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Evaluating practical methodologies in Scottish certificate level physics: electrical circuits

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ABSTRACT

Electrical circuits are central to high-school physics courses globally. However, it is commonly stated that there are challenges both for educators and students with the abstract nature of the concepts. This action research examines the practical methods used by a group of five teachers when teaching electrical circuits at the National 5 level. Participants attended a workshop to test and evaluate these methods, while group discussions allowed consideration of alternatives. The Current Test Evaluate Ideal Reality (C-TEIR) framework was developed during this research to analyse the workshop notes and conversations and give structure to the findings. The main outcomes were that equipment is sufficient though not ideal, a similar teaching pattern is followed by all participants, and there are concerns over the introduction of electrical circuits at earlier stages of students' education. Although schools have the components required, there was concern over the quality and cost of replacements, and the lack of technical support for repairs. Teaching of the concepts tends to begin with building circuits, series before parallel. Voltage and current rules were considered before resistance, which followed alongside Ohm's law. These concepts are core to the understanding of the topic, and this research highlights a need for consideration of when they are introduced, how and by whom.

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Introduction

Practical work is a core element of science teaching and the importance of experimentation and learning through these activities is often promoted (Baillie, 2018; Gatsby Charitable Foundation, 2017; Millar, 2004; Millar & Abrahams, 2009; Oliveira & Bonito, 2023). There is less evidence about which specific elements of practical work have the most benefit for students' learning in the secondary setting. Against a backdrop of perceived cuts in funding and reduction in technical support, practical work appears to be in significant decline (Gray et al., 2024). Practical work is considered to develop a range of skills, including critical thinking (Tenzin et al., 2024) and equipment manipulation (Pols et al., 2021). Given the importance of practical work, it is therefore essential to understand how it can be used most effectively. This paper presents one section of a practical physics project aiming to develop an understanding of practice in secondary-level certificated physics in Scotland. We investigated speed and acceleration, waves and electrical circuits due to their ubiquity in international physics courses (The International Baccalaureate (IB), 2022; Cambridge Assessment International Group, 2022; SQA, 2024; ACARA, 2018). Therefore, the outcomes of this work are applicable globally. Here we present the electrical circuit element of the project.

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Background

Electricity is often cited as one of the most challenging topics within physics teaching (e.g. Burde & Wilhelm, 2020; Saputro et al., 2019). Simple electric circuits are often introduced as part of primary school science curricula (Preston, 2019). This is extended in the early stages of secondary school science before being covered in more depth as courses become specific to physics (Schubatzky et al., 2019). In Scotland, the first examinable physics course is National 5 (N5), which is taken when students are approximately 16 years old (SQA, 2024). By the end of this course, students are expected to have achieved a quantitative understanding of simple resistive circuits, both series and parallel current, voltage and resistance rules and be able to use Ohm's law to calculate values (SQA, 2019). Potential divider circuits are covered specifically. This comes after the Broad General Education phase (BGE) of the Curriculum for Excellence, which students study from approximately 3–14 years old (Education Scotland, 2017). In secondary school, this usually means levels 3 and 4 of BGE, which include outcomes related to current and voltage measurement, and an understanding of the relationship between these terms and resistance. To put this in context, before secondary education, students may have built simple circuits and considered basic terms. Then, in the two to three years before N5, students will often study electrical circuits during their combined science classes. Often these will begin with basic electrostatics – specifically charge, attraction and repulsion. Schools may introduce the concept of voltage, but this will often be qualitative.

In Scotland, as of 2024, there were the equivalent of 900 full-time equivalent physics teachers across 360 secondary schools (Scottish Government, 2025). Physics teachers teach a mix of general science at BGE level and physics certificated classes to older pupils, including N5 and Higher levels. Class sizes in practical subjects, including physics and general science, are limited to 20 pupils (SNCT, 2024). Class lengths vary but are in the region of 3 hours per week to cover the N5 curriculum over 2 years.

Significant work has previously considered myriad misconceptions that occur with circuits (Moodley & Gaigher, 2019). These include that students view power sources as constant current, not constant potential difference (Leniz et al., 2017); current is consumed by components (Peşman & Eryılmaz, 2010) and that current flows from both terminals of the source to the component (clashing current) (Osman, 2017). These are challenging to overcome, with some evidence that even those who are quite advanced in their physics instruction continue to hold them, though they may be better equipped to work through their misconceptions (Masson et al., 2014). These issues may be compounded by the variety of methods used to teach electrical concepts. For example, in Scotland, teachers often use electron current rather than conventional current (Baillie, 2018), which potentially leads to confusion when teaching about ionic current or semiconductors. Similarly, current is often taught first, and students believe that a current drives a potential difference rather than the potential difference driving a current. This issue might be solved by ensuring potential difference is the central theme (Burde et al. 2022). A further consideration is that of the term 'potential difference', which is often used interchangeably with the more popular term in Scottish education, 'voltage'. The terminology used warrants further investigation, but is beyond the scope of this current research.

