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ORIGINAL PAPER

Around the world in electrochemistry: a review of the electrochemistry curriculum in high schools

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Abstract

Electrochemistry education of future researchers and citizens is crucial if we are to decarbonise economies and reach targets for net zero. In this paper, we take an overview of electrochemistry within school education. We used curriculum documents obtained from national and state education department websites and from local teachers, examples of assessments and insights from the chemistry education literature to evaluate the extent of electrochemistry education around the world. We found that there is a great deal of electrochemistry included in the intended curriculum for high schools although there is variability depending on how early students are able to specialise in a smaller number of subjects. A range of contexts are used to illustrate the key ideas including galvanic and electrolytic cells, electrolysis and analysis. There is generally constructive alignment between assessment items and the intended curriculum although in some cases assessment was more simplistic than the intended curriculum would suggest. The effectiveness of the taught curriculum is undermined by low teacher confidence in teaching electrochemistry especially more advanced concepts. Additionally, there are a number of misconceptions generated when students learn electrochemistry with some of these potentially arising from published resources such as textbooks.

Keywords Electrochemistry · Education · Teaching · Scholarship · Assessment

Introduction

Electrochemistry plays an important role in our everyday lives. This is perhaps especially true of our students who have grown up in a world of relatively low-cost, portable technologies facilitated by small, lightweight rechargeable batteries. Electrochemistry has a rich and significant history being key to the discovery of a number of elements, and it continues to drive innovation in many areas including analysis, corrosion prevention, neuroscience and energy [1]. Progress in electrochemistry research is key to widespread decarbonisation of the world economy needed to mitigate climate change [2].

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Education is key to tackling climate change, both in reducing carbon emissions in the present and in inspiring and nurturing the researchers needed to innovate in the future. However, electrochemistry education is somewhat neglected in the chemistry education literature. What literature there is tends to concentrate on the areas covered by undergraduate degree programmes, especially in the USA. Kempler and Boecher report that despite there being a growing number of opportunities in the area, rigorous training of electrochemists is generally lacking at academic institutions in the United States and suggest electrochemistry education is in need of reinvigoration [3].

The transition between high school and undergraduate education is challenging. The chemistry curriculum for the high school systems of many countries is published online, and there are thousands of dedicated resources published each year. Despite this there is a lack of awareness about the concepts studied prior to beginning degree programmes [4]. This is true for all disciplines and topics within individual subjects.

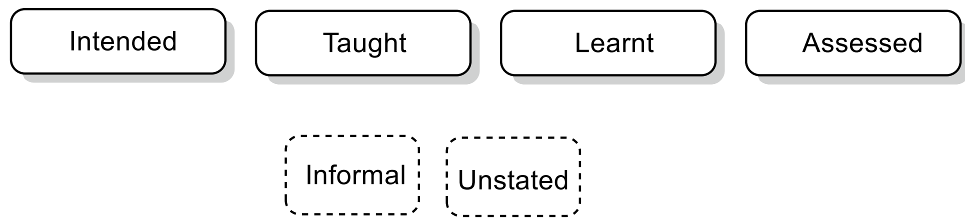


Fig. 1 The different aspects which make up a curriculum as defined by Cambridge assessment

The role of early science education

Electrochemistry education for younger students

Whilst there is no formal teaching of electrochemistry before transfer to high school, students may experience electrochemistry without this being highlighted to them. The lemon battery is a common experiment carried out in the study of electricity in upper primary school [5] and in science outreach activities involving primary-aged audiences [6]. This simple and memorable experiment uses 2 different metals and an electrolyte made up of the lemon. This has been used to spectacular effect; in October 2021, Prof. Saiful Islam and a team from the Royal Society of Chemistry smashed the previous record for the largest voltage produced from a lemon battery [7]. Their measurement of 2307.8 V achieved from 2923 lemons broke the previous record by 1521 V.

As primary school teachers are most commonly generalists teaching many subjects in a school day, their science background may be limited to their own high school education. Many primary teachers report a lack of confidence in teaching science [8] so they may lack confidence in explaining the science in the lemon battery to their students even when they choose to include it in their teaching.

As students move into high school, learning moves beyond observations of simple experiments becomes more theoretical and abstract. Students may study science as one subject or as individual sciences. This manuscript looks at electrochemistry in the high school curriculum.

Understanding the intended curriculum in different countries

Methodology

This research aims to gain an overview of electrochemistry in high schools around the world through a review of the curriculum. This is achieved through examination of curriculum documents accessed through online sources and educators across the world, past examination papers where available and a literature review.

When we use the word curriculum, we often think of the curriculum documents with lists of learning objectives, predicted outcomes and associated skills, essentially reducing curriculum simply to subject content [9]. However, this represents a limited view of curriculum; a broader view of curriculum is shown in Fig. 1.

This structure is used in our research to guide our analysis. Illustration of each of these curriculum levels and the evidence we have used to inform our conclusions is shown in Table 1.

In examining the intended curriculum, we identified a number of concepts which may be considered to be part student's learning journey in electrochemistry. Some of these concepts are very obviously electrochemistry, for example, calculating E^0cell values, but other concepts may be considered foundational to later study in electrochemistry. This list was developed from the professional expertise of the corresponding author and expanded using the curriculum documents accessed in this manuscript. The concepts evaluated are outlined in Table 2.

