Engineering Analysis of Technology Accessibility and Infrastructure Enhancement Strategies for Improving Educational Access in Rural Communities

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ABSTRACT
By 2025, all disadvantaged students in Vietnam will receive a digital learning device. However, children in the Northwest mountainous region (Tây Bắc) of Vietnam are far from realizing these promises. The region is home to many ethnic minorities who make up more than three-quarters of the population in the Northwest. The six Tây Bắc provinces include Lai Châu, where this research was conducted. A needs assessment of digital learning in Lai Châu found that while 26.2% of students across the province possess learning devices, in many remote satellite classrooms, donated learning devices are unable to deliver any learning due to lack of power during the monsoon season. This paper first presents a human-centred analysis identifying which children cannot access digital learning and why. Next, an engineering evaluation of six alternative infrastructure approaches is presented. Each approach is evaluated against the question that matters most to a child: what does the approach deliver in terms of learning hours, cost per student, and depth of reach into the most remote schools? The analysis uses public statistics as well as NASA POWER solar irradiance data for the six Tây Bắc provinces. The results of the engineering evaluation show that a hybrid TV White Space (TVWS) distribution network combined with stand-alone solar power delivers approximately 5.7 out of 6 possible learning hours per day. In terms of five-year cost, the approach delivers 13% less cost than satellite alone. In terms of availability, the hybrid design delivers higher availability at the most remote schools than a satellite-plus-solar system of equivalent availability. Finally, in terms of cost, the hybrid design delivers 40% less cost than a satellite-plus-solar system of equivalent availability. All system-performance figures are modeled rather than field-measured. What converts a device into learning is the device's continuous, self-sufficient availability to the child. Therefore, the decisive design choice is energy autonomy rather than additional bandwidth.

General Terms
Design, Measurement, Performance, Economics, Human Factors.

Keywords
Digital equity; Educational inclusion; Ethnic-minority education; TV White Space; Solar-powered schools; Northwest Vietnam

1. INTRODUCTION
Digital Technology in Education should focus first and foremost on the impact of technology on people, above all children, and on learning opportunities. For remote schools, digital technology ensures that teachers of these schools can use the same resources and materials for learning as teachers in towns and cities. Thus, Digital Technology in Education is a matter of national policy priority in Vietnam. Pursuant to this purpose, the national target is to digitally transform all of the education and training institutions throughout the country and present a learning device to every disadvantaged child by 2025 (Decisions 749/QĐ-TTg [2] and 131/QĐ-TTg [3], 2020 and 2022 of the Prime Minister).

While the majority of the Vietnamese population can now benefit from the digital education promise, large groups of people across the country are yet to experience it. While MIC reports that by the end of 2024, 4G population coverage in Vietnam reached 99.8% and household fiber penetration hit 90%, similar figures for the entire Northwest mountainous region are in the red. Internet use was 84% among rural residents, compared with 90% among urban residents [5]. A recent survey by the local press in Lai Châu Province showed that only 26.2% of the students in the area have a personal digital learning device. Three quarters of the region's population are ethnic minorities who live in rural and remote areas of Vietnam. In the country, this group of people is at the bottom of the digital development. Therefore, the digital divide also translates into the educational opportunity divide for the children of the region.

The study identifies a number of key challenges facing the region's Northwest mountainous area as the digital divide becomes an educational access gap. First, the communication (wireless in particular) challenge within the region's high terrain and dense forest, described in Section 2.2 for other mountainous areas. The region's ground level ranges from 200m up to some 3,143m high. Second, the electricity supply challenge at the commune and hamlet levels. As for the whole of Vietnam, statistics indicate that over 99% of all the households in the country are supplied with electricity. However, statistics also indicate that there are regularly outages of power at branch levels. These power outages have become more regular during the May-to-September period of the year, a time of year when the region's monsoon weather is at its worst. The study also identifies a challenge with the irregular electricity supply to the country's classrooms, described statistics indicating that as of the academic year 2023–2024, some 18% of all such classrooms were not solidly built [9]. Third, the challenge of a sparse and scattered population of the region's Northwest area. Statistics for the whole of Vietnam indicate that each commune in the country is supplied with one main school, which is in turn supplied with a number of satellite classrooms (điểm trường lẻ) that are often scattered over a large area, often over a number of remote mountain roads. Indeed, statistics for the country as a whole indicate that there are a total of 18,115 of such satellite preschools around the country.