While basic circuits are a core part of secondary school curricula, they are considered very difficult to teach (Burde et al., 2021). Students' cognitive development and increasing ability to understand abstract concepts mean that careful consideration is required when deciding which circuit models and analogies are used at a given educational stage (Preston, 2019). It may even be considered appropriate to delay the introduction of circuits to later in school. The abstract nature of the topic (Preston, 2019) and the intangibility of the inner workings of circuits mean that models are used to assist in the teaching of the concepts. Models come with their own challenges. One popular model includes the use of water pipes as an analogy; however, while this increases the tangibility, it suffers from the requirement to teach extensively about the model before considering real electrical circuits (Paatz et al., 2004). Additionally, there is the possibility that circuit misconceptions will transfer to the model (Schubatzky et al., 2019). Another innovative model used air pressure in order to ensure that potential difference (and in this case, difference in air pressure) was core to the development of understanding rather than current (Burde & Wilhelm, 2020). In this case, it is assumed that students are familiar with air pressure as a concept and that this is more tangible than the circuits. Generally, the use of models is important in science,

but careful consideration must be given to the choice of model, their application, and the classroom culture to ensure success (Wade-Jaimes et al., 2018).

A variety of practical research themes have been explored in relation to teaching electrical circuits. Kock et al. (2013) considered if inquiry-based practices can be used. The outcome is familiar to many teachers with three tensions becoming apparent: between open inquiry and using structure to ensure learning, between student exploration and the need to have the 'right' answer, and between the wish to create scientific culture and the requirements of school reality, including exam results and the rigidity of school timetables. This is further developed in a systematic review of laboratory work in secondary science which suggests guided inquiry may be the most advantageous use of laboratory work, and the level of openness should be adjusted for the desired outcome (Gericke et al., 2023). A meta-analysis by Tselegkaridis et al. (2024) considered the simultaneous use of tangible and simulation-based work and found that the combination of the two may be the most advantageous, which has been further suggested by a recent study (Tenzin et al., 2024). It is notable that practical work on its own is not enough, and the teaching and discussion are vital to its pedagogical success (Harrison, 2016). For effective learning it is also important to avoid overloading the working memory of learners by introducing too many new procedural and/or conceptual ideas simultaneously during practical activities (Sweller et al., 2011).

There is no clarity about the methods being used to teach electrical circuits in Scottish schools and, here, it is intended to offer clarity as a basis for potential future research into evidence-based improvements. In this work, we used a workshop setting alongside open discussions to discover which methods are used for teaching circuits at the certificated level in Scotland. There is an emphasis on practical elements and how effective these may be, enabling a consideration of what is currently in effect, and how this might develop in ideal conditions.

Methodology

This project evaluated the practical methods used to teach electrical circuits in National 5 (N5) physics classes in Scotland. We were seeking to understand the following:

- what equipment is currently being used and its implementation
- the challenges of teaching this area of physics, and
- any improvements which would be beneficial.

The research team all have previous experience in secondary school physics education but are now employed in other related roles and know the importance of collaboration and sharing ideas. For this reason, we wanted the outcome to be useful for educators, and felt the research required those currently embedded in the field, the teachers and technicians, to share their experiences. Most secondary schools in Scotland (and the UK) employ technical staff to support the teaching of science (and other areas such as design and technology, and AV/ICT). Responsibilities vary depending on the establishment and local authority. As a guide, in physics, they provide and set up equipment for classes, test and maintain equipment, advise on apparatus use, purchases and health and safety, and perform demonstrations to students. It should be noted that this may not always be possible in all establishments due to staff provision. The most comprehensive study into the technician service across the UK was conducted in 2000, where the central role they play in delivering high-quality education was highlighted (RS/ASE, 2001).

The main focus of the research was on classroom practical work, considered as activities which involve the manipulation and observation of physical objects within the school laboratory or classroom with a view to data collection and analysis (Gericke et al., 2023). The workshop was completed in a similar manner to classroom practice, with the main difference being that the participants were experts in the activities they were performing. This meant that they were able to make more informed decisions about equipment use and setup. Due to the need to understand and potentially transform practice, we adopted an action research (AR) approach (Kemmis, 2009) and implemented a participatory action research (PAR) framework to prioritise participant input, encourage collaboration, and ensure the research team was reactive and adaptable throughout (Cohen et al., 2018). The educators involved have

different working contexts despite all being from Scotland, which adds additional importance to the sharing of expertise (Colucci, 2007).