Table 1 Levels of curriculum used in our analysis including the sources of evidence

Curriculum level	Description	Evidence
Intended	The formal statement of curriculum at school or national level	Curriculum documents
Taught	What a teacher actually delivers in the classroom	Literature review Insights from teacher communications
Learnt	What a student derives from the learning experience, learning outcomes	Literature review
Assessed	How the curriculum is assessed including constructive alignment with the intended curriculum	Published examination papers
Informal	Contributions made by areas of school life outside classroom teaching, e.g. science clubs and enrichment activities	Literature review Web search
Unstated/hidden	Elements of school culture and ethos	n/a

Table 2 Concepts related to electrochemistry which may form part of the 11–18 curriculum in high schools worldwide

Concept	Illustration
Reactivity series	Simple list of the relative reactivity of metals (perhaps including carbon and hydrogen)
Metal displacement reactions	Use of a simple reactivity series of metals to predict displacement reactions, e.g. metal + metal salt
Redox in terms of electrons	OIL RIG definition
Half equations	Construction of simple half equations requiring balancing of atoms and electrons (not inclusion of H^+/OH^-/H_2O)
Electrolysis of molten salts	Electrolysis of molten salts
Electrolysis of solutions	Electrolysis of soluble salts, e.g. sodium chloride
Faraday calculations	$F = Le$, where F is the Faraday constant, L is the Avogadro constant, and e is the charge on an electron (in terms of the number of coulombs it carries)
2 different metals + electrolyte = voltage	Simple electrochemical cell set up with 2 different metals in an electrolyte producing a voltage
Fuel cells	A fuel cell as a device that generates electricity by a chemical reaction. Equations, advantages and disadvantages
Electrochemical series	Electrochemical series as a list of reduction equations together with their reduction potentials
Standard hydrogen electrode	The use of the Standard Hydrogen Electrode (S.H.E.) as a standard ($E^0 = 0.00$ V), set up and conditions
Ecell calculations	E^0cell = E^0red − E^0oxid and related variations
Nernst eqn	Relating the effective concentrations of the components of a cell reaction to the standard cell potential. Either in the general form for all temperatures or shortened form at 298 K
Context: extraction of metals	Extraction of metals relying on the relative reactivity of elements (e.g. reduction using carbon). Electrolysis of metals with higher reactivities
Context: electroplating	Use of electrolysis to electroplate materials, e.g. for decoration or for desirable properties
Context: pH probe	Understanding that a pH probe works by measuring the electrical potential produced by the solution and using the potential difference to determine the pH
Context: corrosion	Sacrificial protection as a method of preventing corrosion
Context: others	Alcosensors, electrochemistry for water treatment

We then sought to match each of these concepts and contexts with various national and examination curricula from different countries. Each set of curriculum documents was examined for the presence of these concepts. Where a concept was present, it was coded to indicate the approximate age ranges where it was taught (Table 3).

Examination of curriculum documents was restricted to the current (2022–23) chemistry curriculum or science curriculum containing chemistry where that may be appropriate for younger age groups.

Insights from the literature

Insights from the literature have been used to get a broader overview of the electrochemistry curriculum. Curriculum documents only show part of the picture of electrochemistry education. Curriculum documents constitute the intended curriculum as laid out by national and regional governments or as interpreted by the awarding bodies of qualifications such as examination boards. The intended curriculum is taught by teachers who themselves place their own emphasis on particular areas; hence, the taught curriculum may be significantly different to the intended curriculum. The curriculum is also experienced by students, through their own lenses of prior experience and within their own social context, and so the learned curriculum is different again. For older students, the assessed curriculum, in the form of the examinations taken, is likely to significantly influence the taught and learnt curriculum. In some countries, this may mean a tighter adherence to the intended curriculum whilst

Table 3 A summary of the codes used in our curriculum analysis

	11–14 *X*			14–16 *Y*		16–18 *Z*	
International grade	6	7	8	9	10	11	12
Approximate age of students*	11–12	12–13	13–14	14–15	15–16	16–17	17–18

*Actual age of students will be dependent on their birthdays and the school calendar for each country in others it may be local knowledge amongst teachers and administrators that some aspects of the intended curriculum are not assessed in the examinations. Whilst the current literature in electrochemistry education is limited, there are a number of manuscripts and reports that can provide insight into these areas.

Results

We examined the intended curriculum for 15 countries together with 2 international curricula or qualifications. The sample used is summarised in Table 4. The sample of countries could be considered a convenience sample, formed from countries which publish their national or local curricula online and those provided by contacts in the researchers' networks. Of course, curriculum documents are published in the language of the country although translations are available for some curricula. For languages within our competencies, these were translated and interpreted by the research team; however in most cases, teachers and lecturers from those countries interpreted the curricula for us.

The intended curriculum in different countries

All of the countries we looked at taught electrochemistry to some degree. All countries covered the foundational concepts such as the reactivity series of metals. In most countries, this was in the 11–14 age range; however, in some countries including China, it was not introduced until 14–16. Another concept taught in the early years of high school is metal displacement reactions including observations of the reactions and the construction of word equations as shown in Fig. 2.

