Zero-emission public transit could be a catalyst for decarbonization of the transportation and power sectors

Anthony Y. Ku1,2,*; Andrew de Souza1, Jordan McRobie1, Jimmy X. Li1 and Jaimie Levin3

1NICE America Research, Mountain View, CA 94043, USA
2National Institute of Clean-and-Low-Carbon Energy, Beijing 102209, P. R. China
3Center for Transportation and the Environment, Berkeley, CA 94704, USA

*Corresponding author. E-mail: anthonyku@nicenergy.com

Abstract

Reaching carbon neutrality will require investment on an unprecedented scale. Here we suggest that there is an underappreciated opportunity to leverage public funds to mobilize private capital in support of these aims. We illustrate the point using examples from public transit. Although the fuelling energy requirements of public fleets represent a small fraction of the eventual total demand across the transportation sector, the predictable and long-term nature of the refuelling profiles can reduce the financing risk. With appropriate coordination across the energy supply chain, near-term investments can be used to support scale-up of wider efforts to decarbonize the transportation sector and electric grid. We present two examples from California—one related to overnight power for battery electric bus charging and the other related to medium-scale supply chains for zero-carbon hydrogen production—to illustrate how this might be achieved.

Graphical Abstract

Despite small overall share of vehicles…

…public transit infrastructure investment can support the wider transition to sustainable, carbon-neutral economies.

Keywords: carbon neutrality; electric vehicles; fuel-cell vehicles; hydrogen; infrastructure; net-zero emissions; public transit; transition
Introduction

Numerous countries, local jurisdictions and private companies have made carbon-neutrality pledges, with time horizons ranging from 2025 to 2060 [1, 2]. The transportation sector currently generates about a quarter of the global anthropogenic CO₂; a transition away from petroleum-based fuels will be an important part of efforts to reach net-zero emission targets [3]. Public transit fleets account for a relatively small fraction of the total vehicle and energy requirements for fuelling, but they can be an important lever for governments to increase public acceptance of new technology, support the maturation of vehicle supply chains, promote the deployment of a large-scale resilient refuelling infrastructure and experiment with different policy frameworks [4–12]. Moreover, ambitious schedules for a zero-emission bus (ZEB) fleet conversion can help to uncover emergent challenges related to energy supply and delivery, as these activities interact with concurrent efforts to reduce emissions from the power sector.

Electrification has emerged as a leading option for decarbonizing ground transportation. The leading commercial options are battery electric vehicles (BEVs) and hydrogen fuel-cell vehicles (HFCVs). In light-duty passenger automobile markets, BEVs currently outnumber HFCVs; in medium- and heavy-duty applications, mixed fleets exist and vehicle selection is based on the relative advantages and limitations of the technology for different use cases. Public transit agencies can opt for battery electric buses (BEBs) or hydrogen fuel-cell buses (HFCBs). BEB fleets are relatively easy to pilot on small scales and will directly benefit as electric grids decarbonize. As fleets grow, the overnight demand from their fixed charging schedules might exacerbate energy-supply challenges for grids with high intermittent renewables generation (e.g. solar, wind) [13–18]. Specifically, as growth in BEVs accelerates, the energy-supply effects from charging vast numbers of these vehicles will result in significant changes to the traditional ‘duck curve’, with resulting consequences still unknown. A critical, related issue and concern is the resiliency associated with heavy reliance on grid power as affected by natural disasters, such as earthquakes, wildfires and hurricanes. HFCB fleets offer greater range, lower weight, faster refuelling times and higher resiliency, but the high capital cost of refuelling stations and nascent supply chains for zero-carbon hydrogen pose significant barriers during the early stages of adoption [19, 20]. The supply issue might be solved by using electrolysis powered by renewable energy; a ‘power-to-gas’ (P2G) approach may help to manage intermittency on the electric grid and provide long-term energy storage [21, 22].

