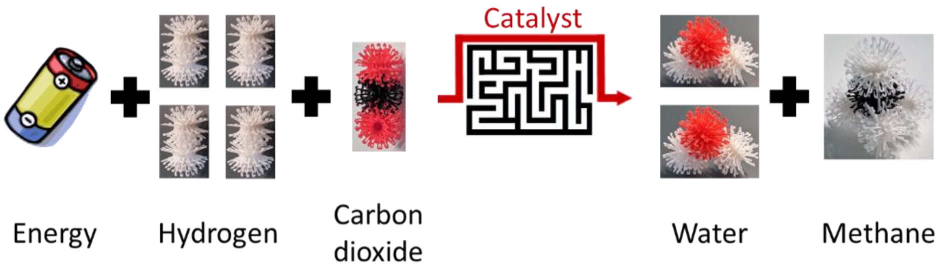

Figure 2. A depiction of the conversion of carbon dioxide back into the starting material, methane.

The attention is then shifted to the fact that such a process does not occur spontaneously and a very large energy input is needed to make it happen. This is represented as a maze on the information sheet. The idea of a catalyst is introduced as a shortcut that represents the reaction path leading to the formation of CH_4. The importance of using carbon-free energy from renewable sources is also emphasised at this stage, focusing on wind and solar, which are the most commonly known by the general public.
At the same table, the issue of hydrogen production is introduced. The participant is made aware that elemental hydrogen is not found in nature and therefore needs to be separated from compounds where it is bound to other chemical species. The participant is then asked what could be a suitable source of hydrogen and introduced to the concept of water splitting, either electrochemical or photochemical. The idea of using renewable sources to power this process is reiterated at this stage.

2.5 Personal Impact on Climate Change

At the end of the activity participants were offered a balloon as a souvenir and, if they still wanted to learn more, were given an information sheet listing common activities (i.e. keeping a light bulb on, using a laptop, using a television, doing a Google search, driving a car for 100 yards, traveling by plane) and products (i.e. quarter pounder burger, can of Coca-Cola) with their respective carbon footprint.[39] The information sheet is available as SI Fig. 5 and 10 in English and Welsh respectively. To try and get around the often abstract concept of carbon footprint or carbon emission in the form of grams, we used a measure of balloons as a way to measure the volume of CO_2. This balloon measurement system served two purposes; firstly it is a more tangible concept for the average person to comprehend and secondly it gives a much more visual representation of what carbon emissions actually are. The souvenir balloons are printed with their carbon content, 16 g or 9 L, should they be filled with CO_2 (see figure 11 in SSI).

2.6 Data Collection

Impact related results of the activity were collected through the use of a direct feedback question answer system based on two questions:

- Can carbon dioxide be recycled?
- Can individuals make a difference to climate change?

Science festival visitors were surveyed for their responses to the two questions before and after participation in *Recycling Carbon* and could choose between "Yes", "No" and "Don't Know". Participants selected their answer before completing the activity by placing an orange sticker in the appropriate box. After the activity they were given a blue sticker and asked to choose again the answers to the two questions.

3 Results

The interaction of people at science festivals tended to last between 10 - 20 mins depending heavily on the age and interest of the participants. During the 2018 and 2019 Swansea Science Festivals impact related results of the activity were collected through the use of a direct-feedback question-answer system based on two questions:

- Can carbon dioxide be recycled?
- Can individuals make a difference to climate change?

These questions were chosen to be non-leading and directly related to the activity. Further, to remove the feeling that the questions could be led by the person asking the questions the participants were asked to mark their answers on a poster using a coloured sticker. These questions were asked at both the start and end of participation in the activity so that the overall effect on people's change in attitude could be assessed. The results for the pre- and post-activity interactions were displayed by different coloured stickers. These stickers also helped to quantify the number of interactions the stand had with people throughout the two-day science festival. However these numbers are likely to be an underestimate as some participants did not want to take part in the feedback system or because larger groups would answer as a group/family unit rather than an individual. Figure 3 shows the results of the question-answer feedback system from the 2018 science festival.