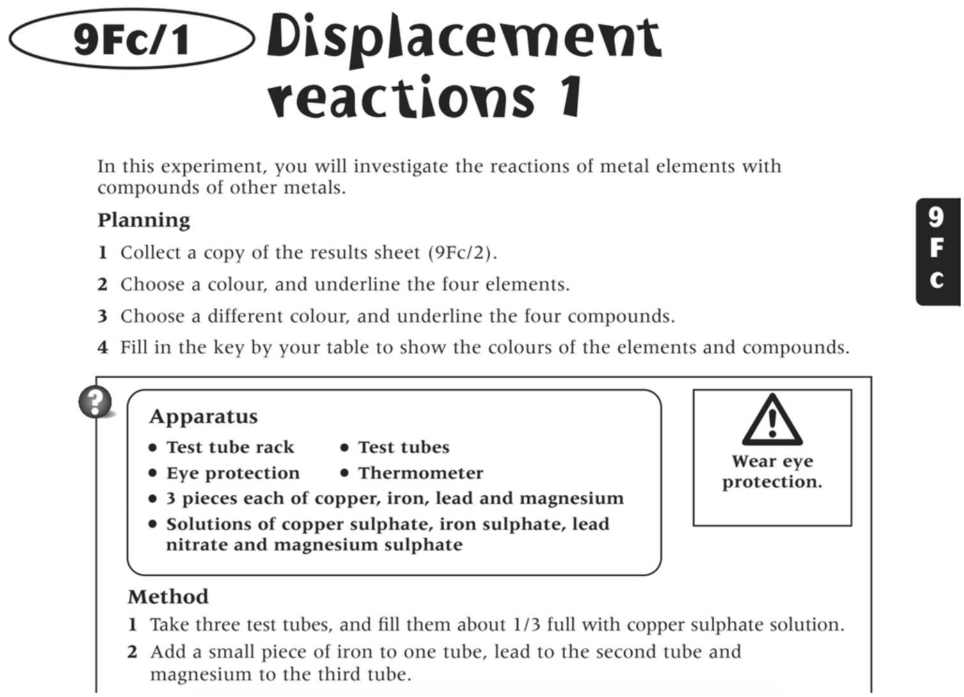
In all the examples we could find, the link between the different reactivities of metals and the role this has in the development of battery technologies was not mentioned; emphasis was purely on illustration of the simple chemistry concepts. Beyond these early concepts, the picture of the intended curriculum in electrochemistry becomes more variable. We have chosen to discuss this through key concepts, contexts and practical work.

Highlighting some key concepts in electrochemistry education

The big idea of redox in terms of the loss and gain of electrons forms part of the intended curriculum in all the countries we analysed. There is a relatively even split of when this is first introduced to students. In around half of the countries, this concept is introduced in the 14–16 age range with the other countries introducing it later, in the 16–18 curriculum. Only one country, Bulgaria, reported this concept as being in their 11–14 curriculum although access to documentation for this age range is difficult as it is less likely to be stated in online documentation. The curriculum in Bulgaria was interpreted by a local teacher so this report may not be representative of all schools in Bulgaria, or other countries may also teach this concept early but we may not have been able to find this out from our searches. A similar

Table 4 A summary of the sample of the countries and qualifications considered in the review of intended curriculum

Region/continent	Country	Curriculum or qualification
North America	USA	New York State Learning Standards in Science leading to Grade 8 intermediate test (science) and Regents Diploma (Chemistry)
	Canada	Ontario 2008
Europe	Bulgaria	National curriculum and Diploma of Secondary Education
	Belgium	French speaking system Brussels and Wallonia
	England	National Curriculum (11–14) GCSE and GCE Advanced Level
	Scotland	National 5, higher
	Lithuania	Lower and upper secondary (gymnasium)
	Germany	Bavarian NTG
	Ireland	Junior Cycle and Leaving Certificate
	Malta	Matriculation and Secondary Education Certificate (MATSEC) intermediate and advanced
	Italy	Upper secondary school certificate (science school)
Asia	China	Guangdong province
	Singapore	See Cambridge International Programme
Africa	West Africa	WASSCE/WAEC CHEMISTRY SYLLABUS
Australasia	Australia	Senior secondary chemistry 4.8
International	International	Cambridge Lower Secondary, middle years, iGCSE and iASAL
	International	International Baccalaureate middle years and diploma


9Fc/1 Displacement reactions 1

In this experiment, you will investigate the reactions of metal elements with compounds of other metals.

Planning

1 Collect a copy of the results sheet (9Fc/2).
2 Choose a colour, and underline the four elements.
3 Choose a different colour, and underline the four compounds.
4 Fill in the key by your table to show the colours of the elements and compounds.

9 F c

Apparatus

- Test tube rack
- Test tubes
- Eye protection
- Thermometer
- 3 pieces each of copper, iron, lead and magnesium
- Solutions of copper sulphate, iron sulphate, lead nitrate and magnesium sulphate

Wear eye protection.

Method

1 Take three test tubes, and fill them about 1/3 full with copper sulphate solution.
2 Add a small piece of iron to one tube, lead to the second tube and magnesium to the third tube.

Fig. 2 A worksheet on the topic of displacement reactions or metals and solutions of their salts taken from a published suite of resources for the 11–14 curriculum in England [10]

pattern is seen for the introduction of ideas around writing half-equations.

The intended curriculum in electrochemistry is most easy to analyse when more advanced concepts which may be considered prior knowledge for study in higher education are evaluated. As the intended curriculum prior to entry to higher education is commonly assessed through a written examination, it is easier to find curriculum documents for this level. Calculation of E^0cell values from combinations of standard electrode potentials was seen in many education systems in the 16–18 curriculum. There were no countries where this was taught to younger students. However, it was notably absent from the intended curriculum in a number of countries including China, Belgium, Lithuania, Italy and Ireland. The Nernst equation is not commonly taught in high school. It is only seen in international qualifications, Bulgaria and China in the 16–18 curriculum. Most electrochemistry in the 16–18 age range is taught with a focus on equilibrium rather than thermodynamics. The link between Gibbs free energy and E^0cell was even less frequently seen in curriculum documentation with only international qualifications, and a single English exam board stipulating this must be studied.

