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Bosh muharrir: Namangan davlat pedagogika instituti rektori B.E.Xusanov
Mas'ul muharrir: Ilmiy ishlar va innovatsiyalar bo'yicha prorektor M.R.Qodirxonov
Mas'ul muharrir o'rinbosari: Ilmiy tadqiqotlar, innovatsiyalar va ilmiy-pedagogik kadrlar tayyorlash bo'limi boshlig'i J.A.Yuldashev

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Filologiya fanlari: fil.f.d., prof. N.Uluqov, fil.f.d., prof. H.Usmanova, f.f.d., dots. X.Shokirova, p.f.n., dots. S.Misirov, p.f.n., dots. Sh.Ubaydullayev, PhD, dots. P.Lutfullayev, PhD, dots. M.Yakubbayev.

Texnik muharrir: R.Tursunov

Tahririyat manzili: Namangan shahri, Uychi ko'chasi, 316-uy.

Pochta indeksi: 160136, **Faks:** (0369) 227-27-21,

Email: Info@namspi.uz

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CASE-BASED TEACHING OF INFRARED THERMOGRAPHIC DIAGNOSTICS OF SUBSTATION EQUIPMENT TO ENERGY ENGINEERING BACHELOR STUDENTS IN DUAL EDUCATION

Abdullabekova D.R.

*Tashkent University of Information Technologies named after Muhammad al-Khwarizmi,
Department of Energy Supply Systems, Head of Department, DSc, Professor.*

abdullabekova_94@mail.ru

0009-0003-8887-6831

Abstract: *The article presents a case-based methodology for teaching infrared thermographic diagnostics of substation equipment to bachelor students of the energy supply programme who study in a dual format, alternating university sessions with work at an electrical substation. The methodology was designed from a task analysis of thermographic inspection, international qualification requirements and the typical errors of infrared surveys. Its core is a bank of teaching cases built from 35 radiometric thermograms of station service equipment recorded by the author at a 110 kV substation in Tashkent in June 2026. The article defines learning outcomes on the levels of the revised Bloom taxonomy, aligns a six-week module with the "2+3" dual schedule, proposes an analytic assessment rubric with four performance levels and describes the design of a pedagogical experiment for its validation. The cases deliberately include findings whose severity class changes when emissivity, reflected temperature and the choice of criterion are taken into account, so that students learn to report a diagnosis together with its uncertainty. Effectiveness data will be collected in the 2026/2027 academic year.*

Keywords: *dual education; engineering education; case-based learning; infrared thermography; substation equipment; diagnostic competence; assessment rubric; work-integrated learning*

DUAL TA'LIM SHAROITIDA ENERGETIKA YO'NALISHI BAKALAVRLARIGA PODSTANSIYA JIHOZLARINI INFRAQIZIL TERMOGRAFIK DIAGNOSTIKA QILISHNI KEYSLAR ASOSIDA O'QITISH

Annotatsiya: *Maqolada universitetdagi mashg'ulotlar elektr podstansiyasidagi ish bilan navbatma-navbat olib boriladigan dual shaklda tahsil olayotgan energiya ta'minoti yo'nalishi bakalavrlariga podstansiya jihozlarini infraqizil termografik diagnostika qilishni keyslar asosida o'qitish metodikasi taklif etilgan. Metodika termografik nazorat bo'yicha mehnat harakatlarini tahlil qilish, xalqaro malaka talablari va infraqizil tekshiruvlarning tipik xatolari asosida ishlab chiqilgan. Uning asosini muallif tomonidan 2026-yil iyun oyida Toshkentdagi 110 kV kuchlanishli podstansiyaning o'z ehtiyojlari jihozlarida olingan 35 ta radiometrik termogramma bo'yicha tuzilgan o'quv keyslari banki tashkil etadi. Blumning qayta ko'rib chiqilgan taksonomiyasi darajalari bo'yicha ta'lim natijalari belgilangan, olti*

