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ORIGINAL PAPER

Electrochemistry education in the twenty-first century: the current landscape in the UK, challenges and opportunities

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Abstract

Electrochemistry education of future researchers is crucial if we are to decarbonise economies and reach targets for net zero, and this arguably begins with education in electrochemistry within undergraduate degrees. This paper reviews the teaching of electrochemistry in UK universities at the undergraduate degree level. We review where and how electrochemical concepts are introduced into chemistry, chemical engineering and materials science programmes. We provide some motivation for this review, which was stimulated by discussions from a workshop on the 'Future of Fundamental Electrochemistry Research in the UK', held in 2022. We summarise briefly how consensus on UK degree programme course content has been reached and inconsistencies that remain. Electrochemistry curriculum content from a convenience sample of UK universities, and disciplines, has been collected and is summarised, with a reflection on some trends. Finally, we present some implications for policy. A roadmap is suggested to ensure that the teaching of electrochemical fundamentals is addressed in the curriculum at an appropriate level to underpin the many technically relevant applications of electrochemistry that graduates will encounter in their further education or employment.

Keywords Education · Policy · Teaching

Introduction

Electrochemical technologies have come to the fore in the last decade or so, driven both by a maturity of those technologies, evidenced by widespread adoption, and a realisation that electrochemical technologies will play an increasingly large part if advanced economies are to attain 'net zero' goals in the near future. This vast increase in the profile of electrochemistry, and its applications, is very welcome but also brings a need to consider the place of electrochemistry in the taught curriculum, both at the high school and higher education levels. The curriculum around electrochemistry from foundational principles to greater specialism in high schools has been recently reviewed by some of the current authors [1]. The purpose of this work is to review how electrochemistry is taught in undergraduate science and engineering programmes in the UK and offer some suggestions for appropriate updates of curricula.

In 1930, E.O. Jones, from our predecessor institution the Victoria University of Manchester, presented a review of electrochemical education in the English higher education (H.E.) setting [2]. This review encompassed theoretical and applied electrochemistry in higher education institutions and technical evening courses and looked at the intended curriculum, practical components and the equipment each institution had to facilitate learning. At the time Jones was writing, electrochemistry was not generally treated as a field distinct from physical chemistry. Indeed, in 1918, it was highlighted by Rideal [3] that electrochemistry lacked status and suffered from a paucity of specialist teachers, in sharp contrast to countries with more favourable H.E. systems such as the US and Canada. Nearly 100 years later, our lives are dominated by technology that depends on advances

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made in electrochemistry. Whilst Jones could only find eight institutions teaching electrochemistry as a distinct field in England, concentrated in the industrial centres of Birmingham, Liverpool, Manchester, Sheffield and London, today, it is assumed that most universities with degree programmes in chemistry will teach electrochemistry in some form.

We also note that electrochemistry does not fit solely within the domain of the discipline of 'Chemistry', at least from a teaching perspective. Contributions to electrochemistry research continue to derive from adjacent domains of science and technology, so it follows that undergraduates in related disciplines such as chemical engineering, materials science and physics will also receive instruction in electrochemistry.

A meeting of UK electrochemistry researchers, held at Gregynog (Wales), in summer 2022, asked various questions about electrochemistry education at the H.E. level including the following:

- Is electrochemistry prominent enough in UK undergraduate courses (chemistry and the other disciplines mentioned above)?
- How much electrochemistry should be taught at UG level, given the increasing relevance of electrochemical energy storage and conversion? Are we teaching enough now?
- 'Philosophically', where is electrochemistry going? Is it not really a part of chemistry any more—given the 'pull' from applications; in the future, will it be more aligned with more applied disciplines, where the 'end use' is the focus—specifically engineering and/or materials science? [4]

Discussions at the meeting showed that there was a lack of knowledge about the content and sequencing of electrochemical education in today's UK H.E. context. Nearly 100 years on, we seek to expand on Jones' initial analysis and give something of an overview of undergraduate instruction in electrochemistry within chemistry and other relevant degree programmes across the UK. Before we do this, to give some context to the work for readers from other countries, we provide a summary of the salient points of the UK degree programmes and their modes of quality assurance.

Definition of the subject curriculum in UK universities

Undergraduate degrees in the UK are highly specialised with most students entering specific subject degrees in year 1 rather than more general courses in science and technology. The exception is some degrees in Scotland, which begin with a number of subjects and then specialise in later years of the degree. This section describes the main national mechanisms for quality assurance of degree programmes in the UK and how these relate to content and curriculum.

Subject benchmark statements

The different parts of the UK share an independent body for the oversight of standards in universities: the Quality Assurance Agency for Higher Education (QAA). The exact role of QAA as reviewer or advisor varies across the nations but the 'UK Quality Code for Higher Education' developed by QAA along with 'Subject Benchmark Statements' underpin standards and quality enhancement in all UK universities. QAA Subject Benchmark Statements define what a graduate in that subject is expected to know and understand when their studies are complete. Defined and revised by subject specialists, they provide a reference point and framework for developing learning outcomes for a degree programme, but they do not set a curriculum for a subject. Indeed, it is expected that whilst the breadth of the subject is covered during a degree, the institution has full flexibility in defining the content and organisation of their programmes. Hence, a Chemistry degree, for example, could have different characteristics depending on the research strengths and specialisation of the home department and academic staff.