Some initiatives have been launched to distribute computers to the schools. For example, in Sóng và máy tính cho em program, in the first phase, 92,629 computers have been distributed to the students all over the country. In the second phase, the

program aims to distribute 400,000 computers to 400,000 students in the country by 2025 [10]. As mentioned above, a computer (even a tablet) does not bring any value to a child when there is no internet connection at school and no energy supply to the school to use the computers during lessons.

This paper aims at investigating the gaps of learning access for children of remote and faraway areas in 6 provinces in the Northwest of Vietnam. The main barriers to learning access for children in these areas are examined. Integrated approaches for connectivity and energy for learning access via digital technology are assessed. These proposed strategies are compared not only on cost, reliability but also on learning hours provided, cost per child and access to the most isolated schools and students. Criteria for evaluating technology for enhanced learning access for children via digital technology are presented. The main emphasis is put on continued availability and on energy autonomous versus peak bandwidth technology. Section 2 reviews the most relevant prior work. Section 3 presents the methodology. Section 4 presents the results. Section 5 concludes.

2. RELATED WORK

2.1 The Human Dimension: Digital Exclusion and Educational Inclusion

The human line of questioning around online resources focuses on who is excluded and at what cost. Technology can increase inequality or decrease it depending on how it is used and who it is serving. When measuring access to online resources for the least-served learner, UNESCO [1] points out that there are many different aspects to take into account. In Vietnam, for instance, digital exclusion affects ethnic groups most strongly, and is independent from income and place of residence [11]. A survey of 719 teachers across 15 ethnic-minority semi-boarding lower secondary schools found that facilitating conditions — infrastructure and support among them — are a leading determinant of whether teachers adopt educational technology at all [12]. The World Bank has documented Vietnam's lagging digital development indicators for disadvantaged groups [7], [13], and multilateral programmes have targeted last-mile connectivity affordability across the region more broadly [14]. A recent pilot project of UNICEF-supported implementation of online resources in kindergarten in Hoa Ban in Lào Cai province, for instance, involved the implementation of tablets, hotspots, screens as well as charging facilities all at once [15]. Access to online resources is a bundle of several conditions and not a single device. What is missing is a connection between the human line of questioning and the engineering line of questioning in order to come up with remedies for the found digital exclusion.

Consistent access, however, can provide ethnic-minority students from remote parts of the country with the opportunity to learn same curriculum as their urban peers. Such access can extend opportunities of semi-boarding schools beyond that offered by local teacher/s. Reliably consistent access to the Internet can bring to reach of classrooms, where they could not afford to otherwise be, a small band of specialists who can teach key subjects to students. These are benefits to teachers and students alike, and occur only when access is consistently reached by the least-served learner [1].

2.2 The Technology Dimension: Connectivity and Off-Grid Energy

The TV White Space (TVWS), a band of spectrum between 470 MHz and 694 MHz, can also be used for penetration of foliage and terrain. There is a good case study for Community Network of 5km to 10km of non-line-of-sight reach at below-microwave cost [16]. TVWS have been pilot tested in Malawi, Zambia and the Philippines with strong penetration and lots of rural spectrum available [17], [18], [19]. However the bandwidth available per station is less than for LTE and subject to sharing as per local regulator. There are also several examples of Community LTE around the world for commercially unviable areas [20]. In a country with very mountainous terrain such as Indonesia, valley bottoms can be very poorly covered by a single technology [21]. This in turn leads to the second engineering problem, that of energy supply to these isolated communities. As with connectivity, energy has almost always been studied as a separate problem from connectivity, when in fact they are two closely interwoven issues.

2.3 Research Gap

The present study aims to address three main gaps in current studies of design of connectivity and/or PV energy systems for learning in absence of electricity to support digitally excluded learners. The first gap concerns the majority of current studies on digital exclusion that provide information on the number of people who are digitally excluded. In engineering design, the process of design typically involves the specification of a detailed, workable solution to a problem. Therefore, in the context of studies of digital exclusion and their corresponding follow-up studies of connectivity and/or PV energy systems for learning in absence of electricity, none of the existing studies detail a specific, workable technical solution to the problem of digital exclusion faced by specific learners in schools without electricity. Loss of connectivity or power has the same consequence for the child's learning; both need to be designed. The second gap is that, while there are studies of design for connectivity, and studies of design for off-grid energy for learning, there are no studies that design both connectivity and energy for learning as a single system to be implemented as a single project. The third gap concerns studies of design for energy for learning in many countries and various contexts around the world. Based on the literature reviewed, there are no published studies that target the six Northwest provinces of Vietnam. The six provinces of Vietnam's Northwest region (denoted in Table 1 by shaded area) have an area of 50,565 km² and a combined population of about five million persons who reside in 1,551 communes of Region III. Of these communes, 466 (30.6%) are located in the Northwest (after [25]). These six Northwest provinces of Vietnam contain the country's highest concentration of educational challenges and thus form the focus of the present work.