haftalik modul "2+3" dual jadvali bilan muvofiqlashtirilgan, to'rt darajali analitik baholash rubrikasi taklif qilingan va uni tekshirish uchun pedagogik tajriba rejasi bayon etilgan. Keyslarga nurlanish koeffitsiyenti, aks etgan harorat va mezon tanlovi hisobga olinganda nuqson toifasi o'zgaradigan holatlar ataylab kiritilgan, bu esa talabalarni tashxisni uning noaniqligi bilan birga ko'rsatishga o'rgatadi. Samaradorlik bo'yicha ma'lumotlar 2026/2027 o'quv yilida to'planadi.

Kalit so'zlar: dual ta'lim; muhandislik ta'limi; keyslar asosida o'qitish; infraqizil termografiya; podstantsiya jihozlari; diagnostik kompetensiya; baholash rubrikasi; ish joyida o'qitish

ОБУЧЕНИЕ БАКАЛАВРОВ-ЭНЕРГЕТИКОВ ИНФРАКРАСНОЙ ТЕРМОГРАФИЧЕСКОЙ ДИАГНОСТИКЕ ОБОРУДОВАНИЯ ПОДСТАНЦИЙ НА ОСНОВЕ КЕЙСОВ В УСЛОВИЯХ ДУАЛЬНОГО ОБРАЗОВАНИЯ

Аннотация: В статье представлена методика обучения инфракрасной термографической диагностике оборудования подстанций на основе кейсов для бакалавров направления энергоснабжения, обучающихся в дуальной форме с чередованием занятий в университете и работы на электрической подстанции. Методика разработана на основе анализа трудовых действий при тепловизионном контроле, международных квалификационных требований и типичных ошибок инфракрасных обследований. Её основу составляет банк учебных кейсов, построенный по 35 радиометрическим термограммам оборудования собственных нужд, полученным автором на подстанции 110 кВ в Ташкенте в июне 2026 г. Определены результаты обучения по уровням пересмотренной таксономии Блума, шестинедельный модуль согласован с дуальным графиком «2+3», предложена аналитическая рубрика оценивания с четырьмя уровнями и описан план педагогического эксперимента для её проверки. В кейсы намеренно включены находки, категория дефекта которых меняется при учёте излучательной способности, отражённой температуры и выбора критерия, чтобы студенты учились указывать диагноз вместе с его неопределённостью. Данные об эффективности будут получены в 2026/2027 учебном году.

Ключевые слова: дуальное образование; инженерное образование; обучение на основе кейсов; инфракрасная термография; оборудование подстанций; диагностическая компетентность; рубрика оценивания; обучение на рабочем месте

INTRODUCTION

Infrared thermography has become one of the main non-contact methods for finding overheated connections, switching devices and transformer elements at substations under load [1, 2]. A thermal image makes an invisible process visible, and this property has long been used in university physics courses [3]. For an energy

engineer, however, a thermogram is evidence for a maintenance decision. Between the image and the decision lie the emissivity of the surface, the reflected apparent temperature, the load, the choice of a severity criterion and the uncertainty of each of these quantities, and it is in this chain, rather than in operating the camera, that the main sources of error lie [4, 5].

The Law "On Education" recognises dual education as a form of education [6], and the Concept for the development of higher education until 2030 sets the task of bringing training closer to the needs of employers [7]. In the energy sector, the President has instructed higher education institutions to organise dual-education practice for energy students systematically [8]. The Energy Supply Systems department of the Tashkent University of Information Technologies runs such a programme with "Issiqlik elektr stansiyalari" JSC and "O'zbekiston milliy elektr tarmoqlari" JSC: classes are held at an electrical substation and a heat centre, and third- and fourth-year students study under a "2+3" schedule (two days at the enterprise, three at the university) in the autumn semester and a "4+1" schedule in the spring.