A review of the Benchmark Statements for degree subjects likely to include some electrochemistry content finds them to be remarkably different in style according to discipline. The QAA Chemistry Benchmark Statement [5] is the most recently updated and describes the required knowledge and understanding of a Chemistry graduate. There is certainly no prescriptive list of topics that a Chemistry degree should cover, and one has to infer that core electrochemical content would fit somewhere under the broad requirement that 'graduates are able to explain and rationalise their understanding of classical and statistical thermodynamics, kinetics, quantum mechanics and spectroscopy and apply this to the solution of theoretical and practical problems to wider topics in chemistry'.

There is no specific Subject Benchmark Statement for Chemical Engineering, but that for Engineering [6] is even less content-specific than Chemistry, focussing instead on broad graduate attributes. The QAA Materials Science and Engineering Benchmark [7] is strikingly more descriptive in listing the expected content of a materials course. Even in the materials science's case, however, there is no specific mention of topics directly related to electrochemistry. It is expected that materials graduates will be familiar with 'functional behaviour—the control through composition and structure of electrical…properties' and 'techniques for determining electrical…properties'. Materials science is described as underpinning many commercial and industrial applications, but again, 'electrochemistry' is not mentioned explicitly, even within 'energy generation (efficient thermal, photovoltaic, nuclear, wind)' and 'electronics (from consumer products to novel smart devices)'.

Degree accreditation

Most chemistry, materials and chemical engineering degree programmes in the UK will seek accreditation from one or more Professional, Statutory and Regulatory Bodies (PSRB), specifically the Royal Society of Chemistry (RSC), Institute of Materials, Minerals and Mining (IOM3) or Institute of Chemical Engineers (IChemE). Some of these bodies accredit under licence from the UK Engineering Council. Such bodies set and maintain validated and internationally recognised standards of competence expected for graduates from accredited degree programmes, with the expectation that such graduates can perform and progress in careers within that field. As representatives from PSRBs are typically involved in developing QAA Subject Benchmark Statements, these are used extensively as the baseline and reference points for the accreditation criteria. The extent to which content and curriculum are defined within accreditation criteria varies with discipline, but in all cases, an emphasis is placed on flexibility for a university to design and deliver the programme that best suits the local needs of their students and that can evolve with the subject.

An underpinning value of the RSC accreditation process for Chemistry degrees is that curriculum content is not specified in detail [8]. Key requirements are based on the QAA Chemistry Benchmark Statements and include 'Evidence of study of the main branches of chemistry…developed at appropriate times' and 'programme outcomes should include a breadth of understanding of chemistry with the ability to solve problems at the threshold level'. Examples of problems at the threshold level are provided for guidance but with the strong caveat that they 'are in no way intended to define curriculum content'. Apart from reference to content described in the Benchmark Statement, the accreditation guidance merely requires students to 'demonstrate a systematic understanding of fundamental physicochemical principles and an ability to apply that knowledge to the solution of theoretical and practical problems', and to 'gain knowledge of a range of inorganic and organic materials and be able to realise their understanding in the synthesis and isolation of such materials and the analysis of their properties'.

The Engineering Council accreditation guidelines are a series of high-level programme learning outcomes and person attributes for graduate Engineers. However, compared to RSC guidance for chemistry, the IChemE accreditation requirements are much more detailed with respect to the chemical engineering curriculum [9]. This is despite a stated wish to avoid being prescriptive about content. Indeed, the guidance states that a significant deviation from the listed content would not prevent accreditation but a good justification would be required, and evidence provided of learning outcomes being successfully achieved. An illustrative example of one requirement for IChemE accreditation is that students must 'understand the principles of equilibrium and chemical thermodynamics, and apply them to basic phase behaviour, and to other basic systems with chemical reactions and to processes with heat and work transfer'. A comparison to the broad high-level requirements adopted by the RSC is quite striking. Nonetheless, the need to address electrochemical principles within a chemical engineering programme is not explicitly mentioned anywhere within the accreditation requirements.

Hence the accreditation requirements as written by the PSRBs do not specify when, where and how electrochemistry should be addressed within the curricula of UK H.E. programmes. Instead, the foundation of the accreditation process is the use of peer review carried out by academic and industrial professionals in these disciplines. Reviewers should have current experience of university-level education and contemporary topics in the subject area. Therefore, reviewers have working knowledge of which topics are taught within their university and to what level, as well as experience of what is taught in other departments, through previous accreditation processes or external examining (see below). A consensus therefore develops in the community about the 'expected' curriculum content and if elements are missing, this is likely to be queried during accreditation review. Of course, this consensus or 'community norm' has a historical or 'institutional memory' aspect. Reviewers would not expect too much deviation from the core content they experienced as students, although it is expected that emerging and frontier topics do gradually start to displace some less fashionable areas. Needless to say, underpinning topics such as thermodynamics never go out of fashion.

External examiners

It is clear then that UK universities have an 'unwritten' national curriculum, agreed by community consensus. This is further upheld by the sector through use of external examiners to provide scrutiny and advice on quality and standards of a programme [10]. Departments usually recruit several external examiners to provide impartial advice; these are practising academics and subject specialists from other UK universities. However, the primary role of the external examiner is to comment on assessment and student achievement, rather than programme structure or content. Often though, departments will discuss the curriculum with examiners as another means of calibrating content amongst different institutions. It is also common that if significant amendments are made to programme or module content, an external examiner is asked to scrutinise the proposed changes and give approval.