Contexts

The use of contexts is common in science teaching. Contextualising knowledge connects the taught content knowledge, the pure science, with an authentic environment in which the content can be applied or illustrated [11]. Turner suggests that we need to help our students connect with the chemistry we need to tell them the stories about where the chemistry they are learning comes from and where it is going in the future [12]. Most of the curricula we examined in this review would be considered to be "content led", structured from the perspective of a scientist with the chemical concepts organised in a way that make sense to a scientist [13]. However, these curricula are not simply dry lists of electrochemistry facts and concepts; a number of contexts are embedded as illustrations of key ideas.

Documents outlining the intended curriculum indicate one of the earliest contexts students tend to be taught is electrolysis for the extraction of metals such as aluminium in the 14–16 age range. The study of electroplating for decoration and protection and of sacrificial protection is also common at this level. Extraction of metals in particular may be considered to be a traditional, even historical context depending on the country. For example, a question on the manufacture of aluminium from bauxite can be found on the A-level chemistry paper of 1951, the first sitting of that particular examination for 18 year olds in England. English students continue to study the extraction of aluminium in the 14–16 GCSE curriculum. This curriculum was designed for teaching from 2015, despite the last aluminium smelting plant in the UK closing in 2009 and aluminium recycling rates above 75% [14, 15]. Aluminium smelting may not seem particularly relevant to the current cohort of English 16 year olds. The use of contexts which do not feel relevant to students may undermine the effectiveness of that context in illustrating the relevant chemistry. One criterion needed for the successful use of context is the setting [16]. The setting of the context should arise from the everyday lives of the students or social and industrial situations that are of contemporary importance to society. Additionally, students must value the setting and recognise that it falls within the domain of chemistry.

One country where context has been carefully designed into a curriculum is Australia [17]. Australian students also study the extraction of aluminium in the 14–16 curriculum, but crucially this is industrially relevant. Australia has six bauxite mines and four aluminium smelters and is the world's 6th largest producer of aluminium metal [18]. For older students, the curriculum mentions a number of innovative and contemporary contexts including the use of "alcosensors". These biosensors work by recording the electrical potential produced by the oxidation of the ethanol at platinum-coated electrodes to measure breath alcohol concentration [19]. As the use of ground water is common in many inland areas of Australia, the context of using electrochemical methods to remove the iron and manganese ions present in bore water which currently make the water undrinkable is also contemporary for Australian students [20]. Despite the curriculum in Australia last being reviewed in 2012–13, it also includes contexts which at the time were experimental, including the use of graphene within varnish coatings of iron or steel in corrosion prevention.

So contexts may be written explicitly into a curriculum or curriculum guidance may be more limited. In countries which do not explicitly state particular contexts that does not mean teachers are not using them in the classroom, teachers may just have more freedom to bring their own examples into their classroom practice. Contexts may also be suggested for teaching but have no link to assessment. For example, the curriculum documents for New York, USA, state *"real-world connections have been identified only to assist teachers in planning and are not meant to link these connections to any assessment*" [21]. This may influence the taught and learned curriculum.

Practical work

It is difficult to get a full picture of practical electrochemistry in the school curriculum. The extent of practical work in any topic area is a function of the intended, taught and assessed curriculum. Inclusion of specific practical work in the intended curriculum encourages its implementation in the classroom; however, the taught curriculum is influenced by challenging factors such as teacher confidence and the availability of equipment. Inclusion of questions in a practical context in the assessed curriculum may also encourage relevant practical work [22].

Some curriculum documents outline specific experiments and practical procedures expected within the course. For example, in the A-level curriculum in England, the construction of electrochemical cells and measurement of electrode potentials is a core practical for all students in order to fulfil the requirements for the practical endorsement which sits alongside the assessment grade [23, 24]. Similarly, in Ontario, Canada, Grade 11 and 12 students are required to build a galvanic cell and measure its cell potential [25].

Chambers reports that many teachers of general chemistry in colleges in the USA have no enthusiasm for the presentation of the applications of electrochemistry [26]. As the concepts in general chemistry in the USA may be more akin to high school in other areas of the world, this observation could extrapolate more widely to teachers of advanced chemistry courses in grade 12 of high schools. Changes to the curriculum are suggested including the inclusion of relevant practical work and demonstrations, but Chambers also highlights a lack of available literature on the presentation of electrochemistry in engaging demonstrations.

There are a number of teaching and learning insights into practical electrochemistry presented in the literature although these tend to be concentrated in the teaching of undergraduates in their early years of degree programmes. These include innovative experiments for the undergraduate laboratory [27, 28] and for distance learning as necessitated by the COVID-19 pandemic [29, 30]. 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 [31].

Level of specialisation at age 18

The level of specialisation within education systems has a strong influence on how much electrochemistry is taught. International qualifications such as AP, international baccalaureate and international A levels have the greatest of study in electrochemistry followed by A-levels taken in England. It is typical for A-level students to only take 3 subjects in their 16–18 education, a high degree of specialisation at a relatively young age. This leads to the greater depth of study in particular areas of chemistry. The exception to this is the international baccalaureate which is a prestigious qualification in the university entrance market but still maintains significant breadth of study across a number of subjects. Students taking the IB diploma must study course in six subject groups, studies in language and literature, language acquisition, individuals and societies, sciences, mathematics and the arts although students may choose an additional science instead of an arts course. Despite this breadth of study, the IB diploma chemistry at higher level covers electrochemistry to the same level of depth as qualifications such as AP (USA) and A-level (England).