Without a deliberate methodology, however, the enterprise days turn into observation and the university days remain lectures on radiation physics, and the two halves are never joined into the competence the employer needs: to plan a survey, acquire a valid thermogram, interpret it with its uncertainty and justify a decision. Qualification requirements for thermographers describe this competence not only in terms of camera handling but also in terms of knowledge of measurement errors, criteria and reporting [9], and inspection guidance recommends recording load, ambient conditions and camera settings [10, 11]. The author's survey of station service equipment at a 110 kV substation in a hot climate showed how sensitive the conclusions are to these factors: the same displayed differences could fall into different severity classes depending on the assumed emissivity and reflected temperature, and the rise over ambient air placed every

hotspot in the two highest over-ambient classes [12, 13]. Such observations show where a student's reasoning must be trained and provide authentic teaching material.

The aim of this article is to develop and substantiate a case-based methodology for teaching infrared thermographic diagnostics of substation equipment to energy engineering bachelor students in dual education. The objectives are to define learning outcomes from an analysis of inspection tasks, to build a bank of teaching cases from real thermograms, to align instruction with the dual schedule, to design an assessment rubric and to plan the experiment that will test the methodology. The article reports the design stage; no data on student achievement are presented, because the module will first be taught in the 2026/2027 academic year. The scientific novelty lies in (i) a model of diagnostic competence in thermography that includes the treatment of measurement uncertainty, (ii) a case bank built from authentic substation thermograms with deliberately ambiguous findings, and (iii) the alignment of the case sequence with the "2+3" dual schedule. The practical significance is that the module, the case cards and the rubric can be used directly in dual programmes in energy engineering.

LITERATURE REVIEW

A review of engineering-oriented studies found broad, though uneven, support for active, collaborative and cooperative learning [14], and a meta-analysis of 225 studies in science, engineering and mathematics reported higher examination scores and lower failure rates under active learning [15]. Case-based teaching, one of the inductive methods, starts from a realistic situation and requires the learner to analyse it and make a decision [16]; its use in a mechanical engineering course was perceived positively by students and yielded practical lessons for implementation [17]. Feisel and Rosa identified thirteen fundamental objectives of engineering laboratories, among them instrumentation, data analysis, learning from failure and safety [18].

Experiential learning theory describes a cycle of concrete experience, reflective observation, abstract conceptualisation and active experimentation [19], and the dual

format maps naturally onto it: the enterprise provides experience and experimentation, the university provides reflection and concepts. Cognitive apprenticeship adds that novices learn from practitioners who model the task, coach and gradually withdraw support [20]. Work-integrated learning develops employability skills most effectively when placements are structured and the university and workplace share expectations; poor alignment between them is one of its main barriers [21]. Uzbek authors likewise link the effectiveness of dual education in higher education to university–industry partnership, updated curricula and the preparation of teachers [22].

Such experiences benefit from constructive alignment of outcomes, activities and assessment [23] and from the revised taxonomy, which separates cognitive processes from types of knowledge, including metacognitive knowledge [24]. Worked examples and gradual fading of guidance work better for novices than open problems presented too early [25]. Authentic assessment should resemble practice in five dimensions – task, physical context, social context, form of the result and criteria [26]. Rubrics can enhance the reliability of scoring, especially when they are analytic and combined with exemplars and rater training [27], and feedback is most effective when it shows the goal, the current position and the next step [28]. The literature on teaching thermography itself concentrates on physics demonstrations [3] and on the method and its errors [1, 4, 5]; no published methodology was found that combines authentic substation thermograms, a dual schedule and the assessment of diagnostic reasoning under uncertainty for bachelor students.

MATERIALS AND METHODS

The study corresponds to the first, design phase of design-based research [29]: the instructional model is developed from theory and practice, and its empirical validation is a separate, planned stage. The methods were theoretical analysis of the pedagogical literature and normative documents, analysis of professional tasks, pedagogical

modelling and generalisation of the author's experience in substation diagnostics and dual education.