Participants ($n = 5$) were self-selecting from a previous survey (Gray et al., 2024). Prior to completing this, they were provided with the participant information sheet (PIS) which gave the project details (including ethical considerations). The online survey required participants to acknowledge they had read the PIS and gave informed consent by selecting yes before commencing. This was also a requirement of an additional pre-workshop survey. This electronic written informed consent covered the data collection and usage, points of exit from the project, the process for anonymity and confidentiality, and the methods for dissemination. The corresponding author's institution's ethics committee approved the request and granted permission for the research to take place. The main inclusion criterion was that participants were practising teachers or technicians in Scottish schools or further education (FE) colleges with experience of the N5 physics course. Due to the small sample size, specifics of establishment location, teaching experience and gender are not detailed to avoid identification, however we were satisfied that we obtained a broad spread across all categories. There were 5 local authorities represented across urban and more rural areas of the country. Pupils in Scotland generally attend their most local secondary school leading to a wide socio-economic demographic. Participants had between 6-35 years of experience, and the male to female ratio was 4:1. All were secondary school physics teachers, so there is work to be done in future projects to ensure technicians and FE educators are represented.

All attendees were assigned a unique code using two randomly chosen letters (DP) followed by a number for each person, and this was used throughout to ensure anonymity and encourage candid participation. It should be mentioned at this point that the small sample size limits the generalisability of the conclusions in this work. There are some indications that the methods completed are likely to be representative of common practices (given the unanimity of them), however we cannot be sure of this without a wider sample of the population.

A workshop provided participants with the opportunity to test and evaluate a variety of practical methods available to teach electrical circuits. This took the form of a full day, with two practical sessions: series and parallel circuits in the morning and Ohm's law in the afternoon. Equipment was available for participants to have free choice of the provided apparatus to perform the experiments applicable within each session in line with the PAR characteristic of being immersed in a realistic scenario (Kemmis et al., 2014a). In advance of the workshop, three of the participants gave details of the equipment they used to teach the topic in an optional survey, which, along with some other school-level items known by the research team (ceramic resistors and PASCO sensors) were made available (see Table 1).

The research team have many years of previous secondary school physics experience and were familiar with the range of equipment. While there are other options available, we felt these gave an accurate representation of the apparatus most commonly found in Scottish classrooms. Unilab meters (Harris, 2025) provide direct measurement options, as do multimeters. The multimeters were a variety of low-cost options in line with what schools have. Finally, we wanted to provide an alternative by introducing PASCO sensors which relay their data to a separate computer allowing further manipulation (Pasco Scientific, 2025).

Table 1. Workshop equipment provision.

Category	Equipment provided (*items added by research team)
Voltage source	Cells (1.5 V)
	0–12V Stepped power supply unit
	0–20V Continuously variable power supply unit (limited to 12 V)
Components	Lamps (MES)
	Resistors (axial metal film)
	Resistors (ceramic)*
	Switches
Connectors	Wires (4 mm plugs)
	Crocodile clips
Meters	Multimeters
	Digital Unilab easy-read (with voltmeter and ammeter shunts)
	Analogue voltmeters and ammeters
	PASCO wireless sensors (voltmeter and ammeter)*

The participants worked independently in the workshop to allow them to be critical about their own practice, but shared their decisions and opinions with others throughout to attempt to reach a wider collective viewpoint, in line with PAR characteristics (Kemmis et al., 2014b). The following prompt questions were provided by the research team:

1. How easy is it to set up?
2. Is what you are measuring clear?
3. Are you measuring variables directly or indirectly?
4. Do the pupils have to manipulate any data?
5. Does it introduce the concept successfully?
6. Are some setups better for one concept over another? (Multipurposeness)
7. Are there elements of the equipment/setups you would want to mix?

These were designed to enable consideration of a variety of aspects of the apparatus and procedures during their evaluation, and to act as a guide to encourage discussions without direct researcher influence (Wellington, 2007). Participants took written notes which corresponded to these. Each session was followed by a group discussion to collate views on the prompt questions, with notes recorded by the research team, who otherwise played a facilitator and observer role (MacDonald, 2012).

The qualitative data was recorded in the form of hand-written field notes either by participants or the research team which captured the main points of the discussions. This was transcribed into a Word document for analysis, where undecipherable words or inferences were recorded as such. Manual coding of the transcriptions was conducted based on the researchers' prompt questions (Braun & Clarke, 2006). A spreadsheet of the codes was created, and three themes emerged: pedagogical, technical and wider considerations. The coding process was performed by one research team member and then reviewed by the others with any discrepancies resolved through discussion to ensure consistency of coding with a view to using themes to analyse the data. The codes which emerged are shown in Table 2.

