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Embracing a culture of talk: STEM teachers' engagement in small-group discussions about photovoltaics

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Abstract

Background Small-group discussions are well established as an effective pedagogical tool to promote student learning in STEM classrooms. However, there are a variety of factors that influence how and to what extent K-12 teachers use small-group discussions in their classrooms, including both their own STEM content knowledge and their perceived ability to facilitate discussions. We designed the present study to specifically target these two factors in the context of photovoltaics, an interdisciplinary field at the intersection of all STEM disciplines with potential to yield widespread benefits related to the use of solar technologies as a sustainable, renewable energy source. Teachers engaged in a series of small-group discussions based on photovoltaic source material (e.g., scientific articles) to build both their STEM content knowledge and capability with discussions, promoting their potential to design and deliver STEM instruction in their own classrooms using small-group discussion.

Results Overall, teachers productively engaged in rich STEM talk as they spent most of the time in the discussion asking authentic questions about photovoltaic topics in alignment with a variety of science and engineering disciplinary core ideas, responding to the questions with rich, elaborative talk, and taking on ownership of the discussions. Teachers also evidenced increases in their photovoltaic knowledge and their perceived capability to facilitate discussions. Finally, most teachers' end-of-program lesson plans included the use of small-group discussions, and a subsample of teachers who completed a follow-up interview one year after the summer program reported greater enactment of discussion in their STEM classrooms.

Conclusion Our manuscript forwards an important contribution that draws from a practice-based approach to professional development in a way that not only better prepares teachers on what to teach (i.e., through enhanced PV content knowledge), but it also supports their ability to implement this instruction into their classrooms more effectively (i.e., though the use of small-group discussion). As such, this manuscript illustrates an innovative pedagogical approach for potential use in supporting teacher education and informs ways to enable teachers to build enhanced curricula for their STEM students.

Keywords Small-group discussion, Practice-based teacher education, STEM discourse

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Introduction

In recent decades, nations and organizations worldwide have largely shifted the focus from teacher dissemination of science, technology, engineering, and math (STEM) knowledge toward emphasizing students' authentic engagement in meaningful STEM learning experiences centered on real-world problems and the integration of STEM disciplines (Moore et al., 2020). As such, preparing teachers to effectively facilitate STEM learning in their K-12 classrooms involves ensuring that teachers possess the requisite STEM content knowledge (Lo, 2021; Luft et al., 2020; Mohamad Hassim et al., 2022) and can implement integrative and cross-disciplinary STEM pedagogical practices (Brand, 2020; Jong et al., 2021).

In line with the shift toward emphasizing students' authentic engagement in disciplinary practices is a concomitant call for a greater recognition of the need to support students' oral and written STEM communication. In the US, for example, the Next Generation Science Standards (NGSS; NGSS Lead States, 2013) recognizes science and engineering as language-intensive disciplines, requiring students to communicate STEM information and ideas in multiple ways (e.g., orally and in writing) and contexts (e.g., individually and in groups; see also, Silvestri et al., 2021). Moreover, there is an increasing expectation that students should acquire the ability to engage in discussions about STEM-related topics such as energy and technological innovations (Cheng & So, 2020; National Academy of Engineering, 2008). Toward this end, small-group discussions may serve as a particularly valuable pedagogical tool for STEM classrooms, given the alignment with the visions and aims of STEM learning worldwide combined with the emphasis on oral communication. Thus, approaches are needed to support teachers' capability to employ small-group discussions in ways that align with STEM commitments to dialogic engagement and provide opportunities for students to explore multiple perspectives, develop their explanations and solutions, and pursue their priorities and purposes (see Jordan, 2022 and Sedova et al., 2016).

When learners are given the opportunity to engage in productive small-group discussions in STEM classrooms, they ask questions, construct explanations in response to those questions, and engage in argument from evidence, all while communicating ideas and information in a group setting (NRC, 2012). Consequently, their participation helps them to strengthen their conceptual understandings, collaboratively apply interdisciplinary knowledge and design solutions, as well as revise their thinking (Bennett et al., 2010; Chin & Osborne, 2010; Silvestri et al., 2021; Silverling et al., 2019). An ever-growing body of research has revealed a consistent, positive impact of small-group discussions on a variety of learning outcomes in STEM disciplines, including critical-analytic thinking and high-level comprehension about text and content (Murphy et al., 2018; Soter et al., 2009), understanding and the use of evidence (Bennet et al., 2005), reasoning and scientific thinking (Chin & Osborne, 2010; Mercer et al., 2004), and interest in science (Juuti et al., 2020).

Despite the known benefits of fostering dialogic approaches to small-group discussion, STEM instruction has traditionally been dominated by teacher-centered, transmissive approaches (Duschl & Osborn, 2002; Howe & Abdein, 2013). Even teachers who are committed to implementing discursive approaches may center transmissive approaches when they are faced with the realities of classrooms (Alozie et al., 2010; Alvermann et al., 1990). A variety of factors may contribute to teachers' tendency to rely on transmissive approaches in practice (Levinson & Turner, 2001). Bryce, Gray, and Day, for example, interviewed in-service science teachers over a series of studies and found that many expressed feelings of discomfort when leading science discussions (Bryce & Gray, 2004; Gray & Bryce, 2006). These feelings were pronounced for issues or topics where the teachers had less content knowledge (Day & Bryce, 2011). Additionally, Bennett et al., (2010) conducted a systematic review of research on the use of small-group discussions in high school science classrooms. Drawing from both systematic and anecdotal evidence they concluded that "many teachers lack skills and do not feel confident with small group discussions" (p. 71). Taken together, we posit that by providing teachers with opportunities to learn about and engage in STEM discussions, participating teachers may come away with increased STEM content knowledge as well as enhanced capability to use small-group discussions in their future classrooms.

Toward this end, we embrace a practice-based approach to teacher education (Ball & Cohen, 1999; Kademian & Davis, 2018). Teachers engaged in a series of small-group discussions primarily to build their STEM content knowledge. However, we also explored multiple sources of evidence regarding the potential impact on their enactment of discussions after participation. In essence, our work employed a "two-pronged effort" (Parker & Hess, 2001, p. 273), where we aimed to build in-service teachers' comprehension about STEM content "*with* discussions", while also preparing them *"for"* using STEM discussions in their own classrooms.

In this study, we focused specifically on integrating science and engineering content knowledge related to the field of photovoltaics (PV; i.e., how light energy is directly converted into electricity using solar cell technologies). PV offers an important and timely field for exploration in K-12 STEM classrooms (e.g., Machuve & Mkenda, 2019) due to its potential to yield widespread social, environmental, and health benefits by mitigating climate change, pollution, water scarcity, and more (Wiser et al., 2016). PV is likely to play a major role in predicted shifts to post-carbon energy transitions, whereby the twenty-first century will largely see the dissolution of current energy infrastructures in favor of societies sustained by renewable energy sources (Abramsky, 2010; Bridge et al., 2018; Pasqualetti, 2021). Any future mix of sustainable energy generation will likely include a substantial global investment in solar technologies (Miller, 2022; Jaxa-Rozen & Trutnevyete, 2021). These global considerations are already creating a greater need for STEM workforces with PV knowledge and skills (Kurtz et al., 2020; Kwatra & Steiner, 2022; SOLA, 2021; US Department of Energy, 2016). These needs are underscored in a variety of different ways. For example, in relation to the NGSS (2013), HS-PS3-3 focuses on students' ability to "design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy", which directly aligns with the fact that PV involves using solar panels to convert light energy into electricity. Moreover, the context of the current study was a Research Experience for Teachers (RET) program funded by the U.S. National Science Foundation (NSF) and Department of Energy (DOE), which testifies to PV as an important stream of ongoing research investment related to global energy futures.

From a STEM learning perspective, PV is an interdisciplinary field requiring the intersection of knowledge across all STEM disciplines to advance solar cell technologies and integrate them with new and existing energy systems (Begmatovich & Anora, 2021; Biniet & Nielsen, 2016; Brogren and Green 2003; Zacchia et al., 2022). Foundational understanding of PV, for instance, includes comparing the electrical conductivity of semiconductor materials, understanding technological tools and chemical processes associated with the manufacturing of solar cells, tracking and calculating the energy generation and transfer through PV electrical power systems, and designing novel applications of solar energy. Science is represented with aspects regarding how PN junctions are formed at the atomic level (Nelson et al., 2017), technology is used to measure solar irradiance through nano-board technology, engineering is used to build and test the manufacturing of solar cells, and math is required to compute complex formulas for power input and output. Real-world applications derived from this integrated knowledge base include, for instance, the use of solar technologies to improve agricultural production, reduce the proportion of carbon-emitting energy sources on electrical power grids, and provide energy access to under-resourced communities, remote telecommunications towers, and space stations. Learners who participate in the RET program engage in all four STEM disciplines as they complete an engineering research project and develop specific plans to bring PV back into their classrooms. The program as a whole emphasizes how scientific and engineering concepts, practices, and discourse form an interconnected system integral to scientific understanding and engineering solutions (NRC, 2012).