Table 1. Profile of the six Tây Bắc provinces

Province	Area (km²)	Population (year)	Non-Kinh (%)	Notable elevation	Region III communes
Lào Cai	6,364.0	787,066 (2024)	66.2	Fansipan 3,143 m	70
Lai Châu	9,068.7	482,100 (2022)	84.1	Pu Si Lung 3,083 m	58
Điện Biên	9,539.9	656,700 (2024)	82.6	Pha Đin 1,648 m	94
Sơn La	14,108.9	1,313,884 (2023)	83.7	Plateau 600–1,000 m	126
Hòa Bình	4,590.8	875,380 (2022)	74.3	200–800 m typical	59
Yên Bái	6,892.7	855,290 (2023)	57.3	≈ 600 m mean	59

Province	Area (km²)	Population (year)	Non-Kinh (%)	Notable elevation	Region III communes
Total	**50,565.0**	**≈ 4.97 M**	**≈75 (wtd.)**	**-**	**466**

Population years are mixed (2022–2024), so the total is indicative. Sources: [8], [26], [25].

3. METHOD AND MATERIALS

3.1 Study Area and the Children It Serves

The study area covers 6 Northwest provinces of Vietnam (Lào Cai, Lai Châu, Yên Bái, Sơn La, Hòa Bình and Điện Biên) as prior to 2025 boundary changes which were executed in June 2025 (Table 1). Of the 1,551 Region III communes nationwide designated by Decision 861/QĐ-TTg [25], 466 (30.0%) lie within the six study provinces, under Decision 861/QĐ-TTg [25] issued by the Prime Minister of Vietnam. They are the most in need of support. The study area is largely defined by its human geography. Around 75% of the study area population is composed of ethnic minority groups. Children from thousands of remote satellite classrooms need access to digital learning.

3.2 Data Sources

The study utilizes four sources of publicly available data, namely, (1) GSO (General Statistics Office of Vietnam) data on the socio-economic situation of the provinces and also from the household surveys [8], [26]; (2) publicly available data from MIC (Ministry of Information and Communication) as well as from the Sóng và máy tính cho em (Connectivity/Waves and Computers for Children) project [4], [10]; (3) NASA POWER solar climatology [27] averaged at the provincial-capital locations for the time period of 2001–2020 under all sky conditions for the downwelling short wave solar radiation at the surface; and (4) retail prices of computer equipment available at the Vietnamese outlets [28]–[31]. The learner level data not yet published at the commune level are estimated.

3.3 Candidate Strategies

Six strategies are compared for connecting a school and keeping it running:

S1 - Fiber only. Extend GPON fiber from the nearest commune endpoint to each school, with grid power assumed.

S2 - 4G/LTE only. Install LTE customer-premises equipment at each school on existing macro-cell coverage, with grid power.

S3 - LEO satellite only (Starlink). One terminal per school; licensed in Vietnam in 2026 at a proposed price of about USD 350 per terminal plus USD 85/month [32], [33].

S4 - TVWS from a 4G aggregation node at the commune center, redistributing to satellite schools over 470–694 MHz TVWS links [34], [35].

S5 - Proposed hybrid. TVWS distribution from a 4G or LEO aggregation node, with stand-alone solar (PV) power at every end site.

S6 - LEO satellite plus PV. As S3 with the S5 PV subsystem; included to separate the value of energy autonomy from the link choice.

S4 and S5 assume Cục Tần số (MIC) authorises TVWS on a pilot licence: commercial TVWS licensing does not yet exist, and the 700 MHz digital-dividend band was auctioned during 2025 [36]; the operational model follows the Philippine DOST and Kenyan Mawingu pilots [19], [37]. Figure 1 shows the S5 architecture.