Task analysis. The task "infrared survey of substation equipment" was decomposed into actions on the basis of the qualification standard [9], the inspection guide [10], testing criteria [11, 30] and the author's field protocol for hot climates [13]. Seven groups of actions were identified: planning and safety; recording of conditions (load, air temperature, reflected temperature, emissivity); image acquisition; temperature correction; choice of a severity criterion; estimation of uncertainty; reporting and decision. These groups, together with the underlying physical knowledge, were converted into seven learning outcomes and placed in the revised taxonomy [24]; for each outcome the place of its development and the evidence of its achievement were defined [23].

Case bank. The source material is the author's survey of station service equipment at the 110 kV "Yuksak" substation in Tashkent on 9 June 2026 (about 12:58–13:16) with a Fluke TC01A camera: 35 radiometric thermograms recorded at about 1 m with the camera defaults of emissivity 0.95 and reflected temperature 25 °C, analysed in detail in [12, 31]. Cases were selected if the object is typical of what a graduate will inspect, the case contains a decision point at which a novice is likely to err, and the numbers needed for the decision are available. The intervals of the temperature differences combine plausible ranges of emissivity and reflected temperature for each surface, camera accuracy and the choice of the measurement area [12].

Sequence and assessment. The activities were arranged around the "2+3" autumn schedule so that each enterprise block is prepared at the university and analysed afterwards [19], with gradual fading of guidance [20, 25]. An analytic rubric was developed for the final task, a supervised survey with a written report [26], and the validation was planned as a quasi-experiment. Safety was a design constraint throughout: students work at the substation only under the supervision of authorised

personnel, measurements are made from a safe distance, and reference marks are applied only to de-energised or earthed parts by authorised staff.

RESULTS AND DISCUSSION

1. Learning outcomes and case bank

The learning outcomes (Table 1) cover five of the six levels of the revised taxonomy, from “understand” to “create”; three of the seven outcomes (LO4–LO6) are at the levels “analyse” and “evaluate”, because these are the levels at which errors in thermographic diagnosis arise. The outcome on uncertainty (LO5) involves metacognitive knowledge: the student must know not only how to correct a temperature but also when the result cannot support a firm conclusion.

Table 1. Learning outcomes of the module

No.	Learning outcome: the student is able to...	Taxonomy level	Developed at	Evidence
LO1	explain how a thermal camera forms its signal and how emissivity, reflected temperature and the atmosphere influence it	Understand	University	Concept test
LO2	plan a survey: choose the time and load, the safe position and the list of identical components to compare	Apply	University, enterprise	Survey plan
LO3	record the conditions of the survey (load, air temperature, reflected temperature, emissivity) and obtain radiometric images	Apply	Enterprise	Field record, files

No.	Learning outcome: the student is able to...	Taxonomy level	Developed at	Evidence
LO4	correct the displayed temperatures for emissivity and reflected temperature and compare similar components	Apply / Analyse	University	Case analysis
LO5	estimate the uncertainty of a temperature difference and state when it does not support a firm conclusion	Evaluate	University	Case analysis, report
LO6	choose and justify a severity criterion and assign a class with its interval	Evaluate	University, enterprise	Report
LO7	write a survey report with a justified recommendation for maintenance	Create	Enterprise	Final report

Six cases were formed from the survey (Table 2). Each is presented as a “case card” with the thermogram, the camera settings, the information available in the field and a question that requires a decision; the conclusion of the author’s analysis [12] is revealed only in the debriefing. Figure 1 shows the estimated temperature differences between similar components with their intervals against the classes of the comparative criterion: 1–3 °C possible deficiency, 4–15 °C probable deficiency and above 15 °C major discrepancy; for the rise over ambient air the same standard uses 1–10, 11–20, 21–40 and above 40 °C ([11], Table 100.18).