To summarise the background of the wider UK H.E. context, it should be clear that expected curriculum content is largely unwritten and derived from community and discipline-specific norms and consensus. The role of a strong subject community is therefore important in upholding the standards of education in a particular topic and ensuring it features prominently in an increasingly crowded curriculum.

Survey of electrochemical content of UK degree programmes

Two approaches were used to obtain information on the electrochemical content of UK chemistry, chemical engineering and materials science degrees. The first route involved study of websites regarding degree programme content. The disadvantage of this approach is that many institutions give little detail on course content on publically accessible sites (as opposed to internal 'Intranet' pages). We also sought information through personal contacts, based primarily on the 40 or so delegates at the Gregynog UK workshop on electrochemistry held in 2022. The disadvantage of this approach is only a sub-set of departments where electrochemistry is taught was represented, i.e. institutions with active researchers in the electrochemical field were present at the workshop. Further efforts were made to obtain information from a wider range of institutions through the personal contacts of the authors, although again, this still limits responses to a sub-set (albeit a larger one) of UK institutions where electrochemistry is taught.

Classroom ('lecture') content of UK chemistry degree programmes

There are currently around 64 universities offering chemistry-based degrees in the UK. We were able to obtain responses from 14 departments. Although the percentage of the total is quite small, the responses cover a reasonable spread in terms of geography and course entrance requirements.

At this stage, it is useful to define what might be classed as 'electrochemistry' in a typical university chemistry curriculum. However, as this definition was not provided to survey respondents, the information they provided was their interpretation. In his 1930 paper, Jones suggested that typically, students would have attended lectures dealing with the fundamental topics listed in Fig. 1, although these would likely be distributed throughout the physical chemistry content, rather than a within a course dedicated to electrochemistry.

Dorrance suggested that the subject matter in electrochemistry courses should be left to the discretion of the teacher; however, [11] in the intervening years, a consensus on core electrochemistry topics has been established, often based on inclusion in common widely used textbooks, such as Atkins' Physical Chemistry [12]. Figure 1 shows the electrochemistry topics included in the 11th edition of

Fundamental electrochemistry topics in university curriculum, Jones (1930)

Principles of Electrolysis:
Faraday's laws; electrolytic dissolution; Arrhenius and Debye-Hückel theories; conductivity; ion mobility; endosmosis; cataphoresis; aqueous and non-aqueous electrolytes.

Electromotive force:
Energy Relations; external and maximum work; affinity; decomposition voltage; reversible and irreversible processes; electrode potentials; oxidation-reduction; concentration cells.

Electrode Reactions:
Anodic solution; cathodic deposition; polarisation and depolarisation; overpotential; passivity and corrosion.

Fundamental electrochemistry topics in Atkins Physical Chemistry, 11th Edition.

Simple Mixtures
Activity; activities of ions; mean activity coefficients; Debye-Hückel limiting law and extensions.

Chemical Equilibrium:
Electrochemical cells; half reactions and electrodes; varieties of cells and notation; cell potential; Nernst equation; thermodynamic functions; electrode potential; standard potential; electrochemical series.

Molecules in Motion:
Motion in liquids; viscosity; conductivity; ion mobilities; diffusion.

Reaction Dynamics:
Homogeneous electron transfer; tunnelling; Marcus theory; diffusion-controlled reactions; processes at solid electrodes; double layer; Butler-Volmer and Tafel equations; voltammetry; electrolysis and working cells.

Fig. 1 Comparison of fundamental electrochemistry topics expected to be taught at UK universities in 1930 [2] with electrochemistry content in a contemporary and commonly used university-level physical chemistry textbook [12]

Atkins (2018) and the chapter headings under which they are found. Although some terminology has changed, a comparison shows that much of the core content around electrolyte properties and cell thermodynamics remains the same. The topics that Jones lists under ‘electrode reactions’ have a different emphasis and focus within a chemistry degree now (but still feature in a Materials Science degree, see below); however, the underpinning kinetic theory remains the same. The development and ubiquity of dynamic electrochemical methods mean that voltammetry now features in undergraduate textbooks, along with microscopic kinetic theories for electron transfer, such as those developed by Marcus and others from the 1950s onwards.

A survey of responses from chemistry departments showed a reasonable commonality between the ‘basic’ level of taught electrochemistry, which is typically introduced in years 1–2 of UK chemistry degrees (with one example of introduction in year 3). The electrochemistry content was part of a compulsory core module in all the universities surveyed, apart from one, where electrochemistry was not taught at all. In all cases, the thermodynamic basis of the subject is taught early on, with topics covered including electrode and cell potentials and the Nernst equation. Subjects including ion mobility, solution non-ideality and Debye-Hückel theory were covered by a large number of institutions, but not all. In terms of the ‘fit’ of electrochemistry into the wider chemistry curriculum, in 44% of the departments surveyed, the area was taught as part of a physical chemistry module. The second most common appearance of electrochemistry content was as part of a general ‘core chemistry’ course.

In only 19% of cases did departments offer a stand-alone electrochemistry module; these are more likely to feature as advanced (years 3 or 4) modules. The most popular topics for ‘advanced’ courses, covering dynamic’ (as opposed to equilibrium) electrochemistry were voltammetry and double-layer structure. There was less uniformity with respect to the sequencing of these courses within the 4 year ‘undergraduate masters’ UK programme, with courses including these topics being offered in years 2, 3 and 4, depending on the institution.