Given how rapidly PV energy technological innovations are advancing, many K-12 teachers do not yet have the necessary interdisciplinary content knowledge to implement effective STEM instruction in this important area (Antink-Meyer & Alderman, 2021; Liarakou et al., 2009; Zyadin et al., 2014). Few studies to date have explored how K-12 students come to understand PV, although notable exceptions include Cole et al.'s (2023) exploration of how the presence of learnscapes influence elementary students' understanding of solar energy systems and Tobin et al.'s (2018) case study of fourth-graders' model-based reasoning. More importantly, however, we could not find any studies that explored how teachers develop PV knowledge. Thus, STEM teachers must be provided with learning opportunities to build on their existing knowledge base and promote their understanding of this content while also enabling them to better incorporate it into their classrooms and prepare the next generation of scientists and engineers to make progress advancing renewable energy innovations (Aschbacher et al., 2010; Ing et al., 2014; Merritt et al., 2023).

Conceptual framework for the use of small-group discussions to promote learning

Over the last 50 years, a relatively large body of research pertaining to discussion-related pedagogies in the classroom has accumulated (Mercer & Dawes, 2014; Wilkinson et al., 2015). These approaches vary widely in nature (e.g., size or structure of the group) and may serve to support different learning goals. We situate our work within this broader body of literature by focusing on small-group discussions that specifically aim to help learners achieve high-level comprehension of STEM text and content. As such, we embrace a complex, multifaceted conceptual framework, drawing from cognitive, social constructivist, and sociocultural theories (see Croninger et al., 2018 for a review)—a common approach within the broader field of discussion-related pedagogies (Wilkinson & Tsai, 2011; Wilkinson et al., 2015). Most centrally, however, our work is informed by Vygotsky's sociocultural perspectives of learning (1978) and Bakhtin's theories of dialogism (1981). We embrace the value of talk as a tool for learning in the classroom, where learning first occurs on the social level between individuals and then internally within a given learner (Vygotsky, 1978), and examine the ways in which small-group discussions can serve to promote learners' thinking and learning as a dialogic process. Moreover, learners' participation in small-group discussions can provide evidence of their learning; as students verbalize their thinking, the talk provides an opportunity to gauge their reasoning (Grangeat et al., 2021). Given our conceptual framing and recognizing that discourse is central to thinking and understanding, we engaged teachers with small-group discussions to benefit their understanding of PV while also aiming to better prepare them to use small-group discussions about PV in their classrooms.

Engaging teachers with small-group, PV discussions STEM teachers are often given opportunities to engage in discussions within professional development contexts or through communities of practice. These discussions, while productive and beneficial, often focus on supporting teachers' pedagogy—that is, teachers talk about and analyze their classroom instruction, the impact on students' learning, and areas to focus on for improvement. The discussions may be informed by scenarios of classroom instruction (e.g., through video-based professional development programs, Borko et al., 2017; Pehmer et al., 2015; Roth et al., 2017; Tekkumru-Kisa & Stein, 2017 or animated classroom scenarios, Aaron & Herbst, 2015) or more loosely guided by teachers' reflections about their classroom experiences and approaches for teaching STEM content (Brand, 2020; Dudley & Vrikki, 2019; Weinberg et al., 2021). There is growing evidence that teachers can benefit from engaging in professional development opportunities from the perspective of the learner (Jaber et al., 2022; Lowell & McNeill, 2020). Lowell and McNeill (2020), for example, asked teachers to take on the learner perspective to engage in investigations and discussions around a sixth-grade unit on light as part of a professional development program. Engaging as if they were students, teachers evidenced an enhanced understanding of the science content in addition to gaining experience in a novel science inquiry approach. However, the extant research that centers specifically on teachers engaging in small-group discussions about STEM texts in order to better understand STEM content is comparatively under-examined.

We have chosen to extend the Quality Talk (QT) approach, based on prior evidence of successful implementation in both high school science classrooms (Murphy et al., 2018) as well as with pre-service teachers (Lloyd & Murphy, 2023). QT is an approach to small-group discussion specifically designed to support participants' critical-analytic thinking and high-level comprehension about text and content (Murphy et al., 2018; Soter et al., 2009). Our use of QT adapts the key components of the framework (Murphy et al., 2022) for the present context (e.g., in-service teachers learning about PV; see also Starrett et al., 2022). Thus, discussions take place in small groups with in-service teachers as learners, are characterized by the asking and answering of meaningful, authentic questions, are learner-centered in that the discussion facilitator guides the discussion rather than using it for didactic teaching, and are guided by the principle that language is a tool for thinking and inter-thinking (Murphy & Firetto, 2018). By engaging in discussions, teachers can build their PV knowledge.

Using a practice-based approach Ball and Cohen (1999) discussed a need for education reform to involve teachers in becoming learners using the targeted pedagogical practices rather than simply being told about classroom approaches. One novel way to address this reform involves utilizing a practice-based approach, whereby teachers are provided with experiential practice, and through their engagement, they enhance their capability to enact the instructional practices (Ball & Cohen, 1999; Kademian & Davis, 2018). There is a growing body of empirical support for the use of practice-based teacher education for STEM education and with discussion-related pedagogies. For example, Osborne et al. (2019) examined three different iterations of a weeklong, practice-based, discussion-focused, professional development and found that all three resulted in enhanced teacher and student discourse practices in the classroom. Likewise, Pehmer et al. (2015) compared two professional development approaches (i.e., Dialogic Video Cycles [DVC] vs. a control) designed to target teachers' use of discussions in science classrooms; the DVC professional development included active, collaborative, and reflective practice-based dialogue and the control did not include facilitated dialogue. These researchers found that students in the classrooms of DVC teachers evidenced greater learning benefits than those in the classrooms of teachers who participated in the control condition. Teachers also reported valuing the opportunity to actively engage and experience learning from a student perspective, ultimately impacting both their self-efficacy and confidence related to implementation (Haug & Mork, 2021). Thus, we also provided opportunities for teachers to engage in STEM discussions in order to better prepare them to utilize small-group discussion approaches in their future STEM classrooms.

The present study

The present study was conducted within the context of a 5-week summer Research Experience for Teachers (RET) program, where we embedded the Quality Talk (QT) discussion approach to support in-service teachers' engagement in and enactment of discussions about PV science and engineering. We maintain that it was necessary to first understand how and in what ways the teachers engaged in the discussions, particularly given that this was the first implementation of QT with in-service teachers in the PV RET context:

RQ1: To what extent do teachers productively engage in small-group PV discussions?

Next, we looked at pre-test to post-test changes for both teachers' PV knowledge and their perceived capability at facilitating discussions. In essence, we wanted to investigate whether there was evidence that the discussions were effective at engaging teachers *with* small-group discussions about PV in ways that (a) yielded a greater foundational understanding of the content and (b) impacted their likelihood of using small-group discussions, based on self-reported changes in their capability *for* facilitating discussions:

RQ2: What changes are evidenced over time with regard to two key variables that can impact teachers' implementation of small-group STEM discussion in the classroom (i.e., teachers' PV knowledge and their perceived capability to facilitate small-group discussions)?

Ultimately, however, it is perhaps of the greatest interest to examine the impact on teachers' instruction in their classrooms. Thus, we looked at teachers' expressed intention to enact small-group discussions in their classrooms at the end of the program. Further, while it was not within the scope of this study to conduct classroom observations or collect data from students, we also gathered retrospective descriptions of classroom practices one year after participation from some of the teachers:

RQ3: To what extent do teachers evidence potential for facilitating discussions in their STEM classrooms, as evidenced in their end-of-program lesson plans and retrospective descriptions of their classroom practices after one year?

Methods

Participants

Participants were in-service K-12 teachers ($N=7$; 6 women and 1 man; 6 White and 1 Latinx) all taking part in a summer PV RET program at a university in a large urban center in the southwestern US. One year after the program, a subsample ($n=4$) of teachers completed an optional, follow-up interview. Additional participant information is noted in Table 1; pseudonyms are used throughout. IRB approval was obtained, teachers consented to participate in the research, and all procedures were followed in accordance with the approved protocol. While there was no compensation for participating in the research for the main portion of the study, those who completed the follow-up interview were provided with a $25 Amazon.com gift card as compensation for the additional time.

Setting

The overarching aim of the PV RET is to enrich in-service teachers' STEM content and pedagogical knowledge to benefit their future students' PV learning. In the program, participating teachers: (a) learn about PV science and engineering content knowledge through a series of seminars taught by content experts (e.g., solar cell scientists); (b) contribute to ongoing PV research in a lab setting while being mentored by an engineering faculty member and graduate student (i.e., manufacturing and experimenting with solar cells); (c) read and view source material (e.g., scientific articles and videos) to learn about PV science and engineering; (d) complete a solar energy engineering research project of their own; and (e) collaborate with educational researchers to create engaging STEM curriculum for future classroom implementation. The PV RET is an ongoing endeavor that has been successfully implemented for over a decade (Jordan & Rowlands, 2021), although the present study reports the findings from the first time the authors embedded Quality Talk into the program (see Starrett et al., 2022 for a more detailed program outline). Part of our desire to refine the RET program by adding QT was to provide participating teachers with a stronger foundational knowledge of PV. Participants in prior years had informally requested additional support in understanding the PV source material in preparation for their research

Table 1 Teacher background information related to PV knowledge and STEM teaching

Name	PV background	STEM teaching experience
Alex*	Limited experience with PV	Advanced science
Barrett*	Limited experience with PV	Novice elementary
Cat	Moderate experience with PV	Advanced middle school science
Dakota*	Limited experience with PV	Advanced middle and high school science, math, and engineering
Ed	Limited experience with PV	Advanced high school engineering and math
Fran*	Moderate experience with PV	Advanced elementary and middle school math and science
Georgia	Limited experience with PV	Advanced science

*Participated in the optional, follow-up interview project and curriculum development. QT was specifically infused into the program to address this need by allowing teachers to learn the requisite content interactively with others (i.e., through the small-group discussions) rather than through passive presentations of content.