The data from the morning workshop notes were recorded in a spreadsheet detailing equipment preference and how this is used in situ. This is detailed in Tables 3 and 4 in the results section. The afternoon workshop data was recorded as equipment choice alongside brief notes of how this was used. This process assisted with an understanding of the data. AR, as a wider term, encompasses the idea of being critical and reflective, and allows creativity and flexibility as a project progresses (McNiff, 2002). This was utilised to develop our own framework, C-TEIR (Figure 1), as it became clear during the data collection phase that we needed to add clarity to the process of identifying best practice. We asked

Table 2. Themes and codes used.

Theme	Codes
Pedagogical	Key teaching points
	Stage and order of teaching
	Demonstrations, models and simulations
	Use of lamps for understanding
Technical	Equipment – meters and components
	Familiarity and ease of use
	Lack of technician support
	Issues with/lack of equipment
Wider considerations	Equipment – preference and cost
	Out of field teaching
	Challenges – language and prior knowledge
	Challenges – mathematical ability
	Additional skills gained

Table 3. Equipment chosen for voltage and current in morning session.

Series and parallel circuits (voltage and current)	D cells	Power supply	Lamps	Unilab easy read meters	Multimeters	Switch
DP6	✓		✓	✓		
DP7		✓	✓	✓	✓	
DP8	✓		✓	✓		
DP9		✓	✓		✓	✓
DP10		✓	✓	✓		

Table 4. Equipment choice for resistance in morning session.

Series and parallel circuits (resistance)	Power supply	Resistors	Multimeters
DP6	✓	✓	✓
DP7		✓	✓
DP8		✓	✓
DP9		✓	✓
DP10		✓	✓

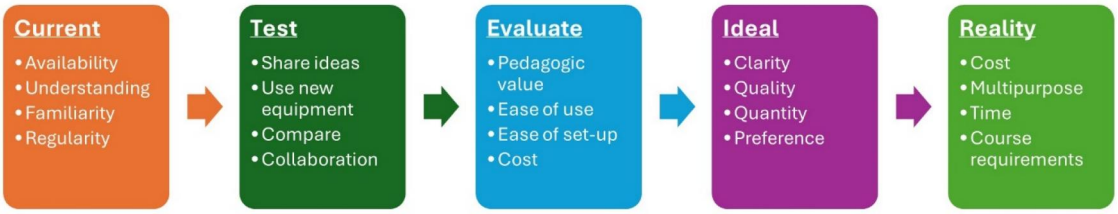

Figure 1. C-TEIR framework.

participants to consider the 'ideal' practical methods to teach these concepts assuming no barriers existed. However, to determine the 'best' method, there had to be inclusion of the realities educators face such as shortage of time through excessive workload (Hulme et al., 2024) and long-term budget constraints, particularly for equipment, in Scottish schools (Farmer et al., 2015).

The main principles of the C-TEIR framework are directly linked to the 7 Cs of PAR framework (Feekery, 2024). As such the research must be cyclical, collaborative, context-specific, critically reflective, combining theory and practice, change-focused, and conversation-driven. The workshop created a context-specific environment replicating the school set-up which allowed exploration, testing and evaluation of the combination of theoretical and practical aspects of the N5 electrical circuits section. At the core was the collaboration between the participants, where they shared their experiences to provide data for the project, but also to encourage knowledge exchange with everyone (including the research team) learning from each other. The inclusion of group discussions to assess the ideal and reality were cyclical and returned to their current situation and the barriers they are exposed to. The inclusion of the ideal meant a vision could be formed of the next steps required to implement change. The C-TEIR framework aided data analysis and added structure to the discussion of the findings by utilising the project plan of understanding the current provision, the workshop test and evaluate stage, then the group discussions. Subheadings highlight the areas we hoped to address using the prompt questions. There is a recurrence of some of these, such as cost, across the framework which created links throughout, but are also discussed within the context of each stage. As such, the framework is presented as a linear process but has capacity to be adapted to be cyclical. When considering future research, the 'ideal' and 'reality' elements will result in direct action which, when implemented, will create a new 'current' situation. Ensuring we capture data which details the impact of the research on participants, and their practice aligns the C-TEIR closer to the change-driven aspect of PAR for the research outcomes to become part of a cycle.

Reporting the findings as a narrative raises questions of reliability and validity; however, AR data must be a clear representation of the views of the participants. To address this, Heikkinen et al. (2007) suggest five principles to evaluate the quality of AR data reporting; historical continuity, reflexivity, dialectics, workability, and evocativeness. We have ensured our research aligns with these and have included the context, ensured the participants were given opportunities to freely discuss and consider their practice, that the outcomes have general applicability, and that the writing style allows the reader to feel a connection to the subject matter. The following section presents and discusses the results according to the discovered themes and codes under the headings of the C-TEIR framework.