A limitation of our data and its interpretation is that categorisation of what course content is ‘electrochemistry’ is open to interpretation. Nearly 100 years ago, Jones noted that in most UK universities, electrochemistry was covered across the physical chemistry curriculum rather than curated into a dedicated course. It appears that not much has changed in this regard as illustrated by this quote from an academic participant in this work.

“we teach very little electrochemistry and it is really not very joined up, in the future I am going to be taking on the 2nd year electrochemistry so hopefully more joined up thinking to follow”…

The fragmentation of the subject is perhaps inevitable given that it spans thermodynamics, kinetics, solution properties and interfaces; hence, students are introduced to different facets of the subject at multiple stages. This is likely exacerbated by the common practice of using the contents and structuring of textbooks (like Atkins’ physical chemistry) as the basis for setting a curriculum. As seen in Fig. 1, this leads to properties of solutions and electrolytes being distributed over three separate chapters: Simple Mixtures (Chapter 5); Molecules in Motion (Chapter 16) and Reaction Dynamics (Chapter 18). Often, therefore, properties of electrolytes are addressed as an extreme case of a non-ideal solution and as an extension (or afterthought) to a course on thermodynamics of mixing. Likewise, electrochemical cells and electrode potentials are introduced as a ‘special case’ to be considered at the end of the Chemical Equilibrium chapter. This seems somewhat backwards and undermining given the ubiquity of electrochemical technology but demonstrates how easily electrochemical content can get lost in a crowded curriculum. A confounding factor is that electrochemical content is often taught by a non-subject specialist, meaning that relationships between the various topics are even more difficult to link (see further discussion of Subject-Specialist Teaching below).

Classroom (‘lecture’) content of UK degree programmes of other subjects including an electrochemical component

There are 33 UK chemical engineering departments, and information on course content (either directly or via personal contact) was obtained on 20 of them. Thermodynamics is a core component of first year chemical engineering courses, but (from the limited information obtained so far) it is not clear how many courses introduce explicit electrochemical aspects of this field. A few chemical engineering departments, with research active staff in the electrochemical area, offer final year modules based on applications of electrochemistry, normally in the context of energy storage.

Materials science is a much smaller discipline in the UK, with only 10 universities running undergraduate degrees in this subject. Detailed information was obtained from 5 of these departments. Thermodynamics is, again, a core part of the initial years of Materials programmes. The electrochemical context is explicitly introduced to Materials degrees because the subject of corrosion is normally covered in some depth. Applications of electrochemistry in the context of electrodeposition or metal extraction are frequently taught to Materials undergraduates who, in some cases depending on the research interest of staff, also receive advance modules on energy storage/conversion. The overall conclusion is that of the three disciplines considered here, UK Materials

Science undergraduates probably receive the most exposure to electrochemical topics.

Finally, it is worth mentioning that some physics and other (non-chemical) engineering programmes also offer advanced courses, usually as options, to undergraduate students. In the former case, the electrochemical material normally appears in the context of a surface science module. Energy conversion is the usual context in the case of engineering degrees. The appearance of such modules again relates to the research interests of specific members of academic staff and, as such, is a 'minority sport', so it is not meaningful to draw wider conclusions about the teaching of electrochemistry in physics or general engineering programmes—other than saying that there is certainly scope for an increase in electrochemical modules.

Practical work

"Nothing can take the place of the laboratory in the study of any branch of physical science, and this is particularly true of the study of electrochemistry."[13]

Nearly 100 years ago in a special issue of the Journal of Chemical Education focused on education in electrochemistry, Kahlenburg was emphatic in highlighting the role of laboratory work in chemistry, generally and electrochemistry, more specifically. Practical laboratory training is a core aspect of degrees in chemistry and the other disciplines discussed in this paper. Practical work motivates and stimulates students' interests towards mastery of concepts [14] so the inclusion of practical electrochemistry within a course should be helpful in engaging students in their overall learning in electrochemistry. Furthermore, if students are to progress to research degrees and employment in the electrochemistry sector, exposure to practical aspects of electrochemistry in their undergraduate degree is essential.

There are a number of literature accounts of practical electrochemistry activities designed for undergraduates in the early years of degree programmes. These include innovative experiments for the undergraduate laboratory [15, 16] and for distance learning as necessitated by the COVID19 pandemic but which may retain utility in blended learning programmes in the longer term [17, 18]. Experiments have also been reported for outreach purposes. Goeltz showed that high school students just prior to leaving school were well able to implement a cyclic voltammetry experiment designed for an undergraduate audience [19].

Practical electrochemistry is a required element of completing the practical endorsement for the A-level qualification in England that is commonly used for entry to degree courses in chemistry and other STEM subjects. Indeed, it is commonly seen in curricula designed for 16–18 year olds around the world [1]. At a basic level, most students will have carried out a simple experiment to measure the voltage of the classic Daniell cell as shown in Fig. 2.

There is a mixed picture of practical work across chemistry departments in the UK. Eleven chemistry departments confirmed that their undergraduate students experienced practical work in their degree with one indicating they have recently purchased equipment and are looking to include teaching laboratory activities in electrochemistry in the near future. However, this question was not clearly answered in the email responses so we are not able to build a complete picture of this. Three universities confirmed that there was no practical work in their degree. These include universities, which are very well-regarded within the sector, including Manchester, where many of the authors of this paper carry out their study and research.