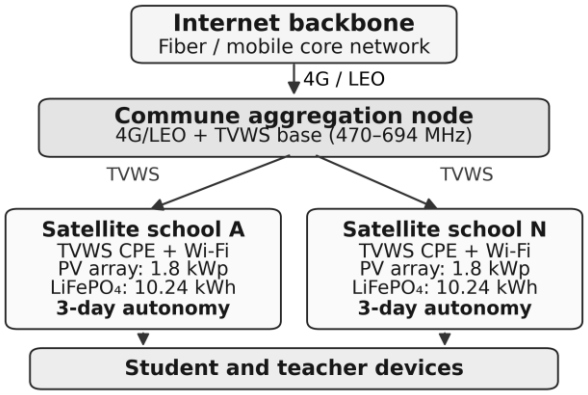

Figure 1: Proposed hybrid (S5) architecture: a commune-center aggregation node with 4G or LEO backhaul feeds TVWS distribution radios in the 470–694 MHz band; each satellite school carries a stand-alone PV–LiFePO₄ subsystem sized to the worst solar month, keeping student and teacher devices online through grid outages.

3.4 Sizing for Continuous Availability

Following established sizing methodologies for stand-alone PV systems [22], schools in the S5 configuration are able to continue to operate when the grid fails. These schools include a PV array and a $LiFePO_4$ battery. The PV array and the battery are sized so that the classroom can operate during the worst solar month and also survive for multi-day blackouts. Schools are sized based on the average daily load and worst-month solar in (1):

$$P_{PV} = E_{load} / (H_{PSH,worst} \cdot \eta_{sys}) \quad (1)$$

where E_{load} is the daily energy demand (Wh), $H_{PSH,worst}$ the December (worst-month) peak-sun-hour value, and $\eta_{sys} = 0.75$ the system efficiency; array sizing follows the worst-month peak-sun-hour method of IEEE Std 1562-2007 [24]; the battery provides three days of autonomy at 48 V, at an assumed 0.8 depth of discharge for the $LiFePO_4$ chemistry specified in Table 4 [29]. $H_{PSH,worst}$ ranges from 2.36 (Lào Cai) to 2.80 kWh/m²/day (Hòa Bình) [27], so the array is oversized 1.7×–2.0× versus the annual mean. Usefully, December is the worst solar month while the May–September monsoon – when grid outages peak – has about twice its irradiance (4.6 vs 2.4 kWh/m²/day in Lào Cai [27]): the December-sized array carries its largest margin exactly when the grid is least dependable.

Service availability – the share of school hours with both a working link and power – is estimated with the availability chain in (2):

$$A_s = A_{bh} \cdot A_{dist} \cdot A_{pw} \quad (2)$$

where A_{bh} is backhaul uptime, A_{dist} distribution-link uptime (unity for direct connections), and A_{pw} power availability during school hours. All strategies except S1 are evaluated at the remote satellite-classroom site class. The factors are stated engineering assumptions, consistent with the monsoon outage pattern of Section 1 but not measured: grid uptime ≈0.85 at remote classrooms (≈0.93 at typical schools); $A_{bh} \approx 0.98$ for a battery-backed commune node (Figure 1); $A_{dist} \approx 0.99$ for the TVWS link; for S2 the ≈0.85 signal factor is a site-average folding valley coverage gaps into one number, and link and power failures are treated as independent although storms can

cause both – simplifications noted in Section 4.5. For S5 and S6, $A_{pw} = 1 - \text{LOLP}$, with LOLP ≈ 0.02 estimated from low-irradiance spells in the NASA POWER climatology [27], pending a daily time-series simulation. Equation (2) then gives $A_{S5} \approx 0.98 \times 0.99 \times 0.98 \approx 0.95$; $A_{S6} \approx 0.97$; $A_{S3} \approx 0.84$; $A_{S2} \approx 0.72$; and $A_{S4} \approx 0.82–0.87$ (its sub-day battery lifts power availability from 0.85 toward 0.90). Sensitivity: across LOLP 0.01–0.05 and A_{bh} 0.95–0.99, A_{S5} spans ≈0.89–0.97 – above every grid-dependent alternative at remote sites in all cases.

3.5 Evaluation Criteria: Engineering and Learner-Centered

The composite score uses five independent criteria: five-year total cost of ownership (TCO), availability, terrain robustness (1–5), energy autonomy (days), and equity of reach to remote schools. The learner-centered indicators – usable learning hours per six-hour day and per-student annual cost – are deterministic transforms of availability and TCO, so they are reported alongside (Table 5) rather than double-counted inside the score; energy autonomy is kept distinct from availability because it captures multi-day storm sequences that a mean masks. The weighted sum is (3):

$$Score_s = \Sigma_m \, w_m \cdot \tilde{x}_{s,m} \quad (3)$$

where $\tilde{x}_{s,m}$ is the min–max-normalized value of criterion m for strategy s and w_m its weight. Multi-criteria approaches to rural electrification planning have combined AHP with VIKOR [38] and with expert-elicited criterion weights [39]; the present study adopts a simpler min–max-normalised weighted sum for transparency and reproducibility. Two profiles are used: balanced (w_m = 1/M, M the number of criteria) and cost-prioritized, reflecting provincial-education budgets – because a solution that is cheap on paper but dark for a third of the school day scores poorly on what matters to the child.