Results and discussion

This section uses the C-TEIR process to frame the results, with each heading relating to each stage of the project. Starting with the current situation to give context to the participants choice of methods, then moving into the test and evaluate phase where there is criticality and reflection on the available

equipment. During discussions in the workshop, we found that participants tended to speak about their ideal situation alongside the reality. In line with the participatory nature of the workshop, therefore, these elements of the framework are presented together.

Current

An optional pre-workshop survey collected anonymous data on current practice from three of the five participants. This is used in the following section to give an overview of the methods being employed and some of the reasons behind these choices. Respondents were asked to give details of practical methods including demonstrations, whole class experiments and simulations alongside the specific equipment used for the topic. The respondents were currently using practical methods to teach circuit rules and Ohm's law. Examples of active learning were given, such as students acting as an electrical circuit being 'carriers' of energy, encountering obstacles which represent resistance, and objects/students which are components/energy changers. It was commented that physical models develop a basic understanding of current and voltage/potential difference:

> *'having a physical representation in the active learning approach supports the introduction of these concepts and prompts discussion and questions'. (Anon)*

Circuit rules are taught with cells, wires (connecting leads), lamps, ammeters and voltmeters, although the measurements can be unreliable due to the apparatus being old, so the free PhET circuit builder (University of Colorado Boulder, 2025) is often used to consolidate learning, in line with research which suggests the combination is ideal (Tselegkaridis et al., 2024). Similar equipment is utilised for teaching Ohm's law with the addition of variable power supplies and resistors. Students are required to plot graphs of their meter readings and determine Ohm's law from the equation of a straight line. There was a comment about investigating non-ohmic devices and comparing graph gradient/resistance as additional activities if time allows:

> *'I utilise similar equipment as previously mentioned but include variable power supplies and resistors. After taking measurements for current and voltage, we plot appropriate graphs and derive Ohm's Law from the equation of a straight line. If time allows, I allow learners to investigate non-ohmic devices and compare graph gradient/resistance'. (Anon)*

All three respondents to the optional survey are performing whole class experiments in the Broad General Education (BGE) phase and N5 classes and also include demonstrations and calculations. They all have enough equipment for students to work in pairs, and specify their resources to be filament lamps, wires (one uses six different colours to help students clearly see the connections), meters (either multimeters or Unilab easy-read), resistors, and variable power supplies. One respondent cited their reasons for only using Unilab easy-read meters due to them being *'as good or better than anything else'*. Another commented that employing three different methods (students acting as a circuit, class experiment with equipment, then PhET simulation) *'allows me to develop a deeper understanding with learners'*, again relating to the background research (Tenzin et al., 2024). They state that an active learning introduction provides a physical representation which encourages discussion; the class practical builds familiarity with the components and construction of circuits; taking measurements develops skills of drawing conclusions, critical thinking and problem solving; and PhET overcomes equipment issues and consolidates learning. The importance of using these methods is highlighted by one of the respondents:

> *'Practical equipment force[s] students to build circuits from wiring diagrams, make changes and see the results' (Anon)*

Test and evaluate

In this section, the outcomes of the workshop are detailed. Participants were given free choice of equipment. The options available, shown in Table 1, aimed to replicate what they are currently using alongside some other apparatus which they may not have access to. The testing and evaluation are combined as they tended to be intertwined during discussions.

The morning session of the workshop focussed on circuit rules. Participants commented that current and voltage have already been covered at BGE level, so at N5 this is a reminder. There was some variation in equipment chosen, identified in Table 3.

In terms of the meters, the preference was for more than one, to allow for multiple measurements and therefore simultaneous readings at various points on the circuit. Although participants had their own preferences for equipment, it was clear their choices were grounded in understanding the most suitable methods for their students. This was highlighted in their comments:

'Block off mA socket on DMMs [digital multimeters] with electricians' PVC tape' (DP9)

'Short leads better to avoid spaghetti' (DP10)

'Multicoloured wires to prevent kids thinking they need to use certain colours (6 colours, 2 of each)' (DP8)

The aim of all of these was to reduce over-complication and make the circuit as clear as possible.

All participants started with simple circuits and built up the complexity, e.g. started with one cell and one lamp and increased in increments to three cells and three lamps, taking measurements at various points. Some taught voltage/potential difference and current in series, then in parallel, others taught current in series and parallel, then voltage/potential difference. It is notable that, generally, current is taught first. These experiments were a revision of what was taught in the BGE stage, which includes measurement of current and voltage in both series and parallel (Education Scotland, 2017). Despite this DP8 commented *'for many it is as though they haven't seen it before'*, and DP9 chose to do *'little or no quantitative work'*, and therefore numerical measurements were new. There was specific mention of backing up the practical work with a PhET simulation:

'would also back up both [current and voltage rules] with PhET sims as it so very versatile' (DP9, supported by DP8)

When considering the experiences of students prior to N5, there was evidence of significant disparity:

'Can't rely on anything from Primary – [what has been taught is] variable' (DP9)

'Don't rely on pupils' understanding [up to S2]' (DP8)

The equipment chosen for measuring resistance in series and parallel circuits was more standardised, shown in Table 4.