A) Can CO_2 Be Recycled?

B) Do You Think Individuals Can Make a Difference to Climate Change?

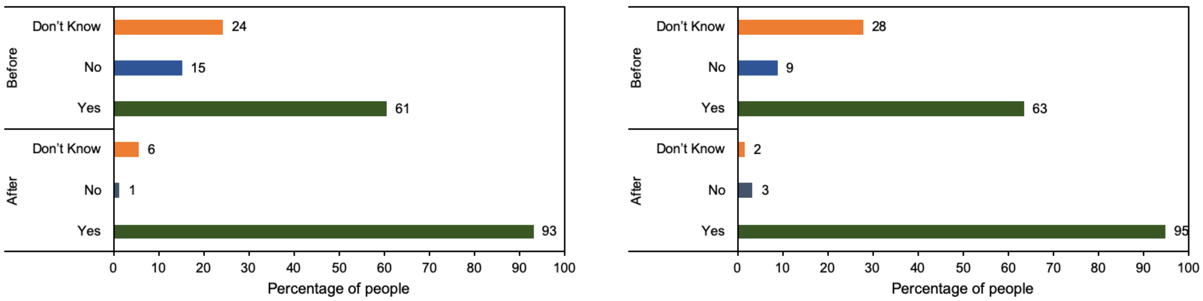

Figure 3. Results of question/answer feedback as a percentage taken before and after interaction with *Recycling Carbon* at the 2018 Swansea Science Festival.

Figure 3A shows the results for the first question “Can CO_2 be recycled?” and indicates that prior to interaction with the activity 61% of people believed that CO_2 could be recycled, 24% did not know if it could or couldn’t and 15% believed that it could not be recycled. After interaction with *Recycling Carbon* the results indicate a marked change with 93% of people believing that CO_2 can be recycled (a 32% increase), 6% not knowing whether it can be recycled (a decrease of 18%) and 1% believing that CO_2 could not be recycled. These results indicate that the activity has a positive effect on participants’ attitudes to the concept of CCU. This hopefully translates to them being more willing to support and adopt such technology when available. Further to the positive effect it should be noted that the activity allowed people who were previously unaware of CCU, and therefore answered “don’t know”, to draw an opinion on the subject indicating that there is a level of knowledge transfer occurring for the activity. However, we recognise that the scope for the feedback is too limited to really investigate this aspect to a more detailed extent.

Figure 3B shows the feedback to the question “Do you think individuals can make a difference to climate change?”. Prior to interaction with the activity 63% of people think that they can, 28% don’t know and 9% think that they cannot. After interaction the results again show a positive skew with 95% of people believing that individuals can have an effect on climate change (a 32% increase) 3% thinking they cannot (a 25% decrease) and 2% not knowing (a 7% decrease). These results indicate that the activity has empowered the participants to believe that they can make a difference to climate change. This was one of the key messages the activity sets out to achieve as described in the introduction.

A) Can CO_2 Be Recycled?

B) Do You Think Individuals Can Make a Difference to Climate Change?