4. RESULTS AND DISCUSSION

4.1 Who Is Excluded, and Why

The 'portrait of the gap' starts with the household level. 90% of the urban population uses the Internet, compared to 84% in rural areas [5]. For the Northwest region and its ethnic-minority population, both figures are substantially lower [7]. From the learner's perspective, Figure 2 indicates that 26.2% of children and young people in Lai Châu Province own a device to access the internet for learning. Other locations across the Region would be expected to be similar based on the current circumstances of their socio-economic development. Importantly, even where households have almost 100% electricity access, this does not translate to schools and especially the remote preschool satellite classrooms (a total of 18,115 preschool satellite points across the country in 2023–2024 – [9]). For children handed a tablet to learn with, power during the monsoon to access online resources is not guaranteed due to the compound effect of the three above-mentioned barriers.

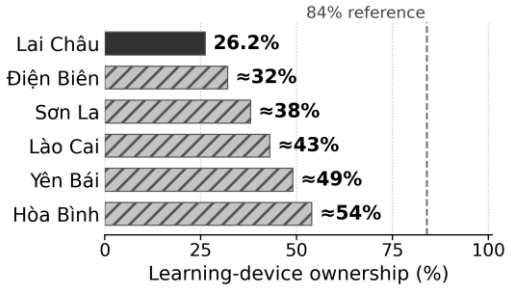

Figure 2: Share of students owning a personal learning device, by province. Only Lai Châu comes from provincial reporting [6] (solid bar); shaded bars are scenario values spaced uniformly up from the 26% floor, bounded by the 84% rural internet-use rate [5], in order of socio-economic rank – planning assumptions to be replaced as provincial statistics become available.

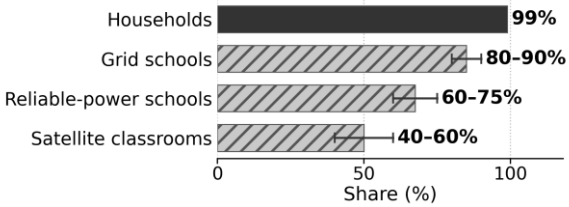

Figure 3: Electrification and power reliability, household to remote satellite classroom. Household figure from national statistics (solid bar); school-level values are scenario ranges (shaded) consistent with the monsoon outage pattern of Section 1 – no quantitative school-level reliability statistics are published.

In addition to the list above, there are several more constraints that do not cancel one another out; in aggregate they compound the problem: online learning requires a device, a connection, and power – all at the same time. Only one provincial device-ownership figure is reported: 26.2% of the children in Lai Châu have a device [6]. Combining 26.2% device ownership with the assumed 40–60% stable-power range in Figure 3 gives approximately 10.5–15.7% of learners with both a device and stable power; this is a scenario estimate, not a measured learning-access rate. Note that since the scenario of independence described above is already very low, there might be a slight increase if there were positive correlation among the above-mentioned gaps but that increase would be too small to measure for now. Hence, as noted before, raising one of the elements above (i.e. devices, signal or power) would not have a significant impact on the number of constraints above. A solution to connectivity-and-energy would therefore need to address several of the constraints listed above in a joint design.

4.2 Comparison of Strategies

Table 2 shows the costs of six alternatives at Vietnamese 2025 prices at the remote satellite-classroom site class, except S1 (fiber), which is evaluated only at deployable sites. LTE alternative S2 is cheapest but signal strength at the school in the bottom of the valley is extremely poor [21]. Therefore, alternative S3 which covers all schools uniformly is dominated by the cost of the airtime of USD 85/month reported in [32] and also suffers from the fragility of the powering grid of the satellite terminal used in alternative S3. Alternative S6 which adds solar to alternative S3 would cost most to “buy back” the fragility of alternative S3 of all the alternatives studied in this paper. Two TVWS hybrids alternatives S4 and S5 studied in the Philippines and Kenya [19], [37] can reach all schools in the deep valleys where LTE signal is too weak. It is the

difference between alternative S5 and alternative S4 and in particular the three days of PV autonomy of alternative S5 that makes all the difference. While alternative S5 is cheaper (approximately 13%) and more available (approximately 95%) than the satellite-only service alternative S3 at the remote satellite-classroom site class, alternative S5 is also approximately 40% cheaper than the same availability alternative S6.