There was a choice of metal film or ceramic resistors. The former are often found in schools, and are cheaper, but are often 0.5 W or 1.0 W rated. In cases where resistance is high (100s of ohms), this is not problematic, but values are often chosen in small, round numbers to simplify calculations for students and give 'good' results. It is often necessary, therefore, that 7 W or 10 W ceramic resistors should be chosen, particularly where supplies of up to 12 V may be available to students, due to risk of overheating. DP6 also chose a variable power supply set to 2 V and noted they would introduce Ohm's law before resistor combinations. This method uses a measurement of voltage and current to determine resistance numerically. The resistance was then checked with an ohmmeter, or by the label, (if assured this is correct), and most participants agreed it was important to show the calculated value was correct. The others were in agreement in using this method but introduced Ohm's law later and therefore used direct resistance measurement at this stage.

A discussion after the morning session, including sharing preferred methods, led to some participants considering alternative methods for the concepts of current, voltage and resistance. For example, DP6, supported by DP7 discussed introducing the concept with the rope model (Carrier, 2013) or similar *'to reinforce ideas of current, useful visual where the actual phenomenon is quite abstract'*, while others liked the ideas of using more connecting leads of different colours, or coloured circuits which show the same current. The Unilab easy-read meters and cells were mentioned as preferred, but not all participants have these in their establishments. DP7 did not teach resistance using equipment, but planned to alter this after the session:

'seeing the ease of setup today, I feel I confident that I could add in quick and meaningful opportunities to measure resistance'

The afternoon session concentrated on Ohm's law. Most participants chose a low voltage stepped power supply, with DP6 commenting that 1.5 V cells could be used instead which would limit voltage, and DP9 mentioning the benefits of using a continuously variable power supply to plot graphs. Resistor choice varied, with the main consideration being the resistance value. Reasons for this were:

'[to] avoid faff with a milliammeter' (DP6)

'Would use a value other than 10 ohms so relationship is not obvious' (DP10)

'Different groups receive different values of R so they can't compare results (values other than 10 ohms)' (DP7)

DP10 commented that they use rheostats in their school as they are *'indestructible'*. There was no clear preference in terms of meters, and either Unilab easy-read (one as a voltmeter and one as an ammeter) or two multimeters were used. Only DP10 used a switch in their circuit stating it *'kept it ohmic'* and *'prevented heat build-up'*, and because the students ask why it works without a switch, suggesting the possibility of a student misconception about the role of the switch. Others felt it was an unnecessary complication. There were concerns about putting it in the wrong place and creating a short circuit, or that the switch may be faulty, but there was a consideration of whether the switch on the power supply was sufficient for the purpose.

Participants were interested in testing the PASCO wireless voltmeter and ammeter. The reliability of the measurements, accuracy and speed of graph production, and ability to share results with students were seen as positives. However, these were outweighed by the prohibitive cost, the challenges of setting up the software, and equipment lag. DP6 commented that ALBA software produced the same outcome. This is similar to the PASCO software and uses sensors connected to a computer to record and analyse data. PASCO was included in our apparatus as ALBA equipment, while still in use in some schools, is now obsolete (djb microtech ltd, 2025).

The Ohm's law experimental procedure (altering the voltage and measuring the current) results in a voltage versus current scatter graph and is replicated with different voltages and resistors to compare gradients of the line of best fit. There was a mention of repeating this with a 12 V lamp as an example of a non-ohmic resistance which produces a curved voltage against current graph.

As with the switch being viewed as an added complication, using rheostats was also considered such. One positive was the visual consolidation of the wound wire being the resistor, but the difficulty in obtaining accurate resistances which are repeatable would be a challenge. This inaccuracy was also raised by one participant as an issue with power supplies and the output voltages not reading as marked on the equipment.

Overall, Ohm's law experiments were seen as easy to set up and simple and quick for students to use. It utilises apparatus that most schools have readily available, and there were no clear barriers to implementing this practical method, although DP7 commented on limited availability:

'Learners sometimes working in small groups rather than pairs due to number of resistors/equipment'

The additional skills developed through this practical work were discussed, such as building knowledge of data collection, changing variables, drawing and analysing graphs, and linking to maths skills such as calculating gradients and using the equation $y = mx + c$. This was reported to cause some complications depending on maths ability and stage, as the equivalent concepts may not be taught in mathematics classes before they are met in physics, and they also may only have plotted whole numbers rather than decimal fractions. Participants commented that physics teachers are having to cover this prior to the students being able to plot the graphs and analyse them which takes up more teaching time summed up by DP7:

'For some learners drawing graphs, line of best fit and calculating gradient can be a challenge based on maths ability and pathway in maths'

DP8 highlighted that the ASE and IOP have published guidance on 'how to draw graphs' (Goldsworthy et al., 2000) which could assist when developing graph skills.