Progress towards zero-emission public transit requires cooperation across a range of stakeholders. Governments provide the overall policy framework and motivate action through regulations and incentives. They also exercise convening power to gather other stakeholders and promote the sharing of information and experience [23]. The primary players are individual transit agencies, who bear responsibility for decisions on bus types and the infrastructure investments to operate their fleets, original equipment manufacturers who have to ramp up production to meet accelerating demand for vehicles and fuel suppliers (e.g. electric utilities, industrial gas companies) who operate capital-intensive businesses and make commercial decisions based on market signals. Cost signals from fuel providers influence transit-agency decisions, and vice versa. Early in the transition, decisions by primary players can be made in a relatively independent manner. As the transition progresses, interactions across the supply chain lead to uncertainty in the planning landscape, increased risk in capital investment, constraints arising from lock-in effects from earlier decisions, conflicting objectives among stakeholders and possible bottlenecks in the adequacy and reliability of energy delivery [10, 17, 24]. However, positive interactions across the landscape may also emerge.

This Perspective article argues that there exist pockets of ‘predictability’ that can be used to reduce investment risk and therefore be leveraged to help close the gap between public and private financing. For the sake of this discussion, we define predictability as an operational attribute that is conducive to regular and sustained capital recovery. The economic value of stable revenue streams is already well appreciated; our contribution is to point out an under-appreciated and significant opportunity to leverage public funds invested for specific and local infrastructure needs to stimulate broader investment across the energy and transportation sectors during the transition period.

To illustrate the point, we draw on our collective experiences in working to decarbonize public transit over the past decade. Using public transit in California as a case study, we present a thought experiment exploring how investments in public transit might catalyse broader transformation across the transportation and power sectors. California currently operates >10 000 buses across >200 transit agencies, and has committed to fully transition to a ZEB fleet by 2040 [25, 26]. In addition, the state has announced goals of 250 000 BEV fast chargers and 200 hydrogen-refuelling stations by 2025, 5 million total zero-emission vehicles on the roads and a 60% share of renewable electricity generation by 2030, a ban on sales of internal-combustion passenger vehicles starting in 2035 and carbon neutrality by 2045 [27]. The scale of public transit and the variety in transit agencies across the state makes California an especially informative example. Our analysis takes advantage of the relative clarity in problem definition (i.e. articulated policy commitments and targets, well-defined segment of the transportation sector with predictable refuelling profiles), availability of relevant public data (i.e. transit-agency operating profiles and transition roadmaps, electricity supply and demand) and complementary studies of transition pathways in other sectors (i.e. light and heavy vehicles, electricity, industry) to examine this issue in detail [28–30].
The paper is organized around two questions. First, what will it take to deliver energy in the right form at the right times? Second, how can the necessary investments in energy delivery for public transit fleets be used to support broader decarbonization efforts? We begin with a statewide energy balance to quantify the energy-delivery requirements at different stages of the transition; we also examine energy demand from ZEB use profiles at the level of individual transit agencies. We then provide a brief introduction, for non-expert readers, of the investment needs for the refuelling infrastructure of two leading options for BEB and HFCB fleets. This leads to a discussion on how the predictable and long-term nature of the refuelling profile might be used to support the scale-up of the fuelling infrastructure in a manner that can benefit the wider efforts to decarbonize the transportation sector and electric grid. Two examples are given to illustrate how this might be accomplished in California. The first involves the expansion of overnight electricity supply in support of BEBs and the second relates to establishing medium-scale low-carbon H₂ supply for HFCB fleets. Although we focus on the specific case of public transit in California, the possibility of mobilizing capital using large, predictable revenue streams could be applied more generally; we conclude with some observations on how the lessons from California might be extended to other locations.

1 State-level energy supply and delivery requirements

Fig. 1a shows the size and share of the public transit bus fleet relative to the entire vehicle population in California. Despite rapid projected growth in the absolute number of ZEBs, they would only account for <1% of all vehicles after full adoption in 2040. For context, success in deploying 5 million total zero-emission vehicles (ZEVs) by 2030 would result in an ~15% vehicle share. In this study, we perform a thought experiment around the two limiting cases of fully BEB or HFCB fleets by 2040. Mixed fleets favouring BEBs are more likely, but this approach allows us to investigate a full range of possibilities with respect to bus technology [31]. Despite the limited numbers of vehicles in absolute terms, the regimented service schedules of ZEBs create a significant and predictable energy demand. Fig. 1b shows the energy footprint for different vehicle types. The height, width, and area of each box correspond to the energy intensity per mile (with the range indicating the average and maximum values reported), average daily mileage and total daily energy demand per vehicle [25, 29].