Variation within countries

There may be variation of the intended curriculum in electrochemistry within a country. Some countries have an education system where students attend different types of school for the later years of their education, typically from age 14. This may split students into subject streams such as arts and humanities or science and mathematics. The split may alternatively be into academic or technical/vocational streams. This is the case in Italy where students in urban areas may attend either a humanities or science school for the later years of their education. Students attending a humanities school would not receive any electrochemistry education. Students in the science school would be taught a basic level of electrochemistry including writing half-equations and studying electrolysis. A similar system is in place in Germany where we looked at the intended curriculum in the state of Bavaria. Students attending NTG (Sciences and Technology Gymnasium) schools will study much more electrochemistry than students in humanistic, languages, musical, social sciences and economy & business schools with these streams beginning in grade 8. Students in NTG schools study a significant amount of electrochemistry including Faraday calculations if they choose chemistry as a major subject. In our analysis, we have chosen to represent the experience of students in schools that are most likely to proceed to further and higher education in the sciences so as best to inform instructors at that level.

In large countries like the USA, Canada, Australia and China, aspects of education may be determined at state level rather than nationally. This can relate to the intended curriculum, for example, in Canada different states have their own curriculum documentation for chemistry. In China, different states have different curriculum documentation but there is very little difference in the intended curriculum between the different states. In Australia, the intended curriculum is set out at a national level but the assessment is organised at state level. Further complications are seen where national and international qualifications are often taken by some students whilst other students take a local curriculum. This is the case in the USA where some students take the Advanced Placement (AP) qualification, administered by the college board whilst in high school whereas many other students take only high school qualifications such as Regents [32]. The AP qualification has significantly more depth in electrochemistry than local qualifications including galvanic (voltaic) and electrolytic cells, the relationship between cell potential and free energy, cell potential under nonstandard conditions, electrolysis and Faraday's law [33]. The AP qualification can also be taken by international students outside of the USA to form part of a university application.

Even in countries where the curriculum is organised nationally, there can be variations in electrochemistry education for different groups of students. In England, there is a national curriculum laid out by government and for students entered for specific qualifications at 16 and 18 and this is then interpreted by one of 4 examination boards into a syllabus which is aligned to assessment. This can lead to variation of student experience within a country as shown in the English GCSE and A-level qualifications.

The subject content for A-level chemistry (16–18) in England is set out by Ofqual. This states that students must study "electrode potentials and their applications" [34]. This is a vague statement of required content and is interpreted in different ways by the exam boards. Only the Edexcel exam board chooses to make the explicit link between electrochemistry and thermodynamics stating that students should *"be able to predict the thermodynamic feasibility of a reaction using standard electrode potentials"* and *"understand that E^o cell is directly proportional to the total entropy change and to ln K for a reaction"* [35]. The Edexcel qualification is taken by less than 10% of A-level students in chemistry each year so would not be considered representative of the whole cohort's experience. A similar picture is seen in the 14–16 curriculum in England. The national curriculum at this level makes no explicit requirement for the study of electrochemistry; however, all of the examination boards have chosen to include it including a requirement for associated practical work. For the more difficult concepts like fuel cells, the focus is on recall of key equations rather than understanding although students are also required to be able to evaluate the use of hydrogen fuel cells in comparison with other technologies.

The taught curriculum: the role of teachers and textbooks

Any intended curriculum is delivered by teachers and supported by learning resources such as textbooks, worksheets and multimedia. Teaching is a human endeavour, and as such, teachers may bring their own biases to their classrooms which may influence the taught curriculum.

The concepts we considered to be foundational to learning later electrochemistry such as the reactivity series of metals are not discussed within the literature as being particularly problematic for teachers to teach. Instead, the literature shows a great deal of discussion of the use of teaching analogies and developing engaging strategies for the classroom. The relationship between the reactivity series and the electrochemical series is also explored [36].

As concepts become more advanced, teachers tend to view this area less favourably. A recent survey of high school teachers in England by the polling company Teacher Tapp showed 10% of science teachers would like electrolysis removed from the 14–16 curriculum [37]. Electrochemistry is ranked by teachers and students as one of the most difficult curriculum domains taught and learnt in secondary school chemistry [38, 39].

One reason for electrochemistry being an unpopular concept could lie in teachers' confidence in teaching electrochemistry. This confidence could arise from their subject matter knowledge (SMK) or pedagogical content knowledge (PCK). Subject matter knowledge lays the foundation of pedagogical content knowledge; a high level of SMK is needed to develop strong PCK but high SMK on its own does not necessarily lead to effective teaching [40]. The development of PCK is very much linked to teacher experience. Barnes and Read investigated the role of subject matter knowledge (SMK) in teaching 16–18 chemistry in England. Teachers reported low confidence in their SMK in electrochemistry. Many teachers reported they did not understand electrochemistry themselves, in their degree-level studies and sometimes in their own 16–18 education [41].

Moreover, the teachers in the study felt that there was an algorithmic approach to the teaching and learning of some aspects of electrochemistry, especially with younger students in compulsory education. This rule-based teaching and learning allows students to get the correct answer and the associated assessment credit without a deep understanding of the concepts. This deficiency in the teaching and learning focus impacts both the students they teach but also their own SMK where they feel their own learning was superficial. Barnes suggested this leads to a cycle where *"students don't have a strong understanding of electrochemistry, some of these students become teachers, these teachers are less confident in their SMK/ability to teach the topic, their students don't have a strong understanding of electrochemistry, and so on"*.