Data sources and materials

Discussion data Over the first two weeks of the program, teachers engaged in five, 20- to 25-min discussions about PV. Before each discussion, teachers engaged with pre-selected PV source material (e.g., articles or videos) related to what they were learning about in the program at that time. Specifically, the first week had a greater emphasis on PV science, while the second week had a greater emphasis on PV engineering in preparation for the completion of their research project, which focused on improving and testing the design of a solar irradiance measuring device (see Table 2). For all five discussions, the first author (i.e., the discussion facilitator) and all seven teachers were seated around a table in a private room with a 360-degree camera and microphone at the center.

Digital journal artifacts Each teacher had a digital notebook they kept throughout the program, where they wrote authentic questions as they were engaging with the source material so that they could be prepared to ask them in the discussions. They also used the notebook to write responses to brief reflection prompts, take notes, and record progress on their research project. On the first day of the program, teachers responded to a set of questions asking about how frequently they engaged in discussion in the previous school year and were asked to describe what it looked like. The digital journals were collected at the end of the program for fidelity and research purposes.

Group observation instrument Pazos et al.'s (2010) Group Observation Instrument contains 10 bi-polar, Likert-type items designed to measure learner-centered group learning through two subscales and has a large body of evidence related to the reliability and validity of scores. For example, both subscales yielded high internal consistency (i.e., $\alpha > 0.86$), high inter-rater reliability (i.e., the intra-class correlation coefficient across four raters was 0.94), and group interaction style subscale scores statistically significantly predicted confidence in course performance ($b = 0.224$, $p = 0.045$).

Given our specific context, we made revisions to the instrument (i.e., three items were removed and two items were revised to reduce ambiguity). All authors rated each discussion based on bi-polar, Likert-type scale items; three items pertained to the degree of elaborative responses in the discussion (i.e., *high* [5] vs. *low* [1]), and four items were associated with who held ownership and responsibility over the discussion (i.e., *learner* [5] vs. *facilitator* [1]). For each discussion, items within each subscale were averaged across ratings by all three authors. Means closer to five indicate higher elaborated talk and more learner ownership over the discussion; standard deviations serve as a measure of agreement (i.e., both across items and between raters with lower standard deviations indicating greater consistency). Across 35 possible ratings (i.e., 7 items and 5 discussions), the three authors had either perfect agreement or agreement within one point (e.g., scores of 5, 5, and 4) for all but one item.

PV knowledge assessment The PV knowledge assessment measured foundational content knowledge specifically related to the science of solar cell manufacturing, requisite for an understanding of the more complex disciplinary core ideas (e.g., HS-PS3-3). Importantly, the assessment was designed to gauge teachers' basic comprehension of PV content as a necessary foundation for teachers within the program (i.e., to more effectively engage in their research project) and beyond (e.g., in their classrooms). The assessment contained six dichotomously scored (0 or 1) multiple-choice items (e.g., "Which characteristic is the same for all photons (choose one answer): (a) speed of the photons; (b) energy stored in photons; (c) wavelength of the photons; (d) all of the above; (e) prefer not to respond.") and two open-ended items scored from 1 to 3 (e.g., "Below, we've drawn a solar cell consisting of a p-doped region (orange), n-doped region (blue). Sketch, label, and explain a PN junction."). The potential range in scores was 0 to 12 points. The same items were administered at both pre-test and post-test. Two researchers independently scored all items and negotiated all points of disagreement. In order to obtain a large enough sample size to calculate an estimate of internal consistency, we collapsed responses across both administrations and combined the data with a larger sample of participants ($n = 44$; $\alpha = 0.77$).

Perceived discussion facilitation capability measure The discussion facilitation capability measure included five items related to teachers' perceptions regarding their ability to facilitate discussions in their classrooms (e.g., "*Right now, in my personal teaching, I am very capable of…* fostering student discourse aligned with STEM content.). The italicized portion of the stem was the same across all items, and anchors ranged from strongly agree (5) to strongly disagree (1). Scores were averaged across the five items to account for a small percentage (~2%) of missing data at the item level. The same items were administered at both pre-test and post-test.

End-of-program lesson plans At the culmination of the program, each teacher designed a STEM lesson plan they intended to use to teach their future students about PV

Table 2 Discussion descriptive information and topics

Discussion (time)	Discussion topic	Assigned source material	Citation	Brief description of source material
D1 (24:28)	The science behind how solar cells work	Five videos produced by former RET participants	QESST. (n.d.). *Instructional videos: Introduction to photovoltaics*. https://qesst.org/education-and-outreach/videos/	Videos, created by former RET participants, were designed to serve as a brief, five-part series focused on introducing the basics of solar cell manufacturing
D2 (20:16)	How industrial silicon solar cells are manufactured	First half of the article	Neuhaus, D.-H., & Münzer, A. (2007). Industrial silicon wafer solar cells (1–15). *Advances in Opto-Electronics*. https://doi.org/10.1155/2007/24521	The first half of this article focuses on manufacturing equipment, giving a step-by-step description of the production of screen-printed solar cells
D3 (25:15)	Alternative methods for manufacturing solar cells	Second half of the article	Neuhaus, D.-H., & Münzer, A. (2007). Industrial silicon wafer solar cells (1–15). *Advances in Opto-Electronics*. https://doi.org/10.1155/2007/24521	The second half of the article focuses on efficiency losses in solar cells, advanced solar cell options, and new solar cell technology
D4 (24:18)	Engineering elements behind PV system performance	Article	Pearsall, N. M. (2017). Introduction to photovoltaic system performance. In The Performance of Photovoltaic (PV) Systems (pp. 1–19). Woodhead publishing. https://doi.org/10.1016/B978-1-78242-336-2.00001-X	This chapter describes the basic functions of photovoltaic systems by introducing design elements, applications of different components, and performance parameters
D5 (22:51)	Design and application of measuring solar irradiance	Article	Wolf, A., Johnson, M., Currier, S., Hall, E., Bowden, S., & Killam, A. (2018). Creating an inexpensive instrument to accurately measure solar irradiance (pp. 1–5). Unpublished report. School of Electrical Engineering and Computer Energy. Arizona State University	This article introduces a new instrument as an alternative way to measure solar irradiance, describing applications and calibration processes

science. Teachers received general pedagogical guidance from expert educators, including the third author who served as the education director of the PV RET program. Importantly, however, the first author, who facilitated the discussions and collaborative discourse sessions, did not have a direct role in teachers' lesson plan development. All teachers used the same template (e.g., materials and equipment, educational standards, vocabulary words) to guide their three-part lesson plan (i.e., Introduction and Motivation, Learning Activities and Strategies, Closure).

Follow-up interviews A subsample of teachers participated in a brief, semi-structured interview one year after the PV RET program. The interviews were guided by three questions: "Over the last school year, how often have you engaged in STEM discussions with colleagues? Over the last school year, how often did you implement STEM discussions with your classes? Can you share how the STEM discussions last year were similar to and/or different from previous years?" Teachers were asked follow-up questions as appropriate, to gather additional details about their use of discussions over time, specifically as they related to frequency, duration, topic, number of participants, location, and quality. At the end of the survey, the interviewer read each of the five statements from the perceived discussion facilitation capability measure and asked teachers to provide a retrospective comment on whether or how their capability in that area has changed over time. The approximately 15-min interviews were conducted and recorded in Zoom; audio transcripts were exported from Zoom and hand cleaned by the authors for analysis.

Procedures

Participating teachers completed all pre-test measures before an interactive orientation session where they learned about the QT discussion approach and basic information about PV science and engineering. The approximately 2-h session included information for teachers about the components that make up QT (e.g., asking questions, responding with reasons and evidence, using teacher moves to facilitate the talk) along with opportunities to practice each one within the context of PV. For example, after teachers learned about the concept of authentic questions, they practiced writing authentic questions about a short informational video about solar cells. Using these questions, the teachers engaged in a brief practice discussion that was recorded. At the end of the session, the recording was used to provide an opportunity for the teachers to share out and reflect on the components of QT and the degree to which they were evidenced in their talk on the recording.