Fig. 1c overlays the electricity demand for overnight charging of BEBs and the solar-power-based electrolysis production of H₂ in support of HFCBs relative to current generation profiles. The aggregate electrical demand during overnight hours is projected to be 2.6–4.8 GWh/night by 2040 (viz. 10k BEB x 2–3.6 kWh/mi/BEB x 132 mi/day). In 2020, the average overnight power generation (10 pm to 4 am) ranged from 90 to 120 GWh/night. For context, the successful introduction of 5 million light-duty BEVs by 2030 would increase the daily demand by an additional 34–70 GWh/day (viz. 5M LDV x 0.22–0.45 kWh/mi/LDV x 31 mi/day). California’s current grid has the ability to satisfy the incremental demand from an all-BEB fleet in 2040, but ~75–90% of night-time generation comes from natural gas, nuclear and imports that are expected to be phased out over the same time horizon during which ZEB demand emerges [32–34]. Renewable portfolio standards requiring 60% renewable generation by 2030, en route to a net-zero grid by 2045, mean investment in both zero-carbon night-time generation and energy storage might be needed to ensure adequate electricity supply [26].

California’s energy infrastructure will also need to evolve to deliver sufficient zero-carbon H₂ for electrified transportation. Over 95% of H₂ production in the USA currently comes from steam methane reforming (SMR). In a net-zero future, H₂ production will need to shift towards alternatives such as biogas reforming, SMR with CO₂ capture and storage (CCS) or electrolysis using electricity from zero-carbon sources [21, 30]. Given its large share in California’s generation mix, the use of solar power in a P2G capacity could become part of the long-term solution [21]. Assuming a daily H₂ demand of 16–30 kg/HFCB/day, statewide supply would need to reach 160–290 tons per day (tpd) to support a fleet of 10 000 FCVs. Curtailed solar energy in 2019 ranged from 0.5 (August) to 7.3 GWh/day (April and May), with an average of ~2.5 GWh/day. Assuming 55 kWh/kg for electrolysis and compression, this corresponds to an H₂ potential of ~45 tpd, but monthly variations in solar power generation means production will vary between 8 and 133 tpd [32]. Curtailed solar power is forecasted to grow to ~15 GWh in 2030 and 100 GWh in 2045 [35]. In this scenario, P2G-derived H₂ could meet the forecasted demand from HFCBs while also supporting up to 1 million light-duty HFCVs by 2045. For context, 43 retail H₂-refuelling stations had a total capacity to deliver 12 tpd at the end of 2019 [36].

Regardless of fleet composition, California has the resources to generate adequate energy for both types of ZEB fleets throughout the entire transition and beyond 2040. The timely mobilization of capital investment in delivery infrastructure is more likely to be the limiting factor. Beyond the investment in fleets themselves, BEBs will require energy storage or additional night-time generation, while HFCBs will need a supply chain capable of delivering ~100 tons per day of clean H₂ along with the construction of refuelling stations. Investment in electricity-transmission and H₂-distribution networks will also be needed.

2 Local energy-delivery requirements

The actual path to full ZEB adoption involves decisions by individual transit agencies concerning bus technology and schedule; these determine the nature and timing for infrastructure projects. Some agencies have already conducted
field evaluation of ZEBs, published strategic roadmaps and begun transitioning their fleets [37], others are still in the planning stage. As of December 2020, 10 transit agencies had filed formal plans and another five had announced roadmaps for their ZEB transitions. An important feature that has emerged is the role of route distance and fleet size in the decision between BEBs and HFCBs. In an ideal world without fuel supply or capital investment barriers, transit agencies with longer routes and larger fleets would tend towards HFCBs due to operating-cost advantages. The exact threshold at which HFCBs become favourable varies based on additional factors such as the frequency of stops, elevation changes, climate and vehicle speeds (see the online Supplementary Information) [37].