Table 2. Bank of teaching cases built from the survey of the “Yuksak” substation
(numbers from [12])

Case	Object and comparison	Estimated difference, °C (interval)	Decision point	Learning outcomes
1	Incoming LV breaker terminals, bay T1 vs identical bay T2	46.0 (45.0 to 65.1)	Unambiguous major discrepancy; worked example	LO4, LO6, LO7
2	LV lead connection, bay T1 vs bay T2	20.9 (19.9 to 30.6)	Major discrepancy; role of load and of equal loading of bays	LO2, LO4, LO6
3	Panel apparatus, upper part, bay T2 vs bay T1	13.0 (12.0 to 15.3)	Probable deficiency; upper bound just above the major-class boundary; which bay is “normal”?	LO4, LO6
4	Lower busbars, phase L1 vs L2 in one bay	6.0 (2.2 to 12.8)	Interval crosses a class boundary; report a range of classes	LO5, LO6

Case	Object and comparison	Estimated difference, °C (interval)	Decision point	Learning outcomes
5	Upper busbars, phase L1 vs L3 in one bay	2.0 (–1.1 to 6.0)	From “no deficiency” to “probable”; repeat the survey	LO3, LO5
6	Breaker and lead connections, rise over ambient air	Lower bounds of the rise from 25.6 to 90.6	Over-ambient criterion puts every component in the two highest classes (6 of 9 “major” at nominal values); it no longer ranks defects	LO1, LO6

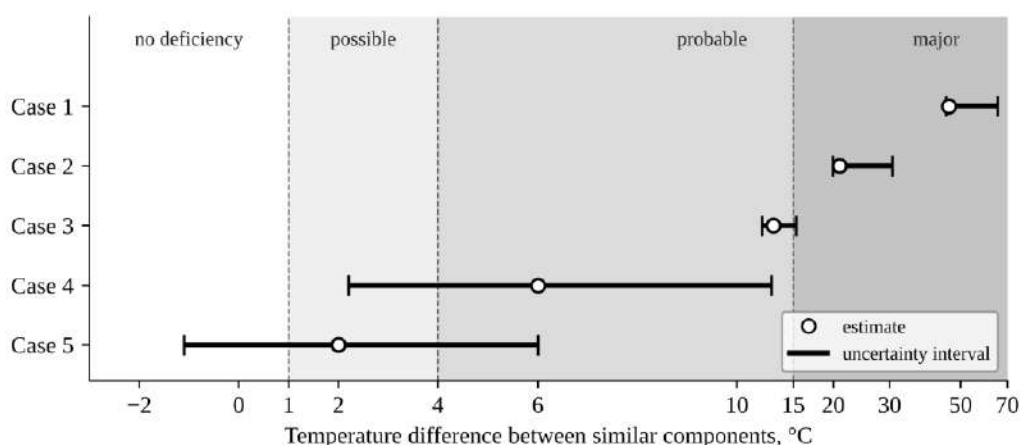


Figure 1. Estimated temperature differences between similar components in Cases 1–5 with their uncertainty intervals and the class boundaries of the comparative criterion; the horizontal axis is linear below 10 °C and logarithmic above (data from [12])

The cases form a progression. Case 1 is an unambiguous defect whose interval lies entirely in the highest class; it serves as a worked example in which the teacher models the full chain of reasoning. Cases 2 and 3 add the role of load, the requirement of equal loading of the compared bays and the question of which bay is the reference; in Case 3 the upper bound (15.3 °C) just exceeds the 15 °C boundary, and because the criterion is stated in whole degrees this is a borderline case that students must discuss. In Cases 4 and 5 the interval crosses one or two class boundaries, so the correct answer is a statement such as, for Case 4, “possible to probable deficiency; repeat the survey with recorded load and a reflected-temperature reference”. In Case 6, on a hot summer day, the rise over ambient air puts all loaded components into the two highest over-ambient classes (six of nine into the highest at nominal values), and the criterion no longer ranks defects [12, 13]; the case is designed so that students who rely on one threshold table discover this contradiction themselves [16].