Table 2. Engineering comparison of the six strategies (per school, 2025 prices)

Metric	S1 Fiber	S2 LTE	S3 Starlink	S4 TVWS+LTE	S5 TVWS+PV (proposed)	S6 LEO+PV
5-yr TCO (USD, indic.)	site-specific	≈2,500	≈5,450	≈3,500	≈4,730	≈7,790
Availability (%)[2]	high[1]	≈72	≈84	82–87	≈95	≈97
Terrain robustness (1–5)	2	2	4	4	5	4
Energy autonomy (days)	0	0	0	0–1	3	3
Reaches remote satellite schools	no	partial	yes	yes	yes	yes

[1] S1 evaluated at its deployable sites; all others at the remote satellite-classroom class. [2] Availability follows Eq. (2). Only S5 is costed bottom-up (Table 4); other TCO values are order-of-magnitude – S4/S5 include a shared base-station share; S6 = S3 + all Table 4 end-site lines except the TVWS CPE. Starlink: 12 × 85 × 5 + 350 ≈ USD 5,450 [32], [33]. Sources: [28]–[33].

Table 3 describes the scores of all six strategies for a balanced profile as well as for a cost-prioritized profile (cost: 0.5; the other four criteria: 0.125 each). The highest score in both cases is reached by strategy S5 with 0.90 for the balanced profile and 0.79 for the cost-prioritized profile. However, the ranking of the other 5 strategies deviates strongly from the balanced profile. S6 ranks second in a balanced profile, but only 5th in a cost-prioritized profile. On the other hand, strategy S4 reaches a rank of 2 in a cost-prioritized profile, whereas it ranked 3rd in a balanced profile. The re-ranking of S4 and S6 between profiles shows that only the top rank is robust to weight choice; mid-ranked strategies are weight-sensitive, which is why procurement bodies should declare weights explicitly. Moreover, changing the assumed anchors for S1 (cost and availability) between the two stated extremes in text above did not change the first rank position of S5 in both cases.

Table 3. Multi-criteria scores from Eq. (3); higher is better

Strategy	Balanced score	Cost-prioritized score	Rank (bal./cost)
S1 Fiber	0.18	0.12	6 / 6
S2 LTE only	0.30	0.56	5 / 3
S3 Starlink (LEO)	0.52	0.50	4 / 4
S4 TVWS + LTE	0.63	0.70	3 / 2
S6 LEO + PV	0.74	0.48	2 / 5
S5 TVWS + PV (proposed)	**0.90**	**0.79**	**1 / 1**

Inputs from Table 2 with S1 cost ≈ USD 8,000, S1 availability ≈ 95%; reach no/partial/yes → 0/0.5/1; S4 autonomy = 0.5 day; ranges at midpoints.

Additional model comparison: S5 provides 1.4 more usable learning hours per day than S2 (5.7 vs. 4.3), at a five-year TCO that is USD 2,230 higher. Relative to S3, S5 provides 0.7 additional hours per day and saves USD 720; relative to S6, it provides 0.1 hour less per day while saving USD 3,060 (Tables 2 and 5). All differences are modeled estimates, not field observations.

Using the worst-solar scenario for school connectivity in Lào Cai province with 2.36 kWh/m²/day, the analysis estimates the required power for 1 school site to be 1.36 kWp (= 2.4 / (2.36 × 0.75), rounded) or 1.8 kWp using a 4-panel setup with 1m spacing between panels, and the required energy for battery storage is 9.5 kWh (i.e. 3 × 2.4/0.8/0.95 ≈ 9.5 kWh) which is provided by a commercial battery of 10.24 kWh [29]. The end-user cost for power + storage in 2025 US$ is $2,940 [28]–[31]. For the school's portion of the commune TVWS base station cost the model assumes $3,500/commune and amortize this over the approximately 8 satellite schools. Thus Year-0 CAPEX and 5-year total CAPEX for the school are $3,380 and $4,730 respectively (see Table 4). The largest line item for CAPEX as expected for off-grid applications [23] is for the storage system.