Fig. 2 compares use profiles across transit fleets at the county level. Fig. 2a and b show differences based on the current fleet size and average route mileage of transit fleets; the marker size indicates the total mileage travelled within each county and is proportional to the energy demand. On this basis, Los Angeles and Alameda counties stand out owing to their larger fleet size and longer average route distance, respectively. The shaded inset in Fig. 2a is enlarged in Fig. 2b to highlight use profiles for the next eight largest county fleets. Together, the top 10 counties account for >83% of the total miles travelled by public transit buses on an average day (Fig. 2c)—indicative of the outsized impact of urban areas. The data also show use profiles in the other 39 counties with transit agencies that must also comply with state targets. Distributions of average route distances by county and bus population are shown in Fig. 2d and e.

Buses in ~80% of counties travel on average <100 mi/day, but the skew associated with urban areas means that
-90% of the buses in California reach this average daily mileage. Counties with large fleets (>200 buses) may host multiple transit agencies and the large fleet sizes allow the possibility of hybrid fleets with both BEBs and HFCBs. Medium-sized fleets tend to support moderate population centres or large service areas. These fleets are expected to be a single bus-technology type due to the desire for transit agencies to simplify the fuelling logistics and maintenance operations. Small fleets account for only 10% of the total bus population, but operate in 26 counties; two-thirds of these counties operate fleets with <50 buses. Most have limited resources to support transition planning and fleet-conversion decisions for this group are likely to be constrained by logistics considerations. However, counties near larger fleets may be able to benefit from infrastructure investment and expertise from their neighbours.

3 Infrastructure investment for zero-emission public transit

The transition to ZEB fleets will require capital investment across the entire energy supply chain. Fig. 3 summarizes the types of investment needed and the relevant actors for each area: transit authorities for bus- and refuelling-station decisions; and utilities and energy providers for energy-delivery decisions. The top panel shows the supply chain for BEBs, where electricity from selected zero-carbon sources is delivered via bus-recharging stations. An

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**Fig. 2:** County-level segmentation of bus fleets and route profiles. (a) Daily mileage vs fleet size for 43 counties with transit agencies operating buses. For labelled counties, the areas of the circles are proportional to the total miles driven. (b) Expanded view of daily mileage vs fleet size, using the same shading scheme as in the first panel. (c) Cumulative distribution function (CDF) for share of total miles/day, segmented by county. The x-axis indicates the fraction of counties and the y-axis shows the cumulative share of daily miles driven across the entire state. The top 20% of counties account for ~75% of miles driven. (d) CDF for average daily mileage, by county. (e) CDF for average daily mileage versus number of buses across the entire state. Five counties are shown for illustration: San Francisco (SF), Orange (OC), San Diego (SD), Los Angeles (LA) and Alameda (AC). Data from ref. [25].
important feature in station costs is the non-linear investment profile as the fleet size grows; a new transmission infrastructure (e.g. substations) may be required to deliver adequate power for the fast charging of large fleets. The bottom panel shows the supply chain for HFCBs. There are two primary paths for station design, based on whether the fuel is stored as a compressed gas or a cryogenic liquid, and three representative options for production and distribution [38, 39].

Bus fleets are the largest capital expense: ~$100 million is needed for a single division, increasing proportionally with larger numbers of divisions. Some of this required capital will have already been committed for the routine replacement of existing assets. Since ZEBs cost ~$200–500 k more than diesel buses, the incremental cost over the existing capital commitments would be ~$20–30 million for a division beyond what would be spent under business-as-usual replacement schedules. ZEB fleets will also require the construction of BEB-charging or HFCB-refuelling stations. Capital investment for stations varies depending on technology; we estimate a depot-based fast-charging facility for a full BEB division could require $5–14 million, while an HFCB station could be less expensive, ranging from $2 to $6 million [14, 39]. During a phased adoption in which buses are added over multiple years, HFCB fleets are more expensive to operate initially because stations must be constructed at their full-service capacity; however, they become more affordable as the number of buses in the fleet increases [31]. California has recognized this barrier and offers policy support to help fund the construction of H2 stations for early adopters. Over time, market mechanisms will need to provide the additional $20–100 million needed for 10 divisions and $200 million–$1 billion needed for full conversion by 2040 [28].