2. Sequence of instruction in the dual format

The module occupies six weeks of the autumn semester; each week combines three university days and two enterprise days (Table 3). Over the six weeks the activities follow a four-phase cycle – preparation at the university, guided observation at the enterprise, case analysis and reflection at the university, and supervised practice at the enterprise (Figure 2). The enterprise phase shifts from guided observation (weeks 1–2) to supervised practice (weeks 3–6), and guidance is reduced from a worked example modelled by the teacher to a survey planned and reported by the student [20, 25]. Mentors receive a short briefing, the case cards and the rubric, so that comments at the substation use the same criteria as assessment at the university [21].

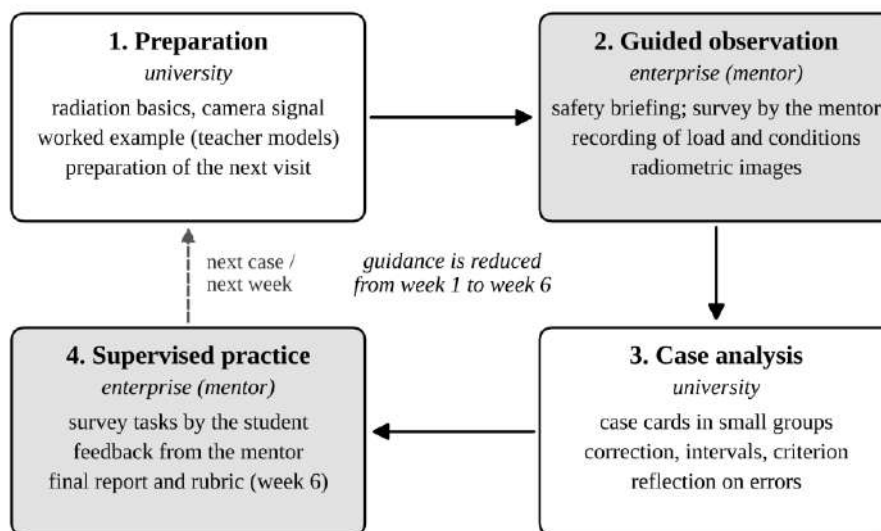


Figure 2. Four-phase cycle of instruction in the dual format

Table 3. Weekly plan of the module in the “2+3” dual schedule

Week	University (3 days)	Enterprise (2 days)
1	Radiation basics; signal of a thermal camera; demonstration of the effect of emissivity on bare and painted metal	Safety briefing; guided observation of a survey performed by the mentor; list of station service equipment
2	Worked example (Case 1): full chain from image to decision, modelled by the teacher	Recording of conditions: load currents, air temperature, reflected temperature with a reflector
3	Cases 2 and 3 in small groups: load, identical bays, emissivity correction	Acquisition of radiometric images of similar components under the mentor's supervision
4	Cases 4 and 5: uncertainty intervals, classes as ranges, decision to repeat a survey	Comparison of phases and bays on the students' own images; discussion with the mentor

Week	University (3 days)	Enterprise (2 days)
5	Case 6: choice of criterion; structure of a survey report; peer review of draft reports	Supervised mini-survey of a group of components selected by the mentor (final task)
6	Analysis of own survey; completion of the report; reflection on errors	Presentation of the report to the mentor; joint scoring with the rubric

3. Assessment and feedback

The final task is a supervised mini-survey of components selected by the mentor, followed by a written report; it reproduces practice in its task, context, form of the result and criteria [26]. The report is scored with the rubric in Table 4: six criteria rated on four levels, giving 6 to 24 points. A report that gives a single class without justifying the criterion and without an interval cannot reach level 3 on C5, however correct the class happens to be. The rubric is given to students at the start, because making criteria explicit is how rubrics are thought to support learning [27].