Textbooks have historically been significant, reliable resources for teaching and learning. Although many students now use digital resources, printed texts are still a useful resource for students [42]. They may however contribute to misconceptions in students despite the best efforts of authors and publishers. Analysis of French and Tunisian textbooks showed most use the teaching model of the Daniell cell, separating the cell into two distinctive compartments. It was noted that the teaching model differed significantly from actual cell constructions and seemingly acts as the principal source of misconceptions about ionic conduction [43]. An analysis of introductory college level textbooks in the USA, which would overlap in content with some European curricula, showed that a number of them corroborated known misconceptions in electrochemistry [44]. The key misconceptions were drawn from the wider literature, and all ten textbooks analysed contained examples of statements or drawings that could lead to a student misconception in electrochemistry.

Misconceptions and the learned curriculum

So whilst there is a great deal of electrochemistry being taught in high schools across the world, especially in the 16–18 phase, good understanding of concepts is not necessarily achieved for many reasons. Student misconceptions in electrochemistry have been the subject of a number of papers and articles.

Teaching practitioners feel students find electrochemistry difficult. Hussein suggests that electrochemistry at 14–16 is a topic synonymous with misconceptions and at 16–18 is considered as calculation-dense. A number line approach, stripping away electrochemical notation such as cell diagrams, is described as a potential intervention for effective teaching of Ecell calculations [45]. This is shown as a way to make the abstract concepts more concrete and give students a visual method for solving complex problems. This article does not present any findings from students. The cross-curricular nature of electrochemistry is also given as a reason for its difficulty. For deep understanding of the topic, students need to be secure in their understanding of a number of other topics such as redox, equilibrium and structure and bonding as well as basic physics [46].

In Spain, Barral found that 15 and 16-year-old students offered a large number of alternative explanations for observations of a simple electrochemical cell in a practical activity. Indeed, only 2 students in the study ($n = 29$) were able to interpret the process correctly to the extent of getting the direction of electron flow correct [47].

Much of what we know about the understanding of high school students in this area is from the work of Garnett and Treagust in Australia. They found that students studying both chemistry and physics were more confused about current flow in metals than students only studying chemistry [48]. As a result of a study of student understanding of electrochemistry involving oxidation–reduction equations and electric circuits, they suggest that educators including curriculum developers and teachers need to have an awareness of the relationships between physics and chemistry teaching in this area. Their research has highlighted a number of misconceptions present in grade 12 students following a programme of study in electrochemistry. These include students attempting to reverse features of electrochemical cells and apply these reversals to electrolytic cells as well as a tendency to over-generalise due to the influence of teachers and textbooks [49]. This agrees with a large-scale study of a random sample of high school students in Germany. Four general alternative conceptions were reported including ideas related to electric current during electrolysis producing ions, electrons migrating through the solution, the cathode being a minus pole, and the plus and minus poles having net electronic charges [50]. The factors they suggest are influencing these alternative conceptions are concentrated in issues of language including transfer of a term used in physics, misleading analogies presented by teachers and messages connected with a particular term, e.g. positive pole.

Schmidt suggests making alternative conceptions explicit within teaching through the use of multiple choice questions would improve electrochemistry teaching and hence learning. Garnett and Treagust agree, suggesting appropriate and careful teaching is key to prevent misconceptions. They do however highlight a crucial caveat; learning is an individual pursuit and there is no guarantee that students will construct the meaning intended by the teacher no matter how careful the teaching [49].

Treagust et al. found that university instructors in their study in Indonesia tended to assume students had already learned particular concepts [51]. This led them to the conclusion that there were inherent weaknesses in the implementation of the electrochemistry curriculum in high schools in Indonesia since curriculum documents suggested that students should have covered the concepts which the university instructors assumed they had. This represents a mismatch between the intended curriculum and the learned curriculum but also perhaps an unfair conclusion since transition between school and university has responsibilities for both schools and universities [52].

Examinations and the assessed curriculum

Assessments in the form of examinations and coursework are common in the later years of secondary school, especially in academic streams designed as preparation for college and university study. Many of the countries we looked at have examinations set at this national level and marked externally whilst others use systems more akin to teacher assessment. Either of these systems may be considered to involve “high-stakes” assessment, where progression to the next level is determined to some extent by performance in the examination.

Examinations are inextricably linked to curriculum in modern high schools. This can be positive; an examination can mean that new courses are introduced or new subject matter is taught [53] and it can also function to clarify and maintain standards at a particular level. However, examinations can also have a negative effect. A recurring criticism of high-stakes tests is that they distort instruction and force teachers to “teach to the test.” [54] Professor Sir John Holman says *“nowhere is this more apparent than in science learning where relentless preparation for tests and exams drives out the important and engaging aspects, especially the practical work”* [55]. If the assessed curriculum is not constructively aligned with the intended curriculum then teachers and students may focus more on particular topics or learning activities, in order to maximise success in the examination. It is therefore useful to consider assessment items in electrochemistry as we seek to build an overall picture of electrochemistry education in high schools.

In education systems which use teacher assessment as the primary mode of assessment, it is difficult to gain access to assessment items which are representative of the experience of students. This applies to most education systems prior to exams at around age 16 and 18 but also to some countries. For example, in the Belgian system we have evaluated, examinations at the end of high school are set by teachers and entry to most university courses is not as competitive as in some more standardised systems such as the USA and UK.

Electrochemistry assessment items are seen in many national or state examinations. Here, we present a convenience sample of items published in English. Further examples can be found in the supporting information of this manuscript.