Table 4. Indicative S5 cost breakdown, Lào Cai satellite classroom (USD, 2025 prices)

Component	Detail	Cost (USD)
PV array (1.8 kWp)	4 × 450 W panels	400
$LiFePO_4$ battery	48 V, 10.24 kWh nameplate [29]	1,180
Hybrid inverter + MPPT	3 kW	360
TVWS CPE + antenna	end site	600
Router / Wi-Fi / switch	-	150
Civil works, mounting, cabling	-	250
Share of commune TVWS base station	≈ USD 3,500 ÷ 8 schools	440
CAPEX subtotal (Year 0)	**-**	**≈ 3,380**
Backhaul + maintenance (5 yr)	≈ USD 270/yr	1,350
Five-year total cost of ownership	**-**	**≈ 4,730**

Prices from [28]–[31]. Base-station cost and eight-school amortization are assumptions pending quotations; battery replacement beyond Year 5 deferred.

4.3 From Connectivity to Learning: What Reaches the Child

In engineering numbers matter, however in terms of how they change what a child receives at school (as opposed to how many sites you can reach with a given amount of money). In Table 5 the six strategies outlined in the foregoing were modeled into learner-centered indicators of two types: indicators of 'availability' of learning time (see the first columns of Table 5); and indicators of 'cost' (of reaching each site, see the last column of Table 5). These indicators have been simplified into a few numbers that convey much meaning. First the numbers indicate how much learning time each of the 6 strategies will deliver at school. Thus, for example, for 6 hours of school per day S5 delivers 5.7 hours of teaching time to children while LTE-only would deliver but 4.3 hours of teaching time and satellite-only 5 hours of teaching time at the farthest ends of the schools reached by that technology. Secondly, the numbers show how much more learning (i.e. hours of learning by children) the various strategies will deliver in terms of absolute numbers and, also, in terms of contrast to the worst case scenario of LTE-only. And, last but not least, the numbers also reveal that while S5 is not the cheapest option in

terms of 'cost per site' it is by far the option that delivers most learning for the money spent – above all for the least-served children in the isolated schools where fiber already is in place. And here LTE-only does not.

The numbers in Table 5 can be translated into a meaningful format, that of a before and after comparison. A child in a distant satellite classroom is dependent on the local teachers and printed learning materials for his/her studies. Even with a donated tablet, the child cannot make use of it for most of the time due to outages. Only about 10% of the children can get online and do their learning, Section 4.1. After the deployment of S5 services, the same classroom can maintain a working connection to the internet with power for almost the whole school day. The conditions of Section 2.1 for access to knowledge can thus be met: same curriculum, same learning materials, same amount of teaching preparation for the national examination as in urban areas. More than one teacher can deliver learning to the children and even specialist teachers can be in that classroom that would not be able to be in that classroom if it were to be staffed by local teachers only [1], [12]. A comparable bundling of devices, connectivity and charging in a real classroom has been reported at the UNICEF-supported Hoa Ban kindergarten in Lào Cai, although that deployment used fixed broadband and grid power rather than the TVWS and PV subsystems proposed here [15]; S5 itself has not yet been deployed. Access to knowledge is not yet equal to learning gain, Section 5 for a field study to measure learning gain.

Table 5. Learner-centered comparison (indicative, from Table 2)

Strategy	Usable learning h/day[a]	Reaches remote schools	Per-student cost (USD/yr)[b]
S1 Fiber	≈ 5.7 (where present)	no	site-specific
S2 LTE only	≈ 4.3	partial	≈ 17
S3 Starlink (LEO)	≈ 5.0	yes	≈ 36
S4 TVWS + LTE	≈ 5.1	yes	≈ 23
S5 TVWS + PV (proposed)	**≈ 5.7**	**yes**	**≈ 32**
S6 LEO + PV	≈ 5.8	yes	≈ 52

[a] Availability × six-hour school day. [b] TCO ÷ 5 yr ÷ ≈30 students sharing ≈10 devices; costs double-to-triple at a 10–15-student site.

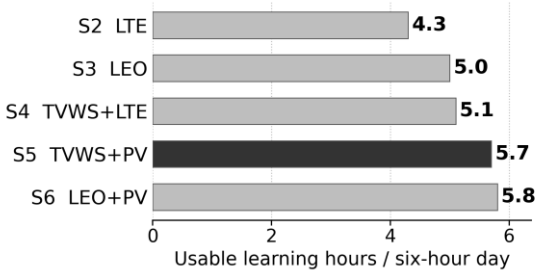

Figure 4: Modeled usable learning time by strategy at remote satellite classrooms (Table 5). S2 serves only sites with adequate LTE coverage; S1 is omitted because it does not reach remote satellite classrooms.