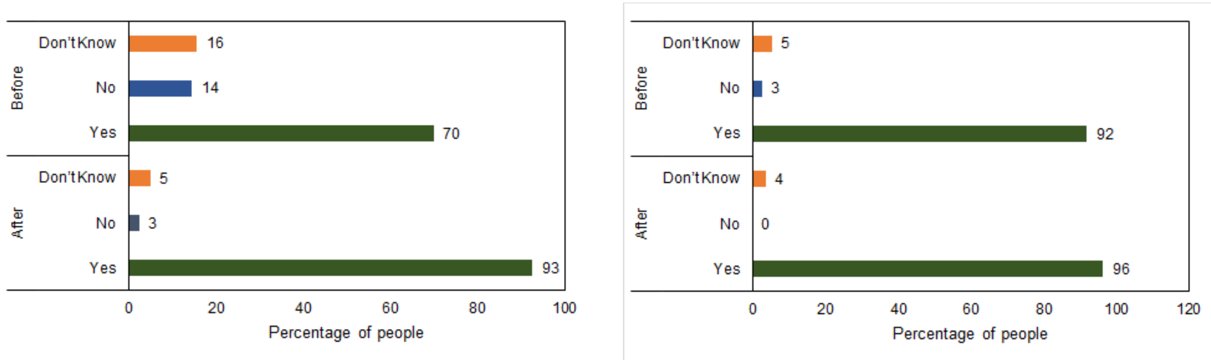

Figure 4 Results of question-answer feedback as a percentage before and after interaction with *Recycling Carbon* at the 2019 Swansea Science Festival.

Figure 4A shows the results for the first question "Can CO_2 be recycled?" and indicates that prior to interaction with the activity 70% of people believed that CO_2 could be recycled, 16% did not know if it could or couldn't and 14% believed that it could not be recycled. After interaction with *Recycling Carbon* the results indicate a marked change with 93% of people believing that CO_2 can be recycled (a 23% increase), 5% not knowing whether it can be recycled (a decrease of 11%) and 3% believing that CO_2 could not be recycled (a 2% decrease).

Figure 3B shows the feedback to the question "Do you think individuals can make a difference to climate change?". Prior to interaction with the activity 92% of people think that they can, 5% don't know and 3% think that they cannot. After interaction the results are mostly unchanged with 96% of people believing that individuals can have an effect on climate change (a 3% increase) 3% thinking they cannot (unchanged) and 2% not knowing (a 3% decrease). The reasons for such a positive response to the question "Do you think individuals can make a difference to climate change?" is discussed in Section 4.

As a secondary form of interactive feedback, a short, three question quiz was devised. We observed, at science festivals, that parents would typically stand back and "tune out" whilst their children participated in the *Recycling Carbon* activity. The quiz enabled us to capture the attention of the parents whilst their children took part in the interactive portions of the activity. The quiz takes the form of people estimating the amount of CO_2 released for a number of activities. The questions for the quiz were displayed and the answers were collected on sheets with questions 1 and 2 being multiple choice and 3 being an estimate. The three questions were:

1. How many balloons of CO_2 are released to make 1 kg of cheese?
2. How many balloons of CO_2 are absorbed by the average tree in 1 day?
3. How many balloons of CO_2 make up the average annual carbon footprint of a person in the UK?

Prior to being asked these questions a member of the team would have gone through a visual aid (SSI figures 5 and 10 in English and Welsh respectively) showing examples of number of balloons of CO_2 released for various activities. The questions were asked as a way to both inform people, as answers were given post quiz, and also as a way to gauge people's perception of CO_2 production in relation to what could be seen as fairly day to day products or activities. The results for the first question, shown in figure 5A, indicate that people would either overestimate or correctly guess the carbon footprint associated with the production of a kilogram of cheese. 40% of people overestimated the carbon footprint, 40 % correctly estimated the carbon footprint and only 17% underestimated the carbon footprint of the production of a kilogram of cheese. This indicates that people are have some awareness of the impact that everyday activities can have on carbon emissions. In comparison when asked how many balloons of CO_2 can be absorbed by an average tree in a day most people overestimated the efficiency of trees to absorb CO_2 with only 25% of people correctly estimating the absorbed amount (Fig 5B). This indicates that the public are overly optimistic about the ability of trees to mitigate CO_2 emissions. We found that this question provided a good starting point for discussion regarding CO_2 mitigation and CCU technology.

A) How many balloons of CO_2 are released to make 1 kg of cheese?

B) How many balloons of CO_2 are absorbed by the average tree in 1 day?