Over the first 2 weeks of the program, the teachers participated in five QT discussions. Teachers took the post-test PV knowledge assessment after week 1, as it focused narrowly on the content from the first three discussions. After the fifth discussion, teachers began developing a lesson plan for their classrooms. To support these efforts, the first author led two collaborative discourse sessions that centered on the pedagogical use of discussion in the classroom. For these sessions, teachers read an article related to the use of small-group discussion in the classroom and collaboratively discussed how they might use discussions in their future teaching (see Starrett et al., 2022). The two collaborative discourse sessions loosely followed the QT format, but they were implemented as part of the larger program and professional development, rather than to support teachers' PV knowledge. These sessions provided a space for the teachers to discuss the role of the teacher and facilitator in small-group discussions after having participated in the five content knowledge discussions, as well as brainstorm pedagogical strategies to embed this structure into their regular classroom routines, further supporting the use of practice-based professional development (Ball & Cohen, 1999; Kademian & Davis, 2018). The last 3 weeks of the program centered on using the foundational knowledge about PV derived from the first two weeks to: (a) complete a PV research project where they built and tested a novel solar irradiance device and (b) designed a lesson plan to use in their classrooms. Teachers' lesson plans and the post-test discussion capability measure were collected in the final days of the program. Approximately one year later, the first author conducted follow-up interviews via Zoom. See Fig. 1 for a timeline of study procedures.

Data analysis and design

Teachers' engagement in QT discussions We took a multi-pronged, mixed methods approach to data analysis for our first research question to gather a comprehensive understanding of the extent to which teachers productively engaged in small-group STEM discussions. We gathered evidence from both the discussion data as well as the group observation instrument to understand both the ways teachers discussed PV during the discussions as well as the extent to which teachers took on ownership over the discussions. We conducted our qualitative content analysis of the video-recorded discussions guided by the Quality Talk Discourse Coding Manual (Murphy et al., 2017) and using Vosaic cloud software (Vosaic, 2021).

We first identified segments of the discussion where teachers were productively engaged in PV talk associated with *authentic question* (AQ) events. AQ events represented segments of talk initiated by authentic, open-ended questions along with all responses to that

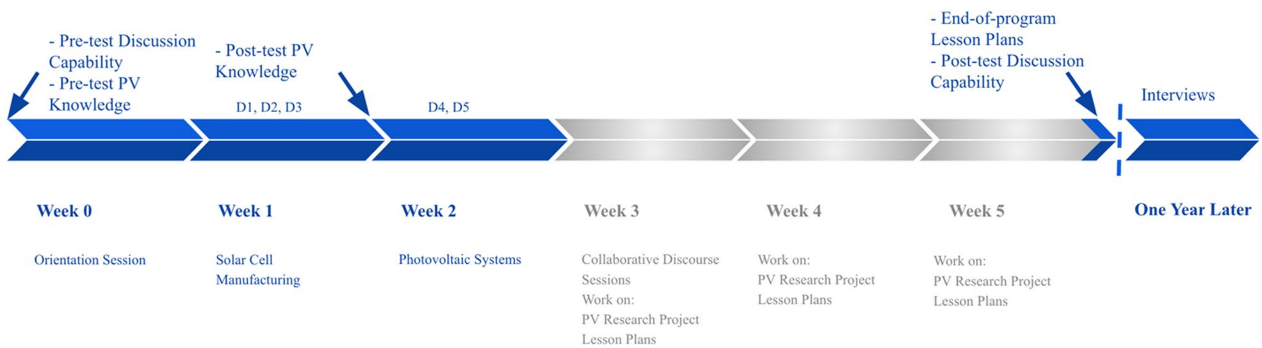

Fig. 1 Timeline of study procedures with data sources. Blue features of the timeline (e.g., arrows and text) represent aspects related to this study within the context of the larger RET program. The top half of the timeline represents measures and data collected, while the bottom half represents related program activities and topics. D = discussion

question. For example, Fran opened the first discussion by asking, "… something I was wondering about is, and I don't know a lot about physics or chemistry, but can two or more lower energy photons work together to knock an electron into the conduction band? …", which the group discussed for 2 min and 37 s. Events were coded based on an evaluation of the full segment of discourse (i.e., the initiating question along with all responses to that question) to determine whether or not the question was authentic or not. Then, for each of the AQ events, we conducted a secondary level of coding that enabled us to get a better sense of the breadth of science and engineering topics teachers talked about in the discussions by identifying the alignment of each AQ event with the disciplinary core ideas (DCIs) forwarded by the NGSS (NGSS, 2013). In the example above, the AQ event was noted as having a primary focus on PS2.B (i.e., PS2: Motion and Stability; B: Types of Interactions).

We also explored the depth of substantive talk teachers engaged in by identifying *elaborated explanations* (EEs; Murphy et al., 2018) within the AQ events. EEs represent single, uninterrupted turns of one participant involving extended talk that includes multiple pieces of reasoning or evidence in support of a claim (Soter et al., 2016). For example, within Fran's AQ event above (i.e., about the number of photons needed to affect the movement of electrons between the valence and conduction bands), Dakota responded by saying, "I think it's a 1 to 1 ratio, isn't it? Because there's only one hole—there has to be one. Well, no, I think something like that did happen where it's two, but one of them kind of shifts over?" We calculated both the frequency and duration of AQs and EEs to gather a better awareness of the depth of the PV talk across the discussions. AQ and EE codes were independently identified by two authors (i.e., initial agreement for the two coders was high and ranged from 91.3% to 98.28%) before coming to a consensus on all codes for all discussions.

In order to get a sense of who held the ownership within the discussions, we identified who asked each AQ and who stated each EE, as well as the proportion of each speaker's *talk time* (TT). TT was calculated automatically via the Vosaic software, whereby a total time (in seconds) was calculated for each speaker in each discussion. Specifically, talk time was only allocated to the speaker who "held the floor" at any given time (i.e., if multiple speakers were speaking only the main speaker accrued talk time). Proportions were calculated for each speaker based only on total talk time, not accounting for the brief pauses between turns or questions. We also incorporated complementary quantitative findings derived from the group observation instrument, specifically with regard to the degree of elaborated responses in each discussion (i.e., high vs. low) as well as who held ownership and responsibility of each discussion (i.e., learner vs facilitator).

Key variables impacting discussion implementation We adopted a convergent mixed methods approach to examine RQ2, whereby we employed paired samples t-tests (IBM Corp., 2021; AI-Therapy Statistics, 2021) to quantitatively examine the pre-test to post-test changes for both teachers' PV knowledge and their perceived discussion facilitation capability. Given our limited sample size, we focus exclusively on the interpretation of effect sizes for the quantitative results in conjunction with the merged qualitative findings from the follow-up interviews. Specifically, for the qualitative portion, the authors used both ATLAS.ti and Google Documents to record detailed analytical memos (Saldaña, 2013) on the transcribed interviews related to both teachers' PV knowledge and their capability to facilitate small-group discussions.

Discussion enactment potential The analyses for RQ3 focused on teachers' design and enactment of discussions in their own classrooms. We employed a single-case study approach with *teacher* as the embedded unit of analysis (Yin, 2009) using both the end-of-program lesson plans and the follow-up interviews to understand how teachers designed and enacted instruction related to classroom discussion. Our analysis of the lesson plans was guided by a theory-driven content analysis (Haggarty, 1995; Krippendorff, 2004), whereby we a priori identified and examined the lesson plans for aspects specifically related to teachers' use of discussions and questioning. Likewise, for the follow-up interviews we searched for a priori identified categories related to their discussion implementation and capability to help guide our analysis (DeCuir-Gunby et al., 2011). To increase dependability and credibility, the first and second authors independently reviewed the lesson plans and interviews, in both ATLAS.ti and Google Documents, and then met to collaboratively produce the resulting table and identify themes, allowing the opportunity to collaboratively debrief and discuss interpretations (Lincoln & Guba, 1985). The third author conducted a final fidelity check.

Results

In the results section below, we discuss results related to each research question, in turn. In line with our first aim, we looked at the extent to which teachers productively engaged in the small-group PV discussions (RQ1). We also looked at changes in teachers' PV content knowledge and their perceived capability to facilitate discussions (RQ2). Finally, we looked at teachers' design and enactment of classroom discussions after participating in the PV RET with QT small-group discussions (RQ3).

Teachers' engagement in QT discussions

Our qualitative examination of teachers' productive engagement in the QT discussions was operationalized through three key indicators. This allowed us to get a better sense of how and in what ways teachers engaged in talk related to PV during the discussions. We first examined the extent and breadth of talk associated with AQ events, as evidenced by the proportion of total talk time designated as part of an AQ event and the distribution of DCI science and engineering topics that they discussed. Additionally, we looked at the talk that occurred during segments that were not coded as part of an AQ event to understand what else was occurring in the discussions. Second, we conducted an examination of the degree of elaborative talk present within the discussions to get a sense of the depth of thinking that teachers evidenced. Finally, we looked at both the patterns of participation by teachers as well as individual talk time to understand if the discussion was more learner-centered (i.e., with teachers holding ownership and responsibility over the discussion) or if the talk was driven by the facilitator.

Authentic questions First, we investigated the extent to which teachers engaged in discussions in ways that involved asking and answering authentic questions about PV science and engineering content. As illustrated in Table 3, we found that the majority of talk time was designated as part of an AQ event related to PV science and engineering (i.e., D1: 70%, D2: 71%, D3: 93%, D4: 75%, D5: 91%; overall: 80%).