Table 1 summarises the range of electrochemistry practical work carried out in teaching laboratories amongst the institutions who reported specific electrochemistry experiments in the undergraduate laboratory programmes. From this, we can see that cyclic voltammetry is the most common experiment. This was often seen as a standalone practical, and as the only electrochemistry practical activity encountered in some courses. Despite this, there is a wide range of electrochemistry focused practical work taking place in HEIs around the UK and this should provide stimulus for other HEIs to consider its inclusion.

Many of the replies mentioned laboratory experiments suitable for supporting learning in electrochemistry but did not indicate that these definitely took place in their degree courses. For example the Daniell 'gravity' cell, redox potentials from potentiometric titrations, cobalt redox chemistry and electrochemical synthesis of metal–organic frameworks were mentioned by one academic as relevant to their chemistry and chemical engineering course but there was no indication these formed part of the course. There seems to be an appetite for more practical electrochemistry within degree programmes, for example, this academic highlights that 'electrochemistry benefits from practical experience.

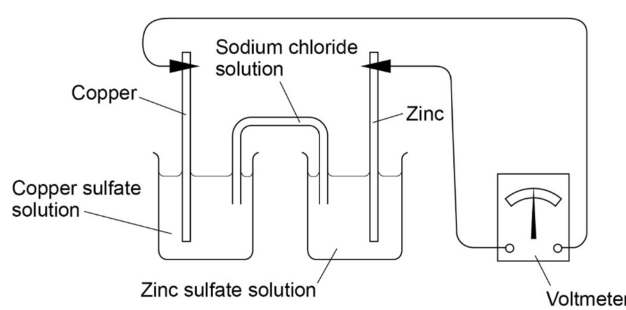

Fig. 2 An illustration of a practical set up for the measurement of the EMF of an electrochemical cell from the AQA examination board [20]

Table 1 A summary of the practical electrochemistry carried out in the universities which reported its inclusion in the undergraduate laboratory

HEI	Year of degree	Practical
Liverpool	3	• Quantitative analysis of vitamin C using cyclic voltammetry • Differential pulse voltammetry
Oxford [21]	1	• Changing oxidation states using electrolysis making persulphate and get v3+ from VO2+ • Metal complexes—electrochemical synthesis of acac complexes • Electrochemical determination of thermodynamic properties—Harned cell
Durham	1	• Nernst equation practically focused on building cells and taking measurements
Keele	2 3	• Lab work closely aligned to taught theory, four experiments associated with 'electrolytes and solution chemistry (McGarvey, 2020) • Electroanalysis
Bath	Not reported	• Voltammetry
Nottingham	2	• Determination of cell potentials as function of temperature
Lancaster	1 2 3	• Simple two electrode cell, entropy study • Cerimetry and voltammetry of ferricyanide to determine diffusion coefficient • Non enzymatic glucose sensor
Newcastle	3	• Use CV to estimate electrode potentials
MMU		• Recently purchased 6 potentiostats for the development of new experiments for 1st and 2nd year teaching labs
Southampton	2 and 3	• Practicals that involve voltammetry
UCL	3	• Core lab on cyclic voltammetry. Covers CV of Fe complexes in aqueous and organic solvents, link CV to ET kinetics, use of peak currents to determine diffusion coefficients as a function of viscosity, followed by student-designed open-ended investigation using CV
UEA	3	• Protein film voltammetry (biochemistry advanced lab)

Especially now with fuel cells and battery technology surging there is a chance to introduce more practical aspects'.

Another academic highlighted that students particularly enjoyed the electrochemistry investigation within their laboratory programme although it did carry a heavy burden in assessment. Project work in electrochemistry for final year students was mentioned by a number of academics, and there is considerable innovation seen in the scope of projects offered with many aligning to research strands within the departments. This is encouraging; however, recruitment of students to these projects may be challenging if students have had little practical electrochemistry training in their undergraduate lab programme.

Subject-specialist teaching in electrochemistry

As this report emerged from a workshop for electrochemistry researchers, the information submitted from universities is likely biased towards departments that offer more electrochemistry taught content, compared to departments where there is no resident electrochemistry specialist. However, we did receive responses from universities that were not represented at the Gregynog workshop and where research activity in electrochemistry was low or non-existent. Overall, we found that about 60% of the electrochemistry curriculum content was delivered by an electrochemistry specialist (researcher) with the rest being taught by a physical chemist with research interests in other aspects of physical chemistry. This percentage is somewhat skewed though, as it includes the stand-alone 'advanced' electrochemistry modules offered at a small number of institutions that were delivered solely by electrochemists. Hence, we estimate that core (year 1–3) electrochemistry content could be taught by an electrochemist less than half the time.

> 'In honesty, I picked [the electrochemistry teaching] up because we don't really have an electrochemistry specialist and no-one really wanted to teach it. It has had many, many different lecturers over the years.'

So, is it a problem if electrochemistry is taught by a non-specialist? Not necessarily, if the lecturer feels confident in the material and is supported by sufficient resources. As discussed above, the fundamentals of electrochemistry are typically fully integrated into 'core' physical chemistry in many curricula and any physical chemist should be able to teach the basics at the year 1–3 undergraduate level. However, problems that seem unique to electrochemistry teaching are (1) the fragmentation of electrochemistry-related material in the curriculum and in textbooks (see Fig. 1 and related discussion), (2) a traditional over-emphasis on notation (cell diagrams etc.) with no context, and (3) underpinning concepts such as electrode potential are difficult for even practising electrochemists to explain and are not often described in an accessible way in general textbooks. These issues can be overcome, but it is expecting a lot of the non-specialist to forge links between diverse areas of the curriculum to understand how to relate text-book electrochemistry notation to contemporary research and to explore more accessible ways of presenting electrode potential. It is not surprising that in many departments, the electrochemistry content is unpopular to teach and kept to the bare minimum.