Capital projects will also be needed to upgrade California’s electricity-transmission and H2-delivery networks. Expansion of night-time electricity capacity to support BEB fleets could include combinations of generation, storage and transmission, as shown in Fig. 3. For electric charging, we focus only on the depot option; interested readers can consult an extensive literature on alternate charging options [6, 11, 13–17]. H2 supply chains can be configured for local production at refuelling stations or central production with distribution. The first option occurs entirely at the station and involves electrolysis, small-scale SMR, gas compression, high-pressure ground storage and, possibly, refrigeration. Electrolysis is currently more expensive than alternatives; cost-reduction roadmaps have been developed, but it could take a decade to fully realize the savings [40]. For production scales and transport distances relevant to California, supply chains using centralized production with liquid-H2 (LH2) distribution is increasingly favoured by industry and offers competitive economics. The costs from liquefaction are more than offset by savings from the reduced cost of distribution and simplification of station design (i.e. liquid pumping in lieu of gas compression, direct filling to reduce ground storage, heat integration with liquid vaporization to reduce refrigeration) [39, 41–43].

Among the options for central production, SMR facilities with CCS will take time to develop, leaving biogas-derived H2 as the leading option in the near term. Air Liquide is in the process of commissioning a 30-tpd biogas-to-liquid H2 facility in Las Vegas, NV [44]; by 2030, aggregate demand from ZEVs in California could consume all of the supply from multiple facilities of this scale. Depending on project details and distance from transit-agency depots, electricity production for a BEB division (50 MWh/night) would require $5–20 million and zero-carbon H2 supply (2–3 tpd) could range from $6 to $15 million. These values would increase by an order of magnitude for 10 divisions and another order of magnitude to support the entire ZEB fleet in 2040.

## 4 Public transit demand as a catalyst for investment

The central hypothesis of this study is that investments made to support energy delivery for public transit can also aid efforts to decarbonize the electricity grid and broader transportation sector. The predictable and long-term energy demand from ZEB fleets is a valuable attribute that can be used to facilitate long-term planning for grid evolution and also mobilize capital for infrastructure development. Increasing variability from growth in renewable-energy generation and expansion from electrified transportation will tend to amplify the reliability challenges for the electricity grid. Whilst time-of-use demand-response programmes can help to spread charging loads throughout the day for passenger vehicles or commercial fleets, there may be limits to their ability to fully rebalance energy requirements for night-time charging [18, 24, 45]. With regard to capital mobilization, the predictability of demand from BEB fleets could allow electric utilities to negotiate commercial supply contracts (e.g. power purchase agreements) designed around stable overnight-charging schedules. Predictability in H2-refuelling demand could be leveraged in a similar way. In both cases, long-term contracts offer secured revenue streams that can be used for capital recovery in the financing of infrastructure projects, as illustrated schematically in Fig. 4. Table 1 shows estimates of how much capital might be mobilized by such supply agreements; assuming simple amortization schedules, a single 100-bus division could support in the order of $10–50 million in capital investment. Applied to 10 000 ZEBs at 100 bus divisions across California, this has the potential to mobilize $1–5 billion for infrastructure projects; on a national basis across the USA, the sums could approach an order of magnitude larger.

### 4.1 Example 1: overnight charging for BEB fleets

Historical patterns in California wind generation show peak power in the evening through to the early morning
Wind generation in 2019 was ~14 TWh from an installed base of ~6 GW, with generation during the winter months about half that of summer production. For context, the California Energy Commission (CEC) expects that 3 GW of wind capacity will be added between 2020 and 2030. This begs the question of whether this resource can help meet the overnight-charging demand, initially for public transit and in the longer term for electrified transportation generally.