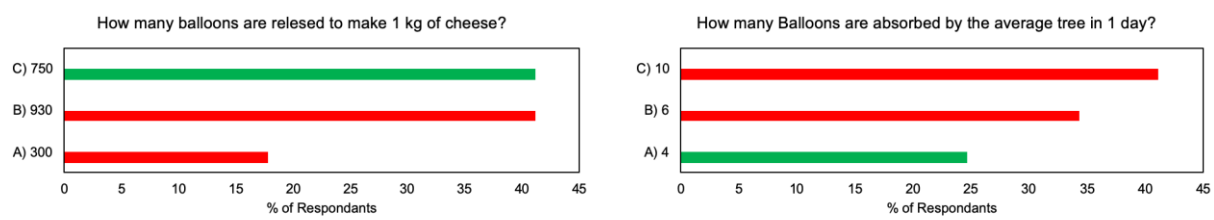

Figure 5. Results of questionnaire multiple choice questions. Green represents the correct answer for the question.

A final question, asking people to estimate their annual carbon footprint, resulted in guesses ranging from 10 balloons to 1,000,000,000 balloons.

4 Discussion

The main aims of *Recycling Carbon* are:

1) To educate people that CCU is a viable technology and demonstrate that CO_2 needs to be controlled and looked after.
2) Impart information to and educate people to have them realise that they can also participate in climate change mitigation on an individual basis.

We have used a number of different techniques to disseminate information about CCS technology and carbon footprints with the general public. Firstly, we have communicated the information in a number of different ways – verbally, pictorially, kinesthetically and through written text. In this way we have made the activity accessible to a people with a number of different learning styles.[40] It has also made the activity accessible to those with additional learning needs e.g. dyslexics find text challenging and can therefore engage with verbal, pictorial or tactile learning. We also present the information bilingually as the activity has predominantly been delivered in Wales – a bilingual Welsh and English speaking nation. Finally, the *Recycling Carbon* team has been multi-lingual with members speaking Italian, German, Farsi, English, Spanish and Polish. The lack of a Welsh-speaking member of the team has fortunately not yet caused a problem, although this is a limitation which is only partly overcome by the Welsh-written material available.

The *Recycling Carbon* activity was first delivered at the 2017 Swansea Science Festival. Participants appeared to enjoy the activity but there was no way of measuring the impact of their participation. Therefore, prior to the 2018 Swansea Science Festival, we developed the direct-feedback, question-answer system. The information gained from the participants is limited, both by the questions posed and the way feedback is given, but it still indicates that the activity is having the desired effect – namely educating participants that CCU is a viable technology. (The percentage of participants who thought that CO_2 could be recycled rose by 32% (2018) and 23% (2019) after participating in the *Recycling Carbon* activity.) Interestingly more participants thought that CO_2 could be recycled prior to participating in the *Recycling Carbon* activity in 2019, compared to 2018. This could be people who participated in 2018 who then returned in 2019. It could also be due to the increase in media coverage of CCS and CCU technology from Climeworks[41] and Carbon Engineering[42] over the last year. Nevertheless, the percentage of participants who thought carbon dioxide could be recycled increased after participating in the activity to over 90% in both 2018 and 2019.
The change in national conversation was also observed in the answer to the question “Do you think individuals can make a difference to climate change?” In 2018 only 63% of respondents answered “Yes” before participating in Recycling Carbon, compared to 92% in 2019. Again this could be due to people returning in 2019 who had previously completed the activity in 2018. However, it is more probable that the rise of the global School Strikes, Extinction Rebellion actions (particularly in the UK) and general media coverage of individual actions to combat climate change have had an effect on the general public. Therefore, measuring the impact of the *Recycling Carbon* activity itself on people’s perceptions of both CCU and their personal contribution to climate change was more challenging in 2019 than 2018. A topic of future work is to develop more nuanced questions alongside a more appropriate scale with which to measure impact.