Within the AQ events, teachers discussed concepts and phenomena in line with the PV science and engineering focus of the PV RET closely aligned with the physical sciences (PS, 11 out of 28, 39%) and engineering, technology, and applications of science (ETS, 19 out of 28, 68%; NRC, 2012) of the NGSS framework. For the physical sciences, the AQs elicited talk related to all four the associated DCIs (PS1: Matter and Its Interactions; PS2: Motion and Stability; PS3: Energy; PS4: Waves and Their Applications in Technologies for Information Transfer) and seven of the associated sub-components. For instance, Fran's question about how one of the devices described in one of the articles works (D5, AQ2, see Table 3) fostered talk that involved a declarative exchange regarding the characteristics of electromagnetic radiation (PS4.B). As for engineering, technology, and applications of science, AQs also elicited talk focused on both of the associated DCIs (ETS1: Engineering Design; ETS2: Links Among Engineering, Technology, Science, and Society) and all five of their sub-components. For instance, Georgia's introduction of a wondering question (D3, AQ2, see Table 3) fostered a lengthy exploration of the interdependence of science, engineering, and technology (EST2.A) involving five participants over 14 talk turns. The talk went beyond the text to consider how future advancements in PV efficiency are dependent on improving or repurposing existing technological tools and the need for reliable data on different chemical elements compared to those currently used in PV manufacturing. Further, the DCIs identified in the talk aligned with the aim of the associated source materials. For example, the discussion that was based on the videos about the science behind how solar cells work (i.e., D1) had a closer alignment with the physical sciences, whereas the discussion that was based on the design and function of a tool that measured solar irradiance (i.e., D5), aligned primarily with engineering design processes and social implications of PV engineering, science, and technology.

While most of the discussion time was spent asking and answering authentic questions related directly to PV science and engineering topics, we also examined the uncoded segments of talk to understand more about what was happening outside of the AQ events

Table 3 Authentic questions (abbreviated) with duration, EE frequency, and associated NGSS disciplinary core ideas (DCI)

D#	Question number: (asker) Abbreviated question	Duration of AQ	EE Freq	DCI
D1	AQ1: (Fran) Can two or more lower energy photons work together to knock an electron into the conduction band?	2:37*	3	PS2.B
D1	AQ2: (Alex) What is the PN junction and what is the purpose?	*4:54*	8	PS2.B
D1	AQ3: (Georgia) In the texturing process, why is the pyramid shape associated with that acid?	*2:18*	3	PS1.B
D1	AQ4: (Barrett) I don't understand the graphs. IV testing, curves, amps, current, voltage—what is the difference between these terms?	*5:26	8	PS3.A
D1	AQ5: (Georgia) How are they creating resistance in the sheet by layering?	1:47*	2	PS3.B
	Total time duration:	17:02	8:12	
D2	AQ1: (Barrett) How do we teach kids about the science behind making solar cells without physically making them?	*1:19*	1	ETS1.B
D2	AQ2: (Alex) How expensive is silicon? Can we buy wafers or is there something thicker and more stable to use in the classroom?	*2:09	2	PS1.A
D2	AQ3: (Dakota) Have you been able to decipher the graphs? What do they mean?	1:47	1	PS3.A
D2	AQ4: (Georgia) What is the most important step in the solar cell manufacturing process, that we can control, that affects the efficiency?	1:35*	1	ETS1.BC
D2	AQ5: (Facilitator) Where could efficiency be increased within the manufacturing process?	*2:53	4	ETS1. C
D2	AQ6: (Fran) Would two PN junctions be better than one? Could you layer the wafers?	2:49	2	ETS1.B
D2	AQ7: (Barrett) How could we redesign solar cells to function more effectively in society?	1:53	1	ETS1.B
	Total time duration:	14:25	5:20	
D3	AQ1: (Fran) Was the article talking more about the design process or chemical processes of the solar cells?	0:42	0	ETS2.A
D3	AQ2: (Georgia) How is cost efficiency balanced with creating new designs for solar cells and can those new designs be built using current equipment to save money?	5:08	4	ETS2.A
D3	AQ3: (Ed) What are the benefits of burying the grid and putting contacts on the back to increase efficiency?	1:30*	2	ETS1. C
D3	AQ4: (Dakota) How can we share this information we are learning with other people to help their understanding of solar powered batteries?	*4:06*	3	PS3.D
D3	AQ5: (Facilitator) Are the solar panels themselves breakable or is the system fragile?	*4:17	6	PS1.A
D3	AQ6: (Alex) One of the graduate students started a business to use less silver for screen printing of solar cells; what else could we do to decrease the cost of the process?	3:01	2	ETS1.B
D3	AQ7: (Cat) Do you think we are reaching the end of new innovations in this industry?	4:48	5	ETS1.A ETS2.B
	Total time duration:	23:32	9:17	
D4	AQ1: (Fran) Are the utility companies responsible for driving the capacity of grid-connected solar energy?	*9:20*	7	ETS2.B
D4	AQ2: (Facilitator/Barrett) Is a hot state the ideal place for solar energy due to the high heat; what other issues might they have in this environment?	*7:03	7	PS3.D ETS2.B
D4	AQ3: (Barrett) Isn't it frustrating how much power nuclear and coal facilities have to slow solar energy down?	1:51	3	ETS2.B
	Total time duration:	18:14	6:54	
D5	AQ1: (Dakota) Why are they using an Arduino nano-board instead of something cheaper?	3:19	1	ETS1.C
D5	AQ2: (Fran) Do you understand how the device works?	2:55	3	PS4.B
D5	AQ3: (Georgia) Will our project be different because we want to measure the power coming out, whereas they measure how much sun was coming in?	1:18	2	ETS1.A
D5	AQ4: (Ed) They collected data over eight days, but what frequency was that data collected and can that be done in less time?	2:36*	4	ETS2.A
D5	AQ5: (Facilitator) Why do you think they are producing solar irradiance devices and what is the need?	*8:37*	11	ETS1.A ETS2.A
D5	AQ6: (Facilitator/Fran) Is being within 1% accuracy acceptable for efficiency and is repeatability the same as reliability?	*2:03	2	ETS1.B
	Total time duration:	20:48	8:14	

*Indicates a silence of > 5 s before or after an authentic question

PS1: Matter and Its Interactions; PS2: Motion and Stability: Forces and Interactions; PS3: Energy; PS4: Waves and Their Applications in Technologies for Information Transfer; ETS1: Engineering Design; ETS2: Links Among Engineering, Technology, Science, and Society

Table 4 Uncoded segments across the five discussions

D #	Segment #: (initiator) *Essence of the segment*	Duration
D1	S1: (Dakota) *Is the vocabulary from the readings necessary to understand what we are doing in the lab, or is it better to experience the concepts in lab first?*	1:52
D1	S2: (Alex) *Are we learning more about PV science from reading or from doing it in the lab; how much background knowledge is necessary to be successful in this program?*	1:38
D1	S3: (Facilitator) *How did the solar cell activity go, was it easier, does it include all steps of the texturing process?*	2:27
D2	S1: (Dakota) *Does doing the process in the lab help you understand the reading?*	0:43
D2	S2: (Fran) *Certain people are more helpful than others in their ability to explain; is there a difference between knowing your stuff and being able to explain what you know?*	3:06
D2	S3: (Fran/Dakota) *Do you understand the modeling software?*	1:54
D3	S1: (Cat) *Parts of the article were too technical and challenging to understand; the sections that discuss processes we have already done were easier to understand.*	0:43
D3	S2 (Cat) *Are we allowed to bring our own tools to be more efficient and save time [since the soldering tool in the lab was not functioning optimally]?*	0:49
D4	S1 (Dakota) *Having opportunities for hands-on engagement helped concepts to sink in more [this was based on confusion over specific terms and materials from the article related to circuits and electricity].*	4:48
D4	S2 (Dakota) *Discussed whether they read/didn't read the equations in the articles, and how they might change their approach in the future. Also discussed different variables and their meaning.*	1:07
D5	S1 (Dakota) *Evaluated the veracity of the assigned article, which was cowritten by former RET.*	1:09
	Total Time:	20:16

(see Table 4). For most of the uncoded time (i.e., about 17% of the total time across all discussions), the teachers engaged in episodes of talk that revolved more around evaluations of their understanding of PV or other general reflections related to their learning in the PV RET program, rather than the science and engineering concepts directly. For example, after the group wrapped up the discussion of an authentic question, Dakota reflected, "The equations make sense now!" [D4; S2]. This statement elicited a segment of talk between AQ2 and AQ3 where the teachers reflected on their differing confidence levels and their ability to comprehend equations in the text. Notably, these uncoded segments were relatively short (i.e., most were less than two minutes), compared to the duration of the AQ events (i.e., most were between 2 and 8 min), and their frequency decreased over time (i.e., three segments in D1 and D2, two segments in D3 and D4, and one segment in D5). Finally, the remaining uncoded time (3%), was made up of the typical pauses that occur between question events, two instances of extended silence (i.e., > 5 s), and a few dropped questions (i.e., questions that were asked but not answered).

Elaborative talk To get a sense of the depth of talk in the discussions, we looked at multiple indicators related to teachers' use of elaborative talk in the discussions. As part of the qualitative coding, we identified numerous EEs within each discussion, ranging from 12 in D2 to 24 in D1, and most of the AQs had multiple associated EEs. Further, EEs made up about 40% of the AQ talk time, on average.