Basic electrochemistry concepts are observed in examinations set for pupils around the age of 15 or 16. These tend to have the form of multiple choice or short-answer questions. For example, the 2022 examination of the Scottish National 5 qualification asked students “*which metal, when paired with magnesium in a cell, will produce the highest voltage?”* with the answer options iron, lead, tin and zinc [56]. This is aligned with the mandatory knowledge described in the curriculum documents for unit 3 Chemistry in society *“Different pairs of metals produce different voltages…The further apart elements are in the electrochemical series, the greater the voltage produced when they are used to make an electrochemical cell*” [57]. Basic chemistry in a practical context is also seen in these examinations. The same examination in Scotland’s national 5 presents students with an image of a beaker containing an electrolyte and strips of nickel and aluminium connected with wires via a voltmeter. Students are asked to pick a statement which describes the electron flow in the cell from the options.

(A) Through the electrolyte from aluminium to nickel
(B) Through the electrolyte from nickel to aluminium
(C) Through the connecting wire from nickel to aluminium
(D) Through the connecting wire from aluminium to nickel

Where quite advanced concepts like hydrogen fuel cells are taught to younger students, the assessment focus may not be of the chemical concepts but in a more social, economic or environmental context. In June 2018, the AQA exam board in England presented GCSE students (14–16) with some data about the use of hydrogen fuel cells and rechargeable lithium ion batteries to power electric cars. The students were asked to *“evaluate the use of hydrogen fuel cells compared with rechargeable lithium-ion batteries to power electric cars”* using the data table and their own knowledge [58] in a question worth 6 marks. The focus of this question is extraction of information from the data given and the presentation of a logical argument rather than in-depth understanding of the chemistry. The associated examiners report for this question noted some students *failed to give a judgement on which method is better; a judgement is an essential part of a question where the command word is "evaluate"* and limited their answers by only using information from the table [59].

In education systems which have less of a STEM focus, these basic ideas are tested with older students. For example, a question from the New York State Education Department regent exam for Grade 12 chemistry involves the practical setup for the electrolysis of water. A paragraph of description is given together with a diagram of an electrolytic cell and both the half-equations and overall equation for the process [60]. On initial inspection, this looks like it could be laying out the information for a challenging question. However, the questions which follow are relatively simple including identifying the change in oxidation number for oxygen, comparing the number of electrons lost with those gained and using the mole ratio in the overall equation to determine the moles of oxygen gas produced. Comparing the assessment to the curriculum outline for New York, relatively few of the relevant knowledge (termed major understandings) and skills have been assessed and the assessment has focused only on the simpler ideas from standard 4, unit VIII oxidation–reduction. If this mismatch between the intended and assessed curriculum is repeated across a number of assessment cycles then it may become widely known by both teachers and students and influence both the taught and learned curriculum. Teachers may place less emphasis on the topics which rarely appear in the examination or students may indulge in question spotting and so neglect some aspects of the intended curriculum in their revision.

Contexts are also used in examinations where they are a factor in the level of demand of particular questions [61]. These concepts may be familiar such as those specifically mentioned in curriculum documents as seen in the national examinations of Malta. The 2022 Maltese national year 11 exam in chemistry used electroplating a metal spoon with silver as a context for questions including construction of relevant half-equations and reactivity of different electrodes [62]. In 2019, pre-pandemic, the same examination used the electrolysis of bauxite in extraction of aluminium as a context [63].

Unfamiliar contexts increase the level of demand of a question. A hearing aid cell was the context of a question in the 2014 A-level examination of the AQA examination board in England (Fig. 3) [64].

In most examples students encounter in the course, the cells are presented with the usual aqueous setup of two beakers of electrolytes containing electrodes, a power source and a salt bridge; therefore, this was an unfamiliar context. The examiner's report for this paper showed that students coped well with simple questions based in this context but only the highest scoring students were able to construct suitable explanations for the identification of the positive electrode.

In our curriculum analysis, Australia was found to have a number of innovative contexts suggested in their curriculum standards. So we looked to see if these contexts were found within assessment items of the corresponding qualifications. In the high school certificate (grade 12) papers for New South Wales, there was a general trend for questions to not be based within a context across all topics in chemistry. Moreover, the papers for the years we sampled, 2019–2022, contained no questions on electrochemistry at all [65–68]. The data book for the examination has a full list of standard electrode potentials so it is clear the topic could be examined; however, four years

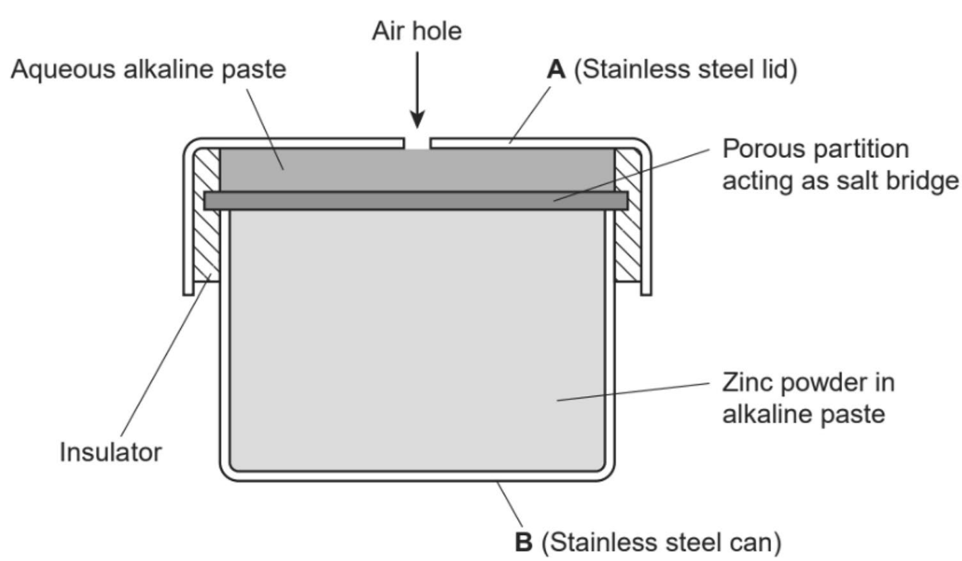


Fig. 3 A diagram of a hearing aid cell provided in the examination of GCE A-level students aged 16–18 in England in 2014

without any electrochemistry questions may lead to deficiencies in the taught and learned curriculum.