Fig. 5a shows the seasonal variation in hourly generation at the four most productive wind power sites in California, which accounted for 90% of the wind generation of the state in 2019 [47, 48]. A fully electrified ZEB fleet in the Bay Area and greater Los Angeles would require ~1.6 GWh/night. (A detailed discussion of aggregated wind generation and BEB demand is included as online Supplementary Information.) While the overbuilding of wind to ensure adequate supply year-round is not inconsistent with CEC forecasts, a more robust approach is to invest in energy storage under the assumption that the daily energy generation is adequate to meet transit needs. Fig. 5b shows the cumulative distribution function for the estimated incremental overnight wind generation in 2030, assuming a profile similar to historical generation (2019). Assuming an hourly generation profile consistent with 2019, ~1.6 GWh/night of added generation would be expected during 17% of the year (63 nights). Fig. 5c and d shows the effect of storage on overnight reliability and
the investment required for different levels of reliability (number of days in a year in which wind generation can cover the incremental charging demand) from different levels of energy storage. Fig. 5c shows the effect of energy storage on reliability. This use profile indicates that energy storage in support of BEB demand would be needed for ~17% of the year, primarily during the winter months and occasionally on days with below-average wind generation. During the remaining days, the facilities would be available as a general capability to support grid stability. Fig. 5d shows the value of investment in energy storage on reliability. Revenue from bus energy-supply contracts could support investment at a level of $90–170 million (cf. Table 1, scaled to 1.6 GWh/night); spending this on energy storage could increase reliability to ~93%.

This simplified analysis uses 2019 data. As such, it does not account for annual variations in wind generation. Moreover, the productivity of added wind capacity may be lower, as the most productive sites are developed first. These effects are expected to impact the exact number of days on which generation is inadequate, but the general range is expected to be consistent with the results obtained from our initial estimate. Further work will be needed to identify specific projects and fully quantify their benefits for renewable power integration.

### 4.2 Example 2: Medium-scale zero-carbon H₂ supply for fuel-cell vehicle fleets

A key difference between BEB and HFCB supply chains is the timing of infrastructure deployment. Whereas BEB-charging

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**Transit agency**

| **Total cost of operation** (transit agency, $/mi) |
|-----------------------------------------------|
| **TA operating revenues** | **Incentives** |
| Fuel cost | Operating costs | Transit agency capital recovery |

**Predictable demand allows long-term contracts**

**Fuel price**

| **Operations (incl profits)** | **Supplier capital recovery** |
|-------------------------------|-------------------------------|
| **Energy supplier** | **Capital markets** |

**Fig. 4:** Use of predictable fuelling schedules to support capital mobilization for energy infrastructure. From the transit-agency perspective, the total cost of operation (top bar) is the sum of the operating revenues and government incentives (second bar) as well as the sum of the operating costs (third bar). Operating costs include contributions from fuel, other transit-agency operating costs and capital-recovery costs for transit-agency investments. Fuel purchased from external providers (fourth bar), in turn, supports the operating costs for energy suppliers and capital recovery for infrastructure projects (fifth bar). Predictable demand allows the negotiations of long-term contracts that can be used by energy providers to mobilize larger sums for capital financing.

**Table 1:** Estimates of capital that could be supported by energy contracts

| Financing terms (rate of return [%], period [yrs]) | 8% | 15% | 8% | 15% |
|------------------------------------------------|----|-----|----|-----|
| **BEB** | **100-bus division** | **$15 million** | **$11 million** | **$22 million** | **$14 million** |
| Short routes: 200 MWh/night | **$37 million** | **$27 million** | **$54 million** | **$34 million** |
| Energy sales value: $30/MWh | **$15 million** | **$11 million** | **$22 million** | **$14 million** |
| **100-bus division** | **$37 million** | **$27 million** | **$54 million** | **$34 million** |
| Long routes: 500 MWh/night | **$15 million** | **$11 million** | **$22 million** | **$14 million** |
| Energy sales value: $30/MWh | **$15 million** | **$11 million** | **$22 million** | **$14 million** |
| **HFCB** | **100-bus division** | **$15 million** | **$11 million** | **$22 million** | **$14 million** |
| 3 tpd; energy value: $2/kg | **$15 million** | **$11 million** | **$22 million** | **$14 million** |
facilities can be built in a stepwise manner, H₂ supply chains require significant upfront investment. Since full conversion to ZEB fleets by 2040 requires 100% of bus purchases and deliveries by 2028, a medium-scale H₂ supply chain is necessary to preserve the option of HFCB adoption in the long term.

Fig. 6a compares two options for clean H₂ supply in the intermediate term. The first involves on-site electrolysis to meet the needs of individual stations. While this is possible for small-scale pilots involving <20 buses, full-scale deployment for a 1000-bus division will be challenging due to footprint and electricity-delivery constraints in many urban areas. The second option uses biogas-to-H₂ with LH₂ distribution. This path requires central production facilities of ≥9 tpd (enough to supply three bus divisions) for economics, but these facilities can also support broader demand from the transportation sector. The Air Liquide Las Vegas project suggests that this path is being taken seriously by industry [44].