4.4 Human Factors for Sustained Adoption

What really matters for improving learning outcomes is not just setting up a connected and powered classroom, but also a set of human factors. The teacher factor: without training and support, even the most powerful learning tools in the world will not be used for long. The issue of local ownership: a well-designed solar system with radio connection to a central server on the internet to download and upload data is only as good as the local light role designed by the author of the framework and the occasional visit of a technician to clean the panels and restart the router from time to time. The relevance of content: learning environment will only be used for learning if there is relevant, curriculum-aligned content available for students to access in the environment, and ideally also content that supports the languages of the community. Community can quickly see benefits of having connectivity and technology in their school if these are used for examination preparation or for increased contact with teachers, while online-safety issues must be openly addressed. Finally, the program integration factor: the framework was designed to be 'pluggable' into existing programs for learning with devices, such as Sóng và máy tính cho em [10] and the semi-boarding model [12], which provide a framework for learning within institutions but lack reliable power and connectivity to support this learning. A bundle of books and installed infrastructure that functions as a single program to support learning in a functioning school is also important for assessing impact of such a program, as suggested by the bundled device-and-connectivity provision reported at Hoa Ban [15].

4.5 Discussion

1. For changing children's learning what matters most is that the technology is always available, not that it has a high bandwidth. Thus a 10 Mbps link available 60% of the time is worth less than a 4 Mbps link available 99% of the time and this difference is made by the PV–battery subsystem and not the radio.
2. Hybridization is what reaches the most excluded children. Thus it is the schools that any single technology fails to reach that are the remote schools, the ethnic minority schools, the satellite schools.
3. As outlined in Section 4.4 without teacher support, without local maintenance, without program integration the working link does not become working pedagogy.
4. The ranking is very solid at the top but very sensitive at the bottom. Thus S5 is by far the best according to both scenarios (0.90/0.79, Table 3) whereas second place is taken by S6 (balanced) and S4 (cost-prioritized) and here it would be very important for the procurement process to explicitly state its weights and to give a real weight to equity of reach as opposed to cost.

Threats to validity. For S4 and S5 a pilot license for TVWS needs to be obtained. The 470–694 MHz band remains allocated to DVB-T2 broadcasting in Vietnam, so S4 and S5 depend on a secondary-use regime that does not yet exist. The 700 MHz digital dividend above 694 MHz has already been cleared and auctioned to mobile operators [33], which confirms that the national digital-switchover process is complete but leaves the 470–694 MHz occupancy question open. For sizing the PVs gridded solar irradiance data is used which in reality might not be the actual yield at a specific site (e.g. due to valley fog which could decrease the yield significantly). The availability factor is calculated based on a factor chain with assumed uptimes and an approximate average LOLP. For data on 4G network coverage at commune level no official data is published. For base-station cost and 8-school amortization quotes from vendors are required. For TVWS link budget and/or channel occupancy a study has to be performed yet. For the learner-centered values in Table 5 only indicative numbers are provided; in a field study these have to be replaced by real numbers.

5. CONCLUSION

The paper explores the opportunity of digital learning for ethnic minority children in 466 Region III communes across six Northwest provinces of Vietnam. All of these schools are located in a massive geographic area of 50,565 square kilometers home to some 4.97 million people. The design and evaluation of a hybrid solution of TVWS connectivity and a standalone solar power system for the schools under consideration here, against both engineering and learner-centered criteria, is the core of the paper. Under a number of simplifying assumptions, the design delivers a continuously connected and powered school for some 95% of school hours or 5.7 hours out of 6. In terms of cost, over 5 years, the hybrid solution here described is some 13% cheaper than a solution that relied entirely on satellite. Furthermore, it is 40% cheaper than a hybrid solution that relies on a satellite and a solar system, of comparable availability, and in practice would leave the fiber/LTE-based schools to serve the satellite schools. As mentioned above, it is human, not technology, that changes a child's learning experience. But that change only occurs when technology is continuously and self-sufficiently available at the child's desk, or in other words, there is energy autonomy, not bandwidth autonomy.

There are four major limitations in this study. The first limitation is that although TVWS has great promise for learning access, there is as yet no TVWS regulatory framework in place in Vietnam among other countries. The second limitation is that solar irradiance has been gridded as opposed to site-measured. The third limitation is that retail-average costs have been used for comparison rather than the lowest possible procurement price. The fourth limitation is that all learner-centered performance figures have been modeled as opposed to being from a field study. As such, a stratified field study with 200+ schools (signal strength as well as pyranometer-grade solar power data for S5 design evaluation) would be the better course of action for future study. The pilot S5 design should be put into operation and allow to learn and collect data during a full monsoon season. Human performance of learning — attendance, access to learning with appropriate teacher support — that the design enables and supports, should be the key design criterion to guide school ICT procurement.

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