Is electrochemistry covered more comprehensively in departments with active electrochemistry researchers? In general it seems so, but all universities act under constraints of competing demands for space in the curriculum. For example, it was noted above that Manchester Department of Chemistry has no electrochemistry practical work at present, despite having the in-house expertise to deliver this. Likewise, although UCL Chemistry covers many aspects of electrochemistry within taught and practical modules, electrolyte solutions (ion activity, conductivity etc.) are not covered at all in the undergraduate curriculum due to lack of space rather than interest or expertise. In some cases, the constraint is placement of electrochemistry in less-traditional parts of the course:

> 'I was told when I first started my course….not to make it "too physical" as it had to fit into the inorganic part of the course.'

Departments with a very strong research profile in electrochemistry typically might embed electrochemistry content across all years of the undergraduate programme and provide a core or optional module in advanced electrochemistry in year 4 (typically electrochemist-led). Such departments are also able to offer meaningful undergraduate and masters research projects in electrochemistry and, hence, are invested in ensuring the undergraduate curriculum provides training for this pipeline of students, continuing on to PhD. In contrast, in departments where electrochemistry does not feature strongly in undergraduate teaching, students may enter research groups with little prior knowledge:

> 'Graduate students coming to electrochemistry labs come with zero electrochemical knowledge'

An open question is whether this inconsistency in quantity of electrochemistry content in the UK undergraduate curriculum is harmful at a national level, especially for training a workforce ready to address a zero-carbon future. It may be that a minimum baseline of content for all students is sufficient (assuming that is what we have now) and that we should instead focus on enhancing training at the postgraduate level and beyond, as suggested by a respondent:

> '[Postgraduate] and professional level electro chemistry is just as important and deserves more emphasis.'

Limitations of the work

In this paper, we have attempted to build a picture of the current landscape of teaching and learning in undergraduate electrochemistry across the UK. The replies we received represent a convenience sample of UK chemistry and other STEM departments and is not intended to be comprehensive, it would likely be impossible to sample this information in a more systematic way. In itself, this highlights the difficulty HEIs have in cooperating around matters of curriculum. Despite this, we believe the work provides breadth and depth enough to stimulate a twenty-first century debate about the future of electrochemistry education in the twenty-first century.

Suggested roadmap for future curriculum development

We note that a recent US National Academy of Sciences workshop, held to consider 'Advances, Challenges and Long-term Opportunities in Electrochemistry', has repeatedly highlighted the need for better education in electrochemistry [22]. Specific comments reported about education in the US H.E. context were that 'electrochemistry is often an afterthought in some courses and then never taught again', and, 'participants echoed the concern about the lack of rigorous teaching of electrochemistry', a claim backed up by Kempler [23]. Deficiencies in electrochemical training in the US have been cited as a factor hampering the 'pipeline' of research [24]. The findings reported here indicate that such statements also apply to UK degree programmes, and we suspect that they could also be valid—at least to some extent—for degree programmes in many advanced economies.

At this point, we should return to the original questions posed at the Gregynog workshop and provide some tentative responses, bearing in mind the limitations in our data as discussed above:

> Is electrochemistry prominent enough in UK undergraduate (chemistry) courses?

It depends. Electrochemistry features prominently in chemistry departments with significant electrochemistry research effort, often embedded within the physical chemistry curriculum and is then further emphasised through stand-alone advanced courses. In the majority of universities, electrochemistry is featured to some extent in the physical chemistry course but the cohesion and context of the presented material varies widely. Commonly cited constraints are space in and organisation of the curriculum and lack of subject-level expertise.

> How much electrochemistry should be taught at UG level, given the increasing relevance of electrochemical energy storage and conversion? Are we teaching enough now?

These questions require further discussion in the community, bearing in mind the constraints previously mentioned, and we invite the readers of this special issue to reflect on this. The most achievable model for UK chemistry programmes is that a baseline of agreed electrochemistry content is covered at all universities. This need not be in a stand-alone module but can be threaded through the core curriculum. Ideally, better connections should be made between diverse areas of electrochemistry and the fundamental concepts presented in an accessible and contextual manner so that students can see the relevance to emerging technologies. Some departments will continue to offer more than this and would perhaps be seen as specialist centres that are more likely to train students who would advance to further study, work or research in electrochemical fields.

> 'Philosophically', where is electrochemistry going? Is it not really a part of chemistry any more—given the 'pull' from applications; in the future, will it be more aligned with more applied disciplines, where the 'end use' is the focus—specifically engineering and/or materials science?

As discussed above, electrochemistry features much more prominently in Materials science programmes than it does in chemistry programmes, but this seems to reflect its role in explaining and characterising material properties (e.g. corrosion, passivation) rather than a major realignment towards 'end use'. In contrast, electrochemistry fundamentals are not covered significantly in chemical engineering degrees until more advanced stages of the programme, so it has not necessarily found a new natural home in the applied disciplines. Indeed, from an education perspective, electrochemistry does not seem to have moved from its original position within physical chemistry, as defined by Jones (Fig. 1). Given this, it would seem that the responsibility lies with chemists to both consolidate its current importance as a key component of an undergraduate education and to provide a refreshed outlook, aligning fundamental concepts with future applications but without losing rigour.