Table 5. Preference of teaching order.

Concept	DP6	DP7	DP8	DP9	DP10
Current in series	1	1	1	1	1
Current in parallel	3	3	2	2	2**
Voltage/P.D. in series	2	2	3	3	3**
Voltage/P.D. in parallel	4	4	4	4	4
Resistance (measurement with ohmmeter)	6	5*	5	6**	5
Ohm's Law	5	6	6	5**	6
Resistance (combinations in series and parallel)	7	7	7	7	7

* Participant did not use practical work for concept.
** Ambiguity over the order of concepts.

Ideal and reality

The conversations about what would be the ideal situation for teaching circuits and Ohm's law were inextricable from the reality which impacts choice. The discussion that follows will therefore include the I and R sections of the C-TEIR process due to the lack of a clear distinction between them during the discussion phase.

The group initially focussed on the teaching order. As a topic, and including what is covered in the BGE phase, all participants started with complete circuits, then series and parallel, voltage/potential difference and current rules. Resistance (series and parallel, and combinations) followed alongside Ohm's law. Within these sections, though, there was variation in order choice, as in Table 5.

DP6 and DP9 stated a preference for introducing resistance with Ohm's law, though earlier discussions contradict this for the latter. DP6 commented that their reason for this choice was that it is the *'quantity that links current to voltage'*. Everyone introduced resistance at N5, however DP8 includes it in S2 (age 12–13) but only as an extension where they used rheostat length to measure resistance. DP6 and DP8 mentioned using lamps as a visual indicator of resistance, due to the correlation between brightness and current, with the added benefit of tangibility. When considering N5 level, there was consensus that a recap of circuits was required, due to the inconsistency of teaching the topic at earlier stages, an idea which requires further research. There was general concern over the disparity in students' experiences prior to N5 level.

Additional methods are seen as useful tools to allow for consolidation with reliable results. For example, simulations are widely used after practical work, as are demonstrations of circuits which are projected onto a large screen. This links back to research which suggests that the combination of hands-on practical and simulation can be most beneficial to students (Tselegkaridis et al., 2024). Participants mentioned that simulations circumvent the issues of having defective equipment or a lack of resources. Throughout the sessions, there were comments about their old apparatus (some was over thirty years old) which is often faulty:

> *"Using individual cells can cause issues with errors in connecting, dead batteries and loose contacts" (DP7)*

> *"Have found easy-read [meters] to become loose [connections]" (DP10)*

> *"Our easy-lab meters do not work as well - therefore more likely to use multimeters in school… require more direct from teacher for measurements to be taken (more independent working with UNILAB easy-read meters) (DP7)*

> *"Multimeters difficult to understand… too easy to pick the wrong measurement." (DP6)*

The reduction in technical support amplifies this as damaged resources gather and there is a lack of available staff to address the problems (Preproom, 2024). Participants commented throughout the workshop on the impact technicians have on the quantity and quality of practical work being carried out:

> *"technician support very limited" (DP6)*

> *"Technician support can be beneficial [troubleshooting faulty equipment]" (DP7)*

> *"Cost of replacing wires [expensive], [and] lack of technician support [to make new]" (DP9)*

> *"Ha[ve] to check own kit [no technician support]" (DP10)*

All participants mention they struggle to provide enough meters for class sets, especially when it would be good to use multiple rather than having to move one around. The cost is prohibitive and there are issues with space given classroom size, desk space and storage.

The availability of free online simulations allows for consolidation of concepts where educators are confident that the results are reliable. PhET was mentioned as having the added benefit of a visual representation of electrons within a circuit, which was felt to be useful for student understanding. A similar theory applied to models, where the use of movement, either with a rope, water, or students themselves, provided a physical link to ideas which are difficult conceptually. With that came the caveat that limitations in the models should be explained to prevent misconceptions (Wade-Jaimes et al., 2018). This led to a discussion of the importance of ensuring the correct terminology is used, as DP10 commented:

"What do you say? Charge flow? Flow per second? Voltage is push? etc. etc. Simplified [language] may be better"

This theme of how definitions are explained, especially at the very early stages of electricity teaching is an area which needs additional research.

All participants reported that one of the frustrations with their apparatus is the likelihood of faults, and even a simple circuit can contain many separate parts which makes troubleshooting problematic. Meters were mentioned as a resource in which establishments are lacking the required quantities. Due to the high cost to purchase Unilab easy-reads, multimeters tend to be chosen as an affordable multipurpose alternative despite students finding them confusing to use. Solutions were offered to address these issues, such as purchasing auto-ranging multimeters (although these are more expensive); a multimeter cover which limits students to the correct settings and sockets; and a 'testing box' for fault-checking wires, lamps and other components were suggested. The latter two are not commercially available, so require time, expertise and tools to create and produce in-house.