Descriptively, many EE responses involved teachers conveying information that directly explained PV concepts to others in the group. For example, in one of Georgia's EE responses to Alex's question about PN junctions [D1; AQ2], she drew from and referenced what she learned from one of the RET program experts to help explain this core PV concept (DCI PS2.B) to her peers:

> *"I think [PV RET program expert] gave us a good explanation yesterday. So, like the silicon is in the band 4, right, and so—of the periodic table—and so they kind of go ahead and dope it before we get the [silicon] wafer. It already has boron added to it, which makes it less negative, cause there, since it's in the third column, so if you kind of look at it more as, less negative equals positive. So that is the P. The wafer is already the P part, and then we give it phosphorus(?), right phosphorus, which makes it more negative, so we are adding more electrons so that's like your inside so that is the positive and negative, almost the same as the battery-wise. If you think of it like that. Does that help?" (4:34-5:16)*

Likewise, when responding to questions that explored applications and extended beyond the content, teachers drew from their own prior experiences, as well as from the program, as they considered possibilities. For example, in response to a question about whether PV science (DCI ETS1.A) is a problem that needs ongoing investigation to achieve further innovation in the industry [D3; AQ7], Cat and Alex initially indicated their position that the field may have reached the point of diminishing returns. However, Dakota countered that notion with two different kinds of examples as evidence:

> *"Well, I disagree with that. Because it's kind of like, we had those old PCs for so long, for years, and then all of a sudden somebody was like, 'maybe a good idea if I could hold one of these in my lap,' you know, but that took forever. I feel like they just needed to get through the whole, 'this is all we know,' and then new brains come in and say, "What about this?" Even like [PV RET graduate student researcher], where she is like "copper, let's try this", and we now are to the point where we have reliable data to look back on, and they can go forward from that." (21:21–21:54)*

Further, additional evidence gathered from ratings on the elaboration subscale of the group observation instrument, suggested that all five discussions were highly elaborative in nature. Mean scores on the elaboration subscale were high (i.e., between 4.44 and 4.89) with relatively small standard deviations (i.e., between 0.73 and 0.33).

Ownership and responsibility The third part of our investigation pertaining to RQ1 looked at the extent to which participating teachers took on ownership over the discussions. When looking at participation patterns across the five discussions, all seven teachers took responsibility over the talk at various points by asking at least one authentic question and responding multiple times with elaborated explanations (see Table 5, "Total" row). Further, in all but two instances (i.e., Alex in D5, Ed in D2), every teacher meaningfully participated in every discussion (i.e., with > 4% talk time and by asking an AQ or by contributing an EE). There were, however, notable differences in the way teachers contributed to the discussions. For example, Barrett and Fran tended to contribute to the discussions by asking questions more frequently (e.g., Fran was the only participant who asked questions in every one of the discussions), but they both contributed comparatively few elaborated explanations. In contrast, Dakota and Cat asked fewer questions but consistently responded to others' questions with elaborated explanations. In looking at who did the most talking, Dakota and Cat generally held the floor for the most talk time (i.e., 17.1–29.2% and 5.4–26.4%, respectively). Barrett talked the least overall (i.e., 5.7%–11.4%), although Alex, Ed, and Georgia all had at least one discussion where they contributed less substantively than others.

Across all discussions, the facilitator participated in a fairly limited capacity, accounting for a very small proportion of the talk time (i.e., less than one minute and less than 5% of the total time for each discussion). Most of the facilitator's talk involved prompting teachers to ask questions (e.g., "Does somebody else have another question?" [D1, 10:31–10:33]) or otherwise managing the flow of the discussion (e.g., "As long as you use reasons and evidence." [D3, 8:16–8:18]). Although the facilitator did ask more questions than many of the teachers, all of them occurred immediately following either an uncoded segment or an extended silence and served to shift the talk back to an AQ event. For example, the facilitator's question in D2 came after the uncoded segment [D2; S3] where teachers were talking about the modeling software and served to re-introduce and extend consideration of Georgia's previously asked authentic question:

Table 5 Individual participation patterns across the discussions

	Alex AQs/EEs (% time)	Barrett AQs/EEs (% time)	Cat AQs/EEs (% time)	Dakota AQs/EEs (% time)	Ed AQs/EEs (% time)	Fran AQs/EEs (% time)	Georgia AQs/EEs (% time)	Facilitator AQs/EE (% time)
D1	1/0 (9.8%)	1/2 (6.4%)	0/7 (26.4%)	0/5 (17.1%)	0/6 (13.1%)	1/1 (9.3%)	2/3 (14.2%)	0/0 (3.7%)
D2	1/2 (23.1%)	2/0 (5.7%)	0/2 (18.5%)	1/5 (29.2%)	0/0 (1%)	1/0 (10.6%)	1/3 (7.8%)	1/0 (4.1%)
D3	1/0 (9.7%)	0/2 (6.1%)	1/6 (23%)	1/6 (27%)	1/1 (4%)	1/1 (9%)	1/6 (20.2%)	1/0 (1%)
D4	0/3 (18.5%)	2*/1 (11.4%)	0/4 (19.1%)	0/3 (16.3%)	0/4 (12.1%)	1/1 (16.7%)	0/1 (4.2%)	1/0 (1.7%)
D5	0/0 (0%)	0/2 (7.1%)	0/1 (5.4%)	1/5 (26.2%)	1/10 (27.1%)	2*/1 (14.7%)	1/4 (15.6%)	2/0 (3.9%)
Total	2/5	5/7	1/20	3/24	2/21	6/4	5/17	5

D1 = Discussion 1; D2 = Discussion 2; D3 = Discussion 3; D4 = Discussion 4; D5 = Discussion 5

*Indicates a question initially asked by the facilitator, but rephrased or extended by a teacher

% time represents the proportion of total talk time that a given speaker "held the floor"

"So, I really liked—I really liked your question about that. And building on that, I was thinking, so we know what aspects we need to do to increase efficiency all the way through, but which of those steps do you think is most promising for moving forward to increase the efficiency? Because where, where are we missing? Where could efficiency be increased along the way? Is there another acid we could be using to wash? Is there—which step do you think has the most promise for increasing efficiency of solar panels in the future." [D2, 13:35–14:15]

An extended excerpt from D4 (Table 6) serves to illustrate further the learner-centeredness of the discussions, as it contains one of the two question events that were initially asked by the facilitator and were then rephrased or re-asked by the teachers. As is evident in the turns that followed the facilitator's question, Barrett, Fran, and Georgia responded by sharing that they had each prepared similar questions (Turns 2, 4, and 5). Consequently, the facilitator invited them to state their version of the question, shifting the discussion back toward a more learner-centered interaction style (Turns 3 and 7).

Notably, the short exchange at the beginning of the excerpt was the only time that the facilitator talked in D4 (i.e., 1.7% of the total talk time). The remainder of the discussion, including the section of the excerpt from Turns 8 to 36, was exclusively learner-centered. This was consistent with the overall quantitative ratings of D4 from the interaction subscale of the group observation instrument (i.e., the mean across all items and all raters = 5). Further, as a whole, all five discussions were consistently rated as being primarily led by the teachers (i.e., mean scores between 4.82 and 5.00 with small standard deviations between 0.00 and 0.39).

Change in key variables impacting classroom discussion implementation

With regard to the changes in teachers' PV knowledge, teachers scored higher on the post-test PV knowledge assessment (M = 8.57, SD = 0.79) than on the pre-test (M = 4.29, SD = 2.69) with a large effect greater than two standard deviations, $t(6) = 4.08$, $p = 0.003$; Cohen's $d = 2.36$. Thus, participating teachers evidenced growth with regard to their knowledge about the science of solar cell manufacturing over the first week of the PV RET where they engaged in discussions about such content. Further, in the follow-up interviews, two teachers referenced the impact of the knowledge they gained from the PV RET program, specifically related to the content they discussed in the QT discussions. Barrett noted that it "helped me become not [only] like a better teacher, but also… more knowledgeable. People come up to me all the time [to] ask me questions about solar and about their house and stuff like that." Likewise, Fran said, "The solar summer school was really me trying to take what I learned in… and use that knowledge to trickle down to my students because I learned so much… about photovoltaics but also the Quality Talk [approach]." Importantly, this point by Fran expressed perceived growth related to both her PV knowledge as well as her potential teaching of it.

Additionally, teachers' perceived discussion facilitation capability scores also increased from pre-test (M = 3.89, SD = 0.23) to post-test (M = 4.34, SD = 0.50), with a large effect greater than one standard deviation, $t(6) = 3.31$, $p = 0.016$, Cohen's *d (pooled variance)* = 1.16. Likewise, in their follow-up interviews, all four teachers expressed an overall growth in their capability to facilitate discussions after participating in the program. Dakota, for example, mentioned that her capability to facilitate discussions had "skyrocketed", and Alex stated, "I feel like I'm more capable. Again, it goes back to—I now know and can encourage them to ask questions and what types of questions they should be asking too. And, so, I feel like I'm more confident in that regard." Fran and Barrett both attributed their increased capability to their experience and practice in the PV RET program. Despite reporting greater capabilities, they also expressed a desire for further growth and professional development. For example, Dakota stated, "[my] confidence level has grown, but I feel like there's still more for me to learn." Likewise, Alex mentioned that she still has "a lot to learn and practice."