Based on this, we provide the following roadmap and suggestions for future curriculum development in electrochemistry. We suggest that in the UK context, large investments in battery research programmes, such as the Faraday Institution [25], should be 'leveraged' by encouraging an increase in prominence of electrochemistry in the curricula of chemistry, materials science and chemical engineering programmes. This could be encouraged by the following actions:

- The UK electrochemistry community could develop a non-prescriptive, suggested 'baseline' content curriculum for electrochemistry in the undergraduate chemistry programme, along with open-access education resources to support lecturers in developing and delivering content. Given that university curricula are developed by consensus, rather than direction, such a move would need to be community-led, voluntary and consensual. Professional body (RSC) buy-in in terms of support would be important, but they would not act as enforcers. We do, however, acknowledge the difficulties that exist in collaborations across the teaching community [26].
- The chemical engineering electrochemistry community could lobby IChemE for coverage of fundamental thermodynamic aspects of electrochemistry within the curriculum in all programmes. Afterall, Chemical Engineers will be required to 'scale up' the machinery of the energy transition, but our findings suggest that coverage of electrochemistry in their degree programmes is very low, compared to Chemists and Materials Scientists.
- The electrochemistry community could suggest and adopt some radical approaches to teaching the subject. For example, given the ubiquity of thermodynamics in the first year of chemistry, chemical engineering and materials courses, the subject could be introduced from the standpoint of electrochemical cells, rather than the traditional thermochemical context used almost universally at present.
- A pooled set of open-access electrochemistry education resources could be developed, including lecture notes, videos, example problems, lab manuals for practicals. This would enable exchange of best practice and support new or non-expert lecturers.
- Inclusion of least one relevant laboratory electrochemical experiment within all UK H.E. programmes in the three disciplines discussed above should be encouraged. The incomplete coverage of meaningful and interesting practical exercises in electrochemistry is probably related to the relative expense of electrochemical instrumentation. However, low-cost apparatus (e.g. mini-potentiostats with low output currents) is available nowadays, so departments could be strongly encouraged to update their laboratory provision in this respect.
- National electrochemistry conferences such Electrochem could hold sessions/symposia dedicated to 'Electrochemistry Education' with invited speakers and opportunities for networking, exchange of best practice and discussion of the issues raised in this paper.
- Subject Interest Groups, such as the RSC Electrochemistry group, SCI Electrochemical Technology group and others could include promotion of electrochemical education and training in their agendas.
- We should discuss as a community a strategy for increasing coverage of advanced courses in electrochemistry, including undergraduate, postgraduate and professional training.

It may be that a baseline of fundamental electrochemical knowledge is sufficient for most students, with those in departments with a strong electrochemistry research presence receiving a more comprehensive education and being more likely to progress into further study or research in the discipline. However, students do not generally choose a university based on the amount of electrochemistry in the programme, so we need to ensure that access to electrochemistry education is accessible to all and evenly distributed nationally.

Conclusions

The work presented is envisaged as an update on that of Jones' survey of electrochemical teaching within English H.E. almost a century ago [2]. Jones' work was motivated by concerns that electrochemistry had not been given the prominence it deserved in the curriculum of the time. 'What goes around comes around', and we have seen that similar concerns have been expressed recently by academics in the US, for example. For Jones, the need for better education in electrochemistry was motivated by the use of electrochemical technology in the metal plating/recovery fields. Today, the motivation for a stronger emphasis on electrochemistry in the curriculum stems from the transition to electrochemically-based energy conversion and storage.

In the UK, Materials science undergraduates are currently those with the most exposure to electrochemistry. Chemists meet the core, thermodynamic aspects of the subject, but advanced courses on dynamic electrochemistry and its applications are very much a function of the research interests of the department's academic staff. The coverage within chemical engineering degrees appears to be even more haphazard, and we would suggest dialogue with the professional body in that area to make understanding of electrochemical principles a core requirement. We suggest that a stimulating undergraduate experiment related to electrochemistry, but tailored to the specific discipline, should be included in all chemistry, chemical engineering and materials science courses. A radical suggestion is to teach thermodynamics, in all of these courses, from the context of electrochemical cells (with thermochemistry as an 'add-on'), rather than the converse approach which has been followed hitherto.

In our analysis, we have presented a picture of electrochemistry in UK higher education; however, we would consider the issues highlighted to have impact beyond our education system. Undergraduate degrees in the UK are for the most part highly specialised and so present a unique opportunity to look at the development of knowledge and understanding of a topic area from that of a relative novice to the level of depth that could support admission to a research programme. In other education systems, the findings may be relevant to postgraduate or even professional education in electrochemistry, and it is clear that there are similar issues to those we have discovered highlighted by authors in the USA.

The replies we received in approaching this project have shown that the electrochemistry community of practice is highly reflective about the current teaching landscape and its future direction. The comments received were drawn from academics whose work is primarily research-focused as well as colleagues who are teaching-focused practitioners. This gives call for optimism that the barriers to collaborative work can be overcome, and a more coherent programme of electrochemistry education can be developed from this community of practice.