Conclusion

This work sought to understand current practical teaching practices with respect to electrical circuits. The low number of participants ($n = 5$) means that care must be taken not to simply generalise the findings, however the presentation of results and the conclusions outlined below are intended to allow practitioners to consider the outcomes in their own contexts around three main areas of pedagogical, technical and wider concerns – in Scotland and beyond.

Pedagogically, there is evidence of similarity across the participants in terms of activities and teaching order, with a particular highlight being the result of one participant intending to introduce additional practical work relating to resistance. Teachers are making good use of models, simulations and practical work in combination which is in line with research (Tenzin et al., 2024). One participant mentioned avoiding quantitative measurements at the BGE phase, and there was consensus that the visual aspect of lamps made the concepts easier to comprehend. More research, including practitioners considering this in their own practice, is required in this area. The teaching order described does appear to ensure that the key teaching points are introduced individually, and we would recommend this to avoid cognitive overload (Sweller et al., 2011).

In technical terms, the impact of budget cuts continues to be a challenge within education. The perceived reduction in technical support has an impact on the quantity and quality of apparatus, which chimes with recent literature (Gray et al., 2024). When purchasing equipment to teach practical physics, costs to replace old and faulty resources are prohibitive, especially for class sets. While it is indicated that an increased quantity (specifically more meters) or more reliable equipment may be advantageous, there is not a significant desire displayed to change equipment type. There was a consensus that mounted components and simple digital meters (which have had a long life span and are robust) are easy to use, though the slightly more complex multimeters are widespread due to cost implications. There is a need for an adequate technical support service to ensure that these items are in good working order and likely to achieve desired results. This would ensure that equipment is in good working order and faults are remedied. The outcome here is that policy makers should consider the wider implications of technical service reduction.

Some wider concerns go beyond the initial scope of this work but are worthy of further consideration. Out of field teachers introducing electrical circuits is a significant concern, as is the language used to describe the concepts. This aligns with the need to choose appropriate methods for the context (Preston, 2019). The concerns raised focussed on the abstract nature of electrical circuits and ensuring consistency in terms of terminology. Alignment of graphing skills across maths and physics is identified as an issue and there is a requirement to teach students about plotting and gradients prior to teaching Ohm's law. This is regarded as an area which should be developed in the maths classroom, but practitioners can be proactive in integrating these elements where required. We see these areas as clear next steps for research involving both teachers and students to bring together the ideas which have surfaced in this research and the previous findings relating to misconceptions (Moodley & Gaigher, 2019). Practical work continues to be core to the physics classroom, and it was noted that wider skills such as data collection an analysis were highlighted, and practitioners should consider this added benefit when allotting time in their classes to these activities. Using PAR, we created this project to enable educators to come together to collectively uncover the main challenges of teaching this area of physics, and to attempt to work with the research team to address these. Our C-TEIR framework was used to arrange the findings and the subheadings in each section (noted in Figure 1) are recurrent themes. Some of these elements appear under more than one heading, but this is indicative of how practitioners discuss them.

In terms of improvements which are actionable, there is a need to consider ceramic resistors where metal film resistors are currently used. Table 5 indicates a relatively consistent teaching order, however there is a need to consider research which indicates that voltage should be the introductory concept (Burde et al., 2022). The small differences in the table for Ohm's law and resistance, and series and parallel rules may act as a prompt for practitioners to consider their own rationale for teaching order with their own learners.

Our final consideration is that subject-specific participatory work appears to be beneficial to the professional development of the participants, allowing them to consider their current practice and extending an opportunity to consider how best to teach concepts which are familiar to them. In fact, this was commented on by one of the participants:

> *"More subject CPD would allow teachers to renew their own practice and discuss alternative approaches and best practices with other subject specialists - better teachers leading better learning experiences." (DP7)*

Further research is required to examine the teaching of electrical circuits at the BGE phase, with a view to address misconceptions and introduce suitable definitions at the first stage of students' secondary schooling.

Ethics approval statement

This study was approved by the University of Strathclyde Ethics Committee (approval no. UEC23/98) on 12/12/2023.

Author contributions

CRediT: **Laura Gray**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing; **Stuart Farmer**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing; **Iain Moore**: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Data availability statement

Data will be made available on reasonable request from the corresponding author. Alternatively, all data underpinning this publication are openly available from the University of Strathclyde KnowledgeBase https://doi.org/10.15129/85253694-72cd-4e15-af29-d3944eb3e1f4

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