Extending and enriching learning in electrochemistry: the informal curriculum

As innovation in electrochemistry research has expanded, so have the opportunities for students to experience electrochemistry outside of the taught curriculum. Reiss and Braund argue that in school laboratory teaching needs to be complemented by out-of-school science learning that draws on the actual world, the presented world and the virtual worlds and that this may be important in reducing the decline in attitudes towards STEM as students progress in their education [69]. Many research institutes and universities are involved in public engagement and schools outreach activities such as science festivals and bespoke workshops [70–72]. Science museums may also have exhibitions with electrochemistry-related content or activities. Examples of this have been seen by the corresponding author at the Science Museum in London and Nemo in Amsterdam.

Learned Societies such as the Royal Society of Chemistry, American Chemical Society and German Chemical Society are also a source of public engagement activities. For example, the most recent “global experiment” from the RSC, launched in 2022, is focused on the exploration of the science behind batteries [73]. These citizen science experiments are designed to use readily available, low-cost materials and are supported with teaching and learning resources, an interactive result page and multimedia content. As of the end of March 2023, the page had logged 14,432 participants with 7238 batteries made in schools around the world. At first glance, this may seem impressive; however, in England alone around 166,000 students are entered for a qualification in chemistry at age 16 so such engagement in enrichment activities is not a significant aspect of the curriculum.

Students may get involved with enrichment activities as individuals/families or through their school which leads to a lack of equity in accessing these opportunities. Participation in out-of-school science learning contexts in particular may be socially structured, for example, the visitor profile for science museums tends to be overwhelmingly white and middle class [74]. For this reason, we have not considered the informal curriculum to be particularly important in taking an overview of electrochemistry education in high schools around the world.

Limitations of the research

This curriculum review has focused on documentation representing the intended curriculum for students in the countries included. We have used insights from the literature to give some indication of how the taught curriculum may differ from the intended but the attitudes and skills of teachers in electrochemistry is a much larger topic which it cannot be wholly represented here.

The learned curriculum, the knowledge that students actually walk away with is again different to both the intended and learnt curriculum. Reports from the literature and other sources have been used to provide insight into these parts of the curriculum, but students are individuals and what they learn is a product of many different factors and it is difficult to fully document the experience of any student or group of students fully.

Conclusion and implications for policy

There are widespread calls for expansion of climate change education [75]. Since innovations in electrochemistry are key to securing a carbon–neutral future, it perhaps follows that education in electrochemistry should form part of this focus. The chemistry that forms the foundations of electrochemistry is taught to all students in compulsory science education across the world; however, the emphasis is on core concepts rather than their later application in the production of electricity from chemicals. Some countries cover an introduction to electrochemistry such as the idea that metals of different reactivities together with an electrolyte produce a potential difference, by the age of around 16 but for many this is covered in the 16–18 age range. A range of contexts is seen in the teaching of electrochemistry; electrolysis is heavily emphasised across the world but examples of cutting-edge innovative contexts such as the use of graphene oxide paints in shipping are also seen.

For students who choose chemistry through to the pre-university level, many countries teach students basic electrochemistry including concepts such as the electrochemical series, the standard hydrogen electrode and the calculation of E^0cell values. Countries with highly specialised education systems at 16–18 and international curricula have the most advanced coverage with some covering topics like rechargeable and fuel cells. There is very little emphasis on the link between thermodynamics and electrochemistry at this level; most countries and qualifications focus electrochemistry around the core concept of equilibrium. Assessment is mostly constructively aligned but at times more simplistic than the documents outlining the intended curriculum suggest it should be. This may lead to more superficial learning as students train themselves for assessments.

Teaching and learning of electrochemistry in high schools is hindered by low teacher confidence in their subject matter content knowledge especially at higher levels. The concepts in electrochemistry are associated with misconceptions in students. They are also observed in teacher exposition and in published resources such as textbooks. There may also be an issue at the transition to higher education with university instructors assuming students have a secure grasp of high school concepts rather than making sure foundational knowledge is secure before introducing more advanced concepts.

This overview of the curriculum has shown that although there is electrochemistry content taught to high school students around the world, there is a great deal of work that needs doing to ensure high school students across the world are able to see electrochemistry as an exciting and worthwhile topic. Many curricula would benefit from modernising the contexts used to illustrate the applications of electrochemistry, allowing students to see it as relevant to their modern lives. We recommend this as a focus for policymakers when national curricula are reviewed. For younger students, the role of core concepts such as the relative reactivity of metals in batteries could be mentioned whilst maintaining and emphasis on the foundational chemistry. Additionally, investment in subject matter knowledge focused continuing professional development for teachers should be a priority for governments and organisations supporting science education such as learned societies.

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Declarations

Competing interests The authors declare no competing interests.

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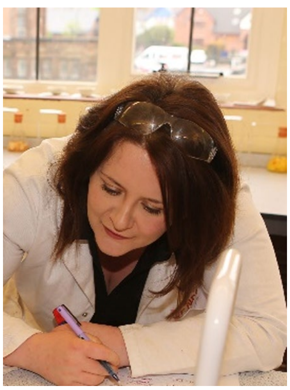

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