Discussion enactment potential

Based on the descriptions from six of the seven teachers at the start of the program, teachers had previously been incorporating various forms of interactive paired or group activities (e.g., think-pair-share or team interaction during project-based learning) into their classrooms. For example, Alex described using talk in ways that involved more informal conversations or jigsaw-like interactive activities (e.g., "I frequently asked students to pair up, choose a specific topic from a more broad one, and research it. Then they traveled from table to table discussing their topics"). These responses were consistent with depictions of their prior instruction that they conveyed at various points throughout the program (see Starrett et al., 2022), where teachers discussed their use of discursive pedagogical strategies such as Kagan structures and Socratic seminars. While this kind of student-centered, interactive instruction certainly represents high-quality instruction, there was no evidence to suggest that teachers had previously been engaging in teacher-facilitated, small-group, text-based discussions in ways that aligned with the QT framework.

Table 6 D4 discussion excerpt; 16:03 to 20:29

Authentic question start [16:03]; Immediately following uncoded talk segment S2		
Facilitator	1	One of the questions that I had—and this builds on something that you said as well—is a hot state really the ideal place? Because they talk about a number of negative factors, particularly temperature ((multiple participants nod))…
Barrett	2	I had the same question. ((points to notebook, laughs))
Facilitator	3	[well, great, why don't you ask your question?]
Fran	4	[I do too.]
Georgia	5	Yeah, I was gonna bring that up. Go ahead
Barrett	6	That's funny
Facilitator	7	Would you like to phrase the question?
Barrett	8	So I read and learned that solar cells run efficiently at 25 degrees Celsius. Obviously, that doesn't really [inaudible crosstalk]…
Fran	9	[Inaudible crosstalk] which, is that room temperature basically?
Georgia	10	[It's like 77.]
Multiple	11	[Yeah.]
Barrett	12	So basically, it was just like what problems does that face in a hot state? How does that affect them?
Fran	13	Or how is it combatted, right? How do we combat that?
Georgia	14	[Or do they?]
Dakota	15	[A cooler city] would be perfect
Georgia	16	Because he was saying on our tour—so connecting our tour to that—he was saying the spike is, or their optimal collection is, only three months. So, do they combat it? Is there a [inaudible] down there to even further work with the high temperatures? **EE**
Cat	17	And also on the tour, they were talking about how shading the area has convection and cooler -cools the bottom of the panels, which actually cools the panels themselves, so they produce their own shade and cooling system. Which is cool. **EE**
Barrett	18	Is that only for the shaded ones? Like what about the roof ones?
Cat	19	The roof ones don't have room for that convection. So,
Fran	20	Wait, which ones were shaded? [Where did we see-]
Alex	21	[Under] by that building
Georgia	22	Yeah, where we were standing under the [trees and everything]
Cat	23	[The walkways.]
Alex	24	Yeah, because he said, there's a breeze that's created from that canopy, basically
Fran	25	So the cells were up here, exposed to full sun
Georgia	26	Yeah, and then there's some that were strategically missing, because that's what we said when we first saw one of them, like, why are there so many missing? And I couldn't hear him when the buses were up there. When we could hear he said that this was purposeful
Alex	27	Yeah, so they're doing, he said, if you missed part of it, they're doing a research project to see what kind of plants grow underground with that when they create sun shading. But then also it, like a bonus; it creates that current that cools the underneath. I was doing a lot of Googling about what people are doing. And it's, um, there's research now to do like misting fans set up somewhere underneath the panel. So I'm guessing it would be like a tiny spray or whatever you know, to kind of keep it cool? Cause it does lose like a about a percent or two efficiency with every five degree Celsius jump. **EE**
Cat	28	Which is, like, 60
Ed	29	There's another type of solar, um, I guess it's not a panel, but it's a thermal solar collector and it's concave. And they have farms for that, too, in some of the more higher temperature areas. So where it's very hot, they can just switch out and use those others which are much more efficient during the hotter periods or places. And what they do is they basically just have conduit pipe at the foci of the concave shape and those are mirrors, and the temperature of that water can get up to and exceed 750 degrees, which then they would use to produce steam, and then to mechanical energy, then to electricity. **EE**
Fran	30	I was wondering about that
Alex	31	Oh, cool
Cat	32	So we could have a combination there so you can have solar panels during the cooler months and those during the hotter months and get the most efficiency out of all
Ed	33	Sure, you can put one underneath the other, and then when the time comes, you just—it just rotates
Dakota	34	You need to patent that
Ed	35	Because you'd probably also, there's a tracking system, so those actually will rotate on a horizontal axis to maintain the optimum angle of incident, you know, towards the sun. And then, of course, the panel would do the same thing, when it's the primary. **EE**
Alex	36	That's cool

Text enclosed within double parentheses, (()), indicates transcriber descriptions, text enclosed in brackets, [], indicates overlapping speech. Any potentially identifying information has been masked or redacted, as appropriate. Turns that were coded as elaborated explanations are noted with the abbreviation in bold **EE**

To gauge the extent to which teachers evidenced potential to enact discussions in their STEM classrooms, we examined both their end-of-program lesson plans as well as the follow-up interviews. First, we looked at whether and how teachers designed instruction using discussions to teach PV science and engineering ideas to their future students. Based on the examination of the lesson plan contents, six of the seven teachers explicitly expressed intentions to use small-group discussions in their classroom to teach their students about PV (Table 7). However, the degree of implementation (e.g., the overall portion of the lesson devoted to discussion) and descriptions of their implementation varied widely. Alex and Georgia wrote lesson plans that incorporated discussions into multiple parts of the lesson plan and in ways that aligned with how they engaged in QT as part of the PV RET (e.g., in small groups, with learner-generated authentic questions, based on articles or videos). Alex and Georgia's lesson plans also explicitly noted intentions to implement QT discussions. Other teachers also indicated intentions to use small-group discussions (Barrett, Cat, Fran), although they were described in ways where the teacher held somewhat more ownership (e.g., teacher-generated questions).

All four teachers who completed the follow-up interview reported enacting regular (e.g., weekly) small-group discussions in their classrooms over the preceding school year. Two teachers (Alex and Fran) noted that they conducted discussions based on articles that students read, and all four reported using discussions to complement larger inquiry projects that their students engaged in. When teachers were asked to describe differences in how they facilitated discussions before and after the PV RET program, each one reported a focus on promoting more learner ownership and responsibility over the talk and emphasizing the importance of students' extended, elaborated talk. For example, Dakota noted, "…this year, I let the students guide their way through it, instead of me telling them… I would allow them to come up with their own ideas of different answers. … [previously] the questions were always [directed] towards me, but now when they would hear each other's ideas, they would ask clarifying questions of each other. They would encourage each other… The kids were talking more and felt more comfortable than in previous years." Barrett noted how she used more small-group discussions than in previous years, and Alex mentioned how she began emphasizing student-generated questions, which allowed students to explore their own ideas. Fran also shared that this past year was the first time she had incorporated formal discussions in her science class, "I didn't even have discussions in years before when I taught science." Notably, teachers did not limit their use of discussions to PV content; all four teachers described using discussions as part of their other STEM instruction, including an agriculture unit and for math instruction.

Table 7 Teachers' intended use of discussion as evidenced in the end-of-program lesson plans

Name	Use of discussions (part of lesson[#])	Use of questioning
Alex	Part 1: Whole-class discussion for the introduction; Part 2: Small-group discussion (four students per group) using "their 5 generated questions to facilitate this discussion in a Quality Talk model"; Part 3: Online discussion as closure	Part 1: Teacher generated with specific examples Part 2: Student generated, five questions per group
Barrett	Part 1: Whole-class discussion; Part 2: Group discussion [implied to be multiple small groups] after engaging in an activity that involved data collection	Teacher generated with examples "to have on the board to help facilitate group discussion"
Cat	Part 1/3: "Teacher leads the students in a discussion" [implied whole class]; Part 2: Small-group discussions (three or four students per group) as part of the learning activity	Teacher generated with examples
Dakota	Discussions throughout [implied whole class], "List the materials they will use in the construction of the house; (Discuss) Explain why they chose those materials"; Team discussion at the end of the lesson based on their energy design choices [implied small group]	Teacher generated with examples
Ed	N/A	N/A
Fran	Part 1/3: Whole-class discussions; Part 2: Small-group investigations guided by teacher-generated "formative assessment questions."	Teacher generated with examples
Georgia	Part 1: Small-group discussion, based on teacher-generated questions; Part 2: Students engaged in "[Q]uality [T]alk to discuss the article/video" [implied small group]	Teacher generated with examples; students generate three questions before the QT discussion

[#] Part 1 = Introduction and Motivation; Part 2 = Learning Activities and Strategies; Part 3 = Closure

Discussion

This study employed a practice-based, two-pronged approach (Parker & Hess, 2001), supporting STEM teachers in embracing a culture of talk by infusing small-group discussions into a larger integrated STEM learning program focused on PV science and engineering. Our results suggest that providing opportunities to participate in teacher-led, text-based, STEM discussions supported in-service teachers' comprehension of STEM content "with discussions" while also preparing them *"for"* leading STEM discussions in their classrooms.