Fig. 6b and c illustrates how capital recovery can be supported by the value streams from refuelling operations. The top bar in each case shows the revenue accrued by the transit agency from operations and government incentives. Contributions from the Low Carbon Fuel Standard (LCFS) are considered for each case. For the on-site electrolysis case shown in Fig. 6b, electricity from the grid still includes a significant contribution from fossil energy; we assume an LCFS credit of ~$2/kg assuming a basis of 33% renewable H₂ and $199/tCO₂ (2020 average) [49, 50]. Assuming financing scenarios from Table 1, ~$3/kg of the revenue would be needed to support capital recovery for the refuelling station and the electrolyser. In this case, the transit agency is responsible for the infrastructure and is the main beneficiary.

The biogas-H₂ with LH₂ distribution case uses a different arrangement. Here, H₂ is produced at a central facility, liquefied and delivered to the station. Fig. 6c differentiates between the revenues available to the transit agency and the H₂ supplier. As with on-site electrolysis, the transit agency allocates revenue and incentives to operating costs and capital recovery; one difference is that the transit agency buys fuel from the H₂ supplier, which then allocates sales revenue to its own operations and capital recovery for the production and liquefaction infrastructure costs. A second difference is the higher LCFS credit; biogas-derived H₂ is 100% renewable and qualifies for the LCFS.

Fig. 5: Prospects for meeting overnight BEB demand using wind and energy storage. (a) Quarterly variability in daily wind-generation profiles in California, plotted at 5-min resolution. (b) CDF for incremental wind generation forecasted by 2030. The x-axis shows days, in ascending order. The y-axis shows the incremental generation potentially available from a 3-GW increase in wind capacity. The dotted line indicates the threshold needed to meet the 1.6-GWh/night incremental demand from all-BEB fleets in the Bay Area and Southern California; a gap exists for 63 nights of the year. (c) Impact of increasing energy-storage capacity (x-axis) on reliability (y-axis), as indicated by the number of days on which the overnight-charging demand would be satisfied. (d) Investment (y-axis) needed to deploy sufficient energy storage to satisfy different reliability thresholds (x-axis), at an assumed energy-storage cost of $250/kWh. The shaded band indicates the level of investment ($90–170 million) potentially available from transit-agency-backed contracts.
for a credit of $4/kg (2020 average), and this value can be effectively allocated between the transit agency and H₂ supplier through supply contract negotiations. Although the value of LCFS credits is expected to decline over time, their current value provides an avenue for intermediate-term development. Predictability of the fuelling profile is important in that it allows the longer-term agreements that can extend time horizons and access to the longer capital-recovery scenarios. The numbers in Fig. 6c reflect an allocation of revenues that can support near-term development of this type of supply chain. In contrast to the distributed-electrolysis approach, this option is compatible with future growth of the H₂ supply chain. Once an initial supply chain has been established, market forces can augment it in response to the growing HFCV population and improving technology. Over time, electrolysis with on-site storage for P2G and SMR with CCS may become competitive alternatives as cost and regulatory hurdles are addressed. As with the BEB example, predictable demand, sustained over decades, from transit agencies is a key enabler for investments in infrastructure that can simultaneously meet immediate needs and act as a bridge to larger, system-wide changes.

5 Broader implications and conclusion

Although we have focused on the situation in California, the predictability of energy demand from large ZEV fleets can be a useful lever for promoting transitions to carbon neutrality in other locales. There are two complementary principles: the leveraging of large, predictable, long-term aggregate demand from vehicle fleets to support capital recovery in the financing of infrastructure projects; and the alignment of projects to support broader system-level
evolution. This approach could be particularly relevant for urban areas in North America, Europe and East Asia where commitments to carbon neutrality intersect with sufficiently large public transit systems or corporate fleets to support meaningful numbers of projects. We note four nuances that should be considered in applying these principles to other situations.