The *Recycling Carbon* activity is highly adaptable. It has been delivered at science festivals, career events, in a pub, in invited lectures and in primary and secondary school classrooms. The resources required can be easily and cheaply obtained. For our activity the cardboard boxes and packing peanuts, used to represent carbon capture, had arrived in our laboratory protecting a glassware delivery. This means that the event can be recreated by a number of educational practitioners at little cost. The activity is also easily portable which will appeal to practitioners surveying and educating the general public at various potential CCS or CCU sites around the UK and beyond. In addition, a booklet “Recycling Carbon An Illustrated Story” to support the activity has been written and produced by Dr Marco Taddei and Carla Nicola. Within two months it was downloaded 640 times and 200 hard copies were distributed over a two week period at the EUROMOF conference (Germany, November 2019) and at the 2019 Swansea Science Festival. We have also found that our use of a unit of "balloon" rather than gram or ton has been very well received by a broad demographic. The "balloon" unit was even used in a community presentation to Lancaster city council (UK) exhorting them to declare a climate emergency (30th January 2019).

Recycling Carbon continues to have an impact. Recent examples are:

- It has led to a number of invited talks at local, community events. The most high-profile was the Royal Society organised "You and the Planet: Energy" event, November 2019. Feedback from one of the community events was that "people that come into the 'not interested in climate' category have said they now understand".
- It has led to the development of a multidisciplinary scheme of work entitled *"You and CO_2"* which engages school students aged 12-15 with their carbon footprint. The scheme of work consists of three workshops, the first of which is heavily based on *Recycling Carbon.*[43]

Overall, we believe that *Recycling Carbon* is a "new education curriculum"[24] which could help integrate "public education and communication into CCS development policy"[29] as it is interesting (people engage with the activity for up to 20 minutes at a time), effective (increase in number of people agreeing that CO_2 can be recycled after participating is over 90%) and adaptable (variety of locations and audiences).

5 Conclusions

A new activity has been designed to engage the general public with the concept of carbon capture, storage and utilisation. It has been trialled at a number of events with a variety of audiences. We have found the activity to be highly adaptable as well as cost-effective and easily transportable. This makes it an easy activity to reproduce by educators or researchers in the area of public perceptions of CCS. We have also found that engagement of individuals with the *Recycling Carbon* activity increases their understanding of CCS and carbon utilisation. Furthermore it presents an opportunity to talk to individuals about their personal contribution to climate change and educate them about their carbon footprint. We hope to see this activity contributing to public perception studies ahead of the deployment of negative emissions technology in the future.

Data Availability

The raw data for used to generate figures 3, 4 and 5 has been uploaded to the Open Science Framework and can be accessed at:
https://osf.io/fzd7s/?view_only=3204efce75e24bbda72b3fc4db8a9440
An online copy of the Recycling Carbon booklet can be accessed at:
http://www.marco-taddei.com/outreach.html

CRediT Statement

MEAW, MT, RJW conceptualisation, MEAW data curation, JAR visualisation, RJW supervision, JAR, MEAW and MT wrote the original manuscript draft. All authors contributed to the review and editing of the draft.

Acknowledgements

We would like to thank all members of the Recycling Team for their commitment and contribution over the last 3 years. Team members include (in alphabetical order by surname), Shirin Alexander, Enrico Andreoli, Odin Bain, Nada Bjelobrk, Lucy Fisher, Chitrakshi Goel, Cathy Gowenlock, Louise Hamdy, Ali Hedayati, Donald Hill, Ewa Kazimierska, Saeid Khodabakhshi, Matthew McPherson, Ben Riseborough, Stephen Shearan and Dan Stewart.

JAR is part of the Reducing Industrial Carbon Emissions (RICE) research operation funded by the Welsh European Funding Office (WEFO) through the Welsh Government. Financial support was also provided to JAR by the Engineering and Physical Sciences Research Council (EPSRC) UK (EP/N009525/1).

MEAW, RJW and MT have received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 663830.

MT thanks the Engineering and Physical Sciences Research Council (EPSRC) for funding the printing of the illustrated booklet through the First Grant scheme EP/R01910X/1

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