With discussions

Participating teachers engaged in a series of discussions characterized by the asking and answering of meaningful, authentic questions with elaborative talk and where they maintained ownership and responsibility over the discussion, using language as a tool for thinking and interthinking (Murphy & Firetto, 2018; RQ1). During the discussions, teachers productively talked about a variety of topics related to *physical science* and *engineering, technology, and applications of science*, that is, the two branches most closely linked to PV science and engineering (NGSS, 2013). This finding also illustrates the potential for PV to serve as a "crosswalk" between engineering and science disciplinary core ideas and the integration of STEM disciplines (Moore et al., 2020). Moreover, as teachers responded to the questions they drew from their robust funds of knowledge as they shared connections between the content and their prior knowledge and experiences (e.g., their individual personal lives and collective program experiences; Merritt et al., 2023). Nonetheless, there were several segments of the discussion where the teachers engaged in uncoded talk (i.e., not associated with an AQ event). During these segments, teachers typically shared their perspectives on program elements as well as reflected on their understanding and mastery of science and engineering concepts related to PV. Yet, even though during these uncoded segments teachers were not directly discussing the PV concepts from the source material, teachers were meaningfully engaged in creating coherence across and/or navigating issues of uncertainty arising from different programmatic elements aspects of the PV RET program (e.g., in the lab). Specifically, the nature of this uncoded talk could be interpreted through a variety of lenses relevant to integrated STEM learning contexts, for example, Allen and Penuel's (2015) conception of sensemaking, Jordan and Babrow's (2013) navigation of uncertainty, Wei et al.'s (2021) epistemic cognition in science discussions, or Lobczowski et al.'s (2020) social regulation of learning in scientific argumentation. While it was not within the scope of this project to investigate this talk, it is noteworthy to report the presence of it, as it serves as a potentially fruitful area for future research to explore how teachers develop STEM content knowledge (Lo, 2021; Luft et al., 2020; Mohamad Hassim et al., 2022) as well as their ability to implement integrative STEM instruction (Brand, 2020; Jong et al., 2021). Taken together, this initial implementation of QT in the context of the PV RET with in-service teachers appeared to elicit the kind of talk consistent with the QT framework (Lobczowski et al., 2020; Murphy et al., 2016; Wei et al., 2021) and other similar implementations of QT (e.g., Lloyd & Murphy, 2023; Murphy et al., 2018; Starrett et al., 2022).

Moreover, teachers' PV knowledge increased and teachers reported greater perceived discussion facilitation capability (RQ2). Echoing the reports of teachers participating in Haug and Mork's (2021) practice-based professional development, the teachers who participated in follow-up interviews acknowledged how their participation in the discussions helped build their understanding related to PV content knowledge and their discussion facilitation capability. We see this as a promising result that can contribute to the understanding of how to better support important science and engineering communication practices. Teachers attributed an increase in their capability to facilitate discussions to their participation in the PV RET program; however, they also indicated a desire for additional support. Future research could further explore the effects of continued support in this respect (e.g., coaching). Further, this study contributes to the literature by serving as a novel implementation of a practice-based approach implemented with in-service STEM teachers (Ball & Cohen, 1999; Kademian & Davis, 2018).

For discussions

We also explored teachers' intentions to use discussions in their classrooms based on both the lesson plans that they produced in the PV RET as well as self-reports of their instruction from the follow-up interviews. While teachers previously reported using interactive and discursive pedagogies in their classrooms, there was no evidence that teachers were facilitating text-based, small-group discussions in their STEM instruction. After the summer program, teachers generally expressed intentions to utilize small-group discussions in their classrooms, as evidenced by the end-of-program lesson plans they designed and follow-up interviews where they self-reported their enactment of discussions in the school year that followed the PV RET, although there was wide variation in how they enacted them. Notably, the evidence related to teachers' design and enactment of lessons was gathered from lesson plans and interviews and did not directly measure discussion implementation in the classroom. Indeed, there may be some overestimation related to teachers' self-report. Alvermann et al. (1990), for example, found a disconnect between teachers' self-identified discussions and the characterizations of researchers observing the classroom. Still, it seems that teachers had taken away from the opportunity by adding another "tool" to their repertoire of effective discursive strategies with which they could infuse into their classroom. The transition away from transmissive approaches toward more dialogic teaching is not only "highly cognitively demanding", but also "requires, for many, a radical shift in beliefs about the value of talk and the teacher–student relationship" (Hennessy & Davies, 2019, p. 247). Thus, the results hold promise in that they serve as preliminary evidence regarding the potential to shift teachers' mindsets toward a more *dialogic stance* (Boyd & Markarian, 2015; Hennessy & Davies, 2019; Jordan, 2022; Wells & Arauz, 2006), and, in turn, help them to embrace a culture of talk in their classrooms. Taken together, converging evidence suggests that teachers not only *intended* to use small-group discussions in their future classrooms but they also self-reported that they *did*, albeit with variation.

Limitations, implications, and future directions

The small sample size of this study limits the generalization of our quantitative findings. Even though most of the teachers (i.e., 4 out of 7) completed the follow-up interviews, there may have been some selection bias present regarding those who elected not to participate. Further inspection of teachers' backgrounds and experiences (see Table 1) does not reveal any notable patterns regarding teachers who elected to participate in the follow-up interviews. Future research conducted with a larger sample of teachers and/or multiple small groups might explore the role of teachers' backgrounds (e.g., science/solar, teaching) and their assigned grade level (e.g., elementary, middle school) as well as how these individual differences might illuminate the findings reported herein (e.g., differences identified between patterns in how teachers asked questions or contributed elaborated explanations as well as their talk equity) and how changes might occur over time (e.g., from the first discussion to the last).

Although the present study centered around in-service STEM teachers, we contend that future research should also explore the impact on students. In addition, teachers and students would likely benefit from some form of supplementary support (e.g., coaching) to promote greater enactment of small-group discussions in K-12 STEM classrooms. This notion was perhaps best summed up by Fran, who shared her desire for a refresher on the QT framework in the follow-up interview: "I really would like to go back and review [the QT] protocol … [to make my discussions] higher quality. Because I think it's, I think the kids like it. And I think it really is a good strategy for them to kind of firm up and crystallize their thinking on things."

Conclusion

As standards, policies, and teacher professional development practices shift the instructional focus from STEM teachers disseminating information toward student inquiry and authentic engagement in STEM practices, small-group discussions offer a way to promote scientific understanding, high-level comprehension, and scientific reasoning in STEM learning contexts. Aiming to explore how to promote teachers' use of small-group classroom discussions in STEM, we conducted a multi-pronged investigation (see Parker & Hess, 2001), looking at how teachers learned PV science and engineering *with* QT discussions. Across five discussions, teachers spent the majority of the time asking authentic questions about PV science and engineering in alignment with a variety of science and engineering key disciplinary core ideas, responding to those questions with rich, elaborative talk, while taking on the ownership and responsibility over the discussion. Participating teachers also evidenced increases in both their PV knowledge as well as their perceived discussion facilitation capability. We also looked at the extent to which teachers were prepared *for* facilitating discussions in their classrooms. Teachers evidenced a shift toward the adoption of a dialogic stance, designing instruction for their future classroom using small-group discussions and reporting greater enactment of classroom discussions after participating in the PV RET infused with QT.

Given that K-12 teachers are often underprepared to implement instruction about PV, our manuscript forwards an important contribution that draws from a practice-based approach to professional development in a way that not only better prepares teachers on what to teach (i.e., through enhanced foundational PV content knowledge), but it also supports their ability to implement integrated STEM instruction into their classrooms more effectively (i.e., through the use of small-group discussion). As such, this manuscript illustrates an innovative pedagogical approach for potential use in providing teachers "opportunities to engage in high-quality professional learning that deepens their knowledge and builds their capacity" (p. 4, Stiles et al., 2017), in ways that can also prepare them to create and implement integrated curricula for their STEM students.

Abbreviations

AQ	Authentic question
D	Discussion
DCI	Disciplinary core idea
DVC	Dialogic Video Cycles
EE	Elaborated explanation

ETS	Engineering, technology, and applications of science
NGSS	Next Generation Science Standards
PS	Physical sciences
PV	Photovoltaics
QT	Quality Talk
RET	Research experience for teachers
RQ	Research question
STEM	Science, technology, engineering, and mathematics
TT	Talk time

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Author contributions
The authors confirm contribution to the paper as follows: study conception and design: primarily CMF with contribution of MEJ; data collection: CMF; analysis and interpretation of results: CMF, ES, and MEJ; draft manuscript preparation and revisions: CMF, ES, and MEJ. All authors read and approved the manuscript.

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Availability of data and materials
The datasets collected and analyzed during the current study are not publicly available given the potential to compromise the privacy and confidentiality of the participants. Datasets are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
IRB approval was obtained through Arizona State University's Institutional Review Board (STUDY00006290). Teacher participants provided electronic written informed consent prior to participating in the research, and all procedures were followed in accordance with the approved protocol.

Consent to publication
As part of the electronic written informed consent process, all participants agreed that the data could be used in the dissemination of study results (e.g., reports or publications) without use of their name. All names used in this publication are pseudonyms and identifying information has been removed or masked, as appropriate.

Competing interests
The authors declare that they have no competing interests to report.

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