First, scale matters. Transportation and energy infrastructure typically involve large projects; the associated capital investments are generally tens of millions of dollars or more (cf. Fig. 3). Large fleets will be needed to generate sufficient revenue to support capital recovery for this magnitude of investment. In the California example, we focused on bus divisions with 100 ZEBs. This is a natural scale relevant to transit-agency operation that also appears capable of generating appropriate levels of revenue; many larger projects will require cooperation between multiple bus divisions. In 2018, the UN identified 42 metropolises with populations of >5 million (along with 264 areas with populations of >1 million) across North America, Europe and East Asia [51]. The size of the public bus fleets in these cities is more than sufficient to participate in the financing model suggested here, and most of these cities have made direct commitments to climate action or are covered by national-level pledges.

Second, predictability can help in multiple ways. In the California example, predictability offered benefits on two levels. On one level, well-defined energy-demand profiles in the form of stable, daily charging schedules for BEBs or known growth rates in cumulative H₂ demand over time can be used by energy providers to plan for operations and growth. Coordination across the supply chain is a natural consequence due to the mutual benefits. This can be as simple as sharing information between transit agencies, energy suppliers and government about strategic intentions in a market-oriented framework or involve active participation by government through public incentives for private capital decisions. Specific projects can then be selected to preserve or even increase strategic flexibility across the energy system. On a second level, the long-term nature of public transit demand unlocks the ability to finance capital over extended periods. Government agencies play a critical role in establishing markets and have a vested interest in the creation of mechanisms that engage private capital markets. The public sector plays a key role in setting transformational targets and providing the seed funding to nucleate action; mechanisms that can de-risk investments, such as the one presented in this paper, can help to mobilize private capital to supplement public funds. While transit agencies are subject to the budgetary priorities of government and their capital expenses are often supported by subsidies (e.g., federal grants, sales taxes, parcel taxes, and road and bridge tolls), public transit is seen as a public good that provides stability to its revenue streams. Although the specific details related to these two facets will vary, the general principles should translate across jurisdictions around the world.

Third, government support can take different forms. California is aggressively pursuing carbon neutrality across multiple sectors using a combination of mechanisms. Within this context, some counties have taken concrete steps to pilot ZEBs and develop detailed transition plans and roll-out schedules coordinated across multiple public agencies (see the online Supplementary Information for details); others are still in the early stages of defining their specific roadmaps. An even wider range of postures exists across the jurisdictions that can apply the principles identified in this study. For example, Shenzhen, China, completed the transition of its entire bus fleet of >16 000 vehicles to electric buses in 2018 [4]. This was accomplished through significant government support across the entire supply chain, leverage of the unique regulatory environment in China [5, 52]. At the other extreme, there are jurisdictions that have announced commitments but are still in the early stages of defining their path forward. For municipalities in this latter group, calibrating across the examples from California and other leading locales could provide guidance for their planning activities.

Finally, commercial fleets might also be able to contribute. Revenue streams from commercial fleets would be backed by business operations, so the financing terms and time horizons would depend on the details of each situation and could be more aggressive than for public transit. Assuming financing terms and vehicle-use profiles similar to the California situation (cf. Fig. 1b and Table 1), fleet sizes in the order of 3400–3900 light-duty (passenger cars), 340–360 medium/heavy-duty trucks and 70–100 Class 8 heavy-duty trucks would have similar energy demand and revenue potential. In reality, commercial fleets operate under a wide range of conditions, so these thresholds are indicative; separate analysis will be needed for each situation.

Reaching carbon neutrality will require significant changes across multiple sectors of the economy. Interactions, within and across sectors, can create feedback loops that introduce complexity and make the transition more difficult. However, these interactions are not always negative and this Perspective article has attempted to show situations in which interactions can be used to aid the transition to a more sustainable future.

**Supplementary data**

Supplementary data is available at Clean Energy online.

**Data availability**

Data and analysis for figures and tables are included as online Supplementary Information. Further information and requests for resources and reagents should be directed to and will be fulfilled by the Lead Contact, Anthony Ku (anthonyku@nicenergy.com). Data on vehicle populations were obtained from the California Transit Authority and verified at individual transit-agency websites. Data on energy production, including capacity and generation, were...
obtained from the California Energy Commission and California ISO (CAISO) websites. Other data were obtained from references as cited in the text.

Conflict of interest statement
None declared.

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