Table 4. Analytic rubric for the final survey report

Criterion	1 – Novice	2 – Developing	3 – Competent	4 – Proficient
C1. Planning and safety	No plan; safety requirements not mentioned	Plan lists objects only	Plan states objects, time, load and safe positions	Plan also justifies the choice of comparisons and conditions

Criterion	1 – Novice	2 – Developing	3 – Competent	4 – Proficient
C2. Recording of conditions	Conditions not recorded	Some of load, air temperature, ε , reflected temperature recorded	All four recorded	All recorded, with the method of determining each
C3. Image quality	Palette images only; objects out of focus	Radiometric files, but poor framing or distance	Focused radiometric images of all phases	Images also suitable for repeat surveys (fixed positions)
C4. Correction and comparison	Displayed values used as true	Correction attempted with errors	Correction and comparison of similar components without errors	Also checks the sensitivity of the result to ε and reflected temperature
C5. Criterion, class and uncertainty	Class without a criterion	Single class with a named criterion	Class with an interval and a justified criterion	Also states when the result is inconclusive and what to do
C6. Report and recommendation	No recommendation	General recommendation	Specific recommendation linked to the class	Recommendation with priority, timing and re-survey conditions

The literature on measurement errors [4, 5] and the author's field experience [12, 13] suggest the most likely student errors: taking the displayed temperature of bare metal

as true; leaving the camera defaults unchanged; ignoring the load; using the rise over ambient air as the only criterion on a hot day; reporting a single class without an interval; and saving only palette images. Most of these errors lead to a visible contradiction in at least one case, and feedback answers three questions – the goal, the current state of the report and the next step [28].

4. Planned validation

The methodology will be tested in the 2026/2027 academic year in a quasi-experiment with an experimental group taught with the module and a comparison group taught with the conventional sequence of lectures and laboratory work. The hypothesis is that the experimental group will show a higher normalised gain on a test of conceptual understanding and higher rubric scores. The test will be given before and after the module, and the result will be expressed as the normalised gain [32]:

$$g = \frac{S_{\text{post}} - S_{\text{pre}}}{100 - S_{\text{pre}}}, \quad (1)$$

where S_{pre} and S_{post} are the group mean scores in per cent before and after the module; the pre-test also checks the equivalence of the groups. Final reports will be scored by two independent raters, with agreement reported as weighted kappa (quadratic weights) for each criterion [33] and as the intraclass correlation ICC(2,k) for the total score [34]; group differences will be tested with the Mann–Whitney U test and reported with effect sizes. Mentors will also rate the students' work at the substation on the same criteria. The test will be reviewed by teachers of the department before use, approval will be sought from the university's competent body, participation will be voluntary and anonymised, and the study will not affect grades.

5. Discussion and limitations

The methodology treats the thermogram as data with uncertainty rather than as a picture, which moves the outcomes to the levels of analysis and evaluation, and it uses the dual format structurally, making the enterprise days phases of the experiential cycle [19, 21]. Cases from a real survey give authenticity that textbook examples lack, while

their link to the author's detailed analyses [12, 13, 31] gives the teacher checked numbers for the debriefing. The limitations are that the case bank comes from one survey at one substation in the hot season and covers mainly low-voltage station service equipment; that the availability of cameras and of authorised personnel limits the number of students surveying at the same time; and that the effectiveness of the methodology has not yet been measured.

CONCLUSION

A case-based methodology for teaching infrared thermographic diagnostics of substation equipment to energy engineering bachelor students in dual education has been developed. It comprises seven learning outcomes derived from an analysis of the professional task; a bank of six cases built from 35 thermograms of a real 110 kV substation, ordered from a worked example to cases whose severity class depends on corrections and on the choice of criterion; a six-week sequence aligned with the "2+3" dual schedule with gradually reduced guidance; an analytic rubric that rewards reporting a diagnosis with its uncertainty; and a quasi-experimental design for validation. The methodology targets not camera operation but the diagnostic reasoning that turns a thermogram into a justified maintenance decision, and it can be transferred to other condition-monitoring methods taught in the dual format. The next stage is teaching the module in 2026/2027, measuring its effectiveness and extending the case bank.

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