We have presented some suggestions for a possible roadmap to improvement. These include some activities which have a relatively low barrier to implementation such as the inclusion of education focused sessions within electrochemistry subject focused conferences. Other more challenging suggestions are also made including the development of a national baseline curriculum in electrochemistry and the establishment of national centres of expertise. Whilst these may be considered extremely ambitious, they are presented here as a stimulus to greater discussion within the electrochemistry community, and we invite readers of this work to continue the debate in their own nations and communities of practice.

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References

1. Turner KL et al (2023) Around the world in electrochemistry: a review of the electrochemistry curriculum in high schools. J Solid State Electrochem. https://doi.org/10.1007/s10008-023-05548-0
2. Jones EO (1930) Electrochemistry education in England. J Chem Educ. https://doi.org/10.1021/ed007p48
3. Rideal EK (1918) Industrial Electrometallurgy: including electrolytic and electrothermal processes. Baillière, Tindall and Cox, London

4. Gregynog (2022) https://www.chem.gla.ac.uk/staff/msymes/Electrochemworkshop2022/Programme.html. Accessed Sept 2023
5. The Quality Assurance Agency for Higher Education (2022) https://www.qaa.ac.uk/the-quality-code/subject-benchmark-statements/chemistry#. Accessed Sept 2023
6. The Quality Assurance Agency for Higher Education (2019a) https://www.qaa.ac.uk/the-quality-code/subject-benchmark-statements/subject-benchmark-statement-engineering. Accessed Sept 2023
7. The Quality Assurance Agency for Higher Education (2019b) https://www.qaa.ac.uk/docs/qaa/subject-benchmark-statements/sbs-materials-17.pdf?sfvrsn=8499f781_14. Accessed Sept 2023
8. Royal Society of Chemistry (2022) Degree Accreditation. https://www.rsc.org/globalassets/03-membership-community/degree-accreditation/accreditation-of-degree-programmes-2022.pdf. Accessed Sept 2023
9. IChemE Accreditation Degree Programmes (2021). https://www.icheme.org/media/19722/university-accreditation-guide.pdf. Accessed Sept 2023
10. External Examining in the Chemical Sciences A Good Practice Guide (2019) R Soc Chem https://www.rsc.org/images/External-Examining-Good-Practice-Guide_tcm18-251331.pdf. Accessed Sept 2023
11. Dorrance RL (1929) Modern methods of teaching electrochemistry. J Chem Educ. https://doi.org/10.1021/ed007p25
12. Atkins P, de Paula J, Keeler J (2018) Atkins' Physical Chemistry, 11th Edition. Oxford University Press, Oxford, UK
13. Kahlenburg L (1930) On the teaching of electrochemistry. J Chem Educ. https://doi.org/10.1021/ed007p28
14. Johnstone AH (1997) Chemistry teaching — science or alchemy ? 1996 Brasted Lecture. J Chem Educ. https://doi.org/10.1021/ed074p262
15. Holder GN (1999) Teaching students to use electrochemistry as a probe of molecular behavior. J Chem Educ. https://doi.org/10.1021/ed076p1478
16. Fruehwald HM, Zenkina OV, Bradley Easton E (2022) A new spin on electrochemistry in the undergraduate lab. Chem Teach Int. https://doi.org/10.1515/cti-2021-0013
17. Ibanez JG, Aguilar-Charfen JL, Castro-Sayago I, Turnbull-Agraz J (2021) Homemade bismuth plating by galvanic displacement from bismuth subsalicylate tablets: a chemistry experiment for distance learning. Chem Teach Int. https://doi.org/10.1515/cti-2021-0002
18. Ibanez JG, Herrera-Loya MR, Cervantes-Herrera LM, Gutierrez-Vallejo S (2022) Leaded or unleaded? Homemade microscale tin electroplating. Chem Teach Int. https://doi.org/10.1515/cti-2021-0024
19. Goeltz JC, Kandahari E, Smith EJ (2021) Beyond the textbook: introducing undergraduates to practical electrochemistry. J Chem Educ. https://doi.org/10.1021/acs.jchemed.1c00155
20. AQA GCE A-level chemistry specification (2015) https://filestore.aqa.org.uk/resources/chemistry/specifications/AQA-7404-7405-SP-2015.pdf. 126. Accessed Sept 2023
21. Stewart MI et al (2022) Developing a skills-based practical chemistry programme: an integrated, spiral curriculum approach. Chem Teach Int. https://doi.org/10.1515/cti-2022-0003
22. National Academies of Sciences, Engineering, and Medicine (2020) Advances, challenges, and long-term opportunities in electrochemistry: addressing societal needs: proceedings of a workshop in brief. Washington, DC: Natl Acad Press.https://doi.org/10.17226/25760
23. Kempler PA, Boettcher SW, Ardo S (2021) Reinvigorating electrochemistry education iScience. https://doi.org/10.1016/j.isci.2021.102481
24. Cabana J et al (2022) NGenE 2021: electrochemistry is everywhere, ACS Ener Lett. https://doi.org/10.1021/acsenergylett.1c02608
25. The Faraday Institution (2023). www.faraday.ac.uk Accessed Sept 2023
26. Stewart MI (2020) #DryLabs20: a new global collaborative network to consider and address the challenges of laboratory teaching with the challenges of COVID-19. J Chem Educ. https://doi.org/10.1021/acs.jchemed.0c00884

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